

Germany's Synthetic Fuel Industry 1927-45

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Germany has virtually no petroleum deposits. Prior to the twentieth century this was not a serious problem because Germany possessed abundant coal reserves. Coal provided for commercial and home heating; it also fulfilled the needs of industry and the military, particularly the navy. In the opening decade of the twentieth century, Germany's fuel requirements began to change. Two reasons were especially important. First, Germany became increasingly dependent on gasoline and diesel oil engines. The appearance of automobiles, trucks, and then airplanes made a plentiful supply of gasoline essential. Moreover, ocean-going ships increasingly used diesel oil rather than coal as their energy source. Second, Germany's continuing industrialization and urbanization led to the replacement of coal with smokeless liquid fuels that not only had a higher energy content but were cleaner burning and more convenient to handle.

Petroleum was clearly the fuel of the future, and to insure that Germany would never lack a plentiful supply, German scientists and engineers invented and developed two processes that enabled them to synthesize petroleum from their country's abundant coal supplies and to establish the world's first technologically successful synthetic liquid fuel industry.¹ Friedrich Bergius (1884-1949) in Rheinau- Mannheim began the German drive for energy independence with his invention and early development of high-pressure coal hydrogenation or liquefaction in the years 1910-25. A decade after Bergius began his work Franz Fischer (1877-1947) and Hans Tropsch (1889-1935) at the Kaiser-Wilhelm Institute for Coal Research (KWI) in Mülheim, Ruhr, invented a second process for the synthesis of liquid fuel from coal. By the mid-1930s IG Farben, Ruhrchemie, and other chemical companies had started to industrialize synthetic liquid fuel production, resulting in the construction of twelve coal hydrogenation and nine Fischer-Tropsch (F- T) plants by the time World War II ended in 1945. Several breakthroughs contributed to the success of coal hydrogenation the most significant of which were the sulfur resistant catalysts and the two stage liquid-vapor phase hydrogenation that Matthias Pier (1882-1965) at BASF (IG Farben) developed in the late 1920s. For the F- T synthesis the cobalt catalysts that Fischer and his co-workers prepared in the 1920s-30s were crucial to its success.

Because of synthetic liquid fuel's high production cost the industry benefited from the financial incentives Germany's Nazi government offered beginning in December 1933, and because liquid fuel was crucial to Germany's war effort the synthetic fuel industry became a major part of Adolf Hitler's Four Year Plan of 1936. As the war dragged on, the synthetic fuel industry, like many German industries, experienced serious labor shortages, and to avoid any loss of production and slowdown of the war effort some of the plants used forced labor that the German government provided.

Of the two processes hydrogenation was the more advanced and contributed much more significantly to Germany's liquid fuel supply than the F-T synthesis. Coal hydrogenation produced high quality aviation and motor gasoline, whereas the F-T synthesis gave high quality diesel and lubricating oil, waxes, and some lower quality motor gasoline. The two processes actually were complementary rather than competitive, but because only coal hydrogenation produced high quality gasoline it experienced much greater expansion in the late 1930s and war years than the F-T synthesis, which hardly grew at all. F-T products were mainly the raw materials for further chemical syntheses with little upgrading of its low quality gasoline by cracking because of unfavorable economics. Hydrogenation also had experienced greater development because brown coal (lignite), the only coal available in many parts of Germany, underwent hydrogenation more readily than a F-T synthesis. In addition, the more mature and better developed hydrogenation process had the support of IG Farben, Germany's chemical leader, which had successfully industrialized coal hydrogenation beginning in 1927. This paper provides a historical analysis of the invention and industrial development of the F-T synthetic fuel processes during several decades of German social, political, and economic unrest follows. A similar study of coal hydrogenation will appear in a future publication.

Early development of the F-T synthesis

Fischer received the PhD at Giessen in 1899, where his research focused on electrochemistry. He continued these

studies spending a semester with Henri Moissan (1852-1907) in Paris, several years in Freiburg's chemical industry and in the institutes of Wilhelm Ostwald in Leipzig and Emil Fischer in Berlin, and from 1911 to mid-1914 at the Technische Hochschule in Berlin-Charlottenburg. Emil Fischer (1852-1919) had an interest in Fischer's electrochemical work, and as a leading figure in establishing the KWIs beginning in 1912 he invited Fischer to direct the new institute for coal research planned for Mülheim in the Ruhr valley. The institute, which opened on 27 July 1914, was the first KWI located outside of Berlin-Dahlem, and like the others the Imperial Ministry of Education provided funding for the operating and administration costs whereas private industrial firms paid for the building and equipment. The Ruhr industries, particularly Hugo Stinnes, supported the Mülheim institute.

Fischer had planned to study a coal-to-electricity direct path conversion, but with the institute's opening four days before World War I began and Germany's lack of petroleum quickly becoming apparent, the institute's program shifted from basic research on coal to methods of converting coal to petroleum. This wartime work was the institute's first comprehensive research program. It involved the decomposition of coal and the production of tar from the low-temperature carbonization (LTC) of different coals, giving yields of 1-25 percent, and the extraction of a coal with different organic solvents such as alcohols, pyridine, and petroleum ether at various temperatures and pressures. The extraction studies showed that decreasing the coal's particle size by grinding increased the tar yields. With benzene as the solvent at 270°C and 55 atm Fischer and W. Gluud in 1916 obtained tar yields many times the low yields obtained at atmospheric pressure. These early studies on coal also led Fischer and Hans Schroder in 1919 to propose their controversial lignin theory of coal's origin in which during the peat-bog stage of coal's formation the cellulose material in the original plant material decomposed leaving only the more resistant lignin that then changed into humus coal.

With the wartime LTC investigations well underway, Fischer's interest shifted to a different hydrocarbon reaction. In 1913 Badische Anilin-und Soda-Fabrik (BASF) in Ludwigshafen patented a process for the catalytic hydrogenation (reduction) of carbon monoxide to give hydrocarbons other than methane, alcohols, ketones, and acids. According to the patent, hydrocarbon synthesis occurred best with an excess of carbon monoxide (2: 1 carbon monoxide: hydrogen volume mixture) at 300-400°, 120 atm, and the metals cerium, cobalt, or molybdenum, or their alkali-containing (sodium hydroxide) metallic oxides as catalysts.² Because of World War I and priority given to industrializing the ammonia and methanol syntheses, BASF never continued its hydrocarbon synthesis. Upon learning of BASF's patent Fischer decided to test its claims. Working with Tropsch he began investigating the catalytic reduction of carbon monoxide at various temperatures and pressures but using excess hydrogen gas, a 2:1 hydrogen : carbon monoxide volume mixture they called synthesis gas. This avoided carbon monoxide decomposition ($2 \text{ CO} \rightarrow \text{C} + \text{CO}_2$ which deposited carbon (soot) on the catalyst and rendered it ineffective. The experiments with synthesis gas continued into the 1920s, and in 1923 Fischer and Tropsch showed that reacting the gas in a tubular, electrically-heated converter at high temperature and pressure, 400-450°C and 100-150 atm, and with alkali-iron instead of oxide catalysts, did not give hydrocarbons but a mixture of oxygen-containing organic compounds such as higher alcohols, aldehydes, ketones, and fatty acids, that they called synthol.³ Additional studies in 1925-26 using small hard glass combustion tubes 4-5 millimeters (mm) long and a gas-heated horizontal aluminum block furnace revealed that with cobalt iron catalysts at 250-300°C and 1 atm (atmospheric pressure), the products were almost free of oxygenated compounds and contained mainly hydrocarbons ranging from ethane gas to solid paraffins. This discovery was highly significant because they had hoped to produce liquid hydrocarbon motor fuels. By 1928 Fischer and Tropsch modified reaction conditions once again. Using an iron-copper catalyst, an even lower temperature of 190°C, and 1 atm, they eliminated completely the oxygenated compounds and the catalytic reduction of carbon and obtained a mixture containing only hydrocarbon gases (ethane, propane, butane) and liquids (octane, nonane, isononene) with a boiling point range of 60-185°C.⁴

Fischer continued his investigations into the 1930s, constructing a small pilot plant in Mülheim in 1932. The plant contained a series of converters 5 meters (m) high, 1.2 m wide, 12 mm thick walls, immersed in an oil bath for cooling and operated at the same conditions he had used earlier (2: 1 hydrogen : carbon monoxide volume mixture, 190-210°C, 1 atm) but with a catalyst having the weight ratio 100 nickel-25 manganese oxide-10 aluminum oxide-100 kieselguhr. The catalyst had a short four to six week lifetime because of sulfur poisoning, and the total yield per cubic meter (m³) of synthesis gas consumed was only 70 grams (g) of a 58 octane number gasoline and a diesel oil boiling above 220°C.⁵

