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OPTIMIZATION OF ENERGY USE IN OIL REFINING

(CASE-STUDIES OF AL-ZARQA OIL REFINERY, JORDAN; AND ADEN OIL REFINERY, YEMEN)*

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* This document was prepared by the ESCWA secretariat with the assistance of a consultant, Mr. Nazar K. Al-Amir.

Bibliographical and other references have, wherever possible, been verified.

EXECUTIVE SUMMARY

Refining processes basically require different forms of energy, mostly heat, for the vaporization and conversion of crude oil or feedstocks into elemental constituents or finished products. Hence refinery operations are energy intensive by nature. In a refinery, generally 60% of the total energy consumed is for direct-process heat, 25% for steam generation and 15% for electricity generation. It has also been estimated that 30% of the energy needs of the refinery could be saved by present-day technology and procedures. The basic aim of this report is to identify and evaluate technically and economically viable schemes and projects for energy optimization and conservation in refineries and to apply such schemes in two refineries selected within the ESCWA area.

This technical report contains seven chapters.

Chapter I outlines the basic conceptual approaches to energy conservation. Sources of energy consumption in the refinery are identified, energy conservation schemes are suggested with calculations of energy savings and then the investment required for such schemes is estimated and their feasibility is evaluated.

Chapter II deals with basic data, information and assumptions used in this report, with emphasis on costs and economic evaluation.

Chapter III identifies major processes in the refinery which are energy consumers, such as distillation units, fluid catalytic cracking units and catalytic reforming units. Some ideas about the composition of petroleum and refinery products were also included.

Chapter IV details the major utility units in refineries that handle fuel and energy, whether for consumption, supply, heat exchange or conservation purposes.

Some particular importance was given to air preheaters and waste-heat boilers as they constitute the obvious choice for energy conservation.

Chapter V reviews present and existing policies and plans of energy conservation as practiced by major oil companies in their refineries. The significance of these plans that is, they look at conservation in totality and as an integrated plan both inside and outside refinery boundary. Some future schemes of conservation are also outlined.

Chapters VI and VII relate to the two refineries selected for energy conservation schemes, namely the Zarqa refinery in Jordan and the Aden refinery in Yemen. The sections include a brief description of each refinery:

(a) The major processing units;

(b) Identification of schemes and the annual saving in fuel and the value of such saving;

(c) Estimation of investment cost for the schemes;

(d) Economic analysis of the schemes including payout time and rate of return on investment;

(e) Conclusions and recommendations.

A summary of the results of economic evaluation of the schemes suggested for refineries is shown in table 1.

Of the six schemes suggested for the Zarqa refinery, four are clearly feasible since the payout time for such projects varies from three to five years; the other two are marginal by virtue of their low capacity. However, if the six schemes are taken together, then they (all combined) become viable. The schemes suggested are of a major nature since they allow the recovery of a considerable amount of heat from fired heaters which are the major source of energy consumption. Some other schemes have already been implemented in the refinery, such as insulation of fuel oil tanks and the rearrangement of the heat exchange train for better heat recovery from hot product streams.

The schemes identified for the Aden refinery are all viable, theoretically at least, except for the insulation of tanks which shows a long payout time. In practice, however, this is reduced drastically by the use of local insulating material and constrictions. However, the problem with conservation schemes for the Aden refinery is somewhat fictitious, since the schemes cannot be implemented on their own. The refinery is quite old, and most of the process units for improving the quality of products are technically and economically obsolete. The refinery is undergoing major renovation plans, although they are still not implemented practically, but the conditions of the refinery warrant their implementation sooner or later and one would expect that the scheme suggested for energy saving would be incorporated into the renovation plan.

Table 1. Summary of economic evaluation of schemes

	Scheme number	Scheme	Capacity (ton/d)	Annual saving, fuel oil (ton)	Annual saving (dollars)	Investment cost (dollars)	Payout time (year)	Rate of return on investment
Zarqa Refinery	1	Preheater CDU3	7 500	7 240	615 480	1 383 000	2.2	>100%
	2	Preheater CDU2	2 000	1 647	139 972	625 600	4.5	25%
	3	Preheater VDU2	1 100	827	70 253	437 200	6.2	low
	4	Preheater VDU1	1 000	710	60 345	413 300	6.8	low
	5	Waste-heat boiler to reformer	1 000	7 285	619 210	3 000 000	4.8	20%
	6	CO-boiler to FCCU	650	5 497	467 240	2 317 000	5	20%
Aden Refinery	1	Crude heater replacement	10 000	12 468	1 059 780	2 300 000	2.2	>100%
	2	Reformer heater modification	1 800	12 430	1 056 500	600 000	0.7	>100%
	3	Insulation of fuel oil tanks	10 302m^2	2 039	173 300	1 250 000	7.1	low

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INTRODUCTION

An oil refinery is a complex plant through which crude oil is processed to produce a wide range of petroleum products to meet the needs of various sectors of fuel consumers, according to specifications.

The basic concept of refining requires the heating and vaporizing of crude oil into its elemental constituents, hence the energy intensive nature of oil refining. Besides heating and vaporizing, energy is consumed in refineries as rotational power for pumps and compressors and as chemical energy for different reactions.

One of the significant items of the yield[1/] of an oil refinery for a specific crude-oil (or combination of crude) feed, is the fuel and loss (F&L), which is a measure of the amount of fuel used in different processes or units of the refinery for direct fire heating or for steam generation. The F&L percentage of yield varies in modern refineries from 3-7% depending on the complexity of the refinery and the energy conservation measures in the refinery.

The refineries built in the 1980s are intrinsically energy-efficient since they were built in times of high energy costs, while plants designed and built when energy prices were low were forced either to shut down or to practise energy conservation through incremental modifications, which resulted in overall significant economic savings.

This study is a technical report about the measures and schemes available for optimizing energy utilization in refineries. The aim of the study is to identify economically feasible measures and the technical background necessary regarding the subject of energy conservation in refineries.

The study is not an energy audit of refineries, and hence any conclusions and recommendations are based mainly on generally recognized concepts, international experiences as documented in energy and refinery literature and technical background on the subject of energy and refinery literature.

The findings of this report have been applied to two refineries within the ESCWA countries, namely the Zarqa refinery in Jordan and the Aden refinery in Yemen, where many schemes have been identified and analysed economically.

The following factors were taken into consideration in selecting the two refineries for this study with regard to energy optimization and conservation:

(a) Both refineries were built during the era of cheap and readily available sources of energy. The Aden refinery was built during the early 1950s, primarily to supply bunker fuel to ships and tankers passing through Aden Port. The Zarqa refinery was built to meet local demand for petroleum products;

[1/] Yield is defined as the percentage (in weight or volume) of different products which one unit of crude oil will produce in a refinery.

(b) The two refineries have different complexities and conversion capabilities. The Aden refinery is basically a simple topping-reforming plant. It has a vacuum unit but not any form of conversion. Most of the units and processes are of the old type, and some have become technically and economically obsolete.

The Zarqa refinery is a more advanced refinery than Aden's. Besides having vacuum distillation units, it also includes two conversion units: a fluid catalytic cracking unit (FCCU) and a unibone hydrocracker, for the conversion of heavy distillates into lighter products. However, it has no conversion units for residues;

(c) The Zarqa refinery is basically a domestic refinery whose design capacity is much higher than its current throughput.

The Aden refinery is currently operating of 50% of its designed capacity.

Both refineries have excess un-utilized capacity which could be employed for additional products such as processing contracts or for processing finished products for export.

The Aden refinery uses half of its current capacity for processing contracts. However, this cannot continue indefinitely because of the higher operational (maintenance and repairs) costs of the refinery due to old age as well as inferior product quality in the international market;

(d) Hence both refineries are perfect candidates, theoretically at least, for upgrading projects (which is outside the scope of this study), as well as projects to introduce economic savings, to make them both more operationally attractive.

The main venue of economic savings is in energy conservation and optimization, which is the aim of this report.

I. METHODOLOGY AND CONCEPTS

A. Energy conservation

Energy conservation is best achieved by aggregating sequential and interacting activities in space and time so that energy systems may supply requirements in a continuous manner in small steps from the highest temperature level to the lowest heat sink. Disaggregation tends to force large temperature changes and results in energy waste.

The greatest possibilities for more efficient energy use in refineries lie in careful management of process heat and direct fuel consumption.

B. Basic energy principles

Principles of energy recovery are governed by the second law of thermodynamics, which states that only a fraction of heat at a certain temperature can be converted into work, and that the remainder must be dissipated at ambient temperature as waste heat. Heat has specific value, closely related to the temperature level. The higher the temperature, the higher the efficiency of heat recovery. Hence it pays more to recover heat at a higher temperature (figure 1).

Thus recovery by sequential use of energy is important. As many steps as possible should be used in heat recovery, with each step declining gradually in temperature. Furthermore, integration of materials and energy flows in processes follows. Recovered energy should be used to preheat material streams, to generate steam for driving processes.

Low-level energy should be used to create low-level heat with high-level heat energy reserved to create work or high-level heat. Consequently, hydrocarbons and natural gas, which are high-value products, are too precious to be burned directly. They can be better used to make high-value goods.[2]

C. Heat recovery

Recovery of heat is governed by the amount of heat available and its temperature level. For the highest efficiency of recovery, this should be done at the highest temperature. However, a practical balance has to be struck between maximum heat recovery at a suitable temperature and the economics of such recovery.

For heat recovery, exchangers are used across the entire range of temperature.[3] In the high region (500-1,000°C), exchangers can be employed for preheating cracking and reformer furnace streams. In the medium temperature range (300-500°C), preheating reactor feed, air for reaction purposes can be used, whilst the lowest level (<300°C) exchangers can be used for preheating distillation column, steam generation, etc. (figure 2).

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[2] G. Goossen, "Thermodynamics laws point way to applications for energy recovery", Energy Management Handbook, p. 3.

[3] Ibid.

Spiralling energy costs result in greater interest in low-level heat recovery with the emphasis on:

(a) Lowering furnace stack temperature on process furnaces and boilers by installing preheaters;

(b) Improving combustion in furnaces and boilers through instrumentation and control;

(c) Recovery of low-level heat in effluent streams;

(d) Insulation of tanks, lines, etc.;

(e) Generation of low or medium process stream.

D. Energy integration

At many locations, refineries are located along chemical plants and/or power generation. The energy-use patterns for these processes differ markedly. In refining, energy requirements are mainly for process, where direct fired oil and gas heaters transfer energy at temperatures ranging from 300-500°C, while in chemical plants, the temperature requirements are in the range of 150-300°C. Hence in such situations, there are greater opportunities for energy integration (figure 3).4/

E. Identification of energy consumption centres in a refinery

It is estimated that there are 50 to 60 ways to improve energy conservation in a refinery plant.5/ Many of these are marginal measures which are closely related to the daily running of the refinery such as proper maintenance, supervision and control. However, for significant energy savings, the major sources of consumption must be identified and investigated for economically viable measures.

The following general formula will be followed in this report:

$$\Sigma \text{ sources of energy consumption} - \Sigma \text{ energy-saving measures} = \Sigma \text{ energy saving}$$

1. Sources of energy consumption and losses

It was computed that aggressive energy conservation programmes can reduce energy usage in the amount of 30% for petroleum refineries; the main savings are in the following sources of major energy-consumption units of the refinery:6/

4/ E. M. Mergens, "How Shell Oil conserves energy", Energy Management Handbook, p. 12.

5/ H. Duckham and J. Fleming, "Energy conservation in HPl plants", Energy Management Handbook, p. 35.

6/ W. Heenan and C. Dalton, "Set burner air by stack analysis", Energy Management Handbook, p. 78.

Figure 1. The exergetic efficiency of heat as a function of temperature (reference temperature: $0^{o}C$)

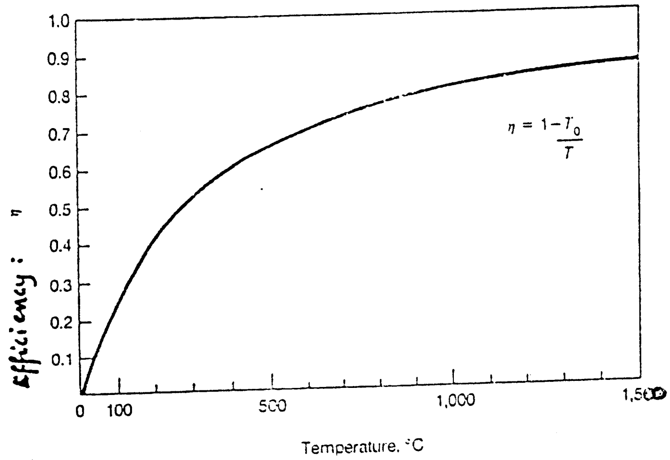
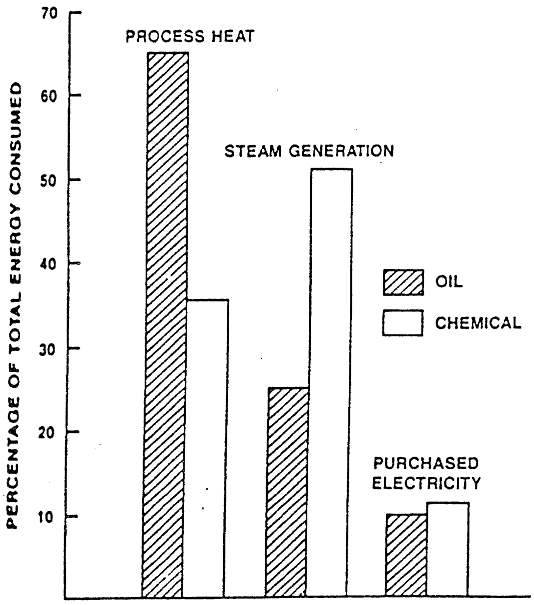


Figure 2. Heat recovery

Temperature Range	Range of η (Fig. 2)	Applications		
		Production of heat in furnaces and boilers	Recovery of furnace heat	Other Applications
500 to >1000° C	0.65 to >0.80	• Gas turbine cycle with furnace heat production in the turbine exhaust. • Steam turbine topping cycles for the production of electricity in back-pressure turbines with exhaust seam for process applications.	• Preheating cracking or reforming furnace feed streams. • Generating high-pressure steam (. . 100 . . . bar). • Steam superheating. • Preheating off-gases for turbo-expander operation.	
300 to 500° C	0.53 to 0.65		• Boiler or furnace air preheating. • Generation of medium to high pressure steam.	• Generation of medium to high pressure steam from exothermic heat. • Organic Rankine cycle.
150 to 300° C	0.35 to 0.53		• Boiler feedwater preheating. • Air preheating.	• Generation of low pressure steam for heating, drying, distillation... • Organic Rankine cycle. • Absorption cooling.
>150° C	>0.35			• Absorption cooling. • Recovery of steam condensate and flash steam. • Heat pump for evaporation, drying, etc.

• Recovery of low level waste heat for space heating, district heating system.

Figure 3. Refinery/chemical energy consumption--process heat, steam generation and purchased electricity



Source: E.M. Mergens, "How Shell Oil conserves energy", Energy Management Handbook.

Direct-fired heaters (furnaces)

Direct heaters are main sources of energy consumption in the refinery. It has been calculated that on average, 70-80% of the energy used in a refinery is consumed in direct-fired heaters.[7] The furnace efficiency of the cheap-energy period is low, and most of the energy goes up the stack, wasted. The temperature of the flue gases going up the stack were around 300-400°C. Modern stack temperatures are around 150°C depending on the composition of the flue gas, its dew point and the percentage of excess air. This difference of temperature accounts for the major energy savings in a refinery.

The furnaces of crude distillation units (CDU) and vacuum distillation units (VDU) are the main sources of energy savings by virtue of their large feed capacity, while other units such as fluid catalytic cracking units (FCCU) and naphtha reforming units could supply additional energy savings.

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[7] Duckham and Fleming, op. cit.

2. Heat recovery from hot product streams

Another source of energy savings are the hot product streams leaving different process units in the refinery, especially the primary distillation units. Optimization of heat train design through different configurations has been developed using sophisticated computer modelling.[8/] This has played a significant role in energy optimization of the refinery.

The energy saved from hot streams is used for preheating feed input into furnaces or for generation of steam for medium- and low-pressure utilization in the refinery.

3. Heat losses through un-insulated areas

Most areas in the refinery where there is possible loss of energy to the atmosphere can be remedied through proper insulation. However, there are still areas where appreciable surfaces are exposed or where insulation is not efficient enough to prevent the loss.

F. Energy-saving measures

The main energy-saving schemes in a refinery can be classified as follows:

1. Combustion air preheating

Fuel consumption in process heaters can be reduced by up to 25% by the installation of air preheat systems. Although air preheaters have been routinely used in steam-generating plants to increase the efficiency of furnaces, they have only recently been adapted to process furnaces. Their use increases furnace efficiency by recovering waste heat from stack gas to heat combustion air. It is estimated that about 1% of fuel is saved for every 18-20^{o}C reduction of fuel gas temperature.[9/]

Fuel savings is not the only advantage:

(a) With preheated air, there is less coking of the burner tips, which minimizes the necessity to clean the burners;

(b) With forced draught preheated air, there is a more controlled flame pattern;

(c) There is more complete combustion;

(d) There is even distribution of heat to process charge.

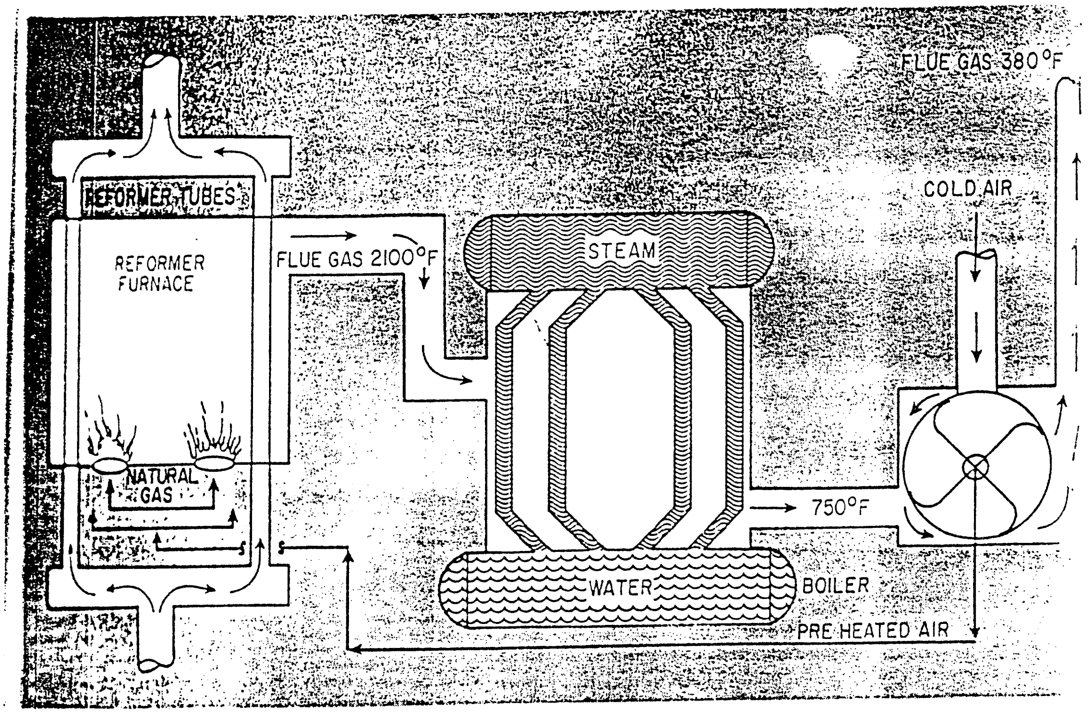
[8/] J. F. Frith, B.M. Bergens and M.M. Shreehan, "Optimization heat train design", Energy Management Handbook, p. 109.

[9/] C.L. Brown and D. Figensder, "Preheat process combustion air", Energy Management Handbook, p. 76.

2. Waste-heat boilers

Waste-heat boilers are commonly used whenever high- or medium-level waste-heat energy is available in the refinery or whenever operational obstruction prohibits the installation of air preheaters. Sometimes a combination of waste-heat boilers and air preheaters are used for sequential heat recovery when initial temperature allows (figure 4).

Figure 4. The Felmont Oil Co. ammonia reformer heater



Source: Felmont Oil Co.

Usually medium-pressure super-heated steam is generated with waste-heat boilers (260°C and 21 kilograms of pressure).

A typical use of waste-heat boilers in a refinery is heat recovery from the flue gas of FCCU regeneration units. The flue gas from the regenerators leaves at about 800°C together with an appreciable amount of unburnt CO gases. It is common practice to recover the heat in this stream by means of a CO boiler.

3. Heat recovery of hot streams by heat exchangers to generate intermediate- and low-pressure steam

Optimization of heat exchange between hot product streams and cold feed streams could save appreciable amounts of energy. The heat recovered could either be used to heat feed streams to furnaces or to generate intermediate- and low-pressure steams for various uses in the refinery.

4. Prevention of heat loss by insulation

Insulation of various areas of refineries such as piping, vessels and tanks is common practice to prevent heat loss into the atmosphere. However, there are major items which are left uninsulated such as fuel oil tanks where heating is necessary to maintain pumpability because of the pour point of the product. Significant savings can be achieved by proper selection of insulation material.

G. Optimization of energy savings

The methodology of selection of energy-savings schemes for a refinery to be followed in this report is as follows:

(a) Identification of major centres of energy consumption in the refinery in terms of tons of fuel oil equivalent or heat units;

(b) Economic and technical choice of the schemes to be adapted for energy savings. For an economically viable project, payout time should be less than five years;

(c) Energy savings is computed as the difference between present energy requirement and that of the energy-savings scheme.

II. BASIC DATA, PARAMETERS AND ASSUMPTIONS

A. Fuel oil equivalent

1. All energy savings are expressed in FOEB, which is defined as a 42 US gallon barrel having a volume of 0.159 m^3 and a gross heating value of 6 MM Btu. This is equivalent in metric units of 10.1 MM kcal/ton of fuel oil (NLHV).

Note: The difference between the "net" and "gross" heat value of a fuel is in the latent heat of condensation of the water vapour produced during combustion of the fuel. For fuel oil the net heat value is 5% less than the gross value (see chapter IV, note 10).

2. In this report, energy will be reported in tons of fuel oil equivalent per year (Tely) or in millions of kilocalories per hour (MM kcal/hr).

3. For electric power production: 0.350 Te of fuel oil per MW hr or 2.78 Te/yr produces 1 kWh for one year.[10/]

4. For additional energy conversion data, OPEC's Conversion Factor Book (Vienna, 1989) was used.

B. Units and conversion factors

Metric units have been used to the greatest extent possible throughout this report. Most references on energy and fuels originated in the United States of America (USA), and the units used in the oil industry are usually English units; these units have been converted to metric units whenever they are used in this report. No attempt was made to change the English units appearing in figures taken from the numerous references used in this report.

The conversion factors used in this report are those published in OPEC's Conversion Factor Book (Vienna, 1989).

C. Currency

The currency used in this report is the United States dollar.

D. Prices of fuel oil

The price of fuel oil used in conversion of energy, is taken as $US 85/ton, which was the average figure for this fuel in the Mediterranean area at the beginning of 1993.[11/]

[10/] Bechtel Co., "Report on energy conservation study in industry in Jordan", 1986.

[11/] OPEC Bulletin, March 1993.

E. Utilization

The refinery process and other units are assumed to operate 330 days per year.

F. Costs and capacities of units and equipment

The formula used for the relationship of costs and capacities is as follows:[12]

$$\frac{\text{Cost (a)}}{\text{Cost (b)}} = \left(\frac{\text{capacity (a)}}{\text{capacity (b)}}\right)^{0.6}$$

and the yearly inflation for prices of equipment is 5%.

G. Operation capacity of process and other units

Economic analysis and energy-savings calculations are computed assuming certain design capacities of the units. Current throughputs have not been considered since it is assumed that any project to be undertaken, would be implemented on the basis of the design capacity of the units and not on the current capacity. For both the Zarqa and Aden refineries, the current capacities are about 50% of design capacities, especially for the main distillation units. However, only operational units will be considered for energy-saving schemes.

H. Sources of data and information

General data and information on energy conservation in refineries are available worldwide in the references listed in the Bibliography. Specific data on the Zarqa and Aden refineries, however, are scant except in "Waste heat recovery in Jordan Petroleum refinery".[13] Most of the data quoted in this report pertaining to the Zarqa and Aden refineries were obtained through private communications and discussions.

I. Economic evaluation of conservation schemes

The economic parameters used for the economic evaluation of different schemes are as follows:

(a) Depreciation rate is 10% (straight line);
(b) Cost of labor/man/year is $3,600;
(c) Overhead charges as a percentage of labour cost are 100%;
(d) Loan/equity ratio is 80-20;
(e) Loan payment period is eight years;
(f) Interest rate is 13%;
(g) Taxes are 0%;
(h) Insurance is 1% of capital;
(i) Maintenance is 5% of capital.

Discounted internal rates of returns on the different schemes are estimated from figure 5.

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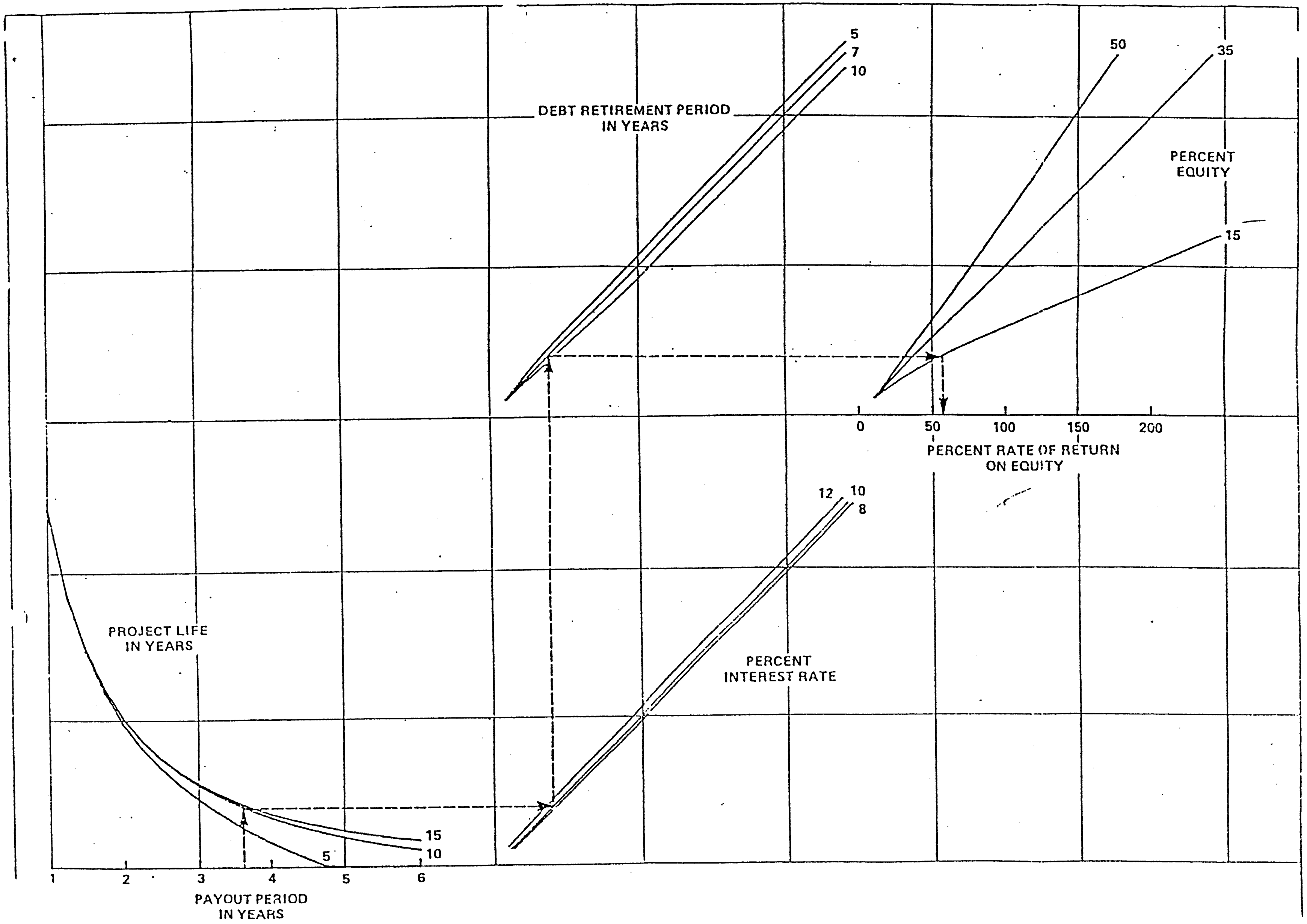
[12] W.L. Nelson, <u>Petroleum Refinery Engineering</u>, p. 879.

[13] R. Aburas, S. Lloyd and M. Webster, November 1988.

Figure 5. Project financial analysis: rate of return on equity without taxes

(Percentage)



Source: Bechtel Co., "Report on energy conservation study in industry in Jordan", 1986.

III. MAJOR ENERGY-USING PROCESSES IN A TYPICAL REFINERY

Table 2 indicates typical refinery energy requirements in terms of direct fired fuel, steam and electricity per unit (m3) of charged crude or stock. Since the refineries selected in this report are basically of the topping-reforming type (with some distillate conversion for the Zarqa refinery), only a few processes will be discussed here, namely: crude distillation, fluid catalytic cracking and catalytic reforming.

The energy consumed in a refinery is basically for the purpose of vaporization and distillation of crude oil into separate fractions according to their boiling points. It is consumed as well for the conversion of some of these fractions into useful products according to acceptable standards; these are always changing in the direction of superior quality to satisfy performance and environmental regulations and standards. It is therefore prudent to discuss briefly the composition of crude oil and its products.

