HISTORIOGRAPHY OF CHEMICAL INDUSTRY: TECHNOLOGIES AND PRODUCTS VERSUS CORPORATE HISTORY

Anthony S. Travis, The Hebrew University of Jerusalem; tony.travis282@gmail.com

Abstract

In the twentieth century, the chemical industry was, in terms of innovation, among the most quickly changing of all industries. What remained constant, at least until the turn of the century, was its control by Western behemoths, such as Du Pont, ICI, and BASF. However, over the past two decades, driven by fragmentation and globalization, there has been a complete transformation of the industry. Thus Du Pont has merged with Dow, and ICI has ceased to exist. BASF remains one of the few survivors of the large, old corporations. The outcome is that historiography of chemical industry according to the model built mainly around these corporations has become complex, if not redundant. What if the historical analysis of corporations is shifted to an analysis of the interactions and transitions between technologies, within the industrial and global contexts, by revisiting and building on past achievements? Here such an approach is taken using as examples of industrial practice a single sector, synthetic ammonia: ICI's technologies, which includes manufacture of hydrogen, and the ceding of the role of high-pressure catalytic process plant design away from chemical companies to chemical engineering contractors. This enables a discussion of ICI's fall, and the complexity of what followed, to be tempered by the legacy of innovation in a sector that through the hydrogen economy is today receiving unprecedented attention.

In April 1986, the BBC's prestigious Richard Dimbleby Lecture was given by Sir John Harvey-Jones, chairman of Britain's Imperial Chemical Industries (ICI). The title of the lecture was, appropriately for the head of the nation's largest manufacturing conglomerate, "Does Industry Matter?" ICI, founded in 1926 as the result of a merger of four leading firms, was in the 1960s and until the early 1970s, in terms of annual sales, second after Du Pont in the league of global chemical manufacturers (1). In 1984, "ICI was the most profitable world chemical company." In 1986, as Harvey-Jones emphasized, ICI performed a vital role in the battle against Britain's widely perceived industrial decline: "ICI alone has a positive contribution to the tune of nearly £2 thousand million a year." Above all, "It is manufacturing industry whose praises I want to sing tonight." There was no other antidote to decline: "It is often suggested that tourism offers salvation. It is equally clear that this cannot be…. if we imagine the UK can get by with a bunch of people in smocks showing tourists around medieval castles we are quite frankly out of our tiny minds" (2).

In 1991, ICI trumpeted the fact that it was "one of the best-known names in the corporate world…. [and] is the most international of the world's chemical groups" (3). Today, ICI no longer makes a positive contribution to the UK economy. In the late 1980s, the corporation embarked on a period of major restructuring, caused by low margins, and often losses, in its cyclical bulk commodities, in part arising from increases in the price of energy (4). In the early 1990s, the management began to sell off the commodities businesses in order to invest in an ultimately expensive move into consumer products. The first major division to go was ICI's soda ash operation, divested in 1991 as Brunner Mond Holdings (and eventually acquired by Tata Chemicals of India in 2006). The nitrogen and fertilizer divisions followed soon after. In 1997, Zeneca, ICI's pharmaceutical spin-off, merged with the Swedish Astra to create AstraZeneca; ICI acquired Unilever's specialty chemicals business; and soon found itself with four billion pounds in debt. In early 2008, what remained of ICI was sold to AkzoNobel of Holland. ICI was completely defunct. No less significant was the fact that many of the once thriving core commodities businesses had been divested or sold off to foreign corporations. ICI, once a great success, had now become irrelevant. It seemed that Britain, at least until the arrival of Covid-19, was getting by with a bunch of people in smocks showing tourists around medieval castles, and contributions from the service industries. There was, however, a decade old, though then struggling, chemical corporation, Ineos, that had brought together commodity divisions from several other firms, including ICI's fluorochemical and chlor-alkali businesses.

ICI's disappearance was part of a pattern that was followed elsewhere in the chemical industry, though in many ways its total collapse was an extreme case (5). In common with ICI, many of the great chemical corporations that dominated the twentieth century had lifetimes of sixty or seventy years (apart from those broken up after 1945 in Germany and Japan). A few managed to survive, mainly intact, for considerably longer, before disconnecting with the past through closedown of traditional manufacturing processes, through mergers and acquisitions, or in response to environmental issues. Mergers were followed by de-mergers and spin-offs. Rivals acquired subsidiaries in order to support expansion. Moreover, corporate reconfigurations often entailed changing focus into biomedicines and specialties, and, as at ICI, research in "biology-based businesses" (3). In other cases corporations became less relevant, such as Monsanto, whose brand name was dropped shortly after it was subsumed by Bayer in 2018 as a result of campaigns by environmental activists against Monsanto's herbicides and genetically-modified crops.

Generally, the media today do not think much of the chemical industry, unless galvanized by stories of toxic releases, or, especially in the business columns, of corporate raiders, and activist hedge funds. "It has more to do with financial engineering than chemical engineering," wrote John Gapper in the *Financial Times*, on 1 June 2017, under the heading "Chemicals were the future once but no longer." Gapper opined that "…. there is not a great future in chemicals. If there were, then companies such as Dow Chemical, DuPont, Evonik, and ChemChina would not be involved in a series of mergers, the biggest wave of restructuring since conglomerates spun off their pharmaceutical divisions in the 1990s" (6).

