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Synthetic Fuel Production in Prewar and World War II Japan: A Case Study in Technological Failure

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Summary

Japan is a country largely lacking supplies of many essential natural resources including petroleum, coal, and iron ore. As her industrial base and economy expanded in the 1920s and 1930s, Japan's dependence on imports of these resources became increasingly evident. The onset of the Depression in the 1930s further threatened Japan's lifeline, and in effort to become economically independent and self-sufficient in natural resources (autarky) Japan's militaristic government pursued a policy of territorial expansion. Beginning in 1937, Japan's military forces swept out of Manchuria into China and then into Southeast Asia in search of strategic materials such as petroleum, coal, copper, zinc, and rubber.

To achieve independence in petroleum, the Japanese developed a dual approach: they would acquire natural petroleum sources in Southeast Asia and at the same time establish a synthetic fuel industry for the conversion of coal to oil. Actually, the Japanese had begun research on synthetic fuel in the 1920s, only a few years after other countries like Germany and Britain that lacked sources of natural petroleum. They did excellent laboratory research on the coal hydrogenation and Fischer-Tropsch conversion processes, but in their haste to construct large synthetic fuel plants they bypassed the intermediate pilot-plant stage and failed to make a successful transition from small to large-scale production. Unable to synthesize liquid fuels from coal, they instead derived significant quantities from the technologically simpler coal carbonization and shale oil distillation processes. In the last year of World War II, the Japanese attempted to revive their synthetic fuel industry and entered into an agreement with IG Farben for technical assistance. Germany's defeat ended this final effort. The Japanese synthetic fuel industry presents a good case study of technological failure. It shows that high-quality basic scientific research does not necessarily translate into large-scale technological success.

Introduction

It has been concluded by some investigators that the research and scientific ability of the Japanese is mediocre. This is believed to be a fallacy. It is rather concluded on the basis of research discussed herein, that their progress has been conspicuous and that within the next few decades Japan may well become one of the foremost technical nations of the world. (*Report of the U.S. Naval Technical Mission to Japan*, “Japanese Fuels and Lubricants,” 1945. Quoted in *Petroleum Processing*, 2 [1947], 819.)

In the Depression years of the 1930s when economic problems threatened Japan's well-being, the Japanese government adopted a policy of autarky. Being a country with limited natural resources, the Japanese intended to achieve economic independence and self-sufficiency in natural resources through territorial expansion. But as Japan's military forces began their drive out of Manchuria and into China's major cities and then into Southeast Asia, the need for additional petroleum to fuel the expansion become increasingly evident. Petroleum consumption had risen from 40,000 metric tons in 1912, to 666,000 tons in 1924, and tripled to 1,980,000 tons in 1932. Production had not kept pace. In 1932 it was only 242,000 tons in Japan proper, 35,000 tons in Taiwan, and represented about one-seventh of Japan's total peacetime consumption. Imports from the United States, British Borneo, the Dutch East Indies, and the Soviet Union made up the balance. Although Japan contributed only 0.1 percent of the world's total petroleum production, the empire had comparatively large coal reserves estimated in 1935 at 22 billion tons.[1]

During this same period Germany and Britain attempted to eliminate their lack of naturally-occurring petroleum by synthesizing liquid fuel from coal. The Japanese adopted a similar approach beginning in 1936. By that time they had calculated a minimum 400-500 year lifetime for their coal reserves if converted to liquid fuel at an annual rate of 15 million tons. The Japanese investigated the three known coal conversion processes: low-temperature carbonization (LTC), coal liquefaction (high-pressure hydrogenation), and Fischer-Tropsch synthesis (F-T, synthesis gas process or indirect coal liquefaction). Of the three, LTC is the oldest and the simplest technologically, requiring neither catalysts nor expensive and complicated high-pressure apparatus. It is not really a synthetic process but a thermal decomposition of coal in the absence of air (destructive distillation) at 500-700°C giving semicoke (a more active fuel than coke), coal tar, and gases. The oil obtained by distilling the tar is derived rather than synthesized. Japanese industrialists had introduced LTC for the production of semicoke not liquid fuel, hoping to substitute semicoke for the more expensive charcoal commonly used in household heating. Only in the early 1930s after the rise of their country's militaristic government did the Japanese recognize LTC as a good liquid fuel source and include it in a comprehensive synthetic fuel plan. Because of its low technological requirements LTC became the most successful of Japan's three coal conversion processes, producing more liquid fuel than liquefaction and F-T combined.

Both liquefaction, the reaction of hydrogen gas with coal or tar to give petroleum liquids, and F-T, the conversion of coal and steam to synthesis gas (a carbon monoxide - hydrogen mixture) and then to petroleum liquids, are synthetic processes and give considerably more liquid fuel per ton of coal than LTC. In the 1930s coal liquefaction was farther advanced than F-T, and it became the focus of Japan's synthetic fuel program. The Japanese carried out extensive and first-rate laboratory research and placed great faith in liquefaction's rapid and successful development. They also conducted high-quality laboratory research on the F-T synthesis. But in both cases the Japanese failed to make a successful transition out of the laboratory because they leaped into commercial-scale synthetic fuel production with insufficient pilot-plant experience. Curtailing or by-passing the intermediate pilot-plant stage of development led to serious operating problems and doomed their synthetic fuel program to technological failure. The failure also illustrates the generally lower level of pre-World War II Japanese engineering compared to the West's. A wartime atmosphere clearly compounded the urgency, and consequently the two synthetic processes contributed little to Japan's liquid fuel sources.

In addition to large coal reserves the Japanese possessed a rather significant potential source of liquid fuel in the 5 billion tons of shale oil located at Fushun in southern Manchuria. Like LTC, shale oil distillation is a low-yield, low-technology process that requires heating the shale to separate the oil. The Japanese constructed only one plant, at Fushun, but during the World War II years it outproduced all the coal conversion plants.

To ensure industry's participation in a synthetic fuel program the government offered several financial incentives beginning in July 1936 when the seventy-first Special Imperial Diet introduced its petroleum substitutes policy. This war measure included subsidies and laws to encourage production, indemnities for losses incurred in synthetic fuel production, and a ¥4.5 million grant from the Ministry of Finance to the Ministry of Commerce and Industry. The following May the government established the Fuel Department within the Ministry of Commerce and Industry to promote synthetic fuel production. Four naval and three army officers served as department directors and section chiefs. In August 1937 the government proposed a Seven Year Plan that contained two major provisions for its implementation: the Imperial Fuel Development Company Law enforced from September 1937 and the Synthetic Oil Production Industry Law from January 1938. At the same time (January 1938) the government established Teikoku Nenryô Kôgyô KK, the Imperial Fuel Development Company (Imperial Fuel), in Tokyo to administer the Imperial Fuel Development Company Law. Imperial Fuel also manufactured and sold synthetic fuel and financed its production by Japanese industry. The Seven Year Plan called for the construction of 87 synthetic fuel plants by 1944, producing annually 6.3 million barrels (one million kL) each of synthetic gasoline and fuel oil. But shortages of plant equipment and strategic metals including nickel and iron, the high purchase and shipping cost of equipment and material resulting from the yen's decreasing value, and the serious technological scale-up problems severely handicapped the plan. When the war ended in August 1945 the Japanese had constructed only 15 plants that in 1944 achieved a peak production of 717,000 barrels (114,000 kL).[2]

Unlike the German and British governments which did not take an active role in their industries' early work on synthetic fuel, the Japanese government, acting through the navy, participated from the beginning. The navy did not depend on private industry for petroleum research and development or for the production of refined products. It recognized the severity of Japan's problem and led the way in trying to make the empire self-sufficient in liquid fuel. But at the same time the navy's participation generated an unnecessary rivalry with non-military scientists over research decisions and promoted undue secrecy and security concerns, which contributed nothing to the synthetic fuel program.[3] By 1942 its synthetic fuel program, despite claims to the contrary, was a failure. Later, in the war's last year and after the navy's program had collapsed, the army tried to revive the production of synthetic liquid fuel. Japan's defeat ended the army's short-lived effort.