A. Composition of petroleum

Most of the compounds found in petroleum are compounds, composed of hydrogen and carbon or hydrocarbons. Other compounds containing small amounts of sulphur, oxygen and nitrogen are also present. The physical operations of refining such as vaporization, fractionation and condensation are governed largely by the properties of the hydrocarbons because they constitute the bulk of petroleum. But the chemical operations such as treating and filtration as well as severe conversion operations such as hydrotreating and hydrocracking are governed by the presence of sulphur, oxygen and nitrogen compounds. Several parts per million of metallorganic compounds containing iron, nickel, vanadium, arsenic, etc., are also present in some petroleums. These metals have contrariant effects on the catalysts in catalytic operations.

Many series of hydrocarbons are present in crude petroleum and still others are produced by cracking and hydrogenation. Among the series that have been identified are those having the formula types C_nH_{2n+2}, C_nH_{2n}, C_nH_{2n-2}, C_nH_{2n-4}, C_nH_{2n-6}, C_nH_{2-8}, C_nH_{2n-10}, C_nH_{2n-14}, and C_nH_{2n-20}.

Paraffin series (formula C_nH_{2n+2})

This is the most stable of the hydrocarbon series. The lower members of the series have been identified in most crude petroleum while the higher members are probably present in most crudes.

Olefin series (formula C_nH_{2n})

These hydrocarbons are composed of unsaturated hydrocarbons whose members are capable of uniting directly with other materials such as chlorine, bromine and sulphur acid without displacing a hydrogen atom. The lower members of the olefin series are probably not present in crude petroleum but are produced in cracking processes.

Naphthene series (formula C_nH_{2n})

These have the same type formula as the olefin series but with greatly different properties. The naphthenes are ring or cyclic compounds, whereas the olefins are straight chain compounds in which a double bond connects two carbon atoms. The naphthenes are saturated compounds.

Table 2. Typical energy requirements in different processes in the in the modern refinery in terms of different utilities output

Process	Energy consumption per m^3 charged Steam (ton)	 Direct-fired heaters (kcal)	 Electricity (kWh)
Crude distillation	0.0713	2.371	0.7
Vacuum distillation	0.114	2.2464	0.5
Thermal cracking	0.2	17.472	3.3
Visbreaking	0.0856	7.2384	1.2
Delayed coking	0.1084	11.6064	1.8
Fluid catalytic cracking	0.0143	10.9824	1.8
Catalytic reforming		0.0143	4
Hydrocracking		0.3619	10
Naphtha hydrotreating	0.0314	2.246	1
Gas oil hydrotreating	0.0571	2.496	1.5
C4 alkylation	1.2126	14.976	4
Butane isomerization	0.1854		1.5
C5/C6 isomerization		4.4928	2.4
Propylene polymerization	0.8873		2.6
Butylene polymerization	0.7703		2.3
Hydrogen production		6.864	0.4

Source: B.G. Tunnah and E. Applebaum, "Use of fuel cells in refinery", EMH, p. 217.

Aromatic series (formula C_nH_{2n-6}) or the benzene series

Only a few petroleums contain more than a trace of the low-boiling aromatics such as benzene and toluene. However, this series is found in catalytically reformed gasolines and they are prized for their high octane number.

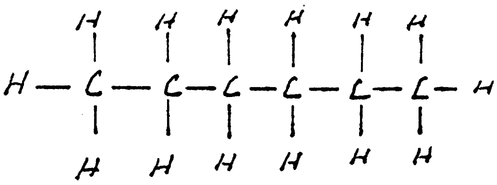
Isomeric compounds

Isomeric compounds have the same molecular formula but different structures. Compounds of the formula type C_nH_{2n} may be either saturated or unsaturated. The formulas of the saturated compound cyclohexane and the unsaturated hexene (normal) can be compared in figure 6 (b) and (c). Likewise the formulas of normal hexane, 2-methylpentane and 2-2-dimethylbutane all have the formula C_nH_{2n+2} or C_6H_{14}; these are shown in figure 6 (a) and (f).

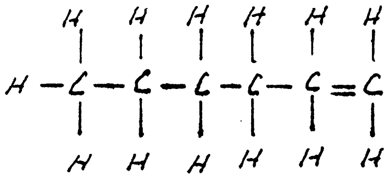
The number of isomeric hydrocarbons increases rapidly as the number of carbon atoms increase. The number of possible isomers of the series C_nH_{2n+2} is:

C-atoms	Isomers	C-atoms	Isomers
6	5	15	4347
7	9	18	60523
8	18	25	36797588
9	35	40	62491178805831
12	335		

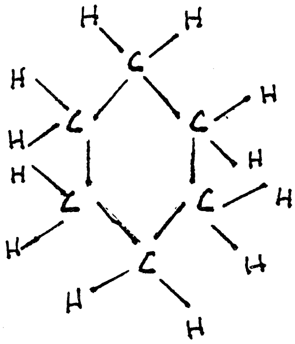
Figure 6. Isomeric compounds



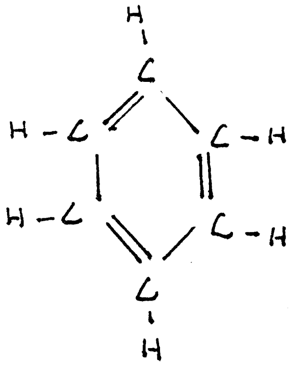
(a) Normal Hexane C_6H_{14}



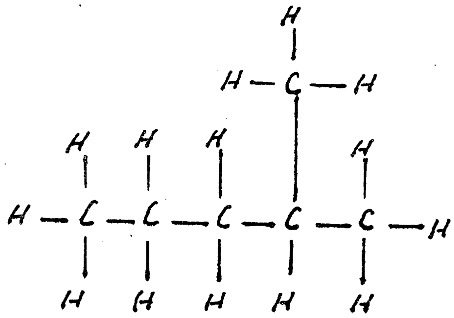
(b) Normal Hexene C_6H_{12}



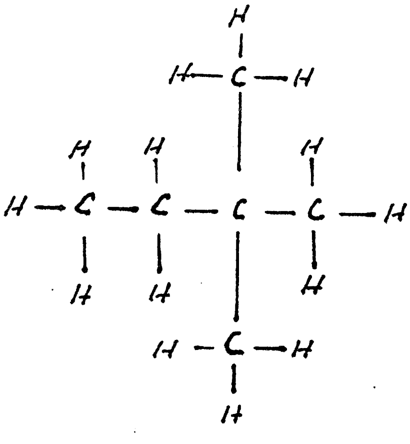
(c) Cuclohexane C_6H_{12}



(d) Benzene C_6H_6



2-Methylpentane C_6H_{14}



2-2 Dimethylbutane C_6H_{14}

(f) Isomeric Isoparaffin Compounds

B. Refinery products[1]

There are numerous types of crude oils in the world with widely differing physical and chemical properties; hence there are different processing methods, not only to refine the different types of crude but also to produce the various types of products with definite specifications.

Refining operations are like any other operations, and can be considered as as economic problem. This is even more true of refining operations; the following factors must be taken into consideration:

(a) The type (value) of the crude and its accessibility;

(b) The value of the products and their marketability;

(c) The yield of products from the crude;

(d) The cost of processing the crude and what percentage of cost is allocated to energy consumption;

(e) Environmental and other legislations.

It is because of the above considerations and factors that so many processes are available.

The following list of refinery products helps one appreciate the reasons that there are so many different refining processes:

(a) Natural and refinery gas: household and industrial fuels;

(b) Liquefied petroleum gas (LPG): household fuels;

(c) Gasoline-fuel for internal-combustion engines;

(d) Naphtha and benzene: solvents, thinners and stocks for conversion to other fuels or for blending motor fuels;

(e) Jet fuel: fuel for jet engines;

(f) Kerosene: oil for household appliances;

(g) Diesel fuel (gas oil): fuels for industrial furnaces and engines;

(h) Lubricants and grease: lubrication for many purposes;

(i) Paraffin wax: food, cosmetics, pharmaceuticals, electrical and other applications;

(j) Fuel oil: industrial and marine fuel;

(k) Asphalt: roads, coatings;

(l) Coke: solid industrial fuel.

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[1] Petroleum Processing Handbook, section 1 and Petroleum Product Handbook.

Figure 7 shows the relationship among raw stocks, intermediate products and finished products.

Figure 8 contains check-lists of commercial products and their sources.

C. General processing[2/]

The most important method of separating petroleum products is by distillation. This implies that products are compared on the basis of their boiling points. The graph in figure 9 is a good example of the relationship between the boiling ranges of different products and their yield (percentage distilled) for a typical crude but with two different processes, a simple topping operation and a more complex lubricating oil process.

There are two important requirements which the great majority of petroleum products must meet:

(a) The boiling range, or the distillation temperature, controls the volatility of fuels and solvents to ensure their satisfactory performance. It also determines the temperature at which the product can be handled;

The following table indicates the boiling range of selected products:

Product	Boiling range (0°C)
LPG	-44 to +2.0
Aviation gasoline	32 to 150
Motor gasoline	32 to 210
Jet fuel	38 to 286
Naphtha	150 to 204
Kerosene	176 to 286
Gas oil	204 to 400
Residual fuel oil	400+

The boiling range of most products overlaps:

(b) The viscosity, which indicates the ability of lubrication for heavy oil fraction, is the only requirement for heavy oil fraction since boiling ranges cannot be specified for such heavy fraction because they cannot be distilled at atmospheric pressure without decomposing.

The following general types of processes are fairly well defined:

Topping or skimming processing: By simple atmospheric-pressure distillation, the crude is separated into gasoline, kerosene, fuel oil or reduced crude oil and sometimes reformer charge stock, jet fuel or gas oil. Topping in some form must be found in all types of refineries [fig 10(a)].

Cracking processing: This type usually refers to a combined operation of topping and cracking where the gas oil is catalytically cracked, resulting in a smaller yield of residual fuel oil and a higher yield of gasoline and lighter, more valuable products [figure 10 (b)].

[2/] Petroleum Processing Handbook, W.L. Nelson, Petroleum Refinery Engineering.

Figure 7. Relationship between finished, intermediate, and raw products

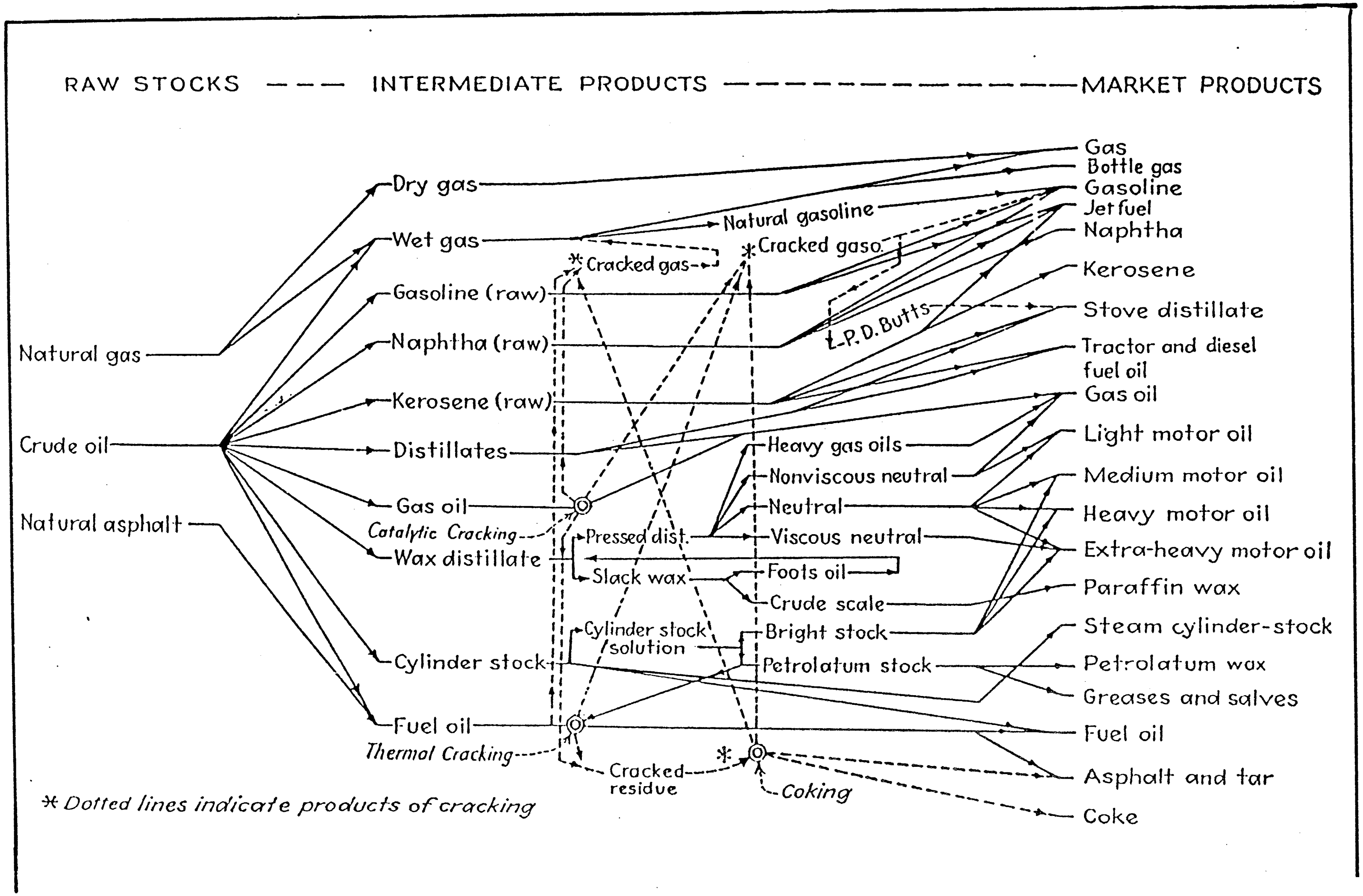


Figure 8. Check-list of commercial petroleum products

THEIR SOURCE AND END USES

From Natural Gas

LP-Gas
Dom. and ind. fuels, motor fuel, gas enrichment, solvent, treating and varied ind. uses

Propane
Component of LP-Gas, raw material for petrochemicals

Butane
Component of LP-Gas and of motor and aviation gasoline, raw material for petrochemicals

Ammonia
(by syn. from methane)
Fertilizer, petrochemical mfg.

Carbon Black
Rubber reinforcing agent, ink mfg., carbon paper, battery cells

Lamp Black
Tinting paints and lacquers

Ethane and Other Raw Materials for Petrochemical Mfg.

Sulfur
(from hydrogen sulfide)

Natural Gasoline
Component of motor and aviation gasoline, special solvents, refinery processing material

From Refinery Gases

Noncondensable Gases

Hydrogen
(from cat. reforming)
Chemical and ind. processing

Ammonia
(from hydrogen)

Carbon Black

Sulfur
(from hydrogen sulfide)

Liquefied Gases

Refinery LP-Gas

Motor Fuels

Processed Derivatives
Olefins, Diolefins

Butadiene
Syn. rubber, petrochemical and plastics mfg.

Ethylene
Polyethylene mfg., raw materials for petrochem. mfg. and alcohols

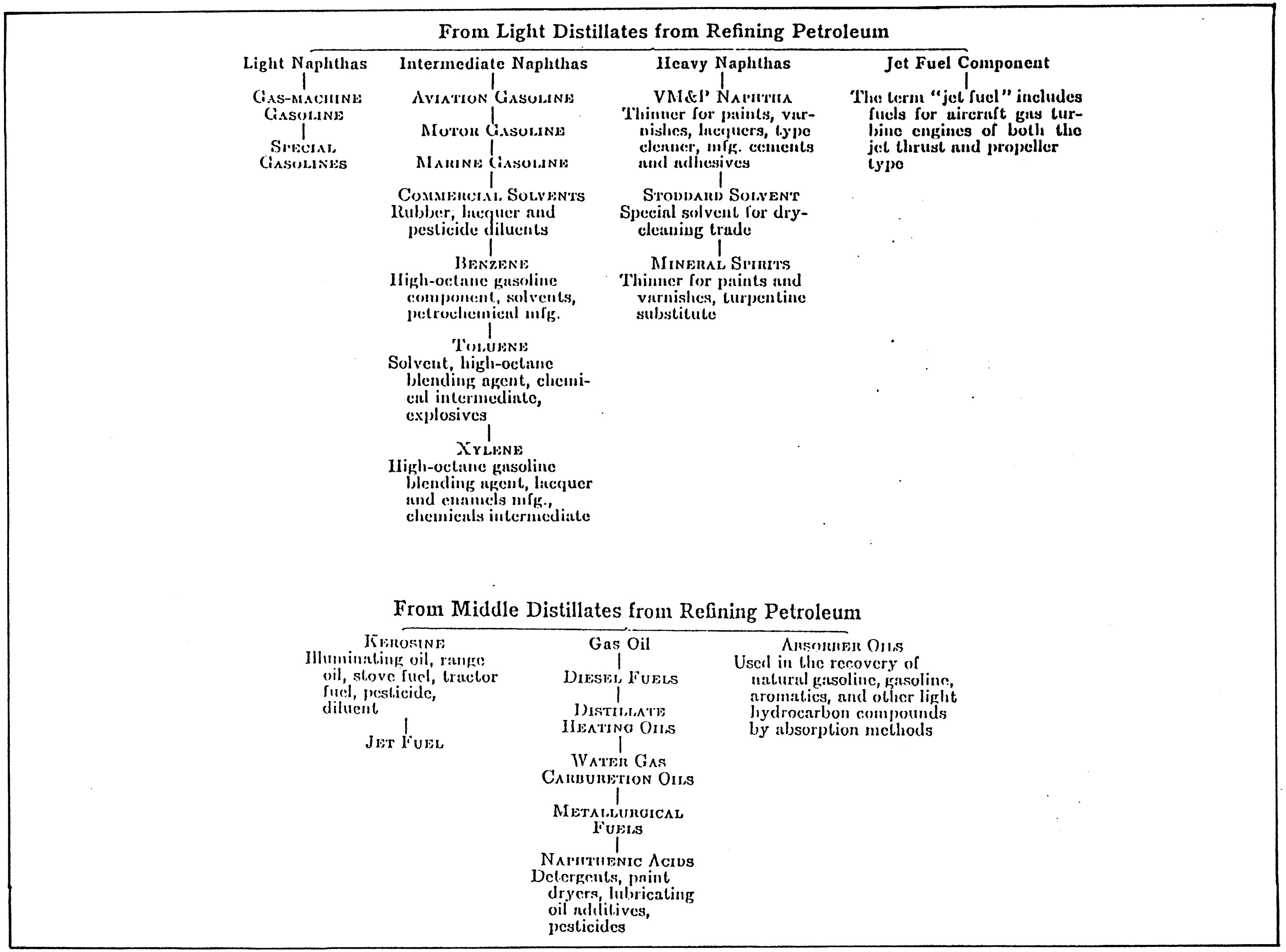
Polymers
Lube oil additives

Antiknock Agents
Aviation gasoline blending

Alcohols, Esters
Ketones, Resins
Antifreeze agents, drug and lacquer solvents

Syn. Plastic Waxes
Inks and paints

Figure 8. (continued)



From Light Distillates from Refining Petroleum

- Light Naphthas
  - Gas-machine Gasoline
  - Special Gasolines
- Intermediate Naphthas
  - Aviation Gasoline
  - Motor Gasoline
  - Marine Gasoline
  - Commercial Solvents: Rubber, lacquer and pesticide diluents
  - Benzene: High-octane gasoline component, solvents, petrochemical mfg.
  - Toluene: Solvent, high-octane blending agent, chemical intermediate, explosives
  - Xylene: High-octane gasoline blending agent, lacquer and enamels mfg., chemicals intermediate
- Heavy Naphthas
  - VM&P Naphtha: Thinner for paints, varnishes, lacquers, type cleaner, mfg. cements and adhesives
  - Stoddard Solvent: Special solvent for dry-cleaning trade
  - Mineral Spirits: Thinner for paints and varnishes, turpentine substitute
- Jet Fuel Component
  - The term "jet fuel" includes fuels for aircraft gas turbine engines of both the jet thrust and propeller type

From Middle Distillates from Refining Petroleum

- Kerosine: Illuminating oil, range oil, stove fuel, tractor fuel, pesticide, diluent
  - Jet Fuel
- Gas Oil
  - Diesel Fuels
  - Distillate Heating Oils
  - Water Gas Carburetion Oils
  - Metallurgical Fuels
  - Naphthenic Acids: Detergents, paint dryers, lubricating oil additives, pesticides
- Absorber Oils: Used in the recovery of natural gasoline, gasoline, aromatics, and other light hydrocarbon compounds by absorption methods

Figure 8. (continued)

From Distillate Lubricating Oil Stocks

- White Oils (technical)
  - Insecticide and Spray Oil Diluent
  - Bakers, Fruit Packers, Candy Makers, Egg Packers, Slab Oils
  - Hydraulic Oils
  - Recoil Oils
  - White Oils (medicinal)
  - Internal Lubricants
  - Salves, Greases, Ointments, Cosmetics
- Saturating Oils, Emulsifying, Flotation Oils
  - Paper, Leather, Wool, Twine Oils
  - Coal Spray Oils
  - Dust-laying Oils
  - Textile Oils
  - Metal Recovery, Quenching Oils
- Petroleum Wax (Paraffin and microcrystalline)
  - Paper manufacturing, sanitary containers, waxed wrappers, candle making, match making, drugs, cosmetics, canning, sealing wax, insulation and coatings, candy, chewing-gum manufacture
  - Fatty Acids
    Lubricating oil pour point depressors, grease and soap lubricant
  - Fatty Alcohols and Sulphates
    Rubber compounds, detergents, wetting agents
- Light Lube Oils
  - Turbine Oils
  - Light Spindle Oils
  - Transformer Oils
  - Household Lubricants
  - Compressor Oils
  - Ice Machine Oils
  - Meter, Dust-laying, Tempering Oils
- Medium Lube Oils
  - Motor Oils
  - Aircraft Oils
  - Diesel Oils
  - Journal Oils
  - Engine Oils
  - Railroad Oils
  - Cutting, Metal Working Oil Base
- Heavy Lube Oils
  - Lubricating Greases
  - Steam Cyl. Oils
  - Valve Oils
  - Transmission Oils
  - Printing Oils
  - Black Oils
  - Tempering Oils

From Lubricating Oil Stocks Bottoms

- Medicinal Petrolatums
  Salves, creams, ointments, petroleum jelly
- Technical Petrolatums
  Rust-preventing compounds, rubber softeners, wire rope lubricants, cable coating compounds

From Residues from Petroleum Distillation

- Residual Fuel Oils
  - Heating Oils
  - Boiler Fuel
  - Bunker C Fuel
  - Wood Preservative
  - Gas-manufacture Oils
- Asphalt
  - Asphalt Cement
    Paving, surfacing, construction materials, base for paints, lacquers, inks, roofing compounds, undercoatings
  - Liquid Asphalt
    Cut-back asphalts, road oils, emulsion bases, saturants, roofing compounds
  - Blown Asphalt
    Waterproofings, rubber substitutes, insulating asphalts, roof coatings
- Petroleum Coke
  - Raw Coke
    Ind. and dom. fuel, calcium carbide manufacture, foundry and blast furnace coke
  - Calcined Coke
    Aluminum anodes, furnace electrodes and linings, graphite specialties
- Refinery Sludges
  - Sulfonic Acid
    Saponification agents, emulsifiers, demulsifying agents, special oils

Lubricating oil processing: Topping with the manufacture of lubricants from the residue of the crude oil is implied by this classification [figure 10 (c) and figure 11].

Complete processing: Most large-type refineries, or what are termed complex refineries, practice topping, viscosity breaking (thermal cracking), catalytic cracking, catalytic reforming and other conversion operations in addition to lubricant production and sometimes petrochemical production. This is enormously complicated; complete processing cannot be shown on a single diagram.

D. Crude distillation units[3]

The function of the crude distillation units is to separate the crude oil into light fractions and residue (reduced crude). This process is called fractional distillation. Crude is heated first by heat exchangers with hot streams of products and finally by a fired heater. Hot crude now partially vaporized enters the main fractionating column at the flash zone. The vapour, containing lighter hydrocarbons, rises towards the top of the column. Liquid flows down to the bottom of the column. The fractionating column contains a series of trays with which the rising vapour is brought into ultimate contact, with the liquid flowing downwards. Vapour rising from the flash zone is cooled by the liquid flowing down the column, so that fractions are condensed to form the light products of the process. To bring about condensation, heat must be removed from the rising vapour. Heat removed is carried out continually by pump recirculation where liquid is withdrawn from the column and pumped back to it after being cooled by heat exchange with the crude feed stream. Vapour flowing from the top of the column is condensed in an external condenser. Part of the condensate liquid is the naphtha fraction while the remainder is returned to the top of the column as a reflex.

Other liquid fractions formed by successive condensation in the main column from the top downwards and withdrawn at usually three points are kerosene, light gas oil and heavy gas oil. Steam is used to strip light hydrocarbons from the side streams.

The liquid product from the bottom of the column is reduced crude, which could be used for fuel oil blending or as a feed for the vacuum distillation process.

Figures 12 and 13 show a typical unit, where oil is pumped continuously through the heat exchange system where it picks up heat from the hot streams leaving the column. It enters the fired heater at 355^{o}F (179^{o}C) and leaves the heater at 601^{o}F (316^{o}C). It goes into the vaporization section of the fractionation column at about 576^{o}F (302^{o}C). At this point, the temperature must be sufficiently high to cause vaporization of all the products above the vaporizer section. This temperature is selected, as mentioned earlier, from vaporization curves of the crude and should take care of 60% of the vaporization process. However, this temperature may be a little

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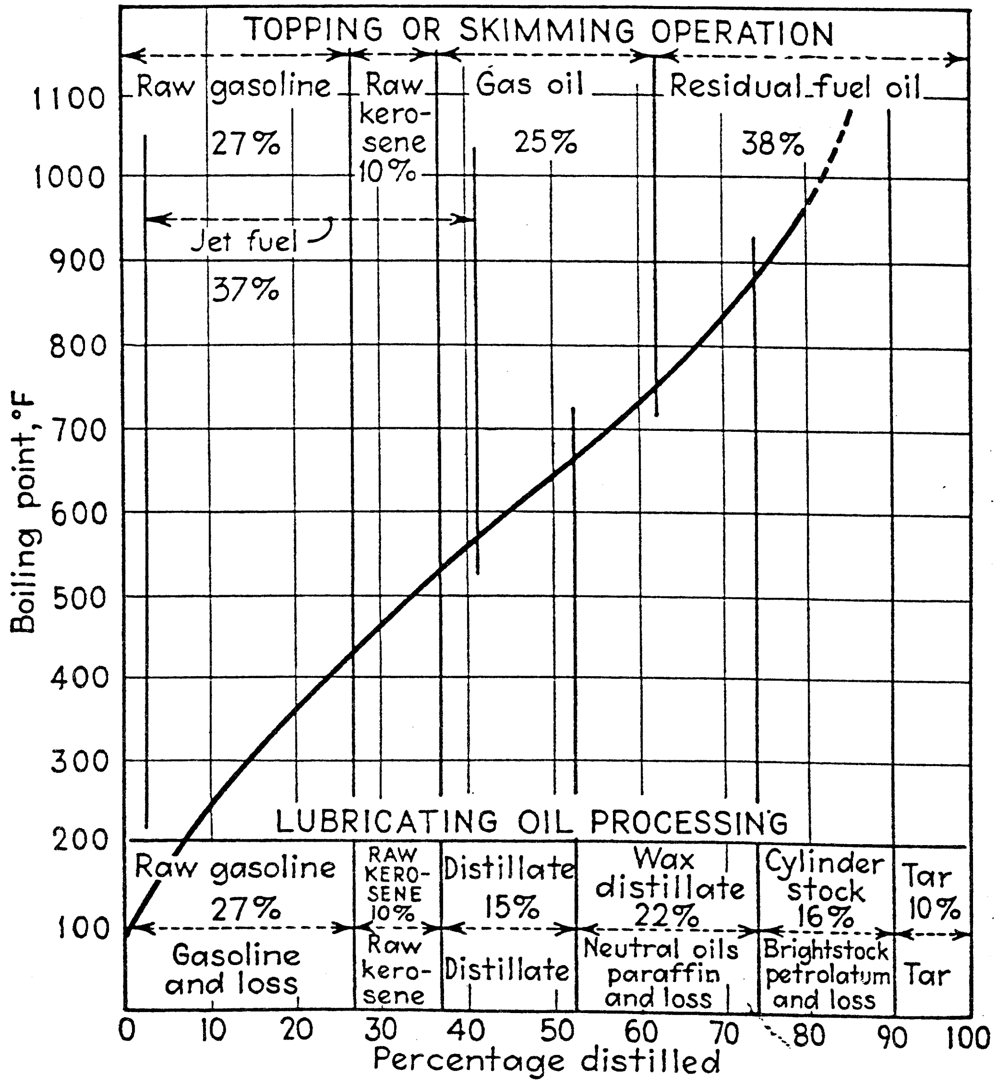
[3] W.L. Nelson, Petroleum Refinery Engineering.

