

MINISTRY OF FUEL AND POWER

Report on the Petroleum and Synthetic Oil Industry of Germany

TO THE RIGHT HON. EMANUEL SHINWELL, M.P.

BY A MISSION FROM .

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1947

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Editor's Preface

This report deals extensively with three specialised fields, namely Carbonisation (Gas Engineering), Hydrogenation and Fischer-Tropsch Synthesis (Chemical Engineering), and Crude Oil Production and Petroleum Refining (Petroleum Engineering). Each section has been written by persons engaged in the appropriate field and the sections will therefore contain technical terms and abbreviations having a special significance to those with knowledge of that field. In order to extend the usefulness of the report to the non-expert without resorting to the use of clumsy phraseology, technical terms and abbreviations have been retained, and a glossary of them has been compiled in Appendix 3.

Similarly, different industries and even different organisations within an industry, use different units (for instance volumes may be measured in cubic metres, cubic feet, Imperial gallons or US gallons). The metric system, which is universally employed for technical purposes on the Continent, has been accepted by many large organisations in the UK, and therefore no attempt has been made to transform metric units into English units.

The unit of weight is the metric ton of 1,000kg and is referred to as the tonne (te). Volumes are given in cubic metres (m^3), and volumes of gases are always given as volumes at 0°C and atmospheric pressure, unless otherwise specified. Composition of gases is given as percentage by volume (unless otherwise specified).

Pressure is given in atmospheres (ats). An atmosphere in Germany generally implies a pressure of $1\text{kg}/\text{cm}^2$ which is equivalent to $14.233\text{lb}/\text{sq.in}$ or 735.6mm Hg . In this country it is customary to take 1 atmosphere pressure as $14.695\text{lb}/\text{sq.in}$ or 760mm Hg .

A table of conversion factors is given in Appendix 4.

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by British Patents or Patent application, this
publication cannot be held to give any protection
against action for infringement.*

Report on the Petroleum and Synthetic Oil Industry of Germany

A—Introduction

1. PREFACE

This report is submitted to the Minister of Fuel and Power by the Committee appointed in November, 1944, to study the technical information obtained from German oil plants. The report is based on information obtained during visits, and by study of captured documents. So great an amount of documentary data was obtained that even now it has not all been sifted.

For further details, the Field Team Reports on individual plants should be read, and the original documents consulted. A list of the relevant reports is given in Appendix 2.

This report starts with a note on the organisation for the investigation. There follows a short survey of the general oil position in Germany. The next section gives a summary of the technical information obtained. For completeness, brief descriptions of the process are included. Finally, there are the detailed technical reports subdivided into appropriate sections.

2. NOTES ON ORGANISATION

On 8th November, 1944, a Committee was appointed by the Minister of Fuel and Power to make arrangements for studying the fuel plants in Germany when they became uncovered by the Allied advance.

It was decided to divide the work under the following headings:—

- i. Carbonisation and Gasification of Coal.
- ii. Hydrogenation Processes.
- iii. Fischer-Tropsch Process.
- iv. Crude Oil Production.
- v. Petroleum Refining.
- vi. Lubricating Oil Production.
- vii. Testing and Evaluation of Products.

Appropriate members of the Committee were appointed to be in charge of each of these sections and, with the co-operation of Government Departments and of various private firms, a team of scientific and industrial staff was built up to cover the ground under each of these headings. The staff provided by private firms was seconded to the Ministry of Fuel and Power to carry out this work.

A full list of the teams is given in Appendix 1.

It was recognised that the study of the various targets would necessarily be undertaken as a joint operation with US representatives. In due course teams of US personnel arrived in this country, and joint UK and US teams were organised to visit each target as it was uncovered.

The organisation became known as the "Group 30, Fuels and Lubricants" team of the Combined Intelligence Objectives Sub-Committee (CIOS), and was responsible to Supreme Headquarters, Allied Expeditionary Forces. In addition, some members of the organisation were allotted to each Army Group in the field for preliminary

assessment of targets, in the organisation known as Consolidated Advance Field Team (CAFT).*

It was decided that all representatives should go as members of the Army, and all the British representatives were commissioned with appropriate ranks for the purpose.

The general arrangement was for the members attached to the Army Groups first to inspect each target as it was captured, and for the combined team to follow as quickly as possible. In spite of the obvious difficulties which arose through transport problems during the rapid advance of the Armies, all the targets concerned were as a rule inspected and German personnel interrogated within a few hours of their capture. The investigations in the field commenced on March 7th, 1945.

The primary objective was to obtain intelligence of military value for the further prosecution of the war, and in particular the war against Japan. The rapid attainment of victory made this objective less important than that of putting on record the processes used by the Germans in obtaining fuels and lubricants during the war. Nevertheless a considerable amount of military intelligence was brought back by these teams before the collapse of Germany, and in particular precise information on the location of underground plants still in enemy hands.

A Field Team Report was issued by each team on its return to the UK; most of these reports have now been published and are generally available.

The reports were written generally on the basis of visual inspection of the plant and interrogation of the German personnel available after capture of the plant. All documents judged likely to be of importance were removed from the plants and taken back to London, where they were available to the British and US teams for further study. Arrangements were made to microfilm all the important documents thus obtained, and microfilm copies are also available both in the UK and in the US.

3. GENERAL POSITION REGARDING OILS IN GERMANY

Germany had only a limited supply of natural petroleum, and thus an important part of the German rearmament programme was to build synthetic oil plants based on her supplies of bituminous and brown coal.

Oil made from coal by various processes reached a maximum output of over 5,000,000t/yr. The output of oil rose steadily until April, 1944, when the Allied

* After the dissolution of SHAEF, the investigations were continued by separate organizations British Intelligence Objectives Sub-Committee (BIOS) and Field Information Agency Technical (FIAT) for Britain and United States respectively. Appendix 2 contains therefore CIOS, BIOS and FIAT reports together with a limited number of JIOA reports which arose from an interim period.

2 REPORT ON THE PETROLEUM AND SYNTHETIC OIL INDUSTRY OF GERMANY

TABLE I
ANNUAL RATE OF OIL PRODUCTION
(tonnes)

	Hydrogenation	Fischer Tropsch synthesis plants	Refining of German and Austrian petroleum	Brown coal and bit. coal tar distillation	Benzole	Total
Aviation fuel	1,900,000	—	—	—	50,000	1,950,000
Motor spirit	350,000	270,000	160,000	35,000	330,000	1,145,000
Diesel oil	680,000	135,000	670,000	110,000	—	1,595,000
Fuel oil	240,000	—	120,000	750,000	—	1,110,000
Lubricating oil	40,000	20,000	780,000	—	—	840,000
Miscellaneous	40,000	160,000	40,000	50,000	—	290,000
	3,250,000	585,000	1,770,000	945,000	380,000	6,930,000

bombing brought about such a drastic reduction that by the end of August, 1944, supplies from these processes had fallen to a mere 120,000te/yr. Production never recovered.

Figure 1, which was compiled by the Germans, shows very clearly the steady growth of the German oil output, and its sudden reduction through bombing. The Allied victory can be due in no small measure to this most successful strategic bombing.

