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Oil Refineries. O. Ocic

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Oil Refineries in the 21st Century

Energy Efficient, Cost Effective, Environmentally Benign

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Dr. Ozren Ocic
NIS-Oil Refinery Pancevo
Spoljnostarcevacka b. b.
26 000 Pancevo
Serbia

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Table of Contents

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Preface

The increasing competition among the oil refineries of the world, which results in fewer and larger installations, calls for a clear understanding of the economics and the technological fundamentals and characteristics.

According to its basic function in the national energy system, the oil-processing industry actively participates in attaining the objectives of energy and economy policy at all levels of a society. In many national economies today, oil derivatives participate in more than one third of the final energy consumption, the same as crude oil in available primary energy. This proves that oil and its derivatives are still among the main pillars of national industry, and the oil-processing industry one of the main branches in energetics, despite all the efforts to limit the application of liquid fuels for thermal purposes, considering the need to limit the import of crude oil.

In addition to being one of the main energy generators, and a significant bearer of energy in final use, oil-processing industry is at the same time a great energy consumer. The importance of the oil-processing industry as one of the main pillars of national energetics, obligates it to process oil in a conscientious, economical way. The mere fact that oil refineries mostly use their own (energy-generating) products does not free them from the obligation to consume these energy carriers rationally. Rational consumption of oil derivatives should start at the very source, in the process of derivative production, and it should be manifested in a reduction of internal energy consumption in the refineries. The quantity of energy saved by the very producer of energy will ensure the reduction in the consumption of primary energy in the amount that corresponds to the quantity of the produced secondary energy.

From the aspect of a rational behaviour towards the limited energy resources, the oil-processing industry should be treated as a process industry that uses considerable quantities of energy for the production. The mere fact that these products are oil derivatives, i.e. energy carriers, does not affect the criteria for rational behaviour. In that sense, oil processing industry is treated in the same way as the other process industries from non-energy branch.

The book gives a detailed practical approach to improve the energy efficiency in petroleum processing and deals with the role of management and refinery operators in achieving the best technological parameters, the most rational utilization of energy, as well as the greatest possible economic success.

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I would like to express my gratitude to Prof. Dr. Siegfried Gehrecke and Dr. Bozana Perisic, both long-time colleagues, who greatly contributed with their professional knowledge to the quality of this book. I would also like to thank Dr. Hubert Pelc of Wiley-VCH and all other staff involved, who made this book available to oil industry experts from all over the world, as well as to those having similar aspirations.

Pancevo, September 2004 *Ozren Ocic*

1

Introduction

In the early 1970s, it was clear that the world economy was facing recession and that the four-fold increase in crude-oil prices by OPEC, a monetary crisis, and inflation were the main reasons for such a trend. The four-fold increase in crude-oil prices in 1974, which was intensified in 1979, is why 1974 and 1979 are called the years of “the first” and “the second crude-oil shock”, respectively. Increases in crude-oil prices had an effect on all importing countries, more precisely on their economic development. This effect depended on the quantity of oil that was being imported and on the possibility of substituting liquid fuel with solid fuel or some alternative forms of energy. The fact remains that oil-importing dependence in developed countries varied, ranging from some 20% in the USA, for example, up to 100% in Japan, and this was how the increase in crude-oil prices that affected developed countries was interpreted differently, starting from “crude-oil illusions” to “sombre prospects”, depending on who was giving the interpretation.

However, in underdeveloped countries, the effects of the rise in crude-oil prices were unambiguous, especially in the countries that lacked both oil and money, and were forced to solve their energy problems by way of import.

When commenting on economic trends and making forecasts, it became customary after each increase in crude-oil and oil-product prices, to predict to what percentage this increase would affect monthly, and therefore annual, inflation. Considering that crude oil has priority in the energy–fuel structure and that oil-product prices in the course of the 1970s and 1980s increased up to twenty times in comparison with the base year – 1972, it became clear that energy was the main cause of inflation.

The fact that economic policy subjects in all those years, had not taken measures to decrease the share of imported energy in the domestic energy consumption, supports the assumption that they attributed much greater importance to demand inflation than to cost inflation.

The compound word “stagflation”, representing the combination of two words “stagnation + inflation”, was related to demand inflation that, being accompanied by the stagnation in economic development, presented the most difficult form of economic crisis and in accordance with that the suggested measures were directed towards decreasing the demand inflation, i.e. decreasing citizen spending capacity. The arguments against this interpretation are economic theory, on the one hand, and in practical terms on the other. Namely, economic theory does not accept the

Oil Refineries. O. Ocic

ISBN: 3-527-31194-7

possibility of a simultaneous apperance of demand inflation and economic-growth stagnation.

"After World War II, economies were often stagnating, meaning that there was no surplus in global demand, but the prices continued to increase. Economists call these situations – stagflation (stagnation + inflation). In situations like these, interpretation of inflation is complicated. It can no longer be explained by overdemand, but by cost inflation, or by both together" [1].

In the sphere of cost inflation, the following are stated: spiral of wages and prices, uneconomic consumption, import costs and sector inflation, and in the sphere of structural inflation: import substitution, inequality regarding the sector economic position and foreign trade exchange.

Bearing in mind the crude-oil price trends in the world market, the dependence of some countries on crude-oil imports and the importance of energetics as a branch with tremendous external effects, it could be concluded that cost inflation is caused by imports and that its mechanism is simple. By incorporating the ever more expensive imported feedstock into product prices, without meaningful attempts to compensate, at least partially, this cost by internal economy measures, selling prices started to increase. Considering that energetics directly or indirectly contributes to the prices of all other goods, inflation started to develop. On the other hand, it was proven in practice that economic-policy measures directed towards decreasing the demand inflation by decreasing citizen spending capacity have not resulted in an inflation rate decrease, which leads to the conclusion that it is some other type of inflation, not demand inflation.

If this "diagnosis" were accepted, i.e. if it were accepted that it was mostly cost, psychological and structural inflation rather than demand inflation, it would mean that adequate "therapy" would have to be accepted as well, that is suitable economic-policy measures affecting inflation in the mentioned order.

It has been shown in practice that product prices incorporate all the faults and drawbacks of the internal economy without any significant attempts to find ways to stop the increase and even cut the prices, by way of a better utilisation of production capacities, greater productivity, better organisation, etc. Each increase in prices was explained by the increase in costs, the tendency to eliminate business losses or by the fear from operating with loss. In the conditions of free price forming, this last argument can mostly explain the so-called psychological inflation typical of the last couple of years. All the activities by business subjects were directed towards forecasting and determining business costs without analysing the cause or finding the possibility to reduce them by adequate internal economy measures.

This is supported by the fact that in one of the basic economy branches that causes inflation in all other branches – the oil industry – there are no cost prices either for semi-products or for products, but only cost calculations per type of costs. Justification for such a practice can be found in the fact that the feedstock, i.e. crude oil (mostly imported) has the greatest share in the cost-price structure, and this is something that the oil industry has no effect on. However, when this problem is more thoroughly analysed, it can be seen that other costs are not irrelevant either, that great savings are possible, but also that the crude-oil share in the cost-price structure shows a tendency to decrease. For years, efforts were made to prove that it was impossible to determine cost prices because it was coupled products that were in question and that it was not possible to distribute the costs per cost bearer.

It is becoming even clearer that a methodology must be established to determine the cost prices and refinery products, so that by way of actual planning calculations, i.e. by way of calculations per unique prices (which would eliminate the inflation influence), refinery business operations could be monitored, by comparing the calculations between the refineries across the world. In order to make this possible, it is necessary to select a common methodology that would be improved through practice.

From the aspect of rational power utilization, it must be pointed out that, when evaluating the total rationality of power utilization in industry, the adopted objectives of energy and economic policy must present a starting point, as well as the question whether and to what extent the existing way of utilizing the power contributes to attaining these objectives.

In addition to giving priority to domestic instead of imported energy carriers, one of the objectives of national energy and economy policy is economic, conscientious, and rational behaviour towards the limited energy resources. This objective is attained by way of numerous technical, organizational and other measures for rational energy consumption. The effects of energy-consumption rationalization are mostly measured by:

- indicators of specific energy consumption per product unit, or
- indicators of specific energy costs per product unit.

Both indicators have their function and complement each other, which indicates that economical behaviour has its technical and economic effects, which may, but do not have to, coincide.

According to its basic function in the national energy system, the oil-processing industry actively contributes to attaining the objectives of energy and economy policy at all levels of a society. In many national economies today, oil derivatives participate in more than one third of the final energy consumption, the same as crude oil in available primary energy. This proves that oil and its derivatives are still among the main pillars of national industry, and the oil-processing industry is one of the main branches in energetics, despite all the efforts to limit the application of liquid fuels for thermal purposes, considering the need to limit the import of crude oil.

In addition to being one of the main energy generators, and a significant bearer of energy in final use, the oil-processing industry is at the same time a great energy consumer. The importance of the oil-processing industry as one of the main pillars of national energetics, obligates it to process oil in a conscientious, economical way. The mere fact that oil refineries mostly use their own (energy-generating) products does not free them from the obligation to consume these energy carriers rationally. Rational consumption of oil derivatives should start at the very source, in the process of derivative production, and it should be manifested in a reduction of internal energy consumption in the refineries. The quantity of energy saved by the very producer of energy will ensure the reduction in the consumption of primary energy in the amount that corresponds to the quantity of the produced secondary energy.

From the aspect of a rational behaviour towards the limited energy resources, the oil-processing industry should be treated as a process industry that uses considerable quantities of energy for the production. The mere fact that these products are oil derivatives, i.e. energy carriers, does not affect the criteria for rational behaviour. In this sense, the oil-processing industry is treated in the same way as the other process industries from the non-energy branch.

Analysis of the oil-processing industry as a processing industry that uses considerable quantities of energy for the production starts, as in all the other industries, energy consumers, with an analysis of the energy system.

This book deals with the possibility of a rational production and consumption of energy, thus with a more economical running of business in the oil-processing industry.

2
Technological and Energy Characteristics of the Chemical Process Industry

In the field of industry, as a branch of the economy, specific forms of material processing have been developed, marked by changes of chemical properties. Such a method of production, characterized by chemical changes, and often followed by physical transformations, is called the process industry. It can be defined as “a group of industry (and mining) sectors in which feedstock is chemically treated for making final products” [2].

The process technology dealing with industrial feedstock processing, by changing their structural and physical properties, appeared at the beginning of the twentieth century, due to the development of the chemical industry, wherein the manufacturing procedure is a chain of several units. The feedstock in each one is treated in a different mode, and their aggregate functioning has to be organized in such a way as to achieve the optimum result, namely to maximize the benefit or profit, to minimize the inputs, and also to meet other criteria, such as for instance, product quality, requirements of regional product market, environmental protection, and other possible specific requirements.

Optimum functioning of each separate unit is not always feasible, when aiming at optimum functioning of the whole combined process plant.

Within the classification of industrial branches, there are some that do not strictly meet the criterion of predominant chemical changes in the feedstock, but nevertheless they are looked upon as a part of the process industry, due to additional criteria, mainly if physical changes are involved.

The main branches in this group of process industry are as follows [3]:

- Electric power,
- Coal mining,
- Petroleum refining,
- Metallurgy of iron and steel,
- Nonferrous metallurgy,
- Non-metal mineral processing,
- Basic chemicals manufacture,
- Processing of chemical products,
- Building material manufacture,
- Manufacture of wood construction materials,

Oil Refineries. O. Ocic

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- Pulp and paper industry,
- Textile fibers and filaments,
- Leather and fur manufacture,
- Rubber processing,
- Food products,
- Manufacture of beverages,
- Tobacco processing,
- Miscellaneous products manufacture.

"When classifying some branches of industry and mining to the field of process industry, the criterion of chemical transformation, at least in a wider sense, has been persistently applied. Therefore, for instance, a chemical industry group – plastics processing with subdivisions: production of wrapping material and various plastics – should not be included into the process industry, because in such technologies they are but physical transformations" [4]. The author of this quotation believes that the following industrial branches should not be included in the group of process industry:

- Cattle-food production,
- Fiber spinning,
- Human foodstuffs and grocery production.

All the process-industry branches are characterized by extremely complex technological procedures; they are materialized in sophisticated production equipment, by highly trained experts in managing and maintenance activities. Because of such advanced production processes, the problems of monitoring the technological and energy efficiency necessarily arise in many cases.

2.1
Possibilities for Process-Efficiency Management Based on Existing Economic and Financial Instruments and Product Specifications in Coupled Manufacturing

From the aspect of existing business operations efficiency, especially in coupled production, the possibilities of efficiency management appear to be limited, due to the development lag of the calculating methods for production costs or product selling prices, in comparison with the advances in overall economy and specific business activities.

"Comparing the developments in accounting, especially the improvements in calculating techniques to the advances of technology, one can hardly understand that calculation as a methodological procedure falls behind the available technical support. Overcoming this draw-back by paying more attention to the accounting, especially to the methods and ways in calculation, many errors could be avoided, which in some cases are a source of big losses" [5].

Former simple calculations, based on estimated direct and fixed costs, which were added in full amounts, nowadays have been changed by ascertaining the calculating costs based on accounting data, as well as by determining the fixed costs in terms of a relevant index, and not in full as up to that period.

Pushing for profit has been the reason for substantial development in cost calculation. It became obvious that distinctive calculation methods had to be defined for different companies and dissimilar industrial branches. The causative principle also has to be followed, as well as the connection between the charges per places of costs, and the charges per cost bearers, namely all that in relation to the extent of costs incurred by a particular product.

The next step in calculation advances was the defining of the standards for costs per product on a scientific basis. In many industrial activities such a procedure enables precise assessment of direct costs, while fixed costs have to be ascribed to the cost bearers and products by relevant keys observing corresponding causalities.

The biggest problem in process technology, in terms of the business-management procedures, is the fact that this process consists of specific manufacturing operations, marked by finishing of coupled products. Therefore, considering the existing economic and financial instruments, it could be concluded that the efficiency management in process technology is to a great extent limited. This fact calls for the improvement of the existing criteria of business efficiency, as well as for research in new assessment methods.

Efficiency management in process technology for increasing the profit and minimizing the process expenses is linked to the prerequisite of defining the cost calculations, and their comparison to the selling prices in the market.

Calculation as an instrument of business policy is especially important in process technology, because there is no direct way of charging the expenditures to the cost bearers. Therefore direct linking of the costs is not possible in the case of feedstock or in other calculation elements.

The main reason lies in the fact that this is a process industry where a full slate of products, differing in quality and by use value, is obtained from a single feedstock on a single unit. Relating the basic feedstock costs to all products, and observing their individual quality as obtained on a particular processing unit, does not, in fact, present the real causality of costs for a single product. All the products cannot be evenly treated from the aspect of production motive. Namely, within a product slate we can recognize the products, on account of which the production process is organized, as well as by-products, which are inevitable, in a process. These products must not be treated in the same way from the aspect of charging the costs to their carriers.

The existing methods for cost calculations are the most convenient for processes without coupled production. Cost calculations in such processes are easy procedures, because ascribing the direct expenditures to the cost bearers is simple, whereas overhead and common expenses are distributed by corresponding keys to the cost bearers.

In the case of coupled products, both direct and indirect charges should be ascribed to the cost bearers by corresponding keys, for instance in the chemical industry, sugar industry, petroleum processing, thermoelectric-power production, etc. In these industry branches, the elective division calculation with equivalent numbers should be used. So far, such accounting has existed only in theory but not in practice, especially in petroleum refining. Subsequent chapters of this book will depict exactly the possibilities of applying these calculations to practice.

2.2
Importance of Energy for Crude-Oil Processing in Oil Refineries

A large amount of energy is used in oil refineries for crude-oil processing.

A refinery itself can ensure all the utilities required for its operation by means of more or less complex energy transformations, using a part of the products obtained by crude-oil processing. Therefore, crude oil for a refinery presents not only a feedstock, but also the main source of energy, required for crude-oil processing. This fact aggravates a clear separation of a refinery-utilities system from crude-oil processing.

On the other hand, this fact ensures that the energy-consumption level, i.e., energy-utilization efficiency in crude-oil processing can be presented by a special indicator, i.e. by the inlet crude-oil amount used by a refinery for its own energy requirements in crude-oil processing. A proportional part of “energy” consumption of crude oil in the total quantity of crude-oil processed is usually observed as an indicator.

Today, in oil refineries, the share of crude oil used for energy generation is in the range of 4% to 8%, depending on the refinery complexity level. Complexity, i.e. “a depth of crude-oil processing” is increased as the range of products and the number of so-called secondary units is enlarged” [6].

The level of energy requirements in an oil refinery, is increased by the level of complexity and it is expressed as follows:

- As the share of energy consumption in total quantity of crude-oil processed, or
- As a specific energy consumption per tonne of processed crude oil, or per tonne of generated refinery products.

The dependence of specific energy consumption on complexity level and oil refinery efficiency is shown in Fig. 1, taking 28 US refineries as examples.

It can be clearly seen that the level of energy requirements is increased by the level of complexity and that the oil refineries with the same level of complexity can have low and high level of energy efficiency [7]. The difference between energy-efficient oil refineries (line b), and energy-inefficient oil refineries (line a), is a real possibility for rationalization of the energy consumption in energy-inefficient refineries. Inefficient refineries can decrease their internal energy consumption by 20–30% by using more efficient technological, energy and organizational solutions. These percentages are not small, considering the share of energy costs in total costs of crude-oil processing. This can be illustrated in the following manner: a refinery whose share of crude-oil energy consumption is 5%, must operate 16 days/y to meet its own energy requirements.

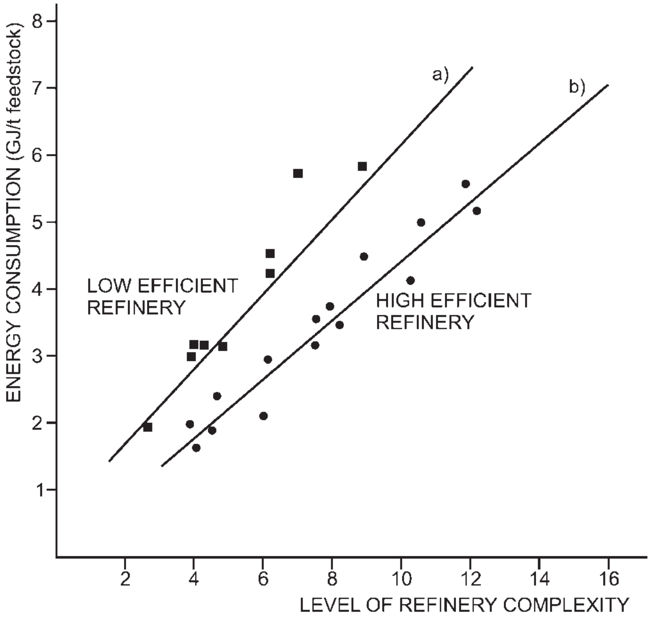


Fig. 1 Dependence of specific energy consumption on the level of complexity and efficiency, taking 28 US oil refineries as examples

Namely, the good possibilities for rationalization of energy consumption exist because existing refineries were built in the time when energy was cheap, and when the investors did not devote much attention to the costs of energy. For that purpose, world-leading oil companies carried out rationalization [8] and suggested energy-saving programmes in the 1970s. These energy-saving programmes consist of the following actions:

- Continuous monitoring of energy costs,
- Identifying the places of irrational energy consumption and preparing the energy-saving project,
- Modernization of equipment and introduction of computer management,
- Reconstruction of existing equipment and intensification of the maintenance process,
- Arranging continuous professional training of operators and increasing the motivation and responsibilities of employees,
- Improvement of process management and direct engagement in rationalization of energy consumption, etc.

The first results of these energy-conservation programmes were obtained in the 1970s: energy costs were decreased by 7.8% in 1974 and by 8.9% in 1975, as compared to 1972 when the energy-conservation programme was implemented.

The process of energy-consumption rationalization is still underway: in the West, it has already reached a more complex and sophisticated level, while in other countries, it is still in the elementary, initial phase.

NOTE: The amount of utilities spent per process, as well as the amount of some process losses is based on the values that are measured in oil refineries from South-East Europe.

The target standards for comparing the energy consumption of an analysed typical oil refinery present the average standards of energy consumption in European refineries.

3
Techno-economic Aspects of Efficiency and Effectiveness of an Oil Refinery

As an example, techno-economic aspects of efficiency and effectiveness of crude-oil processing are analysed in a typical 5 million t/y refinery that consists of the following units: crude unit, vacuum-distillation unit, vacuum-residue visbreaking unit, bitumen, catalytic reforming, catalytic cracking, gas concentration unit, hydrodesulfurization of jet fuel and gas oil and alkylation.

The efficiency, expressed as the input/output ratio, is analysed on each refinery unit separately, from the energy and processing aspects, and the effectiveness, as a value of output, is analysed taking the refinery complex as an example, from the energy and processing aspects, as well.

From the aspect of energy, the efficiency is determined as the input/output ratio, i.e. as a relation of used resources and realized production, through the costs and use of products in the following manner:

- Through the costs, by determining the cost prices of high-, medium- and low-pressure steam generated in some refinery units and that are expressed in the following manner:

$$\frac{\text{Costs of steam generation (in US\$/t)}}{\text{Quantity of produced steam (in tonnes)}}$$

For example, the cost price of medium-pressure steam (MpS) produced in the vacuum-distillation unit is 0.44 US$/t and it is determined in the following manner:

$$\frac{74636\ \text{US\$}}{170000\ \text{t}} = 0.44\text{US/t}$$

- Through the consumption, by determining specific steam consumption per tonne of feed, which is expressed as follows:

$$\frac{\text{Steam consumption (in kg)}}{\text{Feed (in tonnes)}} \text{ or } \frac{\text{MJ}}{\text{t of feed}}$$

For example, the specific gross medium-pressure-steam consumption in relation to the quantity of light residue, on a vacuum-distillation unit is calculated as follows:

Oil Refineries. O. Ocic

ISBN: 3-527-31194-7

$$\frac{89 \text{ kg steam}}{\text{t of feed}} \text{ or } 266.1 \frac{\text{MJ}}{\text{t of feed}}$$

- Also, through the consumption, energy efficiency is determined by the (in)efficiency index and by comparing the net consumption energy objective standards that present, in this case, the average energy consumption standards of Western European refineries and specific energy consumption of a typical oil refinery being analysed and is expressed as follows:

$$\frac{\text{Specific net energy consumption (MJ/t)}}{\text{Objective net energy consumption standard (in MJ/t)}}$$

For example, the (in)efficiency index of the vacuum-distillation unit is 140 %, and it is calculated in the following manner:

$$\frac{1095.5 \text{ MJ/t}}{800.0 \text{ MJ/t}} = 140 \ \%$$

From the aspect of energy, the effectiveness is determined through the money savings that can be achieved by eliminating the cause of inefficiency, i.e. by eliminating differences between the objective energy consumption standard and internal energy consumption of the mentioned refinery units, and is expressed in the following manner:

$$\text{Quantity of feed (in tonnes)} \times \text{difference in objective and internal consumption (US\$/t)}$$

For example, the money savings that can be achieved on vacuum-distillation unit, if certain measures are taken to eliminate the difference between the objective energy consumption standard and internal energy consumption, is 1 273 239 US$. This amount has been determined in the following manner:

$$2122065 \text{ t} \times 0.60 \text{ US\$/t} = 1273239 \text{ US\$/t}$$

From the aspect of the process, the efficiency is determined as the input/output ratio, i.e. as the ratio of the used resources and achieved production, through the cost prices of refinery products that are produced in the refinery units, as semi-products to be blended into market-intended products.

The efficiency of the process is expressed through the costs in the following manner:

$$\frac{\text{Production costs of refinery products (in US\$)}}{\text{Quantity of produced refinery products (in tonnes)}}$$

For example, the cost price of a product named vacuum gas oil that is produced on a vacuum-distillation unit is 190.56 US$/t, and it is determined in the following way:

$$\frac{48873966\ \text{US\$}}{256477.8\ \text{t}} = 190.56\ \text{US\$/t}$$

From the same aspect, the effectiveness of an oil refinery, as an output value in the market, is determined through calculations of the product cost prices, by calculating the profit or loss for each individual oil product. Profit or loss is calculated as the difference between the selling price and cost price,

$$\text{Selling price} - \text{cost price} = \text{profit or loss}$$

For example, the profit of 26.19 US$/t that is made by production of propane is calculated in the following manner:

$$254.60\ \text{US\$/t} - 228.41\ \text{US\$/t} = 26.19\ \text{US\$/t}$$

Considering that the efficiency is observed on the level of smaller organizational parts, i.e. on the level of refinery units, and the effectiveness on the level of refinery, as a whole, it can be concluded that the efficiency is mainly in the competence of the operative management and the effectiveness in the competence of strategic management.

3.1
Techno-economic Aspects of Energy Efficiency and Effectiveness in an Oil Refinery

Energy efficiency is analysed taking an oil refinery complex as an example, which consists of the following refinery units: crude unit, vacuum-distillation unit, vacuum-residue visbreaking unit, bitumen, catalytic reforming, catalytic cracking, gas concentration unit, hydrodesulfurization of jet fuel and gas oil, and alkylation.

From the aspect of costs, the energy efficiency is analysed through cost prices of high-, medium- and low-pressure steam produced in some of the mentioned refinery units, and from the aspect of consumption, the efficiency is analysed by determining the specific steam consumption per tonne of feed, as well as by determining the (in)efficiency index that is calculated by comparing the net energy consumption objective standards (average energy consumption standards of Western European refineries) and specific energy consumption in the units of a typical oil refinery being analysed.

Energy effectiveness is determined on the basis of the money savings that can be achieved by eliminating the differences between objective energy consumption standards and internal energy consumption of the mentioned refinery units.

Analysis of the steam cost prices described in the next chapter demonstrates that the cost price of high-pressure steam (HpS) generated in catalytic cracking is 3.10 US$/t, i.e. it is one third that of the steam generated on a refinery power plant. It can also be seen that the cost price of medium-pressure steam (MpS) generated on a crude unit is 0.47 US$/t, on a vacuum-distillation unit 0.44 US$/t, on a vacuum-residue visbreaking unit 0.22 US$/t, on a catalytic reforming unit 0.45 US$/t, on a catalytic cracking unit 2.53 US$/t, while the cost price of medium-pressure steam generated on a refinery power plant is 9.66 US$/t. It can be seen that the cost prices of medium-pressure steam MpS, generated on a crude unit, a vacuum-distillation unit and catalytic reforming are twenty times lower than those of medium-pressure steam (MpS) generated on a refinery power plant.

Similar trends in cost-price ratios regarding the steam generated in refinery units and that generated in refinery power plant, can be noted in the case of low-pressure steam costs. So, the cost price of the steam generated in refinery units is twenty times lower than that of the steam generated in refinery power plant. The basic explanation for such cost prices of high-, medium- and low-pressure steam generated in refinery units, lies in the fact that this steam is obtained as a by-product, by utilizing the heat of flue gases and heat flux, thus eliminating the consumption of process fuel (fuel oil and fuel gas) that shares in the calculation of the steam cost, generated in refinery power plant, with about 80%. This cost of fuel is completely eliminated on a crude unit, a vacuum-distillation unit, a vacuum-residue visbreaking unit and a catalytic reforming unit and is partially eliminated on a catalytic cracking unit.

In addition to the elimination of process fuel consumption, completely or partially, the steam cost price is also affected by the treatment methodology of steam as a by-product. In this manner, direct costs, for example, of demineralized water, depreciation, current and investment maintenance and insurance premium of the equipment engaged in steam production, are only included in the steam cost price, while the other unit costs are included in crude-oil processing costs, which is the main refinery activity.

From the aspect of utilities consumption, the energy efficiency is analysed by determining the specific steam consumption per tonne of feed. It can be seen that, by analysing the specific steam consumption, on a crude unit, in relation to 5 million tonnes of crude-oil processed, that the specific gross medium-pressure steam consumption is 89 kg/t of feed, whereas the specific net consumption is 86 kg/t. On a vacuum-distillation unit, specific gross medium-pressure steam consumption (MpS), compared to the quantity of light residue is 89kg/t of feed, and specific net consumption is 9.5 kg/t. On a vacuum-residue visbreaking unit, the specific gross medium-pressure steam consumption (MpS), related to the quantity of feed, is 138.7 kg/t. On a bitumen unit, the specific gross medium-pressure steam consumption (MpS), related to the quantity of feed, is 480 kg/t. On a catalytic reforming unit, the specific gross medium-pressure steam consumption (MpS), related to the quantity of feed, is 150 kg/t, whereas the specific net consumption is 233.8 kg/t, etc.

Energy efficiency is analysed by determining the (in)efficiency index that is calculated by comparing the objective standard of net energy consumption (average energy consumption standards of Western European refineries) and specific net energy consumption in each refinery unit on a typical refinery, which is the subject of this analysis. It can be seen, taking the observed refinery complex as an example, that the average (in)efficiency index is 131%, while at the same time, the crude unit (in)efficiency index is 137%, the vacuum-distillation unit (in)efficiency index is 140%, the vacuum-residue visbreaking unit (in)efficiency index is 110%, the bitumen unit (in)efficiency index is 125 %, the catalytic reforming unit (in)efficiency index is 115 %, the catalytic cracking unit (in)efficiency index is 116 %, the jet-fuel hydrodesulfurization unit (in)efficiency index is 164 %, the gas-oil hydrodesulfurization unit (in)efficiency index is 141, and alkylation unit (in)efficiency index is 193.

Energy effectiveness is also analysed taking a typical 5 million t/y oil refinery as an example.

Energy effectiveness is determined through the savings achieved by eliminating the differences between the objective standard of energy consumption and internal energy consumption of each refinery unit, on a refinery complex, which is the subject of the next chapter. The mentioned refinery complex includes the following units: crude unit, vacuum-distillation unit, vacuum-residue visbreaking unit, bitumen, catalytic reforming, catalytic cracking, gas concentration unit, hydrodesulfurization of jet fuel and gas oil and alkylation.

By applying certain measures suggested in this book, significant savings of 9.2 million dollars/annum can be achieved: in the crude unit, possible money savings are 4.7 million dollars, in vacuum distillation, possible money savings are 1.2 million dollars, in the vacuum-residue visbreaking unit, possible money savings are 0.4 million dollars, in the bitumen unit, possible money savings are 0.1 million dollars, in the catalytic reforming unit, possible money savings are 0.5 million dollars, in the catalytic cracking unit, possible money savings are 0.5 million dollars, in the jet-fuel hydrodesulfurization unit, possible money savings are 0.3 million dollars, in the gas-oil hydrodesulfurization unit, possible money savings are 0.3 million dollars, and in the alkylation unit, possible money savings are 1.1 million dollars. The mentioned money savings can be achieved by eliminating the difference between the objective standard of net energy consumption and the consumption of analysed units on a typical oil refinery, i.e. by eliminating the causes of inefficiency.

The most important causes of inefficiency that can be eliminated by corresponding technological and organizational solutions are as follows:

- Inefficient preheating of combustion air by using the heat of flue gases in the process heater,
- Energy nonintegration of the plants,
- Non-economical combustion in the process heater,
- Inefficient feedstock preheating system,

3.2
Techno-economic Aspects of Process Efficiency and Effectiveness in an Oil Refinery

Refinery efficiency and effectiveness are analysed through the cost prices of semi-products and finished products. The emphasis is placed on the problems and dilemmas that the management of refinery units and the refinery, as a whole, have to face when choosing the cost pricing methods for the semi-products, which are then blended into finished products, in the final phase, and then sent to the market.

In subsequent chapters of this book, the following problems will be pointed out:

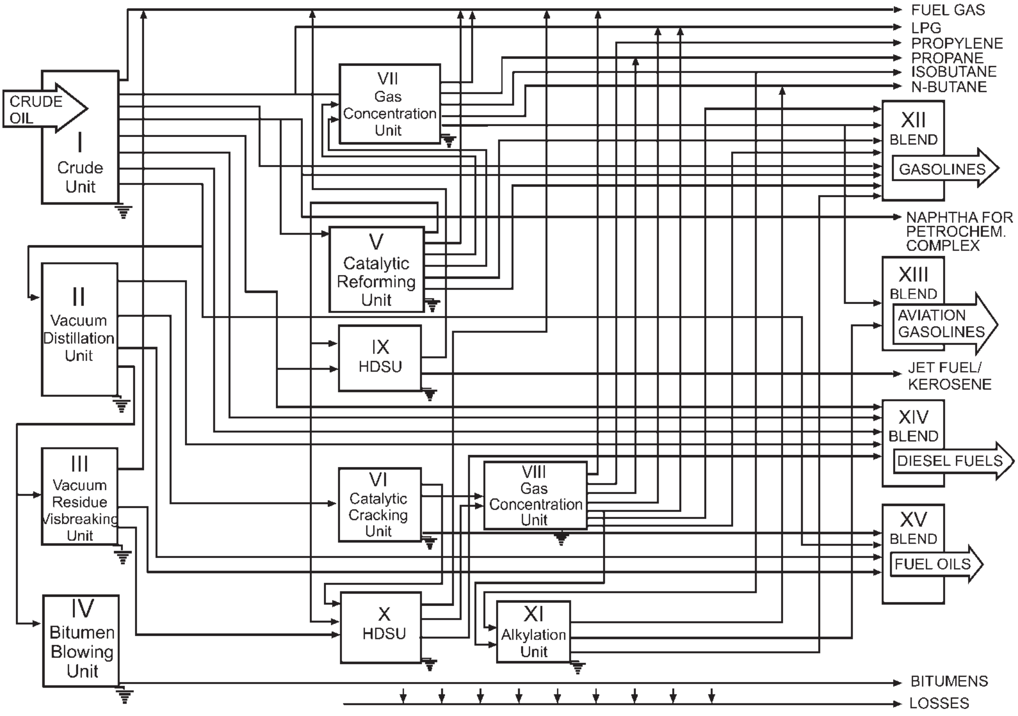
- Complexity of crude-oil processing,
- Complexity of the possible refinery product cost-pricing methodology, i.e. the cost prices of semi-products and finished products, as the instruments for monitoring the process efficiency and effectiveness.

Specific characteristic of the crude-oil processing is the production of “coupled products” where qualitatively different products are simultaneously derived from the same raw material, and that are then blended into the final products.

In Scheme 1 it can be seen that the crude oils are mixed when passing through the refinery units. This demands attentive monitoring of each unit input/output, as well as distributing the cost to the bearers of costs, using computers and multidisciplinary expert teams from inside and outside of petroleum companies.

The complexity of possible methodology for determining the refinery product cost prices is dependent on the complexity of crude-oil processing.

From the methodological aspect, determining the cost prices of finished products is simpler than determining the cost prices of semi-products. Finished product cost



Scheme 1 Material flows and balance in a typical oil refinery

prices are calculated by multiplying the quantity and cost prices of semi-products. The semi-products blended into particular finished products often originate from several refinery units, as for example, in the case of gasoline, which is the result of blending the semi-products from eight refinery units: crude unit, vacuum-residue visbreaking unit, fluidized catalytic cracking, alkylation, gas concentration unit, gasoline redistillation, aromatics extraction and catalytic reforming.

The procedure for determining the cost prices of finished products has three phases.

In the first phase, the total refinery costs are distributed to the refinery units.

In the second phase, the costs of each mentioned unit are distributed to semi-products, which are obtained on these units. In this phase, the role of operative management is important when choosing the calculating base for determining the equivalent numbers, as well as the reference semi-products for determining equivalent numbers, because the use of elective division calculation with equivalent numbers (as the most complex form of accountancy calculation) is necessary.

It must be pointed out that the effect of choice of calculating basis on the level of refinery products cost prices is of extreme importance, and therefore, the choice of one of the following methods must be made very carefully:

- density method,
- thermal value method, and
- average production cost method.

These methods are convenient for determining the semi-product cost prices by using elective division calculation with equivalent numbers. However, advantages and disadvantages of each method should be taken into consideration (see Chapter 4 “Instruments for determining energy and processing efficiency”).

Besides the importance of the choice of calculating base for determining the equivalent number, the choice of reference derivative is also important, but less so than the choice of calculating base. Determining the by-products of every refinery unit, as well as their treatment in the procedure of applying the elective division calculation with equivalent numbers, also appears as the problem, which the management of a refinery has to contend with.

In the third phase, semi-products are blended into finished products. Although it often involves the blending of ten, fifteen, or even more than twenty semi-products, at previously calculated semi-product cost prices, with the inclusion of initial and final stock of semi- and finished products, the phase itself does not present a problem.

These very complex processes present a challenge for the expert teams dealing with the cost prices as instruments of management system in monitoring the process efficiency of crude-oil processing and business effectiveness of a refinery, especially when it is known that the literature about this area is very scant.

Some of the methods, which can be found in the literature, are applied only for determining the finished product cost prices, and this is the biggest disadvantage of these methods. Other methods can be applied for determining the semi-product cost prices as well as the finished product cost prices, which are obtained by blending the semi-products at their internal cost prices.

The sales-value allocation method [9] and the by-product method [10] are methods frequently encountered in determining the cost prices of products.

The sales-value allocation method is one of the simplest cost-determination methods frequently encountered in the literature. According to this method, the cost price is determined in such a way that the sales value of oil derivatives is decreased by actual profit in an equal amount for each tonne of derivatives, and/or increased by actual loss, also in an equal amount for each tonne of derivatives.

The positive aspect of this method is its simplicity and the possibility of cost-price determination in a very short period of time. On the other hand, there is much more criticism on account of this method's application, such as:

- Application of this method is possible only for determining the cost prices of finished products. This method cannot be used for determining the cost prices of semi-products because in crude-oil processing, there are no selling prices for semi-products, but only for finished products.
- Assuming that profit is equal for each product it would mean that from the standpoint of importance, all products are equal, which is absolutely illogical, either from the aspect of product value or product usability. This can signify that equal profit is made on the products treated as "the main products", i.e. on the products for which the production process is organized, as well as on by-products that appear because of the nature of the process, and also on the products used for internal consumption (fuel oil or fuel gas), or for the gas that is burned on the flare.
- At the end, when determining the cost price of products, one should not start with the selling prices, but with the cost of crude oil and operational costs of refinery units, because the selling price is the result of many economic and non-economic factors, which are different in various countries. For example, the influence of the government in those countries where the market prices of refinery products are completely or partially under the government control. It is very often the case that, in addition to price control, the governments of these countries have the authority over the refinery-capacity development policy, even the refinery-processing structure – ratio of white to black products. The selling price results from the following: state tax policy, supply and demand, seasonal oscillations, competition, as well as the consumer-society influence, in the countries where these associations exist.

The second method for determining the cost prices, also encountered frequently in the literature as "conventional methods of refinery analysis" is "the by-product method". This method is based upon the premise that the sale of gasoline is the most important source of income and that the entire profit is made on this product. Other products make income at their production cost levels, i.e. they make no profit.

Disadvantages of this method are as follows:

- First, considering that the cost prices of by-products are made equal to the selling prices, it can be concluded that neither profit nor loss is made on by-products, which is not realistic, although, theoretically speaking, it might happen.

- Secondly, considering that all the profit is made on the main product, i.e. gasoline in this case, it can be concluded that the cost price of gasoline will be lower if profit made per tonne the of main product is higher.
- Thirdly, the cost of all products, the main ones and by-products, is directly related to the selling prices, which should not be related to each other, except in the last stage when the cost price determined is compared to the selling price in order to determine the actual profit/loss level.
- The last disadvantage is that this method is applicable only for determining the cost prices of finished, and not of semi-products, since selling prices are prescribed for finished products only.

Methods for determining the cost prices of semi-products, as well as finished products that are obtained by blending the semi-products, are as follows: density method, thermal value method and average production cost method.

The **density method** implies relating crude-oil costs to products based upon the density relations. This method assumes that it is extremely important to correctly relate the basic feedstock cost to products since crude oil shares in the product cost breakdown up to 80%.

According to this method, the basis for determining the equivalent numbers is the density of products related to the density of the reference product.

Resulting equivalent numbers applied to the quantities produced provide certain calculating units by means of which the respective units are reduced to the basic unit. To calculate the cost of one conditional unit it is necessary to divide the average price of one tonne of crude oil by the sum of conditional units and the value obtained multiplied by the conditional units per product. Relating other costs to derivatives is possible in the same manner as applied in the crude cost distribution, i.e. through equivalent numbers or by adding these in an identical amount.

The advantage of this method is the possibility of determining the cost prices of semi-products, as well as the finished products.

The drawback of this method is a very small range between the highest and lowest cost prices of the products obtained on refinery units. This drawback can be eliminated by applying the other method based on determining the equivalent numbers on the basis of the difference between the density and the number 1000. The procedure for determining the semi-product cost prices is similar to the previous method, but the results obtained differ substantially. Namely, instead of calculating equivalent numbers by means of density related to the selected reference derivatives, the aforesaid relations incorporate the difference between the density of oil derivatives and the number 1000 (density of water).

The main drawback of this method is the extremely large range between the highest and lowest cost prices of semi-products.

The **thermal value method**, the cost calculating method based upon equivalent numbers obtained from the derivative thermal value related to the thermal value of the reference derivative, is one of the methods also mentioned in the literature.

The procedure for applying this method is identical to that of the previous two methods for determining the semi-product cost prices. The main drawback of this method is a very small range between the highest and lowest cost prices.

The **average production cost method** is also worth mentioning [11].

This method is simple to apply because it is based upon cost determination at the average operational cost level per unit/plant. All this leads to the conclusion that the essential issue for this calculation is correct determination of costs per their location since the prices of all semi-products obtained in the refinery units are expressed as average unit costs.

The application of this method is simple, but whether the cost prices of semi-products generated on one unit can be identical to the average manufacturing costs of this unit is disputable.

The supporters of the by-product method, who observe the products as “main products” and “by-products”, from the aspect of the motives for organizing their production, cannot accept the fact that the main products, on account of which the production process has been arranged, and by-products, being a result of the process, have the same cost prices.

After the analysis of differences and similarities, advantages and disadvantages of the methods for determining the cost prices of semi-products and finished products, as the instruments for determining the efficiency and effectiveness of an oil refinery, the next chapter describes a possible method for determining the cost prices in crude-oil processing, based upon the differentiation of refinery product density.

4

Instruments for Determining Energy and Processing Efficiency of an Oil Refinery

In the process of determining the instruments for the management system in oil refinery energy and processing efficiency monitoring, it must be considered that this production process is very specific, being the production of coupled products, and that, from the aspect of the existing techno-economic and financial instruments, management of process-technology efficiency is limited to a great extent.

Management of process-technology efficiency aimed at profit increase and production cost minimization, implies the existence of a specific methodology for cost-price determination, so calculation, as an instrument of business policy, attains special significance in process technologies in which, due to the impossibility of direct cost distribution to the bearers of costs, it becomes necessary to use equivalent numbers. Bearing in mind the significance of energetics, as an industrial segment with extremely external effects, its influence on possible inflationary tendencies, as well as the possibility of transferring the petroleum industry to the market economy, it is clear that the conditions are being created to force the oil industry to start considering methodology for determining cost prices of semi- and finished products in refineries.

Such a methodology would make it possible for the profit, as a factor of successful evaluation in process-technology management, to be chosen by the process management, which would minimize the costs and maximize the positive effects.

Different methods regarding oil semi- and finished product cost-price determination can be found in the literature, some of which could be used for determining the cost prices for finished products only, such as: calculations based on the selling-price ratios, calculations based on the main and by-products ratios. Other methods are used for establishing the semi-product cost prices, and thus the cost prices of finished products, and some of these methods are: calculation based on the density ratio, the difference between density and the number 1000, calculation based on the heat value and the average processing costs on each unit, which was more thoroughly discussed in the previous chapter.