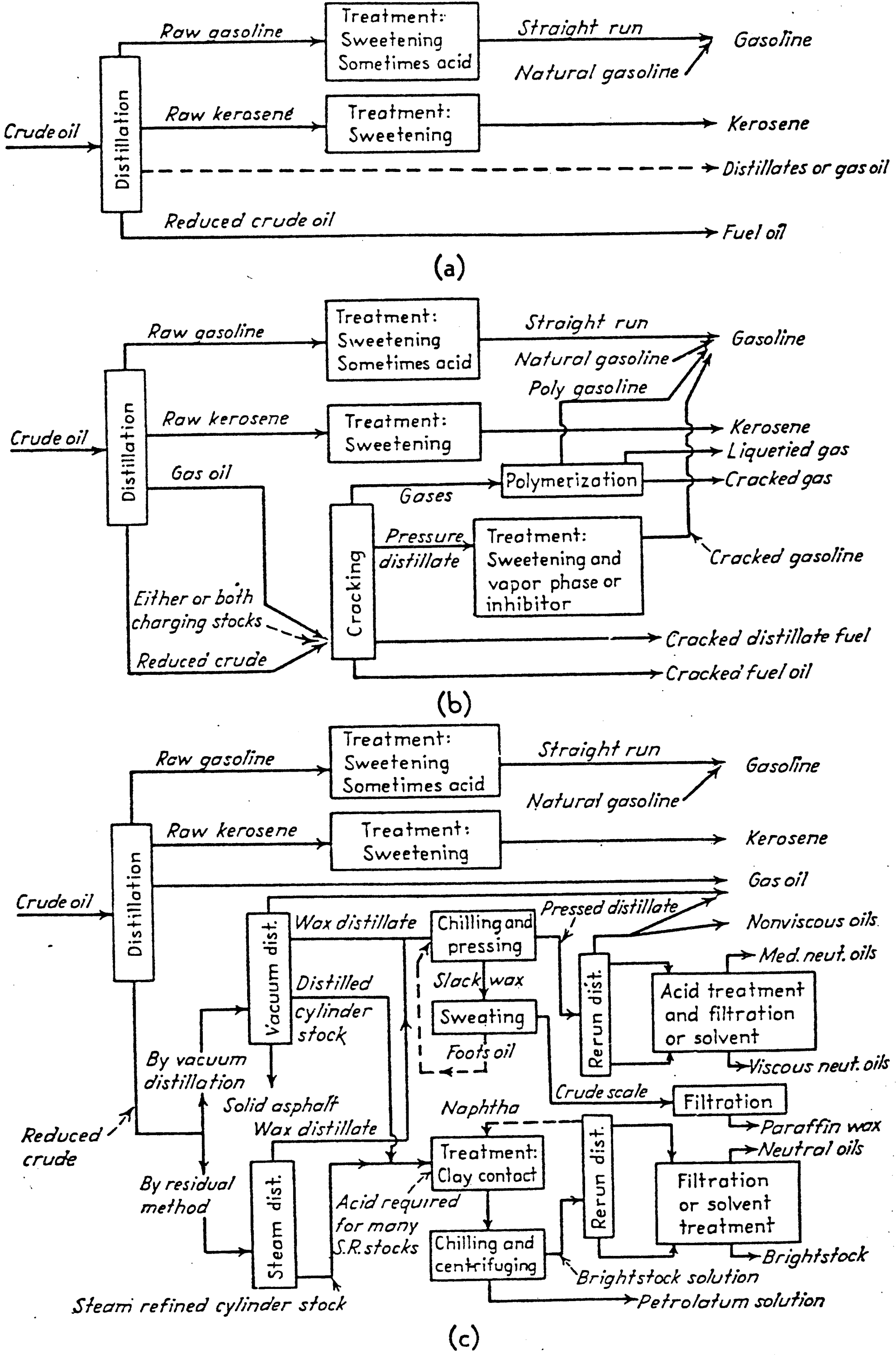
higher, so that about 20% of the bottom stock is also vaporized. The purpose of additional vaporization is to provide better fractionation on the plates that are situated just above the vaporizer. Without excess vaporization, very little reflex will exist at these plates and no reflex will flow from the plate above the vaporizer into the vaporizer section. Reflex is circulated through the top of the column. The hot reflex material is drawn from top of the tower, cooled by heat exchangers and returned to the column in order to cool and condense the vapours that are arising from the vaporizer.

Figure 9. <u>Boiling range of refinery products</u>
(31.7 API Texas mixed-base crude oil)



Source: American Petroleum Institute.

Figure 10. Types of refinery processing



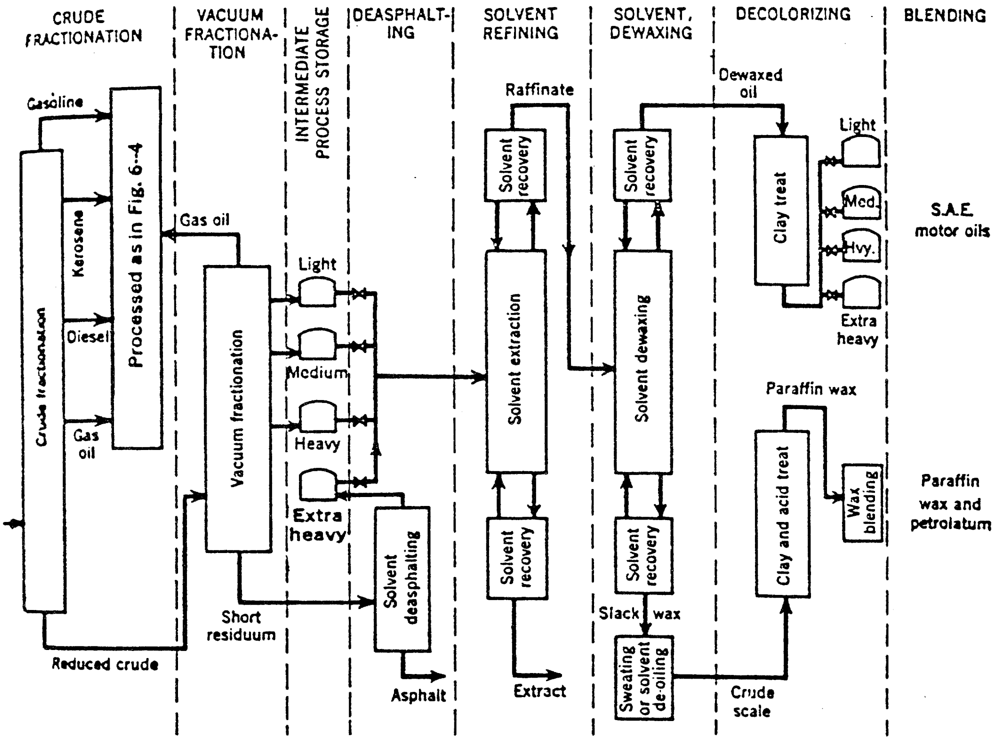
Source: Petroleum Processing Handbook.

(a) Topping or skimming processing (catalytic reforming now also widely used);

(b) Cracking processing (vacuum distillation and catalytic cracking now widely used);

(c) Lubricating-oil processing (solvent treating and dewaxing now used).

Figure 11. Schematic diagram of a refinery for producing lubricating oils



Source: Petroleum Processing Handbook.

The plates above the vaporizer section are called rectifying plates while the plates below are called stripping plates, since steam is admitted below or on the bottom tray, and the low boiling materials in the vaporizer residue are removed so that high-flash point bottom products are produced.

Figure 13 shows a limited production of four products; however, as many as eight products have been withdrawn from one column. Figures 14 and 15 show different refinery configurations.

E. Fluid catalytic cracking units (FCCU)

In modern refineries, these units constitute the major units for conversion of heavy fuel into motor gasoline. There are many types of feed for an FCCU, but in most refineries, the feed is the heavy distillates, especially the vacuum gas oil (VGO) leaving the vacuum distillation units. The most valuable product of the FCCU is high octane gasoline, which has good blending characteristics with other gasoline components.

Figure 41 shows a typical FCCU, although there are many variations of the process. Raw feed is preheated by heat exchange with hot process streams before being introduced at the bottom of the reactor riser. It meets the catalyst, which has left the generator section of the process at about 650°C. The feed vaporizes upon contact with the hot catalyst and the cracking reaction starts in the riser. The mixture of vaporized hydrocarbons and the catalyst flow up the riser into the reactor where the reaction is completed. The coke produced by the reaction is deposited on the catalyst and removed by it.

The products of reaction, other than coke, leave the reactor as vaporized mixture which then flows through a cyclone to remove entrained catalyst. The heavier constituents are then condensed by reflex streams cooled by heat exchanges with raw feed.

The valuable liquefiable products such as LPG and gasoline are removed in the gas concentration section of the process as established gasoline and LPG while a part of the bottom product is taken as part of the gas oil blending stream and the remainder is recycled.

What is of interest to the present discussion is, of course, the large amount of heat contained in the hot flue gases (550-650°) from the regeneration operations. The sensible heat available contains a large amount of combustible CO (carbon monoxide gas). The usual utilization of such heat is through the installation of CO-boilers as described in chapter IV, part G of this report and in the <u>Petroleum Processing Handbook</u>.

Figure 12. <u>Simplified diagram of the distillation of crude oil in a petroleum refinery</u> (Esso Standard Oil Co.)

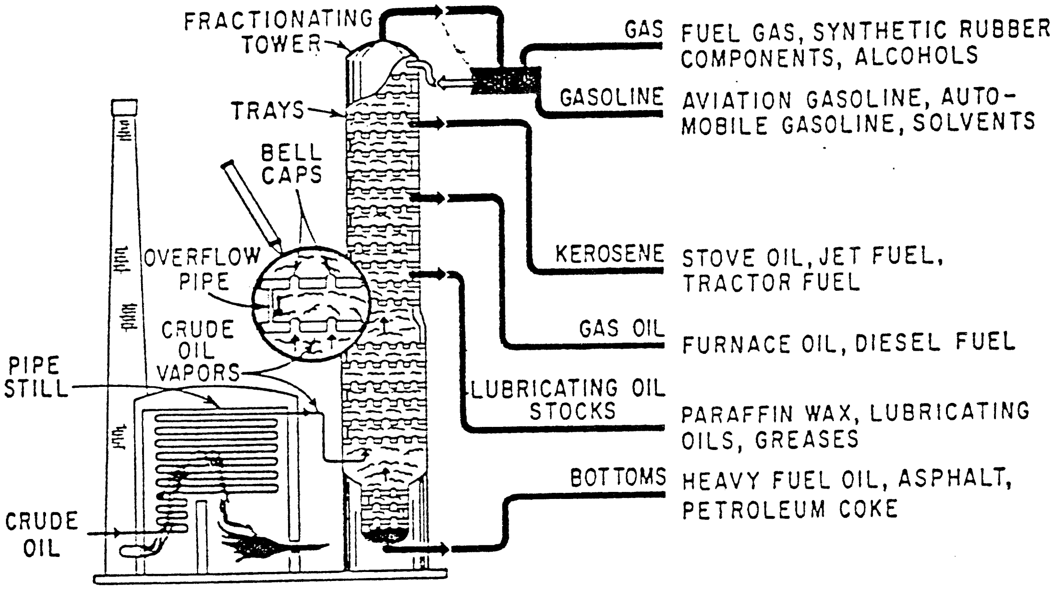
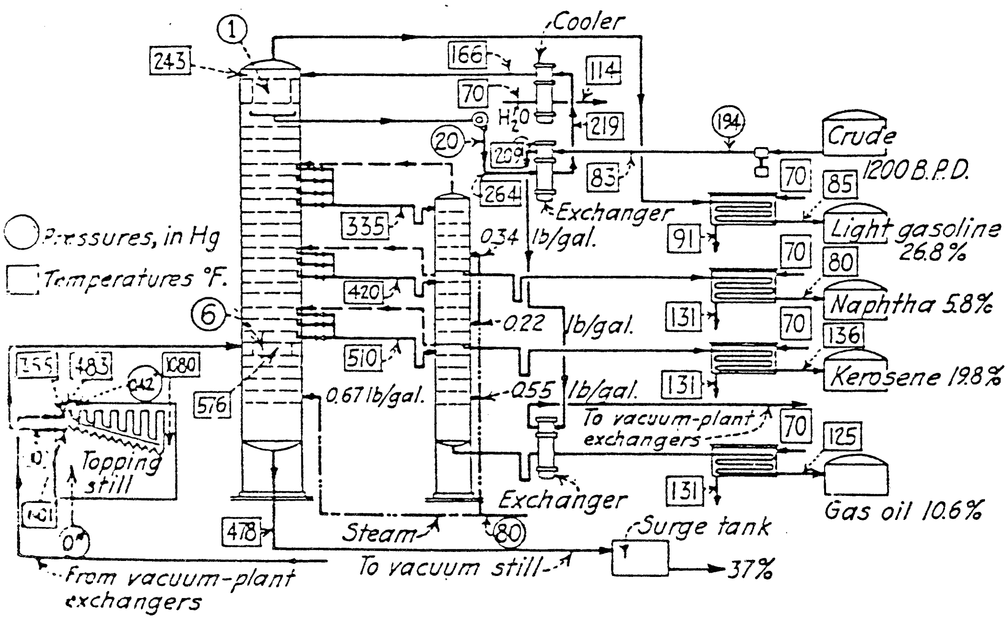
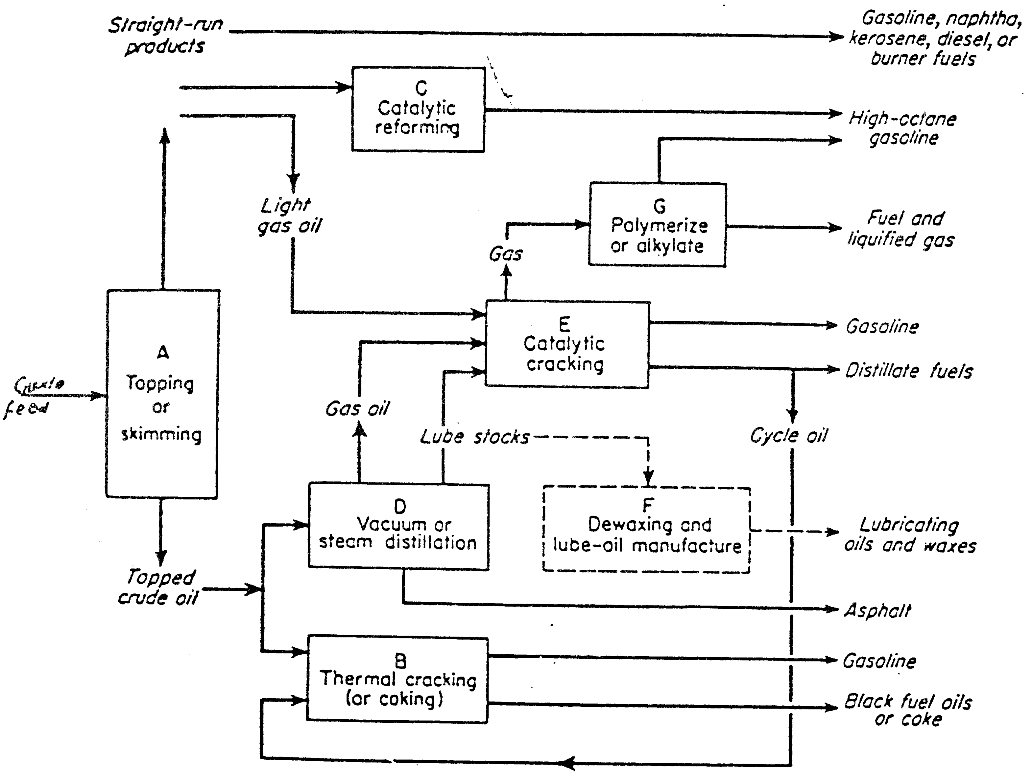


Figure 13. Continuous pipestill topping plant



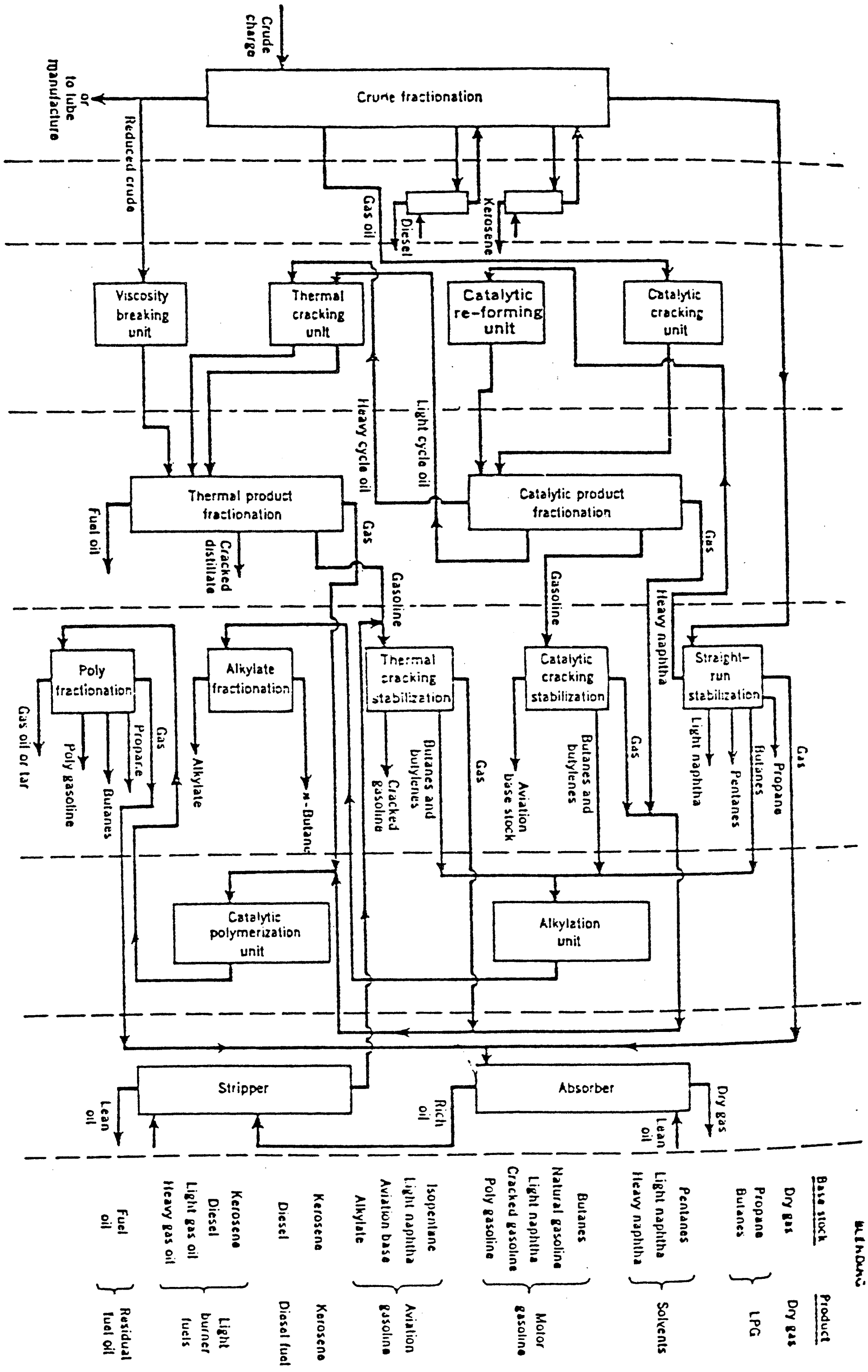
Source: W.L. Nelson, Petroleum Refinery Engineering.

Figure 14. Basic refinery operations of topping, vacuum distillation, thermal cracking, catalytic reforming and catalytic cracking



Source: W.L. Nelson, Petroleum Refinery Engineering.

Figure 15. Schematic diagram of a refinery for light oils (mainly gasolines, kerosene, and distillates)



Source: W.L. Nelson, Petroleum Refinery Engineering.

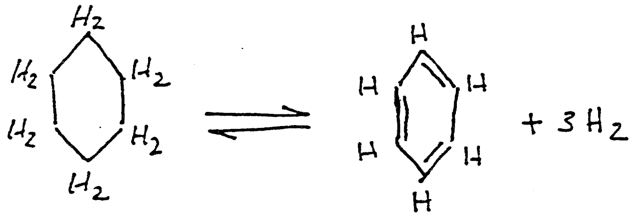
F. Catalytic reforming

Catalytic reforming is a continuous process to upgrade all types of low-octane naphtha into high-octane (reformate) components for motor fuel blending or petrochemical use. The octane number of naphtha varies between 40-60 RON while the reformate yield of the process has an octane number of 92-93 RON depending on the type of reforming process and the fuel.[4]

Basically, catalytic reforming is the rearrangement of molecules in the naphtha (gasoline) boiling range fractions into products of higher anti-knock quality, i.e. octane number.

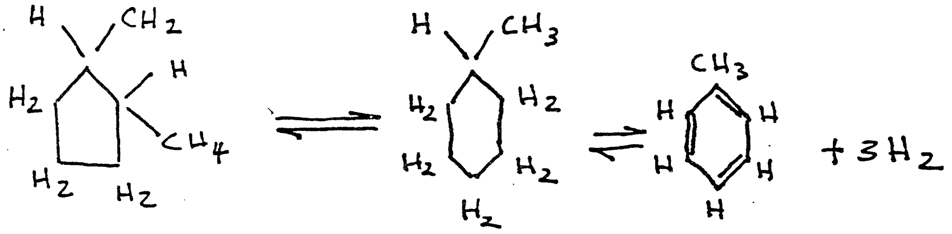
The main reactions of the process are:[5]

1. Naphthene dehydrogenation: e.g., of cycloparaffins to aromatics:



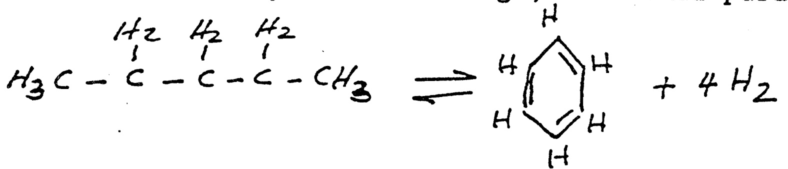
Cyclohexane Benzene Hydrogen

2. Naphthene dehydroisomerization: e.g., of paraffins to cycloparaffins (naphthenes) and to aromatics:



1,2-Dimethylcyclopentane Methylcyclohexane Toluene Hydrogen

3. Paraffin dehydrocyclization: e.g., of normal paraffins into aromatics:



n-Hexane Benzene

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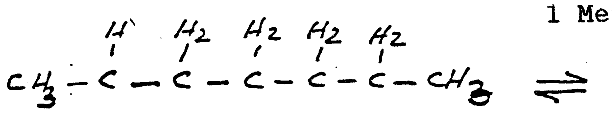
[4] Petroleum Processing Handbook, section 5.

[5] Nelson, op. cit.

4. Paraffin isomerization: e.g., of normal paraffins to their isomers:

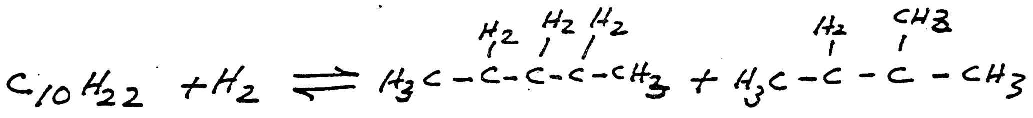


$CH_3-\overset{H}{C}-\overset{H_2}{C}-\overset{H_2}{C}-\overset{H_2}{C}-\overset{H_2}{C}-CH_3 \rightleftharpoons$

1 Methylhexane, etc., isomers

n-Pentane

5. Paraffin hydrocracking: of high carbon paraffin into lower-value carbon normal and isoparaffins:



$C_{10}H_{22} + H_2 \rightleftharpoons H_3C-\overset{H_2}{C}-\overset{H_2}{C}-\overset{H_2}{C}-CH_3 + H_3C-\overset{H_2}{C}-\overset{CH_3}{C}-CH_3$

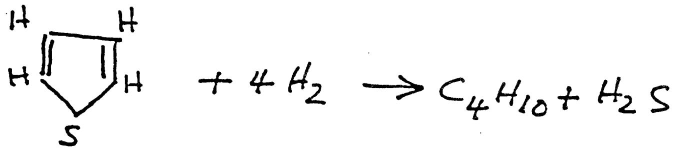
n-Decane n-Pentane Isopentane

6. Olefin hydrogenation: of olefin into paraffins:

$C_5H_{10} + H_2 \rightleftharpoons C_5H_2$

Pentene Pentane

7. Hydrodesulphurization of sulphur compounds into paraffins and H_2S:



Thiophene Butanes

It would be noticed that the first five reactions are the desirable ones (dehydrogenation and isomerization) since they are the ones that produce high-octane products as well as valuable hydrogen gas. While the hydrocracking operations (numbers 6 and 7) produce normal paraffins (low octane) and they use valuable hydrogen. To suppress the hydrocracking reforming processes are usually carried out at mild conditions of temperature and pressure.

A typical platforming process is shown in figure 16. However, the inclusion of waste-heat boiler is not indicated.

G. Other processes[6]

Table 3 shows a summary of major processes in refineries that consume energy, which are not discussed in this section.

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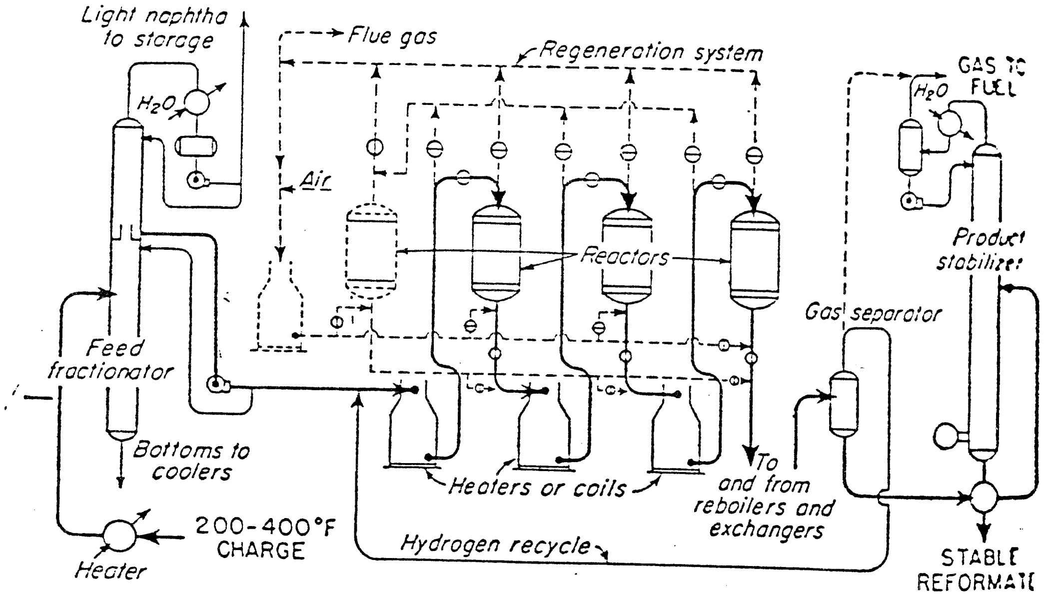
[6] Nelson, op. cit.

Figure 16. Platinum catalyst reforming processes (regenerative and nonregenerative)



Source: W.L. Nelson, Petroleum Refinery Engineering.

Table 3. Summary of modern refining processes

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)		(10)
Molecular change	Kind of physical or chemical change	Energizer, catalytic or thermal	Commercial name of process	Common feedstock	General purpose	Main product	Illustrative reaction	Operating conditions[a]		Catalyst
								Psig	Temp. °F	
Disintegration (breaking into parts)	Desulfurization and hydrogenation	Catalyst	Catalytic desulfurization	Distillates	Remove sulfur	Distillate	$R(SH) = R + H_2S$	300-700	700-750	Cobalt molybdenum
		Catalyst	Catalytic desulfurization	Gasoline	Remove sulfur	Gasoline	$R(SH) = R + H_2S$	40-70	700-800	Bauxite or clay
	Dehydrogenation	Catalyst	(No common name)	Butane	Make olefin	Butene or butadiene	$C_4H_{10} = C_4H_8 + H_2 = C_4H_6 + 2H_2$	Low	850-1150	Chromic oxide on bauxite
	Decomposition	Thermal	Viscosity breaking	Residua	Reduce viscosity and produce gas oil	Fuel oil	$C_nH_{2n+2} = C_{n/2}H_{n+2} + C_{n/2}H_n$	230-250[b]	860-890	
Several (both disintegration and synthesis)	Decomposition and adsorption (catalytic cracking or reforming)	Catalyst	Houdry catalytic cracking	Gas oil	High octane number	Catalytic gasoline		20-50	800-860	Natural clays, aluminum hydrosilicates, bauxite, etc.
		Catalyst	Fluid catalytic cracking	Gas oil	High octane number	Catalytic gasoline		2-15	860-950	
		Catalyst	Thermofor catalytic cracking	Gas oil	High octane number	Catalytic gasoline		10-15	750-900	
		Catalyst	Cycloversion	Gas oil	High octane number	Catalytic gasoline		50-100	900-1100	
	Decomposition and polymerization (cracking)	Thermal	Thermal cracking	Topped crude oil and gas oil	Make gasoline	Cracked gasoline		300-700[b]	850-950	
		Thermal	Reforming	Heavy gasoline or distillate	Make gasoline	Cracked gasoline		400-800[b]	960-1020	
		Thermal	Coking	Topped crude or fuel oil	Eliminate fuel oil	Cracked gasoline		300-500[b]	890-960	
	Decomposition, polymerization, and alkylation	Thermal	Polyforming	Naphtha and refinery gas	Increase gasoline yield	Gasoline		1,000-2,000[b]	1020-1120	
	Dehydrogenation, hydrogenation, and isomerization	Catalyst	Hydroforming	Naphtha	Aromatics	Solvents		100-300	890-1020	Molybdia
		Catalyst	Catalytic reforming	Naphtha	Aromatics	Gasoline		200-750	850-970	Platinum
	Decomposition and hydrogenation	Catalyst	Destructive hydrogenation	Many stocks	Paraffinic stocks	Many	$C_nH_{2n+2} + H_2 = 2C_{n/2}H_{n+2}$, etc.	3,000	800-950	Molybdic trioxide
	Decomposition, hydrogenation, and desulfurization	Catalyst	Hydrodesulfurization	Residua	Produce gas oil	Gas oil		700-1,000	750-800	Cobalt molybdenum
	Dehydrogenation and rearrangement	Catalyst	(No common name)	Heptane and methyl cyclohexane	Aromatic hydrocarbons	Toluene	$C_7H_{16} = C_7H_8 + 4H_2$	Low	1020	Chromic, molybdic, etc., oxides
	Polymerization and decomposition	Thermal	Thermal polymerization	Cracking-still gases	Recover gases	Poly gasoline	$C_3H_6 + iC_4H_8 = C_7H_{14}$	1,500-2,000	900-1025	
Synthesis (uniting)	Alkylation	Catalyst	HF alkylation	Iso and normal butane	High-octane gasoline	Alkylate	$iC_4H_{10} + iC_4H_8 = C_8H_{18}$	100-150	70-115	Hydrofluoric acid
		Catalyst	Sulfuric acid alkylation	Iso and normal butane	High-octane gasoline	Alkylate	$iC_4H_{10} + iC_4H_8 = C_8H_{18}$		30-90	Sulfuric acid
		Catalyst	(No common name)	Propane and benzene	High-octane gasoline	Cumene	$C_6H_6 + C_3H_6 = C_9H_{12}$	100-600	350-550	Phosphoric acid
		Catalyst	(No common name)	Ethene and benzene	Needed for styrene and synthetic rubber	Ethyl benzene	$C_6H_6 + C_2H_4 = C_8H_{10}$	15	150-210	Aluminum chloride
		Thermal	Thermal alkylation	Ethene or propene and isobutane	Recover gases	Neohexane	$C_2H_4 + iC_4H_{10} = C_6H_{14}$	3,000-8,000	900-1000	
	Hydrogenation	Catalyst	(No common name)	Codimer (trimethylpentene)	High-octane blending stock	Isooctane	$C_8H_{16} + H_2 = C_8H_{18}$	15-60	320-400	Nickel
	Polymerization	Catalyst	Phosphoric acid polymerization	Cracking-still gases	Recover gases	Poly gasoline	$2.3(C_nH_{2n}) = C_{2\text{-}3n}H_{4\text{-}6n}$	300-600	300-450	Phosphoric acid
		Catalyst	Sulfuric acid polymerization	Cracking-still gases	Recover gases	Poly gasoline	$x(C_nH_{2n}) = C_{xn}H_{2xn}$		70-190	Sulfuric acid
		Catalyst	(No common name)	Isobutene	Intermediate stock for isooctane	Codimer	$2iC_4H_8 = C_8H_{16}$	350-650	350-500	Phosphoric acid
Rearrangement (of mole structure)	Isomerization	Catalyst	Isomate	Naphtha, pentane, or hexane	High-octane gasoline	Isomate gasoline	$nC_6H_{14} = iC_6H_{14}$	120-200	150-220	Aluminum chloride
		Catalyst	Butane isomerization	Butane	Branched-chain hydrocarbons	Isobutane	$nC_4H_{10} = iC_4H_{10}$	200-350	100-210	Aluminum chloride
		Catalyst	(Several names)	Pentane or hexane	High-octane gasoline	Isomate	$nC_5H_{12} = iC_5H_{12}$	High	800-900	Platinum, etc.