During the war years the Japanese government also increased petroleum imports and their storage. In 1941 Japan required 30 million barrels of petroleum for wartime military and civilian needs and had the capacity to refine 35 million barrels/year (bbl/yr). Domestic crude petroleum production was only 2.5 million barrels, but at the time of Pearl Harbour the Japanese had stored 60 million barrels of crude and refined products. They had acquired these stockpiles mainly from the United States prior to the US-imposed moral embargoes on petroleum and the Japanese invasion of China.[4] The Japanese intended to use these stockpiles until synthetic fuel production and crude imports from Borneo and Sumatra in the Dutch East Indies were sufficient to meet their liquid fuel requirements. By mid-1943 Borneo's and Sumatra's petroleum production equaled expectations, but the Japanese seriously miscalculated the effect of the United States's submarine blockade and the submarines' increasing success in sinking Japanese tankers. The losses reached such heights that in 1944-1945 Japanese petroleum supplies declined rapidly and were nearing exhaustion. The seriousness of Japan's petroleum shortage greatly reduced the time-schedule for synthetic fuel research and development. It resulted in the army's final desperate attempt to develop a synthetic fuel industry.[5]

Japan's unsuccessful prewar and World War II synthetic fuel program has provided a case study in technological failure. It failed, despite highly promising laboratory research and the government's considerable economic incentives, because Japan's impatient engineers tried to make the transition from laboratory to industrial development without pausing to acquire sufficient pilot-plant experience. This experience is what the Japanese engineers needed to negate their country's generally lower level of technological development and the inherent complexity of the synthetic processes, both of which made the transition more difficult but not unattainable.

The United States's prewar embargoes on petroleum and machinery coupled with the wartime exigencies further compounded the urgency, but they did not create it. Indeed, such a pattern of impatient behavior in Japanese engineering appeared much earlier, immediately after the Meiji restoration of 1868. The Japanese were anxious to industrialize, and to acquire Western know-how quickly they brought large numbers of Western scientists and engineers to staff their newly-established universities, technical institutes, and industries. Ten years later, in the 1880s, they were sending their scientists and engineers to the West to acquire the know-how.[6] For the most part the Japanese strategy was reasonably successful, although in their haste to establish a soda ammonia industry in the 1920s, Japanese engineers also tried to eliminate the pilot-plant stage and suffered equally disastrous results.[7] A precedent for technological impatience and haste therefore exists, and it helps explain the synthetic fuel program's failure in the 1930s-1940s.

Development of Japan's Derived and Synthetic Liquid Fuel Sources to 1930

Japanese research on producing liquid fuel from coal and shale began in the 1920s first with shale oil distillation and LTC and then with coal liquefaction and F-T synthesis. With their victory in the 1904-1905 Russo-Japanese war, the Japanese extended their influence in Manchuria, and by 1920 they had recognized the possibility of distilling oil from the huge shale deposits at Fushun. The semigovernment South Manchuria Railway Company (SMR), or Minami Manshû Tetsudô KK, in which by law only the Japanese and Chinese governments and their citizens held shares, directed the research aimed at providing Japan's Imperial Navy with a source of fuel oil.[8] Of the major powers, only the British and United States navies had begun their conversion from coal to oil-fired turbine ships, Britain from 1906 to 1914, the United States from 1909 to the 1920s.[9] The saving in fuel storage space enabled a ship to increase its firepower by introducing bigger guns and to reduce its total weight without sacrificing armor by eliminating the dead weight of coal. Refueling at sea, greater speed and range (40 to 50 percent) were equally important advantages of the conversion to oil-fired ships.[10] Japan's conversion began in 1909 with the navy's liquid fuel investigations at the Naval Research Laboratory in Tokuyama (Honshû). Three years later the navy submitted to the government a program to start construction in 1913 on eight dreadnoughts and eight armored cruisers.[11] Initially, the navy's turbine ships consumed both coal and oil in their furnaces though its faster ships increasingly were oil-fired. The navy completed its first two exclusively oil-fired cruisers, the *Tatsuta* and *Tenryû*, in 1919.[12]

Fushun's shale oil deposit was 150 meters thick and lay right above a coal seam. It contained about 5 billion tons with 2.3 billion at a depth of 300 meters. Because the miners used an open-cut method to remove the coal, they first had to strip the shale, a strong-smelling, dark brown semisolid at normal temperatures. This easy accessibility rather than quality led SMR to investigate Fushun's shale as a potential liquid fuel source.

According to the terms of a contract negotiated with SMR in 1928, the Japanese government agreed to purchase all the oil produced at Fushun. So despite the low yield, SMR continued its shale treatment, doubling each retort's capacity to 100 ton/d in 1928, though actual throughput was 20 to 30 percent less. Constructed at an estimated cost of ¥8.5 million ($1.96 million), the plant had an annual production capacity of 53,000 tons fuel oil, 20,000 tons ammonium sulphate, 15,000 tons paraffin and was in full operation at the end of 1929.[13]

Research on (LTC) began in 1921 as part of a general program at the Imperial Fuel Research Institute in Kawaguchi (Honshû), a northern suburb of Tokyo. The government had established the institute that same year to investigate the utilization of Japanese coals. At that time LTC's primary purpose was to produce semicoke as a substitute for charcoal which cost twice as much but enjoyed widespread use in household heating and cooking because it lacked semicoke's slightly objectionable odor.[14] Yoshikiyo Ôshima (1882-1957), of Tokyo Imperial University and the institute's director, and the chemist Yoshisada Ban, who became the institute's acting director in 1932, conducted the initial experiments in both the laboratory and "first stage plant." In their 1925 study, *Technical Paper No. 1*, the institute's first published paper, Ban reported that a typical Fushun coal, carbonized in a 6 ton/d cast steel retort for 8 hours, gave 66 percent semicoke and 12 percent tar. Although semicoke production was the objective, Ban found the tar, when free from pitch and acid, comparable to a petroleum heavy oil.[15]