At the same time natural oil resources in Germany and Austria were developed to the limit, and reached an output of 2,000,000te/yr.

During the time when Germany had access to Rumania, and other controlled territory in Eastern Europe, considerable additional quantities of oil were obtained from these sources.

The total maximum quantity of oil available to the Germans was as much as 14,000,000te/yr, produced from the following sources:—

German and Austrian crude ..	2,000,000te/yr
Rumania and Controlled Territory ..	7,000,000 "
Various coal processes	5,000,000 "

Table I shows the annual production rate which was achieved in the early part of 1944, when German production was still near its maximum. The table shows the division of the overall German controlled production among products and among methods of manufacture. Products from Rumanian and Hungarian crude oil are not included in the table, which relates only to the production in Germany and Austria.

The table illustrates the following facts:—

Hydrogenation was the biggest "synthetic" oil producer. The most important product was aviation spirit, but the motor spirit and diesel oil outputs were also important.

The Fischer process was less important. A proportion of the production was used for chemical processes such as for the manufacture of synthetic fats.

The bulk of the lubricating oil was derived from petroleum, and a remarkably high proportion of the crude oil was recovered as lubricating oil.

Coal distillation products (apart from benzole) were used mainly as fuel oil. An important role of carbonisation, which does not appear in this table, was the provision of tar which was the raw material for some of the hydrogenation plants.

The large development of "synthetic" oil production, particularly by the hydrogenation process, was purely due to the desire for self-sufficiency, doubtless for war purposes, and was not due to any technical advance beyond the position known before the war.

Costs were entirely uneconomic compared with natural petroleum. The cost of motor petrol from Leuna, for example, the largest plant and operating on extremely cheap brown coal, was RM190 per tonne, equivalent at the pre-war rate of exchange of RM12.5 = £1, to 12.4d. a gallon, before providing any margin for profit. This was more than double the cost of imported motor spirit. Costs from bituminous coal were higher, and the costs of the Fischer process were similar.

German costs have been translated to present-day costs of coal and labour in the UK, and production from coal in this country would seem to be entirely uneconomic by either the hydrogenation or the Fischer process.

The study of the synthetic processes has nevertheless revealed much of technical interest, especially in the field of providing raw materials for chemical manufacture, for which the Fischer process is particularly adapted. German work on synthetic lubricating oils is also noteworthy.

The processes used for refining petroleum, and for producing high octane aviation fuel, were similar to those in general use, and development had in general lagged behind that of the Allies.

As German aviation fuel was based on coal hydrogenation products, the methods of achieving the desired performance differed from those of the Allies. The aviation fuel in use at the outbreak of war was a leaded fuel of 87 octane number. In 1940 a new fuel of 95 octane number was introduced. The aromatic content of the fuel was high enough to give it an equivalent performance in engines to the Allied 100 octane number fuel. In 1942 another fuel of still higher performance was introduced which was equivalent to the Allied Grade 150 fuel which was in use for special requirements in 1944.

4. SUMMARY

The main body of this report contains an account of the information obtained under the following headings:—

- i. Carbonisation and Gasification of Coal.
- ii. Hydrogenation Processes.
- iii. Fischer-Tropsch Process.
- iv. Crude Oil Production.
- v. Petroleum Refining.
- vi. Lubricating Oil Production.
- vii. Testing and Evaluation of Products.

There follows immediately a brief summary of the information gained under each of these headings. A note on estimated operating costs of the two synthetic processes follows these summaries.

1000 T_g/MONTH
INCL
LIQUIFIED GAS

350.

325.

300.

275.

250.

225.

200.

175.

150.

125.

100.

75.

50.

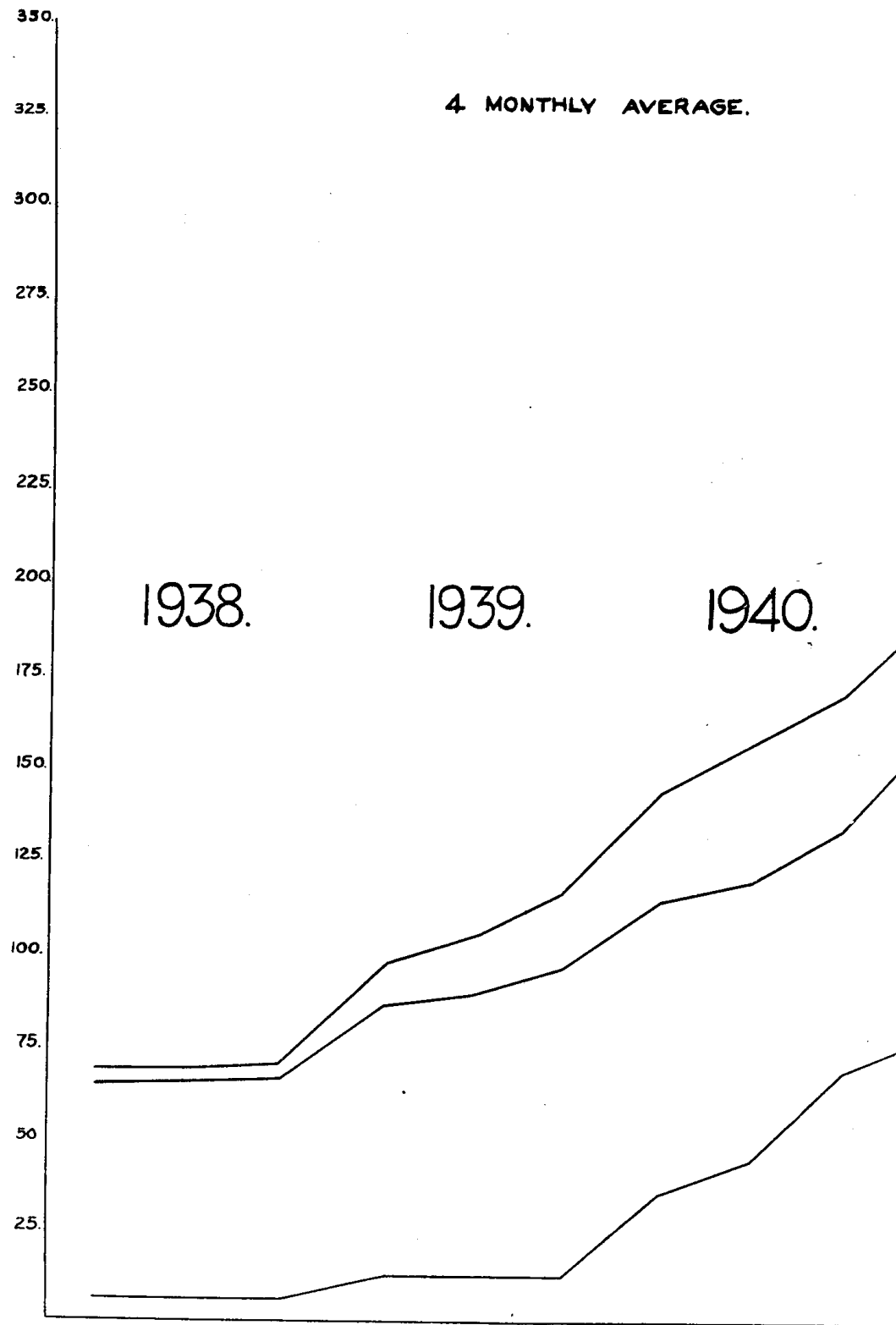
25.