In the procedure of oil-product cost-price determination, distribution of costs to the places of costs is a simpler procedure than that of linking the costs to the bearers of costs, i.e. the products. Distribution and linking, especially for proportional costs, is particularly simplified, considering that the process-technology cost standardizing has advanced considerably. Both the literature and practice are rich in data that define distribution of proportional costs on all refinery units, so that the main organizational

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problem lies in establishing the book-keeping documentation. Thus, material and unit book keeping attain special significance, because precise distribution and linking of the costs to the places of costs is a condition for a precise distribution of the costs from the places of costs to the bearers of costs, i.e. products.

Within proportional costs in the crude-oil-processing industry, emphasis is on the consumption of crude oil, since this is the biggest and the most important cost. Crude oil is linked to the crude unit, which is the primary unit. Other proportional costs, such as utilities, (electric power, HP, MP, LP steam, cooling and demin water), fuel and chemicals, should be linked according to the consumption standards (projected, implemented or planned).

Fixed costs – depreciation of fixed assets, costs of current and investment maintenance, wages – can be accurately linked to the places of costs, while some other costs such as the management costs for the refinery (or lower organizational levels) and costs of common services, must be linked to all places of costs, according to the defined keys.

In the example of a typical refinery used for demonstrating the methods for the determining of the management-system instruments, i.e. cost prices, two basic places of cost are the starting point: crude-oil processing and blending.

Methodology for determining oil-derivate cost prices is demonstrated in the example of an oil refinery with completed primary and secondary processes, consisting of the following: crude-distillation unit, vacuum distillation, vacuum-residue visbreaking unit, bitumen plant, gas concentration unit with fractionation, catalytic reforming, catalytic cracking, hydrodesulfurization of jet fuel, hydrodesulfurization of gas oil and alkylation.

Tab. 1 Oil refinery cost calculation per places of cost, in US$

Item no	Elements for calculation	Refinery	Crude-oil processing	Blending
1	2	3	4	5
1	Derivate sale income	1 193 252 153		
2	Expenditures	1 161 607 333	1 114 594 247	47 013 086
2.1	Crude oil	936 002 547	936 002 547	–
2.2	Slop	9 978 716	9 978 716	–
2.3	Semi-products for finishing	17 490 072	–	17 490 072
2.4	Chemicals	11 406 698	4 075 672	7 331 026
2.5	Water consumption	34 505	34 505	–
2.6	Steam consumption	26 139 640	18 839 862	7 299 778
2.7	Electric power consumption	8 811 619	7 668 126	1 143 494
2.8	Process fuel consumption	18 835 489	18 835 489	–
2.9	Depreciation of fixed assets	6 047 350	3 147 047	2 900 303
2.10	Other costs	9 626 524	9 061 243	565 281
2.11	Wages, gross	27 624 497	21 499 821	6 124 677
2.12	Taxes	10 088 980	9 457 238	631 743
2.13	Management costs	16 981 261	16 425 170	556 091
2.14	Laboratory and maintenance costs	31 395 746	29 904 449	1 491 298
2.15	Common services costs	31 143 689	29 664 365	1 479 324
3	Profit	31 644 821	–	–

According to the complexity of the process, refineries are divided into several types. Nowadays, the most frequently mentioned grouping of refineries is the one according to S. Baarn and G. Heinrich.

Baarn divides refineries into four main types, according to the complexity of technological process.

A – the simplest type of refinery,
B – compound type of refinery,
C – complex refineries,
D – petrochemical refineries.

Group A includes the refineries consisting of crude-distillation unit, catalytic reforming and refining processes.

Refineries of group B, besides the units mentioned in group A, contain the units for vacuum distillation and catalytic cracking.

Group C consists of complex refineries with a complete slate of products including the production of lubricating oils.

Refineries in group D include petrochemical plants, as well as the plants for the production of aromatic hydrocarbons.

Heinrich also divides refineries into four groups:

1. hydroskimming refineries,
2. catalytic cracking refineries,
3. deep conversion refineries (hydrocracking – catalytic cracking),
4. deep conversion refineries (hydrocracking – coking).

According to this author, the mentioned types of refineries include the following units:

Hydroskimming refineries consist of crude unit, pretreatment, gas concentration by amine, catalytic reforming and hydrodesulfurization.

Catalytic cracking refineries in addition to the hydroskimming refinery units, include the following units: vacuum distillation, vacuum-residue visbreaking unit and catalytic cracking usually linked with alkylation.

Deep conversion refineries (hydrocracking – catalytic cracking), besides the units contained in hydroskimming refineries include the following units: hydrogen generation by steam reforming, vacuum distillation, hydrocracking, vacuum-residue deasphaltation by solvent, hydrodesulfurization of deasphalted oil, catalytic cracking with alkylation.

Deep conversion refinery (hydrocracking – coking) is a type of refinery where a coking process can be introduced to solve the problem of vacuum residue and to simultaneously provide hydrocracking feedstock.

The following division of refineries can be found in the literature:

1 – topping (crude unit)
2 – simple
3 – semi-complex
4 – complex

By the suggested methodology for determining the refinery product cost prices, first, it is necessary to define the costs per places of cost, and then to transfer the costs from places of cost to the carriers of cost, i.e. products.

Linking the costs to the cost bearers is carried out by the following procedure: proportional costs are linked, applying the elective division calculation with equivalent numbers, which implies that the equivalent numbers are determined from the relation of the derivate density and the density of reference derivate, while fixed costs are linked according to the yields, i.e. by the unit quantity of product, in fixed value for each tonne of derivate. Application of equivalent numbers makes it possible that more valuable products be burdened with a somewhat greater part of costs. Density is taken as a mutual characteristic of all products. Specific mass or density is always mentioned with other characteristics of oil derivates. It is easy to measure, most frequently by an aerometer, and, in combination with the material origin, it can serve for approximate evaluation. In the oil industry, besides the density in kg/l (usually rounded to 3 or 4 decimal places), API degrees are often used. Correlation between density in API degrees and density in kg/l “d” is expressed by the equation:

$$d = 141.5/(131.5 + S)$$

There are diagrams for rapidly converting API degrees to kg/l. In the countries that use metric system the density values are given for the temperatures of 0, 15 or 20°C.

A reference temperature of 15°C is more often used, due to the similarity with the data from Anglo-Saxon countries, where the basic reference temperature is 60°F (15.6°C).

In European exact science terminology, density is defined as mass of one volume unit. So, density represents a nominated value. One of the characteristics of the unit technical metric system is that water density, at normal temperature and with convenient choice of primary units (for mass and length), takes the value of 1, or in the general case, the value representing a decimal unit.

In determining oil-derivative cost prices, the choice of derivates is very important, whose density is taken as the reference for determining equivalent numbers on the basis of which the distribution of proportional expenses is performed. In the example of a crude unit on a typical oil refinery, crude-oil costs, being the most substantial ones, are distributed by applying the equivalent numbers in the cases where light gasoline and straight-run gasoline C_5-175 are reference derivates (s. Tab.).

It is obvious that reaching the consensus concerning the criterion for choosing a reference derivate is of great importance in the case when more companies decide to take a common methodology for establishing the cost prices of semi-products and finished products that are obtained by blending the previous ones. Derivates with density values lower than that of the reference derivate, in this particular case liquid oil gas and light gasoline, are considered as by-products, i.e. their cost prices are kept on the level of feedstock cost price, since applying the same criterion would lead to the equivalent numbers being higher than 1000, and consequently, to the cost prices being higher than those of the reference derivates, which is illogical, considering the significance of products on account of which the production process is organized.

crude unit

Derivates	Reference derivate: light gasoline			Reference derivate: straight-run gasoline		
	equival. number	density g/cm^3	crude oil US$/t	equival. number	density g/cm^3	crude oil US$/t
Liquid oil gases	–	–	–	–	–	–
Light gasoline	1.00	0.646	235.45	–	–	–
Prim. gasoline C_5-175°C	0.89	0.725	209.86	1.00	0.725	210.46
Gasoline C70-175°C	0.87	0.744	204.84	0.98	0.744	206.25
Jet fuel	0.82	0.790	193.07	0.92	0.790	193.62
White spirit	0.83	0.781	195.42	0.93	0.781	195.73
Petroleum for blending	0.82	0.790	193.07	0.92	0.790	193.62
Diesel D-1	0.79	0.820	186.01	0.88	0.820	185.20
Light gas oil	0.77	0.830	181.30	0.87	0.830	183.10
Heavy gas oil	0.74	0.870	174.24	0.83	0.870	174.68
Light residue	0.68	0.940	160.11	0.77	0.940	162.05

4.1
Instruments for Determining Energy and Processing Efficiency of Crude Distillation Unit

4.1.1
Technological Characteristics of the Process

Crude distillation is a primary crude-oil process. Before entering the rectification column, crude oil is heated to a temperature of up to 380°C that enables evaporation of the wanted fractions. Crude oil flows under pressure and at high velocity, through the heating system, and at the rectification-column entrance, the heated oil passes to normal (atmospheric) pressure, which makes it possible for some fractions to evaporate.

The rectification column is divided into many trays through which volatile components of crude oil move upwards, the temperature in the column decreases towards the top, in accordance with the schedule, which enables one fraction to be separated at each tray. In order to ensure similar quality of the fractions, a constant-temperature schedule must be maintained in each segment (tray) of the column, by providing the constant temperature of crude oil at the column inlet on the one hand, and by cooling the parts of the column, on the other, or by reintroducing part of the condensed fractions into the column (recirculation of the reflux).

Heavier fractions that do not evaporate go to the bottom, and volatile components release the fractions with higher boiling points at each tray, crossing through a liquid phase. In order to improve the flow and to decrease the hydrocarbons partial pressure, overheated steam is introduced in the rectification column, which then leaves the top of the column, together with naphtha vapours, being condensed with them and then it is separated in water separators.

Each fraction that leaves the main rectification column is a mixture of numerous hydrocarbons. Therefore, some fractions are further treated in auxiliary columns, near

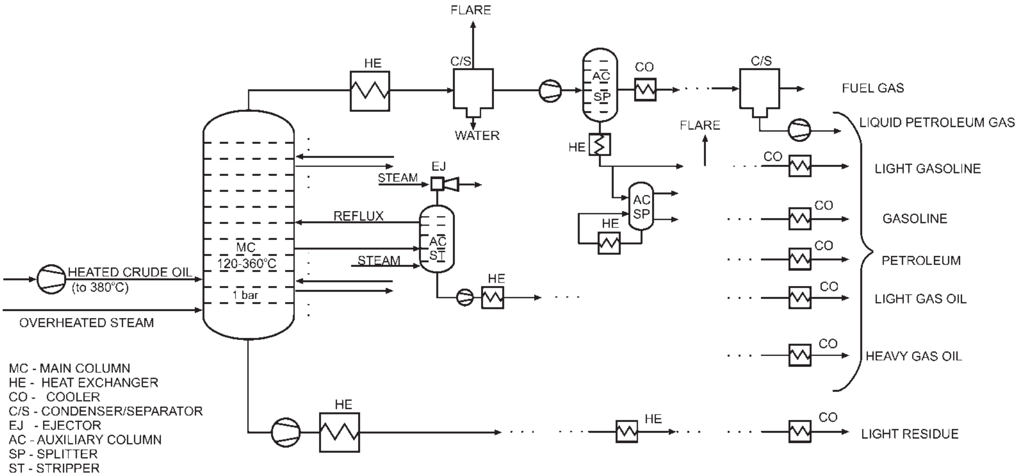


Fig. 2 Technological characteristics of crude-unit process

the main column. Auxiliary units are, for example, debutanizer, stripper and splitter [15].

The mentioned technological characteristics of the crude distillation process are shown in Fig. 2.

Fig. 2 shows that all the products of the crude unit are cooled by the cooling system (cooler), but before that they often pass through other heat exchangers, which are built in for the sake of the best possible utilization of spent energy, for example, for crude-oil preheating, auxiliary column bottom heating, etc.

Numerous pumps and other auxiliary facilities ensure continuous operation of the system. The described process also takes place continuously under atmospheric pressure, and in it, depending on the composition of crude oil, the following main fractions are obtained:

- fuel gas (dry refinery gas),
- liquid petroleum gas (propane-butane mixture),
- gasolines
- kerosene and jet fuel,
- gas oils.

Gas oil is the heaviest fraction obtained on the crude unit. Heavier fractions are not separated in the process, but they remain in the atmospheric or light residue that makes up 35–50% of the entering crude oil and that is taken away from the bottom of the column. The atmospheric residue is usually reprocessed, in the second phase of primary processing, in the vacuum-distillation unit.

4.1.2
Energy Characteristics of the Process

In a typical crude-unit process, the crude oil is preheated in heat exchangers before entering the process heater, by means of crude-oil product flows. Process air, which is needed for burning, is preheated in a heat exchanger by means of the flue-gas flux from the process heater.

It is mostly fuel gas that is not preheated that is used as a fuel in the process heater, as well as one portion of fuel oil being preheated by medium-pressure steam (MpS) and dispersed in burners.

Medium-pressure steam (MpS) is used for the ejector drive at the drier-outlet auxiliary columns, stripper, as well as for spare systems of the main pump drive, through the steam turbines.

One small portion of the medium-pressure steam is generated in this unit, in the heat exchanger by means of light-residue heat flux. Besides the medium-pressure steam, the low-pressure steam is also introduced into the crude unit and is used as process steam in the main rectification column and auxiliary columns – strippers.

Electric energy is used to drive the pumps, fans (air cooling) and other equipment as well as auxiliary installations.

Fig. 3 shows the main energy characteristics of the crude-unit process and all important alternatives in meeting the process energy demands. Each alternative is one of the possible solutions for a process like this.

For the purpose of this process, an energy-flow scheme is shown in Scheme 2, and Senky's diagram for the energy balance in Diagram 1. The values given for the energy

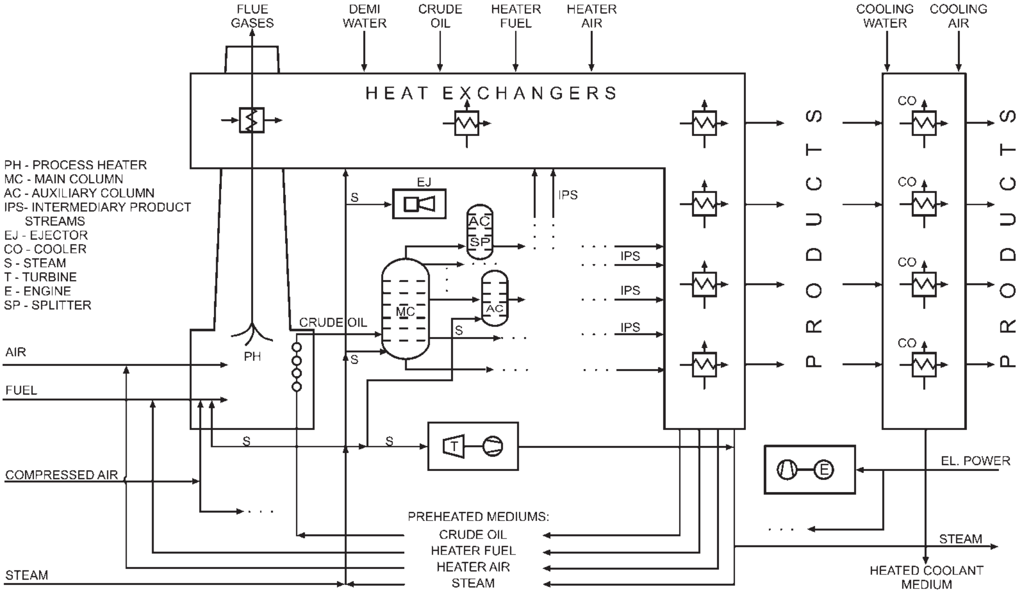
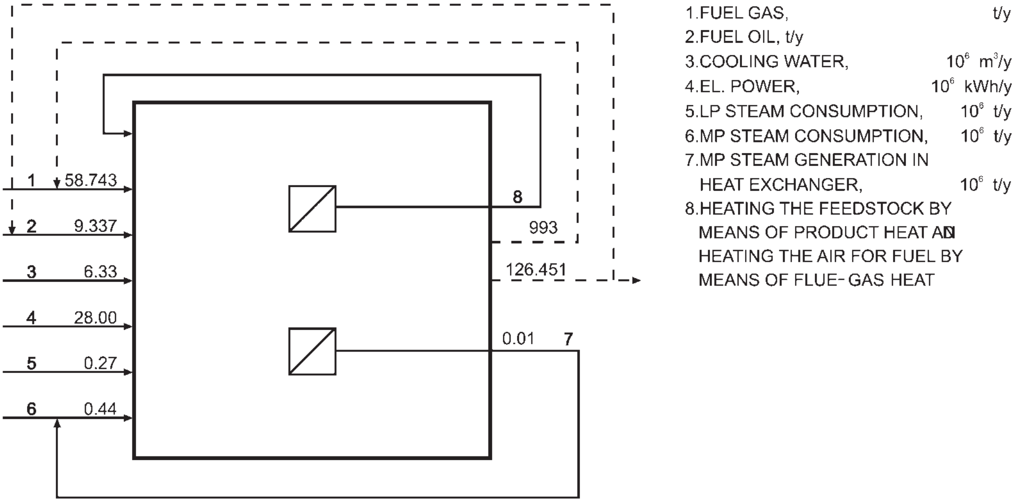


Fig. 3 Energy characteristics of crude-unit process



Scheme 2 Energy flows of crude-unit process

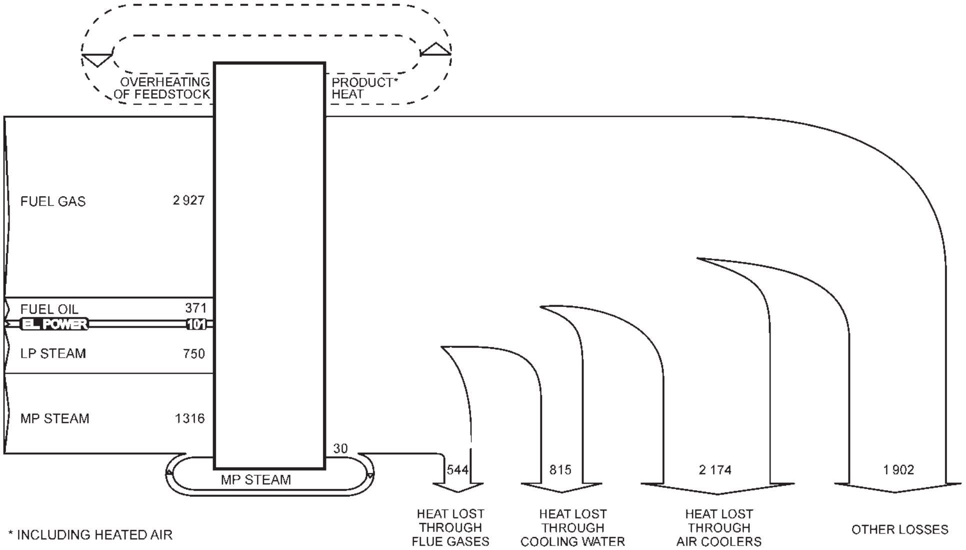


Diagram 1 Senky's diagram of energy flows of crude-unit process, in TJ/y

consumption refer to the annual scope of processing 5 000 000 t of crude oil and for a specific slate of products.

The difference between gross and net power consumption appears in the case of MP steam due to internal steam generation of the plant. The gross consumption of medium-pressure steam is 440 000 t or 1316 TJ, net consumption is 430 000 t or 1286 TJ, and internal steam generation is 10 000 t or 30 TJ.

4.1.3
Determining the Steam Cost Price

The cost prices of medium-pressure steam (MpS) generated on the crude unit, as well as the cost prices of medium and low-pressure steam (LpS) used on the crude unit, are shown in Tables 2 and 3.

From Tab. 2, it can be seen that the cost price of MP steam generated on the crude unit is 0.47 US$/t.

The basic explanation for such a cost price lies in the fact that, on this particular plant, steam is generated as a by-product in the heat exchanger by utilizing the light-residue heat flux, thus offsetting the consumption of engine fuel (fuel oil and fuel gas).

It should be emphasized that, unlike some refinery units that produce the largest part of steam used internally, steam generation on this unit is insignificant, i.e. 2.3% of total MP steam that is used internally.

Internal generation of medium-pressure steam provides only 10 000 t or 30 TJ for internal gross consumption, which is 440 000 t or 1 316 TJ.

The shortfall of steam amounting to 430 000 t or 1 286 TJ is taken from the refinery power plant at the cost price of US$ 9.66 per tonne.

Tab. 2 Cost price of medium-pressure steam

Item no.	Elements for calculation	Medium-pressure steam generation (MpS)			MP steam for internal consumption
		Annual q'ty in t	Cost price US$/t	Total in US$	
1	2	3	4	5	6
1	MP steam supplied from Refinery Power Plant	430 000	9.66	4 153 800	4 153 800
2	MP steam production	10 000	0.468	4 680	4 680
2.1	Demineralized water	10 000	0.165	1 650	
2.2	Depreciation			2 530	
2.3	Current and investment maintenance			300	
2.4	Insurance premium for equipment			200	
3	Total (1+2)	440 000		4 158 480	4 158 480
4	Q'ty in t				440 000
5	Cost price in US$/t				9.45

Tab. 3 Cost price of low-pressure steam (consumption)

Item no.	Elements for calculation	LpS consumption (US$)		
		Annual q'ty in t	Cost price US$/t	Total LpS consumption in US$
1	2	3	4	5
1	LP steam (supply)	27 000	9.29	250 830

By including the mentioned medium-pressure steam amount in the calculation, the average cost price of medium-pressure steam used on the crude unit appears to be 9.45 US$/t.

The low-pressure steam, supplied from the refinery power plant, is also used in the crude unit, at the cost price of 9.29 US$/t (Tab. 3).

It should be pointed out that a significant difference between the cost price of the steam generated in the crude unit (0.47 US$/t) and cost prices of medium- and low-pressure steam, generated in refinery power plant (9.66 US$/t and 9.29 US$/t) results from participation of fuel oil in the calculation of cost prices of the steam generated in refinery power plant (about 80%) that is not included in the calculation of steam generated in the crude unit because the steam generated in the crude unit is produced in the heat exchanger by using light-residue heat flux.

4.1.4
Energy Efficiency of the Process

Specific consumption of medium-pressure steam in relation to 5 million tonnes of crude oil being processed during a year is as follows:

$$\text{gross:}\ \frac{89\ \text{kg of steam}}{\text{t of feedstock}}\quad \text{or:}\ 263.2\ \frac{\text{MJ}}{\text{t of feedstock}}$$

$$\text{net:}\ \frac{86\ \text{kg of steam}}{\text{t of feedstock}}\quad \text{or:}\ 257.2\ \frac{\text{MJ}}{\text{t of feedstock}}$$

Depending on the purpose and the context of energy analysis, both indicators of energy efficiency (specific gross and net consumption) can be interesting, especially when all the interactions in the complex energy utilization within the process itself are taken into consideration, particularly through the numerous heat exchangers. But, for the estimation of the realized energy efficiency of the total process, the specific net energy consumption is of greater importance.

The target standard of net energy consumption and specific gross and net energy consumption, on a typical crude unit, is outlined in Tab. 4 and Tab. 5 shows the financial indicators of energy consumption and money savings of about 4 700 000 US$/y that can be achieved by eliminating the differences between the target standard (average energy consumption of Western European refineries) and energy consumption of this refinery unit.

The target standard of net energy consumption is given for the unit with the higher level of efficiency and the same capacity as the typical unit being observed.

If specific net energy consumption of a typical plant is compared with the target standard, the following conclusions can be drawn:

1. Specific electric energy consumption (for mechanical purposes) is close to the target standard.
2. Specific net consumption of process and thermal energy (fuel and steam) amounts to 1075.3 MJ/t, exceeding the target standard (780 MJ/t) by 38%.

Tab. 4 Target standard of net energy consumption and specific energy consumption in a typical crude distillation unit (quantity of energy per one tonne of feedstock)

Energy carriers	**Target standard of net energy consumption**		**Specific energy consumption in the plant**					
			Specific gross energy consumption			**Specific net energy consumption**		
			(kg/t) ^{1}(kWh/t)	**(MJ/t)**		**(kg/t) ^{1}(kWh/t)**	**(MJ/t)**	
	(MJ/t)	**(kWh/t)**		**per unit**	**total**		**per unit**	**total**
Fuel					668			668
Fuel gas			12.6	627.6		12.6	627.6	
Fuel oil	*	–	1.0	40.4		1.0	40.4	
Heat carriers					413.3			407.3
LP steam	*	–	54	150.1		54	150.1	
MP steam	*	–	88	263.2		86	257.2	
Sources of heat	780	–	–		1 081.3	–	–	1 075.3
Electric energy	20	5.5	5.6^1	20.2	20.2	5.6^1	20.2	20.2
Energy carriers	800	–	–	–	1 101.5	–	–	1 095.5

Tab. 5 Financial presentation of energy consumption and money savings on a typical crude unit (in US$)

Specific gross energy consumption

Energy carriers	Q'ty of feedstock **(crude oil)**			**US$**
	5 000 000			
Fuel gas	5 000 000	(627.6 MJ/t × 0.0027 US$/MJ)	=	8 472 600
Fuel oil	5 000 000	(40.4 MJ/t × 0.00305 US$/MJ)	=	616 100
Low-pressure steam	5 000 000	(150.1 MJ/t × 0.00334 US$/MJ)	=	2 506 670
Medium-pressure steam	5 000 000	(263.2 MJ/t × 0.00316 US$/MJ)	=	4 158 560
Sources of heat	**5 000 000**	**(1081.3 MJ/t × 0.002914 US$/MJ)**	**=**	**15 753 930**
Electric energy	5 000 000	(20.2 MJ/t × 0.0167 US$/MJ)	=	1 686 700
Energy carriers	**5 000 000**	**(1101.5 MJ/t × 0.003167 US$/MJ)**	**=**	**17 440 630**

Specific net energy consumption

			US$/t
Fuel gas	(627.6 MJ/t × 0.0027 US$/MJ)	=	1.69452
Fuel oil	(40.4 MJ/t × 0.00305 US$/MJ)	=	0.12322
Low-pressure steam	(150.1 MJ/t × 0.00334 US$/MJ)	=	0.501334
Medium-pressure steam	(257.2 MJ/t × 0.00316 US$/MJ)	=	0.812752
Sources of heat	**(1075.3 MJ/t × 0.002914 US$/MJ)**	**=**	**3.131826**
Electric energy	(20.2 MJ/t × 0.0167 US$/MJ)	=	0.33734
Energy carriers	**(1095.5 MJ/t × 0.003167 US$/MJ)**	**=**	**3.469166**
Sources of heat:			
Internal net energy consumption	(1075.3 MJ/t × 0.002914 US$/MJ)	=	3.13
Target net energy consumption	(780 MJ/t × 0.002914 US$/MJ)	=	2.27
Difference:			**0.86**
Energy carriers:			
Internal net energy consumption	(1095.5 MJ/t × 0.003167 US$/MJ)	=	3.47
Target net energy consumption	(800 MJ/t × 0.003167 US$/MJ)	=	2.53
Difference:			**0.94**

3. Total specific net energy consumption is 1095.5 MJ/t and is 37% higher than the target standard (800 MJ/t). Compared with the target standard of energy consumption, a typical plant has an efficiency/inefficiency index of 137.

The increase in consumption of process and thermal energy on a typical plant is caused by different factors, and the most important are:

- preheating of fuel by steam in heat exchangers,
- inefficient preheating of combustion air by using the heat of flue gases in the process heater,
- energy nonintegration of the plants (production of steam by means of light-residue heat flux, instead of introducing it directly into the process heater of the vacuum-distillation unit),
- non-economical combustion in the process heater (measuring of the excess air in the process heater is not available), and
- inefficient preheating system of feedstock (low temperature of process heater feedstock).

4.1.5
Refinery Product Cost Pricing

Among all the refinery units through which crude oil passes on its way to final processing the crude processing unit – atmospheric distillation – is a unit in which crude oil is separated into certain components, by way of distillation.

The cost prices of semi-products obtained on the crude unit are determined on the basis of equivalent numbers obtained by means of the density method, as the best method, although equivalent numbers can be determined by the following methods as well:

- thermal value method, and
- average production cost method.

By analysing the results obtained by using the different calculation bases for determining equivalent numbers the considerable differences in the cost prices of oil products generated in this unit can be seen [16].

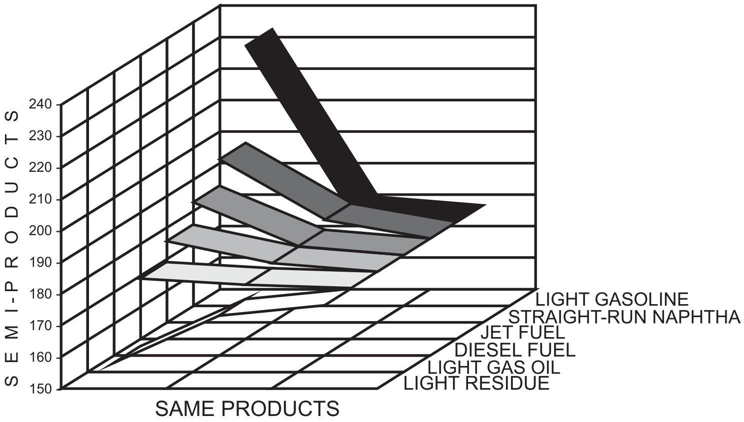
These differences are presented in Tab. 6 and Graphics 1 and 2.

Besides the significant differences in cost prices for the same refinery product (for example, the cost price of light gasoline is from 237.27 US$/t – the base for determining the equivalent numbers is product density to 176.57 US$/t – the base for determining the equivalent numbers is quantity of products), different ranges in oil-product cost prices can be noted even with the same calculating base.

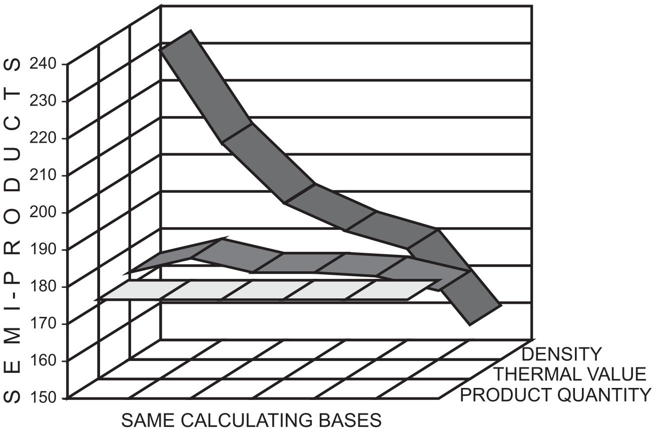
For example, when product density is the base for determining the equivalent numbers, the cost prices range from 234.27 US$/t (light gasoline) to 159.31 US$/t (vacuum residue). The stated examples of the calculating bases' effects on determining the equivalent numbers do not present all the dilemmas that experts dealing with process industry-calculations can face. The effects of the choice of reference derivatives, as well as the treatment of by-products are also important.

Tab. 6 The cost prices of semi-products on the crude unit in US$/t (by using the different calculating bases)

Item no.	Semi-products	Product Density Method	Thermal Value Method	Average Production Cost Method
1	Light gasoline	234.27	179.22	176.57
2	Straight-run gasoline	208.51	182.87	176.57
3	Jet fuel	192.11	179.22	176.57
4	Diesel fuel	185.08	179.22	176.57
5	Light gas oil	180.39	177.39	176.57
6	Light residue	159.31	173.74	176.57



Graphic 1 Cost prices of semi-products on crude unit, per products (in US$/t)



Graphic 2 Cost prices of semi-products on crude unit, per calculating bases (in US$/t)

The effect of the choice of reference derivatives (light gasoline whose density is 0.646 g/cm^3, straight-run gasoline whose density is 0.725 g/cm^3, jet fuel whose density is 0.790 g/cm^3, diesel fuel whose density is 0.820 g/cm^3, light gas oil whose density is 0.830 g/cm^3 and light residue whose density is 0.940 g/cm^3) on determining the equivalent numbers, in the case of using the same calculating base for determining the equivalent numbers (density method) are shown in Tab. 7.

It can be seen that the differences appearing in this case are smaller than those appearing in the previous example of determining the equivalent numbers on different calculating bases (density, thermal value and quantity of products).

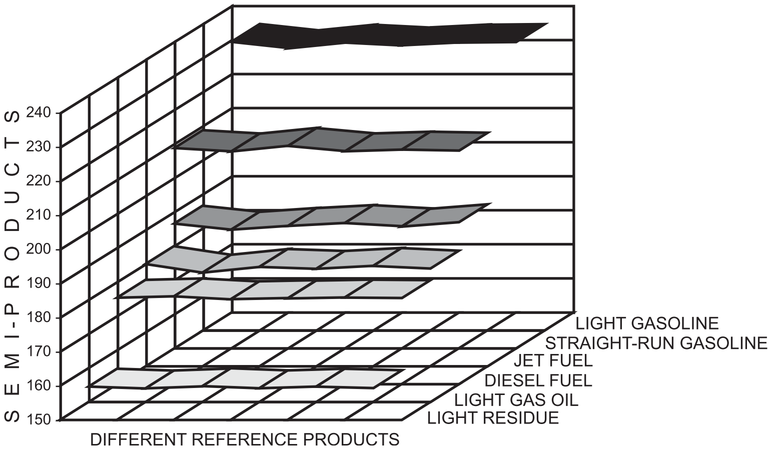
The results obtained by using the different reference derivatives, but the same calculating base, i.e. density method, are shown in Tab. 7 and Graphics 3 and 4).

The cost prices of semi-products generated on the crude unit, were calculated in the following manner, by means of the product density method:

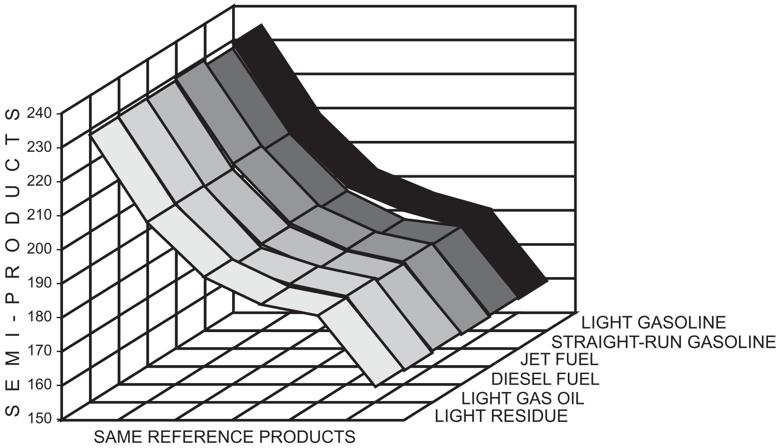
- Proportional costs (crude oil, steam, electric power and fuel) are distributed to semi-products generated in this unit according to the percentages obtained from equivalent numbers by means of the density method and a reference product. In this

Tab. 7 The cost prices of semi-products on the crude unit in US$/t (per reference products)

Item no.	Semi-products	Light gasoline	Straight-run gasoline	Jet fuel	Diesel fuel	Light gas oil	Light residue
1	Light gasoline	237.27	232.4	234.1	233.28	233.36	233.22
2	Straight-run gasoline	208.51	207.5	209.16	207.57	208.03	207.66
3	Jet fuel	192.11	190.9	191.89	191.03	189.94	191.69
4	Diesel fuel	185.08	182.6	184.21	183.69	184.52	183.7
5	Light gas oil	180.39	180.52	180.37	180.01	180.9	180.51
6	Light residue	159.31	159.77	159.27	159.81	159.19	159.74



Graphic 3 Cost prices of semi-products on crude unit, per different reference products (in US$/t)



Graphic 4 Cost prices of semi-product on crude unit, per same reference products (in US$/t)

case, the reference product is a light gasoline whose density is 0.646 g/cm^3 (Tab. 8, Column 5),

- Fixed costs are distributed according to the yield i.e. the quantities produced, i.e. in a fixed amount per tonne of derivatives being obtained on this process unit (Tab. 9, Line 3).

The loss in crude oil that appears as the difference in inlet-outlet feed, is included in the refinery cost prices, since this loss is unavoidable because of the nature of the process. The degree of loss is the topic of a special discussion.

The cost prices of slop and the refinery products, the density of which is lower than that of the reference product, are determined according to the price of the feedstock entering the observed unit. The mentioned products have the character of a by-product.

By using the mentioned methodology, the following cost prices of semi-products are established:

Semi-products	Cost prices in US$/t
1	2
Liquid petroleum gas	176.57
Light gasoline	253.75
Straight-run gasoline	227.13
Gasoline	222.29
Jet fuel	210.20
White spirit	212.61
Kerosene	210.20
Diesel fuel	202.94
Light gas oil	198.09
Heavy gas oil	190.83
Light residue	173.89
Slop	176.57

Tab. 8 Determining of the equivalent numbers for distributing the proportional costs – the crude unit

Item no.	Oil products	Quantity in tons	Q'ty from 1 tonne	Density g/cm^3	Equivalent numbers	Condition units	Cost of 1 condition unit	Cost price in US$/t	Cost of feedstock in US$	(%) for proportional costs	Cost of feed-stock in US$ (entry-exit)
1	**2**	**3**	**4**	**5**	**6**	**7(4 × 6)**	**8**	**9(6 × 8)**	**10(3 × 9)**	**11**	**12**
1	Liquid petroleum gas	51 895.8	–	–	–	–	–	176.57	9 163 241	–	9 163 241
2	Light gasoline	120 256.5	24.49	0.646	1.00	24.49	234.361	234.36	28 183 436	0.032706991	28 539 599
3	Straight-run gasoline	407 551.0	83.00	0.725	0.89	73.87	234.361	208.58	85 007 514	0.098651562	86 081 781
4	Gasoline	531 028.3	108.15	0.744	0.87	94.09	234.361	203.89	108 273 529	0.125651866	109 641 816
5	Jet fuel	150 863.6	30.72	0.790	0.82	25.19	234.361	192.18	28 992 363	0.033645754	29 358 749
6	White-spirit	2 036.4	0.41	0.781	0.83	0.34	234.361	194.52	396 112	0.000459689	401 118
7	Petroleum	37 655.1	7.67	0.790	0.82	6.29	234.361	192.18	7 236 416	0.008397890	7 327 865
8	Diesel fuel	1 849.3	0.37	0.820	0.79	0.29	234.361	185.15	342 386	0.000397341	346 713
9	Light gas oil	1 140 606.4	232.29	0.830	0.77	178.86	234.361	180.46	205 831 522	0.238868310	208 432 680
10	Heavy gas oil	120 978.4	24.64	0.870	0.74	18.23	234.361	173.43	20 980 939	0.024348464	21 246 082
11	Light residue	2 397 467.4	488.26	0.940	0.68	332.02	234.361	157.02	376 450 336	0.436872131	381 207 658
12	Slop	6 174.9	–	–	–	–	–	176.57	1 090 302	–	1 090 302
13	Total	4 968 363.2	1 000.00 4 910 292.50			753.68			871 948 096		882 837 604
									–9 163 241		–9 163 241
									–1 090 302		–1 090 302
									861 694 553	1.000000000	872 584 061
14	Loss	31 636.8									
15	Total	5 000 000.0									

The costs of one conditional unit are as follows:
Feedstock 882 837 601 US$: 5 000 000 t = 176.57 US$/t
Feedstock 176.57 : 753.68 = 0.234361 i.e. 234.361 US$/t

Tab. 9 Determining the cost prices of refinery products on the crude unit

Item no.	Elements for calculation	Total in US$	Liquid petroleum gas	Light gasoline	Straight-run gasoline	Gasoline	Jet fuel	White-spirit	Petroleum	Diesel fuel	Light gas oil	Heavy gas oil	Light residue	Slop
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	15
1	Q'ty in tons	4 968 363.2	51 895.8	120256.5	407551.0	531028.3	150863.6	2036.4	37655.1	1849.3	1140606.4	120978.4	2397467.4	6174.9
2	(%) from equivalent numbers		–	0.03270699	0.09865156	0.12565187	0.03364575	0.0004596892	0.0083978902	0.00039734	0.23886831	0.0243484642	0.4368721315	–
3	(%) from q'ty		–	0.0244907	0.08299933	0.10814597	0.03072395	0.0004147123	0.0076686159	0.06037661	0.2322889	0.0246377189	0.4882534868	–
4	Crude oil	882 837 601	9 163 241	28 539 599	86 081 781	109 641 816	29 358 749	401 118	7 327 865	346 713	208 432 680	21 246 082	381 207 658	1 090 302
5	Chemicals	1 085 758		35 512	107 112	136 428	36 531	499	9 118	431	259 353	26 437	474 338	
6	Water	8502		278	839	1 068	286	4	71	3	2 031	207	3 714	
7	Steam	6 769 162		221 399	667 788	850 558	227 754	3 112	56 847	2 690	1 616 938	164 819	2 957 258	
8	Electric power	1 645 380		47 928	144 562	184 128	49 304	674	12 306	582	350 033	35 680	640 184	
9	Fuel	7 903 373		258 496	779 680	993 074	265 915	3 633	66 372	3 140	1 887 865	192 435	3 452 763	
10	Depreciation	6 609		162	549	715	203	3	51	2	1 535	163	3 227	
11	Other production costs	965 929		23 656	80 171	104 461	29 677	401	7 407	364	224 375	23 798	471 618	
12	Wages	2 291 880		56 130	190 225	247 858	70 416	950	17 576	863	532 378	56 467	1 119 018	
13	Taxes	1 008 141		24 690	83 675	109 026	30 974	418	7 731	380	234 180	24 838	492 228	
14	Unit management costs	1 750 924		42 881	145 325	189 355	53 795	726	13 427	659	406 720	43 139	854 895	
15	Laboratory and maintenance costs	25 927 157		634 974	2 151 937	2 803 917	796 585	10 752	198 825	9 765	6 022 591	638 786	12 659 025	
16	Common services costs	25 719 004		629 876	2 134 660	2 781 407	790 189	10 666	197 229	9 686	5 974 239	633 658	12 557 393	
17	Total costs	957 739 419	9 163 241	30 515 581	92 568 304	118 043 810	31 710 378	432 955	7 914 825	375 279	225 944 918	23 086 507	416 893 319	1 090 302
18	Cost price in US$/t	192.77	176.57	253.75	227.13	222.29	210.20	212.61	210.20	202.94	198.09	190.83	173.89	176.57

4.2
Instruments for Determining Energy and Processing Efficiency of Vacuum-distillation Unit

4.2.1
Technological Characteristics of the Process

The vacuum-distillation process is the second phase of crude-oil processing. Light residue from the crude unit is introduced into the vacuum-distillation process. Light residue is heated to 390–410°C before entering the vacuum-distillation unit. This column is under vacuum – the pressure on the top of the column is 20–30 mmHg – which makes possible evaporation of some fractions. The temperature schedule and other operating characteristics of vacuum column, except for pressure, are the same as for the main crude-unit column.

For the improved streaming and fractionation, overheated steam is introduced to the bottom of the column (the steam for stripping). The steam with light hydrocarbon vapours is routed off the top of the column by the steam ejectors, and in this way, the necessary vacuum in the column is achieved. The steam light hydrocarbon vapours are then condensed and separated, in separators.

In this process, the products are: light vacuum gas oil, heavy vacuum gas oil and non-conditioned fraction. At the bottom of the column there is vacuum or heavy residue representing 35–50% of the total quantity of light residue entering the vacuum-distillation process. The vacuum residue is further treated in the vacuum-residue visbreaking process and in the bitumen blowing process.

All the above-mentioned technological characteristics are shown in Fig. 4.