Only two other Japanese centers of LTC research existed in the 1920s: the Osaka Gasu Kôgyô Kaisha KK plant at Seimi (near Osaka, Honshû) and the navy's Tokuyama Research Laboratory. Each had a different objective. Osaka Gasu used a retort that its president, the American-educated engineer Kôtarô Shimomura (1861-1937), had designed in 1923 to produce a semicoke for blending (mixing) with domestic, high-volatile bituminous coal.[16] The company, which had been producing coke since 1898, operated a trial plant at Iwasaki (Honshû) in April 1923 before constructing a semicommercial plant of similar design at Seimi in September 1923. The Seimi plant underwent expansion and modernization, giving it an annual rated input capacity of 3,000 tons, but from 1923 to 1926 it operated sporadically and carbonized only 700 tons of coal to 500 tons of semicoke. Mechanical operating problems and financial difficulties led to its dismantling in 1930 and to the end of Osaka Gasu's LTC program.[17] Liquid fuel for the fleet was the objective of the navy's program, which ran from 1925 to 1932. It tested coals for their tar content in a horizontal-rotational Thyssen retort before abandoning LTC research because of insufficient tar production and difficulty in marketing the by-product semicoke. LTC's rapid expansion did not occur until 1936 when Japan's militaristic government established the petroleum substitutes policy as a war measure to encourage liquid fuel production. It became Japan's most productive and economical method of obtaining oil from coal in the 1930s-1940s.[18]

Four years after the start of LTC in Japan, studies on the high-pressure hydrogenation (liquefaction) of coal and tar were underway at the Imperial Fuel Research Institute. In 1925 the Japanese navy also began a coal liquefaction program at Tokuyama, and in 1928 SMR initiated a third liquefaction program at its Central Research Laboratory in Dairen, near Port Arthur, in south Manchuria.[19] Indeed, in the 1920s-1930s Japanese scientists and engineers regarded coal liquefaction as the best way to eliminate their almost total dependence on imported oil.[20] Shale distillation and LTC gave only a 6-10 percent yield or about 13 gal/ton. In addition, no market existed for the semicoke, which was about 65 percent by weight of the coal carbonized, whereas coal liquefaction offered the possibility of completely converting coal to oil. With the exception of Germany, coal liquefaction probably received more serious study in Japan than anywhere else.[21] Japan's total petroleum production had fallen in the 1920s despite the tenfold development of Formosa's oil fields, and coal liquefaction appeared to be the most promising and reliable source of liquid fuel.[22]

In 1926 Franz Fischer (1877-1947) and Hans Tropsch at the Kaiser Wilhelm Institute for Coal Research in Mülheim, Germany, published their first paper on the synthesis gas process (F-T synthesis) using newly-developed cobalt-thorium catalysts.[23] The following year Gen-itsu Kita (1883-1952) at the Institute of Physical and Chemical Research, Kyoto Imperial University, began the first Japanese study of the F-T synthesis. Because Japan had no domestic source of expensive cobalt or thorium metal, Kita initially focused on preparing cheaper iron and nickel catalysts. Working in the laboratory and with a small pilot plant of 100 m^3/hr synthesis gas throughput, Kita in 1937 developed an iron catalyst whose yield approached those obtained with cobalt-thorium catalysts at atmospheric pressure. But, like all iron catalysts, it was highly sensitive to any sulphur present in coal. Outside of Kita's research, no other Japanese study of the F-T synthesis occurred until practically the mid-1930s.[24]

During the 1920s-1930s the Japanese made efforts to keep informed of international developments in fuel research. The list of Japanese delegates to the London World Power Conference of September-October 1928 contains twenty-eight names and includes representatives from the military, government, industry, and universities. There is no way of knowing whether all actually came to London, but of those in attendance nine presented papers. Ôshima presented his paper on LTC, the others dealt with the Japanese coal, petroleum, and gas industries. About 1500 delegates representing 48 countries heard 170 papers at the thirteen-day conference.[25] At least one Japanese delegate attended each of the first three International Conferences on Bituminous Coal held at the Carnegie Institute in Pittsburgh in November 1926, 1928, and 1931. In 1926 Ôshima and in 1928 Ban spoke on LTC research. At the 1931 meeting Ôshima and Yashitami Fukuda, his colleague from the Imperial Fuel Research Institute, discussed the combustibility of carbonaceous compounds.[26] Japanese delegates were present at the first and second World Petroleum Congresses held in the 1930s. The navy sent two officer-engineers to the London meeting of July 1933. Friedrich Bergius who recently (1931) had received the Nobel Prize in chemistry for his invention of high-pressure coal hydrogenation gave a short address at the Congress's banquet in addition to a paper on recent developments in coal hydrogenation. Pier, and Kenneth Gordon (1897-1955) of Imperial Chemical Industries (ICI), both synthetic fuel experts, also gave papers. Four delegates attended the 1937 meeting in Paris. The navy's two delegates described their research on the hydrogenation of cracked gasoline, Shingo Andô of the Imperial Fuel Research Institute discussed hydrogenating low-temperature tar, and Kôki Ishibashi of SMR spoke on shale oil refining at Fushun.[27]

Government Support of Japan's Synthetic Fuel Industry

The development of Japan's synthetic fuel industry ran parallel to the military's increasing and eventual control of government in the 1930s-1940s. Prior to the 1930s the government had made little progress in establishing a synthetic fuel industry other than a 1923 discussion of a liquid fuel policy designed to make the country independent of foreign petroleum. But in 1933, after annexing Manchuria and its huge coal and shale oil deposits, Japan's militaristic government decided to aid the LTC industry and to encourage greater oil production from SMR's Fushun shale mine. Beginning in 1934 it offered subsidies (though paying none that year) for the construction of additional LTC plants. Japan proper had produced a mere 330,000 tons of natural crude oil in 1936, the last reliable prewar statistic, and another 175,000 tons came from Sakhalin, which was also the rest of the empire's total production.

Two sources of derived liquid fuel contributed smaller amounts: 125,000 tons from the Fushun shale plant and 4,000 tons total from the four operational LTC plants. For comparison, in 1936 Japan imported 2.14 million tons of crude oil valued at $37.7 million and 2.5 million tons of petroleum products.[28] The wide gap between domestic sources and imports showed clearly the great need for an energy policy designed to give self-sufficiency in liquid fuel. In view of this alarming situation, especially with the military about to launch its Asian expansion program, the Japanese government in 1937 prepared its Seven Year Plan for synthetic fuel production.

While the economy grew steadily in the 1930s so did ultranationalism and violence. The government increasingly found itself under the military's influence and more willing to resort to military solutions. In the summer of 1937 the military got its war but not with the Soviet Union in Manchuria as the Japanese general staff had believed since 1931. Manchuria's industrialization, including the development of synthetic fuel and shale distillation, was part of Japan's overall plan to strengthen its military presence there. The strategy risked another Russo-Japanese conflict. On July 7, 1937, when a small clash occurred between Chinese and Japanese troops stationed at the Marco Polo Bridge outside of Peking, the Japanese, therefore, tried to contain it but could not. Instead, Japan stumbled into a full-scale war with China that became a prelude to World War II in the Pacific.[29]

One month later the Japanese government drafted its Seven Year Plan and passed the two laws aimed at its implementation. It expected the plan, which called for the construction of 87 plants in Japan and Manchuria and the production by 1944 of one million kL/yr each of gasoline and fuel oil, to meet one-half of civilian demands. Of the 87 proposed plants 10 were high-pressure coal hydrogenation plants each contributing 100,000 kL/yr; 11 were F-T plants with a total capacity of 500,000 kL/yr; and 66 were LTC plants each treating 100,000 tons of coal yearly to give the remaining 500,000kL. The Manchurian plants were to supply 25 percent of the production. Total cost was ¥750 million including¥ 360 million for hydrogenation, ¥121 million for F-T, ¥115.5 million for LTC, ¥50 million for the amount already spent on synthetic fuel plants, and ¥15/ton of output for coal field development. The government expected to pay for the plan by increasing the tax on gasoline.