[a] In main reaction.

[b] These are back pressures held in pipestill heaters.

Source: W.L. Nelson, Petroleum Refinery Engineering.

IV. MAJOR REFINERY UTILITY UNITS THAT DEAL WITH ENERGY AND CONSERVATION

A. Process heaters (furnaces)

About 70-80% of the energy used in refineries,[1] is for direct-fire heaters or steam. This chapter discusses the subject of process heaters (furnaces).

Heating value of fuels

The amount of heat liberated when a unit quantity of a fuel is burned is called the "heating value" or "heat of combustion" of the fuel. The heat liberated when 1 pound (0.454 kg) of fuel at 60°F (15.6°C) is burned and the products of combustion are cooled to 60°F (15.6°C) is called the "net heating value".

If the products are cooled to 60°F and in addition the water vapour in the flue gas is condensed, the "gross heating value" is obtained. In most industrial processes, the water vapour in the stock or flue gases is not condensed, and hence the most logical basis for judging the thermal efficiencies of heaters is the net heating value (NHV). The NHV can be computed from the gross heating value by subtracting the quality of heat that is required to condense the water vapour in the flue gas.

Most hydrocarbon gases, liquids and solids and other gases (H_2, CO, H_2S) and liquids that can be used as fuels have the heating value calculated or measured. Hence, the heat value of most refinery fuels can be computed. The most used fuel in a refinery is the fuel gas, which is supplemented usually by fuel oil. Figure 17 shows combustion charts which are used to calculate stack temperature and losses through the stack.

B. Types of furnaces

Most modern process heaters are built with two distinct heating sections, a radiant section which can receive heat directly from the flame and a convection section which recovers heat from the hot gases traveling to the stack. Figure 18 shows the different types of furnaces used in the oil industry. A typical modern process heater is shown in Figure 19, where test points and the control system are incorporated.

The most effective energy saver in furnaces is the installation of an air preheater as explained in details in section E below. There are additional means as well to improve the efficiency of furnaces:

(a) The addition of a convection bank tube;

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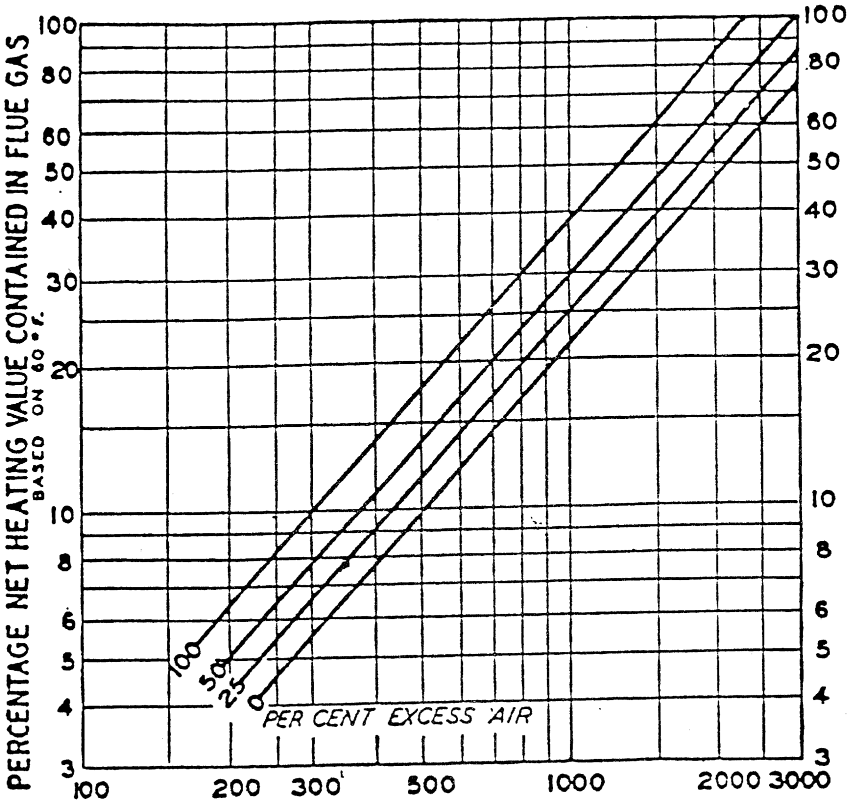
[1] Duckham and Fleming, op. cit.

Figure 17. Fuel-oil combustion and gas combustion charts



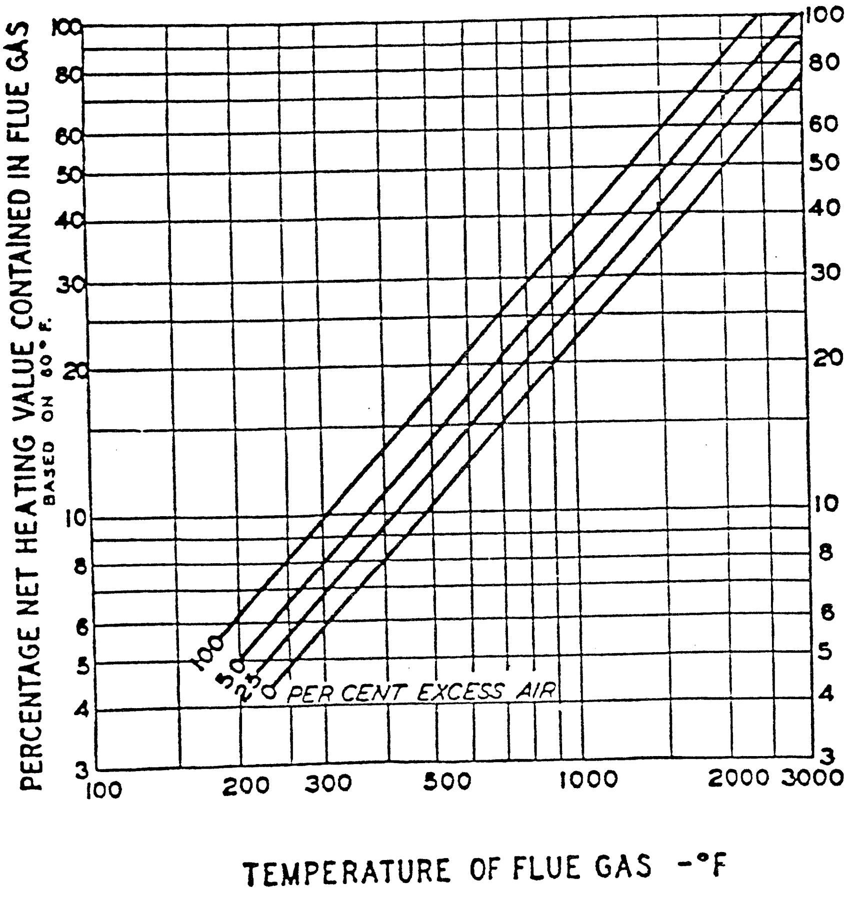
FUEL	NET H.V.	LB.GAS PER LB. FUEL*
25 A.P.I.	18 000	15.6
14 A.P.I.	17 500	16.3
8 A.P.I.	17 200	16.8

ALLOWANCE WAS MADE FOR 0.3 LB. OF ATOMIZING STEAM PER LB. OF OIL.

** AT ZERO PER CENT EXCESS AIR.*

CARBON DIOXIDE AND PER CENT EXCESS AIR FOR 14 A.P.I. FUEL.

PER CENT EXCESS AIR	PER CENT CO_2
0	16.3
15	14.1
25	12.9
50	10.7
100	7.9



FUELS	NET H.V.*	CU.FT. GAS PER CU.FT. FUEL+
WET CR.	1 900	19.4
WET REF.	1 700	17.8
WET NAT.	1 200	12.2
DRY CR.	1 200	12.3
DRY NAT.	1 050	10.9

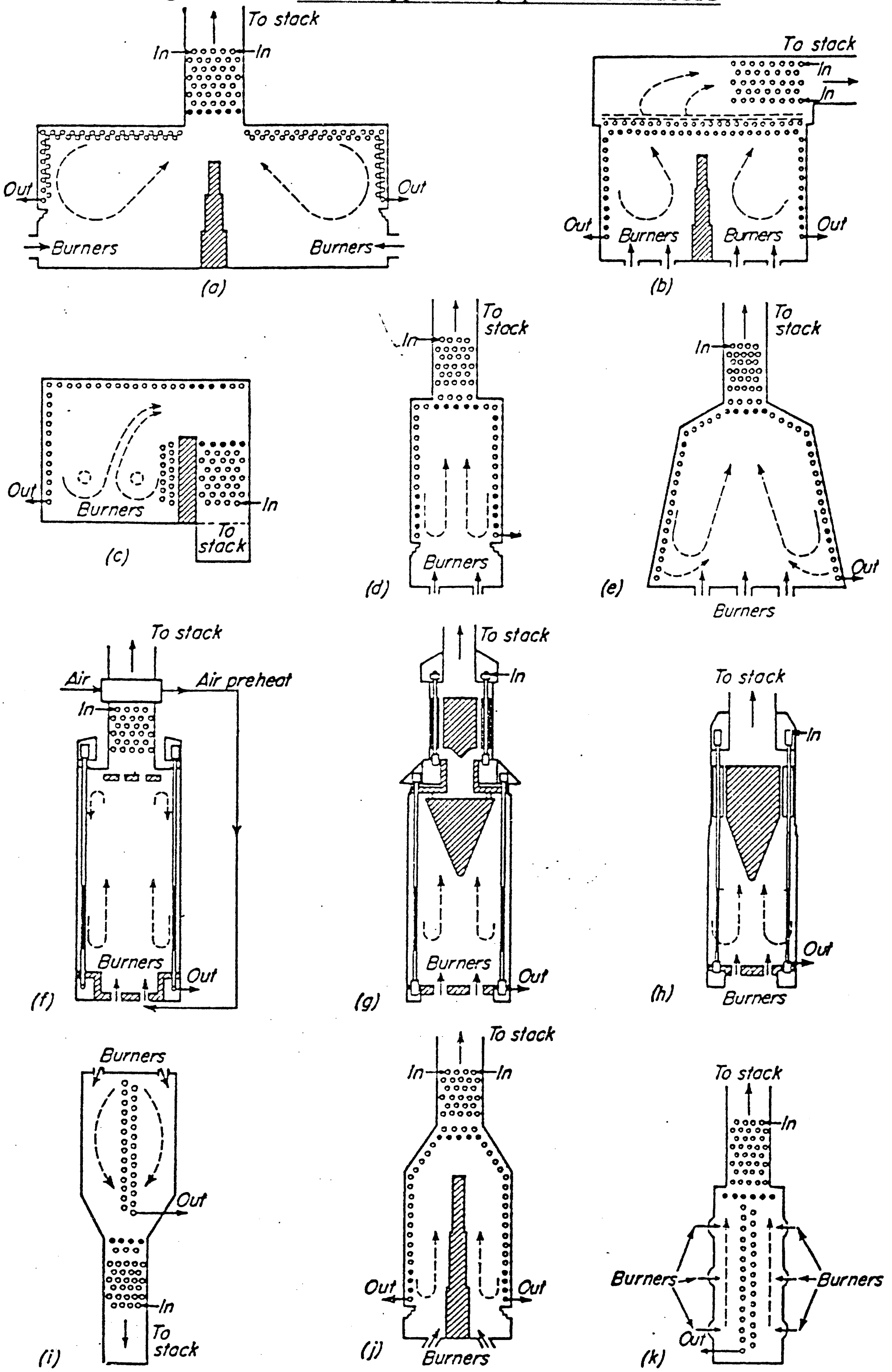
**SHOULD ALLOW FOR SOME AIR AND MOISTURE.*

+ AT ZERO PER CENT EXCESS AIR.

CARBON DIOXIDE AND PER CENT EXCESS AIR.

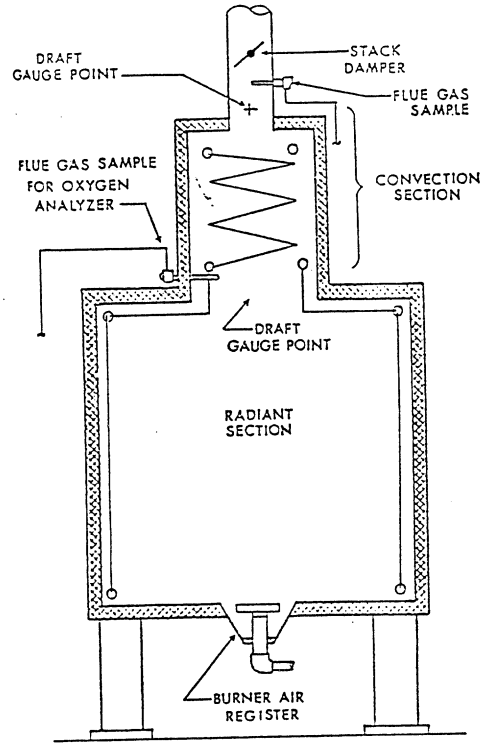
PER CENT EXCESS AIR	PER CENT CO_2 WET	PER CENT CO_2 DRY
0	13.1	12
15	11.4	10
25	10.4	9
50	8.4	7.8
100	6.3	5.7

Figure 18. <u>Basic types of pipestill heaters</u>



<u>Source</u>: H. Duckham and J. Fleming, "Energy conservation in HPI plants", EMH.

Figure 19. Typical process heater--test point and control system



Source: H. Duckham and J. Fleming, "Energy conservation in HPI plants", EMH.

(b) Improvement in the control system of the furnace, including combustion analyses and for measuring and monitoring draft and stack conditions;

(c) The use of soot blowers, fouling inhibitors and materials which reduce the likelihood of fouling.

C. Combustion fundamentals

The first approach to efficient burning of fuels is to understand and appreciate the fundamentals of combustion. There are many misconceptions about this, the most important factor in fuel conservation.

Most fuels are hydrocarbons (see chapter 3, section 1). Each compound in any of the series has a characteristic molecular weight and hydrogen-to-carbon ratio. Fuels from the same series present greater difficulty in blue-flame burning as the molecular weight increases. Compounds having a weight ratio below 0.14 are very difficult to burn with a blue flame.2/

Blue-flame burning is preferred in process firing because it creates the most rapid combustion. Flame colour varies because combustion reactions cause ionization in the flame body, and the ionized material imparts its characteristic colour.

2/ R. Reed, "Save energy at your heater", Energy Management Handbook.

Air quantity has no effect on flame colour. Fuel-air mixtures for a particular fuel determine a flame colour of blue, yellow-blue or yellow. However, a yellow flame does not indicate inefficient burning. Oil can be burned very efficiently with a brilliant, yellow-white flame.

Excess air is an important factor in efficient combustion. All fuels need oxygen for their burning, and oxygen is obtained from air. However, more air (excess) is required for the chemical reaction of burning, since such reactions need an excess of reactant (usually air) for rapid completion and speed is required for burning.

The problem that arises here is how much "excess air" is required and how to monitor such excess air. Normally this excess is on the order of 20%. Any amount of excess air significantly above or below this figure will result in energy loss.

D. Flue gas waste-heat recovery[3]

As indicated previously, the flue gas leaving refinery heaters through the stack contains substantial heat energy. In older refineries, the energy released in the fired heaters can account for 7.5% of refinery throughput; only part of this energy is utilized usefully, the rest being lost through the heater stack. This figure can be reduced by 1-2% by minimizing energy losses from flue gases alone.

The energy available in flue gases is a function of the mass flow of the products of combustion and their available temperature above ambient conditions. This is illustrated in figures 20-23, which show the relationship between energy loss in the stack, stack temperature and percentage of excess air.

There are many ways of recovering this energy:

(a) For heating raw materials and feedstocks;
(b) For steam and power generation;
(c) For preheating combustion air;
(d) For fuel heating.

E. Types of air preheaters[4]

The main types of air preheaters which are incorporated with large heaters are the hot oil belt system, the rotary regenerative system and the static gas-to-gas tubular exchanges. Other types of air preheater systems exist, but they are relevant only to small heaters.

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[3] Aburas, Lloyd and Webster, op. cit.; F. Jones, "Build and run plants to save energy", Energy Management Handbook.

[4] Aburas, Lloyd and Webster, op.cit.

1. Hot oil belt system

In this system, an intermediate heat transfer fluid is used. The hot flue gases pass through an oil coil and by giving up their heat are cooled to the required stack temperature. The heat gained by the oil coil is cooled by preheating the combustion air. The cooled oil is recirculated to be reheated in the flue gas cooler.

The advantages of this system are:

(a) Minimum duct work. Suitable when space is limited;

(b) Flexibility in size and location of the coils. Perhaps possible to eliminate the FD (forced draught) and/or ID (induced draught) fans.

The disadvantages include:

(a) Heat recovery could be limited by the maximum oil temperature;

(b) Safety considerations (hot oil in the combustion air stream);

(c) Return cold oil temperature to the flue gas cooler must be consistent with the flue gas dew-point and sulphur levels of the fuel;

(d) Pumping equipment, control values and so on require maintenance.

The system is ideally suited to the situation where there is a large quantity of heat to be transferred at comparatively low temperatures. The complexity of this scheme, pumps, expansion vessels, etc., is often unjustified for small-size units.

2. Static gas-gas exchangers

These are simple gas-to-gas exchangers. If the walls of the exchangers are above the dew point of the flue gases, then a rugged cast-iron construction can be employed. If there is any prospect of the walls being below the flue gas dew point, then it is possible to use a glass tube for that section of the exchanger.

The advantages of this system include:

(a) No moving parts;
(b) No air-flue gas leakage path;
(c) Dew point problems can be designed out;
(d) Maintenance requirements are minimal.

The disadvantages are:

(a) The units are large, heavy and expensive;

(b) The units require large plot areas;

(c) Performance falls off significantly with fouling; the cleaning process could be difficult.

Figure 20. Effect of excess air and flue gas temperature on energy loss

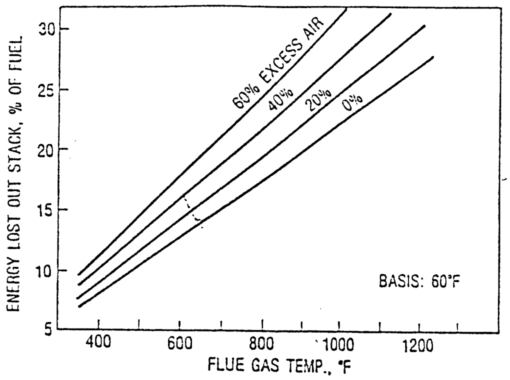
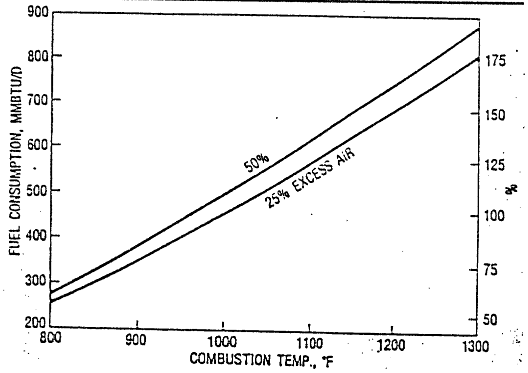


Figure 21. Effect of combustion temperature on fuel consumption for a 300/t/d sulfur plant incinerator



3. Rotary regenerative exchanges

In this system, a rotary metal matrix passes continually through the hot flue gas and cold air streams. The matrix is alternatively heated and cooled by the flue gas and the air.

The advantages of such a system are:

(a) Very compact and low cost;

(b) Dew point corrosion problems can be minimized by enamel or other coating material at the cold end of the metal matrix;

(c) Small mechanical size implies that the replacement of parts are simple;

(d) Fouling on surfaces is comparatively easy to remove by soot blowing.

The disadvantages are:

(a) Mechanical drive is required: typical power requirements are low, 0.5-5.0 kW on refinery-size units with switch gear and maintenance;

(b) Maintenance of seals;

(c) Air-to-flue gas leakages across rotating matrix affects power achieved by fans and final allowable cold end temperature. This is especially true in the smaller units where fixed seals are employed.

Figure 22. Determining excess air

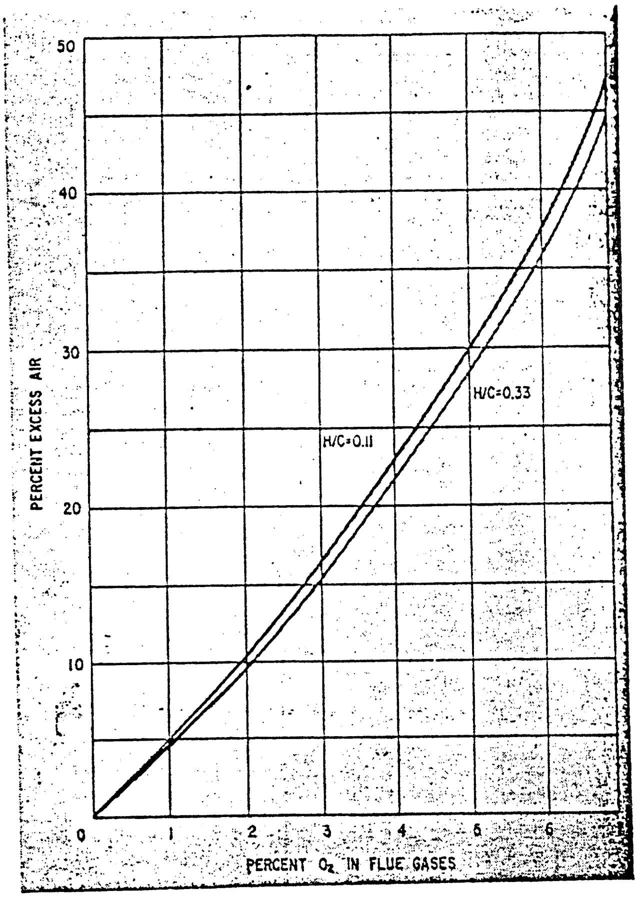
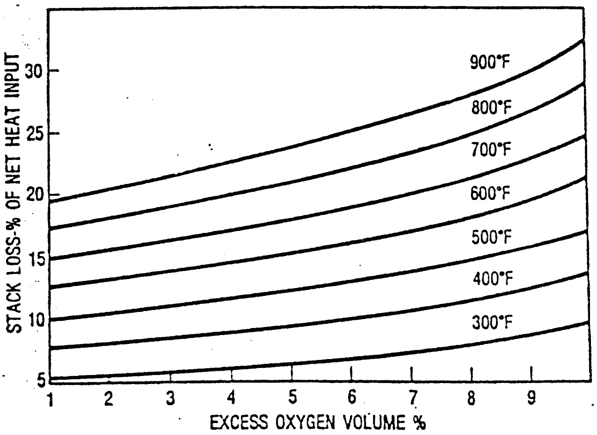


Figure 23. Stack loss vs. excess oxygen and stack temperature



F. Details of rotary, regenerative air preheaters[5/]

Rotary, regenerative air preheaters are the most popular of air-preheater systems and are widely used in refineries for recovering energy from flue gases. It is appropriate therefore to describe in greater detail the concepts and characteristics of rotary, regenerative air preheaters.

1. Layout and operations

A general layout of a rotary, regenerative air preheater is shown in figure 24. This preheater has two major components: a rotor and a housing. The housing separates the air and gas streams and serves as a structural base. The rotor contains the heat transfer plates, and sometimes enamel coating is applied depending on dew point characteristics of the flue gas. The duct connections are arranged to permit counter flow of hot flue gas and cold incoming air. As the rotor absorbs heat while revolving slowly through the flue gas stream, it heats the incoming air on the cold side. Because the heat surface is very compact, many thousands of square feet of heating surface can be contained in a relatively small space. Heat transfer efficiencies of over 75% are obtained.

The system is usually designed with a bypass arrangement for use in case of power failure, at which time the system can revert to natural draft service is so required. The system usually incorporates as well a forced draught (FD) fan and induced draught (ID) fan.

2. Maintenance

The maintenance of the air preheater is minimal. The least cost occurs when natural gas or low-sulphur fuels are burned and when average cold end temperatures are kept at or above recommended levels. Recommended metals and corresponding operating temperatures are shown in figure 25. It has been shown from experience that cold end elements may have to be replaced after four to six years of operation. In general, annual maintenance costs are less that 1% of initial costs.

3. Energy-saving characteristics

(a) Fuel consumption can be reduced in process heaters by up to 25%. About 1% fuel is saved for each 35-40°F reduction in flue gas temperature;

(b) With preheated air, there is less coking of the burner tips, which minimizes the necessity to clean the burners;

(c) With forced draught preheaters, there is more carefully controlled flame patterns;

(d) There is more complete combustion, which results in cleaner furnace side tubes, requiring less soot blowing in the furnace;

[5/] C. L. Brown and D. Figensder, "Preheat process combustion air", Energy Management Handbook, p. 76.