4 MONTHLY AVERAGE.

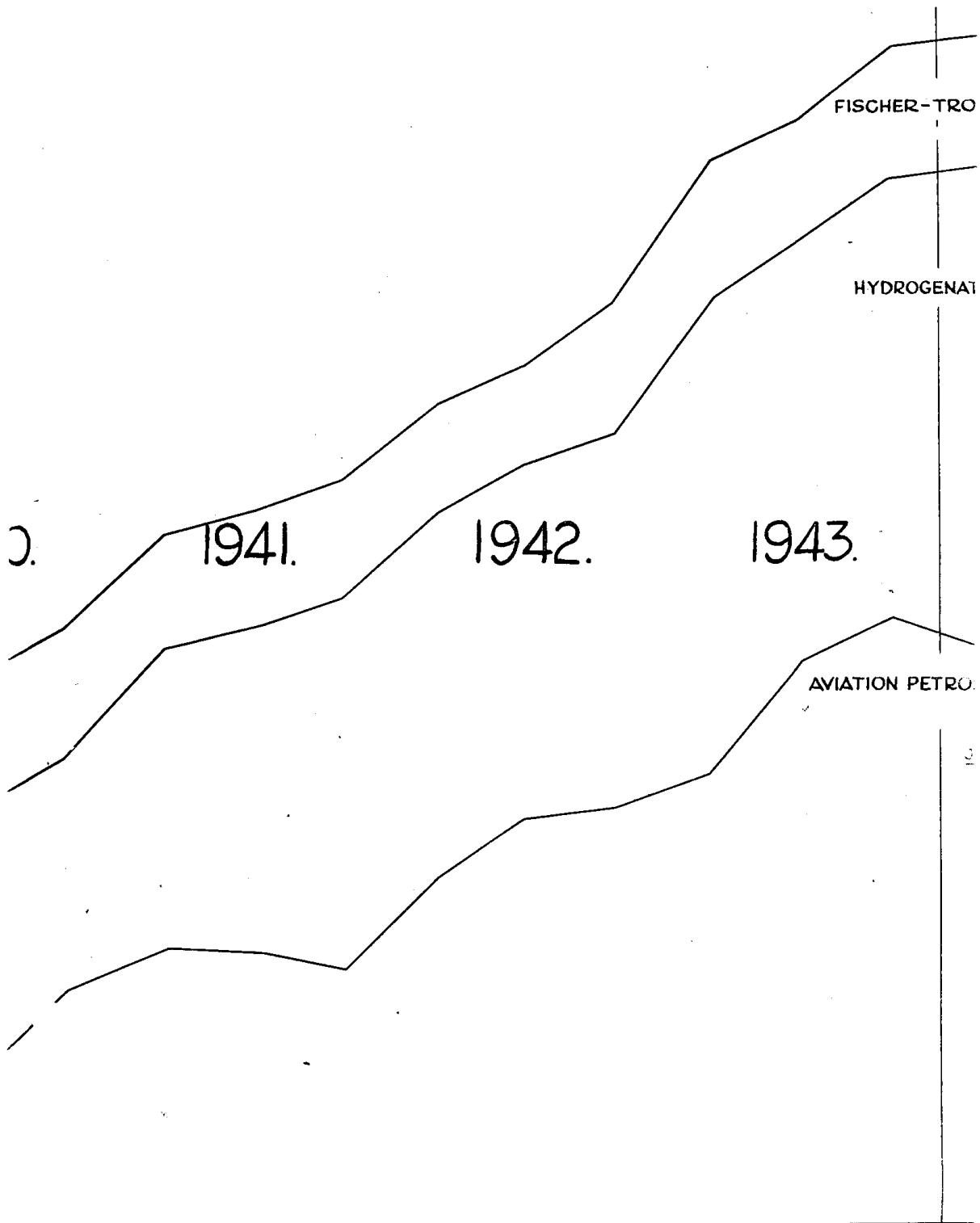
1938.

1939.

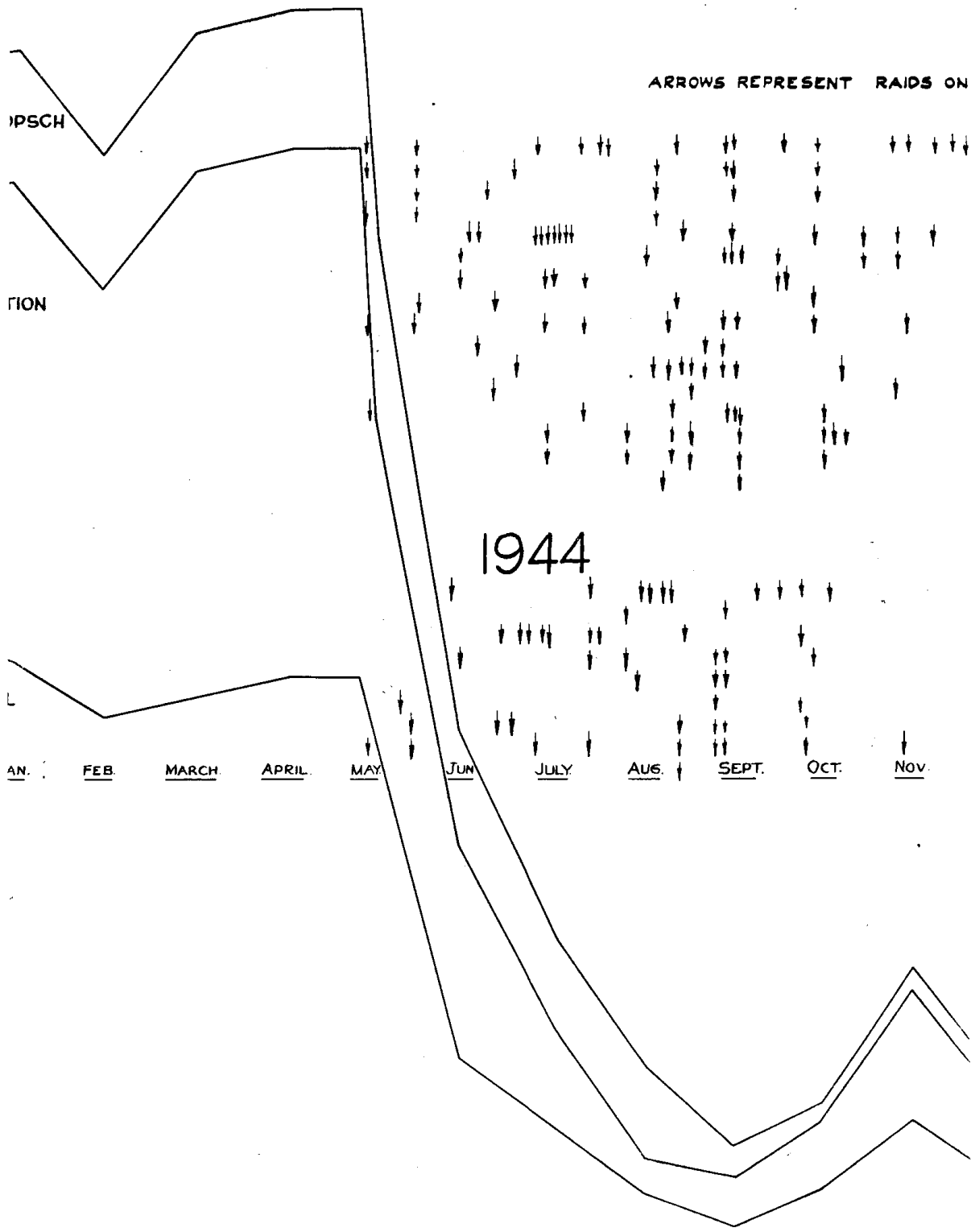
1940.