At first the Synthetic Oil Production Industry Law provided subsidies and payments for losses only to the larger plants in Japan, Korea, Sakhalin, and Formosa. For the F-T and hydrogenation plants, minimum oil production was 10,000 kL/yr. LTC plants using coal or lignite had to carbonize 100,000 ton/yr. By 1941 with the military's expansionist program well underway, the government offered support to every plant that derived crude oil, fuel oil, or lubricants from any raw material except natural petroleum and to plants whose annual production exceeded 1,000 kL of aviation gasoline blending stock. In addition to subsidies, the law exempted participating companies from income and local taxes, import duty on equipment, and allowed them to expropriate land for plant construction.

The Imperial Fuel Development Company Law, the other half of the Seven Year Plan, underwent revisions in 1940, 1941, and 1942, but its major articles summarized here remained the same. (1) The Imperial Fuel Development Company shall transact all business that promotes synthetic oil production. (2) It shall have a capitalization of ¥100 million, one half supplied by the government, which it can increase with government approval and did increase to ¥250 million by the end of the war. (12) It shall finance synthetic oil enterprises, and they may manufacture or sell synthetic oil or manage other business necessary for promoting synthetic oil production, when permitted by the government. (13) It can issue debentures up to an amount equal to five times its paid-up capital. (30) It is not obliged to pay dividends on government-held shares unless the amount of annual profit reaches 6 percent of the value of paid-up shares not held by the government. (32) It shall pay no corporation and business taxation in its first year of existence and in the following ten years.

In 1942 the government introduced its third and final policy. It decided not to subsidize production but instead offered a fixed price including suitable profit for the synthetic fuel. A government company, Sekiyu Kyôhan KK, bought synthetic fuel from the producers, pooled it with natural petroleum products obtained from petroleum refining companies, and then sold the pooled product at a fixed price. The government's purchase price depended on synthetic fuel's production cost and determined the pooled product's retail price.[30] The total subsidy Imperial Fuel received from 1937 to 1944 exceeded ¥29 million ($6.7 million). From 1940 to 1944 Japan produced 430,116 kL (113.6 million gal) of liquid fuel giving an average subsidy of ¥69/kL or 6¢/gal.[31]

The Japanese did not intend to rely solely on the development of a synthetic fuel industry to provide them with petroleum and had established several alternative or supplementary oil sources. Before passage of the Seven Year Plan and the outbreak of war with the United States in December 1941 they had imported large quantities of lubricants and fuels from the United States. The navy used California crude as its source of bunker fuel, diesel oil, kerosene, aviation and motor gasoline. Fushun shale oil also was an important component of bunker fuel and diesel oil for the navy's submarines. After its aggression in Asia Japan no longer had American crude oil available, but by March 1942 it already had completed occupation of the entire Dutch East Indies, gaining access to the crude oil of Borneo and Sumatra. While production from the East Indies equaled expectations by mid-1943, the success of American submarines in sinking Japanese tankers had increased so much that by 1944 oil supplies fell rapidly and significantly shortened the time for research and development on synthetic fuel. The navy still had access to Fushun shale oil, but the fuel situation became so desperate in the war's closing days that the navy resorted to such unlikely sources as pine roots, soy beans, and other vegetables available in Japan. Most of Japan's crude oil refineries had long since shut down for lack of stock or were victims of American air raids that destroyed two-thirds of their capacity. Ships and aircraft remained idle, and pilots went into battle with little training because of fuel shortages. The only available 100-octane gasoline was in laboratory quantities. A battleship sunk at the Battle of Okinawa in May-June 1945 had edible soy bean oil in its bunkers.

In the early years of the war petroleum storage had reached 60 million barrels of crude and refined products, much of it in large reinforced concrete tanks buried in hills and camouflaged with heavy vegetation. At the Sasebo (Kyûshû) Naval Base, which had a total storage capacity of 4 million barrels, one large reservoir held a half-million barrels. Total storage capacity was 1 million barrels at Kure (Honshû) and 9 million at Tokuyama. The navy initiated fuel research in 1909 at Tokuyama and erected its first refinery there in 1920. By wartime, refining capacity had increased to 9,500 bbl/d. Construction on a 17,000 bbl/d refinery at Yokkaichi (Honshû) began in 1940. The two refineries carried out crude distillation, thermal- and hydrocracking, and accounted for 25 percent of Japan's total refining capacity. The following year, the navy established its Ofuna (Honshû) research centre. Prior to that time, the navy had conducted research at Tokuyama and other locations, but once the war began it centralized activities at Ofuna. In 1941 the navy also named its different research centres Fuel Depots with Ofuna the First Naval Fuel Depot. Spread over 100 acres and containing 37 steel and concrete laboratories, Ofuna was one of the largest petroleum research centres in the world. At the time of its establishment in 1941, Ofuna had 1,000 workers and a staff of 45 chemists, chemical engineers, and technicians. When it ceased operation on August 15, 1945, Ofuna's director Vice Admiral Nobusuki Yamaguchi supervised 1,800 workers and 450 staff members including Komatsu, Ofuna's foremost chemist Dr. Haruki Fujimoto, and Dr. Keisaku Mitsui.[32]

Research and Development of the Fischer-Tropsch Synthesis: A Promising Beginning

Kita's investigations were by far Japan's most important research on the F-T synthesis. What started at Kyoto in 1927 as a purely scientific laboratory study using small-scale glass apparatus reached the semicommercial pilot-plant stage in 1937. Kita set out to produce a catalyst superior to cobalt-thorium catalysts. By 1936 the best he developed equalled the activity of cobalt-thorium catalysts, but they were of nickel, not of cheaper and readily available iron.

Shortly after Kita began his pioneering work, centers of F-T research emerged at the Imperial Fuel Research Institute in Kawaguchi, Tôkyô Imperial University, and Mitsui Bussan KK in Rumoi (Hokkaidô). On 16 February 1937 as a result of almost two years of negotiating by Shiro Watanabe, head of Mitsui's coal department in Tôkyô, and Toyohisa Ayai, manager of its German products branch, Doitsu Bussan KK, Mitsui also secured exclusive Japanese commercial rights to the F-T patents from Ruhrchemie AG which now controlled their licensing. Mitsui paid ¥7.2 million (RM 4.5 million) for the license which expired on 31 December 1945. The Japanese military played an active role in developing the F-T synthesis, but unlike shale oil extraction and high-pressure hydrogenation, the army, not the navy, promoted the research. The navy lacked interest, claiming the process could not produce the heavy fuel oil needed for its ships, and conducted only limited catalytic research at the First Naval Fuel Depot in Ofuna.