Figure 24. Typical configuration for air preheating applied to process heaters

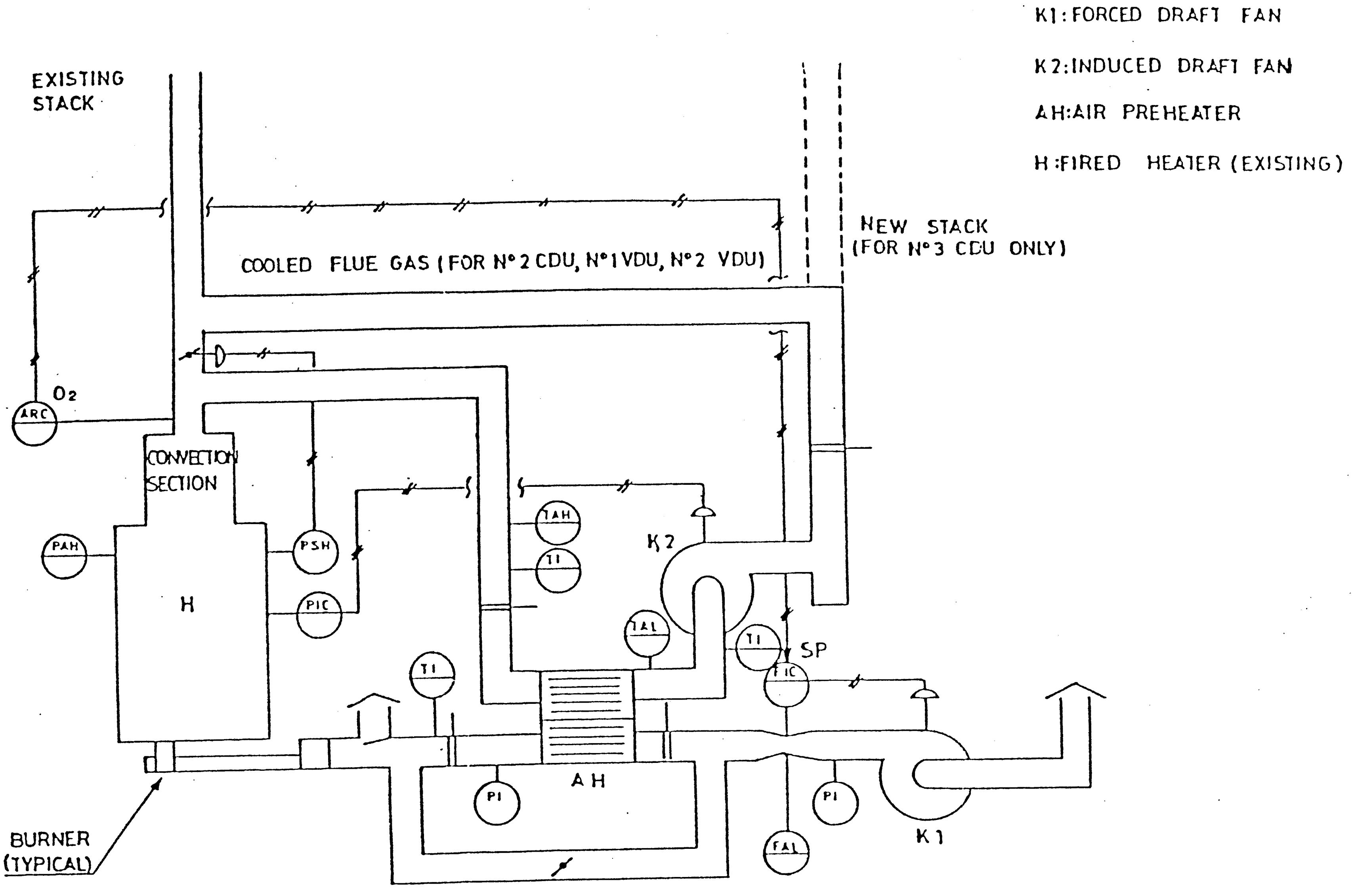
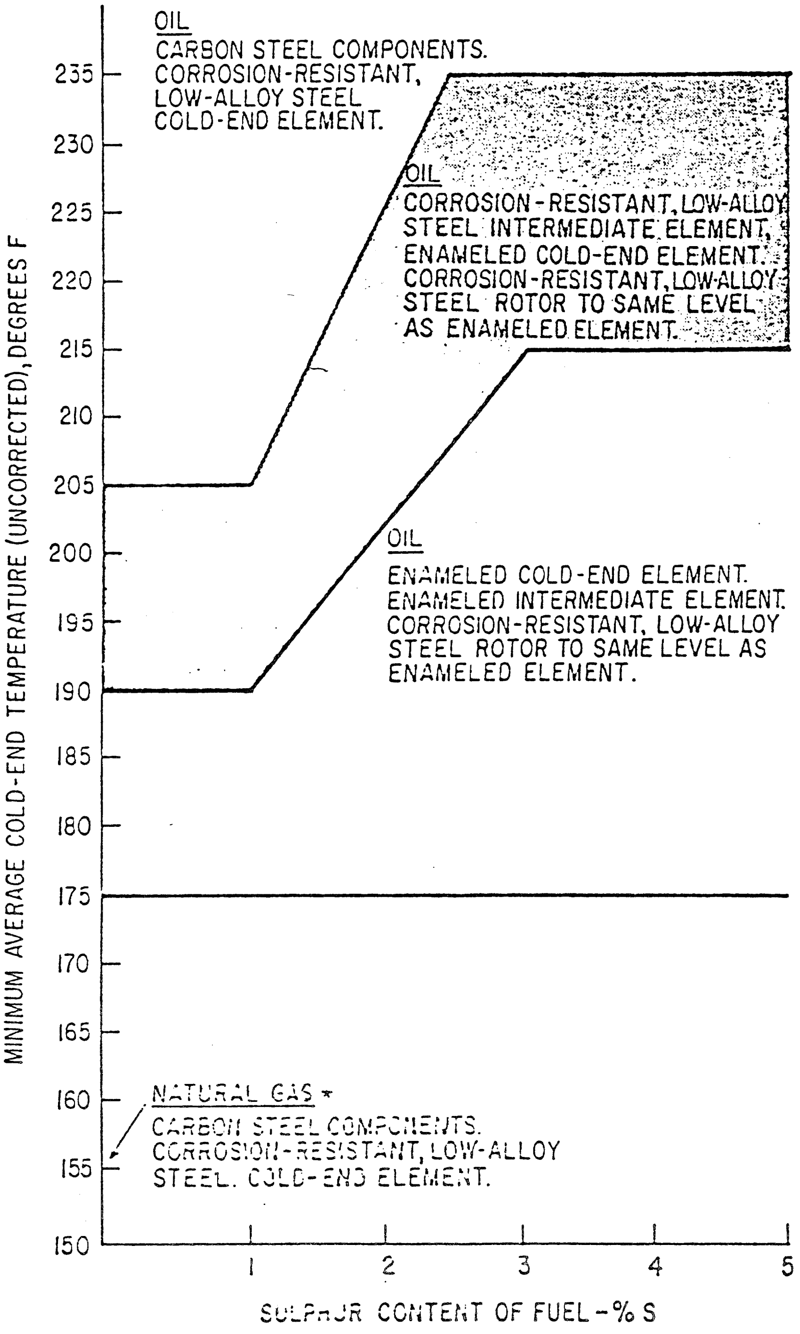


Figure 25. Recommended metals and corresponding temperatures



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* Other gases must be evaluated on an individual basis. The allowable cold end tempertaure from an air pre-heater is fixed by the fuel type and sulfur content, and the materials of construction.

(e) Cleaner furnace side tubes permit more even heat distribution to the process charge, which in turn reduces the coking in the tubes for better product quality.

4. Typical application

Figure 4 shows a typical preheater application. The unit was designed to recover heat from the stack gas by generating steam and preheating combustion air. Flue gas leaves the furnace at 2100°F (1150°C), then passes through the shell side of a steam generator to supply about 70% of the heat required to generate 70,000 lb/hr (31,750 kg/hr) steam. Flue gas from the steam generator at about 750°F (400°C) enters the air preheater, where it transfers heat to the combustion air of the furnace. Under typical winter conditions in the USA, approximately 107,000 lb/hr (48,500 kg/hr) of air is heated from 10°F (-12°C) to 305°F (151°C) while flue temperature is cooled to about 380°F (193°C).

G. Waste-heat boilers

Even after a complete use of heat exchange, some products will go to the outlet coolers at 70-200°C. Feed stocks along with hot flue gases from furnaces may be used to generate steam in a "waste-heat boiler". Such a boiler is shown in figure 26. The feed water which has already been preheated with exhaust steam in an "economiser" is heated further by any suitable hot oil stock on the way and is introduced into the steam generator. Meanwhile, hot water is circulated from the generator through tubes that are heated by flue gases. The high-temperature gases are obtained from a cracking unit furnace or any other furnace.

A typical waste-heat boiler arrangement for a platformer unit is shown in figure 27. In normal operations, hot flue gases from the four heaters will flow through the waste-heat boiler, induced fan (ID) and stack. Upon loss of the ID fan or in the event that the waste-heat boiler is out of operation, the flue gas goes via a bypass directly to the stack. The waste-heat boilers are usually of the free-standing, two-drum natural-circulation type designed with superheaters and an economizer and possibly a steam-feed preheater.

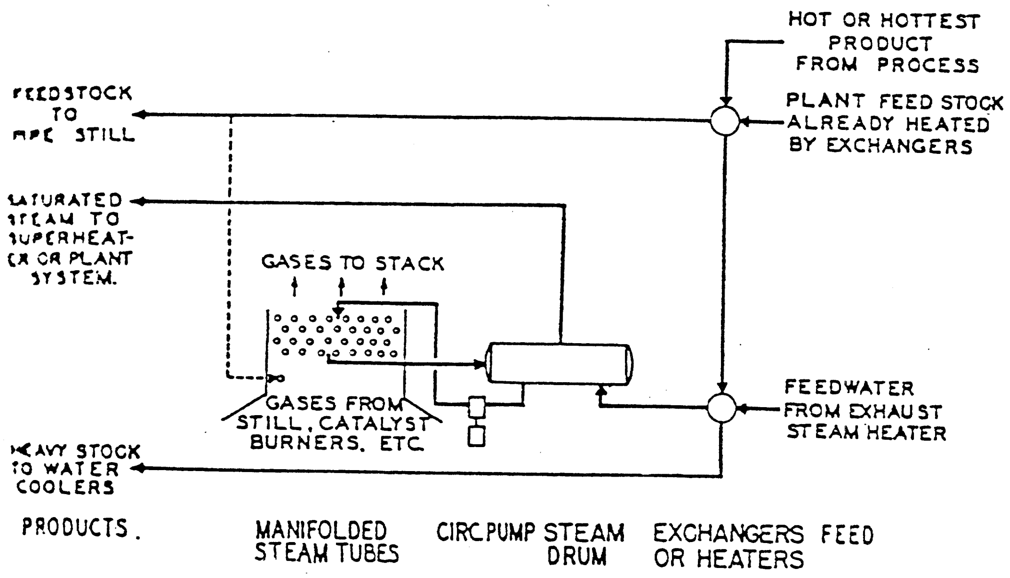
Another arrangement for a "waste-heat boiler" is shown in figure 28 for CO-boiler of a fluid catalytic cracking unit. In the generator section of the FCCU, there is significant heat loss of stack hot gases (at 670°C) which contain a significant amount of CO gas which could be burned to supply further recoverable heat. Both the sensible heat and the heat of combustion of CO could be recovered from regenerator fuel gas by adding a boiler to the stack gas system. Although it is a type of waste-heat boiler, such a boiler is termed a CO-boiler since it burns CO gas also.

In order to maintain the combustion of the CO, the regenerator stock gases must be heated to 800°C. For this reason, it is necessary to burn supplementary fuel in the CO-boiler.

A mathematical evaluation of waste-heat steam generators is given in Knight.[6/]

[6/] W. P. Knight, "Evaluate waste heat steam generators" (sic), Energy Management Handbook, p. 146.

Figure 26. General arrangement of waste-heat boilers



Additional schemes for the recovery of energy from flue gases of FCCU are shown in Miller[7] and Low.[8]

H. Heat exchangers

Heat exchangers are universally used in refineries for the removal of heat from hot streams to cold streams, such as for heating feeds into process columns or even for steam generation in waste-heat boilers.

The number of heat exchangers that might be used will depend upon the quantities and temperature level of several products. Heat exchangers are expected to pay for themselves in two years or less, and it is usual to bring the crude-oil temperature to within 40°F (5°C) of the temperature of the hottest heat exchange stock that is available.[9]

In complete plants which conduct vacuum and cracking operations as well as topping, the crude is advantageously heated by product from these other units because they are at relatively higher temperatures. Figure 29 shows the path of heating crude oil. The crude is pumped through the condenser exchangers of the topping plant, through the condenser exchangers of a cracking plant and finally back to the topping column. In some plants a crude-oil temperature of about 315°C is attained. This figure indicates the many sources of heat in an exchange system.

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[7] G. Miller, "Use of turbo expanders with FCC", Energy Management Handbook, p. 124.

[8] F. Lowe, "Starting FCC power recovery", Energy Management Handbook, p. 132.

[9] Nelson, op. cit., p. 581.

Figure 27. Platformer waste-heat boiler flow scheme

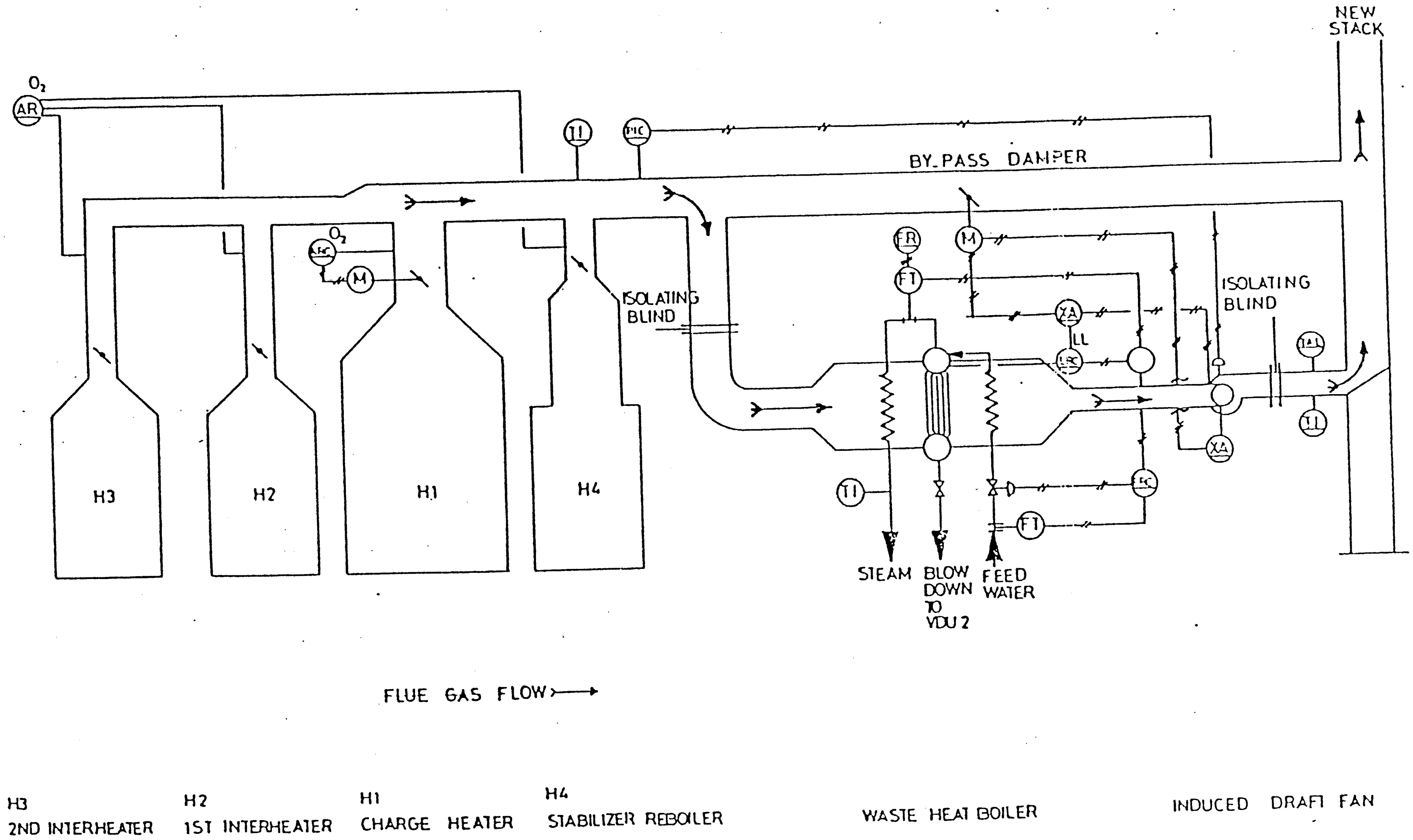
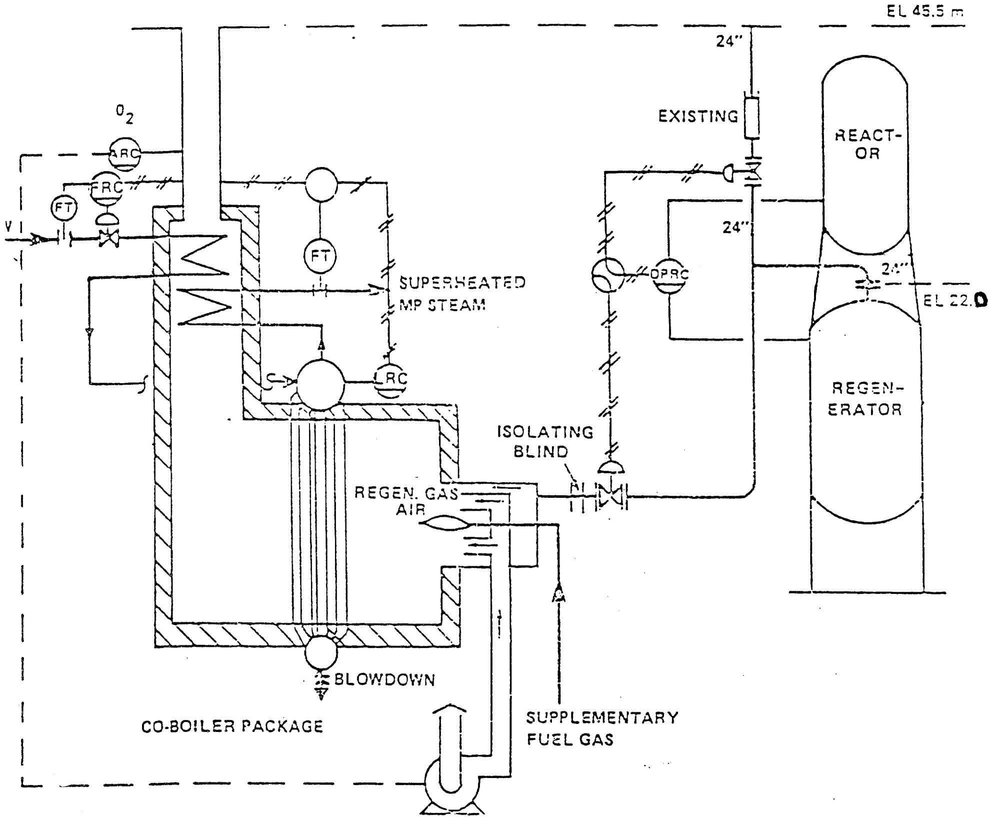


Figure 28. FCCU CO-boiler flow scheme



Several years ago, a new approach was developed to the arrangement and configuration of heat exchanges in a refinery to attain optimal heat recovery through the exchange of heat energy between different hot and cold streams in refinery processes.[10/] There is an almost infinite combination of arrangements of preheat trains for crude distillation. "Heat train design" is the term applied to the optimization of heat exchanger configuration in a refinery. The mathematical modelling and simulation of heat train can only be accomplished using sophisticated computers where any number of schemes can be evaluated for optimization. Multiple options may be evaluated using input data for the sequence of exchangers. A rigorous economic analysis is made based on the output.

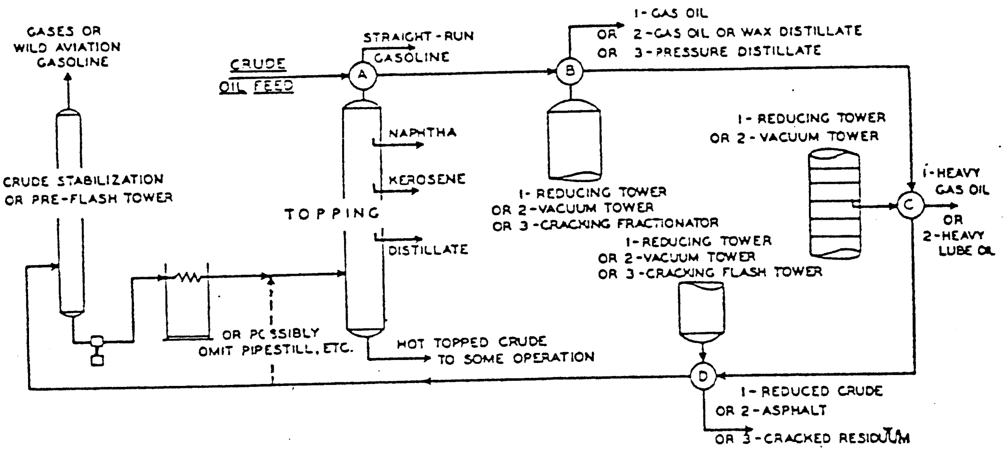
Two aspects are considered in the optimization of heat trains:

(a) Configuration and order of heat exchange duties;

(b) Distribution and amount of heat transfer surface supplied within the chosen configurations.

[10/] Frith, Bergens and Shreehan, op. cit.

Figure 29. Sources of heat for heat exchange



(*Oil Gas J.*)

A number of combinations of configurations are possible, as shown in figure 30 from the simplest, Case I, where heat is removed only from reflexes and products, to the most complicated, Case IV, where heat is removed from all reflexes and additional exchanges are provided for further stream cooling by "looping".

I. Heat conservation through insulation

Although insulation of lines, towers, vessels, furnace walls and tanks in a refinery has been a standard practice since refinery operations began, the significance of insulation has only been appreciated with the advent of energy consciousness. Recent improvements in insulation materials have been one of the main reasons for the renewed interest in the use of insulation as an energy conservation tool.

Many refineries have replaced most of the insulated materials with modern, more efficient materials, especially spray-on type petrochemical-based materials whose cost of purchase, installation and maintenance is superior to conventional materials.

One aspect of refineries which has escaped insulation--especially in older refineries--are the heavy fuel tanks used to store fuel oil. These tanks are heated by steam coil heaters to keep the fuel in a liquid pumpable state. Such fuel is not pumpable at temperatures below 60-75°C, depending on the type of fuel. The insulation of such tanks would be a great source of energy savings in refineries.

It was estimated that a tank farm of heavy fuel oil with a storage capacity of 75,000 m^3, and with tanks maintained at a temperature of 57-66°C by using internal steam heaters, would have heat losses through the uninsulated tanks of 27.7 million Btu/hr (7 million kcal/hr).[11] When spray-on polyurethane insulation of 3.81 cm thickness was installed around the tanks, the savings in energy was estimated at 25.1 million Btu/hr (6.325

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[11] W. Danekind, "Steam management in a refinery", Energy Management Handbook, p. 142.

million kcal/hr), which is equivalent to around 5,000 Te/year of fuel oil valued at $421,500/year, at a cost of about $500,000. Technical procedures for calculating heat savings through the use of insulation are elaborated in: Nelson; Bisi and Menicatti; and Menicatti.[12]

J. Steam management

In Danekind's excellent paper on steam management in refineries, it was estimated that for a medium-size refinery (100,000 b/d or 15,900 m^3/d), about 10% of the crude refined is used as fuel; of this 10% about 30% is used for steam generation.[13] That is why steam management is so vital.

The steam balance in a refinery is part of the energy audit for the refinery. There are many uncertainties in the evaluation of the steam balance, especially in measuring the flow of steam. However, following are some valuable suggestions in this regard:

(a) Steam flow meters are essential, especially in areas producing or consuming large quantities of steam;

(b) Steam flows can sometimes be established indirectly from heat balances on heat exchangers;

(c) Steam usage can be indicated by shutting off steam to individual pieces of equipment for a short period;

(d) Steam flashed across valves can be estimated from valve opening and pressure drop;

(e) Steam flows through turbines can be estimated from design data;

(f) Condensate collected from reboilers and condensers can be estimated by shutting off outlets for a short time and rating level changes;

(g) Condensate from steam traps can be estimated from trap specifications;

(h) Leaks or venting to atmosphere can be also estimated. In modern refineries where measuring and control instruments and computers are installed, the steam balance can be estimated to within ±10%.

It has been estimated that steam losses through simple leaks and steam traps could be significant, but that this problem could be overcome with maintenance:[14]

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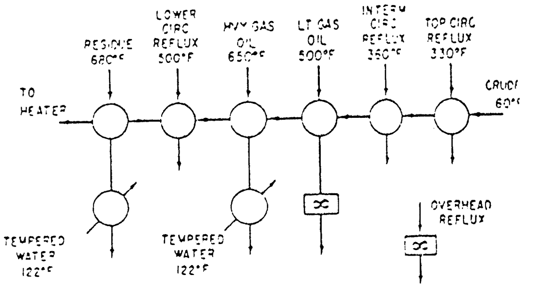
[12] Nelson, op. cit., p. 240; F. Bisi and S. Menicatti, "How to calculate tank heat losses", Energy Management Handbook, p. 260; S. Menicatti, "Check tank insulation economics", Energy Management Handbook, p. 264.

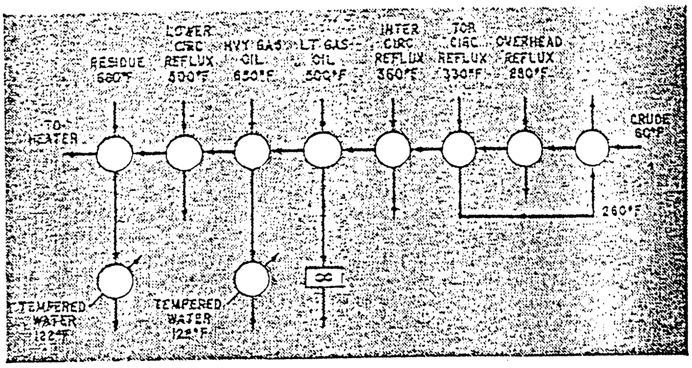
[13] Danekind, op. cit.

[14] A. Salim, "Utilization conservation in refineries and its impact on refining economics", Refining Economics Seminar, Damascus, Syrian Arab Republic, July 1983.

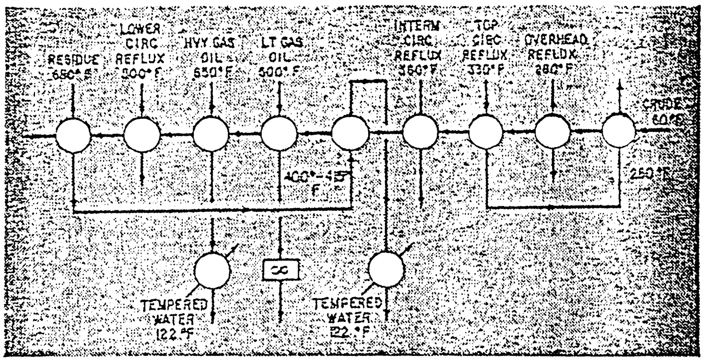
Figure 30. Possible configurations of preheat trains for crude distillation



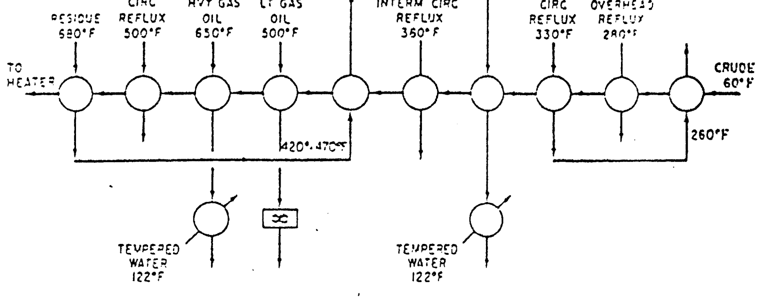
Conventional crude preheat train, Case I.



Crude preheat train using maximum exchange for reflux, Case II.



Crude preheat train using maximum heat exchange for reflux and some "looping," Case III.



(a) Steam loss through leaks: An opening in a steam line with a diameter of 3 mm could lose around 40 kg/hr of 7.5 bar steam, valued at $2,150 per year while a similar opening in a 37 bar steam system loses 160 kg/hr of steam value at $10,000/year assuming cost of FOET (fuel oil equivalent ton) at $85. If one assumes numerous leak openings, the loss would be tremendous.

(b) Steam traps: These are used on a large scale in refineries, for the purpose of keeping steam distribution lines dry in order to conserve the latent heat of steam. Steam-trap design is critical, and continual maintenance is essential.

A faulty steam trap (size 2 inches/51 mm) in a 10 bar steam system loses from 5-20 kg/hr of steam valued at $250 per year. Considering that there are over 2,000 steam traps in a refinery , then the magnitude of loss can be tremendous.

K. Conservation through co-generation

A large portion of electrical energy is generated in refineries by steam turbine-drive generators, with steam being supplied from fuel-burning boilers.[15/] Since the steam leaving the turbines is directly condensed, the thermodynamic cycle is inherently inefficient. Around 65% of the energy supplied to the boiler is wasted in the stack and condenser as exhaust heat.

As shown earlier, refineries consume large quantities of energy to generate steam or supply process heat. This provides a use for much of the waste that occurs in the generation of electricity. Integrating these two systems, i.e., the generation of electricity and the production of process heat, is a major source of energy conservation. The term "co-generation" implies different things to different people. However, the standard definition of co-generation when applied to energy conservation is the sequential generation of electricity or mechanical work and heat that is required or produced in processes operation. Two features of this definition must be emphasized:

(a) It includes the production of mechanical work as well as generation of electricity;

(b) The generation of electricity or mechanical work can come first or last in the cycle.

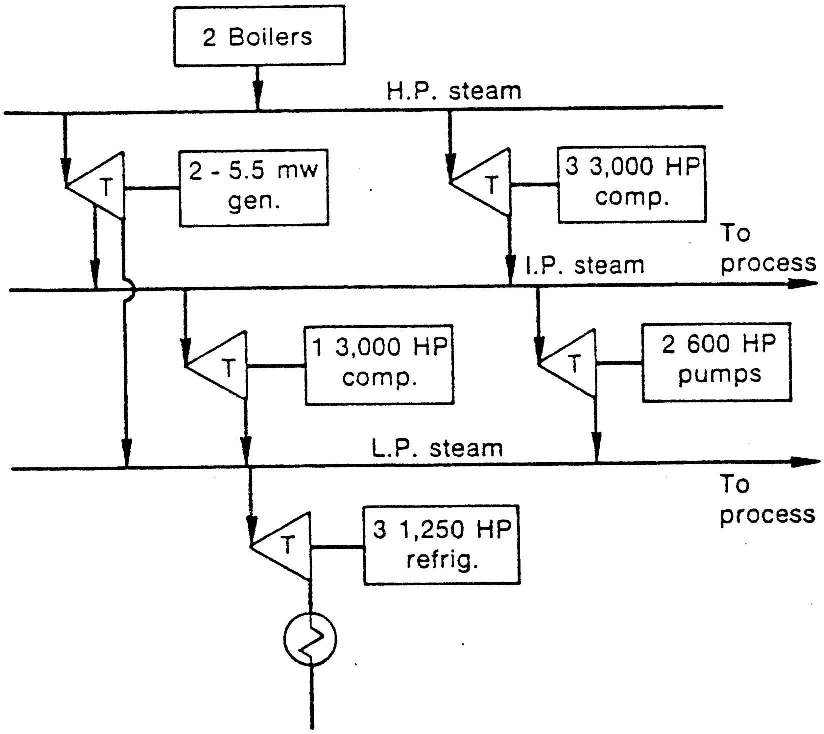
It is important to distinguish between the terms co-generation and self-generation. The distinction is that the portion of electricity generated by condensing steam is not co-generation.

Co-generation schemes are not only capital intensive but also involve third parties, usually authorities outside the refinery boundary. In order to make such project economically attractive (see chapter 5, section A of this report), it must have the cooperation and support of outsiders.

[15/] D. W. Hallman, "Save energy by co-generation", Energy Management Handbook, p. 221.

Figure 31 shows a typical co-generation scheme. Two fuel boilers supply high-pressure steam to two 5.5-megawatt turbo-generators and three 3,000-HP turbine-driven centrifugal air compressors. Extraction steam from the generators and exhaust steam from the compressors supply an intermediate pressure process system. The intermediate pressure steam is also used to drive a 3,000-HP turbine-drive centrifugal air compressor and two 600-HP turbine-driven boiler feed pumps. The exhaust from these turbines supplies a low-pressure process steam system and is used as well to drive three 1,250-HP condensing turbines that drive centrifugal refrigeration compressors.

Figure 31. Typical co-generation scheme of a large chemical plant



V. REVIEW OF EXISTING ENERGY-SAVING POLICIES IN REFINERIES

Although the policy of most large oil companies and oil refiners is to set long- and short-term energy-saving schemes and programmes, such policies have not been tackled meaningfully in the refineries of the Middle East. This, of course, is attributed to the relatively cheap and readily available energy in the area.