While we may question perceptions and profiles of the chemical industry as appearing in the columns of the *Financial Times*, we cannot ignore the fact that in 2017 its readership exceeded 900,000, a significantly greater exposure than any history of chemistry/science/technology journal.

Nevertheless it is true that as a result of various transformations the long-standing heritage chemical industries of Europe and North America bear little resemblance to their standings in the seventy-year epoch that began around 1920 (Table 1). Which is why corporate changes at the turn of the century represent a form of closure of history of chemical industry as it had functioned in the past. This presents a number of challenges to historians of the industry, as does the fact that because corporate raiders play major roles in reformulating the chemical industry, researchers are already confronting the problem of reduced access to archival material in Europe and North America (unless disclosure is required in litigation). Other considerations apply to China and elsewhere. This begs the question: If historiography of chemical industry still matters, how do we pursue it in ways that are different from the past when it was possible to write histories of the great firms during the relatively stable period? Here I would like to consider the prospects for an integrated history of the modern chemical industry by examining a group of important chemicals through their modes and scales of manufacture, and their impacts on certain world affairs, rather than through the complexity of corporate changes.

I take as the starting point ICI's storied vast synthetic ammonia facility at Billingham, in northeastern England, which commenced production of ammonia in 1924 after imitating the BASF Haber-Bosch process (1913), itself a massive endeavor and the template for all subsequent ammonia processes (7). By the 1960s, when ICI was the largest producer of ammonia in the world, it operated four other ammonia facilities: Heysham (constructed for the Ministry of Supply during World War II), Wilton (1949; ammonia production began in 1952), Severnside (1963), and Immingham (1966). By the 1980s, there were eight ICI ammonia facilities. ICI's engagement in the relevant technologies, including novel high-activity catalysts, and two low-pressure ammonia processes, had an almost mythical provenance, at least among chemical

Table 1. Examples of Amalgamations, Mergers and Independent Firms in the European and US Chemical Industries

20th-Century Mergers	
1917	**Union Carbide and Carbon, USA**
1920	**Allied Chemical & Dye, USA. AlliedSignal 1985; Honeywell 1999**
1925	**IG Farben, Germany**. Dismantled after 1945, to form **AGFA**, **BASF**, **Bayer** and **Hoechst**. AGFA is a subsidiary of **Bayer**
1926	**Imperial Chemical Industries** (ICI), **UK**. Alkali division divested, as **Brunner Mond 1991**. Demerger of pharmaceutical and agrochemical divisions to form **Zeneca 1993**. Zeneca merges with **Astra**, Sweden, to form **AstraZeneca**, **1997**. Other divestments discussed in text
1928	**Rhône-Poulenc, France. Société *Chimique des Usines du* Rhône** merges with **Établissements Poulenc Frères**
1929	**American Cyanamid and Chemical Corporation, USA. Cytec,** chemicals, spun off **1993-94;** life sciences, agrochemicals and consumer products to **American Home Products (Wyeth) 1994**
1966	**Montecatini** merges with **Edison** to form **Montedison, Italy**
1970	**Ciba-Geigy, Switzerland.** Renamed **Ciba 1992.** Merges with **Sandoz** to form **Novartis 1996**
1994	**AKZO** merges with **Nobel, Netherlands**
1999	**Hoechst** merges with **Rhône-Poulenc** to form **Aventis**

Major Independent Firms at the Close of the 20th Century
Bayer, Germany
Ineos, UK (founded 1998)
BASF, Germany
Monsanto, USA
Dow, USA
Solvay, Belgium
DuPont, USA

21st-Century Mergers	
2001	**Union Carbide & Carbon** to **Dow**
2004	**Aventis** merges with **Sanofi-Synthélabo** (**Sanofi**), **France**
2007	**Evonik,** merger of German firm **Lyondell Chemical** to **Basell Polyolefins** to form **LyondellBasell, USA/UK**
2009	**Rohm and Haas** to **Dow**
2017	**DuPont** merges with **Dow,** to form **DowDuPont**
2018	**Monsanto** to **Bayer**

engineers. This, however, has received scant attention from historians of chemical industry.

Synthetic ammonia was one of ICI's most important commodities, and though not always profitable, was essential to agriculture. In the 1990s, the corporation's divestment program involved disposal of its ammonia and nitrogen fertilizer units. Their subsequent ownerships, and the eventual consolidation in 2015 as part of CF Industries, of Illinois, today the world's largest manufacturer of ammonia, are shown in Table 2.

This illustrates well how, as in other sectors, unfamiliar names emerged on the way to consolidation. For the historian interested in the chemical industry of the recent past the changes are undoubtedly a source of confusion. We are not dealing with changes in divisions and departments here, but completely different corporate entities. In just over two decades there had been more changes of ownership at ICI's ammonia business than in the previous seven decades. And there was not a great deal to show in the way of technical innovation.

Synthetic ammonia, as a high tonnage chemical, presents itself as an example for a new approach to a broader understanding as to why the chemical industry is not only vital but makes necessary the need for historians to record its processes and products. This includes the study of feedstocks, energy needs, and process improvements, in addition to research, design, and engineering, and the changing structure of the industry.