Two years later Fischer's decade-long research moved to the next level with the construction in 1934 of the first large pilot plant for synthesizing hydrocarbons from carbon monoxide and hydrogen. Ruhrchemie AG, a company Ruhr coal industrialists founded, envisioned the F-T synthesis as an outlet for its surplus coke, and upon acquiring the patent rights to the synthesis in 1934, constructed the pilot plant in Oberhausen-Holten (Sterkrade-Holten), near Essen. The plant operated at the conditions used in Fischer's small pilot plant and had an annual capacity of 1,000 metric tons (7,240 barrels) of motor gasoline, diesel oil, and lubricating oil.⁶ Although the larger pilot plant demonstrated the overall success of the F-T synthesis problems with removing the large amount of heat released in the gas stream during the reaction, with the nickel catalyst's short lifetime, and with the significant loss of catalytic metals (nickel, manganese, aluminum) during their recovery (regeneration) for reuse persisted during the operation. The nickel catalyst's poor performance forced Fischer and Ruhrchemie to abandon its use for commercial development, and at this time research resumed with the more active but expensive cobalt catalysts. Oberhausen-Holten subsequently became the production center for a standardized cobalt catalyst used in all the F-T plants constructed later in the 1930s, for all the development work on synthetic motor fuel and lubricating oil, and for the oxo process.

The successful pilot plant research and development at Oberhausen-Holteln was the major turning point in the F-T synthesis. By November 1935, less than three years after Germany's Nazi government came to power and initiated the push for petroleum independence, four commercial-size Ruhrchemie licensed F-T plants were under construction. Their total annual capacity was 100,000-120,000 metric tons (724,000-868,000 barrels) of motor gasoline, diesel oil, lubricating oil, and other petroleum chemicals. The motor vehicle products comprised 72 percent of the total; petroleum chemicals made up the remaining 28 percent and included alcohols, aldehydes, soft waxes which when oxidized gave the fatty acids used to produce synthetic soap and edible fat (margarine), and heavy oil for conversion to the inexpensive detergent Mersol. All the plants were atmospheric pressure (1 atm) or medium pressure (5- 15 atm) syntheses at 180-200°C, produced synthesis gas by reacting coke with steam in a water gas reaction and adjusting the proportions of carbon monoxide and hydrogen, and used a cobalt catalyst (100 Co-5 ThO₂-8 MgO-200 kieselguhr) that Ruhrchemie chemist Otto Roelen developed in 1933-38. Roelen's catalyst became the standard F-T catalyst because of its greater activity and lower reaction temperature, but its preparation was expensive, costing RM 3.92 per kg of cobalt. For this reason Ruhrchemie recovered the cobalt and thorium from the spent (used) catalyst by treatment with nitric acid and hydrogen gas at a cost of RM 2.97 per kg of cobalt, and re-used them in preparing fresh catalysts.⁷ This gave a total catalyst cost of RM 6.89 per kg of cobalt or nearly 30 percent of the total F-T production cost. By 1937-38 the combined annual capacity of the four F-T plants increased to 300,000 metric tons (2.17 million barrels) and with the completion of five additional plants, total capacity rose to 740,000 metric tons (5.4 million barrels) at the outbreak of World War II in September 1939. Production at the nine F-T plants peaked at 570,000 metric tons (4.1 million barrels) in 1944.⁸

The older F-T plants operated at 1 atm whereas three of the five newer plants were medium pressure 5-15 atm syntheses. Converter design differed depending on the reaction pressure, but all the plants had inefficient externally cooled converters that dissipated the high heat of reaction (600 kilocalories per m³ of synthesis gas consumed) and controlled the reaction temperature by arranging the cobalt catalyst pellets in a fixed bed within the converter and circulating pressurized water through the converter. Synthesis gas entered at the converter's top at the rate of 650-700 m³ per hour per converter and flowed down through the catalyst bed, hydrocarbon products passed out the bottom. The medium pressure synthesis gave a slightly higher yield and extended the catalyst's life from four-seven months to six-nine months.

For the 1 atm synthesis the converter (tube and plate) was a rectangular sheet-steel box 5 m long, 2.5 m high, 1.5 m wide, containing about 600 horizontal water cooling tubes interlaced at right angles with 555 vertical steel plates or sheets. The complicated grid-like arrangement over which the synthesis gas flowed from top to bottom eliminated any localized heat buildup in the converter. Each steel plate was 1.6 mm thick, a space of 7.4 mm separated adjacent plates. The cooling tubes were 40 mm in diameter, 40 mm apart, and led to a boiler (steam drum) for recovery of the heat released in the synthesis. One boiler recovered the heat released from two converters. An empty converter weighed 50 metric tons; the catalyst pellets, which filled the space between the tubes and plates and occupied a volume of 12 m³, weighed 3 metric tons of which 900 kg were cobalt.

The medium pressure converter (concentric double tube) had a simpler design. It consisted of a 50 metric ton vertical cylindrical steel shell 6.9 m high, 2.7 m internal diameter, 31 mm thick walls, and contained 2,100 vertical cooling tubes. Each cooling tube was 4.5 m long and double in construction, consisting of an outer tube of 44-48 mm diameter fitted with a concentric inner tube of 22-24 mm diameter. A top and bottom weld (T-connections) between the converter's horizontal face and an outer tube connected an inner tube with a boiler that allowed cooling water to circulate from the boiler to the main space in the shell around the outer tubes and through the inner tube. One boiler recovered the heat released from four converters. The catalyst pellets filled the annular space between the concentric tubes and occupied a volume of 10 m³.

In the 1 atm synthesis, water sprays in packed towers directly cooled the hot hydrocarbon vapors and gases (primary products or oils) leaving the bottom of the converter. The vapors condensed to give light oil (C₅-C₁₂) boiling point range 25-165°C), middle oil (C₁₀-C₁₄ boiling point range 165-230°C), heavy oil (C₂₀-C₇₀, boiling point range 230-320°C), and hard and soft wax (C₂₀-C₃₀), boiling point range 320-460°C and above). The cooled gases (propane, butane) passed to an absorber for their removal and recovery with activated charcoal and subsequent liquefaction. In the medium pressure synthesis about 35 percent of the primary products left the converter as hydrocarbon liquids. Passage through a tubular-type steel alloy condenser liquefied the hydrocarbon vapors; the remaining hydrocarbon gases, after expansion to atmospheric pressure, underwent recovery and removal with activated charcoal in an absorber.

The biggest converter used in German F-T plants had a production capacity of only 2.5 metric tons per day (18 barrels per day) so that a small, 70 metric ton per day (500 barrels per day) plant had 25 or more converters, requiring considerable amounts of material and manpower for its construction and operation. All the plants operated their converters in stages. The 1 atm plants had two stages, operating two-thirds of the converters in the first stage and one-third in the second. Some of the plants placed the condensers and absorbers between the stages, others placed only condensers; all the plants had absorbers after the second stage converters and condensers. During the last two years of the war the medium pressure plants switched from two stages to three stages, successively operating one-half, one-third, and one-sixth of their converters. They had condensers between each stage and absorbers after the final stage converters and condensers. Average plant yield for the 1 atm synthesis was 130-165 g of liquid hydrocarbons per m³ of synthesis gas, or about 80 percent of the theoretical maximum yield; annual production per converter was 500-720 metric tons. For the middle pressure synthesis the corresponding yields were 145-160 g per m³ and 600-750 metric tons.