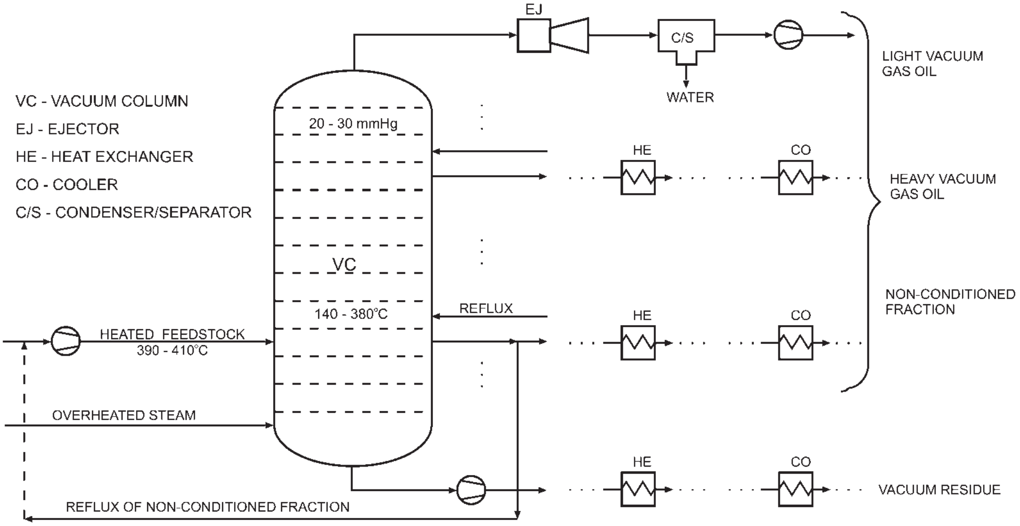


Fig. 4 Technological characteristics of vacuum-distillation process

4.2.2
Energy Characteristics of the Process

In a typical vacuum-distillation process, the light residue from the crude unit is preheated in the heat exchangers before entering the process heater, by means of the flows of these process products.

In the process heater, fuel oil is mainly used as fuel and medium-pressure steam (MpS) is used for its preheating and dispersion in burners.

One portion of medium-pressure steam (MpS) is routed from the power plant and the other part is generated in the heat exchangers using the vacuum residue heat flux.

Medium-pressure steam is also produced by using the heat of the flue gases in the boiler. The total steam generated is used for the ejector drive by means of which the steam and light hydrocarbon vapours are led out of the vacuum residue and the vacuum column, resulting in vacuum.

Besides the medium-pressure steam (MpS), low-pressure steam (LpS) is introduced into the vacuum-distillation process, and it is used for stripping in the vacuum column, after preheating by flue gases in the process heater.

Electric energy is used to drive the pumps, fans (air cooling and leading away the flue gases from the boiler) and other equipment.

The main energy characteristics of the vacuum-distillation process are shown in Fig. 5, which also presents all the important alternatives in meeting the energy demands of the process. Each alternative is one of the potential solutions for a process like this.

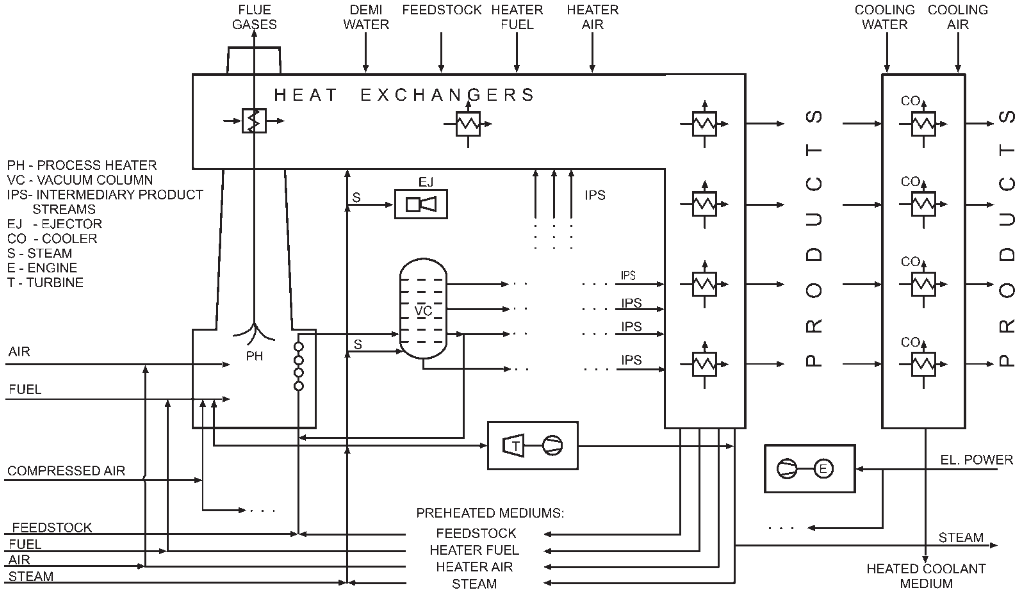
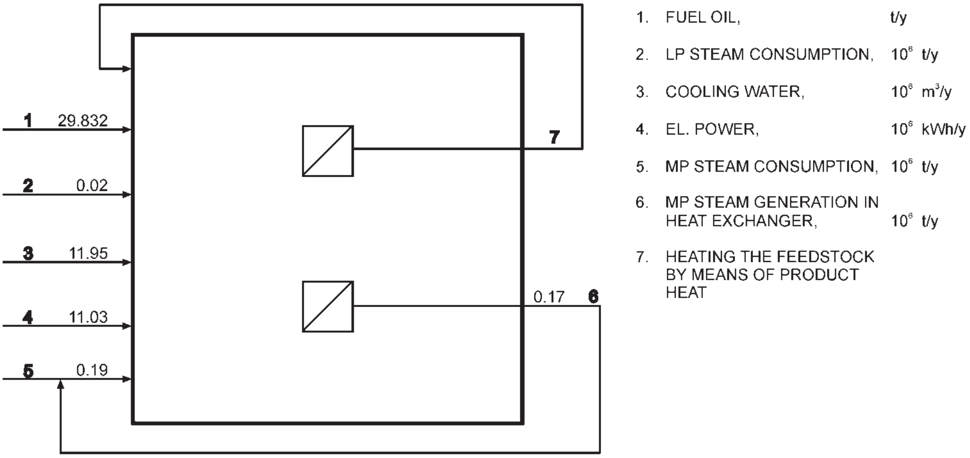


Fig. 5 Energy characteristics of vacuum-distillation process



Scheme 3 Energy flows of vacuum-distillation process

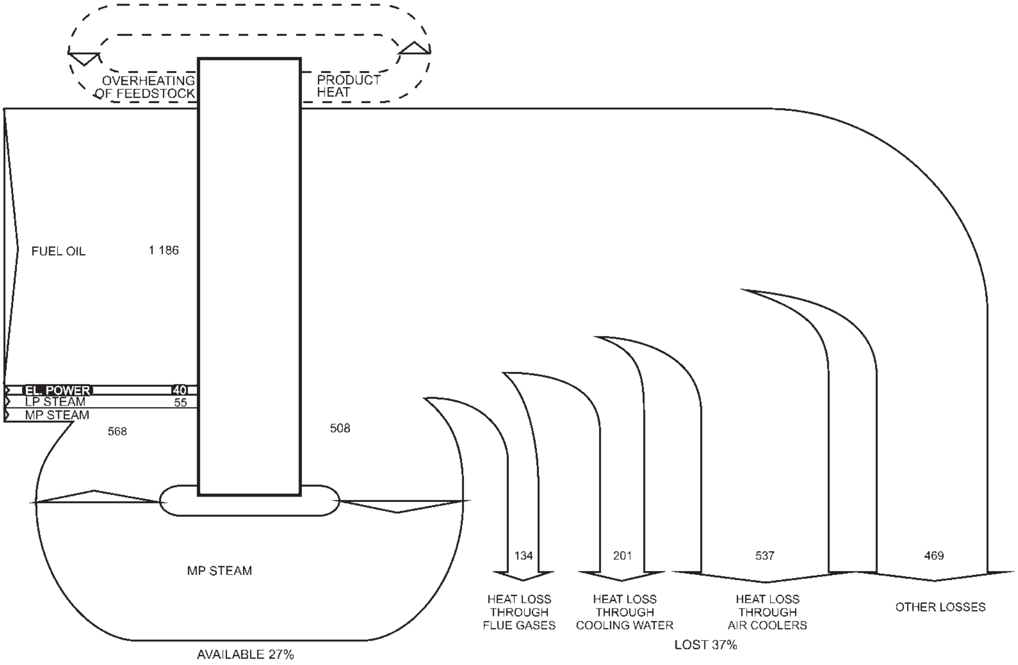


Diagram 2 Senky's diagram of energy flows of vacuum-distillation process, in TJ/y

For this process, the energy-flow block scheme is shown in Scheme 3 and Senky's diagram for the energy balance in Diagram 2. The values given for the energy consumption refer to the annual volume of production amounting to 2 122 065 t of light residue, and to a specific slate of products.

The difference between gross and net power consumption appears with medium-pressure steam due to the internal generation of this energy carrier in the process itself. The gross consumption of medium-pressure steam is 190 000 t or 568 TJ, net consumption is 20 000 t or 60 TJ, and internal steam generation is 170 000 t or 508 TJ.

4.2.3
Determining the Steam Cost Price

The procedure for determining the cost price of steam, as a possible instrument for monitoring the energy efficiency, required by operative management, is given in Tables 10 and 11.

In Tab. 10, it can be seen that the cost price of MP steam generated in the vacuum-distillation unit is 0.44 US$/t.

The basic explanation for such cost prices lies in the fact that, on this particular unit, steam is obtained as a by-product by utilizing the heat of the flue gases in the boiler and the heat flux of the vacuum residue in the heat exchangers, thus offsetting the consumption of engine fuel (fuel oil or fuel gas). By internal generation of medium-pressure steam, vacuum distillation ensures 170 000 t or 508 TJ, i.e. about 90 % of internal

Tab. 10 Cost prices of medium-pressure steam (MpS)

Item no.	Elements for calculation	Medium-pressure steam generation (MpS)			MpS for internal consumption
		Annual q'ty in t	Cost price US$/t	Total in US$	
1	2	3	4	5	6
1	MP steam supplied from Refinery Power Plant	20 000	9.66	193 200	193 200
2	MP steam generation	170 000	0.439	74 636	74 636
2.1	Demineralized water	170 000	0.165	28 050	28 050
2.2	Depreciation			38 821	38 821
2.3	Current and investment maintenance			4 659	4 659
2.4	Insurance premium for equipment			3 106	3 106
3	Total (1+2)	190 000	1.41	267 836	267 836
4	Quantity in t				190 000
5	Cost price of MpS in US$/t				**1.41**

Tab. 11 Cost price of low-pressure steam (consumption)

Item no.	Elements for calculation	LpS consumption (US$)		Total LpS consumption in US$
		Annual q'ty in t	Cost price US$/t	
1	2	3	4	5
1	LP steam (supply)	20 000	9.29	185 800

gross consumption that is 190 000 t or 568 TJ. The difference to the mentioned gross consumption of 20 000 t or 60 TJ is taken from the refinery power plant at the cost price of 9.66 US$/t.

By including the mentioned quantity of MP steam, the average cost price MP steam used for the vacuum-distillation unit internal consumption is 1.41 US$/t.

Low-pressure steam (LpS), obtained from refinery power plant at the cost price of 9.29 US$/t (see Tab. 11) is also used in the vacuum-distillation process in addition to medium-pressure steam. The basic explanation for such a cost price of medium- and low-pressure steam, introduced from refinery power plant, lies in the fact that fuel oil shares in the calculation of the cost price of steam generated in refinery power plant, with about 80%.

4.2.4
Energy Efficiency of the Process

Specific consumption of medium-pressure steam in relation to the quantity of light residue processed, amounts to:

$$\text{gross:}\ \frac{89\ \text{kg of steam}}{\text{t of feedstock}}\quad \text{or:}\ 286.1\ \frac{\text{MJ}}{\text{t of feedstock}}$$

$$\text{net:}\ \frac{9.5\ \text{kg of steam}}{\text{t of feedstock}}\quad \text{or:}\ 28.3\ \frac{\text{MJ}}{\text{t of feedstock}}$$

The target standard of net energy consumption and specific gross and net energy consumption, on a typical vacuum-distillation unit, are outlined in Tab. 12, and Tab. 13 gives the financial presentation of energy consumption and money savings of about 1

Tab. 12 Target standard of net energy consumption and specific energy consumption on a typical vacuum-distillation unit (quantity of energy per one tonne of feedstock)

Energy carriers	**Target standard of net energy consumption**		**Specific energy consumption in the plant**					
			Specific gross energy consumption			**Specific net energy consumption**		
			(kg/t) [1](kWh/t)	**(MJ/t)**		**(kg/t) [1](kWh/t)**	**(MJ/t)**	
	(MJ/t)	**(kWh/t)**		**per unit**	**total**		**per unit**	**total**
Fuels								
Fuel oil	*	–	14.1	558.9	558.9	14.1	558.9	558.9
Heat carriers					291.1			53.3
LP steam	*	–	9.0	25.1		9.0	25	
MP steam	*	–	89.0	266.1		9.5	28.3	
Sources of heat	432	–	–	–	850.0	–	–	612.2
Electric energy	18	5.0	5.2[1]	18.7	18.7	5.2[1]	18.7	18.7
Energy carriers	450	–	–	–	868.7	–	–	630.9

Tab. 13 Financial presentation of energy consumption and money savings on a typical vacuum-distillation unit (in US$)

Specific gross energy consumption

Energy carriers	Q'ty of feedstock (light residue) 2 122 065 t			US$
Fuel oil	2 122 065 t	(558.9 MJ/t × 0.00305 US$/MJ)	=	3 617 367
Low-pressure steam	2 122 065 t	25.1 MJ/t × 0.003378 US$/MJ)	=	179 926
Medium-pressure steam	2 122 065 t	(266.1 MJ/t × 0.000472 US$/MJ)	=	266 531
Sources of heat	2 122 065 t	**(850.1 MJ/t × 0.002253 US$/MJ)**	**=**	**4 063 824**
Electric energy	2 122 065 t	(18.7 MJ/t × 0.0167 US$/MJ)	=	662 700
Energy carriers	2 122 065 t	**(868.8 MJ/t × 0.002564 US$/MJ)**	**=**	**4 726 524**

Specific net energy consumption

			US$/t
Fuel oil	(558.9 MJ/t × 0.00305 US$/MJ)	=	1.704645
Low-pressure steam	(25.0 MJ/t × 0.003378 US$/MJ)	=	0.084450
Medium-pressure steam	(28.3 MJ/t × 0.000472 US$/MJ)	=	0.013358
Sources of heat	**(612.2 MJ/t × 0.002944 US$/MJ)**	**=**	**1.802453**
Electric energy	(18.7 MJ/t × 0.0167 US$/MJ)	=	0.312290
Energy carriers	**(630.9 MJ/t × 0.003352 US$/MJ)**	**=**	**2.114743**
Sources of heat:			
Internal net energy consumption	(612.2 MJ/t × 0.002944 US$/MJ)	=	1.80
Target net energy consumption	(432 MJ/t × 0.002944 US$/MJ)	=	1.27
Difference:			**0.53**
Energy carriers:			
Internal net energy consumption	(630.9 MJ/t × 0.003352 US$/MJ)	=	2.11
Target net energy consumption	(450 MJ/t × 0.003352 US$/MJ)	=	1.51
Difference:			**0.60**

300 000 US$/y, which can be achieved by eliminating the differences between the target standard (average vacuum distillation energy consumption in Western European refineries) and energy consumption of this particular refinery unit.

Through the target standards that present the average energy consumption standards in Western European refineries, it is possible to compare the energy consumption of the unit analysed.

If specific net energy consumption of a typical unit is compared with the target standard, the following conclusions can be drawn:

1. Specific electric energy consumption (for mechanical purposes) is close to the target standard.
2. Specific net consumption of process and thermal energy (fuel and steam) of 612.2 MJ/t, exceeds the target standard (432 MJ/t) by 42%.
3. Total specific net energy consumption is 630.9 MJ/t, which is 40% higher than the target standard (450 MJ/t). Compared with the net energy consumption target standard, a typical plant has an efficiency/inefficiency index of 140.

Increased consumption of process and thermal energy on a typical plant is caused by different factors, the most important being:

- preheating of fuel by steam in heat exchangers,
- inefficient production of steam in a boiler, using the heat of flue gases in the process heater,
- energy nonintegration of the plant (production of the steam in the heat exchanger by means of the heat flux of the vacuum residue, instead of its direct routing to the process heater of vacuum-residue visbreaking),
- inefficient system of feedstock preheating (high level of heat-exchanger fouling),
- non-economical combustion in the process heater (absence of surplus air measuring), and
- unstable preheating of combustion air before going into the process heater.

4.2.5
Determining the Refinery Product Cost Prices

Considering the inlet feedstock for the vacuum-distillation process is light residue that is obtained in the crude unit, it is necessary previously to determine the cost price of this product.

The cost prices of semi-products obtained on the crude unit and vacuum-distillation unit, are determined by equivalent numbers obtained by means of the density method, as the best method, although equivalent numbers can be determined by the following methods as well:

- thermal value method, and
- average production cost method.

Analysing the results achieved by using the different calculation bases for determining equivalent numbers, taking feedstock in the vacuum-distillation unit, which presents 97.4 % of total costs, as an example, significant differences in the cost prices of oil products generated at this unit can be seen.

These differences are presented in Tab. 14 and Graphics 5 and 6.

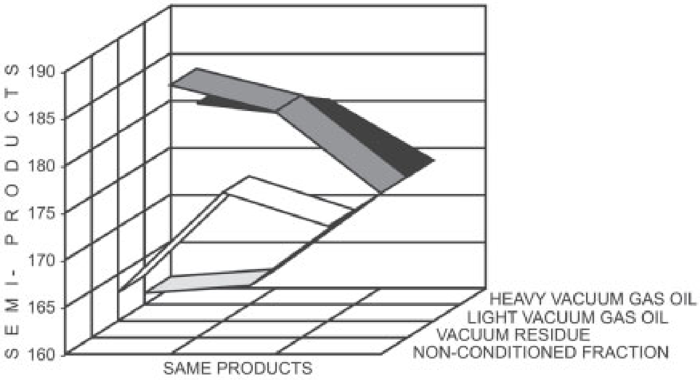
Besides the significant differences in cost prices for the same refinery product that depend on the calculating bases for determining the equivalent numbers, for example, the cost price of light vacuum gas oil is from 185.10 US$/t (the base for determining the equivalent numbers is product density) to 173.59 US$/t (the base for determining the equivalent numbers is quantity of products), different ranges in oil-product cost prices can be noted even with the same calculating base [17].

For example, when product density is the base for determining the equivalent numbers, the cost prices range from 185.10 US$/t (light vacuum gas oil) to 164.73 US$/t (vacuum residue).

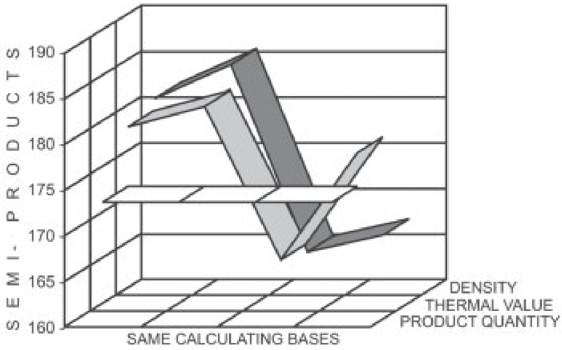
The stated examples of the calculating bases' effects on determining the equivalent numbers do not present all the dilemmas that experts dealing with process-industry

Tab. 14 Cost prices of semi-products on a vacuum-distillation unit in US$/t (per calculating bases)

Item no.	Semi-products	Base for determining the equivalent number for calculating the cost prices		
		Product Density Method	Thermal Value Method	Average Production Cost Method
1	2	3	4	5
1	Heavy vacuum gas oil	181.39	180.04	173.59
2	Light vacuum gas oil	185.10	182.26	173.59
3	Vacuum residue	164.73	165.51	173.59
4	Non-conditioned fraction	166.59	177.23	173.59



Graphic 5 Cost prices of semi-products on vacuum-distillation unit, per products (in US$/t)



Graphic 6 Cost prices of semi-products on vacuum-distillation unit, per calculating bases (in US$/t)

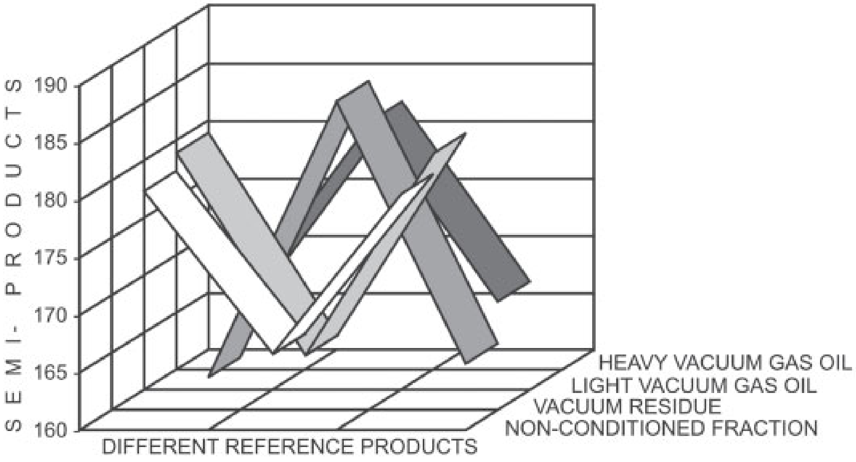
Tab. 15 Cost prices of semi-products on a vacuum-distillation unit in US$/t (per reference products)

Item no.	Semi-products	Reference products		
		Heavy vacuum gas oil	Light vacuum gas oil	Vacuum residue
1	2	3	4	5
1	Heavy vacuum gas oil	166.10	181.39	165.90
2	Light vacuum gas oil	161.12	185.10	162.26
3	Vacuum residue	182.38	164.73	182.31
4	Non-conditioned fraction	180.72	166.59	180.49

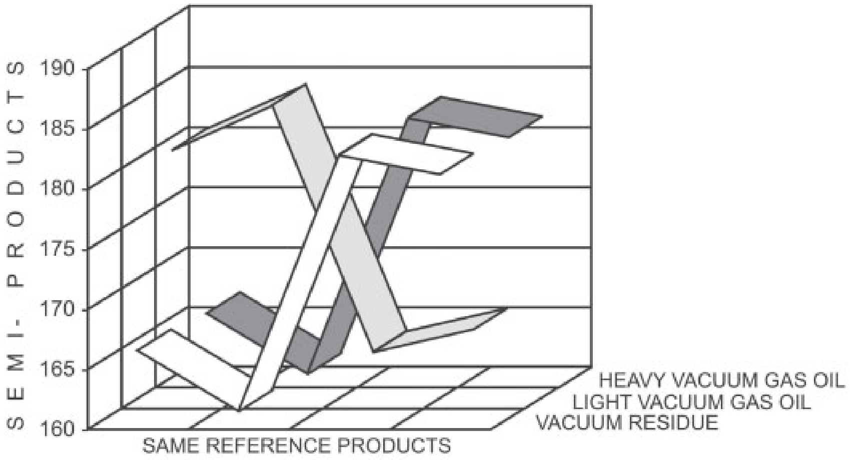
calculations can face. Tab. 15 shows the effects of the choice of reference derivatives (light vacuum gas oil whose density is 0.890 g/cm^3, heavy vacuum gas oil whose density is 0.910 g/cm^3 and vacuum residue whose density is 1.000 g/cm^3) on determining the equivalent numbers, in the case of using the same calculating base for determining the equivalent numbers (density method).

It can be seen that the differences appearing in this case are smaller than those appearing in the previous example of determining the equivalent numbers by different calculating bases (density, thermal value and quantity of products). The results obtained by using the different reference derivatives, but the same calculating base, i.e. density method, are shown in Tab. 15 and Graphics 7 and 8).

The cost prices of semi-products generated on the vacuum-distillation unit, were calculated in the following manner, using the product density method:



Graphic 7 Cost prices of semi-products on vacuum-distillation unit, per different reference products (in US$/t)



Graphic 8 Cost prices of semi-product on vacuum-distillation unit, per same reference products (in US$/t)

- Light vacuum gas oil whose density is 0.890 g/cm^3 (Tab. 16, Column 5) is determined as a reference derivative, in the procedure of determining the equivalent numbers.
- Proportional costs are distributed to semi-products generated in this unit according to the percentages obtained from equivalent numbers by means of the density method and a reference product (Tab. 16, Column 11).
- Fixed costs are distributed to semi-products according to the percentages obtained from the quantity (Tab. 17, Line 3).
- The prices of slop are expressed on the level of average price of inlet feedstock.

By using the mentioned methodology for distributing the proportional and fixed costs of this unit to the bearers of costs, i.e. to the products obtained in this unit, the following cost prices of semi-products are established (see Tab. 16 and 17):

Semi-products	**Cost prices in US$/t**
1	**2**
Heavy vacuum gas oil	186.79
Light vacuum gas oil	190.56
Vacuum residue	169.83
Non-conditioned fraction	171.72
Slop	173.59

Tab. 16 Determining the equivalent numbers for distributing the proportional costs on vacuum-distillation unit

Item no.	Oil products	Quantity in tons	Q'ty from 1 tonne	Density g/cm^3	Equivalent numbers	Condition units	Cost of 1 condition unit	Cost price in US$/t	Cost of feedstock in US$	(%) for prortional costs	Cost of feed-stock in US$ (entry-exit)
1	2	3	4	5	6	7(4 × 6)	8	9(6 × 8)	10(3 × 9)	11	12
1	Heavy vacuum gas oil	999 017.7	401.09	0.910	0.98	393.07	185.095	181.39	181 214 909	0.41912826	181 706 629
2	Light vacuum gas oil	256 474.8	102.97	0.890	1.00	102.97	185.095	185.10	47 472 199	0.10979748	47 601 013
3	Vacuum residue	1 133 594.2	455.13	1.000	0.89	405.06	185.095	164.73	186 742 124	0.43191204	187 248 842
4	Non-conditioned fraction	101 642.9	40.81	0.990	0.90	36.73	185.095	166.59	16 932 233	0.03916222	16 978 178
5	Slop	2 132.7	–	–	–	0.00	185.095	173.59	370 215	–	370 215
6	Total	2 492 862.2	1 000.00			937.83					
			2 490 729.5								
									432 731 680		433 904 877
									–370 215		–370 215
									432 361 465	1.00000000	433 534 662
7	Loss	6 780.7									
8	TOTAL	2 499 642.8									

The costs of one conditional unit are as follows:
Feedstock 433 904 877 US$: 2 499 643 t = 173.59 US$/t
Feedstock 173.59 : 937.83 = 0.185095 i.e. 185.095 US$/t

Tab. 17 Determining the cost prices of refinery products on vacuum-distillation unit

Item no.	Elements for calculation	Q'ty in tons	Total in US$	Cost price US$/t	Heavy vacuum gas oil	Light vacuum gas oil	Vacuum residue	Non-conditioned fraction	Slop
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	Q'ty in tons	2 492 862.2			999 017.7	256 474.8	1 133 594.2	101 642.2	2 132.7
2	(%) from equivalent numbers				0.419128261	0.109797478	0.431912044	0.03916221576	–
3	(%) from q'ty				0.400751256	0.102883656	0.454735993	0.04077357283	–
4	Light residue from visbreaking	115 905	19 396 674	167.35					
5	Light residue from crude unit	2 300 333	400 004 893	173.89					
6	Light residue - charge	83 405	14 503 310	173.89					
7	Feedstock	2 499 643	433 904 877	173.59	181 706 629	47 601 013	187 248 842	16 978 178	370 215
8	Chemicals		49 723		20 840	5 459	21 476	1 947	
9	Water		15 627		6 550	1 716	6 750	612	
10	Steam		1 663 560		697 245	182 655	718 512	65 149	
11	Electric power		1 028 295		430 988	112 904	444 133	40 270	
12	Fuel		3 885 761		1 628 632	426 647	1 678 307	152 175	
13	Depreciation		17 308		6 936	1 781	7 871	706	
14	Other production costs		742 116		297 404	76 352	337 467	30 259	
15	Wages		1 760 835		705 657	181 161	800 715	71 796	
16	Taxes		774 547		310 401	79 688	352 214	31 581	
17	Unit management costs		1 345 221		539 099	138 401	611 720	54 849	
18	Laboratory and maintenance costs		322 968		129 430	33 228	146 865	13 169	
19	Common services costs		320 375		128 391	32 961	145 686	13 063	
20	Total costs		445 831 214		186 608 201	48 873 966	192 520 558	17 453 753	370 215
21	Cost price in US$/t		178.36		186.79	190.56	169.83	171.72	173.59

4.3
Instruments for Determining Energy and Processing Efficiency of Vacuum-residue Visbreaking Unit

4.3.1
Technological Characteristics of the Process

Visbreaking is a form of thermal cracking in which vacuum residue is mildly cracked in order to reduce its pour point and viscosity, i.e. to convert high-density residue into lower-viscosity fuel oil. The incoming feedstock, i.e. vacuum residue, from the vacuum-distillation process is introduced into the heater where the temperature is 340–350°C. The feedstock is then heated to 470–480°C to encourage cracking or fission of long-chained hydrocarbons. As a result of this breaking process, molecules of gas and lighter cuts, such as gasoline and gas oil, are formed before entering the main column.

To stop the reaction in the transfer line (between the heater and the column) evaporating gas oil reflux is introduced to reduce the temperature of the reaction products in the incoming feedstock stream. A cooled incoming stream is introduced into the column, having previously reduced its pressure to the operating pressure of the column. After the pressure decline, steam is injected into the transfer line in order to achieve the required evaporation level in the column expansion zone. Thus prepared feedstock goes to the column where in the normal-pressure region the evaporation of some fractions takes place. For the purpose of visbreaking residue stripping, overheated steam is introduced into the bottom of the column. The products of the cracking process are separated in the column into the following: fuel gas, cracked gasoline, kerosene fraction, gas oil and visbreaking residue. Gas oil and kerosene can be blended into visbreaking residue to further reduce the viscosity. Blending is carried out after product stripping in the auxiliary columns in order to raise their flash points. All the products are cooled through heat exchangers and a cooling system. At the bottom of the column there is visbreaking residue, which is used as a component in fuel-oil blending. All the above mentioned technological characteristics are shown in Fig. 6.

4.3.2
Energy Characteristics of the Process

On a typical visbreaking plant the vacuum residue from the vacuum-distillation process is preheated in heat exchangers using the flows of the products of this process and then routed to the process heater.

In the process heater, the gas is mainly used as a fuel, and oil less so. Medium-pressure steam (MpS) is used for its dispersion and preheating. Low-pressure steam (LpS) is used for stripping in the main and the auxiliary columns, while medium-pressure steam is used for the main pump drive through steam turbines. Utilization of the heat of the flue gases in the boiler and the heat of the products in the heat exchangers results in the production of low- and medium-pressure steam. One portion of LP steam is also generated by MP steam reduction at the main pump drive through steam turbines.

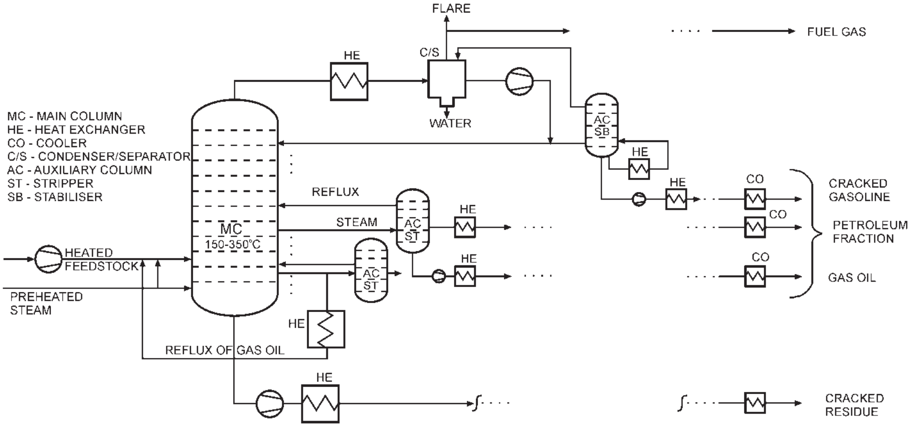


Fig. 6 Technological characteristics of vacuum-residue visbreaking process

The total steam generation exceeds the process requirements; the surplus created is, therefore, routed to a joint low-pressure steam header.

Electric energy is used to drive stand-by pumps, fans and other equipment. The main energy characteristics of the vacuum-residue visbreaking process are shown in Fig. 7, which also presents all the more important alternatives in meeting the energy demands of the process. Each alternative is one of the potential solutions for a process like this.

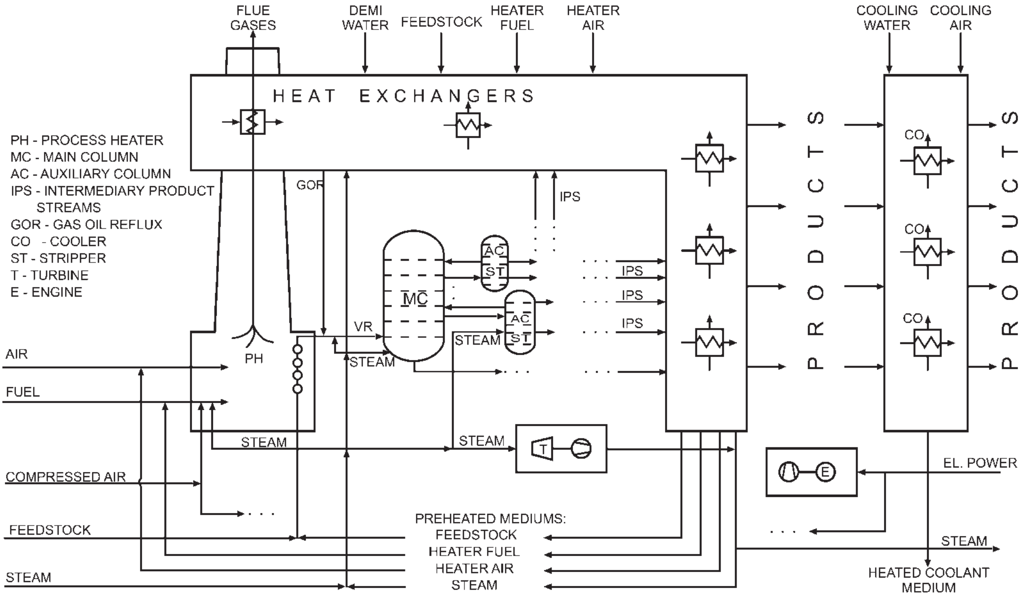
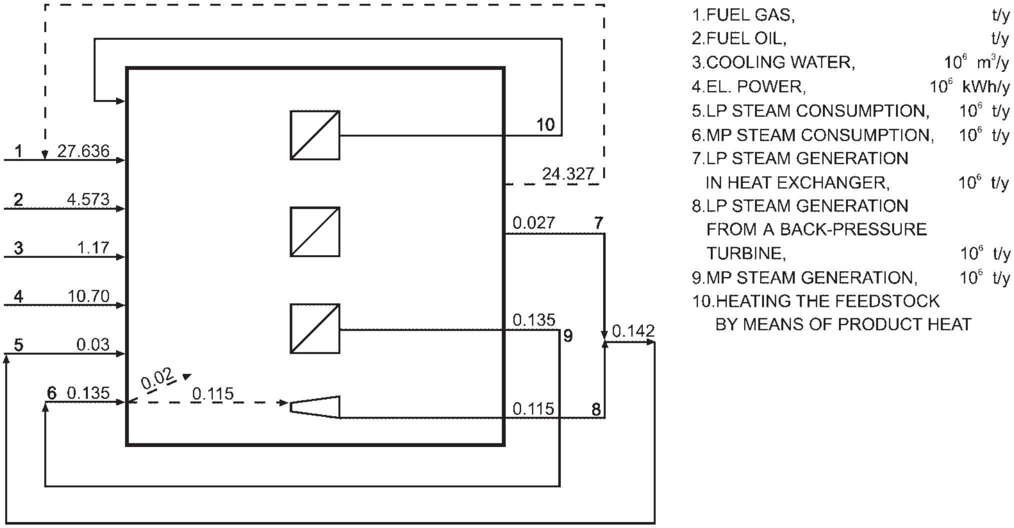


Fig. 7 Energy characteristics of vacuum-residue visbreaking process



Scheme 4 Energy flows of vacuum-residue visbreaking process

For the purpose of this process block, the energy-flow scheme is shown in Scheme 4, and Senky's diagram for the energy balance in Diagram 3. The values given for the energy consumption refer to the annual scope of processing being 973 085 t of vacuum residue and for a specific slate of products.

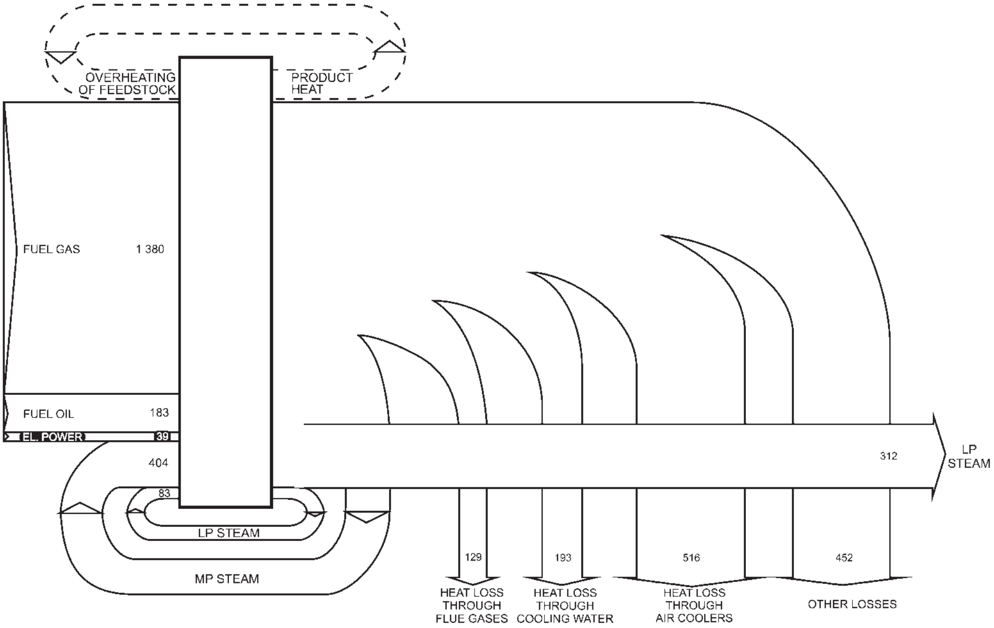


Diagram 3 Senky's diagram of energy flows of vacuum-residue visbreaking process, in TJ/y

The difference between gross and net power consumption appears in the case of MP and LP steam due to internal steam generation in the plant. Internal MP steam generation of 135 000 t or 404 TJ meets the process requirements. Part of the steam, i.e. 115 000 t or 344 TJ, is used for the pump drive through steam turbines and the other part of 20 000 t or 60 TJ for other process purposes.

4.3.3
Determining the Steam Cost Price

The procedure for determining the cost price of steam, as a possible instrument for monitoring the energy efficiency needed by operative management, is given in Tables 18 and 19.

From Tab. 18, it can be seen that the cost price of MP steam generated in the vacuum-residue visbreaking unit is only 0.22 US$/t. The basic explanation for such a cost lies in the fact that on this particular plant, the steam is obtained as a by-product, utilizing the heat of the flue gases in the boiler and the heat of the products in the heat exchangers, thus offsetting the consumption of engine fuel (fuel oil or fuel gas) and it is well known that in the calculation of the power-plant-produced steam, engine fuel bears the largest portion, its share in the total production cost structure being approximately 80%. Other elements used for this calculation (besides energy fuel) that are dictating the cost of 0.22 US$/t are the following: demineralised water (0.165 US$/t), depreciation cost of three heat exchangers and one vessel/boiler determined on the basis of the equipment value of 54 040 US$ and a depreciation rate of 12.5%, the cost of current and investment maintenance and the insurance premium for the above-mentioned equipment covered under "other". Internal LP steam generated in the heat exchangers amounts to 27 000 t or 75 TJ and the steam obtained as a result of

Tab. 18 Cost price of medium-pressure steam (generation-consumption)

Item no.	Elements for calculation	Annual q'ty in t	Price US$/t	MpS generation in US$	MpS consumption (US$)	
					Pump drive through steam turbines	For other process requirements
1	2	3	4	5	6	7
	(%) from quantity			1.00000000	85.185185	14.814815
1	Demin water	135 000	0.165	22 275	18 975	3 300
2	Depreciation			6 755	5 754	1 001
3	Other			170	145	25
4	Cost price (1 - 3)			29 200	24 874	4 326
5	Quantity in t/y			135 000	115 000	20 000
6	Cost price in US$/t			0.2163	0.2163	0.2163

Tab. 19 Cost price of low-pressure steam (LpS)

Item no.	Elements for calculation	Annual q'ty in t	Price US$/t	LpS generation in US$	LpS consumption (US$)	
					for process	for other consumers
1	2	3	4	5	6	7
	(%) from quantity			100.00000	21.126760	78.873240
	LP steam reduction MP steam	115 000	0.22	24 874		
1	LP steam through MP steam reduction	115 000	0.22	24 874	5 255	19 619
	LP steam generation					
2	Demin water	27 000	0.165	4 455	941	3 514
3	Heat-exchanger depreciation			3 273	692	2 581
4	Other			82	17	65
5	Cost price (2-4)	27 000	0.29	7 810	1 650	6 160
6	Total (1+5)	142 000	0.23	32 684	6 905	25 779
7	Quantity in t/y			142 000	30 000	112 000
8	Cost price in US$/t			0.23	0.23	0.23
9	Cost price after delivery to other consumers in US$/t0.05					

the reduction on the back-pressure turbines to 115 000 t or 320 TJ. Such a production level meets this process requirement of 30 000t or 83 TJ, while the difference is used to meet the demands of the process/consumers other than the vacuum-residue visbreaking process. The cost of LP steam obtained through MP steam reduction on back-pressure turbines is 0.22 US$/t and that of the steam produced in heat exchangers is 0.29 US$/t. The average cost of LP steam obtained by the above two methods is 0.23 US$/t and/or 0.05 US$/t after the value of the LP steam supplied to other consumers has been deducted (see Tab. 19).

It is apparent that the cost of the LP steam produced in heat exchangers (0.29 US$/t) is higher than that of the Lp steam obtained through MP steam reduction. Such behaviour of the cost of LP steam obtained by means of reduction and in heat exchangers is determined by the steam-production level and fixed costs (depreciation, current and investment maintenance and capital assets insurance premium) that, viewed per unit of product, decrease as the production level increases and vice versa, increase as the production level decreases. The LP steam cost of 0.05 US$/t is also noticed to be extremely low. In this analysis visbreaking is treated as an independent entity that uses 30 000 t of this steam for its internal purposes and sells all other available quantities (112 000 t) to other consumers at cost price, thus offsetting a part of the costs (25 779 US$/t) that further lowers the cost of the LP steam produced.

4.3.4

Energy Efficiency of the Process

The target standard of net energy consumption and specific gross and net energy consumption on a typical vacuum-residue visbreaking unit is outlined in Tab. 20, and Tab. 21 gives a financial presentation of energy consumption and money savings that can be achieved by eliminating the differences between the target standard and specific gross and net energy consumption of this refinery unit.