Framed within the challenge of nitrogen fixation, synthetic ammonia is accorded a major role in the feeding of humanity, and thus in its growth and expansion. What is less well appreciated is that success is conditioned on production of pure hydrogen in order to prevent catalyst poisoning. ICI happens to hold a special place through its

Table 2. Towards Consolidation in the British Ammonia Industry. Corporate Ownership of Billingham and other Ammonia Factories

1920-1923	Brunner, Mond & Co. develop ammonia synthesis.
1924	Brunner, Mond & Co. produce ammonia at Billingham.
1926	(December 7) ICI (Imperial Chemical Industries) created from merger of Brunner, Mond with Nobel Industries, British Dyestuffs Corporation, and United Alkali.
1965	Shellstar (Shell/Armour Star) ammonia factory opens at Ince, Cheshire, northwest England.[a]
1975	Ince sold to DSM of Holland. Trades as UKF.
1985	Ince sold to Kemira Oyj, of Finland, whose agricultural unit becomes Kemira Agro Oy. Kemira also acquires an ammonia plant at Hull.
1990	ICI pursues options to divest of ammonia operations.
1991	Terra Nitrogen (UK) Ltd, part of Terra Nitrogen Company, of Deerfield, Illinois (founded in 1991), purchases ICI Billingham and Severnside fertilizer ammonia facilities.
2004	Kemira Agro Oy spun off as Kemira GrowHow Oyj.
2006	Terra and Kemira GrowHow Oyj form 50-50 joint venture, GrowHow.
2007	Kemira GrowHow acquired by Yara International (formerly part of Norsk Hydro) of Norway. Ince modernized.
2010	Terra, and its share in GrowHow, sold to CF Industries, of Deerfield, Illinois (founded in 1946 as the Central Farmers Fertilizer Company).
2015	Yara's UK share in GrowHow sold to CF Industries. GrowHow rebranded as CF Fertilisers in November.

[a] The Shellstar factory is included because of the connection with Kemira Oyj. Severnside closed in 2008.

contribution to the complete range of hydrogen generation processes from fossil fuels: from coal by the water gas process, and from naphtha, natural gas, and other hydrocarbons through the process of steam reforming.

Hydrogen

Water Gas, Coking Oven Gas and Electrolysis

Until the 1940s, the main processes for large-scale production of hydrogen were based on coal. ICI manufactured hydrogen by imitating BASF's technology. Red hot coke was treated with steam in gas generators to give water gas, a mixture of carbon monoxide and hydrogen, from which the contaminant hydrogen sulfide was removed using iron oxides. The carbon monoxide was then converted into carbon dioxide by the water gas shift reaction. The shift reaction also gave more hydrogen. The carbon dioxide was scrubbed out with water, and any remaining monoxide was absorbed in a solution of cuprous ammonium formate.

$$C + H_2O \leftrightharpoons CO + H_2 \qquad \Delta H\ +118.7\ \text{kJ/mol}$$

$$CO + H_2O \leftrightharpoons CO_2 + H_2 \qquad \Delta H\ –42.1\ \text{kJ/mol}$$

water gas shift reaction

This was followed by the ammonia synthesis, at a pressure of around 250 atmospheres, in the presence of a magnetite-based catalyst, and at an elevated temperature. The yield was around 5-8 %.

$$3\ H_2 + N_2 \leftrightharpoons 2\ NH_3 \qquad \Delta H\ – 91.8\ \text{kJ/mol}$$

The other main hydrogen process drew on coking oven gas, which is rich in hydrogen, as widely adopted in Europe from the mid-1920s. This source also required extensive purification. Where cheap hydro-electric power was available pure hydrogen was produced in electrolytic cells, mounted in electrolyzers, but in most cases the electricity was too expensive. At the end of the 1920s, the introduction of synthetic methanol created even greater demand for hydrogen, which when generated with carbon monoxide became known as synthesis gas (syngas), and was a cornerstone of many manufacturing processes.

Steam Reforming of Hydrocarbons

ICI's most original contribution to production of hydrogen prior to 1940 was in steam reforming. This started with international interest in synthetic gasoline made by hydrogenation of coal, based on the Bergius process of IG Farben in Germany. In the United States the process was investigated by Standard Oil of New Jersey. However, interest in hydrogenation of coal to provide liquid fuels declined in the United States because of the discovery of large deposits of petroleum. This was not the case in Britain, nor in Germany.

The steam reforming process consists of heating hydrocarbons in the range 700-1100 °C in the presence of steam and a nickel catalyst. Hydrogen and carbon monoxide are formed, as in the water gas reaction. In the case of natural gas (methane):

$$CH_4 + H_2O \leftrightharpoons CO + 3\ H_2 \qquad \Delta H\ +206\ \text{kJ/mol}$$

The most advanced steam reforming plant for manufacture of hydrogen was developed at ICI from 1928. It operated at atmospheric pressure and was installed at Billingham for the ammonia process in 1936. In this case the propane/butane byproducts of coal hydrogenation were reformed to hydrogen. Significantly, this was then of no interest in Germany, which relied on abundant lignite (brown coal), nor in the United States, where there was a growing interest in reforming of natural gas (7, pp 112-113). However, ICI's work was a precursor to the modern methods of reforming liquified petroleum gas (LPG, a mixture of propane and butane).