Product refining, especially by fractional distillation, was the same for both syntheses. Low- grade gasoline, the light oil

fraction, had a 45-53 octane number, which after blending with 20 percent benzol and adding 0.02-0.04 percent lead tetraethyl, increased to 70-78 and provided the German army with motor gasoline. High-grade diesel oil with a 78 cetane number (middle oil fraction) and some of the heavy oil fraction, after blending with 50 percent petroleum oil, served as aviation fuel for the German air force. Further treatment of most of the heavy oil at IG Farben's Leuna plant after its opening in 1927 gave the inexpensive synthetic detergent Mersol; cracking and polymerizing the remaining heavy oil and some of the soft wax gave good quality lubricating oil. Oxidizing the rest of the soft wax produced fatty acids for conversion to soap and small quantities of edible fat. The Gennan wax industry used most of the hard wax for electrical insulation, the manufacture of polishes, and as a paper filler.⁹ The most efficient F-T plants recovered only 30 percent of the total heat energy input as primary products and another 25 percent as steam and residual gas. The net heat energy required for the production of one metric ton of primary products was equivalent to 4.5 metric tons of coal (1 lb coal = 12,600 BTU).¹⁰

Germany's energy plan

The growth of the German synthetic fuel industry remains inseparably linked to events taking place there in the 1930s and 1940s. A special relation existed between the industry and Nazi government, and without it Germany's emerging synthetic fuel industry might have collapsed. The small German oil industry had remained reasonably free from government interference and had benefited from an April tariff increase in 1930 that raised the duty on imported oil from RM 77.40 per metric ton (8.5¢ per US gallon) to RM 129 per metric ton (14.3¢ per US gallon). But government policy began to change with the German banking crisis that followed the failure of the Kredit Anstalt on 3 May 1931 and the Darmstaedter National Bank on 15 July 1931 and led the Weimar government to impose a number of controls and regulations which the Nazi government expanded and intensified beginning in 1933. The Weimar government established Supervisory Boards to allocate raw materials and placed these boards under control of the Reichswirtschaftsministerium (Ministry of Economics) which in 1939 renamed them Reichsstellen (Reich Offices). The Reichsstelle für Mineröl (Office of Mineral Oil) regulated the oil industry; additional regulations came from the Reichsstelle für Rohstoffamt (Office of Raw Materials) and its subdivision Wirtschaftsgruppe Kraftstoffindustrie (Economic Group for Liquid Fuels). All liquid fuel producers reported their production and import figures and any new construction of plants and refineries to the oil regulatory boards. In addition to regulatory boards, the government established four industry associations that had responsibility for the production and allocation of the fuels under their control.

- Association for Crude Oil Production and Refining (REV)
- Association for Hydrogenation, Synthesis, and Low Temperature Carbonization (ARSYN)
- Association of German Benzol Producers (ARBO)
- Association for Allocation of German Bituminous Coal Tar Products (AVS)

The government-industry relation also resulted in risk-free partnership agreements between the government and those industries (coal, chemical) involved in synthetic fuel production. The earliest of these was the Fuel Agreement (Benzinvertrag) that IG Farben, the only company then producing synthetic fuel, and the Reichswirtschaftsministerium signed on 14 December 1933. It required IG Farben to produce at least 300,000-350,000 metric tons (2,490,000 barrels) of synthetic gasoline per year by the end of 1935 and to maintain this production rate until 1944. The agreement set the production cost, which included depreciation, five percent interest on IG Farben's investment, and a small profit, at 18.5 pfennig per liter (1.1 quarts). The government not only guaranteed the production cost but agreed to pay IG Farben the difference between that cost and any lower market price, and to buy the gasoline if no other market emerged. Alternatively, IG Farben had to pay the government the difference between the production cost of 18.5 pfennig per L, which was at that time more than three times the world market price, and any higher price obtained on the market. Because of increasing petroleum costs, as well as improvements in the hydrogenation process, IG Farben paid RM 85 million to the government by 1944.¹¹

Eight months after signing the fuel agreement with IG Farben the government took two additional steps to assist the synthetic fuel industry. The first was the establishment on 24 August 1934 of Wirtschaftliche Forschungsgesellschaft (WIFO, Economic Research Company), a completely government-owned company capitalized at RM 20,000 and charged with the construction and operation of liquid fuel (natural and synthetic) storage depots. German fuel producers sent WIFO their lubricating oil, and their aviation grade products for blending and leading, which WIFO stored and eventually distributed mainly to the air force and minimally to the army.

In 1938 WIFO had a storage capacity of 630,000 metric tons (820,000 m³) of motor and aviation gasoline and 84,000 metric tons (110,000 m³) of lubricating oil. It actually stored 500,000 metric tons of aviation gasoline, most of it in bombproof underground locations within Germany. The government in 1938 planned to increase Germany's total storage to 6,000,000 metric tons of liquid fuel and lubricating oil by 1943 and projected the following contributions: WIFO 2,900,000 metric tons; German industrialists 1,250,000 metric tons; and the navy, which had underground storage tanks and a smaller number of surface tanks in the North Sea and Baltic Sea areas, and in the German interior, the remaining 1,800,000 metric tons. But the government's lofty projection fell short. Germany's total storage reached 2,400,000 metric tons of liquid fuel on 21 June 1941. WIFO's contribution, 500,000 metric tons of aviation gasoline, was a significant amount that represented about one-third the

total 1940 US production of aviation gasoline (40,000 barrels per day) and almost equal to Germany's refining capacity of 420,000 metric tons per month or 5,000,000 metric tons per year, about half of it refined in the Hamburg and Hannover areas.

Two months after establishing WIFO the German government took the second step when it forced the establishment of Braunkohlen Benzin AG (Brabag) to promote and carry out commercial-scale synthesis of synthetic liquid fuel and lubricating oil from coal and tar. Brabag was an association of IG Farben and nine central German brown coal producers (Compulsory Union of German Lignite Producers) that accounted for 90 percent of Germany's brown coal, and at the time of its formation on 26 October 1934, it had a capitalization of RM 100 million financed entirely with a fifteen year loan that the German brown coal producers guaranteed. Gesellschaft für Mineralölbau GmbH, a division of Brabag established two years later in November 1936 by the ten brown coal producers, carried out the design and engineering of the Brabag plants, using technical information that the government required IG Farben, Ruhrchemie, and other synthetic fuel producers provided as a result of entering into licensing agreements with the government. Brabag and Mineralölbau built and operated three coal hydrogenation and one F- T plant during the 1930s and 1940s.

Additional government commitment to the synthetic fuel industry, and indicative of the supportive government-industry relation, emerged at a Nazi party rally in Nürnberg on 9 September 1936. At that time Adolf Hitler announced his Four Year Plan to make the German military ready for war in four years and the economy independent and strong enough to maintain a major war effort. Hitler put Hermann Göring (1893-1946) in charge of the plan, gave him the title Commissioner General for the Four Year Plan, and had Göring officially approve the plan in May 1937. With Hitler's war strategy requiring large supplies of petroleum, a petroleum-independent Germany became the Four Year Plan's major thrust. Of the 289 projects scheduled for the period 23 October 1936 to 20 May 1937 at a cost of RM 1,369 million, 42 percent costing RM 570 million were synthetic fuel projects. In fact in 1936 Hitler urged the petroleum industry, including synthetic fuel produced by both coal and tar hydrogenation and F-T synthesis to become independent of foreign production in eighteen months and called for synthetic fuel production to increase from 630,000 metric tons in 1936 to 3,425,000 metric tons in 1940. As an incentive toward the synthesis of petroleum from coal the German government in December 1936 raised the tariff on imported petroleum from a 1931 levy of RM 219.30 per metric ton (24.4¢ per US gallon) to RM 270.90 per metric ton (30.1 ¢ per US gallon). By this time only four coal hydrogenation and two F- T plants were operating with a combined production far less than required for petroleum independence. The high tariff enabled the synthetic fuel plants to show a profit even though they were highly inefficient and had production costs much greater than the cost of natural petroleum.

In the beginning, private capital coming from bank loans and from the synthetic fuel companies' own funds, stock, and bond issues provided practically all of the financing for the plants. But by 1939, as the cost of the program increased significantly and private capital dried up, the German government provided more and more of the funding. A report of 21 March 1939 showed that of the RM 132 million spent on synthetic fuel in 1939, the government provided RM 70 million to Mineralölbau GmbH for the purchase of plant equipment. Additional government support came in the form of guaranteed purchases of synthetic fuel at prices high enough to allow for short term amortization of plant costs. Total synthetic fuel production from the seven coal hydrogenation and seven F-T plants operating in September 1939 was 1,280,000 metric tons increasing to almost 1,900,000 metric tons in May 1940. It exceeded Germany's refining of crude oil from natural sources (1,256,000 metric tons) and imports mainly from Romania (1,085,000 metric tons) in 1939.

The Reichsamt für Wirtschaftsausbau (Office of Economic Development) constantly revised the Four Year Plan. Its general concerns were the raw material and manpower requirements and the never ending iron and steel shortages, and in particular for the synthetic fuel industry the anticipated shortages of aviation gasoline and fuel oil. The first revision at Karinhall, Göring's vast country palace in the Schorfleide (Berlin- Postdam) on 12 July 1938 gave priority to hydrogenation plants for the production of aviation gasoline and to bituminous coal distillation for the production of fuel oil. The Welheim hydrogenation plant, which had begun production of aviation gasoline and fuel oil for the navy in 1937- 38, already had received priority; and the Brück hydrogenation plant, which produced diesel oil, later benefited from the revised plan. The 1938 revision also dealt with the number of workers required for the construction, operation, and maintenance of the synthetic fuel plants. It called for 30,000 construction workers in 1938, 57,600 workers on 1 July 1939, and increasing from a projected 70,000 workers on 1 October 1939 to 135,000 workers during the last quarter of 1941. The actual construction force, however, numbered about 35,000 at the outbreak of war, about 70,000 by mid-1941, and peaked at 85,000 in spring 1943.