PRODUCTION OF HYDROGENATION AND APPROXIMATE



FISCHER-TROPSCH PLANTS IN 1000 ^{TE}/MONTH. FIGURES.

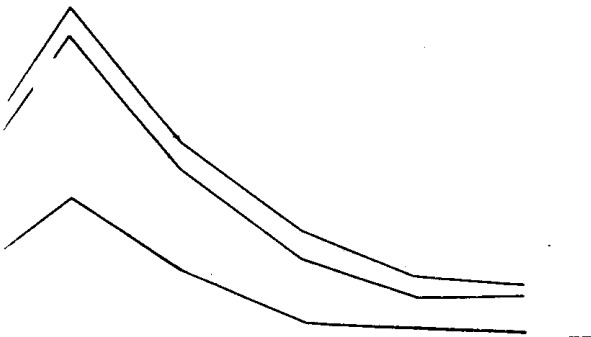


4.

The figure is a map of the northern Adriatic Sea. It shows the coastline of Italy to the east and the Strait of Gibraltar to the south. Eighteen sampling stations are marked with numbers 1 through 18. The stations are distributed across the sea area, with some clusters and others more isolated. The map is oriented with North at the top.

1945.

↓ ↓ ↓ ↓ ↓ ↓ ↓
NOV DEC. JAN. FEB. MARCH.



i. CARBONISATION AND GASIFICATION OF COAL

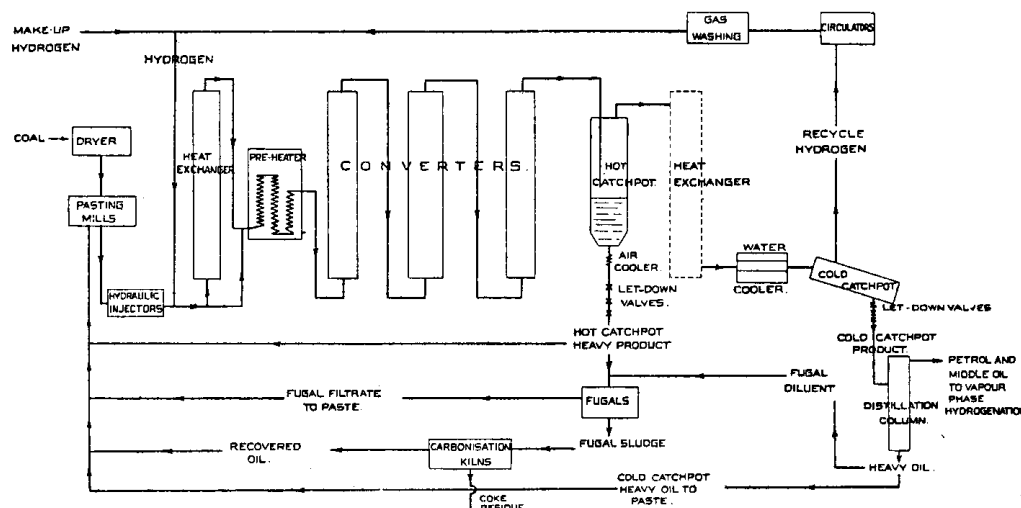
This subject is of great importance for the production of liquid fuels from coal. The Fischer process uses as raw material a mixture of hydrogen and carbon monoxide, and the preparation of this gas mixture counts for approximately 70% of the total cost of the final product. Similarly, in the hydrogenation process, some 50% of the cost is that of the compressed hydrogen, which is made from a gas mixture similar to that used for the Fischer process.

Carbonisation is also of importance for the preparation of tar oils, and particularly brown coal tar oils, which formed a large part of the raw materials used for hydrogenation. In addition, the carbonisation of coal provided benzole and tar oils suitable for use as fuel.

German developments have been directed to replacing the expensive bituminous coal coke by brown coal or brown coal coke. A second line of development has been the replacement of solid fuel by hydrocarbon gases, such as methane. Such gases are formed as by-products from synthetic oil processes, or derived from coke-oven gas.

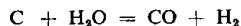
The new gasification processes have thus been directed to the treatment of brown coal and the information cannot be directly applied to British coals. The developments should, nevertheless, indicate the possible lines of progress suited to British conditions. The pressure gasification of coal to give a gas rich in methane is of general interest to gas works, as it may provide a method of balancing outputs of gas and coke.

FIGURE 2

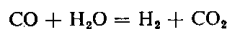


GENERAL SCHEME OF COAL HYDROGENATION

The first process worked out on a big scale for the preparation of hydrogen was devised by Bosch for ammonia synthesis before the 1914-1918 war, and the same general lines are still followed. In this process, bituminous coal is first carbonised to coke. The coke is then treated with steam in a water gas generator and the reaction which takes place can be represented as follows:—



The gas, after purification from sulphur compounds, is now treated with a further quantity of steam in the presence of an iron oxide catalyst to use as much as possible of the carbon monoxide in reducing steam to hydrogen by the reaction:—



The gas is then compressed. Carbon dioxide is removed at some intermediate pressure, usually between 10 and 50 atm, by scrubbing with water. The gas is finally purified from the residual carbon monoxide by scrubbing at the final working pressure with a solution of cuprous ammonium formate, or carbonate.

For making a gas for the Fischer process, only part of the carbon monoxide is used in reducing steam to hydrogen so as to give the required mixture of two volumes of hydrogen and one of carbon monoxide. Little or no compression is required.

ii. HYDROGENATION PROCESSES

The hydrogenation process was the most important source of synthetic oils in Germany. The original experimental work of Bergius was started before the first world war. The first commercial plant was at Leuna, which was started in 1927 and reached an output of 400,000 te/yr before the outbreak of the recent war. When the Nazi party came into power, an extensive building programme was embarked upon. At the outbreak of war the capacity of plants in production was 1,355,000 te/yr. By the end of the war the capacity of hydrogenation plants built was 4,000,000 te/yr, but the greatest recorded production was 3,250,000 te/yr. Practically all the German aviation spirit production of 2,000,000 te/yr was derived from hydrogenation plants.