When after 1940 the United States embarked on expansion of ammonia production for strategic purposes, six of the ten new government-backed plants relied on ICI's process for the steam reforming of natural gas. It was this novel way of producing hydrogen that provided an early opportunity for engineering contractors to enter into the manufacture of synthetic ammonia. From the 1960s, these firms became front runners in the development of new hydrogen and ammonia technologies. Where natural gas was abundant, notably in the United States and Italy, it became the main source of hydrogen for ammonia by the end of the 1940s. In Britain methane was available from coke gasification, but this made it expensive as a feedstock. In Germany, where there was a considerable demand for methane for use in the manufacture of acetylene by the electric arc process, the methane was mainly available from coking ovens gases.

Hydrogen from Naphtha

For hydrogen, ICI relied on hard (bituminous) coal that was, apparently, less well suited to the water gas reaction than the lignite used in Germany. As an alternative feedstock for the ammonia process, ICI's chemists-engineers in the 1950s investigated oxygen gasification of fuel oil, and, at around the same time, the ultimately more successful steam reforming of low-sulfur naphtha, a mixture of light distillate hydrocarbons. They developed a naphtha-based synthesis gas process using pressurized steam reforming and catalysts that prevented poisoning with sulfur and the buildup of carbon in the reformer tubes. In 1959-1960, this steam reforming process was introduced on a commercial scale at Heysham, in 1962 at Severnside, and in 1963 at Billingham. It was the *first ever* large-scale application of pressurized steam reforming to liquid hydrocarbons. In order to extend the life of the furnace tubes, a second reforming stage was introduced in which unconverted hydrocarbon was oxidized. In secondary reforming, a process earlier developed by ICI, the partially reformed hydrocarbon is reacted with air, which at the same time provides the nitrogen for the ammonia process (8). Secondary reforming was followed by heat recovery, a two-stage carbon monoxide shift reaction, and removal of carbon dioxide by washing with hot potassium carbonate solution.

Recovered carbon dioxide was used in the manufacture of urea, an increasingly important fertilizer, by reaction with ammonia, and also sold to the beverage industry. By the mid-1960s, ICI's two-stage pressurized reforming process was licensed to six leading international engineering contractors, including M.W. Kellogg in the US, and Humphreys & Glasgow in the UK (9). In the 1970s, the process was readily adapted to reforming of North Sea natural gas.

$$CH_4 + 2\ O_2 \leftrightharpoons CO_2 + 2\ H_2O \qquad \Delta H\ -35.6\ \text{kJ/mol}$$

secondary reforming

$$CO + H_2O \leftrightharpoons CO_2 + H_2 \qquad \Delta H\ -42.1\ \text{kJ/mol}$$

water gas shift reaction

This brought to an end the use of coal as feedstock in the ammonia industry in Britain. ICI was also a leader in synthesis of methane by steam reforming of naphtha which, along with hydrogen from naphtha, around 1970 aroused considerable interest in the United States where there were concerns over a shortage of natural gas.

From the 1960s, the technology of ammonia production increasingly relied on a change in design philosophy, involving a more holistic approach based on a total-unit-based integrated concept, rather than on a conventional, interdependent, kit of parts, as taken by engineering contractors, in particular M. W. Kellogg. ICI's work on steam reforming under pressure was critical to Kellogg's reconfiguration of synthetic ammonia technology.

M. W. Kellogg's Single Train Ammonia Unit

The synthetic ammonia industry was transformed with development in 1963 of the single-train energy-integrated ammonia unit, powered by a centrifugal compressor. It enabled production of 1,000 tons a day of ammonia in a single synthesis loop. This tripled the output obtained with loops using the previously standard reciprocating compressor (10). The first design was drawn up by Kellogg, then of New York, for ICI's Severnside factory. Though Kellogg did not receive an order from ICI at that time, because catalyst calculations took longer than anticipated, this represents one of the high points in the shift from innovations in the chemical industry over to engineering contractors. Moreover, its success relied on ICI's developments suited to full-scale pressurized steam reforming. Kellogg installed the first pressurized steam reforming unit for ICI, at Heysham. This contributed towards Kelloggs's appreciation of ICI's reforming technology. The reforming process brought about significant savings by integrating heat energy and the energy required for gas compression. It almost completely obviated the need for additional inputs of steam and electricity. The process was a critical component of Kellogg's design of the single-train process (11). In 1964, Kellogg, now in a position to provide catalyst performance data, received a contract from ICI for construction of three single-train units at Billingham.

Versions of the single-train unit were soon after designed by other engineering contractors (for a time Kellogg claimed priority, based on pilot plant studies undertaken in the 1950s). ICI, though maintaining research into synthetic ammonia and related processes, including high-activity catalysts, increasingly outsourced design and erection of its plant for bulk commodities to engineering contractors, including Bechtel, Kellogg, and Humphreys & Glasgow.

The new reformer and single-train ammonia technologies had a major impact in India, and, once the United States opened up to business with the main communist powers, in China and Russia. The technologies of nitrogen products, and also of methanol, became tools of international diplomacy; their global transfers were brought about through engineering contractors, cross-licensing of technologies, and international financing. This was the beginning of a new era in the history of chemical industry, one that has little to do with the traditional Western corporations. Nevertheless its success was an outcome of ICI's pressurized steam reforming technology as integrated into Kellogg's single-train process.