Steel production also failed to meet the Four Year Plan's requirements. A second Karinhall revision of 1 January 1939 called for the production of 4.5 million metric tons of steel by the end of 1943. With this amount of steel Germany expected to expand existing plants and construct new plants to increase synthetic fuel production from 3.7 million metric tons in 1938 to 11 million metric tons per year by 1944. According to the US Strategic Bombing Survey's postwar report the required 4.5 million metric tons of steel equaled the amount necessary to build a fleet 3.5 times the size of the British navy that existed on 1 January 1940.¹²

Commercial developments of the F-T synthesis

The first of the commercial-size F-T plants to produce synthetic fuel was the Steinkohlen- Bergwerk Rheinpreussen plant located in Mörs-Meerbeck (Homberg, Ruhr) near the Rheinpreussen coal mine. Giltenhoffnungshilte, controlled by the

Haniel Group, completed the plant in late 1936. Most of the synthetic fuel plants had scientists or engineers with doctorates in either chemistry or chemical engineering as managers or directors as was the case at Rheinpreussen where plant manager Struever, H. Kobel, and W. Dannefeler, directed a work force of 750. Liquid fuel synthesis took place at 1 atm, 190- 195°C, and in two stages with 60 of the plant's 90 tube and plate converters operating in stage one and the other 30 operating in stage two. Rheinpreussen designed its own coal coking ovens for the production of coke and coke (coal) oven gas, a hydrogen-carbon monoxide-methane mixture used for cracking (reacting) with steam at 1,200°C in a Koppers gasifier to increase the hydrogen content of the gas mixture. Combining this mixture with twice as much water gas, produced by reacting coke with steam, gave the synthesis gas of proper proportions, 2 H₂ : 1 CO. Rheinpreussen's annual capacity was 25,000- 30,000 metric tons (later increased to 70,000 metric tons) of gasoline and diesel oil (primary oils) and paraffin wax. An alcohol plant produced another 3,000 metric tons of propyl and butyl alcohol.¹³

The mining company Gewerkschaft Viktor AG (Klockner AG), a subsidiary of Winters hall AG, constructed the second commercial-size F-T plant at a cost of RM 30 million in Castrop-Rauxel (Ruhr) also in late 1936. The plant site adjoined Gewerkschaft Viktor's coal mine and was the location of a synthetic ammonia plant. Gewerkschaft Viktor designed its own coal coking ovens and gasifier that was similar to a Koppers gasifier. It produced synthesis gas by cracking coke oven gas with steam and mixing the cracked gas with water gas obtained from coke. The plant's 63 tube and plate converters operated in two stages at 1 atm and according to plant manager Braune had an annual capacity of 30,000- 40,000 metric tons of gasoline and diesel oil.¹⁴

Ruhrchemie's Ruhrbenzin AG plant in Oberhausen-Holteln was the third commercial-size F-T plant constructed in the 1930s. Ruhrbenzin, established in September 1935 with a capitalization of RM 4.5-6 million and increased to RM 15 million in 1940, planned in 1936 to complete construction of a plant annually producing 30,000 metric tons (increased to 62,000 metric tons in 1942) of gasoline, diesel oil, and lubricating oil. Production did not begin until 1937, however. The plant differed from the Rheinpreussen and Viktor plants in having two independent synthesis systems: a two-stage 1 atm synthesis with 48 tube and plate converters and a three-stage 10-15 atm synthesis with 72 concentric double tube converters. Water gas, prepared from coke, one-third of which after an iron-catalyzed reaction with steam at 500°C, gave a mixture containing 61 percent hydrogen and 5 percent carbon monoxide; adding the mixture to the remaining two-thirds water gas provided synthesis gas for conversion to gasoline, diesel oil, and lubricating oil. Compared to the eight F-T plants that eventually came into operation the Ruhrbenzin plant was inefficient. It lost RM 2.6 million in 1939 which Ruhrchemie's president and managing director Friedrich Martin, chief designer Willke, and plant superintendent Navelling attributed to the constant experimentation with the plant's reaction conditions and procedures.¹⁵ Oberhausen-Holteln became the research and development center for the catalytic studies of Roelen. Leonard Alberts, Walter Feisst, and others. Its catalyst plant supplied the six F-T plants in the Ruhr area with the standard cobalt catalyst, producing about 3,000 metric tons per year. Brabag's plant in Ruhland-Schwarzheide and beginning in 1938 the Wintershall plant in Lützkendorf also produced the standard cobalt catalyst.¹⁶

Brabag, which also operated three coal hydrogenation plants, completed construction of Brabag II, the fourth F-T plant in Ruhland-Schwarzheide in 1937. Brabag II was a two-stage 1 atm plant and had an annual capacity of 25,000-30,000 metric tons of gasoline and diesel oil. Later expansion, which increased the number of tube and plate converters to 262 and maximum annual production to 162,000 metric tons (200,000 metric tons capacity), made it Germany's largest F-T plant. Brown coal briquettes, gasified in Didier-Bubiag retorts, each with a capacity of 638,000 m³ (22 million cubic feet) per day, and Koppers gasifiers, each with a capacity of 26,100 m³ (900,000 cubic feet) per hour, provided 20 percent and 80 percent of the synthesis gas. Purification of the synthesis gas by passing it through towers containing pellets of iron oxide and sodium carbonate to remove sulfur and other impurities was relatively simple because of the brown coal's low sulfur content. Erwin Sauter, A. Wagner, W. Sapper, and catalyst specialist Karl Meyer directed the plant's operation.¹⁷

In addition to the ongoing catalytic research, both Ruhrchemie at its research center in Oberhausen-Holteln and Fischer at the KWI investigated the F-T medium pressure synthesis hoping to improve F-T efficiency and economics. The studies showed that medium pressure gave a slightly higher yield of gasoline and diesel oil per m³ of synthesis gas, extended the catalyst's life from 4-7 months to 6-9 months without any reactivation, and yielded a higher proportion, about 45 percent versus 18 percent, of heavier hydrocarbons such as soft and hard wax for the production of lubricating oil and chemicals. The middle pressure synthesis also had a higher operating costs. Consequently, only two of the five F-T plants constructed in 1938 and 1939 before World War II began were medium pressure syntheses. A third plant was a combination atmospheric-medium pressure synthesis.¹⁸

The first of the newer F-T plants was the Wintershall subsidiary, Mitteldeutsche Treibstoffplant, constructed in Lützkendorf in late 1938 in the Geiseltal brown coal mining district of central Germany. Mitteldeutsche had 132 tube and plate converters that operated in two stages at 1 atm, but a maximum of 77 converters operated at one time. The plant performed poorly except for its last two years of operation in 1943-44 when annual production reached 30,000 metric tons of gasoline and diesel oil or about 40 percent of its maximum. A synthesis gas problem caused its poor performance. Mitteldeutsche used the first commercial-size Schmalfeldt generator that plant director H. Schmalfeldt had designed for the production of synthesis gas from the direct gasification of powdered brown coal. The coal had a very high sulfur content, and until plant engineers installed activated charcoal absorbers in the purification system to remove the sulfur and eliminate the catalyst's poisoning (a standard procedure in F-T plants), the catalyst lasted only two months instead of the usual 4-7 months.¹⁹

Friedrich Krupp AG in Essen joined the expanding group of synthetic fuel producers in 1937 when it established Krupp Treibstoffwerk GmbH in Wanne-Eickel (Essen) with a capitalization of RM 20 million and a RM 10 million loan. Erich Combles

general manager and assistant general manager H. Fischer directed the 900 workers who operated the only combination atmospheric-medium pressure plant. Krupp-Lurgi gasifiers of 40 metric tons per day capacity converted coke, obtained mainly from high- temperature coal carbonization, to water gas, one-third of which underwent catalytic conversion to synthesis gas. Synthesis gas first passed through one set of 72 tube and plate converters at 1atm for conversion to gasoline and diesel oil; residual synthesis gas, after flowing through standard tubular condensers, activated charcoal absorbers, and compressed to 10-15 atm, traveled through a second set of 24 medium pressure converters to complete the conversion. Of the 24 medium pressure converters, 16 were of a new design called tauschenrohren, in which single tubes of 72 mm internal diameter and fitted with fins of sheet steel, replaced the standard concentric double tube converter. The new converter design increased catalyst capacity by 5 percent but left carbon deposits in the converter. Maximum production of gasoline and diesel oil at the plant reached 54,000 metric tons in 1943, maximum annual capacity was 130,000 metric tons.²⁰