Coal hydrogenation, not F-T, was the navy's first priority. It wanted sole control of coal hydrogenation in Japan and strongly encouraged Mitsui to pursue rights to the F-T synthesis. Mitsui already had tried unsuccessfully to obtain from ICI a license to establish a Japanese coal hydrogenation industry and was consequently quite receptive to reaching an agreement with Ruhrchemie. Mitsui's reputation had suffered at that time because the government believed it was guilty of excessive profit taking and not following Japan's national policy of developing heavy industry. Commercial trading was Mitsui's major involvement, and coal mining its only heavy industry. To improve its public image Mitsui decided to develop the F-T synthesis, and with the establishment of Imperial Fuel in January 1938 it agreed to a nationalizing of its license so that any company in the Japanese empire (Korea, Mancheria, Taiwan) had use of the F-T patents.[33]

At the Imperial Fuel Research Institute, investigations in both the laboratory and semicommercial plant were extensive during the years 1933-1940. Instead of cheaper iron catalysts, the institute worked with nickel-cobalt catalysts that had a one-month maximum life. Laboratory tests gave 100 grams (g) of liquid fuel for each cubic meter (m^3) of synthesis gas (CO : H_2) consumed. The semicommercial plant, which operated at 5 atm, contained a small vertical cylindrical converter (reactor), a product recovery system with air and water-cooled condensers, and a pressure-type scrubber. Liquid fuel capacity was 200 kg/d with a 100 m^3/hr synthesis gas throughput, but actual production never exceeded 30 percent of capacity. Plant engineers blamed the catalysts and the converter's inadequate temperature control for the poor performance. The plant never operated for more than a few days at a time, and when Mitsui's commercial plant at Miike came on stream in 1940 they shut down the troublesome Kawaguchi plant.[34]

After Mitsui acquired the rights to prepare and use Ruhrchemie's catalysts, Soji Kono and other researchers at Rumoi, Koichi Matsubara at Tôkyô Imperial University, and Kita concentrated almost exclusively on developing iron substitutes for standard (1 atm) and middle (10-15 atm) pressure syntheses. Indeed, catalytic research was Japan's most significant contribution to the F-T synthesis. It represented the kind of close cooperative industrial and university research that organizations like Mitsui and Mitsubishi Shoji strongly encouraged.

Mitsui's laboratory investigations at 275°-280°C, 15 atm, and a CO : H_2 synthesis gas mixture gave a 44 percent conversion to gaseous hydrocarbons (50 percent propane and 20 percent butanes) used to prepare isooctane. Investigations on iron catalysts continued in its small pilot plant (10 m^3/hr synthesis gas throughput) and from 1942 in its full-scale plant at Takikawa (Hokkaidô).[35] Matsubara tested a natural iron catalyst in 1943-1944, but he obtained a maximum liquid hydrocarbon yield of only 86 g/m^3. Kita's best iron catalyst, when reacted in the laboratory with 40 cm^3/hr of a CO : 2 H_2 synthesis gas mixture at 240°C and l atm, gave maximum liquid yields of 98-102 g/m^3. This was lower than the 151-158 g/m^3 obtained with the best cobalt-thorium catalyst. His iron catalyst had about a one-month lifetime before carbon poisoning of its surface destroyed its effectiveness.

Kita operated the semicommercial pilot plant for four years, 1937-1941, carrying out reactions at 250°C, 1 atm, and a synthesis gas throughput of 100 m^3/hr. The Japanese army, hoping to expand Kita's program to large-scale production, transported the plant to its Fuel Research Institute in Fuchu (Honshû) in 1942 where testing continued with natural iron catalysts, but liquid yields were only 73 g/m^3.[36] Although Japanese research failed to produce a superior iron catalyst, Kita established that pressures of 10-15 atm greatly favored iron catalysts. As a result, from 1938 and continuing throughout the war, Kita tested 40 cm^3 of different iron catalysts in a small, single-tube converter, but none performed as well as cobalt-thorium catalysts. Maximum liquid yields with an iron catalyst at 210°-240°C, 10-15 atm, and a 40 m^3/hr throughput of a CO : H_2 synthesis gas mixture were 115-120 g/m^3.[37] Construction of the first commercial-size F-T plants began in 1936, the year Mitsui acquired an option on the rights to Ruhrchemie's catalysts and one year before the Japanese government prepared its seven year synthetic oil plan. Of the plan's proposed annual production of 1,000,000 kL each of gasoline and fuel oil, the 11 F-T plants were to contribute 500,000 kL/yr. The Seven Year Plan included considerable subsidies for plant construction, yet by 1940 the government faced serious difficulty financing it and deliberately delayed new construction by limiting support to plants already constructed or scheduled for contruction. The ruling affected five plants. Three of them, at Miike (near Omuta, Kyûshû), Amagaski (Honshû), and Takikawa were completed by the end of World War II. All three were joint Mitsui-Imperial Fuel plants, having about the same unit production costs, and all received subsidies. The two unfinished plants, in Manchuria at Chielin and Chinchu, were under license from Mitsui.

The three completed plants produced good quality liquid fuel, but production never approached capacity, the best being the Miike plant's nearly 50 percent output in 1943. Synthesis gas shortages, low catalytic activity, and leaks in the converter's cooling-water tubes making temperature control difficult remained major problems that Mitsui's engineers failed to eliminate at the pilot-plant stage before beginning commercial-scale F-T operation. Production costs were, consequently, high. Gas oil that had an official retail price of¥ 152-177/kL cost ¥320-340/kL to produce.[38] Hikoshi Sogabe, a Mitsui technical director, and Naosuke Shônô, assistant technical director of Imperial Fuel, provided information on the three jointly-owned plants.

The Miike plant was the first to go on stream. Construction on the ¥12 million plant started in 1936, production followed in May 1940. It was the one F-T plant the U.S. Naval Technical Mission inspected. The plant operated at 1 atm, 180°-200°C, with a standard cobalt-thorium catalyst (21.2 cobalt, 1.2 thorium oxide, 2.4 magnesium oxide, 75.2 kieselguhr), and a synthesis gas mixture of 2 H_2 : CO, prepared by adding water gas to reformed coke oven (coal) gas. Five Koppers water gas producers, each consuming 100 tons of coke daily, manufactured the water gas, and a single Koppers gas reforming unit of capacity 456,000 m^3/d reformed the coke oven gas. The plant contained 56, steel "fin and tube" type horizontal Ruhrchemie converters in which pressurized cooling water circulated through horizontal tubes interlaced by vertical sheets. Each converter held about 4.5 tons of catalyst packed in the spaces between the tubes and sheets and had a synthesis gas throughput of 1,000 m^3/hr with an expected yield of 116 g/m^3. Actual throughput was 750 m^3/hr, and yields were only 70-85 g/m^3. The plant operated in two stages, using 30 converters in the first stage, 18 in the second, and had 8 in reserve. Total production capacity was 30,000 ton/yr (29,721 kL), but during its peak year of 1943 the Miike plant produced 14,000 tons (13,870 kL) of liquid fuel including 40-octane gasoline and 90-cetane diesel oil, as well as propane, butanes, and paraffin waxes. Low-octane gasoline and high-cetane diesel oil were typical of plants that used Ruhrchemie's standard cobalt-thorium catalyst. Failure to meet production capacity resulted from the plant's temperature control problems, reduced activity of Japanese-manufactured catalysts and from using coals that gave insufficient synthesis gas because of their low melting point ash and high sulphur content. Nevertheless, the Miike plant was Japan's most successful F-T plant before bombing in August 1945 damaged its gas generating capacity and ended its operation.

The ¥12 million Amagasaki plant also operated at 1 atm with a production capacity of 30,000 ton/yr. It contained 24 Ruhrchemie converters and used a standard cobalt-thorium catalyst. Production began in September 1943, but in its two years of operation, 1943 and 1944, liquid fuel yields were only 200 kL and 130 kL. It experienced mainly the same problems as the Miike plant.