As already explained, the excess of LP steam produced in this process is given to other processes within the refinery; this fact is taken into consideration for the calculation of specific net energy consumption. Specific net consumption of process and thermal energy is obtained when the energy value of the steam delivered is deducted from the energy value of the fuel consumed, i.e.:

$$\frac{[(1\ 380+183)-312]\mathrm{TJ}}{970\ 085\ \mathrm{t\ of\ feedstock}}=1285.6\frac{\mathrm{MJ}}{\mathrm{t\ of\ feedstock}}$$

If specific net energy consumption of a typical plant is compared with the target standard the following conclusion can be drawn:

1. Specific electric energy consumption is close to the target standard;
2. Specific net consumption of process and thermal energy on a typical plant amounts to 1285.6 MJ/t, thus exceeding the target standard (1164 MJ/t) by 11%,
3. Total specific net energy consumption is 1325.2 MJ/t, which is 10% higher than the target standard (1200 MJ/t). This means that, compared with the net energy consumption target standard, a typical plant has an efficiency/inefficiency index of 110.

Tab. 20 Target standard of net energy consumption and specific energy consumption on a typical vacuum-residue visbreaking unit (quantity of energy per one tonne of feedstock)

Energy carriers	**Target standard of net energy consumption**		**Specific energy consumption in the plant**					
			Specific gross energy consumption			**Specific net energy consumption**		
			(kg/t) **¹(kWh/t)**	**(MJ/t)**		**(kg/t)** **¹(kWh/t)**	**(MJ/t)**	
	(MJ/t)	**(kWh/t)**		**per unit**	**total**		**per unit**	**total**
Fuels					1 605.3			1 285.6
Fuel gas	*	–	24.8	1 417.7		*	*	
Fuel oil	*	–	4.7	187.6		*	*	
Heat carriers					500.9			
LP steam	*	–	31	86.2				
MP steam	*	–	138.7	414.7				
Sources of heat	1 164	–	–	–	2 106.2	–	–	1 285.6
Electric energy	36	10.0	11.0[1]	39.6	39.6	11.0[1]	39.6	39.6
Energy carriers	1 200	–	–	–	2 145.8	–	–	1 325.2

Tab. 21 Financial presentation of energy consumption and money savings on a typical vacuum-residue visbreaking unit (in US$)

Specific gross energy consumption

Energy carriers	Q'ty of feedstock 973 085 t			**US$**
Fuel gas	973 085 t	(1417.7 MJ/t × 0.0027 US$/MJ)	=	3 724 765
Fuel oil	973 085 t	(187.6 MJ/t × 0.00305 US$/MJ)	=	556 780
Low-pressure steam	973 085 t	(86.2 MJ/t × 0.000018 US$/MJ)	=	1 510
Medium-pressure steam	973 085 t	(414.7 MJ/t × 0.000073 US$/MJ)	=	29 459
Sources of heat	973 085 t	**(2 106.2 MJ/t × 0.002105 US$/MJ)**	**=**	**4 312 514**
Electric energy	973 085 t	(39.6 MJ/t × 0.0167 US$/MJ)	=	643 521
Energy carriers	973 085 t	**(2 145.8 MJ/t × 0.002375 US$/MJ)**	**=**	**4 956 035**

Specific net energy consumption

			US$/t
Fuel gas	(1 135.3 MJ/t × 0.0027 US$/MJ)	=	3.0653
Medium-pressure steam	(150.3 MJ/t × 0.00305 US$/MJ)	=	0.4584
Sources of heat	**(1 285.6 MJ/t × 0.002741 US$/MJ)**	**=**	**3.5237**
Electric energy	(39.6 MJ/t × 0.0167 US$/MJ)	=	0.6613
Energy carriers	**(1 325.2 MJ/t × 0.003158 US$/MJ)**	**=**	**4.1850**
Sources of heat:			
Internal net energy consumption	(1 285.6 MJ/t × 0.002741 US$/MJ)	=	3.52
Target net energy consumption	(1 164 MJ/t × 0.002741 US$/MJ)	=	3.19
Difference:			**0.33**
Energy carriers:			
Internal net energy consumption	(1 325.2 MJ/t × 0.003158 US$/MJ)	=	4.19
Target net energy consumption	(1 200 MJ/t × 0.003158 US$/MJ)	=	3.79
Difference:			**0.40**

This relatively small increase in energy consumption compared with the target standard is the result of internal production of large quantities of steam using the heat of flue gases and process products. In addition to this, there are elements that could further improve the energy efficiency of the plant such as:

- efficient preheating of combustion air using the heat of flue gases;
- economical combustion in the process heater (measuring the excess air), and
- energy integration of the plants (obtaining hotter vacuum residue from vacuum-distillation process and visbreaking residue handing over its heat to the incoming feedstock of another integrated process).

4.3.5
Determining the Refinery Product Cost Prices

The purpose of this unit is to reduce the viscosity of fuel oil. Feedstock for the vacuum-residue visbreaking process is the vacuum residue obtained in the vacuum-distillation unit, and about 94 % of the outlet is cracked residue, which presents the component for fuel-oil blending.

The cost prices of semi-products generated on the vacuum-residue visbreaking unit, are determined by equivalent numbers obtained by means of the density method, as the best method, although equivalent numbers can be determined by the following methods as well:

- thermal value method, and
- average production cost method.

By analysing the results obtained by using the different calculation bases for determining the equivalent numbers, in the vacuum-residue visbreaking unit, taking feedstock, which represents 92.27 % of the total costs, as an example, considerable differences in the cost prices of oil products generated on this unit can be seen. These differences are presented in Tab. 22 and Graphics 9 and 10.

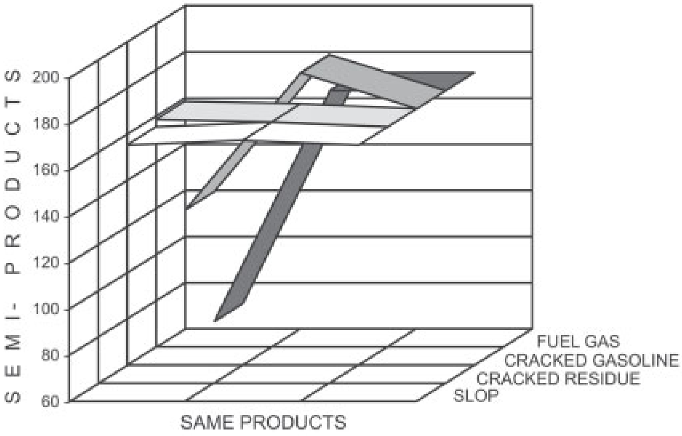
Besides the significant differences in cost prices for the same refinery product that depend on the calculating bases for determining the equivalent numbers, (for example, the cost price of cracked gasoline is from 126.35 US$/t – the base for determining the equivalent numbers is product density, to 169.83 US$/t – the base for determining the equivalent numbers is product thermal value), different ranges in oil-product cost prices can be noted even with the same calculating base.

For example, when product density is the base for determining the equivalent numbers, the cost prices range from 70.96 US$/t (fuel oil) to 173.08 US$/t (cracked residue).

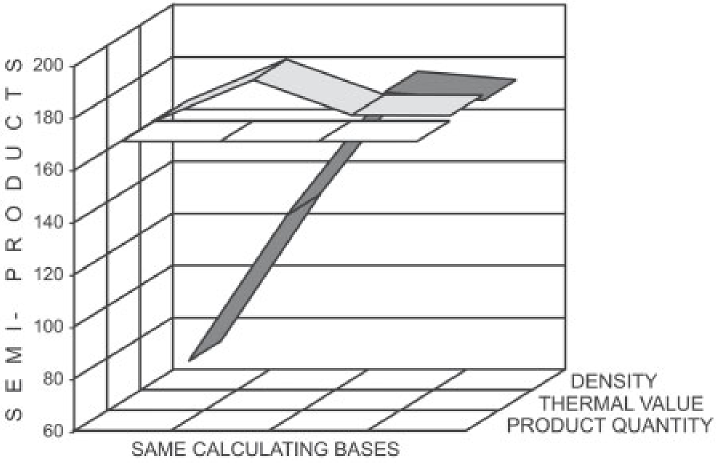
The stated examples of the calculating bases' effects on determining the equivalent numbers do not present all the dilemmas that experts dealing with process-industry

Tab. 22 Cost prices of semi-products on vacuum-residue visbreaking unit in US$/t (per calculating bases)

Item no.	**Semi-products**	**Base for determining the equivalent number for calculating the cost prices**		
		Product Density Method	**Thermal Value Method**	**Average Production Cost Method**
1	**2**	**3**	**4**	**5**
1	Fuel gas	70.96	169.83	169.83
2	Cracked gasoline	126.35	185.42	169.83
3	Cracked residue	173.08	171.86	169.83
4	Slop	169.83	171.81	169.83



Graphic 9 Cost prices of semi-products on vacuum-residue visbreaking unit, per products (in US\$/t)



Graphic 10 Cost prices of semi-products on vacuum-residue visbreaking unit, per calculating bases (in US\$/t)

calculations can face. The effects of the choice of reference derivatives, and the treatment of the by-products are also important.

The effect of the choice of reference derivatives cracked residue (whose density is 0.999 g/cm^3), cracked gasoline (whose density is 0.734 g/cm^3) and fuel oil (whose density is 0.410 g/cm^3) on determining the equivalent numbers, in the case of using the same calculating base for determining the equivalent numbers (density method) are shown in Tab. 23.

Tab. 23 Cost prices of semi-products on vacuum-residue visbreaking unit in US$/t (per reference products)

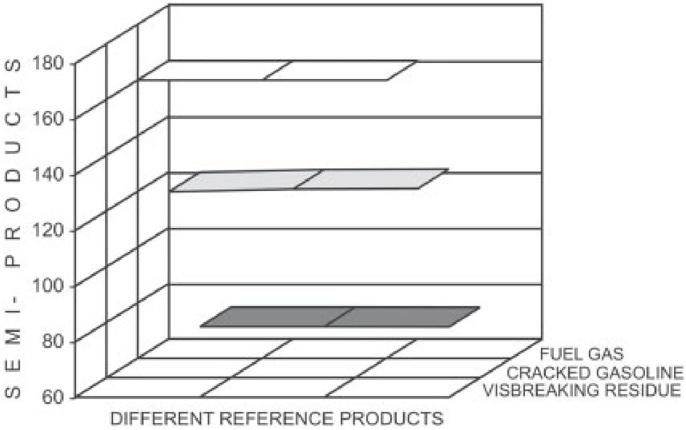
Item no.	Semi-products	Reference products		
		Cracked residue	Cracked gasoline	Fuel gas
1	2	3	4	5
1	Fuel gas	70.96	71.26	71.21
2	Cracked gasoline	126.35	127.25	127.47
3	Cracked residue	173.08	173.05	173.05
4	Slop	169.83	169.83	169.83

It can be seen that the differences appearing in this case are smaller than those appearing in the previous example of determining the equivalent numbers by different calculating bases (density, thermal value and quantity of products).

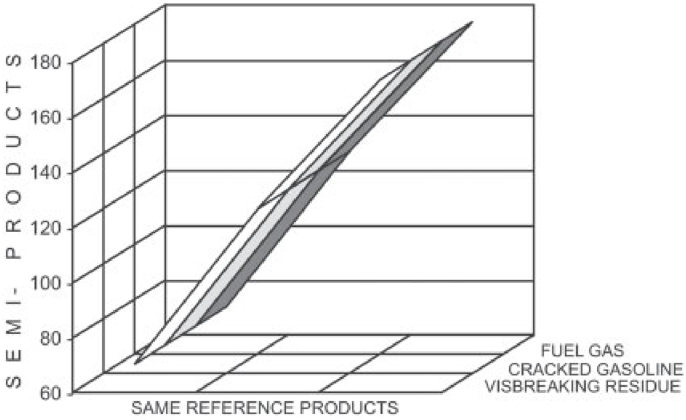
The results obtained by using the different reference derivatives, but the same calculating base, i.e. density method, are shown in Tab. 23 and Graphics 11 and 12.

The cost prices of semi-products generated on the vacuum-residue visbreaking unit were calculated in the following manner, using the product density method:

- Proportional costs are distributed to semi-products generated in this unit according to the percentages obtained from equivalent numbers by means of the density method and reference product, i.e. cracked residue whose density is 0.999 g/cm^3 (Tab. 24, Column 5 and Tab. 25, Line 2).
- Fixed costs are distributed to semi-products according to the percentages obtained from the quantity (Tab. 25, Line 3).
- The price of slop is expressed on the level of feedstock average price.



Graphic 11 Cost prices of semi-products on vacuum-residue visbreaking unit, per different reference products (in US$/t)



Graphic 12 Cost prices of semi-products on vacuum-residue visbreaking unit, per same reference products (in US$/t)

By using the mentioned methodology for distributing the proportional and fixed costs of this unit to the bearers of costs, i.e. to the products obtained in this unit, the following cost prices of semi-products are established:

Semi-products	Cost prices in US$/t
1	**2**
Fuel gas	81.29
Cracked gasoline	139.00
Cracked residue	187.80
Slop	169.83

4.4
Instruments for Determining Energy and Processing Efficiency of Bitumen Blowing Unit

4.4.1
Technological Characteristics of the Process

The bitumen blowing feedstock is vacuum residue from the vacuum-distillation unit. The vacuum residue has to be of an appropriate quality and limited paraffinic content.

The bitumen blowing process consists of continuous oxidation of vacuum residue in the reactor, at a temperature of 250–270°C. Oxidation is carried out by introducing the air via a compressor, under pressure and at the temperature of 60°C. By blowing the air over the heated feedstock, the oxygen from air causes oxidation of highly volatile substances. Feedstock oxidation is followed by reaction-heat separation. For providing heat duty in the reactor, the possibility of leading the part of cooled bitumen into reactor (reflux) is taken into consideration.

Tab. 24 Determining the equivalent numbers for distributing the proportional costs on vacuum-residue visbreaking unit

Item no.	Oil products	Quantity in tons	Q'ty from 1 tonne	Density g/cm^3	Equivalent numbers	Condition units	Cost of 1 condition unit	Cost price in US$/t	Cost of feedstock in US$	(%) for proportional costs	Cost of feed-stock in US$ (entry-exit)
1	2	3	4	5	6	7(4 × 6)	8	9(6 × 8)	10(3 × 9)	11	12
1	Fuel gas	14 708.3	21.51	0.410	0.41	8.82	173.082	70.96	1 043 757	0.008987606	1 043 760
2	Cracked gasoline	15 452.0	22.60	0.734	0.73	16.50	173.082	126.35	1 952 359	0.016811420	1 952 364
3	Cracked residue	653 660.0	955.89	0.999	1.00	955.89	173.082	173.08	113 136 788	0.974200974	113 137 093
4	Slop	12 460.8	–	–	–	0.00		169.83	2 116 221	–	2 116 221
5	Total	696 281.2	1 000.00 683 820.4			981.21					
									118 249 125		118 249 438
									–2 116 221		–2 116 221
									116 132 904	1.000000000	116 133 217
6	Loss	0.0									
7	Total	696 281.2									

The costs of one conditional unit are as follows:
Feedstock 118 249 438 US$: 696 281 t = 169.83 US$/t
Feedstock 169.03 : 981.21 = 0.173082 i.e. 173.082 US$/t

Tab. 25 Determining the cost prices of refinery products on vacuum-residue visbreaking unit

Item no.	Elements for calculation	Q'ty in tonness	Total in US$	Cost price US$/t	Fuel gas	Cracked gasoline	Cracked residue	Slop
1	2	3	4	5	6	7	8	9
1	Q'ty in tons	696 281			14 708.3	15 452.0	653 660.0	12 460.8
2	(%) from equivalent numbers				0.00898761	0.01681142	0.97420097	
3	(%) from q'ty				0.02150906	0.02259659	0.95589435	
4	Vacuum residue	696 281	118 249 438	169.83				
5	Feedstock	696 281	118 249 438	169.83	1 043 760	1 952 364	113 137 093	2 116 221
6	Chemicals							
7	Water		859		8	14	837	
8	Steam		2 304 116		20 708	38 735	2 244 672	
9	Electric power		606 549		5 451	10 197	590 901	
10	Fuel		1 968 308		17 690	33 090	1 917 527	
11	Depreciation		262 778		5 652	5 938	251 188	
12	Other production costs		677 780		14 578	15 316	647 886	
13	Wages		1 608 187		34 591	36 340	1 537 257	
14	Taxes		707 402		15 216	15 985	676 202	
15	Unit management costs		1 228 602		26 426	27 762	1 174 414	
16	Laboratory and maintenance costs		269 139		5 789	6 082	257 269	
17	Common services costs		266 980		5 742	6 033	255 205	
18	Total costs		128 150 139		1 195 612	2 147 856	122 690 451	2 116 221
19	Cost price in US$/t		184.05		81.29	139.00	187.70	169.83

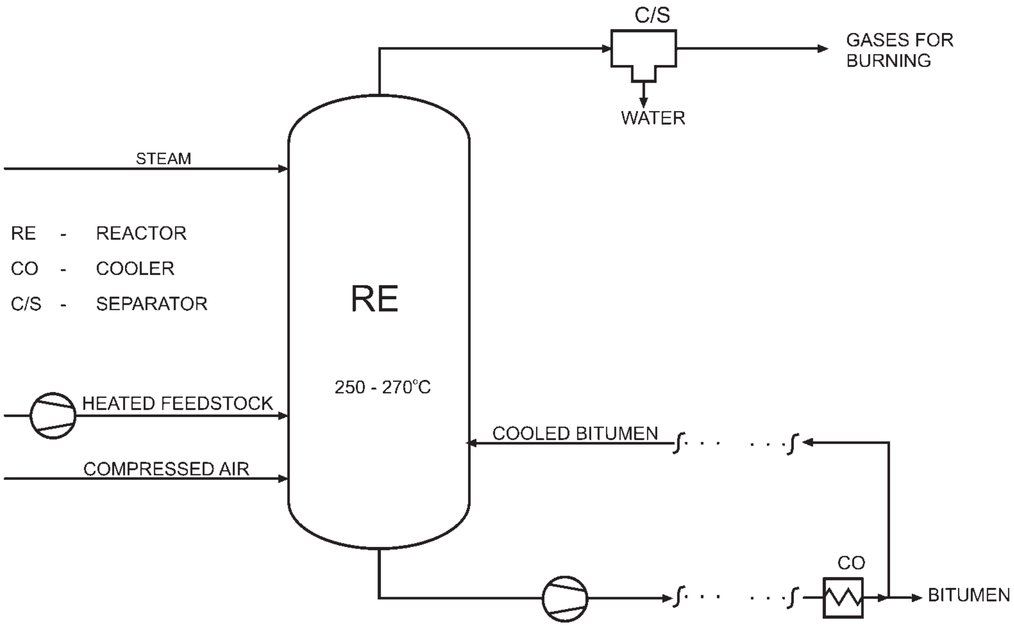


Fig. 8 Technological characteristics of bitumen blowing process

Steam is introduced into the reactor top, so that reaction control is possible.

From the reactor, the finished bitumen is directed via the cooler into storage. Steam, gases and other products formed by oxidation off the reactor top, are routed through the separator to be burned in the process heater.

All the above mentioned technological characteristics are shown in Fig. 8.

4.4.2
Energy Characteristics of the Process

On a typical bitumen blowing unit, the vacuum residue that is introduced from the vacuum-distillation unit at 130–150°C, is heated again in the process heater and directed to the reactor. Fuel gas is used in the process heater as well as in the heater for burning of gases.

Medium-pressure steam (MpS) is used for the pump drive, for the heating of tanks and pipes, for monitoring the bitumen blowing reaction in the reactor, as well as for the heating of compressed air.

Electric energy is used to drive pumps, fans and other auxiliary equipment.

The main energy characteristics of the bitumen blowing unit are shown in Fig. 9, which also presents all the important alternatives in meeting the energy demands of the process.

The block energy-flow scheme of this process is shown in Scheme 5 and Senky's diagram for the energy balance in Diagram 4. The values given for the energy

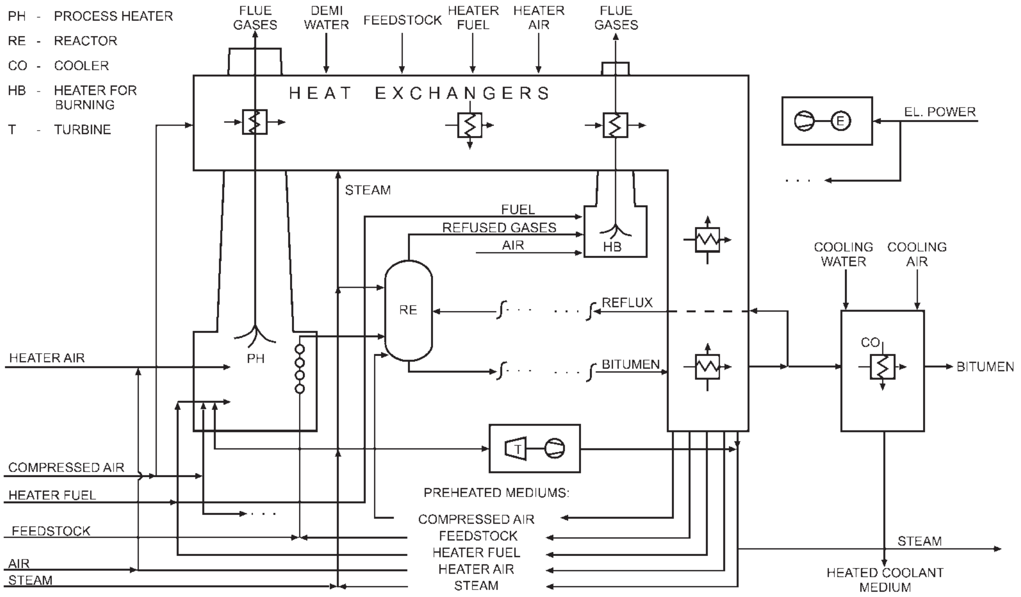
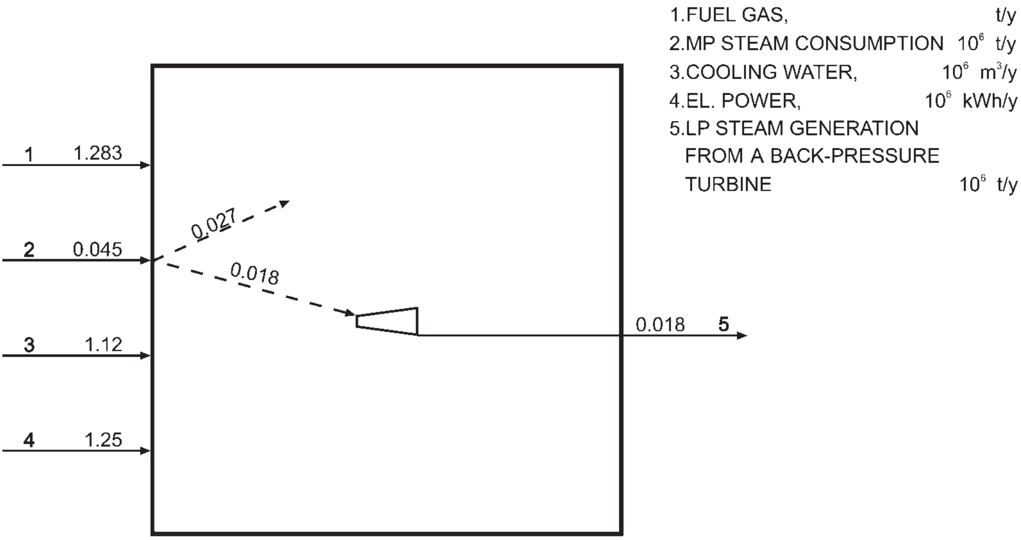


Fig. 9 Energy characteristics of bitumen blowing process



Scheme 5 Energy flows of bitumen blowing process

consumption refer to the annual volume of production amounting to 94 314 t of feedstock.

The consumption of medium-pressure steam is 45 000 t or 135 TJ.

Internal low-pressure steam generation, obtained by reduction on back-pressure turbines, is 18 000 t or 50 TJ and is used for other process requirements.

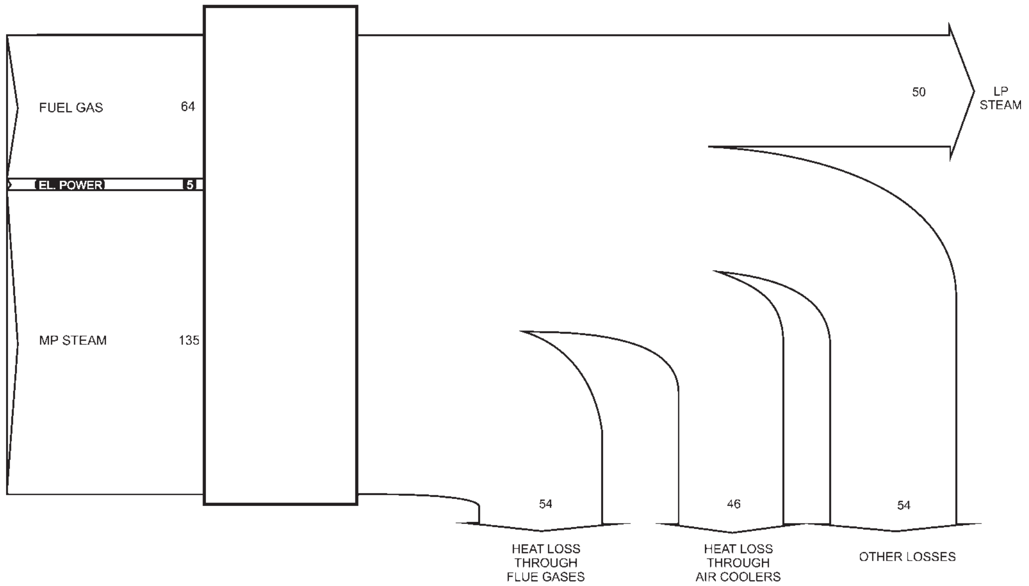


Diagram 4 Senky's diagram of energy flows of bitumen blowing process, in TJ/y

4.4.3
Determining the Steam Cost Price

The cost prices of medium-pressure steam used in this unit, as well as the cost price of low-pressure steam generated in this unit, by reduction of medium-pressure steam on back-pressure turbines, and that is used for other process requirements, are given in Tables 26 and 27.

The basic explanation for such a cost price of low-pressure steam lies in the fixed costs (depreciation, current and investment maintenance and insurance premium of equipment from the breakage and fire) related to the part of equipment that shares in reduction of MP steam in LP steam.

This LP steam is delivered to other processes, i.e. it is not used on this unit.

Tab. 26 Cost price of medium-pressure steam (consumption)

Item no.	Elements for calculation	MpS consumption (US$)		
		Annual q'ty in t	Cost price US$/t	Total MpS consumption in US$
1	2	3	4	5
1	MP steam (supply)	27 000	9.66	260 820

Tab. 27 Cost price of low-pressure steam (production-consumption)

Item no.	Elements for calculation	Low-pressure steam generation (LpS)			LpS consumption for other consumers
		Annual q'ty in t	Cost price US$/t	Total in US$	
1	2	3	4	5	6
1	LP steam by reduction of MpS	18 000	9.66	173 880	173 880
2	Depreciation			3 397	3 397
3	Current and investment maintenance			407	407
4	Insurance premium for equipment			272	272
5	Total	18 000	9.89	177 956	177 956
6	Quantity in t			18 000 t	18 000 t
7	Cost price of LpS in US$/t			**9.89**	**9.89**

4.4.4

Energy Efficiency of the Process

The target standard of net energy consumption and specific gross and net energy consumption is outlined in Tab. 28, and a financial presentation of energy consumption and money savings that can be achieved by eliminating the differences between the target standard and specific gross and net energy consumption of this refinery unit is presented in Tab. 29.

When calculating the specific net energy consumption, the energy value of generated LP steam, being supplied to other processes, is taken into consideration.

Tab. 28 Target standard of net energy consumption and specific energy consumption on a typical bitumen blowing unit (quantity of energy per one tonne of feedstock)

Energy carriers	Target standard of net energy consumption		Specific energy consumption in the plant					
			Specific gross energy consumption			Specific net energy consumption		
			(kg/t) ^{1}(kWh/t)	(MJ/t)		(kg/t) ^{1}(kWh/t)	(MJ/t)	
	(MJ/t)	(kWh/t)		per unit	total		per unit	total
Fuels								
Fuel gas	*	–	13.6	677.6	677.6	13.6	677.6	677.6
Heat carriers								
MP steam	*	–	480	1 435.2	1 435.2	*	*	901.2
Sources of heat	1 257	–	–	–	2 112.8	–	–	1 578.8
Electric energy	43	12.0	13.3^1	47.9	47.9	13.3^1	47.9	47.9
Energy carriers	1 300	–	–	–	2 160.7	–	–	1 626.7

Tab. 29 Financial presentation of energy consumption and money savings on a typical bitumen blowing unit (in US$)

Specific gross energy consumption

Energy carriers	Q'ty of feedstock (crude oil) 94 314 t			US$
Fuel oil	94 314 t	(677.6 MJ/t × 0.00305 US$/MJ)	=	194 917
Medium-pressure steam	94 314 t	(1 435.2 MJ/t × 0.0032308 US$/MJ)	=	437 319
Sources of heat	94 314 t	**(2 112.8 MJ/t × 0.003173 US$/MJ)**	**=**	**632 236**
Electric energy	94 314 t	(47.9 MJ/t × 0.0167 US$/MJ)	=	75 445
Energy carriers	94 314 t	**(2 160.7 MJ/t × 0.003473 US$/MJ)**	**=**	**707 681**

Specific net energy consumption

			US$/t
Fuel oil	(677.6 MJ/t × 0.00305 US$/MJ)	=	2.06668
Medium-pressure steam	(901.2 MJ/t × 0.0032308 US$/MJ)	=	2.911597
Sources of heat	**(1 578.8 MJ/t × 0.003154 US$/MJ)**	**=**	**4.978277**
Electric energy	(47.9 MJ/t × 0.0167 US$/MJ)	=	0.79993
Energy carriers	**(1 626.7 MJ/t × 0.003553 US$/MJ)**	**=**	**5.778207**
Sources of heat:			
Internal net energy consumption	(1 578.8 MJ/t × 0.003154 US$/MJ)	=	4.98
Target net energy consumption	(1 257 MJ/t × 0.003154 US$/MJ)	=	3.96
Difference:			**1.02**
Energy carriers:			
Internal net energy consumption	(1 626.7 MJ/t × 0.003553 US$/MJ)	=	5.78
Target net energy consumption	(1 300 MJ/t × 0.003553 US$/MJ)	=	4.62
Difference:			**1.16**

Specific net consumption of process and thermal energy, in this case, is obtained when the energy value of the steam delivered is deducted from the energy value of the steam consumed, i.e.:

$$\frac{(135-50)\mathrm{TJ}}{94\,314\ \text{t of feedstock}} = 901.2\mathrm{MJ/t}$$

If specific net energy consumption of a typical plant is compared with the target standard, the following conclusion can be drawn:

1. Specific electric energy consumption is close to the target standard.
2. Specific net consumption of process and thermal energy (fuel and steam) on a typical plant amounts to 1578.8 MJ/t, thus exceeding the target standard (1 257 MJ/t) by 26 %.
3. Total specific net energy consumption is 1 626.7 MJ/t, which is 25 % higher than the target standard (1 300 MJ/t). Compared with the net energy consumption target standard, a typical plant has an efficiency/inefficiency index of 125.

This increased consumption of process and thermal energy on a typical plant is caused by different factors, the most important being:

- non-economical combustion in the process heater,
- inefficient utilization of the flue gases heat in the process heater and in the heater for burning the waste gases,
- inefficient utilization of produced bitumen heat,
- preheating of compressed air by steam,
- inefficient utilization of MP steam for pump drive by means of steam turbines, and
- unstable preheating of combustion air before it enters the process heater.

4.4.5
Determining Refinery Product Cost Prices

On a bitumen blowing unit, determining the cost prices is simple because, in this case, the feedstock is vacuum residue from the vacuum-distillation unit, and the product is bitumen. This means that the cost price of this product is determined by adding the costs of this unit to the cost price of feedstock (Tab. 30).

Tab. 30 Determining the cost prices of refinery products on bitumen blowing unit

Item no.	Elements for calculation	Q'ty in tonnes	Total in US$	Cost price US$/t	Bitumen
1	2	3	4	5	6
1	Q'ty in tonnes	180 141.8			180 141.8
2	(%) from equivalent numbers				
3	(%) from q'ty				
4	Vacuum residue	180 142	30 593 490	169.83	
5	Feedstock	180 142	30 593 490	169.83	30 593 490
6	Chemicals		–		–
7	Water		–		–
8	Steam		1 075 755		1 075 755
9	Electric power		516 832		516 832
10	Fuel		139 383		139 383
11	Depreciation		30 841		30 841
12	Other production costs		652 410		652 410
13	Wages		1 547 987		1 547 987
14	Taxes		680 921		680 921
15	Unit management costs		1 182 612		1 182 612
16	Laboratory and Maintenance costs		167 465		167 465
17	Common services costs		166 121		166 121
18	Total costs		36 753 816		36 753 816
19	Cost price in US$/t		204.03		204.03

4.5
Instruments for Determining Energy and Processing Efficiency of Catalytic Reforming Unit

4.5.1
Technological Characteristics of the Process

Catalytic reforming is the process of converting the low-value straight-run gasoline from a crude unit into high-value engine fuel or into components for jet-fuel blending, by means of catalyst in the presence of hydrogen. This process is also used for generating the products from which benzene, toluene, xylene and heavy aromatics are obtained.

This unit consists of reactors, auxiliary columns, heat exchangers, which use the heat of mass flows and the heaters in which heating the feedstock and intermediary products takes place.

Heated feedstock (the straight-run gasoline) goes to the first reactor where the chemical reactions begin by means of which the high-quality products are obtained.

The product leaves the first reactor at a temperature of 330–340 °C, and goes to the separator through a heat exchanger and cooler. In the separator, the gas fraction is separated from heavy fractions. Part of the gas from the separator is returned as a reflux into the feedstock line.

The heavy fractions, after having been treated in the auxiliary column (separating the wet gas and light gasoline) go into the reactor section that consists of process heaters and reactors.

In the reactor section, the reactor feedstock is mixed with recirculated gas rich in hydrogen, then heated in heat exchangers and heaters and passed through the process reactor. In this way, high-octane gasoline can be achieved.

The heaters are placed between the reactors in order to compensate the heat that is used for endothermic reactions. After the heat exchanger, the product from the reactor is cooled and directed into the separator, where the liquid phase is separated from the gas rich in hydrogen. The greater part of the gas is returned to the reactors, while the smaller part goes into the fuel-gas system and the flare in order to maintain pressure in the system.

Liquid phase goes into the stabilizer. The temperatures of the processes are 350–500 °C, pressures 10–25 bar and the obtained products are as follows:

- hydrogen,
- fuel gas,
- wet gas,
- light gasoline,
- light platformate, and
- platformate.

The technological characteristics of the process are shown in Fig. 10.

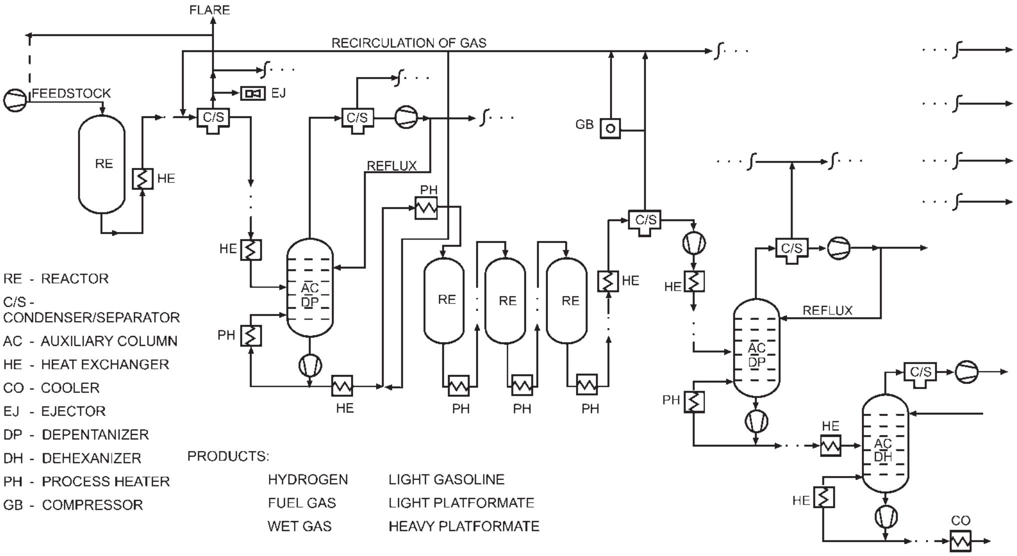


Fig. 10 Technological characteristics of catalytic reforming process

4.5.2
Energy Characteristics of the Process

On a typical catalytic reforming process the feedstock is preheated in heat exchangers by means of product stream of this process, before entering the process heater.

In the process heaters, fuel gas is used as a fuel.

Medium-pressure steam (MpS) is used to drive the ejector, to heat the bottom of the auxiliary column and to drive spare systems of the main pump. One part of medium-pressure steam (MpS) is generated in this unit, by means of the boiler–utilizer of flue gases heat, and the other is provided from external sources.

Electric power is used to drive pumps, fan (air cooling) and other equipment and auxiliary facilities as well.

The main energy characteristics of the catalytic reforming process are given in Fig. 11, where all the important ways of supplying the energy required for the process are shown as well. Each option is a possible solution for such a process.

For the purpose of catalytic reforming process, a block energy-flows scheme and Senky's diagram for the energy balance, are shown in Scheme 6 and Diagram 5. The given energy consumption values apply to the yearly production volume of 380 605 t straight-run gasoline and a specific product slate.

The difference between the gross and net consumption appears only in medium-pressure steam (MpS), due to the internal generation in the unit itself. Gross consumption totals 40 000 t or 119 TJ, net consumption is 30 000 t or 89 TJ and internal generation is 10 000 t or 30 TJ.

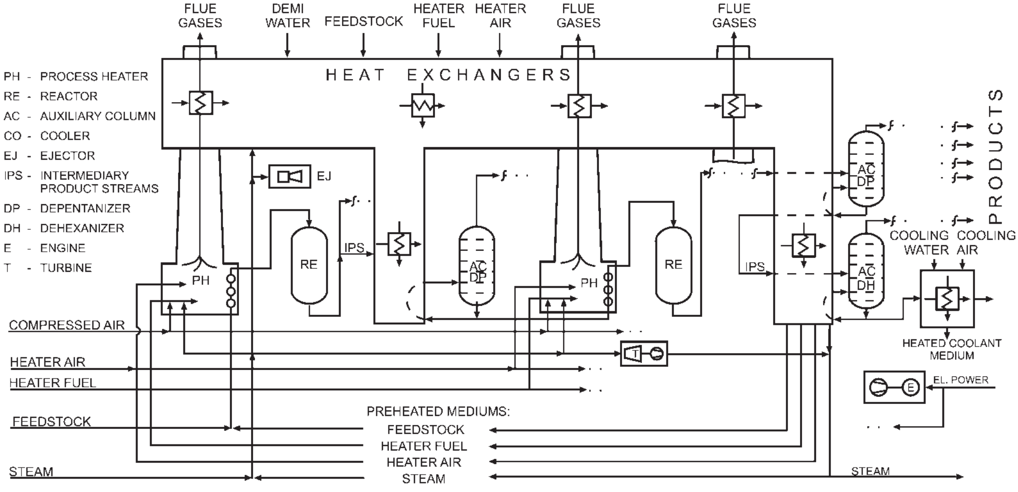
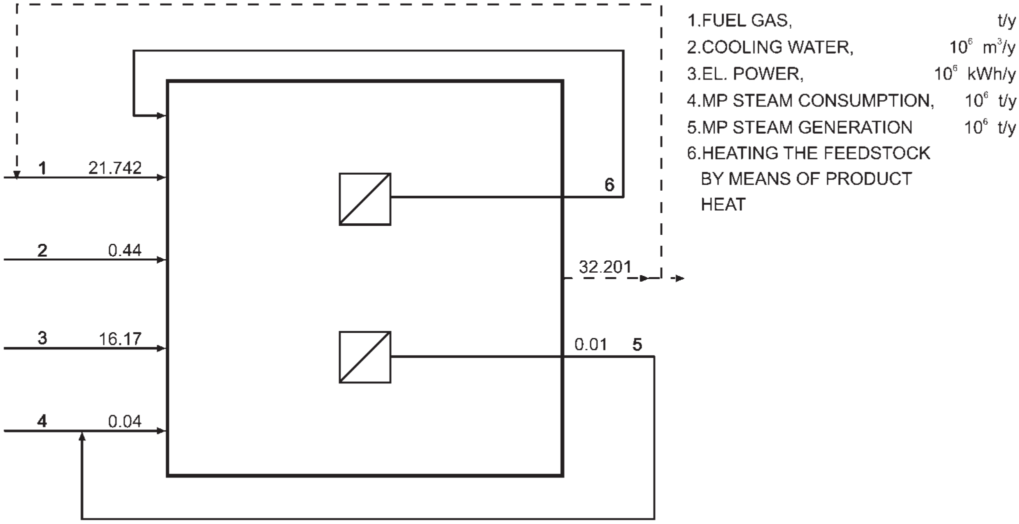


Fig. 11 Energy characteristics of catalytic reforming process



Scheme 6 Energy flows of catalytic reforming process

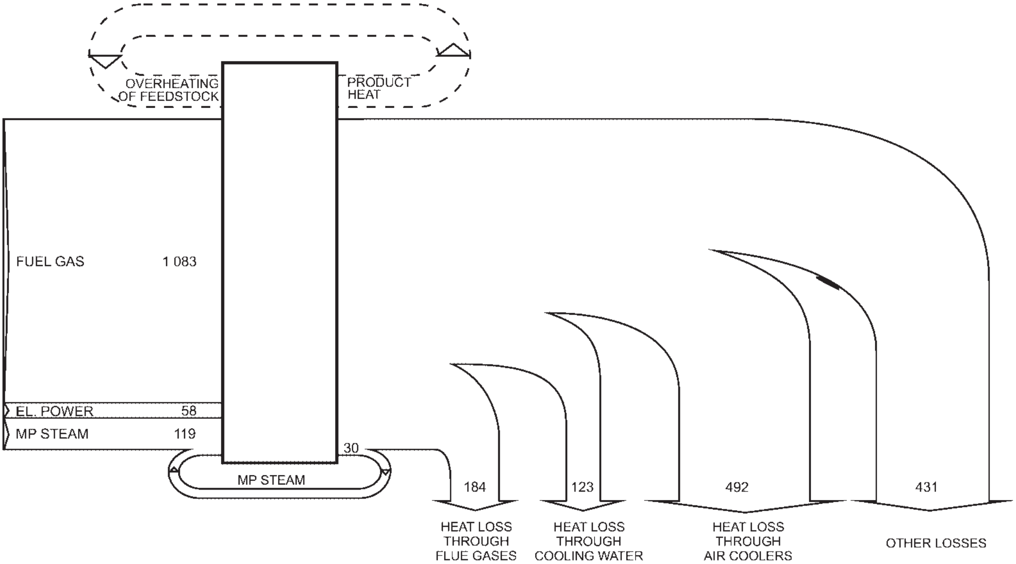


Diagram 5 Senky's diagram of energy flows of catalytic reforming process, in TJ/y

4.5.3

Determining the Steam Cost Price

The cost prices of medium-pressure steam (MpS) generated and used in the catalytic reforming process, as well as the average cost price of medium-pressure steam, are given in Tab. 31.

Tab. 31 shows that the largest portion of medium-pressure steam (MpS) needed for this unit, 30 000 t or 89 TJ, is provided from the refinery power plant at the cost price of 9.66 US$/t, and the difference of 10 000 t or 30 TJ is generated in this unit at the cost price of 0.45 US$/t, so the average cost price of medium-pressure steam used in this unit is 7.36 US$/t.