The experience of large oil companies and refiners in the area of energy saving is worthy of thorough study and analysis.1/

The average cost of energy use in typical refineries is more than 35% of the total operational cost of the refinery; this varies depending upon the location and complexity of the refinery. An energy audit of a medium-size refinery would typically show the following proportions:

Cost of fuel consumption	81%
Cost of purchased electricity	6%
Average loss of hydrocarbons	8%
Average loss in handling	5%

The above items account for 50% of operational costs for a medium-size refinery.

A simple topping refinery consumes the equivalent of 4% of its feed input capacity, while a more complex refinery with different conversion processes and tube oil production consumes 10% or more of its feed. In the conventional energy audit, this usage of energy was assumed to be lost, since it was calculated as the difference between the crude-oil feed to the refinery and the products that are produced (i.e., the yield, see chapter I).

Shell has estimated that a savings of 24% in energy use was obtained by following the conservation programme summarized below.2/ About 50% of the savings was in actual fuel sold as such, the rest was used efficiently as fuel for heaters or to generate steam for other processes:

1. 9% as a result of reducing fuel consumption in process heaters:

    Improving combustion in furnaces (burners, air/fuel ratio)
    Cleaning heat exchangers
    Installing air preheaters
    Reconfiguring and adding heat exchangers
    Installing flue gas analyses

1/ Mergens, op. cit.; R. Taylor, "Energy management at Exxon refineries", Energy Management Handbook, p. 16; C.P. Den Broeder, "An overview of energy saving in Shell refineries", Oil and Arab Cooperation, vol. 9, No. 3, 1983.

2/ Den Broeder, op. cit.

2. 8% as a result of reducing hydrocarbon loss:

   Immediate repairs to leaks
   Better maintenance and access to drainage system
   Installation of recovery units in the flare system
   Addition of floating tanks

3. 3% as a result of steam consumption in process units:

   Control of steam requirement in different processes
   Better maintenance of steam traps

4. 2% as a result of reduction of steam use in tanks:

   Better heat insulation in tanks and pipes

5. 1% as a result of steam reduction to secondary users and buildings.

6. 1% due to efficient furnace combustion.

7. Total 24%.

A. An integral scheme for energy conservation

An ongoing plan for energy conservation that could be applied to any refinery and in any stage of energy conservation has been developed, which covers the following areas: process and utilities units; optimized utilization of refinery installation; and cooperation with other sectors outside the refinery.[3] It must be clarified that such a plan incorporates both short- and long-term planning as well as day-to-day operational improvements. It is a truly integrated and continuous plan.

1. Improvements in process units

Additional savings can be made by carrying out minor improvements in process units; this could lead to a further reduction of 20% in fuel utilization in a refinery in the following fields of activities:

(a) Technology and operation (additional savings of 5 per cent):

(i) Control the amount of steam required for stripping, reboiling, circulation, stabilizers and solvent extraction operations;

(ii) To achieve the above, sensitive control instruments must be used which are computer run and controlled;

(iii) Reduction of pressure in fractionation columns when possible and the use of cooling and condensation equipment which are sensitive to seasonal changes;

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[3] Den Broeder, op. cit.

(iv) Selection of the optimum catalysts (zeolites for cracking and bi-metal for reforming);

(v) Quality control supervision so as to avoid production of off-spec products.

(b) Preventive maintenance and repairs: Another important field of activity through which further savings can be achieved (an additional 2%) is in preventive and programmed maintenance, repairs and replacements:

(i) Increase the level of cleaning of heat exchangers, convection-heated tube banks, preheaters and condensers;

(ii) Installation of "ball cleaners" in convection-heated tube banks and condensers;

(iii) On-sight maintenance and cleaning of exchangers;

(iv) Frequent checks and calibration of control instruments;

(v) Maintenance of steam traps;

(vi) Immediate repairs of steam and hydrocarbon leaks.

(c) Installation of up-to-date equipment and instruments: This field of activity could account for the largest savings in energy use in a refinery (on the order of an additional 13-15%). These projects are medium-size investments which are justified economically:

(i) Modifications and improvements in furnaces and boilers with emphasis on the performance and efficiency of air preheaters. This includes the utilization of hot streams of products in preheaters and the use of chemicals to reduce the flue gas dew point;

(ii) Optimization of steam distribution system (shortening of lines, use of economizers, primary heating of feed water to boilers);

(iii) Expanding the generation of electricity locally by use of gas turbines and/or waste-heat boilers;

(iv) Heating of high-viscosity products such as fuel oil and asphalt by warm-water heating, instead of steam or hot product steams;

(v) Flare gas, heat and hydrocarbon recovery;

(vi) Floating roof tanks;

(vii) Improvement in heat insulation;

(d) Some long-term projects which are presently not economically viable or not technologically applicable: It would be theoretically feasible to expect a further 10-15% reduction in energy use in refineries should the following projects be initiated:

(i) The use of advanced gas turbines: Tremendous research has been undertaken to develop such gas turbines. To illustrate the concepts of advanced gas turbines, it is appropriate to explain the function of energy in a refinery. In reality most of the energy is not used directly in the refining process. Fuel energy is converted to another form (heat), in the end dissipating to the atmosphere (or water) at around 125°C. As mentioned in chapter I, section B, the best type of energy is the chemical energy available in hydrocarbons since it is relatively cheap and easy to handle. In the burning of fuel in a refinery furnace, only a fraction of the available energy is utilized. The flame temperature in front of the burners in the furnaces or boiler reaches 1500°C while the temperature needed for vaporization of crude is less than 500°C. So if we can utilize a turbine which uses such a temperature in its chamber directly (temperatures of 1200-1400°C) to drive a generator, then the exhaust gas produced at a temperature of 500°C can be utilized for process heating. The problem presently is that gas turbines cannot handle such high temperatures in their chambers. They need new materials which further research will develop in the future;

(ii) Provision of low-temperature utilities, such as low-pressure steam and hot water to local areas for home heating, glass house heating and water desalination by utilizing waste heat to add more heat to cooling water and air;

(iii) Sale of surplus electricity to local consumers and hence optimization of the use of heat sources in the refinery;

(iv) Use of glass tubes in air preheaters below the dew point of flue gas;

(v) Use of electric motors with variable speed.

2. Optimization of refinery installations and utilities

Another field of activity that would enhance the overall energy conservation is in the management of energy and optimization of energy use:

(a) Energy management

Energy management is a new area of management in energy-intensive industries such as refineries. Energy is viewed in a holistic, comprehensive way with energy conservation as the prime aim and target.

The actual use of energy in a typical refinery is as follows:

Heating of fractionation columns	55%
Heating of reactors	12%
Rotation power (pump, compressors)	20%
Tank heating and heating for buildings	5%
Hydrocarbon loss (flaring, evaporation)	8%
	100%

It is also of interest to notice that of the total heat content of the fuel used, 98% is utilized, in principle, as heat with temperatures as low as 125°C, while only 2% of the heat content is used as "heat of formation" to produce useful products.

The following enumerates the normal sources of heat and power to operate a typical refinery:

Level of heat	Percentage	Sources
300-500°C	55	Furnaces
210-300°C	5	Hot steams
130-210°C	5	Steam 18 bar
20-130°	15	Hot water, steam 3.5 bar
Power	20	Electric/steam 18 bar (50/50)
Total	100	

Figure 32 indicates typical energy streams through the process and tank area of a refinery.

It is obvious then that such divergent energy levels in a refinery can be managed by the use of sophisticated computer-controlled software and highly developed simulation and modelling programmes that give operators instant data for optimal operation of energy utilization.

One of the major instability factors in refinery operations is the sensitivity of distillation columns to the type of feed crude oil. These columns use up to 30-50% of input energy. Most distillation columns are designed for one or two crude oil feeds. In order to get a similar crude through the refining process, one or more crudes must be blended to get a similar yield of the crude for which the refinery is designed and that will beget the best results. Here also the desirability computer application is evident.

(b) Energy and utility systems

Linear and nonlinear studies have shown that best results can be achieved by co-generation of heat and energy since a significant amount of energy is consumed for the generation of steam and electricity.

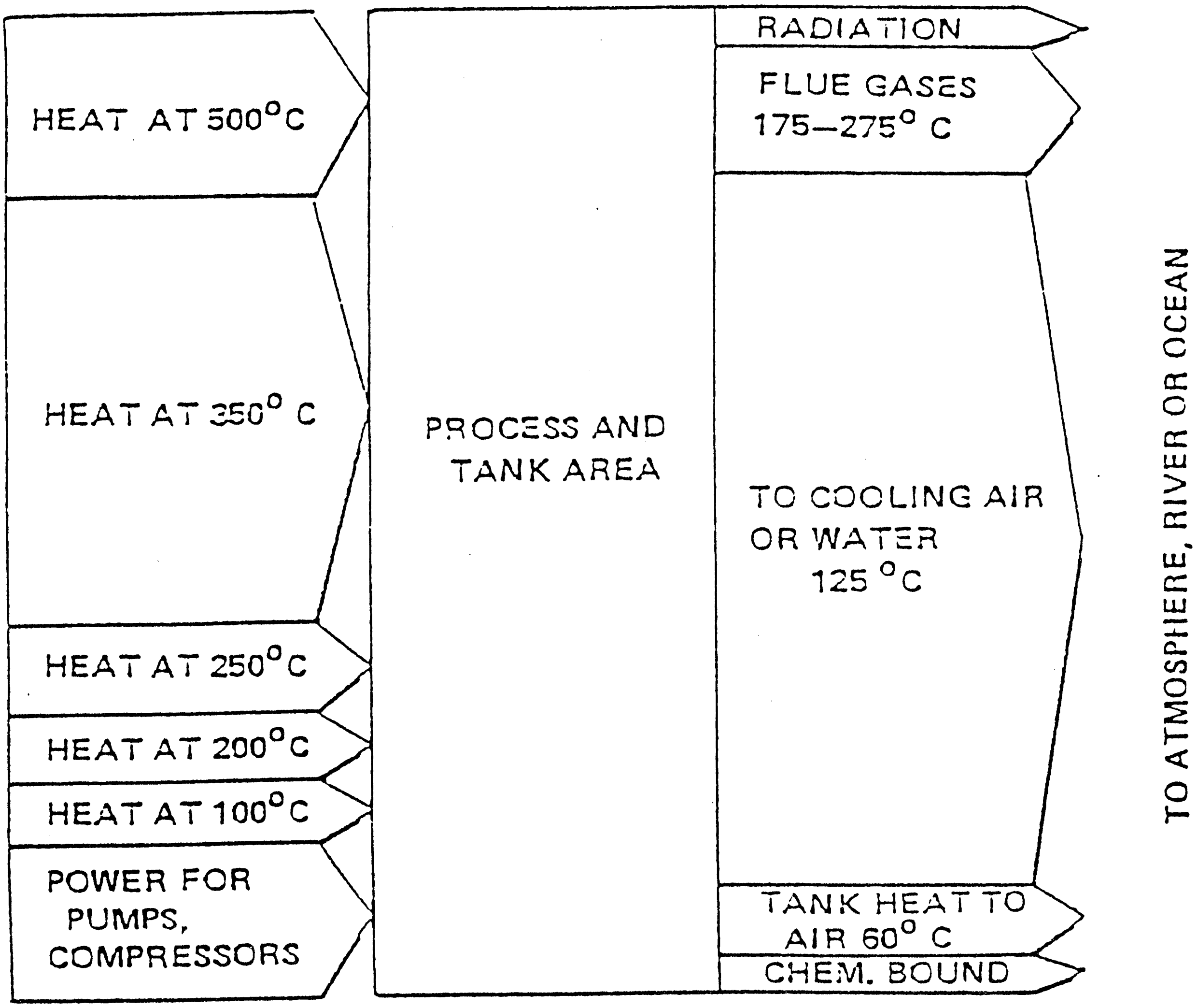
A medium-size refinery will require:

(i) 2% of total energy for chemical reactions;

(ii) 78% of total energy for heating;

(iii) 20% of total energy for electric generation for rotation (pumps and compressors).

Figure 32. Typical energy streams through a process and tank area



and this energy is fed by fuels: 64% fuels for process furnaces; 25% fuels for steam generation; and 11% fuels for electric generation.

Electricity requirements are met as follows: 39% purchased from outside the refinery; and 61% generated inside the refinery as follows: 13% by steam turbines; 42% back pressure turbines; and 6% gas turbines.

From the standpoint of overall efficiency, the refinery must be self-sufficient in electricity generation, either by using gas turbines or waste-heat boilers or back pressure steam turbines.

Following is a simple example explaining the improvement in efficiency of energy use:

The object is the production of 18 bar steam for heating purposes.

Fuel used (tons)	Generation of electricity and steam by:	To provide the refinery with:	
		Electricity (MW)	Steam tons
1.2	Electricity by 18 bar boiler and condensing turbine	1	
	Steam from 18 bar boiler		10
1.0	Steam from 100 bar boiler + back pressure turbine	1	
	100-18 bar for electric generator + 18 bar steam		10
	Electricity generated by gas turbine		2.5
0.85	Use of gas to generate steam		5
	18 bar (waste-heat boiler)		

It is evident that uniting gas turbines and a waste-heat boiler not only has 25-40% better efficiency than the steam and electric generation utilities, but their ratio of electricity to steam is also better.

For heat energy in particular, maximum flexibility and use must be achieved from thermodynamic principles, which implies that during heat exchange operations, the differences between temperature levels must be small and their transfer gradual, with minimum heat loss. If unlimited investment is possible, then this will lead to wider use of large tube banks in convection areas of heating as well as different configurations of heat trains.

The use of co-generation--the simultaneous generation of steam and electricity in the refinery--is widely practiced and is expected to be a standard practice in the future. So when deciding on a scheme for steam generation, electricity generation must be incorporated into it, whether by the installation of a boiler and a generator together (back pressure turbine and recovery) or by using gas turbines with a waste-heat boiler or as mentioned previously by the use of advanced gas turbines which directly utilize the hot flue gases (above 500°C) (figures 33 and 34).

3. Cooperation with sectors outside the refinery

Another field which has been investigated in recent years is the cooperation with sectors outside the refinery. This needs the assistance and cooperation of governmental, local and other authorities as well as utilities authorizes. The cooperation could include the following points:

(a) Co-generation of power and heat: Refineries can be designed to be self-sufficient and even to generate surplus electricity. Any refinery that generates heat and electricity for its own use could be used to generate additional energy that could be sold to local utilities with final savings in energy approaching 30%;

(b) Utilization of low-level heat: The heat energy produced during combustion operations in a refinery is of a high level (1000-1500°C). When this heat is used in process operations, it is usually reduced to below 500°C and the remanent heat is eventually dissipated by cold air or water (100-150°C).

This final low-level heat is ideal for domestic heating and for glass houses. However, the investment necessary for such projects is too high to be undertaken by the refinery on its own, so the cooperation of local authorities is needed for such projects;

(c) Sale of excess gas: In the future, a tremendous increase is expected in the bottom-of-the-barrel conversion operation, i.e, the conversion of heavy fuel in refineries into more useful light products. As a result of such sophisticated conversion processes, there is an excess of gases produced (methane and ethane). These must be sold in order to make any sense of the overall conservation of energy in a refinery since another by-product of these conversion processes is the heavy residual fuel oil with high viscosity which has to be treated with valuable light distillates in order to make it marketable.

B. Future trends for energy conservation in refineries

It would be unrealistic to assume that future development in technology will bring a fundamental breakthrough in energy conservation in refinery operations, but one can safely assume that present developments will lead to further incremental savings in energy. The following developments in energy conservation can be expected to be continually researched and applied:

(a) Reduction of the oxygen content of flue gases;

(b) Improvement in air preheater technology with consequent increase of furnace efficiencies to over 90%;

(c) Increase of areas of heat exchangers;

(d) Increase in the utilization of gas turbines used especially in conjunction with furnaces;

(e) Increase in the use of variable speed motors;

(f) Increase of data recording and control in different energy paths;

(g) Increase in the efficiency of insulation especially with the development of new insulation materials;

(h) Reduction in the use of steam;

(i) Increase in the preheating of feed water to boilers using waste heat;

(j) Increase in the use of computer applications in control, operations and simulation.

Figure 33. Heat recovery in a refinery

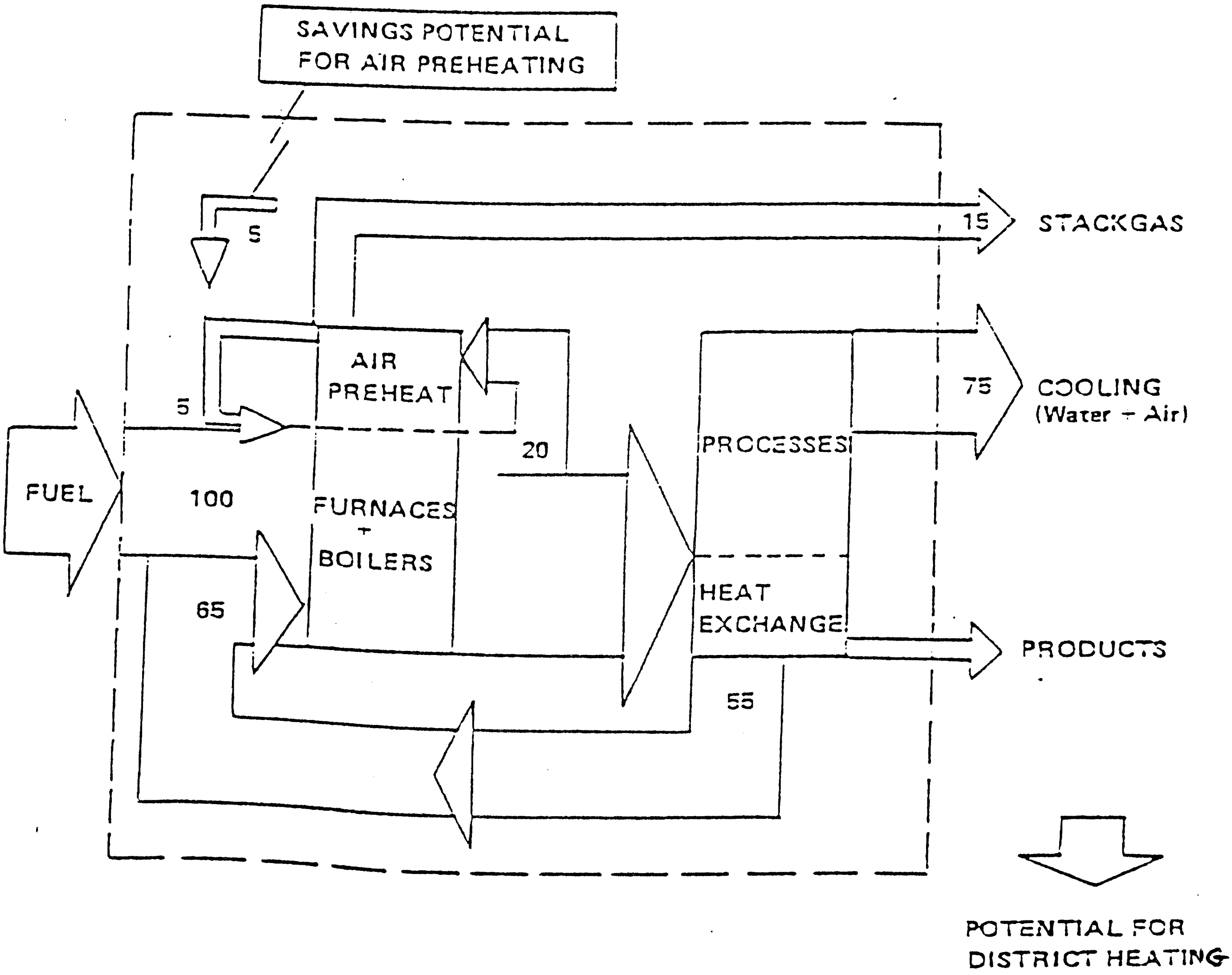
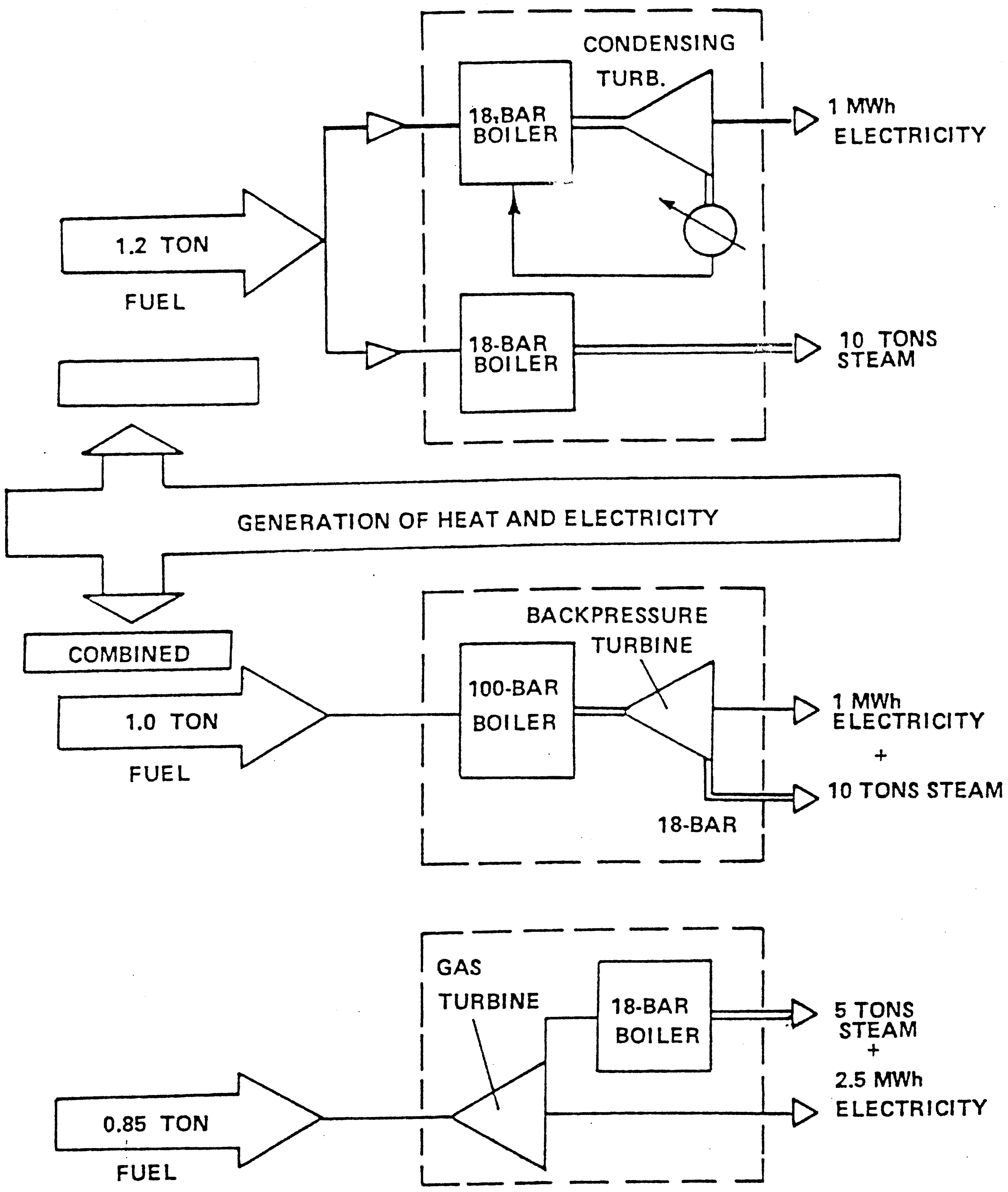


Figure 34. Examples of steam and electricity generation



N.B. TOTAL ENERGY OUTPUT OF ABOVE SYSTEMS IS EQUIVALENT

VI. CASE I: ZARQA REFINERY IN JORDAN

A. Introduction

Zarqa refinery, which is the only refinery in Jordan, has a processing capacity of around 4 million tons of crude oil per year (around 90,000 barrels/day). The main source of crude oil is either Iraqi crude or Arabian light, or a combination of both, depending on the availability.

It produces a variety of petroleum products, mainly for the domestic market, which annually consumes around 2.5 million tons of products per year, i.e., the current throughput of the refinery is around 60% of the maximum capacity.

The refinery consumes energy primarily in the form of heat and secondarily as electric power at the normal current rate of 6,500 T/d. About 15% of this is for electric-power generation and the remainder for process heat and steam generation.

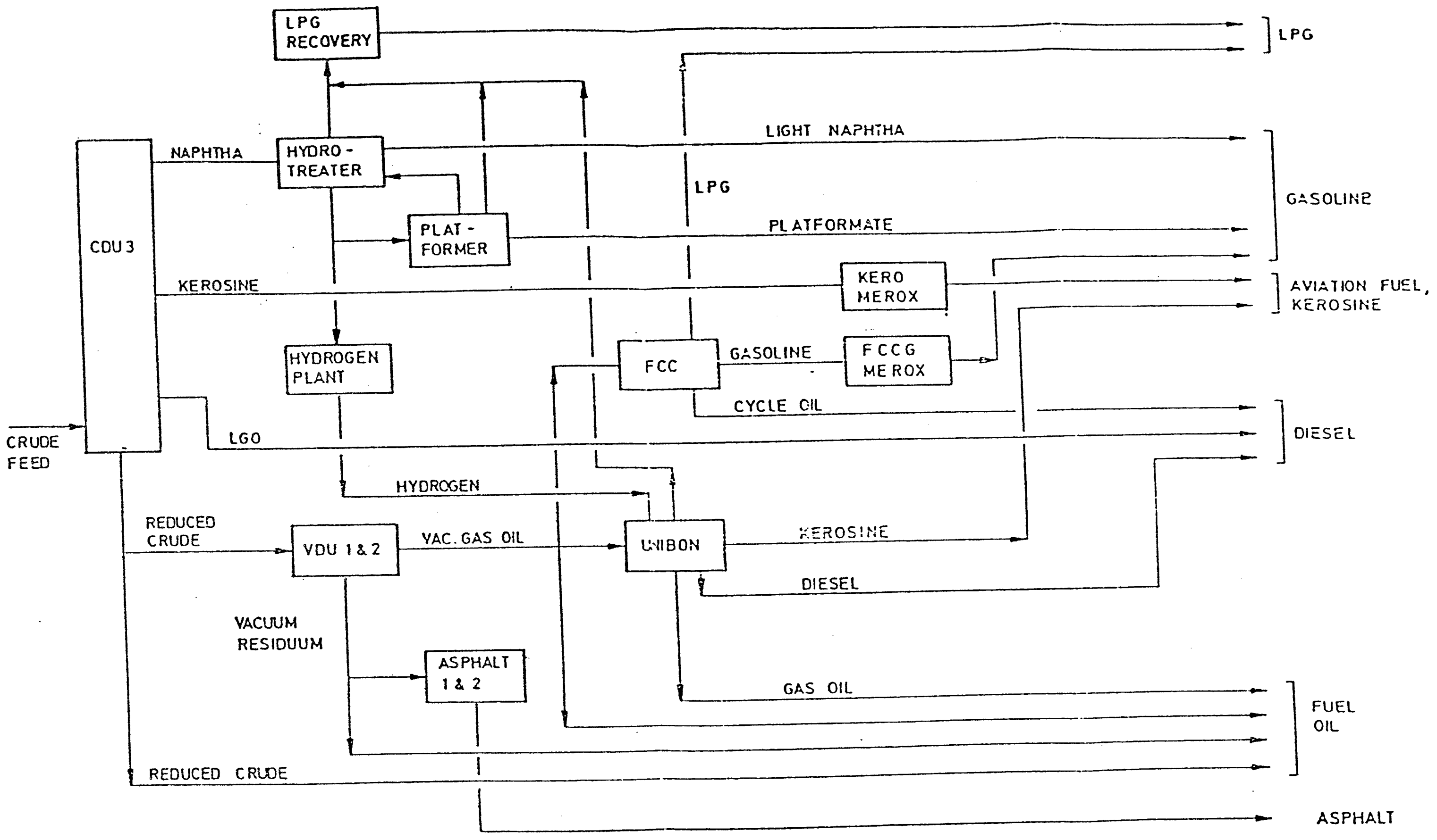
Figure 35 shows the schematic block flow diagram of the units normally operating. An inventory of major refinery units is shown in table 4.

Table 4. Major units of Zarqa refinery

Major units	Capacity T/d
Crude distillation unit 1(CDU1)	3 000
Crude distillation unit 2(CDU2)	2 000
Crude distillation unit 3(CDU3)	7 500
Vacuum distillation unit 1(VDU1)	1 000
Vacuum distillation unit 2(VDU2)	1 100
Fluid catalytic cracking unit (FCCU)	650
Unibon hydrocracker	600
Naphtha hydrocracker	1 300
Kerosene merox plant	1 400
Platformer	1 000
Hydrogen plant	220 knm3/d
LPG recovery plant	225
Asphalt plant (1) and (2)	700
3X HP steam generator each	50
2X HP steam generator each	27.5
2X6 MW turbo-generators	
2.4 MW steam turbine generator	
Tankage, offsite and utilities system	

Source: Bechtel Corp., "Report on energy conservation in industry in Jordan", 1986.

Figure 35. Schematic block flow diagram



B. Brief description of the major operating units of Zarqa refinery

1. Crude distillation unit 3 (CDU3)

This is the main operating unit of the refinery at the current capacity. It is of a modern design with a capacity of 7,500 T/d (figure 36) with extensive use of heat recovery from product steams. This unit has the highest potential for heat recovery from hot flue gases of the fire heater (furnace).

The furnace adsorbed duty is 35 million kcal/hr at throughput of 7,500 T/d with furnace efficiency of about 72%.

The temperature of the flue gas is around 500°C. The crude oil in the CDU is heated to a temperature of 350°C (below cracking temperature) and slight positive pressure.

2. Crude distillation unit 2 (CDU2) (figure 37)

Although not operating at the present throughput of the refinery, its potential for standby or additional throughput is excellent. It has a capacity of 2,000 T/d and would be a good target for a heat recovery scheme.

The furnace adsorbed duty is 8 million kcal/hr at design capacity of 2,000 T/d with furnace efficiency and stack temperature similar to CDU3.