The hydrogenation plants were big units, with outputs ranging from 200,000 to 700,000 te/yr. They used as raw materials brown coal or bituminous coal, tar from the carbonisation of both kinds of coal, pitch or petroleum residues. They made fuel oil, diesel oil, motor spirit and aviation spirit. In one case lubricating oil was an important product. Propane and butane were also made, and generally sold liquefied in cylinders as fuel for motor transport vehicles.

The yield of oil depended upon the raw material and product. The yield of motor spirit from bituminous coal, for example, was 60% by weight on the coal

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hydrogenated calculated on an ash- and moisture-free basis.

In considering the coal required per tonne of petrol, the fuel used for the manufacture of hydrogen, and needed for the generation of power and steam, must be included. The total required is approximately 6 tonnes of (bituminous) coal per tonne of petrol.

The hydrogenation process has frequently been described, but the following account is included for completeness. The diagram in Figure 2 should be consulted.

The hydrogen is made by the methods described in Section B5, and is delivered to the process at the operating pressure—from 250–700ats.

The coal is dried, pulverised, and made into a "paste" with approximately its own weight of heavy oil derived from the process. The paste is injected to the hydrogenation units by hydraulically operated ram pumps, delivering at the operating pressure. The catalyst, usually some form of iron, is added to the paste in the form of a fine powder. The proportion is usually of the order of 1% by weight.

The hydrogen is heated in heat exchangers and mixed with the coal paste. The hydrogen and the paste are heated together in a gas-fired heater to the reaction temperature, usually 450°C. The reaction is carried out at 250–700ats in converters which are heavy steel forgings usually some 5 feet in diameter and 40 feet long, built to withstand the operating pressure. This process is known as liquid phase hydrogenation.

The part of the product remaining as liquid, which contains residual solids, is separated in a "hot catchpot." The bulk of the oil made remains as vapour mixed with the excess of hydrogen. This is cooled in heat exchangers and coolers and the condensed oil is separated in a "cold catchpot."

The excess of hydrogen is recirculated to the process, and is purified from hydrocarbon gas en route.

The heavy oil residue is carbonised to recover as much oil as possible, and the solid residue is used as fuel. The distillate oil recovered in the cold catchpot is distilled by normal refining practice. The heavy oil, together with the oil from carbonisation, is used for preparing paste. The middle oil and petrol is then further treated by the vapour phase process. In this process, the oil is vaporised in a stream of hydrogen and passed over a bed of fixed catalyst, usually in the form of pellets. The plant is externally very similar to that employed for the liquid phase process, but the pressure is usually 300ats. The vapour phase hydrogenation product is in the latest practice carried out in two stages. In the first, a robust catalyst is employed, usually tungsten sulphide. In the second stage, a more active catalyst is used, usually active earth impregnated with tungsten sulphide. The function of the first stage is primarily the removal of impurities, such as nitrogen, which would repress the activity of the catalyst in the second stage. The first stage also refines the petrol in the crude product and converts part of the middle oil to petrol. The function of the second stage is the production of petrol, and the product is higher in knock rating than that from the first stage.

The vapour phase product is distilled and separated into middle oil which is recycled, petrol, and liquefiable gases such as butane and propane.

The main points of interest are as follows:—

a. Coal Hydrogenation

The original German plant at Leuna was designed to

operate at 200ats pressure using brown coal. In their first bituminous coal hydrogenation plant at Scholven, 300ats was employed. In new plants the pressure has been raised to 700ats. Improved yields were thus obtained and catalyst requirements were simplified. It is, however, doubtful whether the additional pressure is economically worth while.

b. Pitch Hydrogenation

Pitch was successfully hydrogenated at 700ats at Welheim. The product was largely fuel oil.

c. Hydrogenation of Brown Coal Tar over a Fixed Catalyst

Purified brown coal tar was successfully hydrogenated at Zeitz over an active fixed catalyst at a relatively low temperature, giving approximately 10% of the product as lubricating oil.

d. Vapour Phase Hydrogenation

The two-stage process described in Section C3(ii) was known before the war; there have been no improvements, and changes in catalyst have been designed to economise in catalyst materials rather than improve quality or yield.

e. Overall Yields

Table II summarises the more important data:—

TABLE II

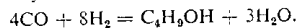
Raw material	Operating pressure, ats	Product	% Wt. yield on ash and moisture-free coal or on tar	Tonnes hydrogen used for 100t _e product
Bituminous coal ..	700	Motor spirit	60	23.6
" "	700	Aviation spirit	50	30
" "	300	Aviation spirit	48	30.5
Brown coal ..	250	Motor spirit	46	19.8
" "	250	Aviation spirit	40	23.2
Brown coal tar	300	Motor spirit	75	7.8
Bituminous coal tar ..	700	Motor spirit	79.5	17.6

f. Improvement in Petrol Quality

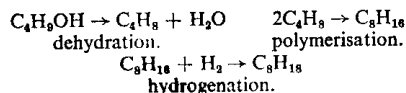
In the later stages of the war it was necessary to increase the quality of hydrogenation aviation petrol still further and two processes were employed. Both of these processes operated on the same principle, which was the increase of the content of aromatic components by dehydrogenation of naphthenes (saturated cyclic compounds). The first process, applied mainly to straight run petroleum petrols, was hydroforming, a process similar to that employed in the US. The second process, for treatment of hydrogenation petrols, was known as the DHD process, in which the raw material was passed, together with hydrogen, over a catalyst at a high temperature (530°C) and at about 50ats.

g. Iso-octane and Alkylate Production

The quality of aviation petrol was still further raised by blending the base petrols from the hydrogenation, hydroforming and DHD processes with iso-octane and alkylate. The original process employed by IG utilised as a starting-point the modification of the synthesis of methanol from carbon monoxide and hydrogen to give largely isobutyl alcohol. The overall reaction is:—



In practice a big proportion of methanol and other alcohols is formed but these can be utilised by recycling. The isobutyl alcohol is next dehydrated by passing over a catalyst to give isobutylene, which is polymerised and then hydrogenated to give iso-octane.



The last two stages of the process were similar to those commonly employed.

During the war IG developed an alternative method for the production of isobutylene, which consisted of the dehydrogenation of the butane made in the hydrogenation process. In this process butane was passed through tubes heated in a furnace. Catalyst flows slowly down the tubes in the reverse direction of the gas, and thus can be removed continuously for regeneration. The butylene from this process was worked up by the polymerisation process described in the previous paragraph, and also by the alkylation process, in which butylene and isobutane are reacted together to give a mixture of octanes known as alkylate:—



This part of the German fuel technology was not developed to anything like the extent of that of the Allies. The output of these materials was relatively small and the costs were extremely high.

iii. FISCHER-TROPSCH PROCESS

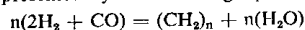
The quantity of oil produced during the war by the Fischer-Tropsch process in Germany was much less than by the hydrogenation process. The output given for 1943, in Table I, Page 2, was 585,000 te/yr by the Fischer process compared with 3,250,000 te/yr by hydrogenation. Very little extension of output of the Fischer process took place during the war.