The basic explanation for such a low cost price of medium-pressure steam (MpS) generated on this unit (0.45 US$/t) lies in the fact that the steam is obtained as a by-product, by utilizing the heat of the flue gases in the boiler-utilizer thus offsetting the consumption of engine fuel (fuel oil or fuel gas) which shares in calculating cost prices of the steam generated in refinery power plant, with about 80%.

4.5.4

Energy Efficiency of the Process

In relation to the medium-pressure steam (MpS) specific consumption, the feedstock to be processed is as follows:

Tab. 31 Cost prices of medium-pressure steam (MpS)

Item no.	Elements for calculation	Medium-pressure steam generation (MpS)			MpS for internal consumption
		Annual q'ty in t	Cost price US$/t	Total in US$	
1	2	3	4	5	6
1	MP steam provided from Refinery Power Plant	30 000	9.66	289 800	289 800
2	MP steam generation	10 000	0.45	4 525	4 525
2.1	Demineralized water	10 000	0.165	1 650	
2.2	Depreciation			2 400	
2.3	Current and investment maintenance			285	
2.4	Insurance premium for equipment			190	
3	Total (1+2)	40 000	7.36	294 325	294 325
4	Quantity in t				40 000
5	Cost price of MpS in US$/t				**7.36**

$$\text{gross}: \frac{105\ \text{kg of steam}}{\text{t of feedstock}} \quad \text{or}:\ 312.6\ \frac{\text{MJ}}{\text{t of feedstock}}$$

$$\text{net}: \frac{79\ \text{kg of steam}}{\text{t of feedstock}} \quad \text{or}:\ 233.8\ \frac{\text{MJ}}{\text{t of feedstock}}$$

Tab. 32 presents the target standard of net energy consumption and specific gross and net energy consumption, and Tab. 33 shows the financial presentation of energy consumption and money savings of 548 100 US$/y (380 605t x 1.44US$/t) that can be achieved by eliminating the differences between the target standard (average energy

Tab. 32 Target standard of net energy consumption and specific energy consumption on a typical catalytic reforming unit (quantity of energy per one tonne of feedstock)

Energy carriers	Target standard of net energy consumption		Specific energy consumption in the plant					
			Specific gross energy consumption			Specific net energy consumption		
			(kg/t) ^{1}(kWh/t)	(MJ/t)		(kg/t) ^{1}(kWh/t)	(MJ/t)	
	(MJ/t)	(kWh/t)		per unit	total		per unit	total
Fuel								
Fuel gas	*	–	57.1	2 845.4	2 845.4	57.1	2 845.4	2 845.4
Heat carriers								
MP steam	*	–	150	312.6	312.6	79	233.8	233.8
Sources of heat	2 656	–	–		3 158.0	–	–	3 079.2
Electric energy	144	40.0	42.5^1	153.0	153	42.5^1	153	153
Energy carriers	2 800	–	–	–	3 311	–	–	3 232.2

Tab. 33 Financial presentation of energy consumption and money savings on a typical catalytic reforming unit (in US$)

Specific gross energy consumption

Energy carriers	Q'ty of feedstock 380 605 t			US$
Fuel gas	380 605 t	(2 845.4 MJ/t × 0.0027 US$/MJ)	=	2 924 028
Medium-pressure steam	380 605 t	(312.6 MJ/t × 0.002462 US$/MJ)	=	292 922
Sources of heat	380 605 t	**(3 158.0 MJ/t × 0.002676 US$/MJ)**	**=**	**3 216 950**
Electric energy	380 605 t	(153 MJ/t × 0.0167 US$/MJ)	=	972 484
Energy carriers	380 605 t	**(3 311 MJ/t × 0.00332446 US$/MJ)**	**=**	**4 189 434**

Specific net energy consumption

			US$/t
Fuel gas	(2 845.4 MJ/t × 0.0027 US$/MJ)	=	7.682580
Medium-pressure steam	(233.8 MJ/t × 0.002462 US$/MJ)	=	0.575656
Sources of heat	**(3 079.2 MJ/t × 0.0026819 US$/MJ)**	**=**	**8.258236**
Electric energy	(153 MJ/t × 0.0167 US$/MJ)	=	2.555100
Energy carriers	**(3 232.2 MJ/t × 0.0033455 US$/MJ)**	**=**	**10.813336**
Sources of heat:			
Internal net energy consumption	(3 079.2 MJ/t × 0.0026819 US$/MJ)	=	8.26
Target net energy consumption	(2 656 MJ/t × 0.0026819 US$/MJ)	=	7.12
Difference:			**1.14**
Energy carriers:			
Internal net energy consumption	(3 232.2 MJ/t × 0.0033455 US$/MJ)	=	10.81
Target net energy consumption	(2 800 MJ/t × 0.0033455 US$/MJ)	=	9.37
Difference:			**1.44**

consumption of Western European refineries) and specific gross and net energy consumption of this refinery unit.

By comparing net energy consumption of a typical plant with the target standard, the following conclusions can be drawn:

1. Specific electric energy consumption is close to the target standard.
2. Specific net consumption of process and thermal energy (fuel and steam) of 3079.2 MJ/t exceeds the target standard (2656 MJ/t) by 16%.
3. Total specific net energy consumption is 3232.2 MJ/t, i.e. 15% higher than the target standard (2800 MJ/t). Compared with the target standard of net energy consumption, a typical plant has an efficiency/inefficiency index of 115.

Increased consumption of process and thermal energy on a typical plant is caused by different factors, the most important being:

- non-economical combustion in the process heater,
- inefficient feedstock preheating system,

- inefficient application of the heat from process heater,
- no preheating of air before entering process heaters.

4.5.5
Determining the Refinery Product Cost Prices

The feedstock for catalytic reforming process is 70–175 °C gasoline that is obtained on the crude unit.

It is necessary to perform desulfurization of this gasoline, by chemical reactions, in order to increase the octane number. In this way this gasoline can be used as a component in motor gasoline blending.

The heavy platformate that is blended into gasoline as a high-octane component, is mostly the product of this unit, but also the light gasoline that presents the feedstock for gas concentration unit and light platformate that presents the feedstock for the aromatics extraction unit.

The cost prices of semi-products generated on the catalytic reforming unit, are determined by equivalent numbers obtained by means of the density method, although equivalent numbers can be determined by the following methods as well:

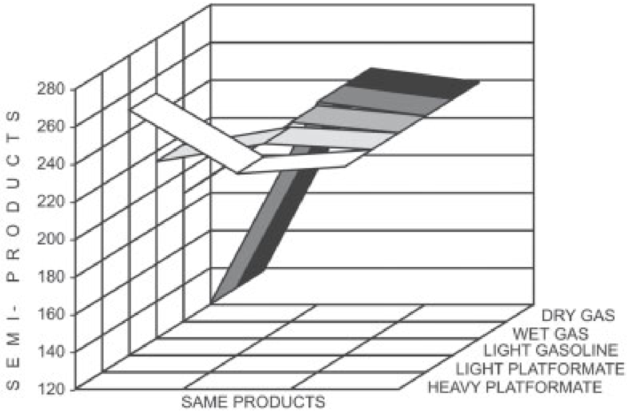
- thermal value method, and
- average production cost method.

By analysing the results obtained by means of the different calculation bases for determining equivalent numbers, significant differences in the cost prices of oil products generated in this unit can be seen. These differences are presented in Tab. 34 and Graphics 13 and 14.

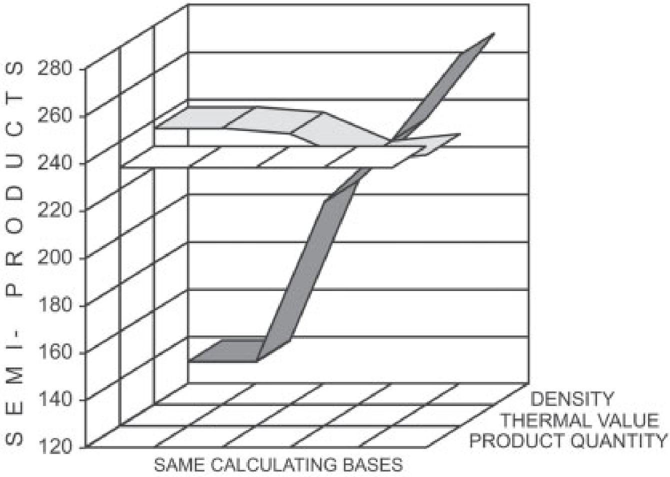
Besides the significant differences in cost prices for the same refinery product, which depend on the calculating bases for determining the equivalent numbers, for example, the cost price of heavy platformate is from 268.34 US$/t (the base for determining the equivalent numbers is product density) to 234.60 US$/t (the base

Tab. 34 Cost prices of semi-products on catalytic reforming unit in US$/t (per calculating bases)

Item no.	**Semi-products**	**Base for determining the equivalent number for calculating the cost prices**		
		Product Density Method	**Thermal Value Method**	**Average Production Cost Method**
1	**2**	**3**	**4**	**5**
1	Dry gas	138.23	245.93	238.31
2	Wet gas	138.23	245.93	238.31
3	Light gasoline	205.89	243.66	238.31
4	Light platformate	231.91	241.40	238.31
5	Heavy platformate	268.34	234.60	238.31



Graphic 13 Cost prices of semi-products on catalytic reforming unit, per products (in US$/t)



Graphic 14 Cost prices of semi-products on catalytic reforming unit, per calculating bases (in US$/t)

for determining the equivalent numbers is product thermal value), the different ranges in oil-product cost prices can also be noted even with the same calculating base.

For example, when product density is the base for determining the equivalent numbers, the cost prices range from 138.23 US$/t (dry and wet gas) to 268.34 US$/t (heavy platformate).

The stated examples of the calculating bases effects on determining the equivalent numbers do not present all the dilemmas that experts dealing with process-industry

Tab. 35 Cost prices of semi-products on catalytic reforming unit in US$/t (per reference products)

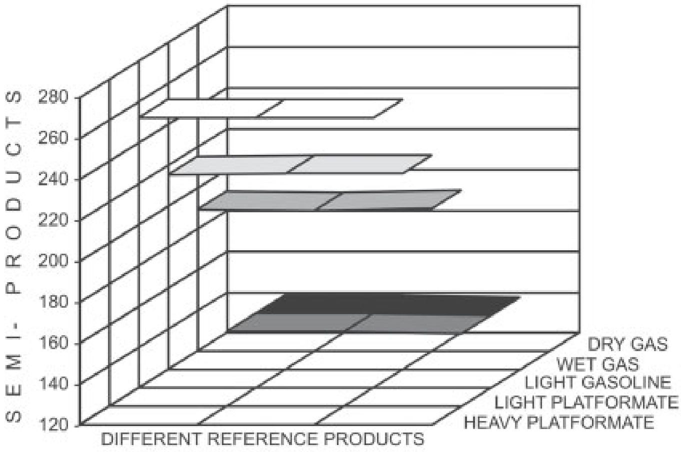
Item no.	Semi-products	Reference products		
		Heavy platformate	Light platformate	Light gasoline
1	2	3	4	5
1	Dry gas	138.23	138.23	137.17
2	Wet gas	138.23	138.23	137.17
3	Light gasoline	205.89	205.52	206.65
4	Light platformate	231.91	232.44	232.46
5	Heavy platformate	268.34	268.33	268.19

calculations can face. The effects of the choice of reference derivatives (heavy platformate whose density is 0.825 g/cm^3, light platformate whose density is 0.712 g/cm^3 and light gasoline whose density is 0.630 g/cm^3) on determining the equivalent numbers, in the case of using the same calculating base for determining the equivalent numbers (density method) are shown in Tab. 35.

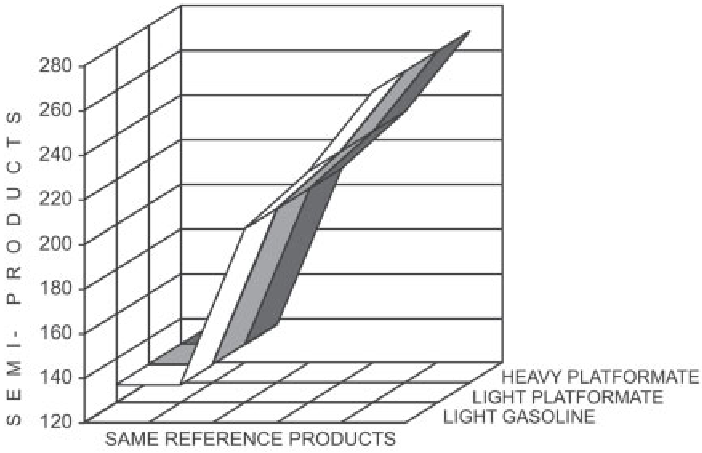
It can be seen that the differences appearing in this case are smaller than those appearing in the previous example of determining the equivalent numbers by different calculating bases (density, thermal value and quantity of products) [19].

The results obtained by using the different reference derivatives, but the same calculating base, i.e. density method, are shown in Tab. 35 and Graphics 15 and 16)

The cost prices of semi-products generated on the catalytic reforming unit, were calculated in the following manner, by means of the product density method:



Graphic 15 Cost prices of semi-products on catalytic reforming unit, per different reference products (in US$/t)



Graphic 16 Cost prices of semi-products on catalytic reforming unit, per same reference products (in US$/t)

- Proportional costs are distributed to semi-products generated in this unit according to the percentages obtained from equivalent numbers by means of the density method and reference product, i.e. heavy platformate whose density is 0.825 g/cm^3 (Tab. 36, Column 11 and Tab. 37, Line 2).
- Fixed costs are distributed to semi-products according to the percentages obtained from the quantity (Tab. 37, Line 3).
- For determining the feedstock value (Tab. 37, Line 7), it is necessary to previously determine the cost prices of crude distillation semi-products, considering that 70–175°C gasoline, which presents the feedstock, is generated in this unit.

By using the mentioned methodology for distributing the proportional and fixed costs of this unit to the bearers of costs, i.e. to the products obtained in this unit, the following cost prices of semi-products are established:

Semi-products	**Cost prices in US$/t**
1	**2**
Dry gas	138.23
Wet gas	138.23
Light gasoline	205.89
Light platformate	231.91
Heavy platformate	268.34

Tab. 36 Determining the equivalent numbers for distributing the proportional costs on catalytic reforming unit

Item no.	Oil products	Quantity in tonnes	Q'ty from 1 tonne	Density g/cm^3	Equivalent numbers	Condition units	Cost of 1 condition unit	Cost price in US$/t	Cost of feedstock in US$	(%) for proportional costs	Cost of feed-stock in US$ (entry-exit)
1	**2**	**3**	**4**	**5**	**6**	**7(4 × 6)**	**8**	**9(6 × 8)**	**10(3 × 9)**	**11**	**12**
1	Dry gas	39 905.8	67.95	0.410	0.50	33.98	251.568	125.78	5 019 511	0.038406716	5 019 511
2	Wet gas	25 631.7	43.65	0.410	0.50	21.83	251.568	125.78	3 224 052	0.024668791	3 224 052
3	Light gasoline	102 100.5	173.86	0.630	0.76	132.13	251.568	191.19	19 520 770	0.14936289	19 520 770
4	Light platformate	74 999.6	127.37	0.712	0.86	109.54	251.568	216.35	16 182 770	0.123822233	16 182 770
5	Heavy platformate	344 823.9	587.17	0.825	1.00	587.17	251.568	251.57	86 746 469	0.66373937	86 746 469
6	Total	587 261.5	1 000.00			884.65			130 693 572	1.00000000	130 693 572
7	Loss	0.0									
8	Total	587 261.5									

The costs of one conditional unit are as follows:
Feedstock 130 693 572 US$: 587 261.5 t = 222.55 US$/t
Feedstock 222.55 : 884.65 = 0.2515684 i.e. 251.568 US$/t

Tab. 37 Determining the cost prices of refinery products on catalytic reforming unit

Item no.	Elements for calculation	Q'ty in tonnes	Total in US$	Cost price US$/t	Dry gas	Wet gas	Light gasoline	Light platformate	Heavy platformate
1	2	3	4	5	6	7	8	9	10
1	Q'ty in tons	587 261.5			39 905.8	25 631.7	102 100.5	74 799.6	344 823.9
2	(%) from equivalent numbers				0.038406716	0.024668791	0.14936289	0.123822233	0.66373937
3	(%) from q'ty				0.067952349	0.043646071	0.173858694	0.12737009765	0.58717266499
4	Feedstock	587 261.5	130 693 572	222.55	5 019 511	3 224 052	19 520 770	16 182 770	86 746 469
5	Chemicals		66 434		2 552	1 639	9 923	8 226	44 095
6	Water		632		24	16	94	78	419
7	Steam		642 439		24 674	15 848	95 957	79 548	426 412
8	Electric power		1 503 720		57 753	37 095	224 600	186 194	998 078
9	Fuel		2 269 677		87 171	55 990	339 006	281 036	1 506 474
10	Depreciation		1 574		107	69	274	200	924
11	Other production costs		685 936		46 611	29 938	119 256	87 368	402 763
12	Wages		1 627 536		110 595	71 036	282 961	207 299	955 645
13	Taxes		715 913		48 648	31 247	124 468	91 186	420 364
14	Unit management costs		1 243 385		84 491	54 269	216 173	158 370	730 081
15	Laboratory and maintenance costs		251 198		17 069	10 964	43 673	31 995	147 496
16	Common services costs		249 180		16 932	10 876	43 322	31 738	146 312
17	Total costs		139 951 195		5 516 138	3 543 038	21 020 476	17 346 010	92 525 534
18	Cost price in US$/t		238.31		138.23	138.23	205.89	231.90	268.33

4.6
Instruments for Determining Energy and Processing Efficiency of Catalytic Cracking Unit

4.6.1
Technological Characteristics of the Process

Fluidized catalytic cracking is the most important secondary process in crude-oil processing, viewed from the processing and, maybe, from the energy aspect.

Heavy vacuum gas oil, from the vacuum-distillation process, is the entering charge for this process. The main target of this process is the conversion of heavy vacuum gas oil, which has relatively low value, into olefines that enter the alkylation process, into liquefied petroleum gas, gasoline with high octane numbers and medium distillates.

Feedstock is introduced into a reactor through heat exchangers and a process heater for preheating. The process of cracking the heavy vacuum gas oil takes place in the reactor by a catalyst that speeds up a chemical reaction. The catalyst stream circulation goes from the reactor, through the stripper, regenerator and back to the reactor, while, the cracking process takes place in the risers. In this process, coke is deposited at the catalyst and is burnt in the regenerator. In the stripper the adsorbed catalyst hydrocarbons are stripped by steam. The catalyst that circulates from the regenerator to the reactor should have sufficient heat for heating the preheated feedstock to the temperature of evaporation, which makes it evaporate and the feedstock is heated in the reactor, thus providing the reaction heat and compensating for various heat losses. The superheated reactor overhead feedstock is introduced into the fractionation column where the wide-range inlet hydrocarbon mixtures separate into the fractions having a relatively narrow distillation range, and go further to the gas recovery and hydrodesulfurization unit, and then are processed into the products.

This separation is achieved by condensing and re-evaporating hydrocarbon components, while the steam goes to the top through the fractionation column trays. Light components with a wider range of distillation are being condensed while passing through the column and emerge at the top as steam. Heavy components with a wide range of distillation are condensed while passing through the column in the area with lower temperature.

The product from the fractionator top is condensed and led to the separator. Product in vapourous phase is led to the gas concentration unit, and one part of condensed hydrocarbon phase is returned as a fractionator reflux, and the other is led to the gas concentration unit. Semi-reflux that is obtained at the bottom of the fractionator is cooled in the heat exchanger and led back to the column, together with the overhead products.

Light recirculated oil from the main column is led to the auxiliary column-stripper where the light evaporated hydrocarbons are separated and returned to the fractionator. From the bottom of the stripper, the light recirculated stripped oil is led away from the unit via the heat exchanger where the feedstock is preheated.

Medium recirculated oil is separated at the bottom of the column and led to the stripper equipped with a heater (reboiler). The heater of the process furnace is

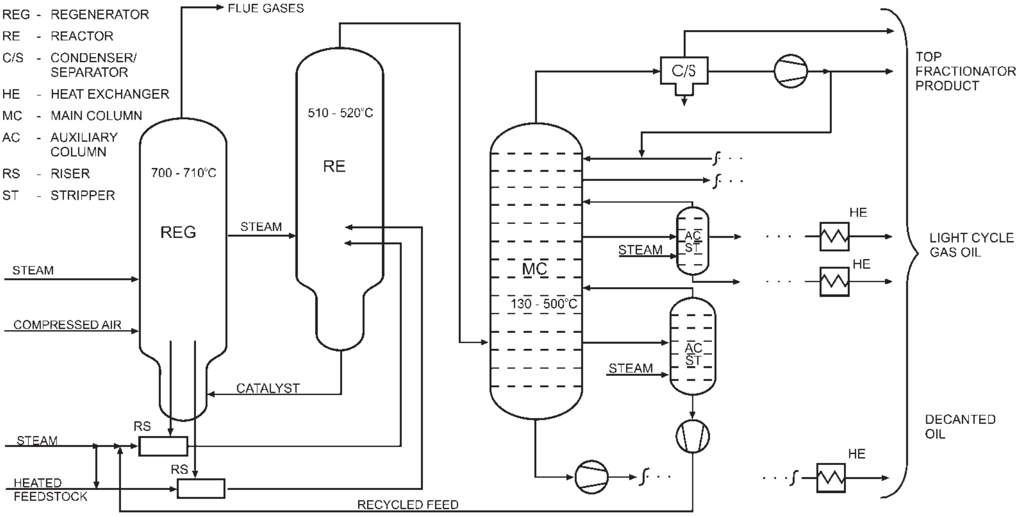


Fig. 12 Technological characteristics of catalytic cracking process

used for heating the stripper bottom reflux for stripping and preheating the reactor reflux charge. The steam from the stripper is returned to the fractionator.

Decanted oil, as a product from the fractionator bottom, is cooled in the heat exchangers and led out of the unit.

The temperatures in the reactor are 510–520 °C, in the regenerator 700–710 °C and in the fractionator 130–500 °C.

Technological characteristics of the process are shown in Fig. 12.

4.6.2
Energy Characteristics of the Process

In a typical fluidized catalytic cracking process, the heavy vacuum gas oil from the vacuum-distillation process is preheated in heat exchangers by means of product reaction heat, before entering the process heater.

The high-pressure steam (HpS) is produced in the boiler by utilization of flue-gas heat flux from the regenerator. One portion of the steam generated is used for the main pump drive and compressors, through the high-pressure turbines. The medium-pressure steam (MpS) is generated in the heat exchangers and it can also be generated by reduction of high-pressure steam through the high-pressure turbines. A total amount of generated medium-pressure steam is used for this unit, but this makes only 40% of the total requirements. The medium-pressure steam is used for the pump drive through the medium-pressure turbines, for blowing in the regenerator, for stripping, etc.

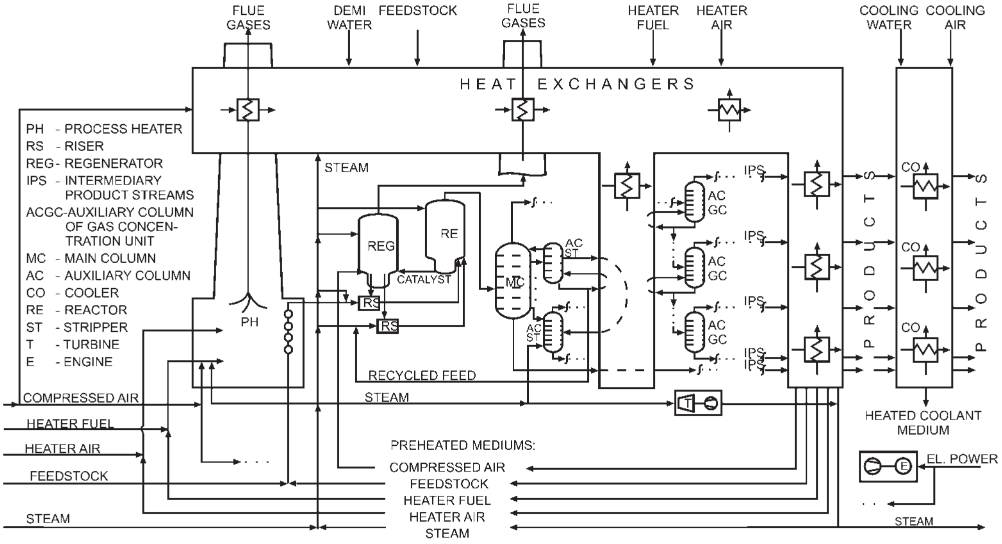


Fig. 13 Energy characteristics of catalytic cracking process with gas concentration unit

The low-pressure steam (LpS) is obtained by reduction of medium-pressure steam in the medium-pressure turbines. One portion of this steam is used for heating tubes, some other equipment, etc.

Electric energy is used to drive the pumps, fans and other equipment and, also, some auxiliary facilities.

Compressed air is preheated in the heat exchanger by means of the medium-pressure steam, and introduced into the regenerator.

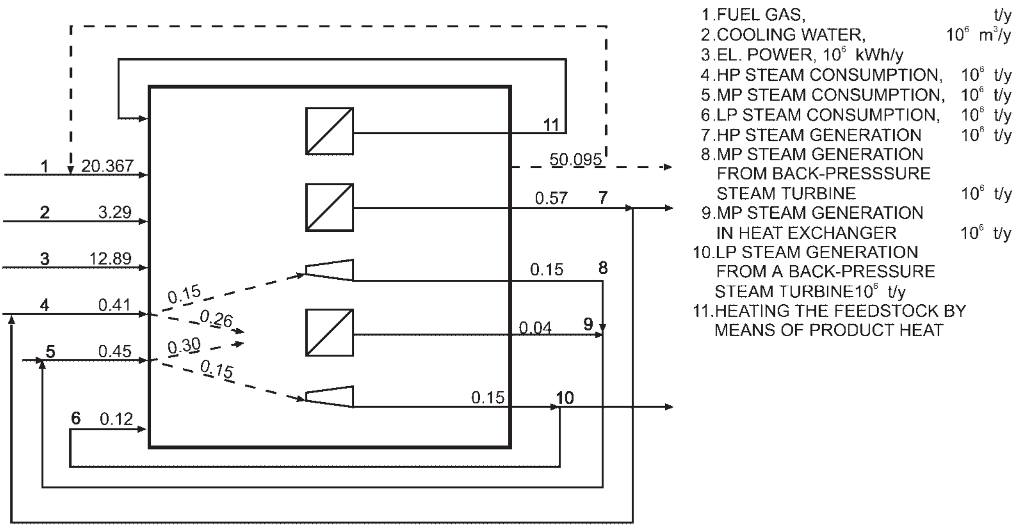
The main energy characteristics of the fluidized catalytic cracking process are given in Fig. 13 where the more important alternatives of supplying the energy required for the process are also shown. Each of these alternatives is one of the possible solutions for such a process [20].

For the purpose of this process a block energy-flow scheme, and Senky's diagram for the energy balance are shown in Scheme 7 and Diagram 6.

The values given for the energy consumption refer to the annual volume of production amounting to 821 239 t of inlet charge for a specific slate of products.

The difference between gross and net energy consumption appears in the case of high-, medium- and low-pressure steam due to the internal generation of these heat carriers in the same process.

Internal generation of high-pressure steam is 570 000 t or 1835 TJ and meets the process requirements of 410 000 t or 1 320 TJ. One part of this steam, 150 000t or 483 TJ is used for pump drive and compressors over turbines, and the other part of 260 000 t or 837 TJ for other process requirements. Gross consumption totals 410 000 t or 1320 TJ, and net consumption is zero. The difference between internal generation and gross consumption, which amounts to 160 000 t or 515 TJ, is given to the other consumers within the refinery [21].



Scheme 7 Energy flows of catalytic cracking process with gas concentration unit

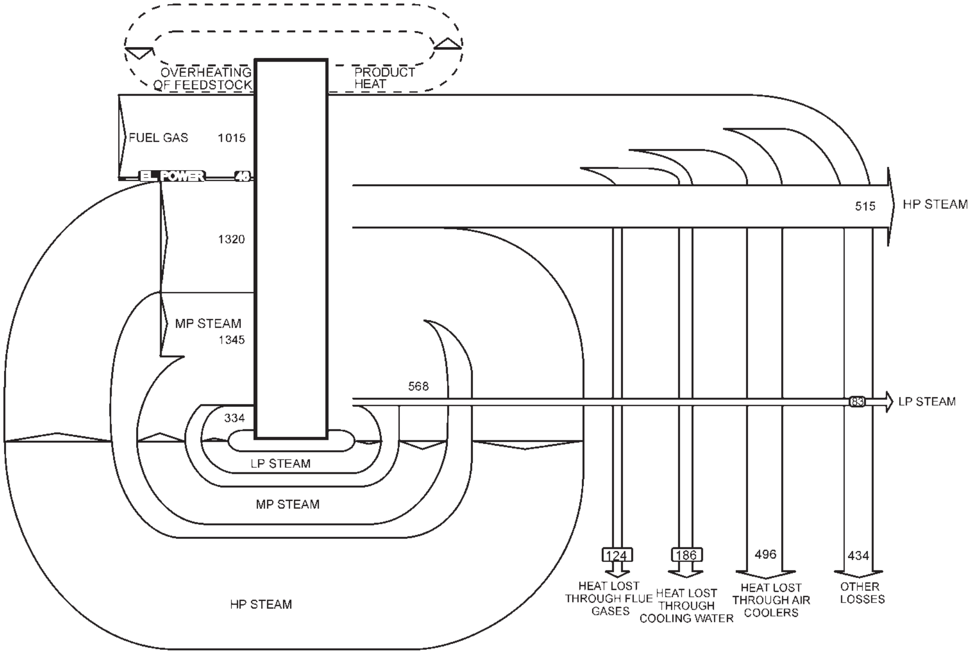


Diagram 6 Senky's diagram of energy flows of catalytic cracking process with gas concentration unit, in TJ/y

4.6.3
Determining the Steam Cost Price

The cost prices of high-, medium- and low-pressure steam are determined by the methodology for determining the cost prices of by-products, considering that the main activity of this refinery unit, as well as the other refinery units, is crude-oil processing and the production of refinery derivatives.

The cost of internal generation of high-pressure steam is 5.09 US$/t. Considering the fact that 160 000 t/y, out of the total steam generated (570 000 t/y), is intended for the other consumers within the refinery, the costs of internal steam generation amount to 3.10 US$/t, which is approximately three times lower than those of high-pressure steam generated in the refinery power plant (Tab. 38).

Internal generation of medium-pressure steam is 190 000 t or 568 TJ. Out of this quantity, 40 000 t or 120 TJ is obtained in heat exchangers, and 150 000 t or 448 TJ by reduction of high-pressure steam on back-pressure turbines. Gross consumption of this steam is 450 000 t or 1345 TJ. The difference between the gross consumption and internal generation is the net consumption of medium-pressure steam brought to this process from the outside. Net consumption is 260 000 t or 777 TJ.

Internal generation of medium-pressure steam (MpS) in the amount of 190 000 t/y is achieved in two ways: 150 000 t of MpS is achieved by reduction of high-pressure steam on back-pressure turbines at the cost of 3.16 US$/t, and 40 000 t in heat exchangers at the cost of 0.19 US$/t.

The average cost price of medium-pressure steam, generated in this unit, is 2.53 US$/t however, because of the consumption of the steam brought from the power plant at the cost price of 10.19 US$/t, the average cost price for gross medium-pressure steam consumption is 6.96 US$/t (Tab. 39).

Tab. 38 Cost price of high-pressure steam (HpS)

Item no.	Elements for calculation	Annual q'ty in t	US$/t	Generation of HpS in US$	HpS consumption (US$)		
					for process	HpS→ MpS	other consumers
	(%) from q'ty			**100.000000**	**45.614036**	**26.315789**	**28.070175**
1	Fuel gas in boiler	20 347	135.0	2 746 845	1 252 947	722 854	771 044
2	Demineralized water	570 000	0.165	94 050	42 900	24 750	26 400
3	Depreciation			46 965	21 423	12 359	13 183
4	Current and investment maintenance			5 636	2 571	1 483	1 582
5	Insurance premium			3 757	1 713	989	1 055
6	Gross wages			3 360	1 533	884	943
7	Other costs			1 792	817	472	503
8	Cost prices (1-7)			2 902 405	1 323 904	763 791	814 710
9	Quantity in t/y			570 000	260 000	150 000	160 000
10	Cost prices US$/t			5.09	5.09	5.09	5.09
11	Cost prices reduced for other consumers US$/t				3.10	3.10	

Tab. 39 Cost price of medium-pressure steam (MpS)

Item no.	Elements for calculation	Annual q'ty in t	US$/t	MpS generation in US$	MpS consumption (US$)	
					for process	MpS→LpS steam
	(%) from quantity			100.00	66.67	33.33
1	Entrance of HP steam	150 000	3.10	465 000	310 016	154 985
2	Depreciation			7 215	4 810	2 405
3	Current and investment maintenance			866	577	289
4	Insurance premium			577	385	192
5	MP steam by reduction of HP steam	150 000	3.16	473 658	315 788	157 870
6	Demin water in heat exchanger	40 000	0.165	6 600	4 400	2 200
7	Depreciation			838	559	279
8	Current and investment maintenance			101	67	34
9	Insurance premium			67	45	22
10	MP steam from heat exchanger	40 000	0.19	7 606	5 071	2 535
11	Internal generation (5+10)	190 000	2.53	481 264	320 859	160 405
12	Steam from Power Plant	260 000	10.19	2 649 400	1 766 355	883 045
13	Total MP steam (11+12)			3 130 664	2 087 214	1 043 450
14	Quantity in t/y			450 000	300 000	150 000
15	Cost price in US$/t			6.96	6.96	6.96

Tab. 40 Cost price of low-pressure steam (LpS)

Item no.	Elements for calculation	Annual q'ty in t	US$/t	LpS generation in US$	LpS consumption (US$)	
					for process	for other consumers
	(%) from quantity			100.00	80.00	20.00
1	Entrance of HP steam	150 000	2.53	379 500	303 600	75 900
2	Depreciation			7 213	5 770	1 403
3	Current and investment maintenance			866	693	173
4	Insurance premium			577	462	115
5	Total LP steam	150 000		388 156	310 525	77 631
6	Quantity in t/y			150 000	120 000	30 000
7	Cost price in US$/t			2.59	2.59	2.59
8	Cost prices reduced for other consumers US$/t				1.94	

Internal generation of low-pressure steam (LpS) amounts to 150 000 t or 417 TJ and it is obtained by reduction of MpS on back-pressure turbines. Gross consumption totals 120 000 t or 334 TJ, and net consumption is zero. The difference between internal generation and gross consumption in the amount of approximately 30 000 t or 83 TJ is given to the other consumers within the refinery.

The cost price of low-pressure steam obtained by reduction of medium-pressure steam on back-pressure turbines amounts to 1.94 US$/t (after the medium-pressure steam supplied from the refinery power plant has been excluded from the calculation, and after the costs of 30 000 t of low-pressure steam supplied to the other consumers within the refinery have been cleared) (Tab. 40).

4.6.4
Energy Efficiency of the Process

Specific steam consumption is related to the quantity of incoming feedstock of 821 239 t. As already explained, the surplus of high- and low-pressure steam generated in this process is supplied to the other processes within the refinery. Because of this, in the procedure of calculating the specific net energy consumption the energy value of the delivered steam should be subtracted from that of the fuel consumed, i.e.:

$$\frac{1015-(515+83)\ \mathrm{TJ}}{821\ 239\ \mathrm{t\ of\ feedstock}} = 507.4\frac{\mathrm{MJ}}{\mathrm{t\ of\ feedstock}}$$

The target standard of net energy consumption and specific gross and net energy consumption are outlined in Tab. 41, and Tab. 42 is the financial presentation of energy consumption and money savings that can be achieved by eliminating the differences between the target standard and specific gross and net energy consumption of this refinery unit.

If the specific net energy consumption of a typical plant is compared with the target standard, the following conclusions can be drawn:

Tab. 41 Target standard of net energy consumption and specific energy consumption on a typical catalytic cracking unit with gas concentration unit (quantity of energy per one tonne of feedstock)

Energy carriers	**Target standard of net energy consumption**		**Specific energy consumption in the plant**					
			Specific gross energy consumption			**Specific net energy consumption**		
			(kg/t) [1](kWh/t)	**(MJ/t)**		**(kg/t) [1](kWh/t)**	**(MJ/t)**	
	(MJ/t)	**(kWh/t)**		**per unit**	**total**		**per unit**	**total**
Fuel								
Fuel gas	*	–	24.8	1 235.6	1 235.6	*	*	507.4
Heat carriers					3 696.2			944.8
LP steam	*	–	146	450.9		–	–	–
MP steam	*	–	548	1 638.5		316	944.8	
HP steam	*	–	499	1 606.8		–	–	–
Sources of heat	1 246	–	–	–	4 931.8	–	–	1 452.2
Electric energy	54	15	15.7[1]	56.5	56.5	15.7[1]	56.5	56.5
Energy carriers	1 300	–	–	–	4 988.3	–	–	1 508.7

Tab. 42 Financial presentation of energy consumption and money savings on a typical catalytic cracking unit with gas concentration unit (in US$)

Specific gross energy consumption

Energy carriers	Q'ty of feedstock			**US$**
	821 239 t			
Fuel gas	821 239 t	(1 235.6 MJ/t × 0.0027 US$/MJ)	=	2 739 752
Low-pressure steam	821 239 t	450.9 MJ/t × 0.001906 US$/MJ)	=	705 785
Medium-pressure steam	821 239 t	(1 638.5 MJ/t × 0.002328 US$/MJ)	=	3 132 557
High-pressure steam	821 239 t	(1 606.8 MJ/t × 0.000963 US$/MJ)	=	1 270 743
Sources of heat	821 239 t	**(4 931.8 MJ/t × 0.001938 US$/MJ)**	**=**	**7 848 837**
Electric energy	821 239 t	(56.5 MJ/t × 0.0167 US$/MJ)	=	774 880
Energy carriers	821 239 t	**(4 988.3 MJ/t × 0.002105 US$/MJ)**	**=**	**8 623 717**

Specific net energy consumption

			US$/t
Fuel gas	(507.4 MJ/t × 0.0027 US$/MJ)	=	1.369980
Medium-pressure steam	(944.8 MJ/t × 0.002328 US$/MJ)	=	2.199494
Sources of heat	**(1 452.2 MJ/t × 0.002458 US$/MJ)**	**=**	**3.569474**
Electric energy	(56.5 MJ/t × 0.0167 US$/MJ)	=	0.943550
Energy carriers	**(1 508.7 MJ/t × 0.002991 US$/MJ)**	**=**	**4.513024**
Sources of heat:			
Internal net energy consumption	(1 452.2 MJ/t × 0.002458 US$/MJ)	=	3.57
Target net energy consumption	(1 246 MJ/t × 0.002458 US$/MJ)	=	3.06
Difference:			**0.51**
Energy carriers:			
Internal net energy consumption	(1 508.7 MJ/t × 0.002991 US$/MJ)	=	4.51
Target net energy consumption	(1 300 MJ/t × 0.002991 US$/MJ)	=	3.89
Difference:			**0.62**

1. Specific electric energy consumption is close to the target standard.
2. Specific net process and thermal energy consumption (fuel and steam) of 1452.2 MJ/t is 17% higher than the target standard that amounts to 1246 MJ/t, i.e. 0.51 US$ per tonne of feedstock.
3. Total specific net energy consumption of 1508.7 MJ/t is 16% higher than the target standard (1300 MJ/t, i.e. 0.62 US$ per tonne of feedstock). This means that, in comparison with the target standard of net energy consumption, the typical plant has an efficiency/inefficiency index of 116.

The cause of the relatively high energy efficiency of the unit is the production of a considerable quantity of steam in the heat exchangers by using the heat of products, and in the boiler by using the heat of gases from the catalyst regenerator [22].

Regardless of the relatively high energy efficiency of the unit, there are certain factors, by elimination of which, the energy efficiency could be increased further. The most important factors are:

- non-economical combustion in the process heater,
- nonexistence of the air preheating before entering the process heater,
- inefficient preheating of feedstock before entering the process heater (high level of heat exchanger fouling), and
- nonutilization of the flue gas flux in the process heater.

4.6.5

Determining the Refinery Cost Prices

The main purpose of the catalytic cracking unit is to convert heavy hydrocarbons into light, more valuable hydrocarbons by a cracking process in the presence of a catalyst and at high temperature.

For determining the cost prices of semi-products obtained on this unit, it is necessary first to determine the cost prices of semi-products obtained on the crude unit and vacuum-distillation unit (considering that light residue from the crude unit presents a feedstock for vacuum distillation and vacuum gas oils are the products obtained on the vacuum-distillation unit).

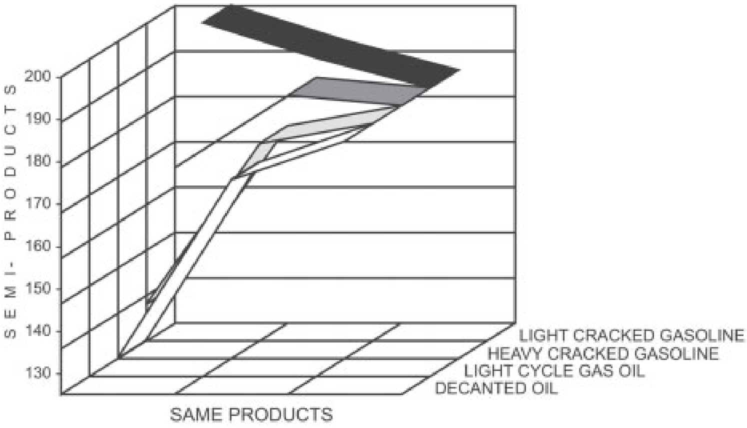
The cost prices of semi-products produced on the catalytic cracking unit are determined by equivalent numbers obtained by means of the density method, as the best method, although equivalent numbers can be determined by the following methods as well:

- thermal value method, and
- average production cost method.

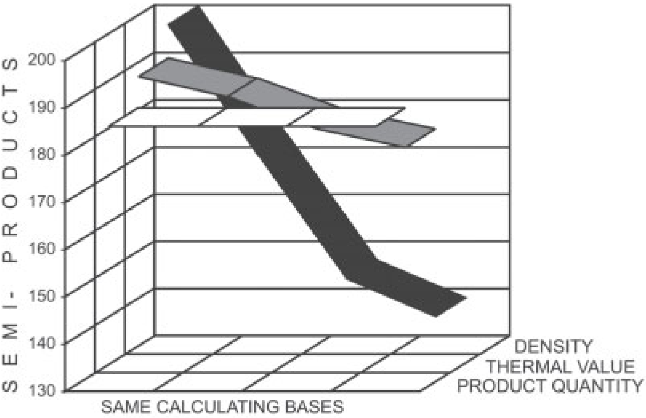
By analysing the results obtained by using different calculation bases for determining the equivalent numbers, taking feedstock in the catalytic cracking unit, which presents 86.84% of total costs, as an example, considerable differences per tonne can be seen. These differences are presented in Tab. 43 and Graphics 17 and 18.

Tab. 43 Cost prices of semi-products on catalytic cracking unit in US$/t (per calculating bases)

Item no.	**Semi products**	**Base for determining the equivalent number for calculating the cost prices**		
		Product Density Method	**Thermal Value Method**	**Average Production Cost Method**
1	**2**	**3**	**4**	**5**
1	Light cracked gasoline	199.75	192.01	185.48
2	Heavy cracked gasoline	171.79	187.70	185.48
3	Light cycle gas oil	145.82	181.09	185.48
4	Decanted oil	137.90	177.15	185.48



Graphic 17 Cost prices of semi-products on catalytic cracking unit, per products (in US$/t)



Graphic 18 Cost prices of semi-products on catalytic cracking unit, per calculating bases (in US$/t)

Besides the significant differences in cost prices of the same refinery products that depend on the calculating bases for determining the equivalent numbers, for example, the cost price of light cracked gasoline is from 199.75 US$/t (the base for determining the equivalent numbers is product density) to 185.48 US$/t (the base for determining the equivalent numbers is quantity of production), different ranges in oil-product cost prices can be noted even with the same calculating bases. For example, when product density is the base for determining the equivalent numbers, the cost prices range from 199.75 US$ (light cracked gasoline) to 137.90 US$ (decanted oil).