The last of the three operating F-T plants, at Takikawa, had an initial capitalization of ¥20 million (later increased to ¥50 million). It was the largest of the plants with a 50,000 ton/yr (49,535 kL) capacity and the only one to operate at a middle pressure of 10 atm and to use iron and cobalt-thorium catalysts. Production started in December 1942 with 36 Ruhrchemie converters and 4 of Japanese design, including one developed at Kyoto that used an iron-magnesium catalyst. The Kyoto converter produced fuels with a high olefin (unsaturated) content characteristic of an iron catalyst, and although iron catalysts were sulphur sensitive they had a six month lifetime versus two months for cobalt-thorium. Like the other plants, the Takikawa plant never approached design capacity. In its four years of operation, 1942-1945, production was 1,550 kL, 1,600 kL, 6,610 kL, and 2,480 kL.[39] The two unfinished Mitsui-licensed F-T plants in Manchuria, Manchû Jinzô Sekiyu KK (Manchu Artifical Oil Co. Ltd.) in Chielin and Manchû Gosei Nenyro KK (Manchu Synthetic Fuel Co. Ltd.) in Chinchu, had capacities of 1,000 kL/yr and 40,000 kL/yr. This gave the five F-T plants a total capacity of 178,500 kL/yr, but for the duration of the war they produced only 55,720 kL.[40] Their main product was diesel oil, most of which came from the Miike plant. The navy used small quantities for blending with 90 percent Borneo crude or for submarine fuel. The army was the country's chief consumer, burning about 50 percent of all Japanese-produced diesel oil in its tanks.[41]

Coal Liquefaction: High Hopes But Little Success

Of the three coal conversion processes that the Japanese investigated and expanded to the industrial stage, high-pressure coal hydrogenation (liquefaction) was by far the biggest disappointment. The 1937 Seven Year Plan called for the construction of 10 plants in Japan and Manchuria, each producing 100,000 kL/yr, although the plants proposed and the two actually constructed were much smaller. Plant proposals included a ¥12.5 million Ube Chisso Kôgyô KK (Ube Nitrogen Industry Co. Ltd.) plant and a ¥10 million Chosen Sekitan Kôgyô KK (Chosen Coal Industry Co. Ltd.) plant. The two plants constructed were at Fushun, Manchuria, and Agochi, Korea, and, according to the US Naval Technical Mission, only one apparently produced any synthetic petroleum, Fushun's meagre 1,460 kL. In 1944, when total synthetic and derived liquid fuel production in the Japanese empire, excluding Fushun shale oil, was 113,166 kL (750,000 barrels), hydrogenation contributed 690 kL. The remainder came from F-T, 18,000 kL, and LTC, 95,000 kL. Yet, the Japanese regarded hydrogenation as the most promising process for converting coal into oil.[42]

Conclusion

At the time IG entered into negotiations with the Japanese army, Germany had practically twenty years experience in the industrial production of synthetic liquid fuel. Twelve coal hydrogenation and nine F-T plants were converting coal and tar into liquid fuel and lubricants. Japan, too, had considerable experience in synthetic liquid fuel production. But in 1945, after experimenting for twenty years, only three F-T and no coal hydrogenation plants were in operation. Unlike the German plants, they had no effect on the outcome of World War II. The older and technologically simpler LTC and distillation process produced most of the liquid fuel the Japanese obtained from coal and shale oil.

The Seven-Year Plan of 1937 had called for the annual production of 12.6 million barrels of synthetic gasoline and fuel oil. Yet in 1944 production was only 750,000 barrels, all of which came from F-T, and LTC plants. Shale oil distillation contributed another 582,000 barrels. The Japanese carried out considerable laboratory research on coal hydrogenation, more than any other country except Germany, and developed their own standard iron oxide-sulphur-tin hydroxide [Fe_2O_3-S-$Sn(OH)_2$] catalyst that performed reasonably well. They also obtained rights to the F-T process from Ruhrchemie for ¥7.2 million, and chemists such as Kita spent years developing cheaper iron catalysts to replace Ruhrchemie's more expensive cobalt-thorium catalysts. Yet yields were always lower with iron catalysts. In their rush to synthesize liquid fuel from coal, the Japanese leaped into industrial-scale production lacking sufficient pilot-plant experience, and consequently neither hydrogenation nor F-T was particularly productive. The Japanese enjoyed their greatest success with LTC, the simplest of the three coal conversion processes. It required no expensive and elaborate high-pressure equipment or extensive catalyst research, but even here the best retorts were German-designed Lurgi or Koppers and American-designed Knowles. In fact, the Japanese synthetic fuel experience seems to support the often-made charge that the Japanese were good adapters or modifiers of existing technologies but not creative or innovative. Such an assessment, however, ignores or insufficiently acknowledges their successful laboratory research. Japanese laboratory science was sound, their technological scale-up was lacking.

The Japanese synthetic fuel experience therefore requires historians of science and technology to examine why some scientific ideas, technologies, or inventions succeed while others fail. Is it the innovation's intrinsic quality or social-economic events that determine success or failure? For the synthetic fuel industry both answers are correct. In Germany, coal hydrogenation was a technological success six years before the Nazi government rose to power in 1933 and proceeded to subsidize large-scale development. Commercialization may not have occurred otherwise. ICI's technologically successful coal hydrogenation process received similar economic incentives from the British government in the 1930s. The F-T synthesis, though not as advanced as coal hydrogenation in Germany and non-existent in Britain, was nevertheless a technological success but an economic failure. The US Bureau of Mines' post-World War II synthetic fuel program succeeded technologically, but because of unfavorable economics and the abundance of cheap petroleum, neither coal hydrogenation nor F-T achieved commercialization in the United States. In Japan the opposite happened. The Japanese government provided every possible economic and social incentive in the 1930s and 1940s, Japanese investigators understood the science of synthesizing liquid fuel from coal and tar and carried out a successful laboratory research program. Technologically the production of synthetic fuel was a failure because the impatient Japanese tried to make the transition from a small-scale laboratory process to commercial-scale production without first developing a successful intermediate pilot-plant operation. The pre-World War II embargoes and the war clearly compounded Japan's urgency. In addition, the navy's interference at the two coal hydrogenation plants hindered synthetic fuel production. But the leap from the laboratory to commercial development was simply too much for the Japanese to overcome. This same impatience and rush to commercial production largely contributed to the failure the Japanese initially experienced when they tried to establish a soda ammonia industry in the 1920s, although both cases also clearly indicate the generally lower level of Japan's technological development in the pre-World War II period.

By the 1930s the Japanese had recognized that the lack of petroleum seriously would hinder their long-contemplated Asian expansion. The very real possibility of a major Pacific war led to their establishing a large reserve of crude petroleum and refined products and to developing a synthetic fuel industry within their empire to guarantee independence from foreign petroleum supplies. But in the end the Japanese empire collapsed and with it the sources of crude petroleum for Japan's refineries. Another victim was the Japanese synthetic fuel industry.

Notes

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1. Yoshio Kodama, “The Coal-Hydrogenating Industry in Japan,” *Journal of the Fuel Society of Japan*, 14 (1935): 71-2; Kodama, “Hydrogentation of Coals,” *ibid*., 14 (1935): 691-701; Kodama, “The Coal-Hydrogenating Industry in Japan," Chemical Abstracts, 29 (1935): 7043; Kodama, “Hydrogenation of Coals," *ibid*., 29 (1935): 5629. Throughout the text, tons means metric tons; articles cited in Japanese journals are in Japanese.