Chemische Werke Essener Steinkohle AG in Essen, established in early 1937 as a partnership of Essener Steinkohlen Bergwerke AG and Harpener Bergbau AG in Dortmund with a capitalization of RM 12 million and a RM 10 million loan, constructed the second largest and the most efficient of the 1 atm plants. Plant manager Gabriel and assistant manager E. Tengelmann directed the 600 plant workers. Gasifying coke in water gas generators and cracking the resulting coke oven gas produced synthesis gas for conversion to gasoline and diesel oil in 124 tube and plate converters operating in two stages. The high efficiency of the Essener plant, according to postwar Allied investigations, appeared to depend on the purity of its synthesis gas, the equal distribution of the catalyst between the two stages, and the frequency of reactivating the catalyst by treating it with nitric acid and hydrogen gas. Gabriel and Tengelmann believed, however, that the constant composition of the synthesis gas and the plant's freedom from interruptions and breakdowns, which most likely resulted because of all the above factors, were the major reasons for the plant's successful operation from the time of its start up in 1939. Essener Steinkohle's maximum annual production was 86,500 metric tons of gasoline and diesel oil.²¹

The last of F-T plants were the medium pressure operations of Hoesch-Benzin GmbH in Dortmund (Ruhr) and Schaffgotsch Benzin GmbH in Deschowitz-Beuthen, Odertal (Upper Silesia), both of which began operation in 1939. Hoesch-Benzin, a subsidiary of Bergwerksgesellschaft Trier GmbH (owned by Hoesch-Köhn-Neussen AG), had a capitalization of RM 3 million and a workforce of 800 under the direction of plant manager H. Weitenhiller and plant superintendent Werres. The Hoesch plant converted coke to water gas and then cracked the water gas with additional steam to produce synthesis gas. Its 65 concentric double tube converters converted synthesis gas to gasoline and diesel oil in two stages and added a third stage during the war. Operating efficiency, measured by production per converter per month, was the highest of all the plants, its production reaching a maximum of 51,000 metric tons per year.²²

Plant manager A. Pott, formerly director-general of Ruhrgas AG, supervised the Schaffgotsch Benzin plant operation. Pintsch generators produced synthesis gas from hard coke and coke oven gas and until mid-1943 synthesis gas conversion to gasoline and diesel oil occurred in two stages. The addition of a third stage at that time resulted in a plant similar to the Hoesch-Benzin plant. Schaffgotsch had 68 converters, 50 of them wide-tube 22-23 mm diameter converters that contained single catalyst tubes rather than the concentric double tubes used in the other medium pressure F-T plants. Its engineers claimed that their modified design increased catalyst capacity by 10 percent and that their converters functioned particularly well in the second and third stages despite having to drill interior carbon deposits in order to remove the catalyst for reactivation. Schaffgotsch achieved a maximum annual production of 39,200 metric tons of gasoline and diesel oil; its annual capacity was 80,000 metric tons.²³

F-T plant construction ended with the outbreak of the war, resulting in standardization of plant apparatus and operation, although during 1943-45 research continued on designing better converters and finding cheaper iron catalysts to replace scarce wartime supplies of coal compounds. Ruhrchemie, which conducted 2,000 investigations, Rheinpreussen, KWI, IG Farben, Lurgi, and Brabag developed six iron catalysts, and all gave satisfactory results in comparative tests carried out in September 1943 at Brabag's Schwarzheide plant. The Reichsamt für Wirtschaftsausbau, which arranged for the tests, never decided on the best iron catalyst, concluding only that all six were inferior to cobalt catalysts. None of the commercial-size plants used iron catalysts.

The three new converter designs developed during the war operated at 20 atm, used iron catalysts, and were internally cooled compared to the inefficient externally cooled fixed bed converters in the existing F-T plants. Their design summaries appear below.

- 1 gas as a heat transfer medium: IG Farben's fixed bed hot gas recycle process
- 2 oil as the heat transfer medium
- 3 fluidized bed, oil slurry process of fG Farben, Ruhrchemie, and Rheinpreussen .
- 4 fixed bed, IG Farben oil circulation process

The first of these new converters removed the heat the synthesis released in the gas stream by recirculating residual gas through a wide shallow bed containing a powdered iron-one percent borax catalyst. IG Farben developed this converter design and successfully tested it on a small scale with 5 L of catalyst for 10 months. Large-scale tests were unsuccessful because of the catalyst's overheating. The converter had high energy requirements and cost more to operate than the older design converters, and for these reasons IG Farben abandoned its development before the end of the war. The gasoline produced had a 68-70

octane number that additional refining increased to 75-78 and 84.

Both of the remaining converter designs used oil as the heat transfer medium. The fluidized bed or oil slurry process forced water gas through a ceramic plate at the bottom of a cylindrical converter that contained a catalyst of iron with carbonate or borate suspended in a high boiling heavy synthetic oil. The tests were small scale and aimed at the production of C₂₀-C₇₀ olefins in the gas oil boiling point range (232-426°C) for use in chemical syntheses.

The other oil-cooled converter had the iron catalyst (iron oxide and other metallic oxides) arranged in a fixed bed and removed the heat of reaction by circulating oil through the catalyst bed. IG Farben tested this converter for an extensive time in a pilot plant of 8-10 metric tons capacity, synthesizing a gasoline with a 62-65 octane number.²⁴

Emphasis also shifted at this time from the production of fuels and lubricants to the production of olefins, (unsaturated hydrocarbons), waxes, alcohols, and other organic compounds. The oxo synthesis from the German "oxiering," meaning ketonization, was the most important result of this research. In the oxo synthesis, straight-chain olefins such as C₂H₄ and C₃H₆, reacted with carbon monoxide and hydrogen at 110-150°C, 150 atm, and with a cobalt catalyst to form an aldehyde that had one more carbon atom in the chain. Hydrogenating the aldehyde under the same conditions gave the corresponding alcohol. Roelen of Ruhrchemie patented the process in 1938, and in 1940 Ruhrchemie and IG Farben cooperated in its development. Their objective was the production of long-chain alcohols (C₁₂-C₁₈) for conversion to detergents (sulfate esters), but the process had general applicability to all olefin-like compounds. Ruhrchemie, IG Farben, and Henkel et Cie, organized a new company called Oxo-Gesellschaft and in 1944 completed construction of an oxo plant in Sterkrade-Holteln that had an annual capacity of 12,000 metric tons of alcohols and a production cost of 78.23 pfennig per kg. Allied bombing in August - October 1944 permanently prevented the plant from beginning production.

Information on F-T plant construction and operating costs has come from two main sources: captured German synthetic fuel documents and their summaries and interrogation of German synthetic fuel scientists, such as Martin, Ruhrchemie's managing director; Heinrich Biltfisch, an IG Farben director and government economic advisor on wartime petroleum production; and F-T plant managers and operating personnel. The collective information indicates that capital and production costs were high. A F-T plant cost approximately RM 30 million, production cost, including catalyst, water gas manufacture, synthesis of primary products and all other costs was 23.5-26 pfennig per kg (RM 240-330 per metric ton) for both the 1 atm and medium pressure operation. Hoesch-Benzin's medium pressure plant with an annual production of 40,000 metric tons had a capital cost of RM 26 million (RM 650 per metric ton per year) and a production cost in 1942 of 25.81 pfennig per kg of products. The Essener Steinkohle 1 atm plant with 80,000 metric tons annual production had a capital cost of RM 32 million (RM 400 per metric ton per year) and a production cost of 23.71 pfennig per kg of synthetic products. Ruhrchemie's combined atmospheric-medium pressure plant with an annual production of 42,000 metric tons had a production cost in 1939-40 of 23.57 pfennig per kg of products. The nine F-T plants provided 12-15 percent of Gennany' s total synthetic fuel production during their nine years of operation (Table 1).²⁵

Summary of commercial development in Germany 1927-45

Despite substantial government support and Hitler's 1936 call for petroleum-independence, the synthesis of petroleum from coal and tar never completely solved Germany's liquid fuel problem. Bureaucratic confusion, material shortages, and later Allied bombing limited its effectiveness. But production increased dramatically under the Four Year Plan and its renewal in October 1940. In 1933, only three small synthetic fuel plants were operating, Ludwigshafen, Leuna, and Ruhrchemie Oberhausen-Holteln, the last a F-T plant, that produced mainly diesel oil and petrochemicals. At that time, Germany's petroleum consumption was about one-half of Great Britain's, one-fourth of Russia's, and one-twentieth that of the United States. Yet, even at such low consumption, domestic resources were inadequate. Total consumption of liquid fuels (including 274,000 metric tons of lubricating oil) in 1932 was 2,755,000 metric tons, 73 percent of which (2,020,000 metric tons) Germany imported mainly from the United States. For gasoline consumption the situation was the same; Germany consumed 1,460,000 metric tons, two-thirds of which (930,000 metric tons) it imported. By September 1939 when World War II broke out seven coal hydrogenation (plus Ludwigshafen) and eight F-T plants were in operation and were beginning to contribute increasingly to Germany's domestic liquid fuel supply. When plant construction ceased in 1942 twelve coal hydrogenation and nine F-T plants converted coal and coal tar into gasoline, diesel oil, and other petroleum products (Table 2).