It is commonly thought that, as operated in Germany, the Fischer process and the hydrogenation process were competitive for the manufacture of oil from coal. The products made by the two processes, however, were quite different and the processes were complementary and not competitive. For the manufacture of high grade aviation petrol and motor spirit, the hydrogenation process alone came into consideration. It is for this reason that the hydrogenation output in Germany was increased during the war to a proportionately greater extent than the Fischer output.

The Fischer process gave some petrol of low quality, a diesel oil of high cetane number and a large proportion of solid wax. Whilst it would have been possible to improve the quality of the Fischer petrol by secondary processes and to increase its proportion by cracking heavier fractions, such steps were considered uneconomic.

The products of the Fischer process were used to a substantial extent in Germany for raw materials for further chemical synthesis, for which purpose the process is of great interest.

In the Fischer process the whole of the raw material, for which coke is preferred, is converted into synthesis gas, a mixture of carbon monoxide and hydrogen, which is then purified. The synthesis gas is passed over a catalyst at about 200°C.; the reaction which takes place can be represented by the following equation:—



The heat of reaction is very large—600k.cal/m³, 23% of the heat of combustion of the gas. The removal of this heat without allowing the temperature outside narrow limits is the chief engineering difficulty of the process.

In the original plants the reaction was carried out at atmospheric pressure but a later development was to perform the synthesis at 10ats pressure. The

quality and proportion of the various components was altered but the pressure process does not seem to have any particular advantage in yield or cost. The object of the increase of pressure is to increase the amount of wax produced.

The liquid product formed is from 130–165gm/m³ of CO + H₂. The theoretical production corresponding to the equation given above is 208gm/m³, so that yields of approximately 70% of theory are obtained. The distribution of the product with the normal and medium pressure processes is as follows:—

	Normal pressure % by weight	Medium pressure % by weight
Condensable gas	14	10
Petrol	47	25
Middle oil	28	36
Soft wax	8	15
Hard wax	3	14

In assessing the yield, the condensable gases, propane and butane, are included. The propane and butane were bottled and sold as fuel for transport purposes. The petrol was blended with benzole and tetra-ethyl lead. The middle oil was used as a diesel oil component by blending with tar oils.

The cracked Fischer product was used for the production of lubricating oil (see Section G2).

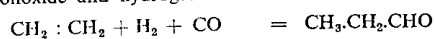
The main interest of the Fischer process is in providing raw material for chemical synthesis. This is because the products are generally of a simple straight chain structure, and the lower fractions may contain as much as 50% of olefins.

The soft wax from the Fischer process was converted into synthetic fatty acids by oxidation. The product was used both for the preparation of soap and for the preparation of edible fat.

The larger part of the heavier fraction of the Fischer middle oil was treated at Leuna for the manufacture of a detergent known as "Mersol." The oil was first hydrogenated to remove unsaturated hydrocarbons and then treated with chlorine and SO₂. This product was saponified and used as a substitute for soap.

There was considerable development work on the Fischer process directed to such matters as the production of olefins for chemical synthesis, the use of iron catalysis, the synthesis of isoparaffins such as isobutane, and the synthesis of very high melting point waxes.

A development of general interest is the so-called "OXO" synthesis, which was in the pilot plant stage at the end of the war. The raw material was an olefin made by the Fischer process but the olefins formed by oil cracking can also be employed. The olefin is treated with carbon monoxide and hydrogen at temperatures ranging from 200–300°C and at 150–200ats in the presence of a cobalt catalyst similar to that used in the Fischer process. The reaction can be carried out either in the vapour phase or in the liquid phase. In Germany the main intention was to produce alcohols with about 12 carbon atoms to the molecule, but the reaction can be illustrated by the simplest case, the synthesis of propionaldehyde from ethylene, carbon monoxide and hydrogen.



From the aldehyde can be made either the corresponding alcohol by reduction or the acid by oxidation. The interest of this process is that it results in the primary alcohols, in place of the secondary alcohols usually obtained from olefins.

6 REPORT ON THE PETROLEUM AND SYNTHETIC OIL INDUSTRY OF GERMANY

TABLE III
SUPPLY OF GERMAN LUBRICATING OILS—1942
(tonnes per year)

Supplier	Methods of manufacture	Volume of supply	Disposition	
			Aircraft oils	Others
Various mineral refiners ..	Conventional refining methods ..	630,000	30,000	600,000
Brabag Zeitz ..	TTH hydrogenation of tars ..	24,000	—	24,000*
Stettin-Pölitz ..	Olefin polymerisation ..	10,000	10,000	—
Rhenania Ossag ..	Olefin polymerisation ..	8,000	8,000	—
Ruhrchemie ..	Olefin polymerisation ..	8,000	—	8,000†
Rheinpreussen ..	Aromatic-paraffin condensation ..	2,000	—	2,000†
IG-Leuna ..	Ethylene polymerisation ..	12,000	12,000	—
IG-Leuna ..	Ester synthesis ..	4,000	4,000	—
	TOTAL ..	698,000	64,000	634,000

* Relatively low quality, used for industrial and automobile lubricants.

† Used by Army for trucks, tanks, etc.

‡ Consumed entirely by German Navy for diesel engines.

iv. CRUDE OIL PRODUCTION

During the major part of the war Germany relied to a considerable extent on imports of petroleum products from Rumania and Eastern Europe generally. Production in Germany itself was small. The investigations into methods of exploration and exploitation are confined to Germany proper and owing to difficulties in getting into Austria do not include separate information as to production there. It has proved difficult to make all the figures obtained agree with one another as they were culled from a number of different sources, and some deal with production throughout the "Greater Reich" and some are confined to Germany proper.

The production policy at the outbreak of the war was based on the expectation of a short war, and therefore production was stepped up regardless of the future of the fields. As it became obvious that the war was likely to be protracted, a saner policy was adopted so as not to waste reserves. From an initial production of 50,000–60,000 te/month, the first onslaught raised it to over 100,000 te/month, but it was quite clear that the policy was a wasteful one. Later, when production was more carefully regulated and new fields were found, a steady production of 60,000 te/month was maintained from Germany.

v. PETROLEUM REFINING

The crude oil was refined reasonably near to the fields in the refineries which, before the war had run on imported crude as well as on the indigenous production. Therefore there was at no time any shortage of refinery capacity to deal with the available crude, except for dewaxing equipment, until the intensive bombing put an end to serious refining.

The refineries used conventional processes throughout, and there was no evidence of any interesting developments. In view of this there was not much point in collecting data on refining costs.

Although the refineries prepared the usual petroleum products, it was upon the production of lubricating oil that they were mostly concentrated. Apart from a relatively small quantity of synthetic lubricating oil which was used exclusively for aircraft, the bulk of the lubricating oil (which was obtained in approximately 50% yield) was prepared from indigenous petroleum crude oil.

vi. LUBRICATING OIL PRODUCTION

Although the refining of crude petroleum accounted for the major portion of the supply of this material, it

was only natural that the Germans should pay a great deal of attention to the synthesis of lubricants from olefins and other suitable starting materials. The approximate production from all sources is given in Table III.