2. “Synthetic Oil in Japan: An Attempt to Gain Self-sufficiency,” *Industrial Chemist* 23 (1947): 333-40; “Coal Hydrogenation in Japan: A Seven Year Plan,” *Iron and Coal Trade Review,* 135 (1937): 716; “Hydrogenation Industry,” *Journal of the Fuel Society of Japan*, 16 (1937): 8; “Coal Oil in Japan,” *ibid*., 18 (1939): a47; S. Ando, “Artificial Petroleum Industry in Japan and Manchukuo,” *Journal of the Society of the Chemical Industry, Japan*, 43, no. 9 (1940) 265B-66B; “Hydrogenation of Coal-Japan,” *Chemistry and Industry*, 55 (1936): 131; “Japan Seeks NEL Oil for Co-prosperity Sphere,” *Oil and Gas Journal,* 39, no. 33 (1940): 82-3, 108, 110, 112, 113; “Japan’s Synthetic Output Virtually at Standstill,” *ibid.*, 44, no. 51 (1946): 96; C.S. Goddin and D.P. Thornton, Jr., “Low-Temperature Carbonization of Coal Produced Most of Japs’ Synthetic Oil,” *Petroleum Processing*, 3 February 1948, 121-31. The designation KK, kabushiki kaisha, means a joint stock limited company. For conversions: 1 kiloliter (kL) = 1.03 (metric) tons, 1 kL = 6.11 barrels (bbl), 1 kL = 264 gal, 1 (metric) ton = 256 gal.

3. Barbara Molony, *Technology and Investment: The Prewar Japanese Chemical Industry* (Cambridge, Mass: Council on East Asian Studies, Harvard University, 1990): 226-33

4. Michael A. Barnhart, *Japan Prepares for Total War* (Ithaca, NY: Cornell, 1987): 130, 156, 166, 180, 190, 196, 255-6. Embargoed materials included aircraft, machine tools, scrap iron, steel, aluminum, nickel, copper, zinc, vanadium, manganese, and tungsten. The embargo on lead tetraethyl, crude oil, and aviation gasoline (87-octane and higher) began in late July 1940.

5. D.P. Thornton, Jr., “Desperate Japs Tried to Make ‘Avgas’ Even from Pine Tree Roots, Needles,” 2 (November 1947): 815-18.

6. Yuji Jido, “The Establishment of Ammonia Soda in Japan and its Technology,” *Ritsumeikan Business Management*, Ritsumeikan Business Management Society, 29, no. 3 (September 1990):1-82 (in Japanese).

7. Eikoh Shimao, “Some Aspects of Japanese Science, 1868-1945,” *Annals of Science*, 46 (1989): 69-91.

8. “Synthetic Oil in Japan” (ref. 2): 333-40.

9. E.B. Potter, ed., *Sea Power: A Naval History* (Englewood Cliffs, NJ: Prentice Hall, 1960): 392.

10. Joseph Borkin and Charles A. Welsh, *Germany’s Master Plan: The Story of Industrial Offensive* (New York: Duell, Sloan and Pearce, 1943): 186-7.

11. William L. Langer, *An Encyclopedia of World History*, fifth edition (Boston: Houghton Mifflin, 1972): 923.

12. Hector C. Bywater, *Sea-Power in the Pacific*, reprint of 1921 edition (New York: Arno Press and the New York Times, 1970): 211-12, 215.

13. “Synthetic Oil in Japan,” (ref. 2): 340; “Shale Industry Authorized,” *Journal of the Fuel Society of Japan*, 7 (1928): 39; R.W. Rutherford, “Oil From Coal in Japan,” *Coke and Smokeless Fuel Age*, 6 (April 1944): 68-70. Conversion of yen to dollars: ¥ = $0.4641. The yen varied in the 1930s: 1929 ($0.4610);1931 ($0.4885); 1933 ($0.2565); 1935 ($0.2871); 1937 ($0.2879); 1939 ($0.2596). See *Statistical Abstract of the United States* (Washington, DC: GPO, 1938 and 1946).

14. “Synthetic Oil in Japan” (ref. 2): 339.

15. Yoshisada Ban, “The Low-Temperature Carbonization Plant at the Imperial Fuel Research Institute,” *Proceedings of the Second International Conference on Bituminous Coal* (Pittsburgh: Carnegie Institute of Technology, 1928), II 303-11. To test the quality of tar, Ban used a single cylinder, four cycle, vertical type Niigata diesel engine with cylinder dimensions 280 mm by 416 mm and a rating of 33 bhp at 230 rpm. Neither a pitch-free oil nor one high in tar acid performed satisfactorily, although a partial removal of tar acid provided good quality diesel oil.

16. Kotaro Shimomura, Japanese patent 50,532 (21 August 1923). Shimomura studied organic chemistry at Worcester Polytechnic Institute where he received the Bachelor of Science degree in 1888 and did research under Ira Remsen at Johns Hopkins for one year (1888-1889). Shimomura became the president of Doshisha University in Kyoto (1904-7). He received the doctor of engineering degree from the Japanese government in 1915. At that time no Japanese University had the authority to award the degree. See “Personal History of Kotaro Shimomura,” Doshisa University Archives, 3 pp. See also Genji Jimbo, Noriaki Wakao, and Masahiro Yorizane, “The History of Chemical Engineering in Japan,” in *History of Chemical Engineering*, edited by William F. Furter (Washington, DC: American Chemical Society, 1980): 273-81.

17. William T. Reid, “Low-Temperature Carbonization of Coal in Japan,” *US Bureau of Mines Information Circular 7430* (February 1948): 1-82, (pp. 17, 20, 53-6). Reid was a member of the US Bureau of Mines (pp. 32-3). His report is the most comprehensive and accurate English language source of information on Japan’s LTC industry. Some of the same information appears in the reports of the US Naval Technical Mission to Japan. (ref. 18).

18. Goddin and Thornton (ref. 2): 122; US Naval Technical Mission to Japan (NTMJ), Microfilm Reel JN-200L, Report X-38 (N)-7, Japanese Fuels and Lubricants, Article 7: “Progress in the Synthesis of Liquid Fuels from Coal,” p. 21, Texas A&M University Archives. The reports contained in this microfilm are the best source of Japan’s synthetic fuel industry. The Naval Technical Mission was in Japan from September 1945 to November 1946. It published a few of its 185 reports in technical journals (1946-1948). The Operational Archives Branch, US Naval History Division, Washington, DC, published a complete microfilm edition of all the reports in 1974. Information on Japan’s synthetic fuel industry also is available in *Materials about Five Year Plan*, Part 2, Volume 3 (Liquid Fuel), edited by the Commerce and Industry Section of SMR, microfilm YD/324, section MOJ 275, National Diet Library, Tokyo; and in GHQ/SCAP, Record Group 331 (Records of General Headquarters/Supreme Commander for the Allied Forces), National Archives and Records Administration, Washington, DC. According to members of the Naval Technical Mission, very little information on the Japanese navy’s LTC program existed.

19. NTMJ (ref. 18): 9.

20. “Synthetic Oil in Japan” (ref 2): 334.