From the first coal hydrogenation plant that began operation at Leuna on 1 April 1927, the twelve coal hydrogenation plants in early 1944 reached a peak production of over three million metric tons (21.5 million barrels) of synthetic fuel. The nine F-T plants contributed another 535,000 (570,000) metric tons of primary products to the war effort, or 12-15 percent of Germany's total liquid fuel requirements. Their production also fell significantly because of Allied bombing, decreasing from 43,000 metric tons in the first four months of 1944 to 27,000 metric tons in June, to 7,000 metric tons in December, and to 4,000 metric tons in March 1945.²⁶

The average cost of hydrogenating coal or tar was high, 19-26 pfennig per kg (RM 190-260 per metric ton) or the equivalent of 24¢ per US gallon (\$10 per barrel) of gasoline. The average cost of primary products at the F-T plants was a comparable 23.71-25.81 pfennig per kg (RM 240-330 per metric ton). These figures were more than double the price of imported gasoline, but for Germany, with only a limited supply of natural petroleum, no alternative remained during the war other than the

construction of synthetic fuel plants. In this way Germany utilized its naturally abundant supplies of bituminous and brown coal.²⁷

Labor force in the synthetic fuel plants

Faced with a growing labor shortage as the war dragged on, German industrial firms including synthetic fuel producers such as IG Farben, Brabag, Sudetenlandische Treibstoffwerke AG, and Hydrierwerke Pölit AG, increasingly supplemented their labor force with paid coerced (forced) laborers and (or) concentration camp inmates (slave laborers) of many nationalities. French, Belgian, Polish, British, Serbian, Czech, Hungarian, and Russian laborers, Jews and non-Jews, worked in the prewar plants in Ludwigshafen in west Germany and Leuna in east Germany and in several of the synthetic fuel plants constructed after the war had started. Pölit in north Germany (July 1940), Lfitzkendorf in central Germany (1940), Wesseling in west Germany near Bonn (August 1941), Brüx in Bohemia (October, 1942), and the Blechhammer plant (1942) and Heydebreck saturation plant in Upper Silesia (April 1944) used forced laborers and (or) concentration camp inmates. IG Farben's labor force contained about 9 percent forced laborers and concentration camp inmates by 1941, the number increased to 16 percent in 1942, and to 30 percent of all workers in its synthetic fuel plants near the war's end. In addition to the forced laborers and concentration camp inmates, some free foreign workers came from Germany's allies, mainly Italy and Romania.

All skilled and unskilled foreign workers in a specific industry (automotive, coal, steel) earned the same wage as an unskilled German worker in that industry, about 64.1 pfennig per hour or RM 38 for a 60 hour week, but received RM 18-25 after deductions for taxes, room and board. A skilled German worker received 81 pfennig per hour or about RM 49 for a 60 hour week.²⁸ At the coal hydrogenation and F-T plants the average wage for all workers involved in synthetic fuel production was RM 1.30 per hour, a considerably higher amount. This was the wage plant officials told postwar Allied investigating teams they used to calculate synthetic fuel production costs.²⁹

The never-completed IG Farben synthetic fuel plant at Auschwitz (Auschwitz III) or Oswiecim, in south Poland west of Cracow, was a different story. Free German and Polish workers as well as forced eastern European workers contributed to its construction, but the largest group of workers was the approximately 300,000, concentration camp inmates that included Germans, Greeks, Dutch, Czechs, Hungarians, Poles, and Russians, most of whom were Jews. IG Farben paid all its unskilled workers 30 pfennig per hour (RM 0.30 per hour) or RM 3 for a 10 hour work day and all skilled workers 40 pfennig per hour (RM 0.40 per hour) or RM 4 per day after deductions for taxes, room and board. This was the same wage as the 1944 average industrial wage for unskilled and skilled foreign workers for a six-day week (RM 18-25) with one difference. Free and forced foreign workers received these wages, but the total wage each concentration camp inmate earned went instead to the SS (Schutz-Staffel) for taxes and expenses (room and board and clothing). In effect, IG Farben was paying the SS for the labor it provided.³⁰

Auschwitz, however, never produced a drop of synthetic fuel. Construction started in 1941, and it remained largely unfinished at the time Soviet troops overran it on 27 January 1945. Its scheduled production of 24,000 metric tons per year, making it the smallest of the coal hydrogenation plants, was only a fraction of the Leuna plant which produced at its rated capacity of 620,000 metric tons of synthetic liquids per year. Auschwitz cost 25,000-30,000 lives and RM 900 million for all operations including the never-completed synthetic rubber plant, but it was a miserable failure.³¹

To determine an accurate production cost in the operational synthetic fuel plants, or in any of the wartime plants used forced laborers and concentration camp inmates, remains very complicated, however. mainly because of difficult-to-measure factors and incomplete data. First of all, even though concentration camp inmates received no wages, the cost of their guarding, housing, even their near-starvation feeding involved some expense. The production cost calculation also requires knowing the number of years each plant was in operation; what percent of workers in each plant was forced or concentration camp; how long each worker worked at the plant; and worker efficiency which, according to Fritz Sauckel, Reich Commissioner for Labor, ranked Polish forced workers one-half as efficient, and concentration camp inmates one-third as efficient as German workers. Total German synthetic fuel production in fact fell to its lowest in the last months of World War II when the number of coerced and concentration camp inmates reached a maximum. Other factors to consider are plant operation time versus shutdown time because of bombings and equipment malfunctions and what reduction in production cost resulted completely from technical improvements in each plant.³² Some of this information, such as the composition of the workforce in a few of the plants, is available. The Leuna plant as of 1 October 1944 employed 34.9 percent foreign workers; in Ludwigshafen, which was a research facility and only a small producer of synthetic fuel, the foreign work force numbered 36.6 percent. Auschwitz, by the same date, had 55.1 percent foreign workers, 26.6 percent concentration camp inmates both foreign and German, and 18.3 percent free German workers.³³

Postwar court settlements, such as the 1957 Braunschweig court case settlement between a Jewish concentration camp inmate and the Bussing Company of Braunschweig, have provided additional information on wartime labor. Bussing manufactured trucks for the German army and during the war it had used foreign inmates from the Neuengamme concentration camp. Because the inmates received no compensation for their wartime work the court set the wage at RM 1 per hour (before deductions) for a 10 hour work day arguing that it was the scale established according to wartime wage controls.³⁴

In another postwar settlement IG Farben and the Conference on Jewish Material Claims Against Germany (a consolidation of twenty-three major Jewish organizations) and reached an agreement to provide compensation for IG Farben's

use of unpaid concentration camp inmates. By 1958, IG Farben had arranged to pay DM 27 million to the Jewish Material Claims Conference.³⁵ Its settlement followed an earlier 1952 agreement between the Federal Republic of Germany and the Material Claims Conference in which the German government paid DM 450 million (\$105 million) to the Material Claims Conference and also sent DM 3 billion (\$700 million) worth of goods such as petroleum and steel to Israel over a ten-year period. The German government estimated that its payments would have to continue beyond the year 2000 and its total payments would reach DM 100 billion (\$40 billion).³⁶