The stated examples of the calculating bases' effects on determining the equivalent numbers do not present all the dilemmas that experts dealing with process-industry

Tab. 44 Cost prices of semi-products on catalytic cracking unit in US$/t (per reference products)

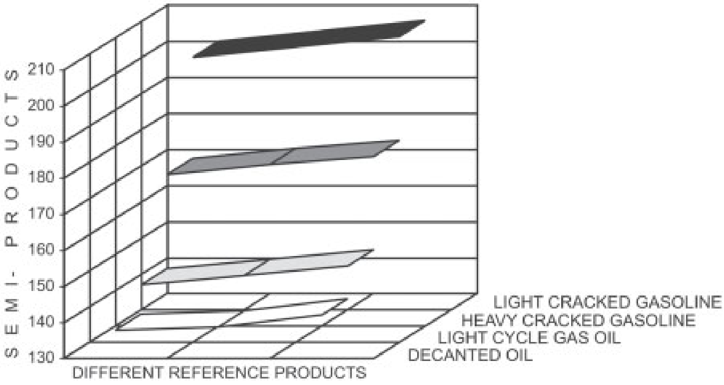
Item no.	**Semi-products**	**Reference products**		
		Light cracked gasoline	**Heavy cracked gasoline**	**Light recycled gas oil**
1	**2**	**3**	**4**	**5**
1	Light cracked gasoline	199.75	202.53	205.47
2	Heavy cracked gasoline	171.79	174.59	176.76
3	Light recycled gas oil	145.82	148.41	151.08
4	Decanted oil	137.90	138.67	142.01

calculations can face. The choice of reference derivatives on determining the equivalent numbers is also important. The effects of the choice of reference derivatives (light cracked gasoline whose density is 0.667 g/cm^3, heavy cracked gasoline whose density is 0.773 g/cm^3 and light cycle gas oil whose density is 0.905 g/cm^3) on determining the equivalent numbers, in the case of using the same calculating bases for determining the equivalent numbers (density method) are shown in Tab. 44.

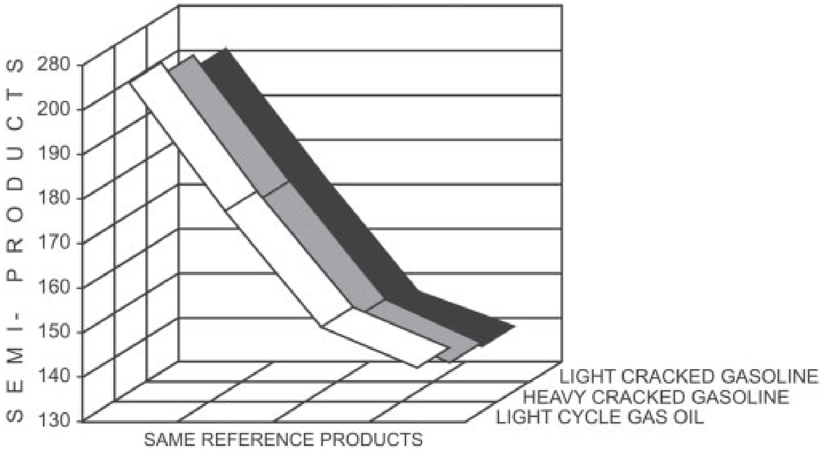
It can be seen that the differences appearing in this case are smaller than those appearing in the previous example of determining the equivalent numbers by different calculating bases (density, thermal value and quantity of products).

The results obtained by using the different reference derivatives, but the same calculating base, i.e. density method, are shown in Tab. 44 and Graphics 19 and 20).

The cost prices of semi-products generated on the catalytic cracking unit were calculated in the following manner, using the product density method:



Graphic 19 Cost prices of semi-products on catalytic cracking unit, per different reference products (in US$/t)



Graphic 20 Cost prices of semi-products on catalytic cracking unit, per same reference products (in US$/t)

- Proportional costs are distributed to semi-products generated in this unit according to the percentages obtained from equivalent numbers by means of the density method and reference product, i.e. light cracked gasoline whose density is 0.667 g/cm^3 (Tab. 45, Column 5).
- Fixed costs are distributed to semi-products according to the percentages obtained from the quantity (Tab. 46, Line 3).
- Liquid petroleum gas, dry gas and slop are expressed on the level of the average feedstock price.
- From a methodological aspect, the loss (coke in this case as well) is included in the refinery cost prices.

By using the mentioned methodology, the following cost prices of semi-products, i.e. refinery products obtained in this unit, are set:

Semi-products	Cost prices in US$/t
Dry gas	185.48
Propane	185.48
Propylene	185.48
Butane	185.48
Propane-butane mixture	185.48
Light cracked gasoline	280.63
Heavy cracked gasoline	244.94
Light recycled gas oil	211.80
Decanted oil	201.60
Sulfur	120.02
Slop	185.48

Tab. 45 Determining the equivalent numbers for distributing the proportional costs on catalytic cracking unit

Item no.	Oil products	Quantity in tonnes	Q'ty from 1 tonne	Density g/cm^3	Equivalent numbers	Condition units	Cost of 1 condition unit	Cost price in US$/t	Cost of feedstock in US$	(%) for proportional costs	Cost of feed-stock in US$ (entry-exit)
1	**2**	**3**	**4**	**5**	**6**	**7(4 × 6)**	**8**	**9(6 × 8)**	**10(3 × 9)**	**11**	**12**
1	Dry gas	64 989.9	–	0.410	–	0.00	224.159	185.48	12 054 332	–	12 054 332
2	Propane	16 436.9	–	0.508	–	0.00	224.159	185.48	3 048 710	–	3 048 710
3	Propylene	34 939.3	–	0.518	–	0.00	224.159	185.48	6 480 539	–	6 480 539
4	Butane	90 342.5	–	0.583	–	0.00	224.159	185.48	16 756 720	–	16 756 720
5	Propane-butane mix	1 737.6	–	0.545	–	0.00	224.159	185.48	322 291	–	322 291
6	Light cracked gasoline	109 231.9	139.90	0.667	1.00	137.90	224.159	224.16	24 485 313	0.166656406	24 485 313
7	Heavy cracked gasoline	403 642.9	509.58	0.773	0.86	438.24	224.159	192.78	77 812 967	0.529624822	77 812 967
8	Light recycled gas oil	177 346.3	223.89	0.905	0.73	163.44	224.159	163.64	29 020 253	0.197522945	29 020 253
9	Decanted oil	99 700.2	125.87	0.973	0.69	86.85	224.159	154.67	15 420 607	0.104958553	15 420 607
10	Sulfur	2 191.8	2.77	1.800	0.37	1.02	224.159	82.94	181 782	0.001237277	181 782
11	Slop	23 134.7	–	–	–	0.00	224.159	185.48	4 291 026	–	4 291 026
12	Total	1 023 694.0	1 000.00			827.45					
			792113.10								
									189 874 539		200 069 966
									–42 953 617		–42 953 617
									146 920 922	1.000000000	157 116 349
13	Loss	0.0									
14	Total	1 023 694.0									

The costs of one conditional unit are as follows:
Feedstock 200 069 966 US$: 1 078 661 t = 185.48 US$/t
Feedstock 185.48 : 827.45 = 0.224158559 i.e. 224.159 US$/t

Tab. 46 Determining the cost prices of refinery products on catalytic cracking unit

Item no.	Elements for calculation	Q'ty in tonnes	Total in US$	Cost price US$/t	Dry gas	Propane	Propylene	Butane	Propane-butane mixture	Light cracked gasoline	Heavy cracked gasoline	Light recycled gas oil	Decanted oil	Sulfur	Slop
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Q'ty in tons	1 023 694			64 989.9	16 436.9	34 939.3	90 342.5	1 737.6	109 231.9	403 642.9	177 346.3	99 700.2	2 191.8	23 134.7
2	(%) from equivalent numbers				–	–	–	–	–	0.16665641	0.52962482	0.19752294473	0.104958553	0.00123728	
3	(%) from q'ty				–	–	–	–	–	0.13789936	0.50957737	0.22389012736	0.12586616384	0.00276698	
4	Vacuum light gas oil	8 378	1 596 582	190.56											
5	Vacuum heavy gas oil	974 349	181 998 633	186.79											
6	Non-conditioned fraction	95 934	16 474 752	171.73											
7	Feedstock	1 078 661	200 069 966	185.48	12 054 332	3 048 710	6 480 539	16 756 720	322 291	26 184 446	83 212 719	31 034 084	16 490 705	194 396	4 291 026
8	Chemicals		2 587 644							431 247	1 370 480	511 119	271 595	3 202	
9	Water		5 317							886	2 816	1 050	558	7	
10	Steam		4 031 731							671 914	2 135 305	796 359	423 165	4 988	
11	Electric power		1 382 497							230 402	732 205	273 075	145 105	1 711	
12	Fuel		1 973 960							328 973	1 045 458	389 902	207 184	2 442	
13	Depreciation		2 162 021							298 141	1 101 717	484 055	272 125	5 982	
14	Other production costs		2 656 757							366 365	1 353 823	594 822	334 396	7 351	
15	Wages		6 303 747							869 283	3 212 247	1 411 347	793 428	17 442	
16	Taxes		2 772 862							382 376	1 412 988	620 817	349 010	7 672	
17	Unit management costs		4 815 859							664 104	2 454 053	1 078 223	606 154	13 325	
18	Laboratory and maintenance costs		822 373							113 405	419 063	184 121	103 509	2 275	
19	Common services costs		815 771							112 494	415 698	182 643	102 678	2 257	
20	Total costs		230 400 504		12 054 332	3 048 710	6 480 539	16 756 720	322 291	30 654 036	98 868 571	37 561 617	20 099 611	263 052	4 291 026
21	Cost price in US$/t		213.60		185.48	185.48	185.48	185.48	185.48	280.63	244.94	211.80	201.60	120.02	185.48

4.7
Instruments for Determining Energy and Processing Efficiency of Gas Concentration Unit

4.7.1
Technological Characteristics of the Process

Treatment of liquid and gas products from the top separator of a catalytic cracking fractionator is performed in the gas concentration unit with fractionation. In such a way, all liquid products of light hydrocarbons are separated and other gas products are sent to the fuel-gas system.

The products of this process are as follows:

- fuel gas,
- liquid propylene for the storage,
- liquid propane for the storage,
- liquid butane for alkylation unit or for the storage,
- light gasoline for the storage (after sulfur removal),
- heavy gasoline for the storage (after sulfur removal).

All the above-mentioned technological characteristics of this process are shown in Fig. 14.

Energy characteristics of the gas concentration process, the cost prices of steam, as well as energy efficiency of the unit, are given in the part of this book dealing with the energy efficiency of the catalytic cracking unit with gas concentration and fractionation.

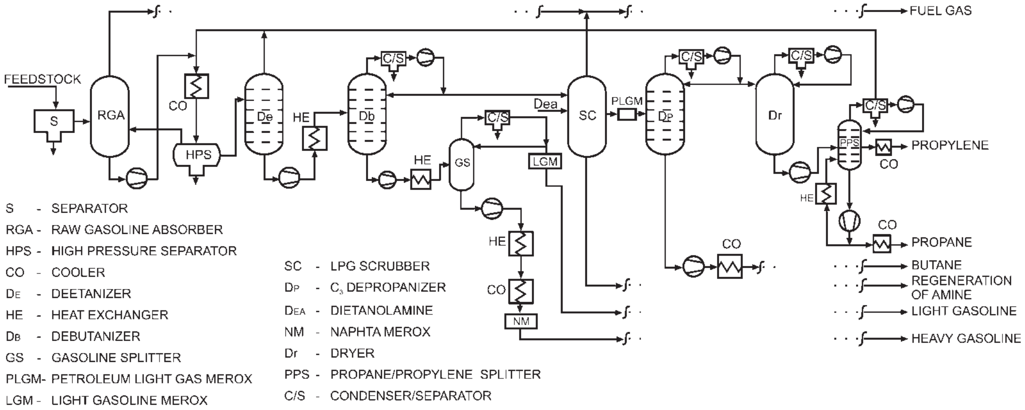


Fig. 14 Technological characteristics of gas concentration process

4.7.2
Determining the Refinery Product Cost Prices

The feedstock for this unit is wet gas and light gasoline from the catalytic reforming unit, liquid petroleum gas and light gasoline from the crude unit and light gasoline from gasoline redistillation. In this unit, the following products are obtained by the fractionation process: propane, butane and stabilized gasoline (about 40% of the total production).

The cost prices of semi-products obtained in the gas concentration unit are determined by equivalent numbers obtained by means of the density method, although equivalent numbers can be determined by the following methods as well:

– thermal value method, and
– average production cost method.

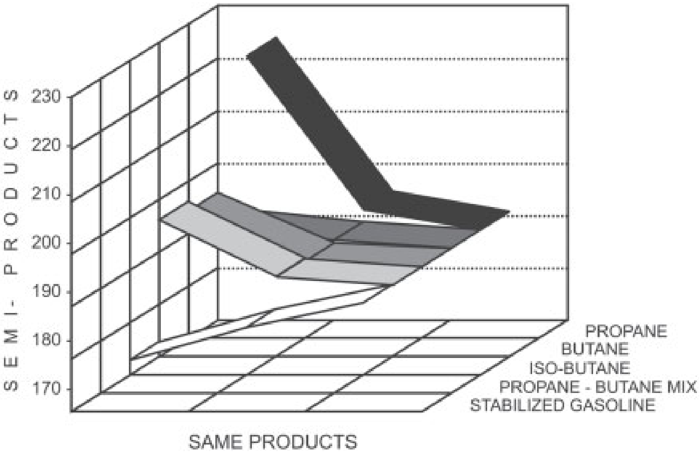
By analysing the results obtained by using the different calculation bases for determining equivalent numbers, taking feedstock of gas concentration as an example, considerable differences in the cost prices of oil products generated in this unit can be noted. These differences are presented in Tab. 47 and Graphics 21 and 22.

Besides the significant differences in cost prices of the same refinery product that depend on the calculating bases for determining the equivalent numbers, for example, the cost price of stabilized gasoline is 174.47 US$/t (the base for determining the equivalent numbers is product density) to 190.66 US$/t (the base for determining the equivalent numbers is quantity of products), the different ranges in oil-product cost prices can be noted even with the same calculating base. For example, when product density is the base for determining the equivalent numbers, the cost prices range from 174.47 US$/t (stabilized gasoline) to 223.68 US$/t (propane).

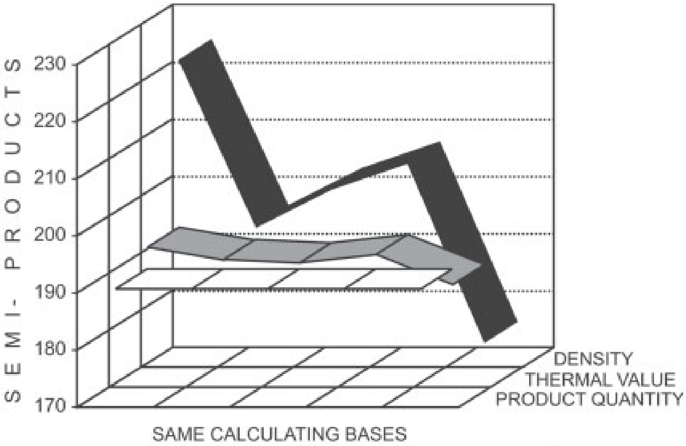
The stated examples of the calculating bases' effects on determining the equivalent numbers do not present all the dilemmas that experts dealing with process-industry calculations can face. The effects of the choice of reference derivatives (propane whose

Tab. 47 Cost prices of semi-products on gas concentration unit in US$/t (per calculating bases)

Item no.	Semi products	Base for determining the equivalent number for calculating the cost prices		
		Product Density Method	Thermal Value Method	Average Production Cost Method
1	2	3	4	5
1	Propane	223.68	194.42	190.66
2	Butane	194.60	192.18	190.66
3	Iso-butane	201.31	191.68	190.66
4	Propane-butane mixture	205.78	193.13	190.66
5	Stabilized gasoline	174.47	187.92	190.66



Graphic 21 Cost prices of semi-products on gas concentration unit, per products (in US$/t)



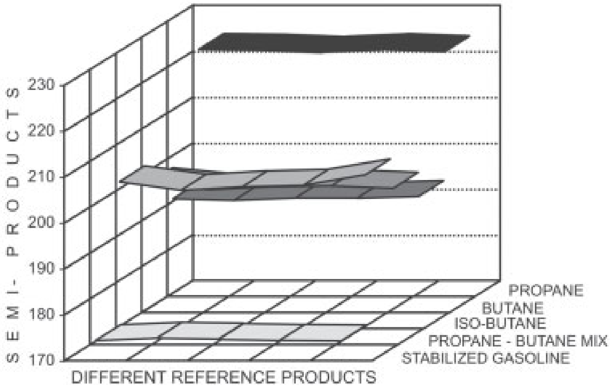
Graphic 22 Cost prices of semi-products on gas concentration unit, per calculating bases (in US$/t)

density is 0.508 g/cm^3, butane whose density is 0.583 g/cm^3, iso-butane whose density is 0.564 g/cm^3, propane-butane mixture whose density is 0.551 g/cm^3 and stabilized gasoline whose density is 0.650 g/cm^3) on determining the equivalent numbers, in the case of using the same calculating base for determining the equivalent numbers (density method) are shown in Tab. 48.

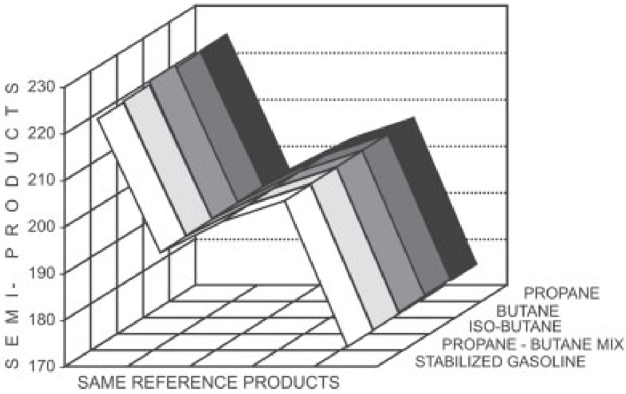
It can be seen that the differences appearing in this case are smaller than those appearing in the previous example of determining the equivalent numbers by different calculating bases (density, thermal value and quantity of products).

Tab. 48 Cost prices of semi-products on gas concentration unit in US$/t (per reference products)

Item no.	Semi-products	Reference products				
		Propane	Butane	Iso-butane	Propane-butane mixture	Stabilized gasoline
1	2	3	4	5	4	5
1	Propane	223.68	223.47	222.90	223.59	223.10
2	Butane	194.60	194.32	194.79	194.87	195.22
3	Iso-butane	201.31	200.15	200.81	201.03	200.45
4	Propane-butane mixture	205.78	204.04	204.83	205.13	207.42
5	Stabilized gasoline	174.47	174.89	174.70	174.36	174.30



Graphic 23 Cost prices of semi-products on gas concentration unit, per different reference products (in US$/t)



Graphic 24 Cost prices of semi-products on gas concentration unit, per same reference products (in US$/t)

The results obtained by using the different reference derivatives, but the same calculating base, i.e. density method, are shown in Tab. 48 and Graphics 23 and 24.

The cost prices of semi-products generated on the gas concentration unit, were calculated in the following manner, using the product density method (as the best method):

- Proportional costs are distributed to semi-products generated in this unit according to the percentages obtained from equivalent numbers by means of the density method and a reference product. In this case, reference derivate is propane whose density is 0.508 g/cm^3 (Tab. 49, Column 5).
- Fixed costs are distributed to semi-products according to the percentages obtained from the quantity (Tab. 50, Line 3).

By using the mentioned methodology the cost prices of semi-products on the gas concentration unit are as follows:

Semi-product	**Cost prices in US$/t**
1	**2**
Fuel gas	190.57
Propane	260.07
Butane	230.06
Iso-butane	236.98
Propane-butane mixture	241.60
Stabilized gasoline	209.28
Slop	190.57

4.8
Instruments for Determining Energy and Processing Efficiency of Jet-fuel Hydrodesulfurization Unit

4.8.1
Technological Characteristics of the Process

Hydrodesulfurization of jet fuel is a process in which the feedstock, above the catalyst, is brought into contact with recirculated gas rich in hydrogen, at high temperature and pressure, in order to remove the unwanted components.

This unit consists of three sections:

– feedstock preparation,
– reactor,
– product treatment.

Tab. 49 Determining the equivalent numbers for distributing the proportional costs on gas concentration unit

Item no.	Oil products	Quantity in tonnes	Q'ty from 1 tonne	Density g/cm^3	Equivalent numbers	Condition units	Cost of 1 condition unit	Cost price in US$/t	Cost of feedstock in US$	(%) for proportional costs	Cost of feed-stock in US$ (entry-exit)
1	**2**	**3**	**4**	**5**	**6**	**7(4 × 6)**	**8**	**9(6 × 8)**	**10(3 × 9)**	**11**	**12**
1	Fuel gas	21 829.5	–	0.410	–	0.00	–	190.57	4 160 045	–	4 160 045
2	Propane	27 013.1	170.67	0.508	1.00	170.67	223.571	223.57	6 039 345	0.200227674	6 039 374
3	Butane	47 991.2	303.22	0.583	0.87	263.8	223.571	194.51	9 334 610	0.309478497	9 334 656
4	Isobutane	7 221.0	45.62	0.564	0.90	41.06	223.571	201.21	1 452 957	0.048171148	1 452 964
5	Propane-butane mixture	2 353.6	14.87	0.551	0.92	13.68	223.571	205.69	484 099	0.016049762	484 102
6	Stabilized gasoline	73 695.3	465.62	0.650	0.78	363.18	223.571	174.39	12 851 376	0.426072918	12 851 440
7	Slop	89.6	–	–	–	0.00	–	190.57	17 071	–	17 071
8	Total	180 193.2	1 000.0			852.39					
			158 274.1								
									34 339 503		34 339 652
									–4 177 116		–4 177 116
									30 162 387	1.000000000	30 162 536
9	Loss										
10	Total	180 193.2									

The cost of one conditional unit is as follows:
Feedstock 34 339 652 US$: 180 193 t = 190.57 US$/t
Feedstock 190.57 : 852.39 = 0.223571 i.e. 223.571 US$/t

Tab. 50 Determining the cost prices of refinery products on gas concentration unit

Item no.	Elements for calculation	Q'ty in tonnes	Total in US$	Cost price US$/t	Fuel gas	Propane	Butane	Isobutane	Propane-butane mixture	Stabilized gasoline	Slop
1	2	3	4	5	6	7	8	9	10	11	12
1	Q'ty in tons	180 193.2			21 829.5	27 013.1	47 991.2	7 221.0	2 353.6	73 695.3	89.6
2	(%) from equivalent numbers				–	0.20022767	0.3094785	0.048171148	0.016049762	0.42607292	–
3	(%) from q'ty				–	0.17067292	0.30321574	0.045623123	0.014870353	0.46561809	–
4	Wet gas	10 464	1 449 644	138.54							
5	Liquid petroleum gas	51 896	9 163 241	176.57							
6	Light gasoline	102 101	21 069 463	206.36							
7	Light gasoline	15 188	2 531 615	166.69							
8	Light gasoline	546	125 689	230.39							
9	Feedstock	180 193	34 339 652	190.57	4 160 045	6 039 374	9 334 656	1 452 964	484 102	12 851 440	17 071
10	Chemicals		–								
11	Water		1 264			253	391	61	20	538	
12	Steam		755 478			151 268	233 804	36 392	12 125	321 889	
13	Electric power		229 277			45 908	70 956	11 045	3 680	97 689	
14	Fuel		–								
15	Depreciation		43 744			7 466	13 264	1 996	650	20 368	
16	Other production costs		685 936			117 071	207 987	31 295	10 200	319 384	
17	Wages		1 627 536			277 776	493 495	74 253	24 202	757 810	
18	Taxes		715 913			122 187	217 076	32 662	10 646	333 342	
19	Unit management costs		1 243 385			212 212	377 014	56 727	18 490	578 942	
20	Laboratory and maintenance costs		152 512			26 030	46 244	6 958	2 268	71 013	
21	Common services costs		151 288			25 821	45 873	6 902	2 250	70 443	
22	Total costs		39 945 986		4 160 045	7 025 365	11 040 760	1 711 255	568 633	15 422 858	17 071
23	Cost price in US$/t		221.68		190.57	260.07	230.06	236.98	241.60	209.28	190.57

Feedstock preparation

It is common practice that one fraction is introduced into the hydrodesulfurization process. When the feedstocks are mixed, they can be mixed in the tanks or pipes. In order to keep a certain consumption of hydrogen, the mixture and feedstock flow must be constant.

Reactor

Recirculated gas with the additional quantity of gas rich in hydrogen (from the catalytic reforming process) is mixed with the feedstock and, through the heat exchangers and process heater, is introduced into the reactor at a temperature of 260–270°C. Here, exothermic reactions take place in the presence of a catalyst. Outlet flow from the reactor goes into the separator, via the heat exchanger and coolers. Gas phase is led into the gas system, and liquid phase via the heat exchangers into the column-stripper.

Product treatment

Hydrogen sulfide and light components absorbed from recirculated gas are separated by stripping from the treated product, and the product from the stripper bottom is routed to storage via heat exchanger and cooler.

Technological characteristics of jet-fuel hydrodesulfurization process are shown in Fig. 15.

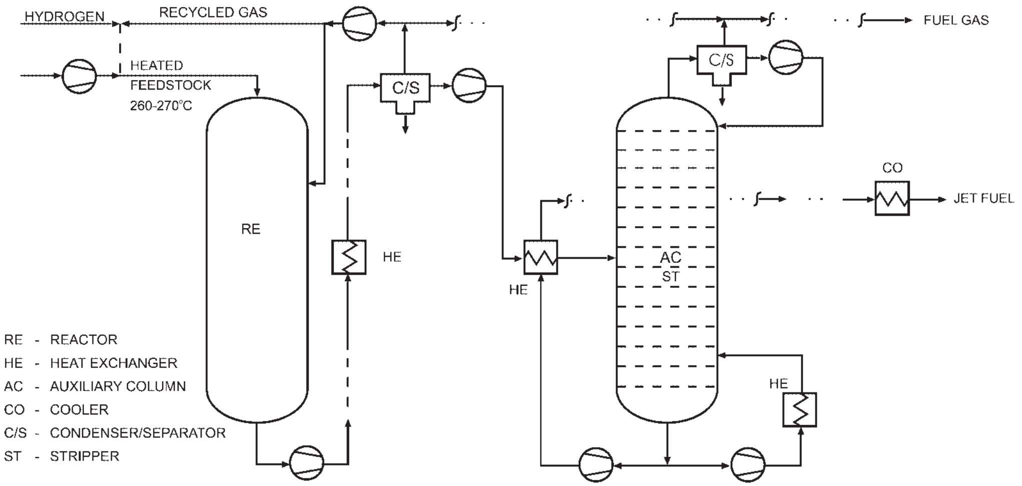


Fig. 15 Technological characteristics of jet-fuel hydrodesulfurization process

4.8.2
Energy Characteristics of the Process

In a typical jet-fuel hydrodesulfurization unit, the jet fuel from the crude unit is preheated in heat exchangers, by means of the flows of the products of this process, and then enters the process heater. In the process heater, fuel gas is used as a fuel.

Medium-pressure steam (MpS) is used to drive the auxiliary pump and compressors, through the steam turbines.

Electric energy is used to drive the main pump, fan and other equipment.

The main energy characteristics of the jet-fuel hydrodesulfurization unit are shown in Fig. 16 as well as all important options concerning the energy demands of the process.

For the purpose of this process, the block energy-flow scheme is shown in Scheme 8 and Senky's diagram for the energy balance in Diagram 7. The values given for the energy consumption refer to the annual volume of production amounting to 141 471 t of jet fuel for a specific slate of products.

4.8.3
Determining the Steam Cost Price

Medium-pressure steam (MpS) that is used for heating the auxiliary column, dispersing the fuel oil in the process heater, for pump drive and compressors, as well as for heating the tubes in the process, is provided from the refinery power plant at the cost price of 9.66 US$/t (Tab. 51).

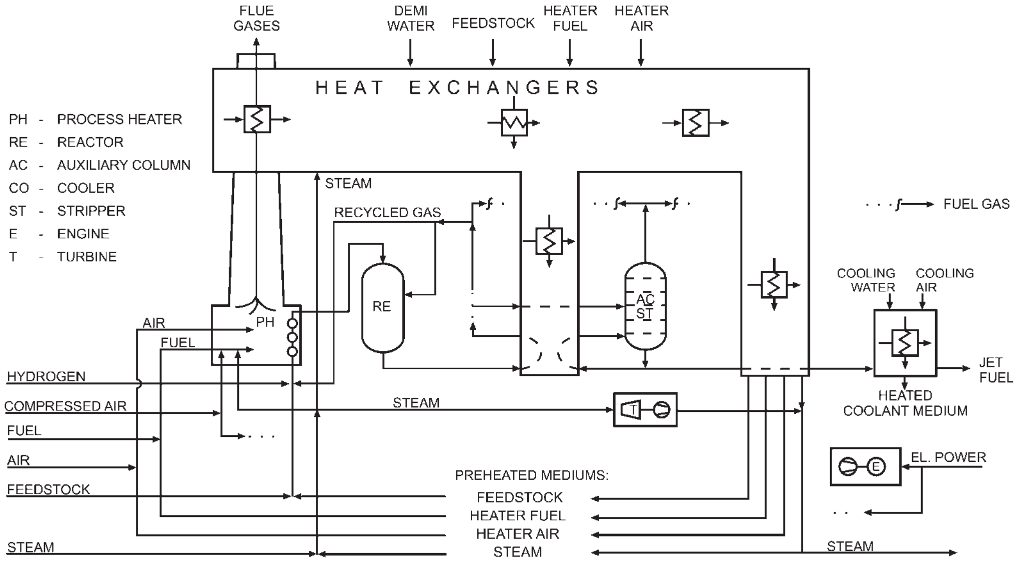
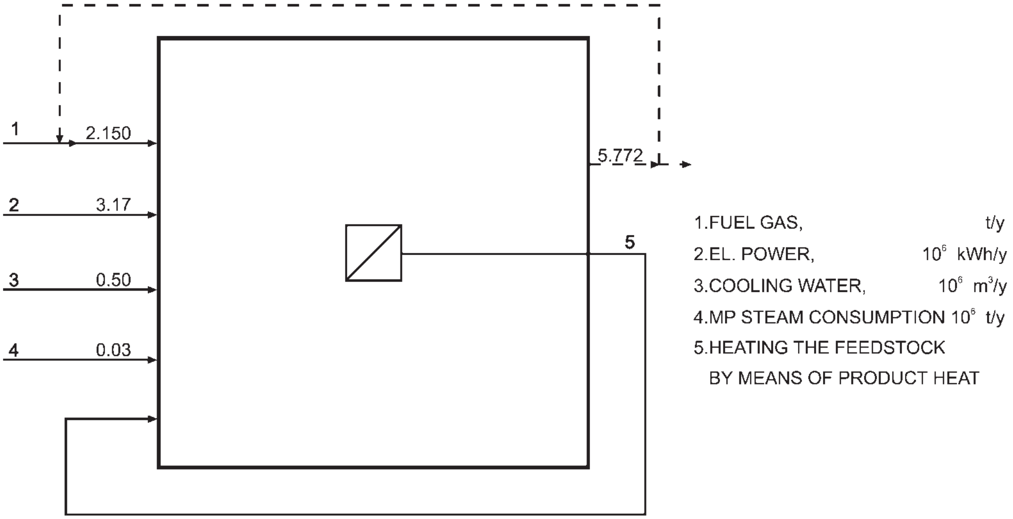


Fig. 16 Energy characteristics of jet-fuel hydrodesulfurization process



Scheme 8 Energy flows of jet-fuel hydrodesulfurization process

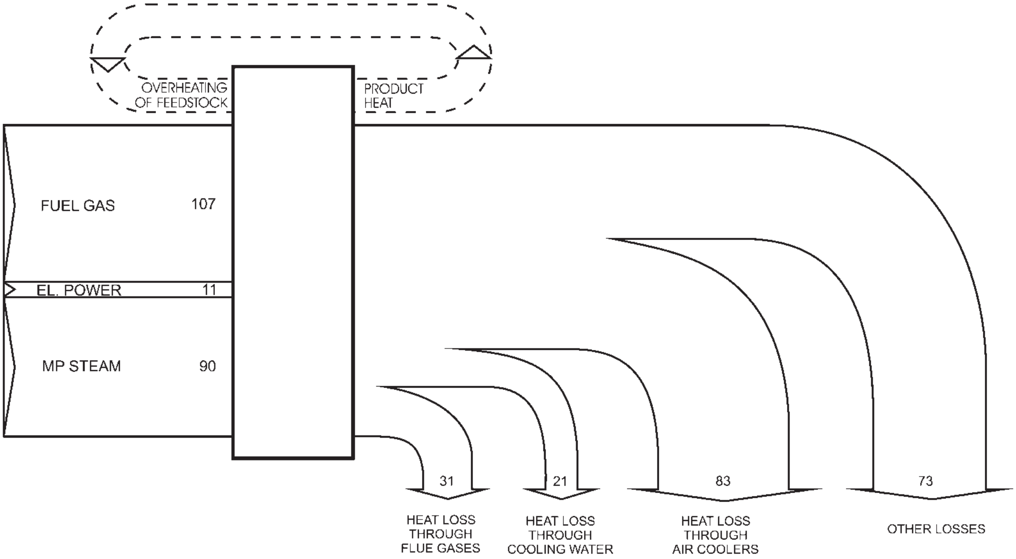


Diagram 7 Senky's diagram of energy flows in jet-fuel hydrodesulfurization process, in TJ/y

Tab. 51 Cost prices of medium-pressure steam MpS (consumption)

Item no.	Elements for calculation	Annual q'ty in t	Cost price US$/t	Total consumption in US$
1	2	3	4	5
1	MP steam supplied from Refinery Power Plant	30 000	9.66	289 800

4.8.4

Energy Efficiency of the Process

The target standard of net energy consumption and specific gross and net energy consumption is outlined in Tab. 52 while Tab. 53 shows the financial presentation of energy consumption and money savings of the analysed jet-fuel hydrodesulfurization unit. It can be seen that gross energy consumption is equal to net energy consumption.

If specific gross or net energy consumption of a typical plant is compared with the target standard, the following conclusion can be drawn:

1. Specific electric energy consumption is close to the target standard.
2. Specific gross and/or net consumption of process and thermal energy (fuel and steam) amounts to 1391.2 MJ/t, thus exceeding the target standard (828 MJ/t) by 68 %.
3. Total specific net energy consumption is 1471.8 MJ/t, which is 64 % higher than the target standard (900 MJ/t). Compared with the net energy consumption target standard, a typical plant has an efficiency/inefficiency index of 164.

Tab. 52 Target standard of net energy consumption and specific energy consumption on a typical jet-fuel hydrodesulfurization unit (quantity of energy per one tonne of feedstock)

Energy carriers	Target standard of net energy consumption		Specific energy consumption in the plant					
			Specific gross energy consumption			Specific net energy consumption		
	(MJ/t)	(kWh/t)	(kg/t) [1](kWh/t)	(MJ/t) per unit	total	(kg/t) [1](kWh/t)	(MJ/t) per unit	total
Fuels								
Fuel gas	*	–	15.2	757.3	757.3	15.2	757.3	757.3
Heat carriers								
MP steam	*	–	212	633.9	633.9	212	633.9	633.9
Sources of heat	828	–	–	–	1 391.2	–	–	1 391.2
Electric energy	72	20	22.4[1]	80.6	80.6	22.4[1]	80.6	80.6
Energy carriers	900	–	–	–	1 471.8	–	–	1 471.8

Tab. 53 Financial presentation of energy consumption and money savings on a typical jet-fuel hydrodesulfurization unit (in US$)

Specific gross energy consumption				
Energy carriers	Q'ty of feedstock			**US$**
	141 471 t			
Fuel gas	141 471 t	(757.3 MJ/t × 0.0027 US$/MJ)	=	289 267
Medium-pressure steam	141 471 t	(633.9 MJ/t × 0.0032308 US$/MJ)	=	289 733
Sources of heat	141 471 t	**(1 391.2 MJ/t × 0.0029419 US$/MJ)**	**=**	**579 000**
Electric energy	141 471 t	(80.6 MJ/t × 0.0167 US$/MJ)	=	190 423
Energy carriers	141 471 t	**(1 471.8 MJ/t × 0.00369529 US$/MJ)**	**=**	**769 423**
Specific net energy consumption				
				US$/t
Fuel gas		(757.3 MJ/t × 0.0027 US$/MJ)	=	2.044471
Medium-pressure steam		(633.9 MJ/t × 0.0032308 US$/MJ)	=	2.048004
Sources of heat		**(1 391.2 MJ/t × 0.0029419 US$/MJ)**	**=**	**4.092714**
Electric energy		(80.6 MJ/t × 0.0167 US$/MJ)	=	1.34602
Energy carriers		**(1 471.8 MJ/t × 0.00369529 US$/MJ)**	**=**	**5.438734**
Sources of heat:				
Internal net energy consumption		(1 391.2 MJ/t × 0.0029419 US$/MJ)	=	4.09
Target net energy consumption		(828 MJ/t × 0.0029419 US$/MJ)	=	2.44
Difference:				**1.65**
Energy carriers:				
Internal net energy consumption		(1 471.8 MJ/t × 0.00369529 US$/MJ)	=	5.44
Target net energy consumption		(900 MJ/t × 0.00369529 US$/MJ)	=	3.33
Difference:				**2.11**

Increased consumption of process and thermal energy on a typical plant is caused by different factors, the most important being:

– inefficient utilisation of the heat of the flue gases from the process heater,
– nonexistence of the air preheating before entering the process heater,
– non-economical combustion in the process heater (measuring the excess air is not available), and
– inefficient utilization of jet fuel heat flux.

4.8.5
Determining the Refinery Product Cost Prices

The cost prices of semi-products from Merox units are determined in the same manner as the cost prices of semi-products treated in the hydrodesulfurization unit (Tab. 54) considering that mercaptanes are removed in these units by means of chemical treatment or are transformed into disulfides, thus reducing the sulfur percentage below the maximum permitted level prescribed by the standard.

Tab. 54 Determining the cost prices of refinery products on jet-fuel hydrodesulfurization unit

Item no.	Elements for calculation	Q'ty in tonnes	Total in US$	Cost price US$/t	Jet fuel	White-spirit
1	**2**	**3**	**4**	**5**	**6**	**7**
1	Q'ty in tonnes	30 468.0				
2	(%) from q'ty				0.96696645	0.03303355
3	Jet fuel	29 462	6 192 816	210 2		
4	White-spirit	1 006	213 985	212 61		
5	Feedstock	30 468	6 406 801	210 28	6 192 816	213 984
6	Chemicals		12 635		12 217	417
7	Water		21		21	0
8	Steam		26 375		25 504	871
9	Electric power		5 368		5 192	177
10	Fuel		–		–	–
11	Depreciation		84		81	3
12	Other production costs		50 343		48 680	1 663
13	Wages		119 451		115 505	3 946
14	Taxes		52 544		50 808	1 735
15	Unit management costs		91 257		88 243	3 014
16	Laboratory and Maintenance costs		8 971		8 674	297
17	Common services costs		8 900		8 606	294
18	Total costs		6 782 750		6 556 349	226 401
19	Cost price in US$/t		222.62		222.54	224.95

Besides the mentioned procedure at Merox, it is possible to apply the procedure of converting the sulfur to some other chemical forms, but from the economic aspect, it is important that the semi-products of this unit are treated in the same manner and can equally bear the costs of this unit that are distributed to the cost bearers, i.e. products per quantities, i.e. in a fixed amount per a product unit. The cost prices determined in the mentioned manner are as follows:

Semi-product	Cost price of feedstock in US$/t	Unit operation costs in US$/t	Cost price in US$/t
1	2	3	4
Jet fuel	210.2	12.34	222.54
White spirit	212.61	12.34	224.95

4.9
Instruments for Determining Energy and Processing Efficiency of Gas-Oil Hydrodesulfurization Unit

4.9.1
Technological Characteristics of the Process

Hydrodesulfurization is a process of hydrogenation that is used to saturate olefines and eliminate pollutants from gas oils. Hydrogenation reactions occur at high temperatures and under high pressure, in the presence of a catalyst.

Desulfurisation (replacing sulfur with hydrogen) and saturation of olefines and aromatics are the most important reactions. Cracking does not play a very large part here. All reactions are exothermic, which increases the temperature through the catalyst bed. Deactivation of catalyst is a result of coke formation and it is stopped by adding the surplus of high-pressure hydrogen. Catalyst regeneration causes removal of coke and catalyst reactivation.

Warm feedstock from the feed vessel is mixed with hydrogen, then heated in the heat exchanger and heater, and is introduced into the reactor at a temperature of 290–300°C.

The reactor outlet flow is led to the warm separator, via a heat exchanger. The liquid from this separator is led to the stripping column via a feed vessel, and steam phase is led to the cold separator, via coolers.

In a cold separator, the following phases are obtained:

1. Steam phase (composed of H_2, H_2S, C_1, C_2, C_3) whose greater part goes to the column-scrubber of recirculated gas. Amine that binds hydrogen sulfide from gas, is introduced into the scrubber. From the top of the scrubber, the gas, free from hydrogen sulfide and containing about 95% of hydrogen, is separated. Such gas is returned to the process through the compressor. For ensuring enough gas for the process, an additional quantity of hydrogen is led to the compressor suction point. For ensuring constant pressure in the reactor part (about 40 bar), the surplus of gas is led into the fuel-gas system through a pressure regulator.
2. Hydrocarbon phase is directed to the cooled feed vessel and then, as a reflux flow, to the column-stripper.
3. Sour water is led to the sour-water accumulation vessel, from the pocket of the cold separator vessel, and after that to the process of sour-water treatment.

Overheated stream of the stripper is condensed in the stripper top accumulator, via a cooler. From this vessel, one part is returned to the stripper, as a reflux, together with hydrocarbon phase from the cooled feed vessel. Gas phase from the accumulator of the stripper is led to gas concentration. From the bottom of the column-stripper, whose temperature is maintained by a heater, desulfurized gas oil is separated and led into storage, via the exchanger and cooler system.

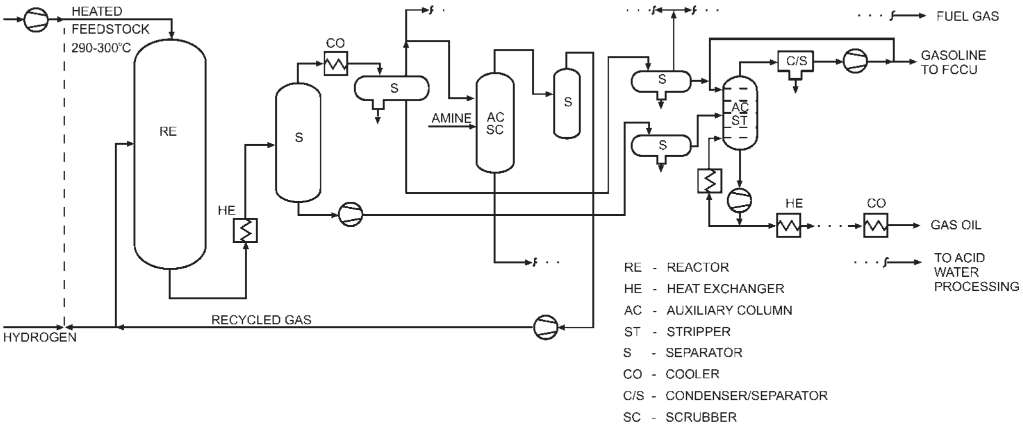


Fig. 17 Technological characteristics of gas-oil hydrodesulfurization process

The technological characteristics of the gas-oil hydrodesulfurization process are shown in Fig. 17.