The synthetic oils were almost exclusively used by the Luftwaffe as a 50 : 50 mixture with mineral oil. The mineral oil alone was used by the other arms and by industry—the latter having the lower priority in its claim for quality.

Some of the methods of synthesis are of considerable interest and worthy of examination.

vii. TESTING AND EVALUATION OF PRODUCTS

The methods used by the Germans for the improvement of their fuels and lubricants were made the subject of a special study. All the available laboratories and testing stations were visited and a large number of people were questioned on the problems which had arisen and on the methods which had been used to investigate and, if successful, overcome them. Only a brief summary of these investigations can be given in this report, and as the work of translating and correlating all the reports found on this subject is not yet complete, the present information in this section must be looked upon very much as a preliminary summary. A fuller report will be issued later.

5. ESTIMATED COSTS OF OPERATION OF SYNTHETIC OIL PROCESSES IN UK

In the sections of the report dealing with the hydrogenation and the Fischer processes will be found data supplied by the Germans on the cost of operation of these processes under specific conditions. The chief interest of these costs is to provide a basis for estimation of costs under present day conditions in the UK. The following calculations are submitted with due reserve. In preparing a cost estimate for any specific scheme, it is necessary to take into account the exact cost of coal, labour, services and so forth.

i. CAPITAL COSTS OF HYDROGENATION PROCESS

The Scholven plant (Table IV) was in operation before the war, and the Gelsenberg plant was partly constructed at the outbreak of war. Compared with present day figures in Germany, it is necessary to increase these costs, and it is considered that the overall capital costs to-day of plants of the nature of these two would be RM600 per te/yr of motor petrol. So far as can be seen, the

INTRODUCTION

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TABLE IV
CAPITAL COSTS OF HYDROGENATION

	Scholven	Gelsenberg
Date of construction	1937	1939
Plant capacity—Aviation petrol (te/yr)	240,000	400,000
Motor fuel („)	280,000	460,000
<i>Capital costs</i>	RM	RM
Hydrogen production, purification and compression ..	31,300,000	49,000,000
Paste preparation, sludge recovery, kilns, etc. ..	10,700,000	12,000,000
Liquid phase hydrogenation	28,000,000	43,100,000
Vapour phase hydrogenation	8,400,000	20,000,000
Product distillation, rich gas purification, etc. ..	8,000,000	27,600,000
Drainage, pipe bridges, electrical distribution, etc. ..	15,800,000	34,300,000
Stores, offices, sewage, canteens, workshops ..	28,300,000	22,000,000
TOTAL	130,500,000	208,000,000
Capital costs, RM per te/yr aviation fuel	545	520
Capital costs, RM per te/yr motor fuel	465	455

corresponding costs in the UK for similar plants, would be £60 per te/yr.

ii. MANUFACTURING COSTS OF COMPRESSED HYDROGEN

Unfortunately no figures were obtained for actual operating costs at the plants referred to above.

A useful table was obtained from Leuna for the overall cost of hydrogen, analysed down to fundamental items. At Leuna a large part of the hydrogen was manufactured from brown coal in Winkler generators, and the balance was obtained from imported coke. The figures for brown coal consumption given below include also the coal used for the generation of steam and power for the manufacture of hydrogen. It is considered that a sufficiently good picture of the cost of compressed hydrogen under English conditions can be obtained by calculating the quantity of bituminous coal giving the same amount of heat as brown coal.

In calculating the table below, we have taken the British coal price as £2.1/ton and coke at £3/ton. The

cost of labour has been taken at £0.13 (2.6/-) per man-hour. The other costs have been converted on the basis of RM10 = £1, which appears to give a reasonable direct relation between war-time German costs and present day UK costs.

iii. ESTIMATED OPERATING COSTS OF HYDROGENATION PROCESS

The figures in Table VI are based on estimates supplied by the IG staff and seem reasonably in line with actual cost figures so far as they can be ascertained. Further details are given in Section C3(v) of this report.

The figure inserted for the hydrogen cost is the actual figure obtained from Leuna, as shown in Table V, but without obsolescence. For the corresponding costs in England, the unit costs which appear to be reasonable are included in the table so that a fresh calculation can be made for any other set of conditions.

In cases where no other method was available, the German costs have been translated on the basis of RM10 = £1.

TABLE V
HYDROGEN COSTS

	Costs for 1,000m ³ of compressed hydrogen			
	German figures		Corresponding English figures	
	tonnes	RM	tons	£
Raw brown coal	1.61	3.65	—	—
Other coal	0.004	0.1	—	—
Bituminous coal, equal to above ..	—	—	0.554*	1.16
„ „ coke	0.54	14.47	0.54	1.62
Brown coal coke	0.15	1.77	0.15	0.45
Total expenditure on fuel		19.99		3.23
Purchased electricity		1.32		0.2
Operating labour	man-hours	4.59	man-hours	0.54
Repair	4.14	2.78	4.14	0.31
Salaries	2.39	2.1	2.39	0.21
Materials	—	2.1	—	0.21
Other items of cost	—	4.84	—	0.5
Overhead charges	—	—	—	0.5
Depreciation		37.72		5.7
		4.28		0.42
TOTAL		RM42.00		£6.12

* 1.61te brown coal + 0.004te at 2,250tecal/te equivalent to 0.554te bituminous coal at 6,550tecal/t.

TABLE VI
PRODUCTION COST PER TONNE OF HYDROPETROL

	COST PER UNIT			COAL HYDROGENATION			TAR HYDROGENATION		
	Unit	Germany RM	UK £	Units	Germany RM	UK £	Units	Germany RM	UK £
Coal (including cleaning charges) ..	tonne	21.5	2.3	1.84	39.5	4.2	—	—	—
Tar ..	tonne	40.0	3.5	—	—	—	1.29	51.5	4.52
Hydrogen ..	1,000m ³	37.72	5.7	2.8	106.0	16.0	2.090	79.0	11.9
Catalysts ..	—	—	—	—	5.0	0.5	—	7.2	0.72
TOTAL ..					150.5	20.7		137.7	17.14
Operating labour ..	man-hrs	1.3	0.13	10.9	14.15	1.41	7.4	9.6	0.96
Salaries ..	—	—	—	—	2.85	0.28	—	1.95	0.19
Water ..	m ³	0.01	0.002	190	1.90	0.38	160	1.60	0.32
HP steam ..	tonne	3.0	0.4	0.63	1.90	0.25	0.53	1.60	0.21
LP steam ..	tonne	2.25	0.25	2.23	5.0	0.60	1.35	3.0	0.36
Electric power ..	1,000kwh	15.00	2.50	0.946	14.1	2.36	0.546	8.1	1.37
Fuel gas ..	1,000m ³	6.0	0.6	2.7	16.2	1.62	1.9	11.4	1.14
Maintenance ..	—	—	—	—	20.6	2.06	—	15.7	1.57
Materials ..	—	—	—	—	1.6	0.14	—	0.95	0.09
Taxes, insurance ..	—	—	—	—	7.85	0.78	—	6.05	0.60
Export costs ..	—	—	—	—	3.0	0.30	—	3.0	0.30
General costs ..	—	—	—	—	11.05	1.10	—	9.65	0.96
TOTAL ..					250.5	31.98		210.3	25.21
Less Credit:									
Liquefied gas ..	tonne	200	10.0	0.23	46.0	2.3	0.186	37.0	1.86
Fuel gas ..	1,000m ³	6	0.6	3.4	20.4	2.04	2.0	12.0	1.2
TOTAL ..					184.1	27.64		161.3	22.15
Add:									
Amortisation at 10% of capital st ..	—	—	—	—	60.0	6.0	—	45.0	4.5
TOTAL COST ..					244.1	33.64		206.3	26.65
Cost of petrol (pence gallon) ..					27.5			21.9	