India: Ammonia for a Developing Economy

The global map of the synthetic ammonia industry changed with the emergence of the so-called Green Revolution, in the mid-1960s, which relied on new hybrid high-yield varieties of wheat and rice, and nitrogen fertilizers. This enhanced the transition of sites of production from Western countries and Japan to locations close to areas of consumption (12).

From the end of 1965, the United States and World Bank encouraged India and Pakistan to accept assistance from Western multinational engineering contractors in developing large-scale nitrogen fertilizer industries (13). While the plant installation costs were high, it was emphasized that home-produced ammonia and nitrogen fertilizers would remove the need for valuable foreign currency to pay for imports of much needed grain. The situation became critical as the result of a severe drought in 1966.

In the same year, ICI's naphtha steam reforming process was adopted in a new 500 mtpd (metric tons per day) ammonia plant for Gujarat State Fertilizer Co. Ltd, on the west coast of India, constructed by Humphreys & Glasgow and Japan's Hitachi-Zosen (14). In 1969, ICI's synthetic ammonia technology was introduced at Kanpur (Uttar Pradesh); the ammonia was converted into urea by the process of Japan's Toyo Engineering. Also in 1969, Japan's Chiyoda Chemical Engineering & Construction was appointed lead contractor for an ammonia-urea project at Kota, Rajasthan, in the northwest of the country, incorporating processes licensed from European and American firms (10, pp 136-137). Kellogg designed and constructed the first large scale, natural gas fed, all-centrifugal ammonia unit in India, at Kalol, Gujarat, for Indian Farmers Fertiliser Cooperative. It was part of a 120-million dollar ammonia fertilizer complex, producing urea and NPK fertilizers, formally opened by Prime Minister Mrs Indira Gandhi on 8 November 1974 (15). Finance came from the United States Agency for International Development and the United Kingdom Overseas Development Association.

With the support of Indian-made nitrogen fertilizer, the increase in food grain yield enabled India to become self-sufficient in wheat, and no longer to rely on imported rice. Significant, for long-term growth, was the know-how transfer to Indian scientists and engineers (16). Indian food production rose from 50 million metric tons in 1950-1951 to 152.4 million tons in 1984-1985 (17). In Pakistan during 1975, Kellogg began construction of a 900 mtpd single-train ammonia plant, financed by the International Bank for Reconstruction and Development (18). Ammonia factories had become the front line against hunger and malnutrition.

Western Firms and China

When in the 1970s, Western chemical and engineering contractors were badly hit by the economic impact of increased energy prices and competitive pressures they found some relief in the shape of the growing markets in Asian and Eastern Bloc countries. The People's Republic of China was of particular significance to American contractors. In 1971, at the mid-point of the Cultural Revolution (1966-1976), China became interested in trade with the United States. President Nixon was then dealing with major problems in the American economy and the war in Vietnam. Industries were encouraged to increase exports, in order to support the dollar, and to explore new markets. The US administration hoped that by opening up to China it might be possible to take advantage of frictions between China and the Soviet Union, then the main backer of North Vietnam, in order to bring pressure to bear on the Russians, which could in turn be used to help bring about an end to the war. Nitrogen fertilizer plants were among the main bargaining tools.

In February1972, Nixon travelled to China to meet with Mao Zedong and Premier Zhou Enlai. The Chinese government soon after ordered thirteen large ammonia-urea complexes, of which eight were assigned to Kellogg, and five to European and Japanese firms. The Kellogg order, for 1,000 mtpd single-train ammonia units, represented "the largest dollar volume [order] ever placed by the PRC with a U.S. firm in the industrial sector" (19). Moreover, the combined size of the Chinese orders was unprecedented in the history of chemical industry.

By 1986, as a result of the importation of Western ammonia technologies, there were fourteen ammonia plants operating with rated capacities of 1,000 mtpd, and three more under construction. China, by building world-scale ammonia plants, became the global leader in ammonia production in the early 1990s. China also emerged as an important innovator. An example, in the context of this paper, is a high activity novel catalyst for the ammonia synthesis based on wüstite ($Fe_{1-x}O$) discovered in the 1980s at Zhejiang University of Technology (20). The technology was licensed to Süd-Chemie in Germany; production of what were called Amo-Max® catalysts commenced in 2003. Billingham was one of the users of this catalyst. This represented a major departure from the traditional magnetite catalysts that had been used over the previous century.

The Soviet Union

From the late 1960s, developments in the Soviet Union paralleled those in China. At that time, European firms were already open to direct business with Soviet and Eastern Bloc enterprises. To obtain a foothold in these markets, Kellogg engaged in partnerships, licensing, and other arrangements with Japanese and European engineering contractors. In 1969, Kellogg provided Japan's Toyo Engineering with the process design for a 1,500 tpd ammonia unit at a fertilizer factory located in the foothills of the Caucasus Mountains. It went on stream in 1973.