3. Vacuum distillation unit 2 (VDU2) (figure 38)

Reduced crude from crude distillation units (CDU) is fed into the vacuum distillation units in order to maximize the production of middle distillates. Distillate production is maximized by operation at higher temperature (around cracking temperature of 370°C) but at reduced pressure of about 0.1 atmosphere.

It is common practice to feed the distillates of VDU (light and heavy vacuum gas oils) into the FCCU and unibon units (these are called conversion units) to produce lighter valuable products.

The principle process of VDU is similar to that of the CDU. Energy consumed is in the form of heat as well as the heat content of the reduced crude feed coming out at the bottom of CDU at around 320°C.

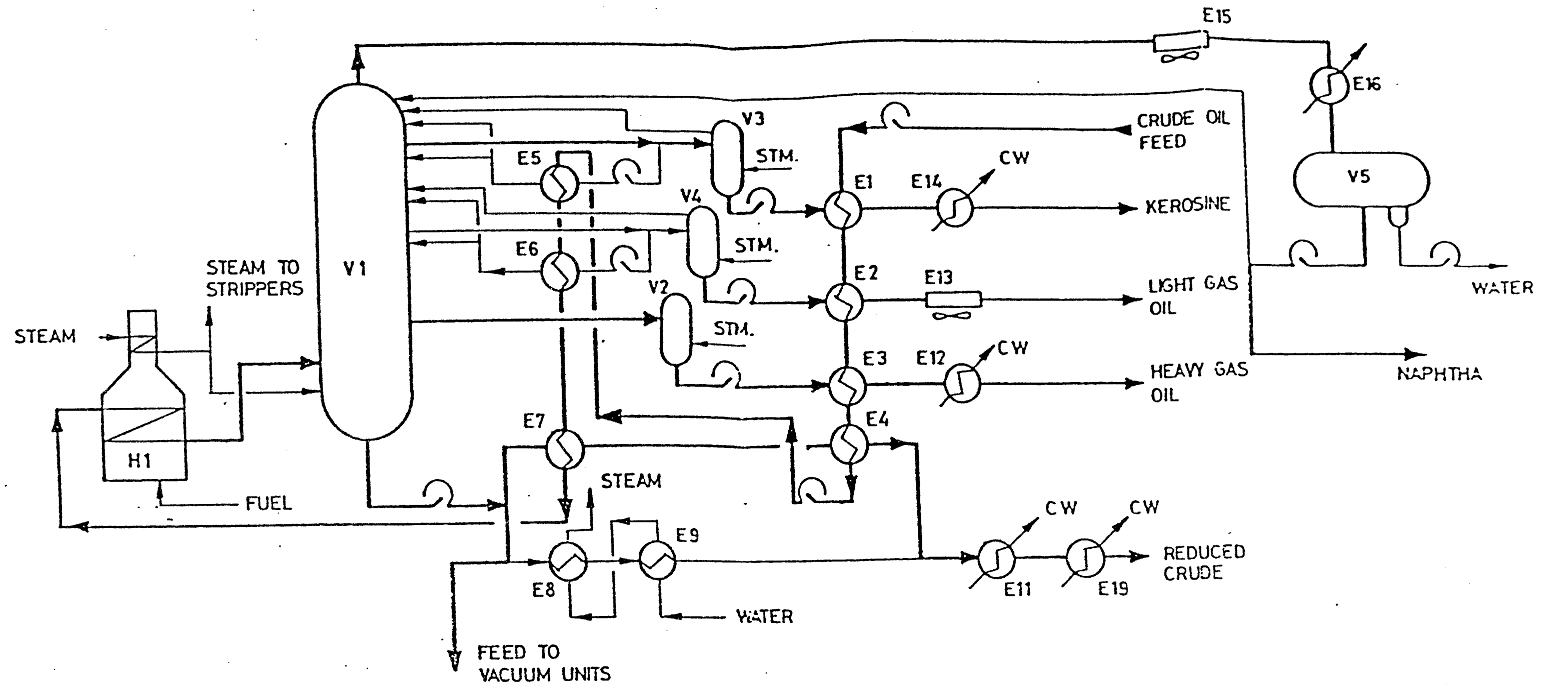
VDU2 rated capacity is 1,100 T/d and the adsorbed duty of the furnace is 3.5 million kcal/hr, at a furnace efficiency of 70% and flue gas temperature of 550°C.

4. Vacuum distillation unit 1 (VDU1) (figure 39)

This is the old vacuum unit, which was designed to operate in conjunction with the presently idle CDU1. It has a capacity of 1,000 T/d and is presently operating in parallel with VDU2 to increase the feed into the conversion units.

The adsorbed duty of the furnace is 3.0 million kcal/hr; furnace efficiency is 70%; flue gas temperature is 550°C.

Figure 36. Crude distillation unit 3



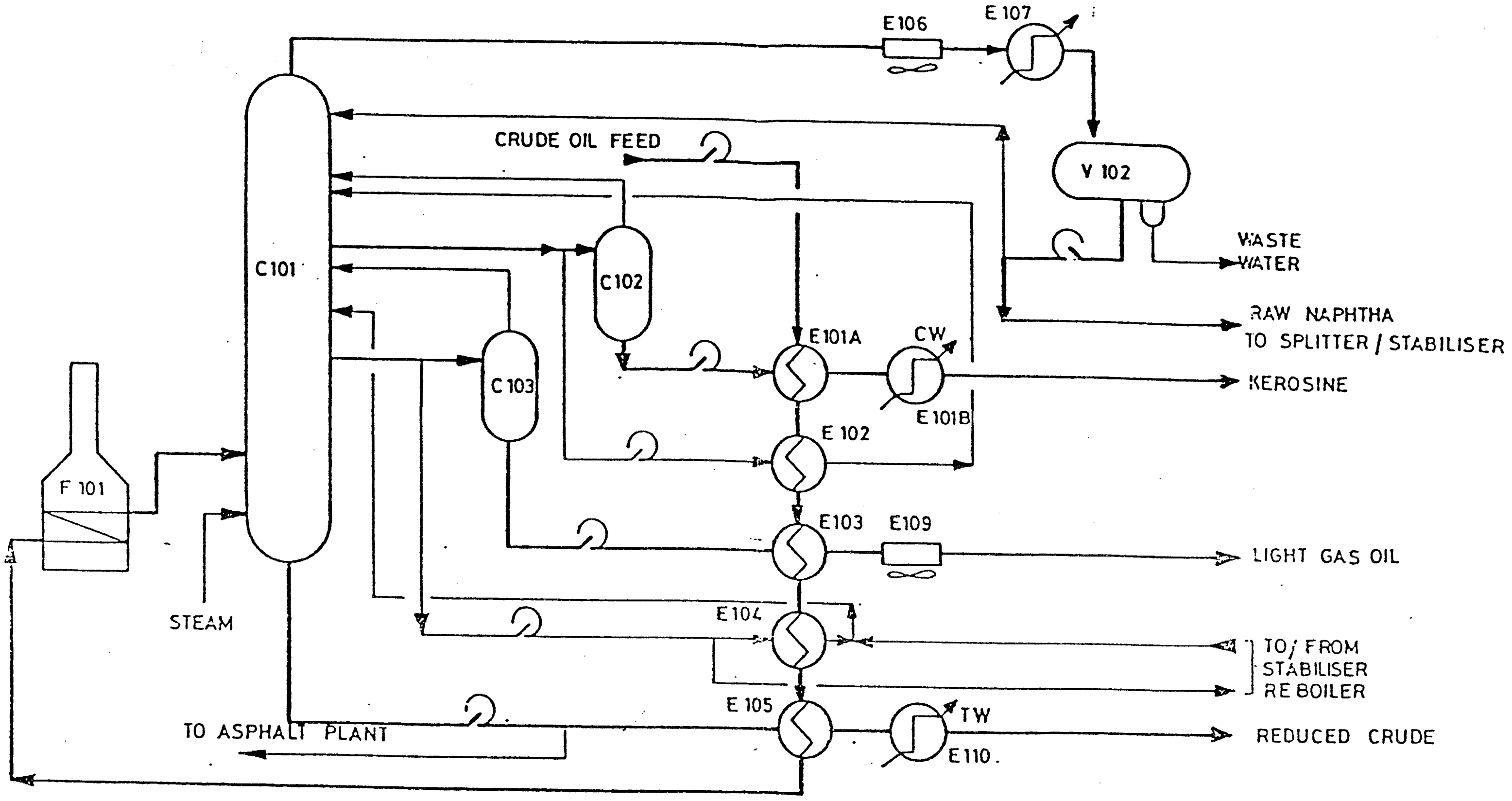
COLUMNS
V1 MAIN COLUMN
V2 HEAVY GAS OIL STRIPPER
V3 KEROSINE STRIPPER
V4 LIGHT GAS OIL STRIPPER
V5 OVERHEAD RECEIVER

FIRED HEATER
H1 CHARGE HEATER

HEAT EXCHANGERS
E1 CRUDE/KEROSINE
E2 CRUDE/LIGHT GAS OIL
E3 CRUDE/HEAVY GAS OIL
E4 CRUDE/REDUCED CRUDE
E5 CRUDE/KEROSINE PUMPAROUND
E6 CRUDE/LIGHT GAS OIL PUMPAROUND
E7 CRUDE/REDUCED CRUDE
E8 REDUCED CRUDE/STEAM GENERATOR
E9 REDUCED CRUDE/FEED WATER

COOLERS
WATER COOLED
E11 REDUCED CRUDE
E12 HEAVY GAS OIL
E14 KEROSINE
E16 TRIM CONDENSER
E19 REDUCED CRUDE
AIR COOLED
E13 LIGHT GAS OIL
E15 MAIN COLUMN CONDENSER

Figure 37. Crude distillation unit 2



COLUMNS

C101 MAIN COLUMN
C102 KEROSINE STRIPPER
C103 GAS OIL STRIPPER

VESSELS

V 102 OVER HEAD RECEIVER

FIRED HEATER

F101 CHARGE HEATER

HEAT EXCHANGERS

E101A CRUDE/KEROSINE
E102 CRUDE KEROSINE REFLUX
E103 CRUDE LIGHT GAS OIL
E104 CRUDE L.G.O. REFLUX
E105 CRUDE REDUCED CRUDE

COOLERS

WATER COOLED

E101B KEROSINE
E107 TRIM CONDENSER
E110 REDUCED CRUDE

AIR COOLED

E106 MAIN COLUMN CONDENSER
E109 LIGHT GAS OIL

Figure 38. Vacuum distillation unit 2

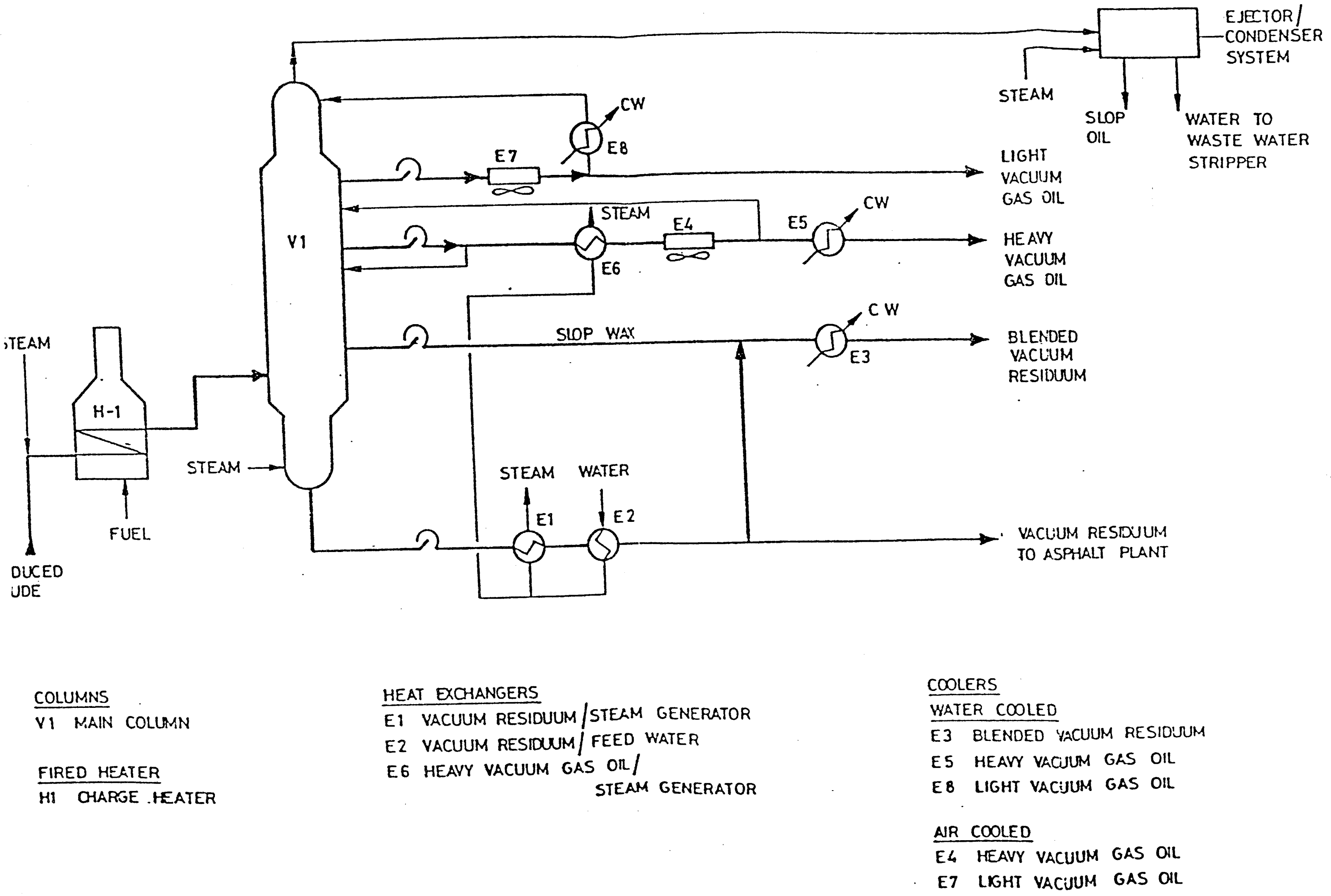
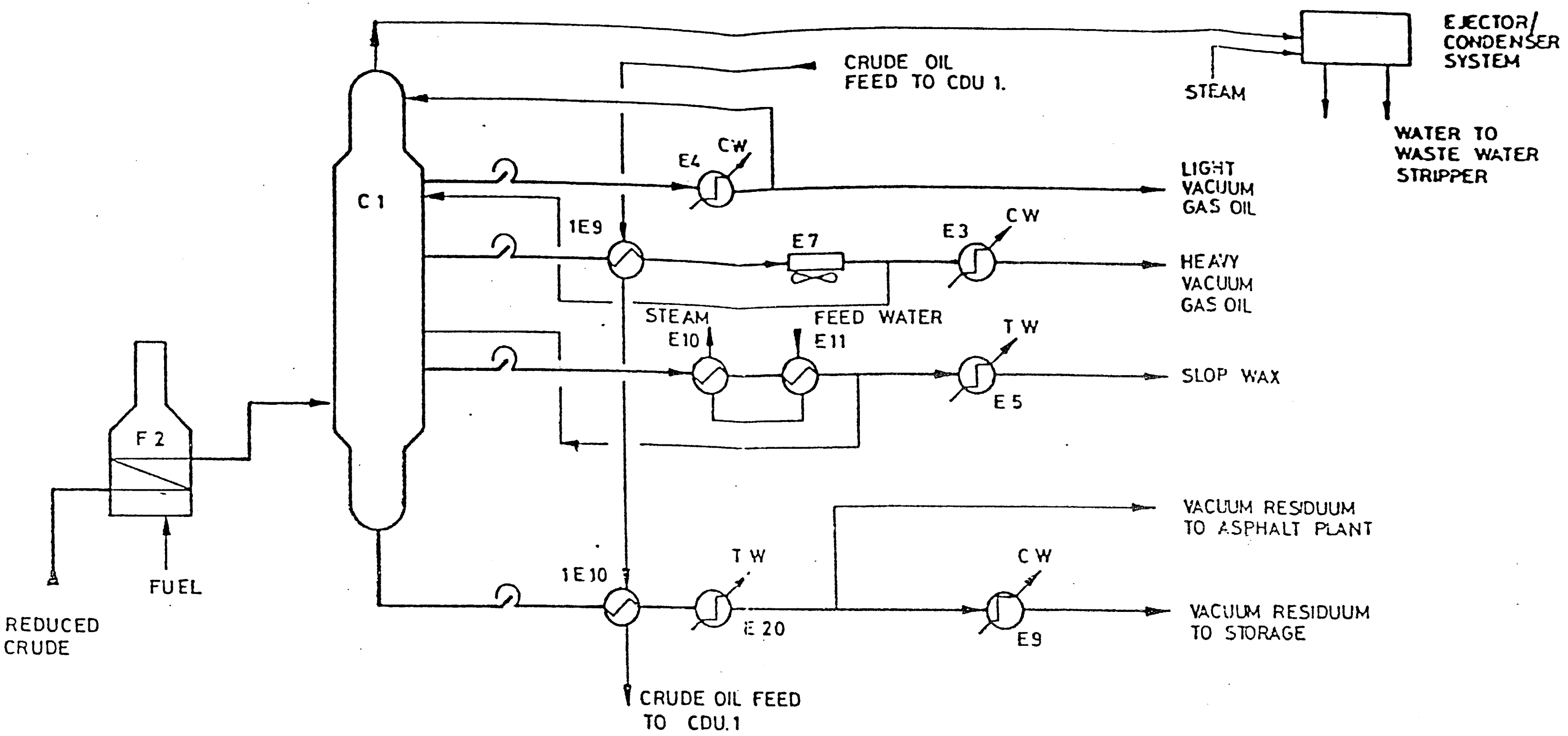


Figure 39. Vacuum distillation unit 1



COLUMN

C 1 MAIN COLUMN.

FIRED HEATER

F 2 CHARGE HEATER.

HEAT EXCHANGERS.

E 10 SLOP WAX / STEAM GENERATOR.
E 11 SLOP WAX / FEED WATER.
1E9 HVGO / CRUDE OIL.
1E10 VACUUM RESIDUUM / CRUDE OIL.

COOLERS

WATER COOLED

E3 HEAVY VACUUM GAS OIL.
E4 LIGHT VACUUM GAS OIL.
E5 SLOP WAX.
E20 VACUUM RESIDUUM.
E9 VACUUM RESIDUUM (OFF PLOT).

AIR COOLED

E7 HEAVY VACUUM GAS OIL.

5. Platforming unit (figure 40)

The platforming unit is a catalytic reforming process using a platinum catalyst for the conversion of heavy naphtha into high-octane reformate to be blended in the gasoline pool. The main aim of the process is the conversion of straight-chain paraffins into cyclo and iso paraffin to increase the octane number.

At the design capacity of 1,000 T/d, the absorbed heat duty of the four fired heaters is around 20 million kcal/hr. The average flue gas temperature is high, around 700°C; consequently the efficiency of these heaters is around 65%.

Because of the high temperature of the flue gases, it is more appropriate to recover the heat of the flue gases by installing a waste-heat boiler.

6. Fluid catalytic cracking unit (FCCU) (figure 41)

FCCU is a heavy distillate conversion unit for coversion into lighter products such as high octane gasoline. Although this unit has an extensive heat-recovery system and no significant heat input into it other than the heat of combustion of coke in the regenerator, there is significant heat loss through the regenerator stack. The stack temperature is around 670°C, but the flue gases also contain a significant proportion of CO gas which has significant heat if burnt.

Heat recovery of flue gases and CO gas could be achieved by installing a waste-heat boiler. However, this would require an additional input of fuel in order to maintain the combustion of CO gas to maintain a stack temperature of around 800°C for waste-heat steam generation.

C. Energy conservation schemes for Zarqa refinery

The only literature available on energy conservation schemes in Zarqa refinery is found in Aburas, Lloyd and Webster,[1] which is a summary of the report prepared by Bechtel Co.[2] Both these references give enough data and information to identify energy-saving measures for the Zarqa refinery. The measures identified fall under the following general categories:

(a) Schemes to recover heat from fired-heater flue gas by the installation of air preheaters or waste-heat boilers;

(b) Schemes to recover heat from hot product streams;

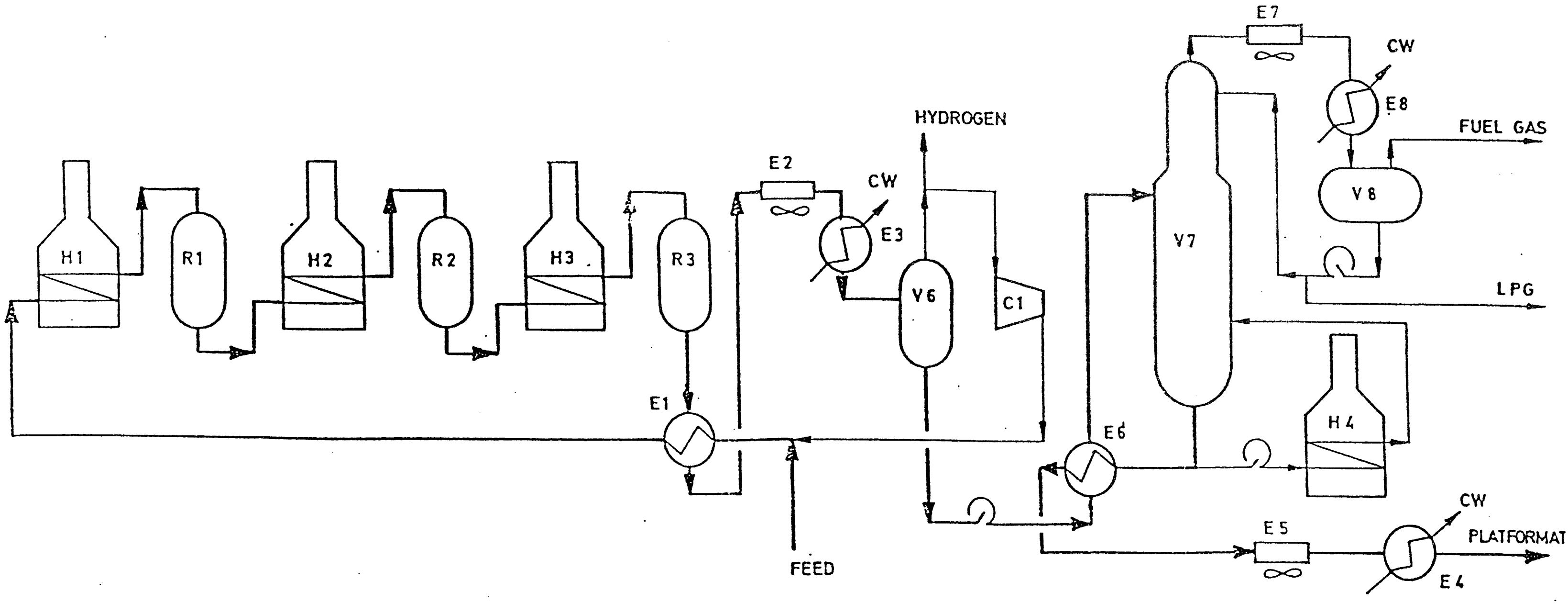
(c) Insulation of tanks;

(d) Other schemes.

1/ R. Aburas, S. Lloyd and M. Webster, "Waste Heat Recovery in Jordan Petroleum Refinery", HP1, November 1988.

2/ Bechtel Co., "Report on energy conservation study in industry in Jordan", 1986.

Figure 40. Platformer



VESSELS	
R1 R2 R3	REACTOR
V6	REACTOR PRODUCT SEPARATOR
V7	STABILISER COLUMN
V8	STABILISER REFLUX DRUM

AIR FIN COOLERS	
E2	REACTOR EFFLUENT CONDENSER
E5	PLATFORMATE COOLER
E7	STABILISER CONDENSER

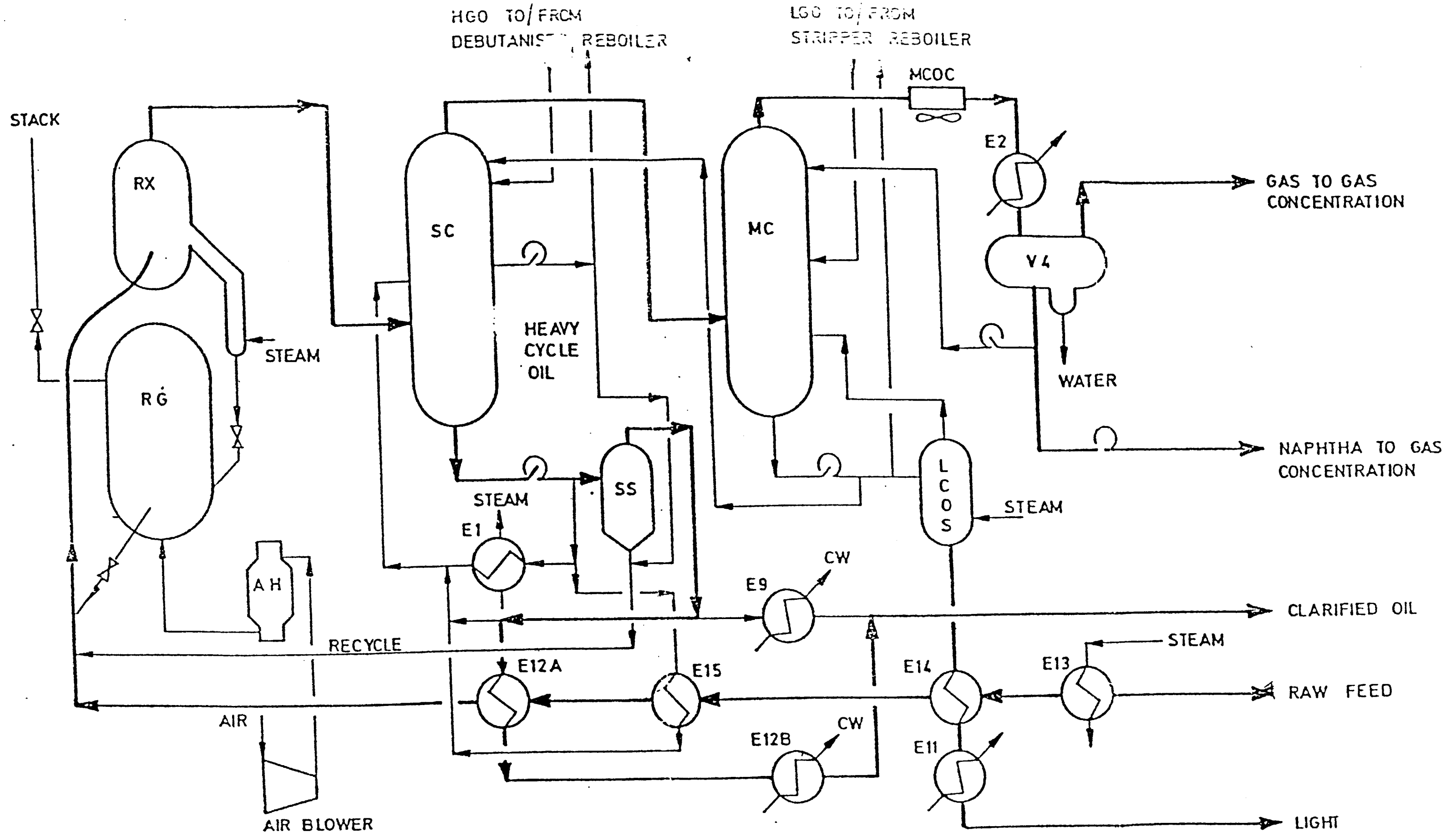
COMPRESSOR	
C1	RECYCLE COMPRESSOR

FIRED HEATERS	
H1	CHARGE HEATER
H2 H3	INTERHEATERS
H4	STABILISER REBOILER

WATER COOLED COOLERS	
E3	REACTOR EFFLUENT TRIM CONDENSER
E4	PLATFORMATE TRIM COOLER
E8	STABILISER TRIM CONDENSER

HEAT EXCHANGERS	
E1	REACTOR FEED EFFLUENT
E6	STABILISER FEED BOTTOMS

Figure 41. **Fluid catalytic cracker reaction and fractionation section**



VESSELS	
RX	REACTOR
RG	REGENERATOR
SC	STUB COLUMN
MC	MAIN COLUMN
SS	SLURRY SETTLER
LCOS	LIGHT CYCLE OIL STRIPPER
V4 ·	MAIN COLUMN OVERHEAD RECEIVER

HEATER	
AH	AIR HEATER

HEAT EXCHANGERS	
E1	SLURRY/STEAM GENERATOR
E12A	CLARIFIED OIL/RAW FEED
E13	STEAM RAW FEED
E14	LIGHT CYCLE OIL/RAW FEED
E15	SLURRY/RAW FEED

WATER COOLED COOLERS	
E2	TRIM CONDENSER
E9	CLARIFIED OIL
E11	LIGHT CYCLE OIL
E12B	CLARIFIED OIL

AIR FIN COOLER	
MCOC	MAIN COLUMN CONDENSER

1. Schemes already implemented in Zarqa refinery

It was learned from private discussions and communications that the refinery has already implemented several schemes for energy conservation in categories (b), (c) and (d) listed above. However, these schemes are minor compared with those of category (a) as the amount of savings in terms of fuels are modest. In addition, the investments needed were not large, and, most of all, they were implemented by the refinery authority directly using local material and human resources:

Insulation of fuel tanks: A total of three fuel oil tanks with 70,000 m^3 capacity were insulated with local rock wool. These tanks were heated using steam to a temperature of 70°C. The insulation energy saving is estimated to be equivalent to 2,500 Te/year, valued at $212,500/year, and at a cost of $1.6 million for a total surface area of 9,450 m^2.

Improving debutanizer feed preheat in naphtha hydrotreater unit: The waste heat of the splitter bottom product stream was utilized to heat the debutanizer feed in addition to heat transferred from debutanizer bottoms. The fuel savings are estimated at 1,100 Te/year, valued at $93,500/yr.