Conclusion

Clearly, Germany had the first technologically successful synthetic fuel industry producing eighteen million metric tons (128 million barrels) from coal and tar hydrogenation and another three million metric tons from the F-T synthesis in the period 1939-1945. After the war ended German industry did not continue synthetic fuel production because the Potsdam (Babelsberg) Conference of 16 July 1945 prohibited it.³⁷ The Allies maintained that Germany's Nazi government had created the industry for strategic reasons under its policy of autarchy and that in postwar Germany there were, economically, better uses for its coal than synthetic fuel production. Four years later on 14 April 1949, the Frankfurt Agreement ordered dismantling of the four coal hydrogenation plants in the western zones, all of which were in the British zone.³⁸ But shortly after the formal establishment of the West German government in September 1949, a new agreement, the Petersberg (Bonn) Agreement of 22 November 1949, quickly halted the dismantling process in an effort to provide employment for several thousand workers.³⁹ The West German government completely removed the ban on coal hydrogenation in 1951, although by this time Ruhröl GmbH (Mathias Stinnes) had deactivated the Welheim plant, and the plants in Scholven, Gelsenberg, and Wesseling after design modifications. Were hydrogenating and refining crude oil rather than hydrogenating coal. The Russians dismantled the Magdeberg plant located in their zone and the three plants in Poland at Pölitz, Blechhammer, and Auschwitz. They used parts from the Magdeberg and Auschwitz plants to reconstruct a plant in Siberia that had an annual production capacity of one million metric tons of aviation fuel and a second plant in Kemerow-Westbirien that also produced aviation fuel from coal. The Pölitz and Blechharnrner plants provided scrap iron. Three other plants in their zone, at Leuna, Böhlen, Zeitz, and the Sudetenland plant at Brtux (Möst), which the Russians gave to Czechoslovakia, continued with coal and tar hydrogenation, and after modification, refined petroleum into the early 1960s. Some dismantling and conversion to synthetic ammonia production for fertilizers occurred at the Leuna plant which by 1947 the Russians had renamed the Leuna Chemical Works of the Soviet Company for Mineral Fertilizers. The last of the coal hydrogenation plants in the Soviet Zone at Lützkendorf did not resume production after the war. Three of the F-T plants continued operation after the war. Schwarzheide in the Soviet Zone, which had a labor force of 3,600, produced gasoline for Russian civilian and military construction. Gewerkschaft Victor in Castrop-Rauxel and Krupp Treibstoffwerk in Wanne-Eickel in the British zone, as of February 1946 were producing oils and waxes from fatty acids and using them to make soaps and margarine.⁴⁰ The six other plants remained inoperative.

The German synthetic fuel industry succeeded technologically because in the 1920s Pier at IG Farben developed suitable catalysts for the hydrogenation of coal and divided the process into separate liquid and vapor phase hydrogenations, improving both economics and yield. A short time later Fischer and his co-workers at the KWI prepared the catalysts and established the reaction conditions that made the F-T synthesis a success. But neither coal-to-oil conversion process could produce a synthetic liquid fuel at a cost competitive with natural petroleum. Coal hydrogenation and the F-T synthesis persevered and survived because they provided the only path Germany could follow in its search for petroleum independence.

Notes

Most of the information on the Fischer-Tropsch and coal hydrogenation plants has come from the Allied investigative teams that went to Germany during World War II's closing months. These teams, such as United States Technical Oil Mission (TOM) and the British Intelligence Objectives Subcommittee (BIOS), examined the thousands of technical reports Allied troops captured at the synthetic fuel plants, interviewed many of the German synthetic fuel scientists, and sent their information to the Combined Intelligence Office Subcommittee (CIOS) in London for translating and abstracting. CIOS prepared 141 microfilm reels, and after moving its operation to the United States produced another 164 reels. CIOS, BIOS, TOM, and Field Intelligence Agency Technical (FIAT) also printed and released more than 1,400 reports on the German synthetic fuel plants, many of which are on TOM microfilm reels.

In addition to the 1,400 investigative reports several exhaustive summaries of the reports are available. The most important of these are the Ministry of Fuel and Power, *Report on the Petroleum and Synthetic Oil Industry of Germany* (London, 1947) and the Joint Intelligence Objectives Agency, *High-pressure Hydrogenation at Ludwigshafen-Heidelberg*, FIAT, *Final Report 1317* (9 vols., Dayton, Ohio: Central Air Document Office, March 1951). The Ministry's *Report* deals with the Fischer-Tropsch synthesis and the coal hydrogenation process whereas the Joint Intelligence's *High-pressure* discusses only coal hydrogenation. A third comprehensive source is Henry H. Storch, Norma Golumbic, and Robert B. Anderson, *The Fischer-Tropsch and Related Syntheses* (New York, 1951). It also relies heavily on the captured German World War II synthetic fuel documents. These are the best and most comprehensive sources, and I have relied on them extensively. Other important sources that I have used in this study are Peter Hayes, *Industry and Ideology, IG Farben in the Nazi Era* (Cambridge, 1987); Raymond G. Stokes, *Divide and Prosper: The Heirs of IG Farben Under Allied Authority*,

1945-1951 (Berkeley, 1988), John Gimbel *Science, Technology, and Reparations: Exploitation and Plunder in Postwar Germany* (Stanford, 1992), and Jeffrey A. Johnson, *The Kaiser's Chemists, Science and Modernization in Imperial Germany* (Chapel Hill, 1990).

During the early 1970s after the Arab oil embargo and crisis of 1973-74 Richard Wainerdi and Kurt Irgolic established the German Document Retrieval Project at Texas A&M University. They set as its objective the collecting, translating, and organizing of the thousands of German World War II documents and reports that the Allied intelligence teams had brought to the United States and now were scattered around the country in various government repositories, archives, and even with members of the TOM. The German Document Retrieval Project, of which I was a member, accomplished its objective, and as a result Texas A&M's archives contain what is very likely the most comprehensive collection of information on Germany's World War II synthetic fuel industry. I have used this collection in this and other papers I have written on the history of synthetic fuel. This paper's citations on the plant descriptions are from the Ministry's and the Joint Intelligence's summaries, with other sources included when required for greater detail or clarification.