The large Eastern Bloc market was a factor in Kellogg's acquisition in January 1973 of 51% of the Dutch firm Continental Engineering from Verenigde Machinefabrieken (VMF). Continental Engineering, renamed Kellogg Continental BV, opened up the market for Kellogg ammonia technology in the Soviet Union (21). Process design was licensed through Kellogg Continental to Toyo Engineering, which with Soviet engineers erected five plants in Russia (22). In June 1974, the engineering contractor Chemico (a former division of American Cyanamid) signed a $200 million contract for construction of four ammonia facilities on the Volga River. Funding for these factories was provided by the Export-Import Bank of the United States, the official export credit agency of the US government (23).

The Energy Crisis

The change in the scale of ammonia production resulting from new technologies included process efficiencies that enabled a substantial reduction in the use of natural gas, as the result of the introduction of pressurized reformers and centrifugal compressors (7). Quite unexpected, however, were events in the 1970s that would upset the world energy balance.

Between late 1973 and early 1975, in the wake of the Yom Kippur War, the free market economies suffered from the almost fourfold increase in the price of hydrocarbons. This, however, had little impact on orders for ammonia plants from countries with central and regional planning, notably China and the Soviet Union. The *Wall Street Journal* in December 1974, under the heading "No slump here: builders of ammonia plants benefit from global demand," emphasized the fact that American engineering contractors were engaged in twelve ammonia projects in the Soviet Union, nine involving Kellogg and three Fluor Corporation, of Los Angeles, in addition to eight projects in China (24).

In 1976, Kellogg, by then moved to Houston, signed a contract for supply of a 1,500 tpd synthetic ammonia unit to the Soviet Union, bringing to eighteen the number of Kellogg designed ammonia plants operating in, or contracted for, Russia (25). At the same time, Montedison's engineering division, Tecnimont SpA, received an order from the Soviet Union for a urea plant of 500,000 tons annual capacity (26). These plants contributed greatly to the Soviet Union's role as the leading global producer of synthetic ammonia until around 1990, when it was overtaken by China.

Significantly, in the 1970s the Middle East countries were emerging as major producers of ammonia, drawing on natural gas and Western technologies. In Iran during 1970, Kellogg completed a petrochemical complex incorporating a 1,000 tpd ammonia unit; a second unit was installed five years later (27). In the mid-1970s, the Saudi Arabian Fertilizer Company (SAFCO) commenced large-scale manufacture of ammonia and urea (28). Regime changes, and in the early 1980s a drop in the price of oil, did however cause difficulties for Western engineering contractors, resulting in bankruptcies, takeovers, mergers, and consolidations.

ICI's Catalysts

The 1970s and 1980s saw several major improvements in the technologies of high-pressure catalytic processes. In steam reforming, ICI's nickel catalysts enabled increases in the pressure, permitting use of even fewer tubes, which were made of expensive alloys, and smaller furnaces. Heat was recovered for use in other sections of the ammonia unit (29). Iron oxide and copper catalysts were used in the shift reactions. A nickel catalyst brought about more efficient removal of carbon oxides from synthesis gas by methanation, a process introduced in the 1960s.

$$CO + 3\,H_2 \leftrightharpoons CH_4 + H_2O \qquad \Delta H\ -206.1\ \text{kJ/mol}$$

$$CO_2 + 4\,H_2 \leftrightharpoons CH_4 + 2\,H_2O \qquad \Delta H\ -164.9\ \text{kJ/mol}$$

In the mid-1970s, ICI invested two million pounds sterling on extending its catalyst division, known as ICI Katalco, for manufacture of hydrogen, ammonia, and methanol catalysts. New catalysts, along with the introduction of centrifugal compressors, enabled large plant throughputs in both ammonia and methanol under milder conditions.

An important ICI contribution to the Soviet Union's chemical industry was a low pressure methanol process which, using novel high-activity catalysts, reduced the operating pressure from 300 atmospheres to 30 to 120 atmospheres. There were also considerable savings in consumption of feedstock. The process, introduced in 1968, was in use at Billingham from the mid-1970s (30). Contracts for two methanol plants were drawn up with Russia in the summer of 1977. Finance came through a buyer credit arranged by Morgan Grenfell Ltd, under the terms of the 1975 Anglo-Soviet Credit Agreement. The plants, at Gubaha in the Urals, and Tomsk, in Siberia, were the largest methanol facilities in the world, and represented Britain's largest ever deal with the Soviet Union. This brought to 26 the number of facilities that worked the ICI methanol process, which accounted for some 80% of world capacity (31).

ICI's active catalysts contributed to the development of a new, lower energy ammonia process at Billingham. It was called Ammonia V, abbreviated to AMV, and developed by 1984. The process featured a low-pressure synthesis loop, operating at about 80 to 110 atmospheres, half the pressure generally in use until the 1960s (32). It employed, for the first time, a cobalt-promoted high-activity synthesis catalyst (Katalco74-1) (Table 3) (33).

Though the same basic process was common to other new designs developed in the 1980s, the operating conditions were different (Figure 1).

Unfortunately for ICI, depressed economic conditions were impacting on all sectors of the economy, no less the synthetic ammonia industry. As a result, the AMV design was not adopted at Billingham. The first prototype was put into operation in August 1985 at the Nitrogen Products Factory (formerly CIL, Canadian Industries, Ltd), at Courtright, Ontario, Canada.