In the German figures, the liquefied gas, which was sold in special cylinders for motor transport, has been credited at a price nearly equal to that of the final product. In the case of the English costs, the same figure cannot be taken since it would clearly be necessary to offer the liquefied gas to consumers at a lower price than that of petrol itself, to enable them to utilise it. It would further be necessary to make an additional debit for the cost of cylinder filling and transport. We have for these reasons allowed a credit for liquefied gas of £10 per ton. It should be understood that if the liquefied gas cannot be sold for this purpose, and is used in the process, for example for hydrogen manufacture, the credit will be lower.

IV. ESTIMATED OPERATING COSTS OF THE FISCHER TROPSCH PROCESS

According to the information available in Section D2(vii) of this report the costs of the Fischer process varied considerably. The capital cost ranged from 1400 to RM900 per tonne year and the production costs from RM240 to RM330 per tonne of marketable primary product, including hydrocarbon gases. The costs for the medium-pressure plant of the Hoesch Benzin GmbH which were intermediate between these extremes have been selected for conversion to English conditions.

The hydrocarbon gases, which in Germany were utilised

as motor fuels and included among the main products of the process, would under English conditions be regarded as by-products, and credited accordingly. The costs given in Table VII are amended in this way, and set out in a similar manner to those in Table VI for the hydrogenation process. The English costs are based on a coke price of £3 per ton, and where no other method was available, on the basis of £1 = RM10, which is satisfactory for the purpose.

The costs of the hydrogenation and Fischer processes cannot readily be compared since the products they make are so different. Considering these processes as sources of liquid fuels, and taking into account that the current price of imported motor spirit in the UK is about 6d. per Imperial gallon (approximately £7.5 per ton), or, after allowing for the present protection of 9d. per gallon, 1s. 3d. per gallon (£18.4 per ton), there seems little prospect, by means of any of the German developments in the direction of increased efficiency, of obtaining anything approaching economical production by either process.

If these processes were utilised as a means of producing not only fuels but also high-priced chemicals as special products, a purpose for which the Fischer process is particularly suitable, the economic position might be somewhat more favourable. The possibility of effecting a reduction in the costs of both processes as a result of further research cannot be ruled out.

TABLE VII
PRODUCTION COST FOR FISCHER-TROPSCH PRIMARY PRODUCT

	Unit	COST PER UNIT		Units	PER TONNE OF LIQUID PRODUCT	
		Germany RM	UK £		Germany RM	UK £
Coke	tonne	17.79	3.0	4.38	85.55	13.14
Catalysts	—	—	—	—	20.83	2.08
Wages	—	—	—	—	10.71	1.07
Salaries	—	—	—	—	2.41	0.24
Water	m ³	0.006	0.002	447	2.86	0.89
Steam	tonne	2.60	0.3	15.8	41.10	4.75
Electric power	1,000kwh	17.60	2.50	0.596	10.45	1.49
Fuel gas	—	—	—	—	3.99	0.40
Compressed air	—	—	—	—	0.13	0.01
Maintenance	—	—	—	—	17.55	1.75
Materials	—	—	—	—	12.57	1.26
Taxes and various costs	—	—	—	—	21.70	2.17
TOTAL					229.85	29.25
Less Credit:						
Liquefied gas	tonne	200	10	0.097	19.40	0.97
Steam	—	—	—	—	26.63	2.66
Residual gas	—	—	—	—	8.16	0.82
TOTAL					175.66	24.80
Add:						
Capital charges	—	—	—	—	91.10	9.11
TOTAL COST					266.76	33.91
Cost of primary product (pence/gallon)						27.1

B—Carbonisation and Gasification of Coal

1. INTRODUCTION

The production of synthetic oils, as will be seen from the attached chart (Fig. 3), is fundamentally dependent on coal carbonisation and gasification processes. The hydrogenation process for production of low molecular weight hydrocarbons from more complex structures requires compressed hydrogen of a fair degree of purity, usually not less than 96%, whereas the starting material for the Fischer-Tropsch synthesis is a gas containing hydrogen and carbon monoxide in the volume ratio of about 2 : 1.

The first step in the production of either hydrogen or Fischer-Tropsch synthesis gas is the manufacture of water gas. The conventional water gas process consists of steaming high-temperature coke from selected bituminous coal in intermittent generators, the heat required for the steaming reaction being supplied and stored in the coke bed during periods of blowing with air. The gaseous products from the blow period, consisting of nitrogen, carbon dioxide and a little carbon monoxide, are purged to atmosphere. This process was still used extensively in Germany, but it required lump coke, preferably of high ash-melting point, and limited availability of suitable coking coal had necessitated development of a wide variety of alternative processes capable of using inferior coal cokes, brown coal cokes and brown coal itself.

Low-quality cokes containing a high proportion of low melting point ash constituents were dealt with in continuous slagging generators. Heat was supplied continuously by adding oxygen to the steam, and ash

withdrawn as liquid slag, thus eliminating the need for mechanical grates.

The main method developed for the direct gasification of brown coal was the Winkler generator, which operated continuously with a mixture of oxygen and steam reacting with powdered brown coal or brown coal coke in a fuel bed maintained in an ebullient state of suspension. Latterly, this type of generator has been used largely on brown coal coke. It has a comparatively poor carbon efficiency because a large amount of un-gasified dust is blown overhead.

The next most important method was the Pintsch-Hillebrand process, using brown coal briquettes which were gasified continuously by reaction with a current of preheated steam and recycled carbonisation and water gas. The Wintershall-Schmalfeldt process was similar to the Pintsch-Hillebrand process, but used brown coal dust which was wholly gas-borne during gasification. The less-developed Koppers complete gasification process used brown coal briquettes, and was also similar to the Pintsch-Hillebrand generator.

Special low-temperature carbonisation processes were developed in Germany for the production of the coke required for water gas production. These were applied mainly to brown coal and to poorly coking bituminous coals. The two most important methods were the Lurgi-Spülgas and the Krupp-Lurgi systems. These processes were important to the German oil production programme not only because of their contribution to coke and water gas manufacture, but also because they gave rise to large quantities of low-temperature tars