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1. A third process, the distillation or carbonization of coal at either a high temperature (HTC) of 700-1000°C or a low temperature (LTC) of 500-700° C produces petroleum. The process is not a synthesis but a decomposition and gives small yields of only gallons per metric ton of coal rather than barrels. It is a derived process and was never a major contributor to Germany's liquid fuel requirements. Its simplicity, distilling the petroleum from coal not its yield, has resulted in its use.
 2. BASF, German patent 293,787 (8 March 1913); BASF, British patent 20,488 (10 September 1913); BASF, French patent 468,427 (13 February 1914); BASF (Alwin Mittasch and Christian Schneider), US patent, 1,201,850 (17 October 1916).
 3. Franz Fischer and Hans Tropsch, "Über die Reduktion des Kohlenoxyds zu Methan am Eisenkontakt unter Druck," *Brennstoff-Chemie*, 4 (1923): 193-7; Fisher and Tropsch, "Über die Herstellung synthetischer Ölgemische (Synthol) durch Aufbau aus Kohlenoxyd und Wasserstoff," *ibid.*, 4 (1923): 276-85; Fischer and Tropsch, "Methanol und Synthol aus Kohlenoxyds als Motorbetriebsstoff," *ibid.*, 6 (1925): 233-4; Fischer, "Liquid Fuels from Water Gas," *Industrial and Engineering Chemistry*, 179 (1925): 574-6; Fischer and Tropsch, German Patent 484,337 (22 July 1925); Fischer and Tropsch "Die Erodölsynthese bei gewöhnlichem Druck aus den Vergangsprodukten der Kohlen," *Brennstoff-Chemie*, 7 (1926): 97-104; Fischer and Tropsch, German patent 524,468, (2 November 1926); Fischer and Tropsch, "Über Reduktion und Hydrierung des Kohlenoxyds," *Brennstoff-Chemie*, 7 (1926): 299-300; Franz Fischer, "Über die synthese der Petroleum Kohlenwasserstoffe," *Brennstoff-Chemie*, 8 (1927): 1-5 and *Berichte*, 60 (1927):1330-4; Fischer and Tropsch, "Über das Auftreten von Synthol bei der Durchführung der Erdölsynthese unter druck und über die Synthese hochmolekular Paraffin Kohlenwasserstoffe aus Wassergas," *Brennstoff-Chemie*, 8 (1927) 165-7; BASF, British patents 227,147, 228,959, 229,714, 229,715 (all 28 August 1923); Fischer, "Zwölf Jahre Kohlenforschung," *Zeitschrift angewandte Chemie*, 40 (1927): 166; BASF (Alwin Mittasch, Matthias Pier, and Karl Winkler), German Patent 415,686 (application 24 July 1923, awarded 27 July 1925); BASF, US patent 1,558,559 (27 October 1925); BASF (Mittasch and Pier), US patent 1,569,775 (12 January 1926); BASF, French patents 571,285 (29 September 1923); 571,354, 571,355, and 571,356 (all 1 October 1923); 575,913 (17 January 1924); 580,914 (30 April 1924); 580,949 (1 May 1924); 581,816 (19 May 1924); 585,169 (2 September 1924); Fischer and Tropsch, "Über die direkter synthese von Erdöl-Kohlenwasserstoffen bei gewöhnlichem Druck," (Erste Mitteilung), *Berichte*, 59 (1926), 830-831; *ibid.* 832-836; Fischer and Tropsch, "Über Einige Eigenschaften der aus Kohlenoxyd bei gewöhnlichem Druck Hergestellten Synthetischen Erdöl-Kohlenwasserstoffe," *Berichte*, 59 (1926): 923-5. Henry H. Storch, Norma Golumbic, and Robert B. Anderson, *The Fischer-Tropsch and Related Syntheses* (New York, 1951): 115.
 4. Franz Fischer and Hans Tropsch, German patent 484,337 (22 July 1925); Fischer and Tropsch publications (ref. 3); Fischer, "The synthesis of petroleum," International Conference on Bituminous Coal, *Proceedings* (Pittsburgh, 1926), 234-246; Storch, Golumbic, and Anderson (ref. 3), 116-7.
 5. Storch, Golumbic, and Anderson, *Fischer-Tropsch* (ref. 3), 135; Franz Fischer, Helmet Pichler, and Rolf Reder, "Überblick über die Möglichkeiten der Beschaffung geeigneter Köhlenoxyd-Wasserstoff-Gemische für die Benzinsynthese auf Grund des heutigen Standes von Wissenschaft und Technik," *Brennstoff-Chemie*, 13 (1932): 421-8; Franz Fischer, Otto Roelen, and Walter Feisst, "Über die nunmehr erreichten technischen Stand der Benzinsynthese," *ibid.*, 13 (1932) 461-8; Franz Fischer and Herbert Koch, Über den Chemismus der Benzinsynthese und über die motorischen und senstigen Eigenschaften der dabei auftretenden Produkte (Gasol, Benzin, Dieselöl, Hartparaffin), *ibid.*, 13 (1932): 428-34; Herbert Koch and Otto Horn, "Vergleichende Untersuchung über das motorische Verhalten eines synthetischen Benzins nach Franz Fischer (Kogasin I) und eines Erdöl-Benzins, *ibid.*, 13 (1932): 164-7.
 6. Storch, Golumbic, and Anderson (ref. 3), 337; "Synthetic Petrol by the Fischer Process," *Gas World*, 105 (1936), 362-363; H.H. Storch, "Synthesis of Hydrocarbons from Water Gas," H. H. Lowry, ed., *Chemistry of Coal Utilization* (3 vols., New York, 1945 and 1963): 2, 1797-1845, on 1800. The motor fuel's estimated average cost was 22 pfennig per kg. According to Arno Fieldner and American engineers the wartime cost of either the F-T or the hydrogenation process was 20-30¢ per US gallon. See Arno C. Fieldner, "Frontiers of Fuel Technology," *Chemical and Engineering News*, 26, no. 23 (7 June 1948), 1700-1. For the conversion of metric tons to barrels use 1 metric ton = 7.2 barrels.

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7. Ministry of Fuel and Power, *Report on the Petroleum and Synthetic Oil Industry of Germany* (London, 1947): 82-90; "Germany's Home Production of Motor Fuels," *Gas World*, 104 (9 May 1936): 421; Franz Fischer, "The Conversion of Coal into Liquid Fuels," *Chemical Age*, 35 (24 October 1936): 353-5; "The Fischer Process," *Chemical Age*, 35 (31 October 1936): 367.
 8. Storch, Golumbic, and Anderson (ref. 3), 336-8; *Report* (ref. 7); G. Wilke, "Die Erzeugung und Reinigung von Synthesegas für die Benzinsynthese," *Chemische Fabrik*, 11 (1938), 563-8; "Substitute Motor Fuels in Europe," *Petroleum Press Service*, 5 (1938): 301-4; Fieldner (ref. 6). Average exchange rate from 1934 to 1941 was RM 1 = 40¢, *Banking and Monetary Statistics, 1914-1941*, Federal Reserve System (Washington DC, 1947): 671.
 9. *Report* (ref. 6): 82-90.
 10. *Ibid.*: 91 (Table LV); the German Health Office officially approved the synthetic fat as fit for human consumption, but the Nazi government suppressed the findings of certain (unnamed) university scientists which threw considerable doubt on the fat's safety. Synthetic fat always contains esters of branched-chain fatty acids some of which are toxic (see p. 94). C. C. Hall, "Oils and Waxes from Coal," *Chemical Age*, 55 (9 November 1946): 569-70.
 11. *Trials of War Criminals before the Nürnberg Military Tribunals* (Washington DC, 1953), see vol. 7, the IG Farben Case (Case 6), testimony of defendant (Carl) Krauch. The Fuel Agreement is *Nürnberg Industrialists Document* NI-881, reel 9, 14 December 1933. See also Wolfgang Birkenfeld, "Leuna, 1933," *Tradition*, 8 (1963): 107-8; Wolfgang Birkenfeld, *Der synthetische Treibstoff 1933-1945* (Göttingen, 1964): 23-34; Peter Hayes, *Industry and Ideology* (Cambridge, 1987): 115-20.
 12. The United States Strategic Bombing Survey, *The German Oil Industry Ministerial Report, Team 78*, Oil Division, 1st ed. 5 September 1945, 2nd ed. January 1947, 19-20.
 13. *Report* (ref. 7): 89; T. E. Warren, *Inspection of Hydrogenation and Fischer-Tropsch Plants in Western Germany during September 1945*, FIAT, *Final Report no. 80, item no. 30* (London: British Intelligence Objectives Subcommittee 1945), 1-28 on 16-18; *Germany, Liquid Fuels, v-Synthetic Oil Plants-Fischer-Tropsch Synthesis*, (typed) Report 75687, Reference numbers 5.01-5.09; "Coal Hydrogenation-Germany, Hydrocarbons Synthesis," *Petroleum Press Service*, 6 (1939): 529-32.
 14. *Report* (ref. 7): 89 Warren (ref. 13): 23-4; *Germany Liquid Fuels* (ref. 13).
 15. *Report* (ref. 7): 89 Warren (ref. 13): 14-15; *Germany Liquid Fuels* (ref. 13).
 16. *Report* (ref. 7): 85.
 17. *Report* (ref. 7): 90; "Coal-Hydrogenation-Germany" (ref. 13); "Coal Hydrogenation-Germany, Hydrocarbons Synthesis," *Petroleum Press Service*, 7 (1940): 31-2; *Germany Liquid Fuels* (ref. 13).
 18. *Report* (ref. 7): 87 (Table L); Hall (ref. 10).
 19. *Report* (ref. 7): 90 *Germany Liquid Fuels* (ref.13).
 20. *Report* (ref. 7): 89; Warren (ref. 13): 21-2; *Germany Liquid Fuels* (ref.13); "Motorkraftstoff von Kohl," *Teer und Bitumen*, 35 (1937): 231-2.
 21. *Report* (ref. 7): 89-90 (table LIV); Warren (ref. 13): 16; *Germany Liquid Fuels* (ref. 13); "Coal Hydrogenation, Germany" (ref. 13); "Motorkraftstoff" (ref. 20).
 22. *Report* (ref.7): 90; Warren (ref.18); "Motorkraftstoff" (ref. 20).
 23. *Report* (ref. 7); *Germany Liquid Fuels* (ref. 13).
 24. *Report* (ref. 7): 96-100
 25. *Ibid.*: 92-5, 101-2.

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26. Strategic Bombing Survey (ref. 12).
 27. *Report* (ref. 7): 1-2, 50, 61, 67, 68, 93. The prewar exchange rate is from *Statistical Abstract of the United States 1939* (Washington, 1939): 208. RM 1 = 25¢.
 28. Edward Homze, *Foreign Labor in Nazi Germany* (Princeton, 1967): 171.
 29. *Report* (ref. 7), 61 (Table XXVI).
 30. Homze, (ref. 28): 171; Joseph Borkin, *The Crime and Punishment of IG Farben* (New York, 1978): 117. RM 10 = DM 1 = 40¢ US currency conversion law of 1948.
 31. *Report* (ref. 7): 48 (Table XXVI).
 32. Jurgen Kuczynski, *Germany: Economic and Labor Conditions under Fascism* (New York, 1968): 213.
 33. Homze (ref. 28): 238-9.
 34. Ibid.
 35. Benjamin B. Ferencz, *Less than Slaves* (Cambridge, MA, 1979): 52.
 36. Ibid.: xvi-xvii.
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