Installation of soot-blowers at the heaters of VDU2 and CDU3: The stack temperature of both the heaters reached 550°C due to ash deposition on the convection section tubes, reducing efficiency to 70%. With the installation of soot-blowers, the stack temperature was reduced to 440°C, with efficiency reaching 78%.

Additional steam generation from hot product streams in VDU1 and asphalt plant.

2. Suggested schemes of energy conservation

Since most of the modest-size schemes for energy conservation have already been implemented, this paper shall concentrate on schemes that fall under category (a) which involve recovery of the flue gas heat of various process heaters, through the installation of air preheaters or waste-heat boilers.

3. Schemes to recover heat from flue gas by installation of air preheaters and waste-heat boilers

As discussed in chapter IV, section D of this report, the installation of air preheaters to recover heat from flue gas constitutes the most efficient and cheapest way of heat recovery. It is estimated that furnace efficiency could be increased to about 90% by lowering the temperature of flue gas to the minimum allowed by the dew point of the flue gas (i.e. about 25-30°C). The minimum temperature selected for this report is 180°C.

Scheme 1: Installation of air preheater in CDU3

Capacity of the unit: 7,500 T/d
Heat output of the furnace: 35 million kcal/hr

Present conditions

Temperature of flue gas: 500°C
Efficiency of the furnace: 72%
Heat input = 35 ÷ 0.72 = 48.61 million kcal/hr.......(i)

After installation

Temperature of the flue gas: 180°C
Efficiency of furnace: 90°C
Heat input = 35 ÷ 0.9 = 38.89 million kcal/hr.......(ii)
Heat saving = (i) - (ii) = 9.72 million kcal/hr
Roughly 5% of this saving will be used for driving air preheater fans (force drive and induced drive),
i.e., net heat saving = 9.23 million kcal/hr
since 1 ton of fuel oil = 10.1 million kcal
Annual savings in fuel oil = (9.23 ÷ 10.1) x 24 x 330
= 7,240 T/yr
1 ton of fuel oil = $85
Annual savings = $615,480

Another quick and conservative estimate of energy savings for air preheaters[3] is to assume a 1% reduction in fuel for every 18°C lowering of flue gas temperature:

In this case, the temperature difference is 500-180=320°C,
i.e. 18% savings of fuel
since heat input to furnace = 48.6 million kcal/hr
i.e. savings = 48.6/0.18
= 8.75 MM kcal/hr
Equivalent to = 6860 T/yr fuel savings
or = $583,200

Scheme 2: Installation of air preheater in CDU2

Capacity of the unit: 2,000 T/d
Furnace heat output 8 million kcal/hr

Present conditions

Temperature of flue gas: 500°C
Efficiency of furnace: 72%
Heat output = 8 ÷ .72 = 11.1 million kcal/hr

After installation

Temperature of flue gas: 180°C
Efficiency of furnace: 90%
Heat output = 8 ÷ 9 = 8.89 million kcal
Heat saving = 2.21 million kcal/hr

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[3] C.L. Brown and D. Figender, "Preheat Process Combustion Air", p. 76, EMH.

Net heat savings = 2.1 million kcal/hr
Annual fuel oil savings = 1,647 T/yr
Annual savings = $139,972/yr

Scheme 3: Installation of air preheater in VDU2

Capacity of unit: 1,100 T/d
Heat output of furnace: 3.5 million kcal/hr

Present conditions

Temperature of flue gas: 550°C
Efficiency of furnace: 70%
Heat input = 3.5 ÷ .9 - 3.89 million kcal/hr
Heat savings = 1.11
Net heat saving in FOR = 1.05 million kcal/yr
Annual saving in FO = 827 T/yr
Annual savings = 70,253/yr

Scheme 4: Installation of air preheater in VDU1

Capacity of unit: 1,000 T/d
Heat output of furnace: 3.0 T/d
Net heat savings = 0.91 million kcal/hr
Annual savings in fuel oil = 710 T/yr
Annual saving = $60,345/yr

Scheme 5: Installation of waste-heat boiler to recover heat from flue gas of the platformer unit

Capacity of unit: 1,000 T/d
Heat output of the 4 fire heaters: 20 million kcal/hr
Stack temperature: 700°C
Furnace efficiency: 60%
Adding waste-heat boiler by cooling flue gas to 180°C will recover about 10 million kcal/hr, which is equivalent to 10 • 526 ÷ 566 = 9.29 million kcal/hr of MP steam[4/]
Annual fuel savings = 7,285 T/yr
Annual saving = $619,210/yr

Scheme 6: Installation of CO-boiler in the FCCU regenerator

Capacity of the unit: 650 T/d
Temperature of flue gas for steam generator: 800°C
Additional fuel required: 0.14 T/hr
MP steam generator: 16 T/hr
Heat value of steam: 16 x 526 = 8.42 million kcal/hr

[4/] Bechtel Corporation, "Report on energy conservation study in industry in Jordan", 1986.

Minus heat value of additional fuel: 0.14 • 10.1 = 1.41
Net heat savings = 7.01 million kcal/hr
Net fuel savings = 5,497 T/hr
Net savings = $467,240/yr

D. Investment costs of schemes for Zarqa refinery

As indicated in chapter II, section F of this report, the following formula is used for relating costs and capacity

$$\frac{\text{Cost (a)}}{\text{Cost (b)}} = \left(\frac{\text{capacity (a)}}{\text{capacity (b)}}\right)^{0.6}$$

assuming 5% escalation of costs per year.

Aburas, Lloyd and Webster[5] have indicated two important cost indices:

(i) Air preheater for an 11,000-t/d capacity heater at a cost of $1.5 to $2 million for 1988;

(ii) Waste-heat boiler for 1,200-t/d capacity heaters at a cost of $2 million to $5 million for 1988.

These two cost indices will be used to estimate the cost of investment for each scheme mentioned according to the following:

Scheme Number	Investment cost 1993 (dollars)
1	1 383 000
2	625 600
3	437 200
4	413 300
5	3 000 000
6	2 317 000

E. Economic evaluation of schemes for Zarqa refinery

With the prospective energy schemes having been identified in section C, including annual fuel savings, and the investment costs for such schemes identified in section D, these schemes will be evaluated economically in the present section in two ways:

(1) Payout time (year) = $\frac{\text{Investment (\$)}}{\text{Annual Saving (\$/yr)}}$

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[5] "Waste Heat Recovery in Jordan Petroleum Refinery", HPI, November 1988.

(2) Rate of return on investment:

This is estimated from the monogram in figure 5 and parameters in chapter II, section I for each project.

(3) A summary of all economic parameters for all the schemes is shown in table 5.

F. Conclusions and recommendations for Zarqa refinery

A total of six major schemes were identified for detailed technical and economical analysis; the summary of the results are shown in table 5.

The payout time of these schemes varied between 2.2 and 6.8 years and the rate of return on investment varied from over 100% to small values. Hence there is a wide divergence in the choice of projects, which is not unexpected in economic analyses of such schemes.

One of the most critical factors in the feasibility of such a project is the cost of fuel and the magnitude of annual savings in fuels. The projects with the largest fuel savings are the most attractive since payout time varies between two and five years, which is economically reasonable and acceptable for such projects (nos. 1, 2, 5, and 6).

The most attractive projects are those that utilize an air preheater compared to those where waste-heat boilers are selected for heat saving, for example, heat recovery from flue gas of crude distillation units (CDU), since these units have the highest capacity of any of the refinery units and their heaters consume the largest share of fuel used.

If one looks at all these projects as one integrated project for heat recovery in the refinery, it can be seen that such an integrated project is also attractive, with payout time of four years and a rate of return of about 27%.

At least four projects are economically and technically attractive and their order of priority as follows:

(a) Installation of air preheater in CDU3;
(b) Waste-heat boiler to reformer;
(c) CO-boiler to FCCU.

Table 5. Zarqa refinery--summary of economic evaluation of schemes

Scheme number	Description	Capacity (tons/d)	Annual savings F.O. (tons)	Annual savings (US dollars)	Investment cost (US dollars)	Payout time (years)	Rate of return on investment
1	Installation of preheater in CDU3	7 500	7 240	615 480	1 383 000	2.2	100%
2	Installation of preheater in CDU2	2 000	1 647	139 972	625 600	4.5	25%
3	Installation of preheater in VDU2	1 100	827	70 253	437 200	6.2	low
4	Installation of preheater in VDU1	1 100	710	60 845	413 300	6.8	low
5	Waste-heat boiler in reformer	1 000	7 285	619 210	3 000 000	4.8	20%
6	CO-boiler in FCCU	650	5 497	467 240	2 317 000	5	20%
	Total			1 972 500	8 176 100	4.1	27%

VII. CASE II: ADEN REFINERY IN YEMEN

The Aden refinery was commissioned in 1954 by the British Petroleum Co. (BP), which owned and operated the refinery. By agreement, the refinery was handed over to the People's Democratic Republic of Yemen (PDRY) in 1977. Very minor investments had been allocated to the development or upgrading of the refinery since 1967 except for the addition of a vacuum distillation unit, an asphalt and an LPG plant in 1986.

The original refinery was a simple topping-reforming plant designed to produce fuel for local consumption. However, the main aim of the refinery was the production of bunker fuel oil for ships and tankers passing through the port of Aden since fuel oil accounted for about 50% of the products. However, with time and the diminishing importance of Aden as a major port in the area, the refinery was operated to provide for domestic product requirements as well as for various oil companies to process their crude against payment of processing fee.

Because of the age of the refinery, its simple mode of operation and the lack of investment to update or to renovate as well as the high cost of operation and maintenance, processing contracts became unattractive to oil companies and the urgent need to upgrade the refinery became obvious, especially with the discovery of oil in Yemen as well as the increase in demand for petroleum products in Yemen.

The total refining capacity is about 8 million tons per year (about 150,000 b/d); however, the current operational throughput is about 4 million tons/year, of which approximately half is under processing deals.

The refinery has no conversion capability and it has been reported that major modernization and upgrading programmes are still under consideration, which could make the refinery more attractive economically for international processing deals.

A. Brief description of major process units of the Aden refinery

Figure 42 shows a block flow diagram of the refinery in its present status. The units of the refinery produce the following range of products: Motor gasoline, kerosene, aviation fuel, light distillate feedstock, diesel oil, fuel oil, asphalt and small quantities of LPG.

1. Crude distillation units (CDU)

There are two identical, two-stage crude distillation units, each having a capacity of 3.5 million tons/yr, with integral stabilizers which separate the feed crude oil into eight primary products. Boiling ranges are selected to permit the production of specification products by blending.

2. Vacuum distillation unit (VDU)

This unit, which is of relatively recent design, is capable of processing 500,000 tons/yr of 345°C TBP (true boiling point) and heavier residue from any of four Middle East crude oils to produce vacuum residue, after additional

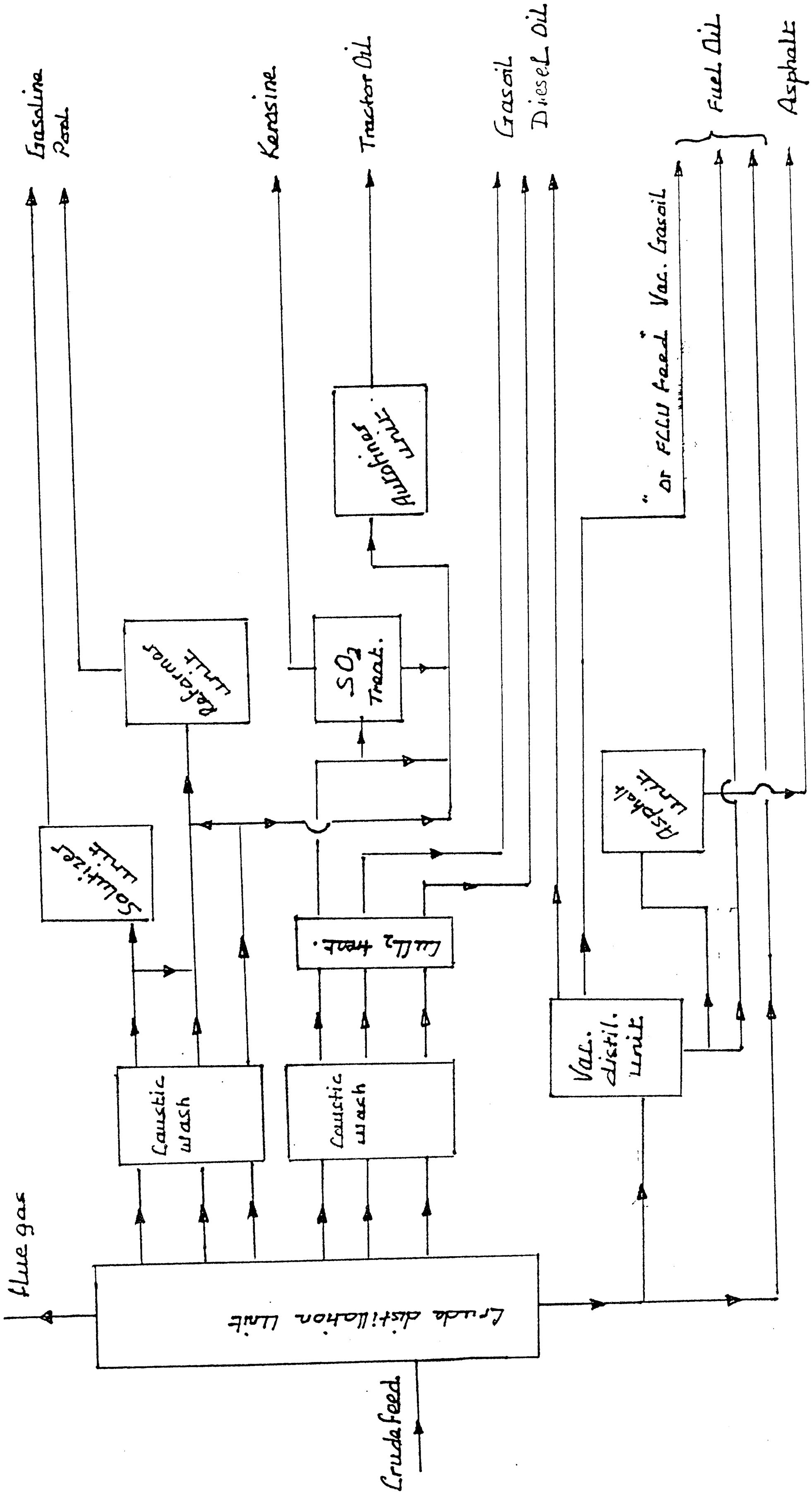


Figure 42. Aden refinery (present status)

processing, for sale as asphalt as well as premium grade vacuum gas oils (VGO) suitable for FCC feedstock. Provisions are also included to recover the contained diesel boiling range components as a separate product.

3. Platformer

This unit has a charge capacity of about 600,000 tons/yr of heavy and medium naphtha cuts, for conversion into 90 octane reformate for gasoline blending.

4. Solutizer treating units (No. 4 units)

For removal of mercaptans from light straight-run gasoline to improve odor and lead response of finished gasoline. The capacity of this unit is about 300,000 tons/yr.

5. Copper chloride treating unit

Four fixed copper chloride units "sweeten" lighter products in conjunction with the solutizer units.

6. Sulphur dioxide (SO_2) extraction unit

An SO_2 unit is available to improve the burning quality of premium- and regular-grade kerosene. It also produces extracts as a component for the autofiner unit. The raw kerosene from distillation units is treated with liquid SO_2 to remove components which have poor burning properties (capacity 400,000 tons/yr).

7. Autofiner unit (capacity 100,000 t/y)

This unit removes sulphur from gas oil and kerosene treatment plants. The feed to the autofiner is a mixture of naphtha, kerosene and SO_2 extracts. The feed is desulphurized with improved properties. The finished product is tractor oil (T.V.O).

8. Caustic washing system

Eight systems of caustic wash with total capacity of 1 million tons/year are available (four systems on each CDU). The function of caustic wash is to remove organic acids and some sulphur compounds in order to improve the color and odor of primary products prior to further finishing treatments.

9. Asphalt unit

This unit has a capacity of 0.5 million ton/yr of blown asphalt.

10. Refinery steam and electric power plants

The refinery has a steam power station. This plant supplies electric power, process steam, distilled water and cooling water to the refinery. The power plant has three 7.5 MW turbo-generator units (plus a 7,800 kW diesel stand-by unit), four boilers having a combined capacity of 73 tons/hr of steam of 40 kg/cm^3 and 400^oC.

B. Renovation plans of Aden refinery

The existing facilities of the Aden refinery are nearly 35 years old. In order for the refinery to have a modern refining configuration capable of producing quality products economically and for it to be competitive in the international processing market, a renovation plan has been proposed, since the continuation of present refinery operations will increase maintenance and repair costs with time.

Furthermore, some of the existing refining units which were selected prior to construction in 1954 are technically and economically out of date and are not suitable to meet the product specifications required in the current domestic and international market.

The renovation plan under consideration foresees two phases of development as follows:

Phase 1: Energy conservation and improvement of product quality;

Phase 2: Improvement of the refinery utility system and hence further reduction in operational costs.

The renovation plan will involve the following major items with the aim of upgrading product quality and reduction of costs by means of rehabilitation of older units and facilities and the utilization of new units as well as replacement of outdated units with modern units:

(a) Closure of existing units due to age, inefficiency or obsoleteness:

(i) SO_2 extraction units
(ii) Solutizer units
(iii) $CuCl_2$ sweetening unit
(iv) Autofiner units
(v) Power station;

(b) The construction of new units to replace closed units:

(i) Naphtha hydrodesulphurization unit (HDS) of 6 million ton/yr capacity;

(ii) Gasoline Merox unit, for removal of mercaptans and for sweetening (improvement in odor and color), 700,000 ton/yr capacity;

(iii) Kerosene Merox unit, 1 million ton/yr capacity;

(iv) Light gas oil hydrodesulphurization (LGO HDS), 1.2 million ton/yr capacity;

(v) Hydrogen plant;

(vi) Gas treating plant (5,000 Nm^3/hr);

(vii) Sulphur recovery plant (46 ton/d);

(viii) Control rooms for units and central;

(ix) New power station:

Boiler (125 ton/hr x 3)
Power generation (10 MW x 3)
Diesel engine generator (1,800 kW)

(c) Rehabilitation and replacement of the following units:

(i) Crude unit heater replacement;
(ii) Air cooler installation for crude unit overhead condenser;
(iii) Crude charge pump replacement;
(iv) Reformer catalyst replacement;
(v) Reformer heater replacement;
(vi) Reformer stabilizer modification;
(vii) Heater modification for vacuum unit;

The renovation plan will basically replace or modify most units of the refinery, but no additional conversion capacity is installed, i.e. no FCCU or other modern conversion units are included in the renovation plan. The configuration of the refinery after the implementation of the renovation plan is expected to be as shown in figure 43.

C. Energy saving schemes in Aden refinery

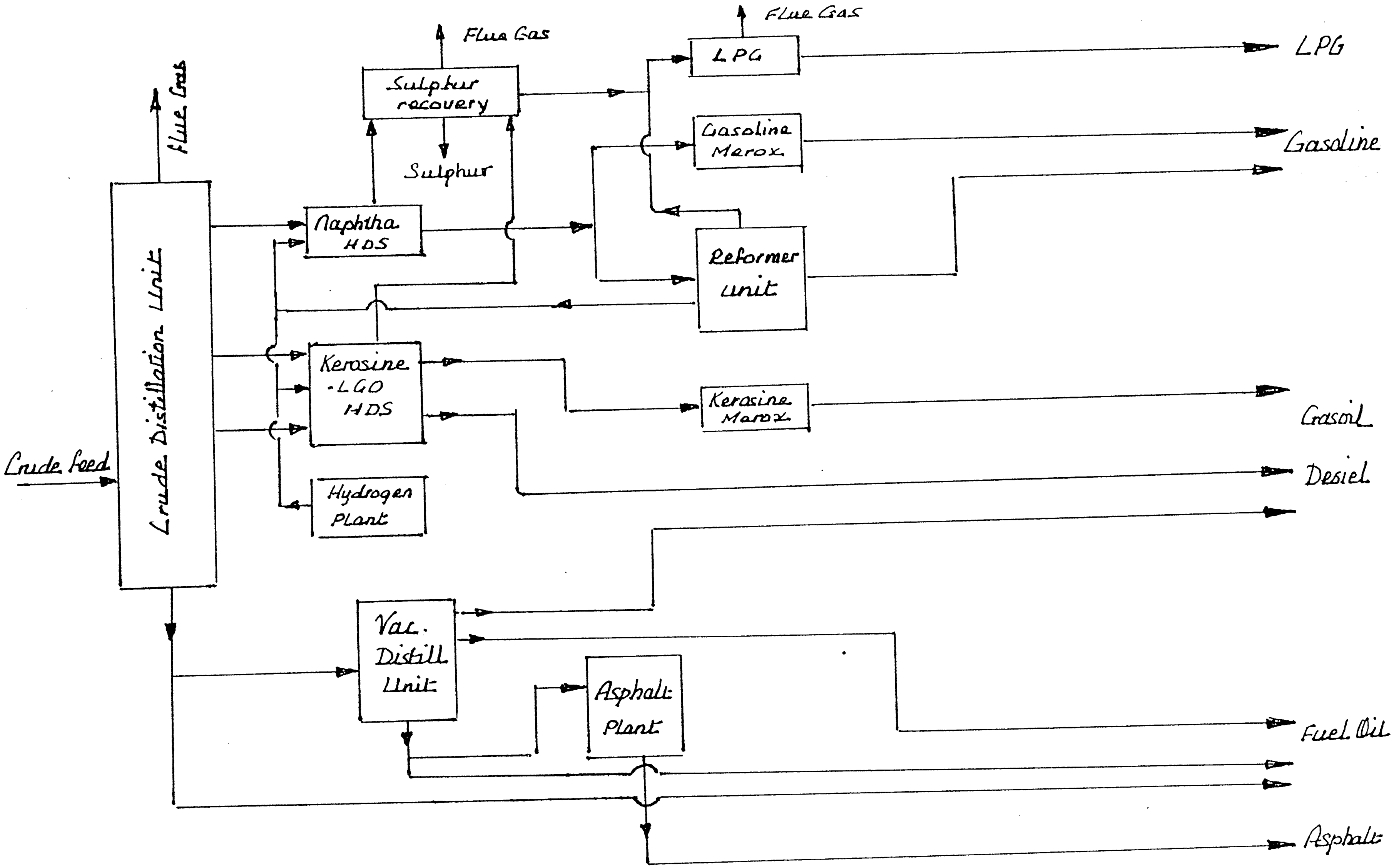
As explained previously, the Aden refinery is undergoing major renovation, hence individual schemes for energy conservation do not have the same meaning as compared, for example, to the schemes for the Zarqa refinery, since the latter is an established refinery with relatively modern units and, most important, it has been modified and upgraded continuously since its commissioning.

In the case of the Aden refinery, the concern is with major upgrading projects which deal with replacement of complete processing units or the overhauling of older units. Hence, individual identifications of energy saving schemes are meaningless since: (a) if the refinery were not renovated, then energy schemes would not add to fuel savings because the overall inefficiency of the heat balance of the refinery would not be affected, and (b) if the renovation plans were implemented, then one would presume that energy saving schemes would be incorporated into the new design.

Nevertheless, some schemes can be identified and considered which are expected to be incorporated into renovation plans or could be incorporated at a later stage. These schemes are:

Crude unit heater replacements
Rearrangement of heat exchangers in CDUs
Modification of reformer heater
Rearrangement of reformer heat exchangers
Insulation of fuel oil tanks
Replacement of the power station

Figure 43. Aden refinery "A possible configuration"



It must be re-emphasized here that because of difficulties encountered in obtaining specific data on the performance of the proposed new units, the computations for energy savings and their economic evaluation are as dependable as the assumptions used but are within the acceptable limits and give the right order of magnitude. In addition, as explained in chapter VI of this report regarding the Zarqa refinery, some schemes cannot be evaluated technically without proper and actual technical, operational and energy audits of the refinery process and utility units, where actual data are monitored and measured. Hence, for such a scheme only qualitative ideas will be suggested.

1. Quantitative energy saving schemes

(a) Scheme 1: crude unit heater replacement

There are two identical crude distillation units, each with a capacity of 10,000 tons/day. The old heaters are to be replaced with new crude oil charge heaters complete with air preheaters and other accessories such as forced and induced fans, stack and central and monitoring equipment.

The specification of the new heaters are as follows:

Crude oil charge: 10,000 ton/day
Inlet temperature of crude: 210°C
Outlet temperature of crude: 340°C
Weight percentage vaporization of crude: 60%
Heat adsorbed duty for such conditions:[1] 50 million kcal/hr

Energy savings:

	Existing heater	New heater
Absorbed duty:	50	50
Assumed excess air:	25%	20%
Furnace efficiency:	70%	90%
Stock temperature:	500°C	180
Fired duty of furnace: (mm kcal/hr)	50÷0.7 = 71.4	50÷0.9 = 55.5

Savings = 71.4-55.5 = 15.9 million kcal/hr
1 ton of FO = 10.1 million kcal

Savings = 1.574 ton/hr
Annual savings = 12,468 ton/yr (per unit)
Annual savings= $1,059,780 (per unit)

(b) Scheme 2: modification of reformer heater

There are two major schemes for recovery of heat from the flue gas of reformer units:

Installation of air preheaters
Installation of waste-heat boilers

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[1] W.L. Nelson, Petroleum Refinery Engineering, p. 414.

Since the renovation of the Aden refinery includes the replacement of the refinery's powerhouse, the installation of a waste-heat boiler is not a priority and the obvious choice will be the installation of an air preheater, which requires lower investment cost and, in any case, is more efficient as a scheme for heat recovery.

The capacity of the reformer unit is 600,000 tons/yr or 1,800 tons/yr
Temperature of the flue gas: 700°C
Absorbed duty of heaters: about 30 MM kcal/hr
Furnace efficiency: about 60%

With the installation of preheaters:

Temperature of flue gas: 180°C
Furnace efficiency: about 90%
Fired duty of heater without air preheater: $30 \div 0.6 = 50$
Fired duty of heater with air preheater: $30 \div 0.9 = 33.3$
Savings in energy = 50-33.3 = 16.7 million kcal/hr
Since 5% of this energy will be consumed in air preheater blowers (forced and induced)
The net savings in energy = 15.95 million kcal/hr
The savings per year of fuel oil = 12,430 tons/yr
The financial savings per year = $1,056,500

(c) Scheme 3: installation of fuel oil tanks

There are the following fuel oil tanks in the refinery:

Old tanks	(5)	44,500-ton capacity or 49,500m^3
New tanks	(1)	30,000-ton capacity or 33,300m^3
Total	(6)	74,500-ton capacity or 82,800m^3

The tanks are 32.2 m in diameter and 17 m high, i.e. a total surface area of 10,302 m^3.

In order to maintain the pumpability of the fuel oil, the temperature in the tank should be kept at about 75°C:

Heat loss of uninsulated tanks is 4.685 million kcal/hr
Heat loss of insulated tanks is 0.349 million kcal/hr
Assuming 60% of tanks are full:

Then savings in heat loss: 0.6 (4.685-0.349)
= 2.6 million kcal/hr
or = 0.257 ton of fuel/hr

Annual savings of fuel = 2,039 tons
Annual financial savings = $ 173,300

2. Qualitative schemes of energy savings

These schemes will only be mentioned here to show their significance in energy conservation:

(a) Heat exchanger modification for CDU and reformer units: it would be impossible to give a quantitative assessment of such a project given the present status of the refinery. The project can only be evaluated properly when complete heat and energy audits are undertaken during the design process of the renovation plan;

(b) Replacement of the powerhouse of the refinery: in strict terms, this is not an energy scheme as much as a major renovation project.

D. Investment cost of schemes for the Aden refinery

The same methodology as in chapter VI, section D will be applied:

Scheme 1: Crude unit heater replacement

The Bechtel report[2/] indicates a cost of $1,633,000 for a 3,000 t/d capacity unit in 1986. The equivalent cost for a 100,000 t/d unit in 1993 prices is $2,300,000

Scheme 2: Reformer heater modifications

With a capacity of 1,800 t/d, the cost of such a unit will be around $600,000 (see table 5).

Scheme 3: Insulation of fuel oil tanks

There are many ways of insulating tanks, depending on the type and cost of the insulating material. However, the same parameters used in the Bechtel report will be used to estimate the cost of the insulations which shows a cost index of \$120/m^3 of surface insulated. With a 10,302 m^2 surface area, the cost of insulation is $1,250,000.

E. Economic evaluation of schemes for the Aden refinery

Similar treatment of data for the Aden refinery as those for the Zarqa refinery shown in chapter VI, section E is used for payout time and rate of return. Table 6 provides a summary of all economic parameters of the schemes.

F. Conclusion and recommendations for the Aden refinery

Were it not for the peculiar situation of the Aden refinery, one would draw conclusions and recommendations from the analysis of the results of the economic evaluation of the energy conservation schemes suggested earlier.

There are plans for major renovation and rehabilitation of the Aden refinery which, although still under consideration, will have to be implemented sometime in the near future. The refinery in its present condition cannot continue operating indefinitely, as rising maintenance and repair costs, not to mention obsolete processing units and inferior product quality, will render future prospects very bleak indeed.

[2/] Bechtel Corp., "Report on Energy Conservation Study in Industry in Jordan", 1986.

Table 6. Aden refinery--summary of economic evaluation of schemes

Scheme Number	Description	Capacity	Annual savings F.O. (tons)	Annual savings (US dollars)	Investment cost (US dollars)	Payout (years)	Rate of return on investment
1	Crude units heater replacement	10 000 t/d	12 468	1 059 780	2 300 000	2.2	high > 100
2	Reformer heater modification	1 800 t/d	12 430	1 056 500	600 000	0.7	high > 100
3	Insulation of fuel oil tanks	10 302 m^2	2 039	173 300	1 250 200	7.1	low

All the schemes suggested are economically viable, except for the insulation of the tanks where the cost of investment is high. For insulation operations, however, the costs tend to go down steeply due to the prospects of using local materials and labour since no special technical requirements are warranted.

In conclusion, individual conservation schemes are of no use to the refinery in its present status. What is required, sooner or later, is the implementation of the renovation plan. However, it is obvious that the delay in implementation is due to lack of capital for such a plan which could run into the hundreds of millions of dollars.