However, ICI's Severnside facility, with its then two ageing units, was modernized, using the corporation's new Leading Concept Ammonia (LCA) process, announced in 1988. It employed catalysts enabling even lower operating pressures than the AMV process, that is, between 70 and 80 atmospheres. (ICI's LCA and AMV processes had been developed under the guidance of Alwyn Pinto.) In the redesign of the steam reforming process, the primary reformer was arranged to receive heat from the process gas exiting the secondary reformer. This concept, proposed by Chiyoda in 1984, did away with the need for a primary reformer furnace. The LCA process was suited to ammonia units of relatively low daily capacity, for which there was still demand, and

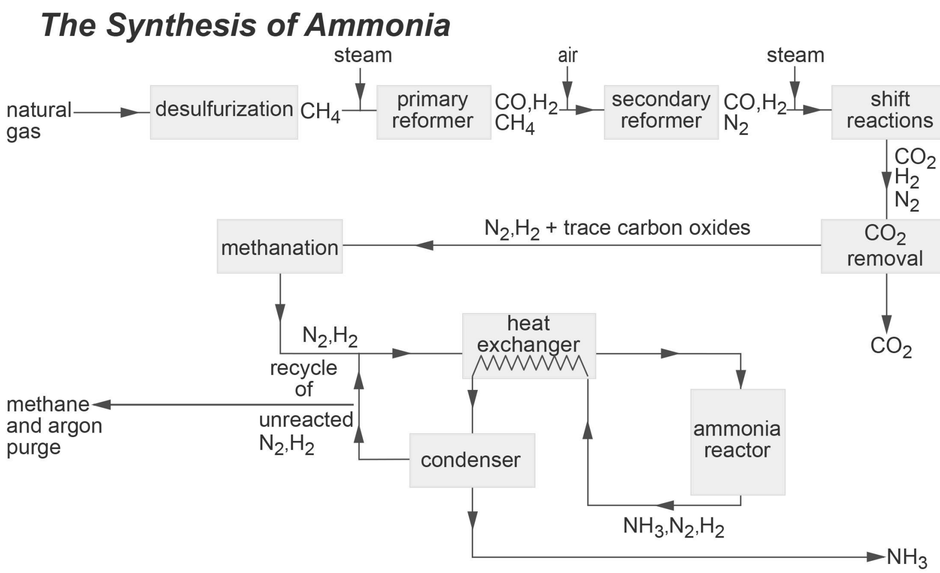

Figure 1. *Ammonia synthesis from natural gas, at ICI Billingham, 1970s.*

with a yield of 12 to 15% compared favorably with other processes.

By 1990, ICI ammonia production had been losing money for four years. Rather than use its advanced technology to improve the ammonia units at Billingham, ICI decided to dispose of its ammonia facilities. ICI, however, continued to license the LCA process, and remained in the catalyst business. In September 1990, the catalyst unit, ICI Katalco, became Katalco. In 1997, Katalco purchased BASF's synthesis gas catalyst division. Five years later, Katalco was acquired by Britain's Johnson Matthey, which has continued to develop novel catalysts at Billingham.

The foregoing account is no more than a fragment of the modern industrial ammonia story. From the 1980s, the high cost of installing new plant stimulated a sector based on plant upgrading, including redesign of converter internals, as well as improved reformer technologies, offering not only higher capacities but even greater savings in energy. More recently, designs have been drawn up for ammonia units with capacities of up to six thousand tons a day, based on sustainable ammonia production. Steam reforming of natural gas remains the dominant process for manufacture of hydrogen, with, increasingly, moves towards complete carbon capture. In the long term, electrolysis of water, drawing on wind and solar power, is expected to rival steam reforming. Both processes are critical to the emerging hydrogen economy, now focused on energy production, in particular the much-lauded fuel cells, and the use of hydrogen as an energy carrier. Ammonia and hydrogen have a long shared history that promises much for the future, and for the future historian of chemical technology. But it is no longer a story of Western corporations alone.

Conclusion

The history of the modern chemical industry is not unlike larger national histories in that it refracts a complex story of how major but sometimes lesser known challenges are met. A case in point is ammonia production, including of hydrogen, in which ICI, notwithstanding its disappearance, played a prominent role. ICI's connection with ammonia is certainly less chronicled than the corporation's remarkable range of science-based innovations, including phthalocyanine and fiber-reactive dyes, polyethylene, Perspex, and beta-blockers and other cardiovascular drugs used to treat high blood pressure.

Table 3. Examples of ICI Katalco Catalysts Developed for the Synthesis of Ammonia (33)

Katalco 61-2	The first low-temperature hydro-desulfurization (HDS) catalyst
Katalco 83-1	The first application of a process gas heated reformer (GHR), isothermal shift catalyst developed to resist the high operating temperature
Katalco 11-4	A low-temperature methanation catalyst
Katalco 74-1	A cobalt-promoted high-activity synthesis catalyst suited to the low pressure process for naphtha or natural gas

ICI has deserved our attention not just because it was a bastion of British industry. It was an example of in-house major innovations, of competitive advantage, of growth, and in the end of contraction. ICI was once a household word, and for many a mirror of the state of a nation. As Carl Mortished wrote in May 2018 in the London *Evening Standard* (34):

> In the old days, there was a very large enterprise called Imperial Chemical Industries, later stream-

> lined to ICI. The company did what it said on the tin, manufacturing chemicals and some consumer products, notably Dulux paint.
>
> It was so big that newspaper scribblers dubbed it 'the bell-wether of British industry'; stockbrokers and fund managers hung their investment decisions on its very utterance.
>
> ICI is no more; outgunned and outclassed by smarter, more efficient German, US and Far Eastern rivals. Today the fortunes of a company that publishes an online scrapbook command a lot more international attention than the likes of BASF, Dow Chemical and Britain's Ineos, but the chemical industry still tells us very important things about the state of the economy.