21. NTMJ (ref .18): 11; see also ref. 1. Neither was the methanol synthesis from water gas (a carbon monoxide-hydrogen gaseous mixture produced from the reaction of steam with coal, coke, or methane) seriously considered at the industrial scale

beacuse there was no great peacetime demand for methanol.

22. "Production of Petroleum in Japan," *Journal of the Fuel Society of Japan*, 7 (1928): 73.

23. Franz Fischer and Hans Tropsch, "Die Erodölynthese bei Gewöhnlichen Druck aus den Vergasungsproducten der Kohlen," *Brennstoff-Chemie*, 7 (1926): 97-104; Franz Fischer, "Liquid Fuels from Water Gas," *Industrial and Engineering Chemistry*, 17 (1925): 574-6. Synthesis gas is a variable mixture of carbon monoxide (CO) and hydrogen (H2) usually prepared by reacting steam with coal. Treating the gas with catalysts converts it to liquid hydrocarbon fuels such as gasoline and diesel oil.

24. NTMJ (ref. 8): 10, 16. See also Kita, *Über die Benzinesynthese aus Kohlenoxyd und Wasserstoff unter gewohnlichen Druck* (Tokyo: Institute of Physical and Chemical Research, 1936). Prior to the outbreak of World War II the Japanese imported cobalt from Katanga, Belgian Congo (Zaire) and thorium from the United States.

25. *The Transactions of the Fuel Conference: World Power Conference* (2 vols. London: Percy Lund, Humphries & Co., 1928). See vol. I, cvii-cvix for the list of Japanese delegates and pp. xlii-cxiv for the complete list of delgates and other conference representatives. The table of contents in each volume lists the papers presented by Japanese delegates. Ôshima's paper, "Coal Carbonisation in Japan," is in vol. II, 426-36.

26. Ban (ref. 15): 301-11; Y. Kosaka and Y. Ôshima, "The Formation of Naphthalene. During High-Temperature Carbonization," *Proceedings of the International Conference on Bituminous Coal* (Pittsburgh: Carnegie Institute of Technology, 1926): 463-71; Yoshikiyo Ôshima and Yashitami Fukuda, "The Effect of Ash on Reactivity and Combustibility of Carbon Materials," *Proceedings of the Third International Conference on Bituminous Coal* (Pittsburgh: Carnegie Institute of Technology, 1931), II: 448-84. At the 1931 meeting Bernard Lewis of the US Mines Branch read Ôshima and Fukuda's paper. Because there is no list of delegates, there is no way of knowing whether they actually attended.

27. A third Japanese delegate, Dr. J. Somiya, attended the 1933 congress, but the delegate list gave him no affiliation; *Proceedings of the World Petroleum Congress*, (London: Offices of the Congress, 1933) I. Japanese delegates published the following papers at the 1937 congress; Shingo Ado, "Catalytic Hydrogenation of Low-Temperature Tar Under high Pressure," *Proceedings of the Second World Petroleum Congress* (Paris, 1937), II: 237-48; Kosuke Kûdô and Haruki Fujimoto (an engineering commander in the Japanese Navy), "On the Hydrogenation of Cracked Gasoline," *ibid.*: 271-5; Koki Ishibashi, "Present Status of Properties and Refining of Fushun Shale Oil," *ibid.*: 183-96.

28. Morio Otaki, "Japanese National Petroleum Policy," *World Petroleum*, 8 (September 1937): 64; "Synthetic Oil in Japan" (ref. 2): 333.

29. Kenneth B. Pyle, *The Making of Modern Japan* (Lexington, Mass: D.C. Heath and Co., 1978), 137-50; "Chemical Industry in the Far East," *The Chemical Trade Journal and Chemical Engineer*, 104 (31 March 1939): 316; G.C. Allen, *A Short Economic History of Modern Japan 1867-1937* (London: George Allen & Irwin Ltd., 1946): 98-9, 146-9.

30. NTMJ (ref . 18): 321-6.

31. Reid (ref. 17): 7-12. Reid used ¥ = $0.23. This is approximately the average for the years 1940 ($0.2346) and 1941 ($0.2349). These were the only figures available during the war years. The new rate set in April 1949 was ¥360 = $1.00, in coordination with American occupation forces.

32. "Synthetic Oil in Japan" (ref. 2): 336-40; Thorton (ref. 5): 815-22.

33. Ryoichi Ishida, *Story of Coal Liquefaction* (Tokyo: Chuo Shuppan Insatsu, 1990): 27-42 (in Japanese). Mitsui signed an optional contract with Ruhrchemie on 11 February 1936, and during the next year it kept two or three researchers in Germany, studying the F-T synthesis. See also the US Naval Historical Center's ATIS Report 4575, document numbers ND 26-0004.1 through ND 26-0001.31.

34. NTMJ (ref. 8): 16-17.

35. "Synthetic Oil in Japan" (ref. 2): 339. Other pressure units used in the Japanese reports were kg/cm2 and psi. 1 atm = 1 kg/cm2 = 15 psi.

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36. *Ibid*.: 17. Matsubara's catalyst (100 ochre + 1 Cu + 1 H3BO3 + 6 K2CO3) consisted chiefly of ochre, a natural yellow earth 64.8 percent ferric oxide, obtained from Niwasaka near Fukushima. The composition of Kita's best iron catalyst was 100 Fe + 25 Cu + 2 Mn + 125 kieselguhr + 15 H3BO3 and of the best cobalt-thorium, 100 CO + 5 Cu + 12 U3O6 + 4 Mn + 100 Kieselguhr. After the war ended, the petroleum section of the Naval Technical Mission inspected the Fuchu plant on 12 January 1946.

37. Composition of the iron catalyst was 100 Fe + 25 Cu + 125 kieselguhr + 6 K2CO3. Later the Japanese developed an iron catalyst identical to that used in the Kyoto semicommercial pilot plant but also containing five parts of magnesium. It supposedly increased yields and was the best middle pressure catalyst. But in the one result repeated, its yield was 111 g/m3. Goddin and Thornton (ref. 2):125, 127, 130. See also "Chemical Industry in the Far East," *Chemical Trade Journal*, 108 (23 January 1941): 8.

38. NTMJ (ref. 8): 18-19, 326; "Synthetic Oil in Japan" (ref. 2): 335, 337-9; Goddin and Thornton (ref. 2): 122, 125, 129, 130; Ando (ref. 2); "Hydrogenation of Coal-Japan" (ref. 2).

39. "Synthetic Oil in Japan" (ref. 2): 335, 337-9; NTMJ (ref. 18): 18-19; Goddin and Thorton (ref. 2): 122, 125, 127, 130. Coke oven gas is mainly a mixture of hydrogen (53 percent and methane (32 percent) plus carbon monoxide, nitrogen, other gases, and illuminants. The Naval Technical Mission also visited the semicommerical Fuchu plant (see ref. 18). The capitalization of the Mike plant was ¥50 million in October 1943, and after Mitsui brought in two other partners to form Nippon Jinzo Sekiyu KK in October 1944, final capitalization was ¥150 million. See Ishida (ref. 33): 87 and NTMJ (ref. 18).

40. Goddin and Thornton (ref. 2):122; "Synthetic Oil in Japan" (ref. 2): 335.

41. Thornton (ref. 5): 818.

42. Goddin and Thornton (ref. 2): 122; "Synthetic Oil in Japan" (ref. 2): 334.