4.9.2
Energy Characteristics of the Process

In a typical gas-oil hydrodesulfurization unit, the gas oil from the catalytic cracking unit and gasoline from the vacuum-residue visbreaking process are preheated in heat exchangers, by means of the flows of this process products, and then introduced into the process heater. Fuel gas is used as a fuel in the process heater.

The high-pressure steam is used to drive the main pump and compressors through the steam turbines, and low-pressure steam is used to heat tubes, some other equipment, etc.

Electric energy is used to drive the pump, fan and other equipment.

The main energy characteristics of the gas-oil hydrodesulfurization unit are shown in Fig. 18, which also presents all important options for the meeting of the process energy demands.

For the purpose of this process, a block energy-flow scheme is shown in Scheme 9 and Senky's diagram for the energy balance in Diagram 8. The values of the energy consumption refer to the annual volume of production amounting to 220 092 t of gas oil, 24 327 t of gasoline, and for a specific slate of products.

The consumption of high-pressure steam (HpS) is 90 000 t or 290 TJ.

Internal generation of medium-pressure steam (MpS), obtained by reduction on high-pressure steam through the back-pressure turbines, is 50 000 t or 149 TJ and it is used for other process requirements.

Internal production of low-pressure steam (LpS), obtained in the heat exchangers, is 30 000 t or 84 TJ. The low-pressure steam, produced by reduction of high-pressure steam through the back-pressure turbines, amounts to 40 000 t or 111 TJ. This low-pressure steam amount is used for internal consumption.

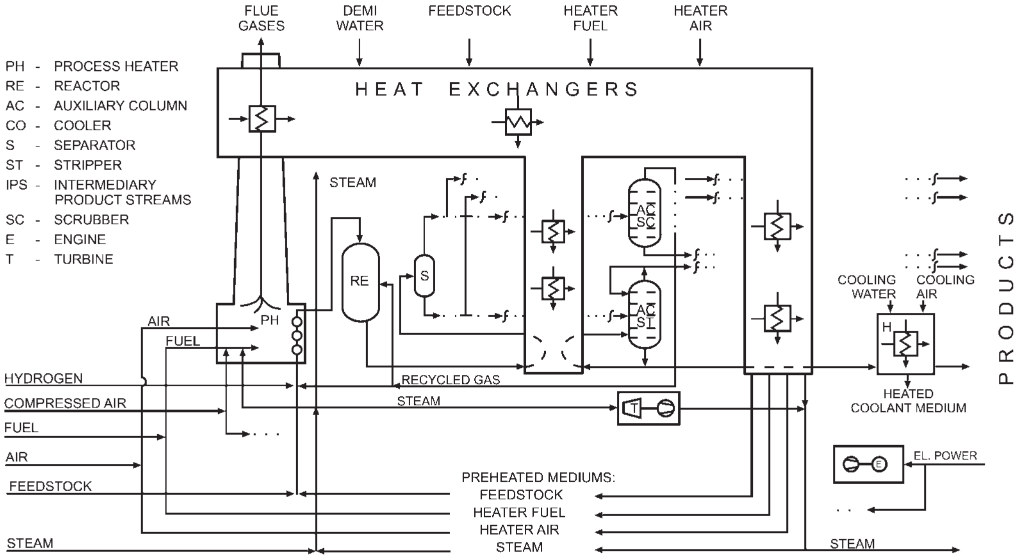
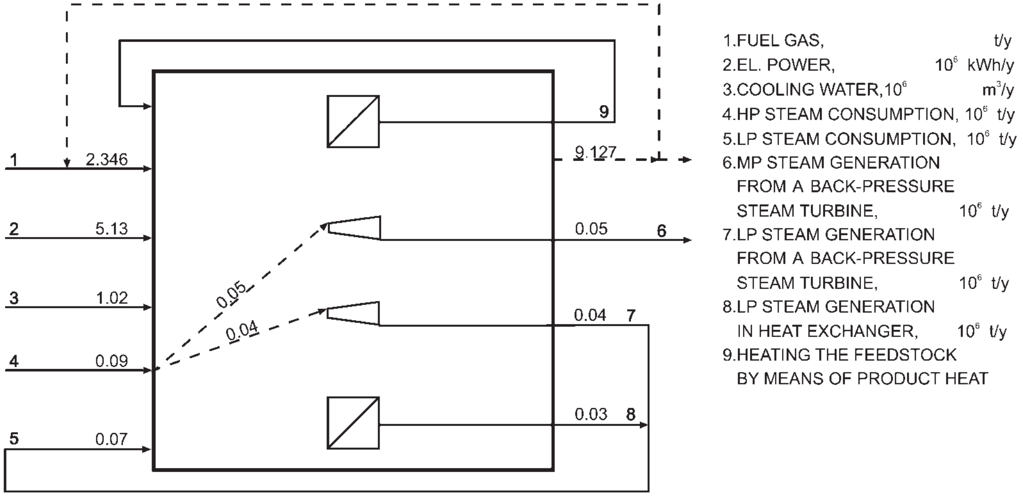


Fig. 18 Energy characteristics of gas-oil hydrodesulfurization process



Scheme 9 Energy flows of gas-oil hydrodesulfurization process

4.9.3
Determining the Steam Cost Price

The cost prices of medium-pressure steam (MpS) and low-pressure steam (LpS), obtained by reduction of high-pressure steam (HpS), as well as the cost price of low-pressure steam (LpS) generated on this unit, are given in Tables 55 and 56.

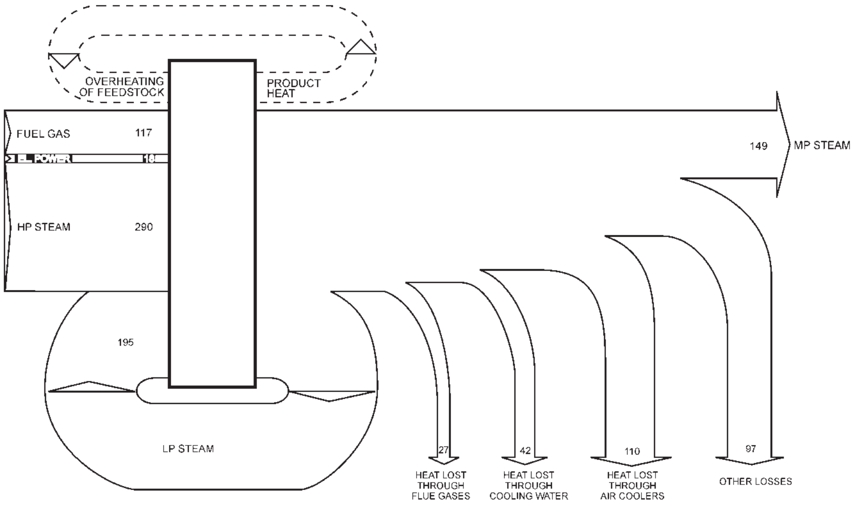


Diagram 8 Senky's diagram of energy flows of gas-oil hydrodesulfurization process, in TJ/y

From Tab. 55, it can be seen that the cost price of medium-pressure steam (MpS) of 11.13 US$/t is obtained by adding the following costs: depreciation cost, cost of current and investment maintenance and the insurance premium for the equipment participating in reduction of HP steam supplied from the refinery power plant at the cost price of 10.83 US$/t.

Tab. 55 Cost prices of medium-pressure steam (production-consumption)

Item no.	Elements for calculation	Medium-pressure steam generation (MpS)			MpS consumption for other consumers
		Annual q'ty in t	Cost price US$/t	Total in US$	
1	2	3	4	5	6
1	HP steam supplied from Refinery Power Plant	50 000	10.83	541 500	541 500
2	MP steam by reduction of HP steam	50 000	10.83	541 500	541 500
3	Depreciation			12 405	12 405
4	Current and investment maintenance			1 489	1 489
5	Insurance premium for equipment			992	992
6	Total (2–5)	50 000	11.13	556 386	556 386
7	Quantity in t			50 000 t	50 000 t
8	Cost price of MpS in US$/t			11.13	11.13

Tab. 56 Cost price of low-pressure steam (production-consumption)

Item no.	Elements for calculation	LpS production (US$)			
		Annual q'ty in t	Cost price US$/t	Total in US$	LpS for int. consumption in US$
1	2	3	4	5	6
1	LP steam by reduction of HP steam	40 000	10.83	433 200	433 200
2	Depreciation			12 162	12 162
3	Current and investment maintenance			1 459	1 459
4	Insurance premium for equipment			973	973
5	Total (1-4)	40 000	11.19	447 794	447 794
6	LpS internal production	30 000	0.47	14 041	14 041
6.1	Demineralized water	30 000	0.165	4 950	4 950
6.2	Depreciation			7 576	7 576
6.3	Current and investment maintenance			909	909
6.4	Insurance premium for equipment			606	606
7	LpS generation (5+6)	70 000	6.60	461 835	461 835
8	Quantity in t	70 000 t			70 000 t
9	Cost price in US$/t			6.60	6.60

The cost price of low-pressure steam (see Tab. 56) generated on this unit (6.60 US$/t) is the average cost price of 40 000 t low-pressure steam obtained by reduction of HP steam, at the cost price of 11.19 US$/t and 30 000 t low-pressure steam generated on this unit, at the cost price of only 0.47 US$/t.

The basic explanation for such a low cost lies in the fact that, on this particular plant, steam is obtained as a by-product in heat exchangers by utilizing the heat flux, thus offsetting the consumption of engine fuel and it is well known that in the cost calculation of the steam generated in the power plant, the engine fuel cost presents the largest portion; its share in the total production cost structure being approximately 80%.

Generated low-pressure steam is used for internal consumption of this unit, while medium-pressure steam is given to the other refinery units.

4.9.4
Energy Efficiency of the Process

The target standard of net energy consumption and specific gross and net energy consumption is outlined in Tab. 57 while Tab. 58 is the financial presentation of energy consumption and money savings that can be achieved by eliminating the differences between the target standard (average energy consumption of Western European refineries) and energy consumption of the plant being analysed.

In the procedure for the calculation of specific net energy consumption, the energy value of the MP steam, produced in this process and delivered to other processes within a refinery, is taken into consideration for the calculation of specific net energy

Tab. 57 Target standard of net energy consumption and specific energy consumption on a typical gas oil hydrodesulfurization unit (quantity of energy per one tonne of feedstock)

Energy carriers	**Target standard of net energy consumption**		**Specific energy consumption in the plant**					
			Specific gross energy consumption			**Specific net energy consumption**		
			(kg/t) ^{1}**(kWh/t)**	**(MJ/t)**		**(kg/t)** ^{1}**(kWh/t)**	**(MJ/t)**	
	(MJ/t)	**(kWh/t)**		**per unit**	**total**		**per unit**	**total**
Fuels								
Fuel gas	*	–	9.6	478.0	478.0	9.6	478.0	478.0
Heat carriers					1 980.0			576.8
LP steam	*	–	286	795.1		*	*	
HP steam	*	–	368	1 184.9		*	*	
Sources of heat	728	–	–	–	2 458.0	–	–	1 054.8
Electric energy	72	20	21.0^1	75.6	75.6	21.0^1	75.6	75.6
Energy carriers	800	–	–	–	2 533.6	–	–	1 130.4

Tab. 58 Financial presentation of energy consumption and money savings on a typical gas oil hydrodesulfurization unit (in US$)

Specific gross energy consumption

Energy carriers	Q'ty of feedstock (light residue) 244 419 t			US$
Fuel gas	244 419 t	(478.0 MJ/t × 0.0027 US$/MJ)	=	315 447
Low-pressure steam	244 419 t	(795.1 MJ/t × 0.0023741 US$/MJ)	=	461 319
High-pressure steam	244 419 t	(1 184.9 MJ/t × 0.003363 US$/MJ)	=	974 066
Sources of heat	244 419 t	**(2 458.0 MJ/t × 0.002914266 US$/MJ)**	**=**	**1 750 832**
Electric energy	244 419 t	(75.6 MJ/t × 0.0167 US$/MJ)	=	308 504
Energy carriers	244 419 t	**(2 533.6 MJ/t × 0.0033256 US$/MJ)**	**=**	**2 059 416**

Specific net energy consumption

			US$/t
Fuel gas	(478.0 MJ/t × 0.0027 US$/MJ)	=	1.2906
Low-pressure steam	(231.6 MJ/t × 0.0023741 US$/MJ)	=	0.549934
High-pressure steam	(345.2 MJ/t × 0.003363 US$/MJ)	=	1.161028
Sources of heat	**(1 054.8 MJ/t × 0.00284562 US$/MJ)**	**=**	**3.001562**
Electric energy	(75.6 MJ/t × 0.0167 US$/MJ)	=	1.26252
Energy carriers	**(1 130.4 MJ/t × 0.00377219 US$/MJ)**	**=**	**4.264082**
Sources of heat:			
Internal net energy consumption	(1 054.8 MJ/t × 0.00284562 US$/MJ)	=	3.00
Target net energy consumption	(728 MJ/t × 0.00284562 US$/MJ)	=	2.07
Difference:			**0.93**
Energy carriers:			
Internal net energy consumption	(1 130.4 MJ/t × 0.00377219 US$/MJ)	=	4.26
Target net energy consumption	(800 MJ/t × 0.00377219 US$/MJ)	=	3.02
Difference:			**1.24**

consumption. Specific net consumption of the process and thermal energy is obtained when the energy value of the steam delivered is deducted from the energy value of the steam consumed, i.e.:

$$\frac{(290-149)\mathrm{TJ}}{244\ 419\ \mathrm{t\ of\ feedstock}} = 576.8\mathrm{MJ/t}$$

If specific net energy consumption of a typical plant is compared with the target standard, the following conclusion can be drawn:

1. Specific electric energy consumption is close to the target standard.
2. Specific net consumption of process and thermal energy (fuel and steam) amounts to 1054.8 MJ/t thus exceeding the target standard (728 MJ/t) by 45%.
3. Total specific net energy consumption is 1130.4 MJ/t, which is 41% higher than the target standard (800 MJ/t). Compared with the net energy consumption target standard, a typical plant has an efficiency/inefficiency index of 141.

Process and thermal energy consumption increase on a typical plant is caused by different factors, the most important being:

- no preheating of air before entering process heater,
- non-economical utilization of HP steam for compressor and pump drive by means of steam turbines,
- inefficient utilization of flue gases heat from the process heater,
- non-economical combustion in the process heater (measuring of the excess air is not available), and
- inefficient utilization of gas oil heat flux.

4.9.5
Determining the Refinery Product Cost Prices

Determining the cost prices of the gas-oil hydrodesulfurization semi-products (Tab. 59) is very simple, because of this unit's processing characteristics. Namely, on this unit, the sulfur is separated in the form of hydrogen sulfide, in the presence of hydrogen and catalyst. This occurs at the corresponding temperature and pressure. Also, in this process, hydration of olefin components is performed in gas oils. Since the sulfur removal, improvement of cetane number, chemical stability and colour as well as the removal of unpleasant odour is carried out on this unit, its costs can be evenly distributed per tonne of derivatives among the bearers of costs. The cost prices of semi-products being the charge for this unit, are determined in the mentioned manner:

Tab. 59 Determining the cost prices of refinery products on gas oil hydrodesulfurization unit

Item no.	Elements for calculation	Q'ty in tonnes	Total in US$	Cost price US$/t	Fuel gas	Jet fuel	White-spirit	Light gas oil	Slop
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	Q'ty in tons	199 300.5			15 278.0	121 307.8	1 014.5	61 667.2	33.0
2	(%) from q'ty				0.07667064	0.60876879	0.00509139	0.30946918	–
3	Jet fuel	121 402	25 518 709	210.20					
4	White-spirit	1 030	218 965	212.61					
5	Light gas oil	61 701	12 222 281	198.09					
6	Gas for catalytic reforming unit	15 168	2 101 366	138.54					
7	Feedstock	199 301	40 061 320	201.01	2 116 610	25 498 909	215 703	12 223 467	6 632
8	Chemicals		66 434		5 094	40 443	338	20 560	
9	Water		632		48	384	3	196	
10	Steam		642 439		49 256	391 097	3 271	198 816	
11	Electric power		1 503 720		115 291	915 418	7 656	465 355	
12	Fuel		2 269 677		174 018	1 381 708	11 556	702 395	
13	Depreciation		1 541		119	939	8	477	
14	Other production costs		685 936		52 592	417 577	3 492	212 277	
15	Wages		1 627 536		124 785	990 793	8 286	503 672	
16	Taxes		715 913		54 890	435 826	3 646	221 553	
17	Unit management costs		1 243 385		95 331	756 933	6 330	384 790	
18	Laboratory and maintenance costs		251 198		19 260	152 922	1 278	77 738	
19	Common services costs		249 180		19 105	151 693	1 269	77 114	
20	Total costs		49 318 910		2 826 398	31 134 642	262 838	15 088 409	6 632
21	Cost price in US$/t		247.46		185.00	256.66	259.07	244.67	201.00

Semi-product	Cost price of charge in US$/t	unit operating costs in US$/t	Cost prices in US$/t
Fuel gas	138.54	46.46	185.00
Jet fuel	210.20	46.46	256.66
White spirit	212.61	46.46	259.07
Light gas oil	198.09	46.46	244.63

The cost price of slop is determined at the level of feedstock average cost.

4.10
Instruments for Determining Energy and Processing Efficiency of Alkylation Unit

4.10.1
Technological Characteristics of the Process

In alkylation of iso-butane with olefins, the hydrocarbon isomers in the boiling range of gasoline are obtained in the presence of sulfuric acid as a catalyst. Reaction occurs in the liquid phase when olefins come into contact with acid and large excess of iso-butane, the bigger portion of which has an impact on improvement of alkylate quality. In this process, a high-octane component – raw alkylate – is produced, which is then used in motor gasoline blending, (see Fig. 19).

C_4 hydrocarbon olefin feed is mixed with isobutane and introduced into a reactor to mix with sulfuric acid (98.5 %). This mixture goes from the reactor into a settler where acid is separated and circulated from the settler bottom back into the reactor.

The hydrocarbon phase mixture is introduced into the expansion vessel via the reactor (tube bundle), at a reduced pressure, hence a large expansion and concurrent reactor section cooling occurs, due to flashing.

The expansion vessel consists of two parts. In the first part, a mixture of alkylate and iso-butane is separated and in the second part, mainly iso-butane, which is sent back

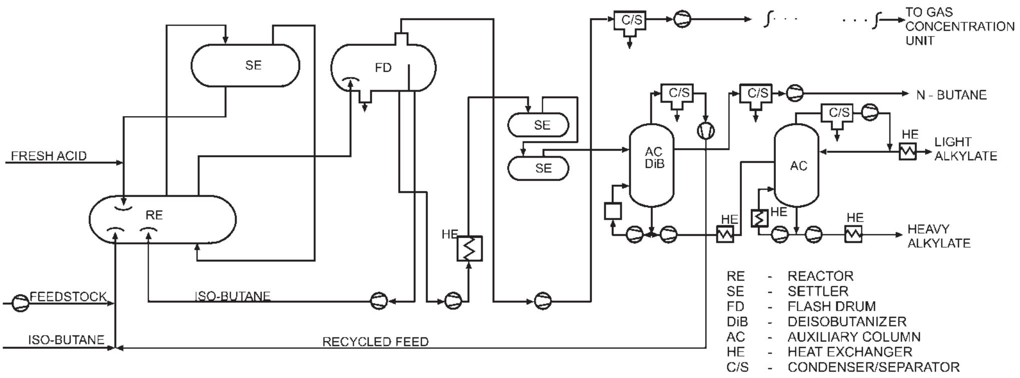


Fig. 19 Technological characteristics of alkylation process

into the reactor to provide the necessary excess of iso-butane and to maintain the process optimum temperature (4–7°C).

The expansion vessel is under pressure (higher than 1 bar) so the complete vapour phase, mainly propane, butane and iso-butane, is fed into the compressor absorber to introduce a part of the phase into the other part of the expansion vessel where iso-butane is employed as a cooling agent, whereas the remaining steam phase is fed via a cooler and a separator back to the gas concentration depropanizer to serve as the alkylation process feed.

Alkylate and iso-butane mixture from the first part of the expansion vessel is charged, via a heat exchanger, to the washing system. First, washing is performed by caustic, to remove residual acid, and then by water to remove residual caustic. Then, the mixture is introduced into the column-debutanizer. Isobutane is separated on the top of the column and is partly sent, via the cooler and separator, back to the column as a reflux and partly returned to the process as a recycle with make-up iso-butane from the storage. n-Butane, as a side-stream product, is discharged to storage, via the cooler and separator.

The column bottoms' product, alkylate, can be used in motor gasoline blending or can be separated in the redistillation column, as light and heavy distillates.

4.10.2
Energy Characteristics of the Process

In alkylation with sulfuric acid, iso-butane and butane fractions are introduced into a reactor where an exothermic reaction occurs.

High-pressure steam is used for the main pump and compressor drive, through the high-pressure steam condensing turbines.

Medium-pressure steam is used to heat the auxiliary column, through heaters, and to drive pumps and compressors, through medium-pressure steam turbines.

Low-pressure steam (LpS) is obtained by reduction of medium-pressure steam (MpS) on the medium-pressure steam turbines.

The total amount of steam is used for heating of tubes, equipment and other requirements.

Electric energy is used to drive pumps, fans and other equipment.

The main energy characteristics of the alkylation process are shown in Fig. 20.

For the purpose of this process a block energy-flow scheme is presented in Scheme 10 and Senky's diagram for the energy balance in Diagram 9. The values given for the energy consumption refer to the annual volume of production amounting to about 60 000 t/y.

High-pressure steam consumption is 80 000 t or 258 TJ. The consumption of medium-pressure steam is 140 000 t or 419 TJ. Internal generation of low-pressure steam, obtained by reduction on back-pressure turbines, is 20 000 t or 55 TJ and it is used internally.

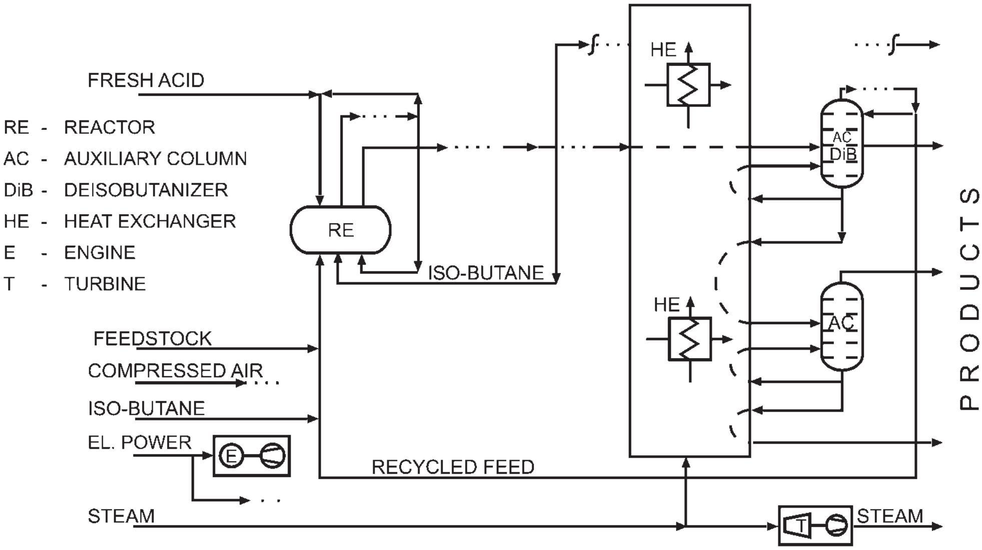
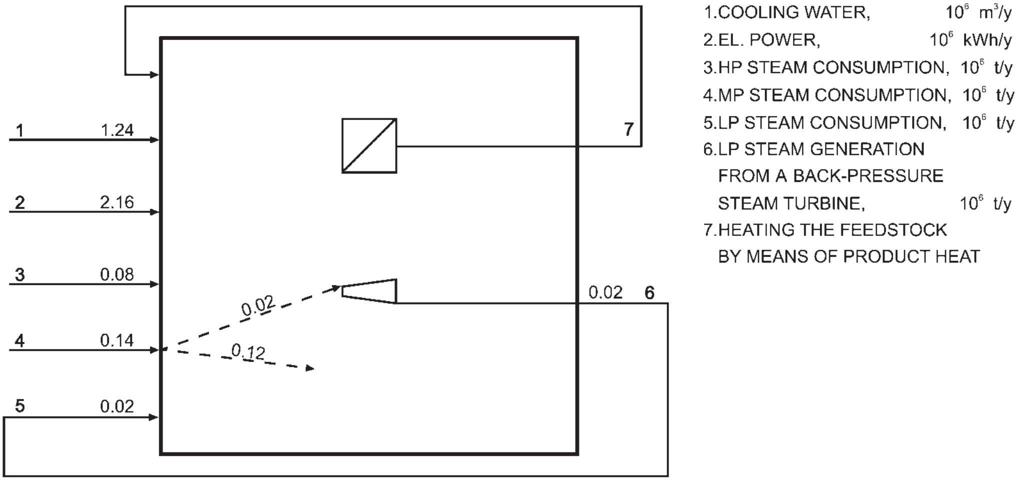


Fig. 20 Energy characteristics of alkylation process



Scheme 10 Energy flows of alkylation process

4.10.3
Determining the Steam Cost Price

The cost prices of high-, medium- and low-pressure steam, which are used or produced on the alkylation unit, are shown in Tables 60, 61 and 62. It should be emphasized that high- and medium-pressure steam is supplied from refinery power plant at 10.83 US$/t, i.e. 9.66 US$/t, while low-pressure steam is generated on the alkylation unit, by reduction of medium-pressure steam, and internally used.

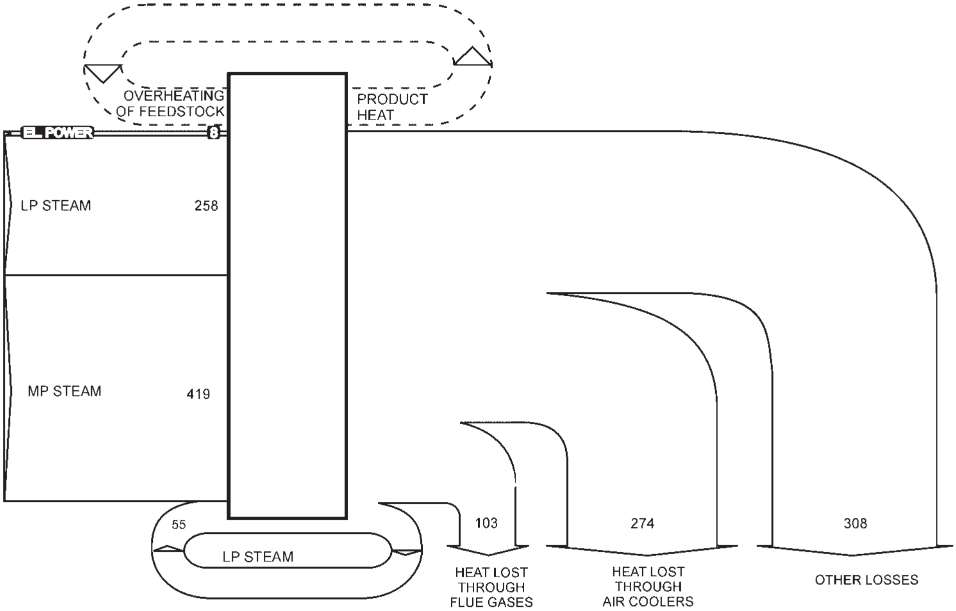


Diagram 9 Senky's diagram of energy flows of alkylation process, in TJ/y

Tab. 60 Cost prices of high-pressure steam HpS (consumption)

Item no.	**Elements for calculation**	**High-pressure steam generation (HpS)**		
		Annual q'ty in t	**Cost price US$/t**	**Total in US$**
1	2	3	4	5
1	HP steam supplied from Refinery Power Plant	80 000	10.83	866 400

Tab. 61 Cost prices of medium-pressure steam MpS (consumption)

Item no.	**Elements for calculation**	**Medium-pressure steam generation (MpS)**		
		Annual q'ty in t	**Cost price US$/t**	**Total in US$**
1	2	3	4	5
1	MP steam supplied from Refinery Power Plant	120 000	9.66	1 159 200

From Tab. 62 it can be seen that the cost price of LP steam that is generated by reduction of MP steam, is very high (11.78 US$/t). It is higher than the cost price of medium-pressure steam (9.66 US$/t) and high-pressure steam (10.83 US$/t).

Tab. 62 Cost price of low-pressure steam (production-consumption)

Item. no.	Elements for calculation	LpS production (US$)			LpS for int. consumption
		Annual q'ty in t	Cost price US$/t	Total in US$	
1	2	3	4	5	6
1	MP steam supplied from Refinery Power Plant	20 000	9.66	193 200	193 200
2	LP steam by reduction of MP steam	20 000	9.66	193 200	193 200
3	Depreciation			35 453	35 453
4	Current and investment maintenance			4 145	4 145
5	Insurance premium for equipment			2 763	2 763
6	Total (2-5)	20 000	11.78	235 561	235 561
7	Quantity in t			20 000	20 000
8	Cost price in US$/t			11.78	11.78

This price of LP steam is firstly effected by the price of MP steam that is provided from the refinery power plant at the price of 9.66 US$/t and added by fixed costs, i.e. depreciation, current and investment maintenance, breakage and fire insurance of the equipment used to convert the MP steam into LP steam, at the total costs of 2.21 US$/t, so the final LP steam price is 11.78 US$/t.

4.10.4
Energy Efficiency of the Process

Specific consumption of steam related to the amount of feedstock is:

$$\text{gross:}\ \frac{338\ \text{kg of steam}}{\text{t of feedstock}}\quad \text{or:}\ 939.6\ \frac{\text{MJ}}{\text{t of feedstock}}$$

$$\text{net:}\quad 0\ \text{kg/t}\qquad\qquad \text{or:}\ 0\ \text{MJ/t}$$

The target standard of net energy consumption and specific gross and net energy consumption, on a typical alkylation unit, is outlined in Tab. 63 while Tab. 64 is the financial presentation of energy consumption and money savings that can be achieved by eliminating the differences between the target standard (average energy consumption of Western European refineries) and energy consumption of this refinery unit.

The difference between gross and net energy consumption appears in the case of LP steam, by reason of internal generation in the process.

If specific net energy consumption of a typical plant is compared with the target standard, the following conclusion can be drawn:

1. Specific electric energy consumption is close to the target standard.

Tab. 63 Target standard of net energy consumption and specific energy consumption on a typical alkylation unit (quantity of energy per one tonne of feedstock)

Energy carriers	**Target standard of net energy consumption**		**Specific energy consumption in the plant**					
			Specific gross energy consumption			**Specific net energy consumption**		
			(kg/t) ^{1}(kWh/t)	**(MJ/t)**		**(kg/t) ^{1}(kWh/t)**	**(MJ/t)**	
	(MJ/t)	**(kWh/t)**		**per unit**	**total**		**per unit**	**total**
Heat carriers					12 394.8			11 455.2
LP steam	*	–	338	939.6				
MP steam	*	–	2 370	7 095.3		2 370	7 095.3	
HP steam	*	–	1 354	4 359.9		1 354	4 359.9	
Sources of heat	5 866.8	–	–	–	12 394.8	–	–	11 455.2
Electric energy	133.2	37	39.0^1	140.4	140.4	39.0^1	140.4	140.4
Energy carriers	6 000	–	–	–	12 535.2	–	–	11 595.6

Tab. 64 Financial presentation of energy consumption and money savings on a typical alkylation unit (in US$)

Specific gross energy consumption				
Energy carriers	Q'ty of feedstock (light residue) 59 053 t			US$
Low-pressure steam	59 053 t	(939.6 MJ/t × 0.0042374 US$/MJ)	=	235 117
Medium-pressure steam	59 053 t	(7 095.3 MJ/t × 0.0032308 US$/MJ)	=	1 353 701
High-pressure steam	59 053 t	(4 359.9 MJ/t × 0.003363 US$/MJ)	=	865 855
Sources of heat	59 053 t	**(12 394.8 MJ/t × 0.0033536 US$/MJ)**	**=**	**2 454 673**
Electric energy	59 053 t	(140.4 MJ/t × 0.0167 US$/MJ)	=	138 460
Energy carriers	59 053 t	**(12 535.2 MJ/t × 0.00350309 US$/MJ)**	**=**	**2 593 133**
Specific net energy consumption				
				US$/t
Medium-pressure steam		(7 095.3 MJ/t × 0.0032388 US$/MJ)	=	22.980258
High-pressure steam		(4 359.9 MJ/t × 0.003363 US$/MJ)	=	14.662343
Sources of heat		**(11 455.2 MJ/t × 0.00328607 US$/MJ)**	**=**	**37.642601**
Electric energy		(140.4 MJ/t × 0.0167 US$/MJ)	=	2.344680
Energy carriers		**(11 595.6 MJ/t × 0.00344849 US$/MJ)**	**=**	**39.987281**
Sources of heat:				
Internal net energy consumption		(11 455.2 MJ/t × 0.00328607 US$/MJ)	=	37.64
Target net energy consumption		(5 866.8 MJ/t × 0.00328607 US$/MJ)	=	19.29
Difference:				**18.36**
Energy carriers:				
Internal net energy consumption		(11 595.6 MJ/t × 0.00344849 US$/MJ)	=	39.99
Target net energy consumption		(6 000 MJ/t × 0.00344849 US$/MJ)	=	20.69
Difference:				**19.30**

2. Specific net consumption of process and thermal energy (steam) amounts to 11 455.2 MJ/t thus exceeding the target standard (5866.8 MJ/t) by 95%.
3. Total specific net energy consumption is 11 596.6 MJ/t being 93% higher than the target standard (6000 MJ/t). Compared with the net energy target consumption, a typical plant has an efficiency/inefficiency index of 193.

Increased consumption of process and thermal energy on a typical plant is caused by different factors, the most important being:

- non-economical utilization of high-pressure steam for pump and compressor drive, by means of steam condensing turbines, and
- non-economical utilization of medium-pressure steam for pump and compressor drive by means of steam turbines.

4.10.5
Determining the Refinery Product Cost Prices

Considering the feedstock of this unit is butane, which is obtained on the catalytic cracking unit, and iso-butane, which is obtained on the gas concentration unit, it is necessary to first determine the cost prices of these products. The process is based on catalyst reaction of iso-butane with light olefins due to the production of alkylate, which presents about 90% of output, and that is blended, as an octane component, into gasolines.

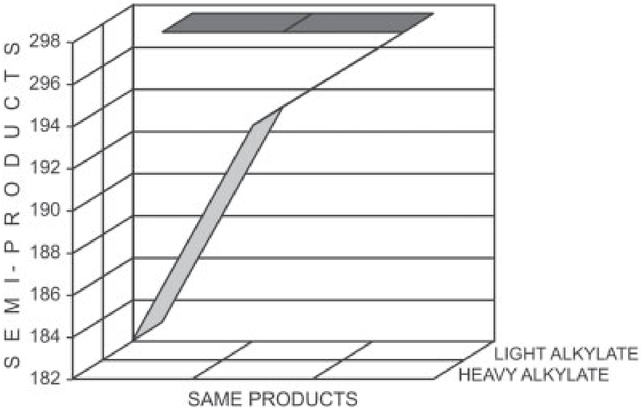
The cost prices of semi-products produced on the alkylation unit are determined by equivalent numbers obtained by means of the density method, as the best method, although equivalent numbers can be determined by the following methods as well:

- thermal value method, and
- average production cost method.

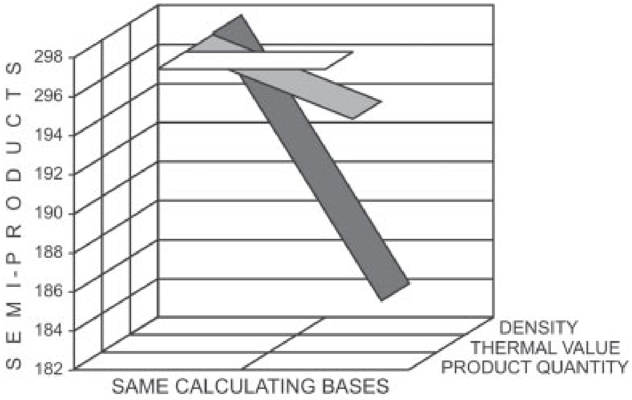
By analysing the results obtained by the different calculation bases for determining equivalent numbers, significant differences in the cost prices of oil products generated on this unit can be noticed.

Tab. 65 Cost prices of semi-products on alkylation unit in US$/t (per calculating bases)

Item no.	Semi-products	Base for determining the equivalent number for calculating the cost prices		
		Product Density Method	Thermal Value Method	Average Production Cost Method
1	2	3	4	5
1	Light alkylate	197.58	197.53	197.51
2	Heavy alkylate	183.75	194.03	197.51



Graphic 25 Cost prices of semi-products on alkylation unit, per products (in US$/t)



Graphic 26 Cost prices of semi-products on alkylation unit, per calculating bases (in US$/t)

These differences are presented in Tab. 65 and Graphics 25 and 26.

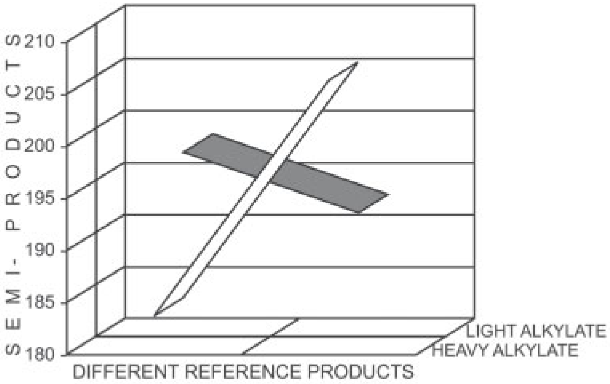
Besides the significant differences in cost prices of the same refinery product that depend on the calculating bases for determining the equivalent numbers, different ranges in the feedstock cost prices can be noted even with the same calculating base.

Besides the influence of calculating base, the choice of reference derivate is also important.

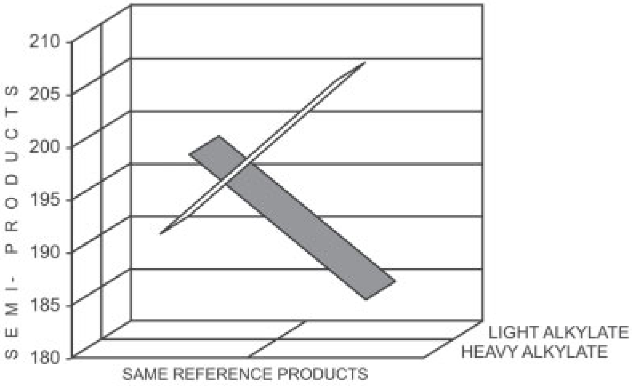
The stated examples of the calculating bases' effects on determining the equivalent numbers do not present all the dilemmas that experts dealing with process-industry calculations can face. The effects of the choice of reference derivatives (light alkylate whose density is 0.699 g/cm^3 and heavy alkylate whose density is 0.754 g/cm^3) on determining the equivalent numbers, in the case of using the same calculating base for determining the equivalent numbers (density method) are shown in Tab. 66 and Graphics 27 and 28.

Tab. 66 Cost prices of semi-products on alkylation unit in US$/t (per reference products)

Item no.	Semi products	Reference products	
		Light alkylate	Heavy alkylate
1	2	3	4
1	Light alkylate	197.58	191.86
2	Heavy alkylate	183.75	206.31



Graphic 27 Cost prices of semi-products on alkylation unit, per different reference products (in US$/t)



Graphic 28 Cost prices of semi-products on alkylation unit, per same reference products (in US$/t)

It can be seen that the differences appearing in this case are smaller than those appearing in the previous example of determining the equivalent numbers by the different calculating bases (density, thermal value and quantity of products).

Tab. 67 Determining the equivalent numbers for distributing the proportional costs on alkylation unit

Item no.	Oil products	Quantity in tonnes	Q'ty from 1 tonne	Density g/cm^3	Equivalent numbers	Condition units	Cost of 1 condition unit	Cost price in US$/t	Cost of feed-stock in US$	(%) for proportional costs	Cost of feed-stock in US$ (entry-exit)
1	**2**	**3**	**4**	**5**	**6**	**7(4 × 6)**	**8**	**9(6 × 8)**	**10(3 × 9)**	**11**	**12**
1	Isobutane	379.8	–	0.564	–	0.00	197.581	197.581	75 032	–	75 032
2	*n*-Butane	550.7	–	0.584	–	0.00	197.581	197.581	108 800	–	108 800
3	Light alkylate	11 188.9	994.92	0.699	1.00	994.92	197.581	197.580	2 210 718	0.99527785	2 262 918
4	Heavy alkylate	57.1	5.08	0.754	0.93	4.72	197.581	183.750	10 488	0.00472187	10 736
5	Total	12 176.4	1 000.00 11 246.00			994.64					
									2 405 039		2 457 487
									–183 832		–183 832
									2 221 207	1.000000000	2 273 655
6	Loss	265.9									
7	Total	12 442.3									

The cost of one conditional unit is as follows:
Feedstock 2 457 487 US$: 12 442.3 t = 197.51 US$/t
Feedstock 197.51 : 999.64 = 0.197581 i.e. 197.581 US$/t

Tab. 68 Determining the cost prices of refinery products on alkylation unit

Item no.	Elements for calculation	Q'ty in tonnes	Total in US$	Cost price US$/t	Isobutane	*n*-Butane	Light alkylate	Heavy alkylate
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	Q'ty in tons	12 176			379.8	550.7	11 188.9	57.1
2	(%) from equivalent numbers				–	–	0.99527785	0.004721865
3	(%) from q'ty				–	–	0.994924528	0.00507547
4	Entering charge	12 442	2 457 487	197.51				
5	Feedstock	12 442	2 457 487	197.51	75 032	108 800	2 262 918	10 736
6	Chemicals		46 463				46 244	219
7	Water		1 264				282	1
8	Steam		755 478				373 143	1 770
9	Electric power		229 277				67 161	319
10	Fuel		–					
11	Depreciation		43 744				613 064	3 127
12	Other production costs		685 936				564 355	2 879
13	Wages		1 627 536				1 339 058	6 831
14	Taxes		715 913				589 019	3 005
15	Unit management costs		1 243 385				1 022 997	5 219
16	Laboratory and maintenance costs		152 512				130 912	668
17	Common services costs		151 288				129 861	662
18	Total costs		39 945 986		75 032	108 800	7 139 015	35 437
19	Cost price in US$/t		221.68		190.57	260.07	638.04	620.84

The cost prices of semi-products generated on the alkylation unit, were calculated in the following manner, using the product density method:

- Proportional costs are distributed to semi-products generated in this unit according to the percentages obtained from equivalent numbers by means of the density method and a reference product named light alkylate whose density is 0.699 g/cm^3 (Tab. 67, Column 5).
- Fixed costs of the unit are distributed to semi-products according to yields, that is, in equal amounts per tonne of derivatives obtained on this unit (Tab. 68, Line 3).
- The loss is calculated in the refinery cost price.