While the legacy businesses and their offshoots have lost their glamour in the digital age they, or their reincarnations, are still essential. Most, unlike ICI, were hardly known outside the chemical industry. Around three decades ago, as the chemical industry was expanding in Asia and the Middle East, several of the venerable Western firms, set in their ways, were cumbersome, and unwieldy. They had lost direction. The reasons are varied. Company scientists draw attention to the neglect of research, and innovation, as diversification accelerated in directions far removed from core interests, which pulled some firms down. This was certainly the case at ICI. In 1994, ICI, rather than choose a leader within its ranks with knowledge of the manufacturing divisions, appointed an executive from Unilever. The commodity manufacturing units continued to be sold off, but at far lower prices than expected, which left the corporation in serious debt (35).

ICI epitomizes the rise and fall of Western chemical firms, a theme that has attracted a great deal of attention, in particular from business historians. According to standard accounts, which take the story until around the year 2000, mergers of powerful firms gave way to monopolies, which created barriers to entry of new innovative firms. From the 1970s, when there was a perceived lack of innovation in the chemical industry, several firms used their immense capital and logistics networks, including in research and development, to diversify into pharmaceuticals (36). They subsequently divested of subsidiaries that dealt in bulk commodities, or no longer undertook research into improving manufacturing processes (Here, however, ICI's ongoing research into the ammonia process was an exception).

Less attention has been paid to the fact that this created opportunities for the entry of new players. A different form of chemical industry emerged, as represented by the UK's Ineos, which acquired two of ICI's commodity chemicals businesses in 2001, and BP's Innovene, an olefin and refining division, in 2005. By 2008, Ineos had acquired twenty-two companies; and went on to engaged in strategic and international partnerships. In other cases, failing or moribund firms reinvented themselves. Here, and relevant to this account, is the example of the Swiss firm Ammonia Casale, which from 1980, under a new leadership of experienced chemists and engineers offered a revamping (retrofitting) service to the ammonia industry. Its success led to advanced converter and reformer designs. Today, Casale (Ammonia Casale until 2014) is a leader in the technologies of nitrogen products, including in development of novel catalysts. Jointly with the Swiss firm Clariant (which acquired Süd-Chemie in 2011), Casale developed a highly active variant of the AmoMax® 10 catalyst, for which the two firms received the 2021 Sandmeyer Award of the Swiss Chemical Society.

No doubt, accelerated structural trends in chemical industry will continue as firms adapt to suit different needs. Despite the upheavals, changes in chemical technology remain relevant, even if often incremental, driven by sustainability, and environmental considerations.

The foregoing account offers a way of navigating the historiography of the recent past. It suggests a new way of thinking about industry by focusing on processes and products, and how they reach the marketplace, rather than by trying to make sense of the bewildering array of corporate fragmentation patterns and rearrangements. It requires a synthesis of contrasting approaches and perspectives, and a need to connect and harmonize with the past. Themes include sources of feedstocks and energy; the environment; international financing for large projects; the global reach involving transfer of scientific and technical skills from Europe and North America; joint studies between corporations and academic institutions; control and licensing of patents; the role of engineering contractors; and political and trade policies. Certain of these elements appear in the still evolving story of synthetic ammonia. The approach also represents a way of overcoming the boundaries created by the complexities of corporate changes. And in some ways even of explaining those changes.

Perhaps one could argue that while approaches to the post-twentieth-century history of chemical industry might not matter as much as in the past, in the way that has so far appealed to and constrained historians, the history of industrial processes and products is a completely different matter. Understanding process changes and their implementations provides a clearer appreciation of how and why innovations appear and change over time, and, indeed, why historiography of chemical industry has a future. Until now the historical studies have been the domain of scholars from the United States and Europe (37). In the future, as synthetic ammonia illustrates, they will need to create partnerships with their peers elsewhere, including chemists, economists, business historians and political scientists. One thing is certain: history of the chemical industry, in particular of its processes and products, and their expanding new uses, including, for hydrogen and ammonia, in the new "Chemical Century," still matters, especially if we wish to understand the recent past as a guide to the future.

Postscript

In mid-September 2021, high natural gas prices led to widespread cutbacks in the European ammonia industry. Manufacture in Britain ceased. With state support, at least until January 2022, the Billingham ammonia factory restarted production in order to ensure a continuous supply of food grade carbon dioxide (the by-product of reforming), of which it is the UK's main source.

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About the Author

Anthony S. Travis is associated with the Sidney M. Edelstein Center for the History and Philosophy of Science, Technology and Medicine at The Hebrew University of Jerusalem.