By using the mentioned methodology for distributing the proportional and fixed costs of this unit to the bearers of costs, i.e. to the products obtained in this unit, the following cost prices of semi-products are established:

Semi-product	**US$/t**
Iso-butane	197.58
n-Butane	197.58
Light alkylate	638.04
Heavy alkylate	620.84

5

Blending of Semi-Products into Finished Products and Determining Finished Product Cost Prices

The procedure of blending semi-products into finished products can begin after determining the semi-product cost prices on each refinery unit (primary and secondary units). Determining the cost prices of finished products is simpler than those of the semi-products.

Once semi-product cost prices are determined, the cost price of finished products is calculated by multiplying the semi-product quantity by its cost price. It is also necessary to define the cost prices of initial and final stocks both for semi- and finished products.

In this particular case, the cost prices of stocks are defined at the level of cost prices of semi-products and/or finished products, because a typical oil refinery is taken as an example for demonstrating the cost prices, in the case when the cost prices in oil refineries do not exist. Considering that semi-product blending is performed at a special place of costs, it is necessary to distribute the costs of this place to the cost bearers, i.e. the products, in order to obtain the full cost price. Thus-determined full cost prices of finished products, in comparison with the finished-product selling prices, provide the possibility of determining the profit, i.e. loss per derivative. In such a way, the profit is considered as a function of choosing the optimum mode of managing the crude-oil processing technology.

The procedure of blending the semi-products into finished products is demonstrated by taking the blending of gasoline, diesel fuel and fuel-oil medium as an example (see Tables 69, 70 and 71).

The profit or loss, depending on the achieved ratio between selling and cost prices, is a result of the positive and/or negative difference in prices, on the one hand, and the difference between the produced and sold products, on the other.

Oil Refineries. O. Ocic

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Tab. 69 Determining the cost price of gasoline premium; quantity: 504 273.1 t

Item no.	Semi products	Refinery unit	Quantity in tonnes	Cost price US$/t	Total in 10^3 US$
1	2	3	4	5	6
1	Butane	Catalytic Cracking and Gas Concentration Unit	23 540.4	207.82	4 892
2	Iso-butane	Alkylation and Gas Concentration Unit	232.3	217.3	51
3	Aliphatic solvent	Redistillation Unit	715.4	426.24	305
4	Benzene (aromatic)	Aromatics Extraction	82.8	354.84	29
5	Stabilized gasoline	Gas Concentration Unit	22 912.8	209.36	4 797
6	Merox gasoline	Crude Unit	3 035.2	207.87	631
7	Raffinate	Aromatics Extraction	3 376.5	279.99	945
8	Light platformate	Catalytic Reforming	5 750.5	232.44	1 337
9	Heavy platformate	Catalytic Reforming	120 954.3	268.96	32 532
10	Light gasoline	Crude Unit	12 923.9	253.75	3 279
11	Pyrolytic gasoline	Purchasing	53 472.6	241.75	12 927
12	Light alkylate	Alkylation	3 873.9	638.06	2 472
13	Light cracked gasoline	Catalytic Cracking	45 832.5	280.62	12 862
14	Heavy cracked gasoline	Catalytic Cracking	181 400.6	244.93	44 430
15	Platformate	Catalytic Reforming	23 052.2	261.13	6 020
16	Light and heavy cracked gasoline	Catalytic Cracking	1 640.6	262.78	431
17	Toluene	Aromatics Extraction	75.8	347.76	26
18	Dyes	Purchasing	889.7	3 920.00	3 488
19	Unifinate	Catalytic Reforming	128.8	245.50	32
20	Visbreaking gasoline	Visbreaking	186.6	139.00	26
21	FCC gasoline	Purchasing	8.4	249.45	2
22	Heavy alkylate	Alkylation	34.6	620.87	21
23	Paraffin	Purchasing	152.6	46.55	7
24	Total cost price		504 273.1	260.85	131 542
25	Cost of blending		504 273.1	5.58	2 814
26	Cost price of Gasoline Premium		504 273.1	266.43	134 356
27	Selling price			400.40	
28	Made profit/loss		504 273.1	133.97	67 555
29	Initial stock		13 947.0	400.40	5 584
30	Sales		476 785.0	400.40	194 909
31	Final stock		31 435.1	400.40	12 587

Tab. 70 Determining the cost price of diesel fuel D-1; quantity: 100 364.9 t

Item no.	Semi-products	Refinery unit	Quantity in tonnes	Cost price US$/t	Total in 10^3 US$
1	2	3	4	5	6
1	Petroleum	Crude Unit	325.9	210.20	69
2	Jet fuel	Hydrodesulfurization	6 992.0	237.67	1 662
3	Diesel fuel	Crude Unit	23 469.5	189.20	4 440
4	Light gas oil	Crude Unit	48 283.5	196.52	9 489
5	Light gas oil	Hydrodesulfurization	12 569.4	244.63	3 075
6	Jet fuel	Crude Unit	2 873.1	210.20	604
7	White-spirit	Hydrodesulfurization	5 581.5	191.27	1 119
8	Total		100 364.9	203.83	20 457.39
9	Costs of blending		100 364.9	5.58	560
10	Cost price of Diesel D-1		100 364.9	209.41	21 017
11	Selling price			276.70	
12	Made profit/loss		100 364.9	67.29	6 754
13	Initial stock		3 378.4	276.70	935
14	Sale of Diesel D-1		96 452.1	276.70	26 688
15	Final stock		7 291.2	276.70	2 017

Tab. 71 Determining the cost price of fuel-oil medium; quantity: 662 612.4 t

Item no.	Semi-products	Refinery unit	Quantity in tonnes	Cost price US$/t	Total in 10^3 US$
1	2	3	4	5	6
1	Light gas oil	Crude Unit	6 874	198.09	› 1 362
2	Heavy gas oil	Crude Unit	35 011.4	190.83	6 681
3	Light residue	Crude Unit	19 992.5	173.89	3 476
4	Light vacuum gas oil	Vacuum Distillation	18 964.4	190.56	3 614
5	Heavy vacuum gas oil	Vacuum Distillation	1 132.1	186.79	211
6	Vacuum residue	Vacuum Distillation	116 399.5	169.83	19 768
7	Visbreaking residue	Visbreaking	333 103.1	187.70	62 523
8	Non-conditioned fraction	Vacuum Distillation	3 351.8	171.73	576
9	Light recycled gas oil	Catalytic Cracking	73 434.8	211.79	15 553
10	Decanted oil	Catalytic Cracking	54 301.1	201.68	10 951
11	Paraffin	Purchasing	47.7	44.55	2
12	Total		662 612.4	188.22	124 718.2
13	Costs of blending		662 612.4	5.58	3 697
14	Cost price of Fuel-oil medium		662 612.4	193.80	128 416
15	Selling price			161.60	
16	Made profit/loss		662 612.4	–32.20	–21 337
17	Initial stock		23 126.7	161.60	3 737
18	Sale of Fuel-oil medium		627 017.7	161.60	101 326
19	Final stock		58 721.4	161.60	9 489

The mentioned differences are presented by taking fuel-oil medium as an example:

Fuel-oil medium 1	t 2	US$/t 3	Total in 10^3 US$/t 4
Production	662 612.4	193.80	128 414
Sales	627 017.7	161.60	101 326
Difference	35 594.7	32.20	27 088

The difference based on the quantity: 35 594.7 t x 161.60 US$/t = –5 752 000 US$
The difference based on the prices: 662 612.4 t x 32.20 US$/t = –21 336 000 US$

Total: **–27 088 000 US$**

The cost prices of products, determined by the procedure applicable in determining the cost prices of gasoline, diesel fuel and fuel-oil medium are as follows:

Item no. 1	Products 2	Cost price US$/t 3
1	Propane	228.41
2	Butane	214.44
3	Propane-butane mixture	218.36
4	Aliphatic solvent 60/80	431.82
5	Aliphatic solvent (medical)	440.77
6	Aliphatic solvent 65/105	348.47
7	Aliphatic solvent 80/120	432.42
8	Aliphatic solvent 140/200	432.42
9	Benzene (aromatic)	356.42
10	Toluene	353.34
11	Gasoline regular	256.90
12	Gasoline premium	266.43
13	Unleaded gasoline	277.66
14	Gasoline G-92	266.27
15	Pyrolytic gasoline	247.33
16	Straight-run gasoline	240.04
17	Fuel gas	164.51
18	Gasoline G-92/0.4	289.94
19	Propylene	191.06
20	Cracked gasoline	222.50
21	Lighting kerosene	243.77
22	Diesel special DS	205.30
23	Jet fuel	244.20
24	Diesel fuel D-1	209.41
25	Diesel fuel D-2	202.37
26	Fuel oil EL	202.07
27	Low sulfur fuel	184.60
28	Ecological fuel EL	250.21
29	Fuel-oil medium	193.80
30	Sulfur	125.59
31	bitumen	209.60

The cost prices of finished products, obtained by applying the proposed methodology, are in the range of 1:3.6 between the highest and the lowest cost prices, so it can be considered as a satisfactory range. At the same time, the cost prices of semi-products are in the range of 1:4.6. The range of product cost prices is the result of the participation of semi-products in the structure of finished products. The cost prices of semi-products depend on the unit and the number of units the crude oil passes through. The finished products obtained on the crude unit, or that are mainly blended from the semi-products obtained on the primary sections, have lower cost prices (for example: motor gasoline, diesel, jet fuel, the cost prices of which range from 200 to 250 US$/t) than the products produced on the final refinery units (for example: aliphatic solvents produced on an alkylation unit, the cost prices of which can be up to 650 US$/t).

Taking gasoline premium as an example, it can be seen that the semi-products, the cost prices of which range from 200 to 270 US$/t, contribute 87% to the gasoline premium structure, while the semi-products with the cost prices ranging from 630 to 650 US$/t contribute only 0.8%. The cost price of gasoline premium is 266.43 US$/t as a result.

Taking diesel fuel as an example, it can be seen that the semi-products generated mainly on the primary sections, the cost prices of which range from 185 to 210 US$/t, are the main cause for the cost price of diesel fuel to be 209.41 US$/t (about 75% of semi-products blended into diesel fuel are generated on the crude unit).

In the end, determining the profit or loss per individual refinery product, by comparing the finished product cost prices, obtained by the proposed methodology, to their selling prices, represents a simple procedure.

6
Management in the Function of Increasing Energy and Processing Efficiency and Effectiveness

6.1
Management in the Function of Increasing Energy Efficiency and Effectiveness

Determining the efficiency and effectiveness of an oil refinery, by way of the instruments mentioned in the previous chapter, is analysed from the aspect of energy and technology.

From the aspect of energy, the efficiency of refinery units is determined through the cost prices of high-, medium- and low-pressure steam, while effectiveness is presented through the savings possibly achieved by eliminating the differences between the target standard (average energy consumption standard of Western European refineries) and the specific energy consumption of a typical refinery, which is the subject of this study.

Energy efficiency is analysed through the cost prices of steam generated in the following refinery units: crude-distillation unit, vacuum-distillation unit, vacuum-residue visbreaking unit, bitumen, catalytic reforming, fluid catalytic cracking, gas concentration unit, hydrodesulfurization of jet fuel and gas oil and alkylation.

By comparing the cost prices of medium- and low-pressure steam generated in the mentioned refinery units, and the cost prices of steam generated in refinery power plant, substantial differences can be observed. These differences are presented in Tab. 72.

At the same unit depreciation level, the main reason for such cost-price trends lies in the savings achieved on fuel, as the most important component in the cost-price calculation in the units being observed, as well as in the surplus of steam supplied to other consumers. For example, the cost of fuel is completely eliminated on the crude unit and vacuum-residue visbreaking unit and partially eliminated on the catalytic cracking unit, while in the cost-price calculation for the steam generated in refinery power plant, fuel consumption contributes about 80 % to the total costs structure. This comparison is given in Tab. 73.

In oil refineries, internal energy consumption depends on the level of the complexity of a refinery. Complexity, i.e. “the depth of crude-oil processing” is increased by enlarging the product slate and by a number of so-called secondary units.

Oil refineries with the same level of complexity can have low and high levels of energy efficiency. The difference between energy-efficient and energy-inefficient

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Tab. 72 Cost prices of high-, medium- and low-pressure steam in US$/t

Item no.	Refinery unit	Cost price of steam in US$/t		
		HpS	MpS	LpS
1	2	3	4	5
1	Crude Unit	–	0.47	–
2	Vacuum Distillation	–	0.44	–
3	Vacuum-residue visbreaking Unit	–	0.22	0.05
4	Bitumen	–		9.89
5	Catalytic Reforming	–	0.45	
6	Catalytic Cracking	3.10	2.53	1.94
7	Gas Concentration Unit	–	–	–
8	Jet-fuel hydrodesulfurization	–	–	–
9	Gas Oil Hydrodesulfurization	–	11.13	6.60
10	Alkylation	–	–	11.78
11	Refinery Power Plant	10.83	9.66	9.29

Tab. 73 Steam cost prices and fuel oil consumption in US$/t

Item no.	Refinery unit	HpS		MpS		LpS	
		Cost price	Fuel consumption	Cost price	Fuel consumption	Cost price	Fuel consumption
1	2	3	4	5	6	7	8
1	Crude Unit	–	–	0.47	–	–	–
2	Vacuum Distillation	–	–	0.44	–	–	–
3	Vacuum-residue visbreaking Unit	–	–	–	–	0.05	–
4	Bitumen	–	–	–	–	9.89	–
5	Catalytic Reforming	–	–	0.45	–	–	–
6	Catalytic Cracking	3.10	2.98	2.53	2.40	1.94	1.83
7	Gas Concentration Unit	–	–	–	–	–	–
8	Jet-fuel hydrodesulfurization	–	–	–	–	–	–
9	Gas Oil Hydrodesulfurization	–	–	11.13	–	6.60	–
10	Alkylation	–	–	–	–	11.78	–
11	Refinery Power Plant	10.83	9.45	9.66	8.09	9.29	7.02

oil refineries, on each level of complexity, presents the possibility for rationalization of energy consumption in inefficient refineries.

Comparison of energy-efficient and energy-inefficient oil refineries is presented by taking an average energy consumption standard in oil refineries from the former Yugoslavia, and the average energy consumption standard of Western European refineries (the target standard), as an example. Energy (in)efficiency indices of refinery units are presented in Tab. 74 and Graphic 29.

From Tab. 74 and Graphic 29, it can be seen that significant savings may be achieved on each refinery unit. It has been calculated that for the analysed refinery complex, the possible savings amount to about 9.2 million US$ per year (see Tab. 75).

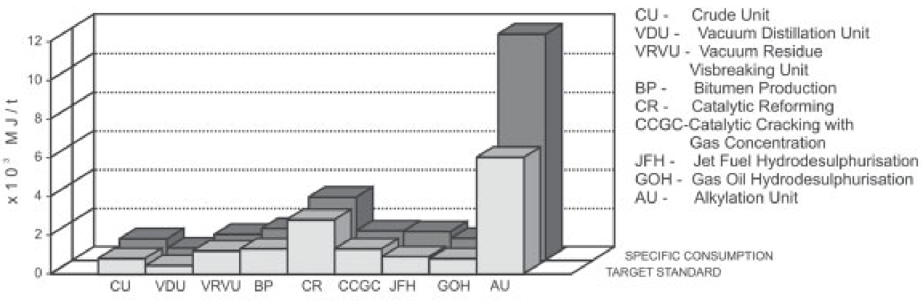
Tab. 74 Total specific net energy consumption and target net energy consumption standard in crude-oil processing

Item no.	Refinery unit	Total specific net energy consumption MJ/t	Target net energy consumption standard MJ/t	(In)efficiency index
1	**2**	**3**	**4**	**5**
1	Crude Unit	1 095.5	800	137
2	Vacuum Distillation	630.9	450	140
3	Vacuum-residue visbreaking Unit	1 325.2	1 200	110
4	Bitumen	1 626.7	1 300	125
5	Catalytic Reforming	3 232.2	2 800	115
6	Catalytic Cracking with Gas Concentration Unit	1 508.7	1 300	116
7	Jet-fuel hydrodesulfurization	1 471.8	900	164
8	Gas Oil Hydrodesulfurization	1 130.4	800	141
9	Alkylation	11 595.6	6 000	193
10	Total refinery complex	2 384.9	1 824.3	131

These savings can be achieved by applying more efficient-energy and technological solutions.

Namely, substantial possibilities for rationalization of energy consumption exist because present refineries were built at the time when energy was cheap, and when the investors did not pay any attention to the cost of energy. These possibilities include the following actions:

- continuous monitoring of energy consumption and costs,
- identification of the places of irrational energy consumption and preparation of the energy-saving programmes,
- modernization of equipment and introduction of computer management,



Graphic 29 Total specific net energy consumption and target standard of net energy consumption in crude-oil processes

Tab. 75 Savings achieved by eliminating the differences between the target standard and internal energy consumption (processing capacity of 5 000 000 t)

Item no.	Refinery unit	Quantity of feedstock (t)	Difference between target and int. consumption (US$/t)	Possible savings in US$
1	**2**	**3**	**4**	**5**
1	Crude Unit	5 000 000	0.94	4 700 000
2	Vacuum Distillation	2 122 065	0.60	1 273 239
3	Vacuum-residue visbreaking Unit	973 085	0.40	389 234
4	Bitumen	94 314	1.16	109 404
5	Catalytic Reforming	380 605	1.44	548 071
6	Catalytic Cracking with Gas Concentration Unit	821 239	0.62	509 168
7	Jet-fuel hydrodesulfurization	141 471	2.11	298 504
8	Gas Oil Hydrodesulfurization	244 419	1.24	303 080
9	Alkylation	59 053	19.30	1 139 723
10	Total savings			9 270 423

- reconstruction of existing equipment and an increment of maintenance,
- permanent professional training of operators and increase in motivation and responsibilities of employees,
- process-management improvement and direct engagement in rationalization of energy consumption, etc.

Such outlined possibilities present an important step for rationalization of energy consumption and that is why they have an important role in strategic business management.

6.2
Management in the Function of Increasing Processing Efficiency and Effectiveness

Monitoring processing efficiency and business effectiveness in oil refineries, by way of the cost prices of semi-products and finished products, is especially difficult due to the complexity of the process (production of coupled products) on the one hand, and due to non-existence of the measures and instruments, which the management system could be based upon (in this case, non-existence of semi- and finished product cost prices), on the other hand.

Namely, in oil refineries, the costs are monitored per type of costs, in total, at the level of actual production. Because of this, a corresponding methodology for determining the semi-product cost-price calculation should be established and then also for the products obtained by semi-products blending.

From the aspect of the process, the efficiency of refinery units is determined through the deviating elements in the semi-product cost-price calculation, observed in relation to the planned costs, standard costs, or corresponding calculations of other refineries.

Business effectiveness is observed through the finished-product cost prices in the following manner: through the break-even point, i.e. through the point of transition from the zone of loss to the zone of profit, on the one hand, and through the profit or loss realized by each product separately, as the difference between the cost prices and selling prices, on the other hand, since production cannot exist for its own sake but for the sake of profit or benefit to be achieved by that production. Therefore effectiveness has to be observed strictly from the aspect of market.

6.2.1

Monitoring the Efficiency of Crude-oil Processing Through the System of Management Oriented Accounting of Semi-Product Cost Prices

In a modern company, the management accounting presents the main source of information indispensable to operative and strategic management to make business decisions. In the case when one refinery unit is observed as an accounting centre, it is clear that the cost prices of semi-products, which are obtained on this unit, are very important.

Management accounting can offer, through the system of management-oriented accounting of the semi-product cost prices, the following information:

- semi-product cost prices obtained on this unit (in this case, by the methodology proposed in the previous chapter),
- semi-product cost price trends, compared to the cost prices from the previous accounting period, in the previous years, then in relation to the planned cost prices, cost prices in other companies dealing with the same type of activities, in the state and abroad or in relation to the average cost prices of the group companies, etc.
- reaction of the fixed, relatively fixed, proportional and total costs (as elements of the calculations) to the changes in the production quantity, i.e. the level of capacity utilization,
- besides the above mentioned, some information that the management accounting offers by way of the cost prices, can be in the function of the incentive remuneration of the personnel employed in the unit being observed. In the first phase, this incentive remuneration can be observed from the aspect of all employees from a given unit or a group of employees from a particular unit, and then in the second phase, this incentive can be given to each individual employee by finding the appropriate criteria and measures.

Operative management can make some decisions, based on the mentioned information of management accounting, which can facilitate the fulfilment of the unit objectives. These decisions can simultaneously help fulfil long-term targets and the strategy of the company.

"Strategic management is oriented to its surroundings. The role of strategic management is to adapt the existing and future organizational potentials to the changes and challenges of the surroundings for a longer period of time. The efficiency of strategic management has direct influence on the total business efficiency and long-term stability of a company. Considering the importance and influence of strategic management on the total development of a company, this function is always given to the top management (the board of managers or the top manager). Top managers are advocates of strategic development of a company. The efficiency of strategic management depends on the possibility of anticipating the changes of the surroundings, organizational potentials and capability of the highest level of management to make efficient strategic decisions. Strategic management should have qualitative information and comprehension about its surroundings as well as about the potentials of the company.

Efficient strategic management coordinates elements such as: product/market, investigative-research potentials and financial resources, expert potentials and management function. Today, much more attention has to be given to the life cycle of a program or idea and to the necessity for their innovations. Due to the saturation of the market, the life of technology is shorter and shorter and it is increasingly difficult to realize a permanent product value in the market" [23].

In contrast to the top management, operative management (management of refinery units) controls and manages the process and employees, and they are persons through which employees contact the other levels of management.

For this reason, cost price (in addition to the other parameters needed for managing such complex and specific processes) is a very important instrument for the medium-level managers, in making business decisions, in the area of process-technology efficiency.

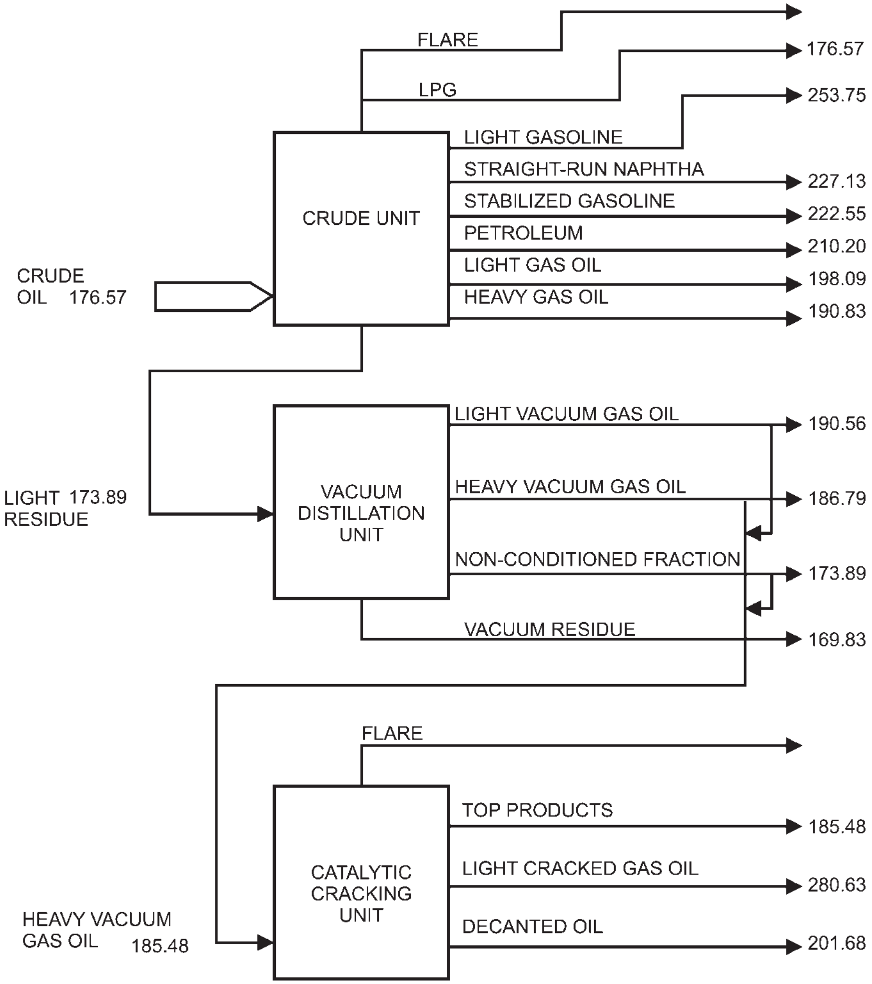
The cost prices of semi-products produced on a crude unit, a vacuum-distillation unit and in fluid catalytic cracking, determined by the proposed methodology, are shown in Scheme 11.

Any possible deviations in semi-product cost prices calculation can be determined by comparing the real semi-product cost prices to the semi-product cost prices from another accounting period, or to the semi-product cost prices in other refineries. After determining the cause of such deviations, operative management of a refinery can undertake corresponding activities to eliminate negative and intensify positive deviations.

The differences in cost prices of jet fuel produced in the course of two successive periods are outlined in Tab. 76.

By comparing the cost prices of jet fuel, produced in the course of two successive periods, the following can be noticed:

- that the cost price of jet fuel, realized in the second period, is higher by 7.56 % than that realized in the first period;
- that the basic cause of this increase in cost price is the cost of crude oil, whose increase is 8.58 %, and
- that in the second period there was a significant increase in the fuel cost (by 37.50 %).



Scheme 11 The cost prices of semi-products on the units: crude unit, vacuum distillation and catalytic cracking, in US$/t

The mentioned elements are good reason for the operative management to examine the causes of the outlined costs trend and to find a solution to their correction.

Management accounting also gives information about cost reaction: total costs, fixed, proportional and relative-fixed costs, as well.

Tab. 76 Comparison of jet-fuel cost prices in two successive periods in US$/t

Item. no.	Elements of the calculation	Cost price of jet fuel		
		I year	II year	% of increase
1	2	3	4	5 (4:3)
1	Crude oil	179.24	194.61	108.58
2	Chemicals	0.25	0.24	96.00
3	Water	0.00	0.00	0.00
4	Medium-pressure steam	0.18	0.20	111.11
5	Electric power	0.45	0.33	73.33
6	Fuel	1.28	1.76	137.50
7	Depreciation	1.02	1.02	100.00
8	Other productive costs	0.94	0.20	21.28
9	Wages	0.47	0.60	127.66
10	Taxes	0.99	0.50	50.51
11	Unit management costs	1.71	0.36	21.05
12	Laboratory and Maintenance costs	4.52	5.28	116.81
13	Common services costs	4.49	5.23	116.48
14	Cost price in US$/t	195.54	210.33	107.56

6.2.2
Management Accounting in the Function of Monitoring the Main Target of a Company – Maximising Profit through Accounting System of Finished-Product Cost Prices

Making profit in the function of choosing an optimum process from the aspect of minimising the costs and maximising positive effects, in complex production processes, as for example in crude-oil processing, presents a special problem due to the impossibility to determine the profit, i.e. the loss per tonne of products, from the difference between cost prices and selling prices.

The basis for the application of elective division calculation with equivalent numbers is density as a common characteristic of all products (semi-products and finished products). Equivalent numbers, which are the basis for distributing the proportional costs to the products, i.e. to the bearers of costs each place of costs, are obtained by relating the density of products to the density of reference derivatives.

Unlike the proportional costs, fixed costs are distributed to the products in equal amounts per tonne. Finished-product cost prices are obtained by blending semi-products into finished products per semi-product cost prices. Profit or loss per product separately is determined by relating the cost prices to the selling prices (see Tab. 77).

From Tab. 77 it can be seen that profit is made by selling propane, benzene, gasolines, propylene, diesel fuel and some types of fuel oil, while loss is evident in the case of other products.

Starting from the target function-maximization of profit or benefit, it can be seen that the operative management should direct crude-oil processing towards a bigger

Tab. 77 Comparison of the selling prices to cost prices, realized profit-loss per 1 t (in US$/t)

Item no. 1	Refinery products 2	Selling price 3	Cost price 4	Profit - Loss 5
1	Propane	254.60	228.41	+26.19
2	Butane	170.91	214.44	–43.53
3	Propane-butane mixture	219.60	218.36	+1.24
4	Aliphatic solvent 60/80	341.60	431.82	+90.22
5	Aliphatic solvent (medical)	315.80	440.77	–124.97
6	Aliphatic solvent 65/105	341.30	348.47	–7.17
7	Aliphatic solvent 80/120	295.40	432.42	–137.02
8	Aliphatic solvent 140/200	208.60	432.42	–223.82
9	Benzene (aromatic)	393.60	356.42	+37.18
10	Toluene	298.00	353.34	–55.34
11	Gasoline regular	356.80	256.90	+99.90
12	Gasoline premium	400.40	266.43	+133.97
13	Unleaded	432.40	277.66	+154.74
14	Gasoline G-92	251.80	266.27	–14.47
15	Pyrolysis gasoline	226.70	247.33	–20.63
16	Straight-run gasoline	212.18	240.04	–27.86
17	Fuel gas	69.13	164.51	–95.38
18	Gasoline	267.30	289.94	–22.64
19	Propylene	465.00	191.06	+273.94
20	Cracked gasoline	183.90	222.50	–38.60
21	Petroleum for lighting	228.90	243.77	–14.87
22	Diesel special	486.30	205.30	+281.00
23	Jet fuel	239.40	244.20	–4.80
24	Diesel fuel D-1	276.70	209.41	+67.29
25	Diesel fuel D-2	279.79	202.37	+77.42
26	Fuel oil EL	244.10	202.07	+42.03
27	Low sulfur fuel	209.60	184.60	+25.00
28	Ecological oil EL	590.30	250.21	+340.09
29	Fuel-oil medium	161.60	193.80	–32.20
30	Sulfur	113.40	125.59	–12.19
31	Bitumen	196.69	209.60	–12.91

share of the gasolines and diesel fuels in the total production. At the same time, the following limiting factors should be considered:

- quality of crude oil,
- capacity of crude-oil processing,
- structure of refinery units,
- requirements of the regional product market,
- inevitable production of by-products, due to the nature of process technology,
- societal demands for all the products obtained by crude-oil processing, etc.

Each of the mentioned factors has an effect (positive or negative) on the quantity of refinery derivatives produced and contributes to the level of refinery profit.

Refineries that have predominantly primary crude-oil processing, such as, for example, a type of refinery named “topping” and “simple”, have to use light crude oil (mainly over 34 API). Refineries of “semi-complex” and “complex” types (with primary and secondary crude-oil processing) can use heavy crude oil (under 34 API) because they have the secondary crude-oil processing, and also because such crude oil has lower prices. The structure of refinery units is directly related to the production of gasoline and diesel and these products are mentioned as important profit makers per tonne. For example, in the refineries that have predominantly primary crude-oil processing, extraction of gasoline and diesel from crude oil makes about 50 %, while crude residue makes about 45 %. In the refineries that have secondary crude-oil processing, about 40 % of gasoline can be extracted from the mentioned crude residue. It can be seen that the quality of crude oil, capacity of crude-oil processing and structure of refinery units are directly in proportion to profit. From the aspect of the mentioned factors, it can be concluded that the operation of crude-oil processing should be directed to the production of the maximum quantity of gasoline and diesel, because they yield the largest profit. However, operative management has to appreciate constraints, such as, for example, demand of the regional product market, because the production cannot exist for its own sake but for the sake of profit or benefit achieved by that production and realized on the market.

Furthermore, from the aspect of society in general, the demand for a wide slate of products obtained by crude-oil processing, which have caused loss in production, should be considered. This means that the petroleum industry, and society in general, must express their interest through the pricing system.

6.2.3

Break-Even Point as the Instrument of Management System in the Function of Making Alternative Business Decisions

The analysis of break-even point gives some important information for making business decisions, although it is predominantly based on static premises.

“Each company has fixed costs that are independent of the product quantity. Positive business results suppose covering the fixed costs from the contributed income, which presents the difference between the income and proportional costs. The business loss appears in the case when the contributed income is not enough for covering the fixed costs. The break-even point can be found on the margin between the zone of loss and the zone of profit. The break-even point presents the quantity of the production and sale in which the realised contributed income is equal to the fixed costs, observing all business periods. So it means that the income and total costs (proportional and fixed) should be equalized taking one year as the business period observed. It can be seen that the comprehension about the break-even point is very important to a company as well as to the parts of a company” [24].

The break-even point, as an instrument of management in the function of making business decisions will be presented by taking a typical oil refinery, with primary and secondary crude-oil processing, which is the subject of this analysis, as an example.

Realised income, costs and business results, in one business year, for an observed refinery, are as follows:

1. Income from the refinery product sale	723 325 686 US$
2. Proportional costs	623 577 015 US$
3. Contributed income (1 – 2)	99 748 671 US$
4. Fixed costs	80 566 211 US$
5. Net profit (3 – 4)	19 182 460 US$
6. Proportional cost rate (2 : 1)	86.21%
7. Contributed income rate (3 : 1)	13.79%

The break-even point is as follows:

$$\mathrm{BEP} = \frac{\text{Fixed costs} \times 100}{100 - \text{proportional cost rate}} = \frac{80\ 566\ 211 \times 100}{100 - 86.21} = 584\ 236\ 480\ \text{US\$}$$

It can be seen that the break-even point is realized on 584 million dollars and that the observed refinery needs almost 10 months to reach the transition point from the zone of loss to the zone of profit and it can be concluded that its security margin (SM) is relatively low:

$$\mathrm{SM} = \frac{\text{Income from refinery product sale} - \text{amount of break-even point}}{\text{Income from refinery product sale}} \times 100 =$$

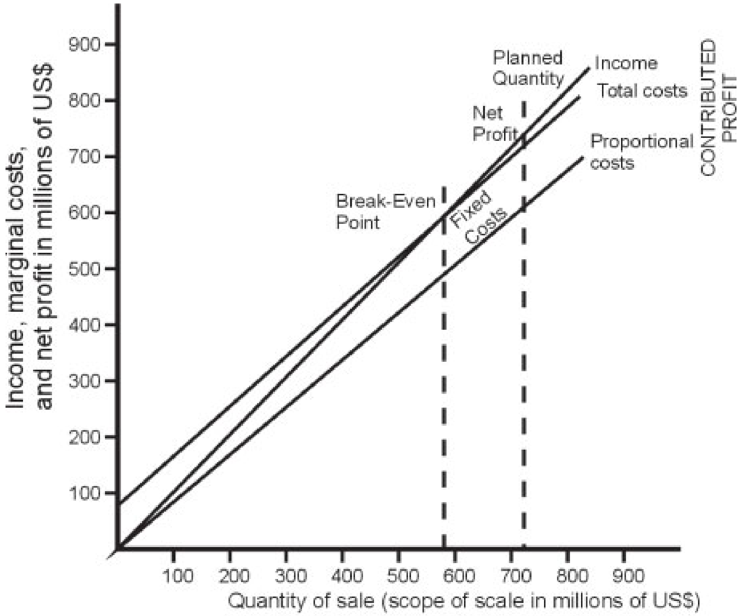
$$= \frac{723\ 325\ 686 - 584\ 236\ 480}{723\ 325\ 686} \times 100 = 19.2\%$$

The security margin shows that it is possible to decrease the quantity of refinery product sales by 19.2% without the worry of bringing the refinery into the zone of loss. Graphic 30 shows the break-even point.

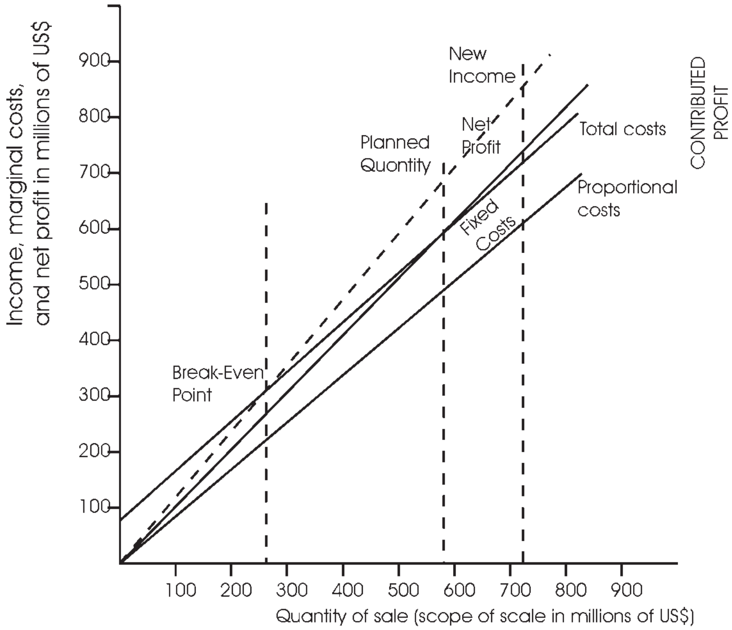
By applying the break-even point, the management of a refinery comprehends the changes in contributed income, profitability threshold and net income in the following cases:

– changes in selling prices,
– changes in production quantity and sale, and
– changes in proportional costs, etc.

By introducing the outlined selling-price change, for example, by 20%, it can be seen, in Graphic 31, that the break-even point is realized at a lower level, i.e. instead of 584 million dollars, at 285 million dollars, so it takes only 4 months to get out of the zone of loss, and its security margin is increased from 19% to 67%. (See Graphic 31)



Graphic 30 Break-even point



Graphic 31 Break-even point after changing the selling prices

1. Income from the refinery product sale,	867 990 823 US$
2. Proportional costs,	623 577 015 US$
3. Contributed income (1 – 2)	244 413 808 US$
4. Fixed costs	80 566 211 US$
5. Net profit (3 – 4)	163 847 597 US$
6. Proportional cost rate (2 : 1)	71.81%
7. Contributed income rate (3 : 1)	28.19%

The break-even point is, in this case, as follows:

$$\text{BEP} = \frac{\text{Fixed costs} \times 100}{100 - \text{proportional cost rate}} = \frac{80\ 566\ 211 \times 100}{100 - 71.81} = 285\ 797\ 130\ \text{US\$}$$

$$\text{SM} = \frac{\text{Income from refinery product sale} - \text{amount of break-even point}}{\text{Income from refinery product sale}} \times 100 =$$

$$= \frac{867\ 990\ 823 - 285\ 797\ 130}{867\ 990\ 823} \times 100 = 67.07\%$$

Changes in the production quantity, by-products slate, changes in the fixed and proportional costs as well as the effects of combined changes can be expressed in a similar manner. The mentioned combined changes are the most important indicators, because a change of one element only happens very rarely in practice.

The problem of monitoring the energy and processing efficiency and effectiveness of an oil refinery is observed as a segment of the refinery's management and the emphasis is placed on establishing a management system and the measures and instruments upon which the management system could be based.

Establishing such a management system is very difficult in the area of special processes, such as, for example, crude-oil processing, the basic characteristic of which is the production of "coupled products", where qualitatively different products are simultaneously derived from the same raw material, and are blended into the final products.

In such processes, monitoring the efficiency and effectiveness of process technology is limited, due to the complexity of the process on the one hand, and due to considerable backwardness in development of measures and instruments for monitoring the efficiency and effectiveness, on the other hand. Because of this, it can be concluded that continuous improvement of existing and the search for the new instruments and measures for monitoring the process-technology efficiency and effectiveness, are necessary.

In this book, techno-economic aspects of determining the efficiency and effectiveness of process technology are presented taking a typical five million t/y oil refinery as an example, which includes the following units: crude unit, vacuum-distillation unit, vacuum-residue visbreaking unit, bitumen, catalytic reformer, catalytic cracking, gas concentration unit, hydrodesulfurization of jet fuel and gas oil and alkylation.

Efficiency is being observed, from energy and technological aspects, as input/output on each refinery unit, and the effectiveness through the relation of a refinery to its surroundings.

From the aspect of energy, the efficiency is determined through the cost prices of high-, medium- and low-pressure steam generated as by-products in the mentioned refinery units, and it is interesting to note that the cost price of steam obtained in this way is twenty times lower than that of the steam generated in refinery power plant. The main reason for such cost trends of the steam generated in refinery units lies in the fact that this steam is generated as a by-product by utilizing the flue gases and flux heat. This is how the fuel consumption (fuel oil or fuel gas), which accounts for approximately 80 % of the cost-price calculation of steam generated in refinery power plant, is eliminated.

From the technological aspect, the efficiency is determined through the cost prices of oil products generated in the mentioned refinery units. Emphasis is placed on the problems that management has to face in choosing the methodology for determining the cost prices of semi-products, which, in the final phase, are blended into products and as such are put on the market. Emphasis is also placed on some problems and dilemmas such as the complexity of crude-oil processing technology (production of "coupled products") and the complexity of the possible methodology for determining the cost prices of semi-products.

The procedure for determining the refinery product cost prices, presented in this book, consists of three following phases:

In the first phase, the total refinery costs are distributed to the places of cost, i.e. to the refinery units, and the realization of this phase is particularly easy.

In the second phase, the costs of every refinery unit are distributed to semi-products, which are obtained on these units. In this phase, the role of operative management is important when it comes to choosing the calculating base for determining the equivalent numbers, the reference semi-products for determining equivalent numbers, as well as defining the by-products, because the use of elective division calculation with equivalent numbers (as the most complex form of accountancy calculation) is necessary.

The influence of calculating bases is presented by taking three methods used in determining the equivalent numbers for distributing the proportional costs to the bearers of costs as an example. The mentioned methods are based on using density, thermal value of products and quantity of the produced derivatives.

The effect of the reference derivative chosen is also presented. It is emphasized that the effect of the reference derivative is smaller than that of the calculating base for determining the equivalent numbers, in the procedure of calculating the refinery-product cost prices.

In the third phase, semi-products are blended into finished products. The principle applied is multiplication of the semi-product quantity with their cost prices, including the initial and final stocks of semi- and finished products. This phase is simpler than the previous one. And finally, the procedure of determining the profit or loss, per refinery product, i.e. finding the difference between the cost prices and selling prices, is even simpler.

In addition to the aspects of energy and processing efficiency, the aspects of energy and processing effectiveness are also demonstrated in this book.

From the aspect of energy, the effectiveness is presented through the savings that could be achieved by eliminating the differences between the target standard of energy consumption and internal energy consumption of each mentioned refinery unit. By using certain measures, suggested in this book, taking a typical refinery with the processing capacity of five million tonnes per year as an example, a significant saving of 9.2 million dollars/annum can be achieved.

From the technological aspect, the effectiveness is presented through the cost-price calculation of products along with calculating the profit or loss per oil product, separately, by way of the difference between the cost price and selling price. Taking a typical oil refinery as an example, it can be seen that the sale of propane, benzene, gasoline, propylene, diesel fuel and some types of fuel oil produces the profit, while the other products make a loss.

It should be emphasized that cost prices, as management instruments, exist because of this knowledge of profit and loss made per individual product, so that the refinery's management could undertake the following:

- certain activities for decreasing the cost prices in order to yield higher profit or decrease the loss, and
- certain attitude in the policy of determining the selling prices of oil products making a loss, within the policy of oil-product costs implemented by the state, so that the oil industry and the state, through the costs, can find corresponding interests satisfying both sides.

In the end, it can be concluded that the rationalization of energy consumption and establishing the methodology for determining energy and processing efficiency and effectiveness of crude-oil processing, should be treated as a strategic commitment.

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[6] According to S. Baarn, refineries can be classified into the following four groups, from the aspect of process complexity:
A – The simplest refinery that has only a crude unit and a catalytic reforming unit.
B – More complex refinery which, besides the mentioned units, has vacuum-distillation unit and catalytic cracking unit. Some refineries from this group can have corresponding equipment for processing bitumen as a residue of the distillation.
C – Complex refineries with a total slate of products, including the production of lubricating oils.
D – Petrochemical refineries, which are technologically completed for production of basic intermediary products for petrochemical industry.

[7] Lower level of energy efficiency is shown through increased specific energy consumption and vice versa.

[8] In the 1973 to 1977 period, energy efficiency in Exxon refineries was increased by 5 to 27%, depending on the kind of process.

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Subject Index

Index by Page

Oil Refineries. O. Ocic

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