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FRITZ HABER—A CONFLICTING CHEMIST

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Haber is inextricably linked to the synthesis of ammonia and chemical warfare. The same scientist that gave humanity a tool for feeding millions was also instrumental in institutionalizing a terrible weapon for killing. Haber was an extremely versatile chemist; he started as an organic chemist and then moved to physical chemistry and electrochemistry. There is hardly a subject in these two areas to which he had not made fundamental contributions. His research on electroreduction and oxidation, fuel cells, ammonia equilibrium and synthesis, flame and combustion, etc., established the fundamental principles that regulated the phenomena.

Beyond the bitter discussion regarding his activities during World War I, there is no question that Haber was one of the greatest chemists ever.

Key words : Ammonia synthesis, Books & Patents, Chemical war fare, Nobel Prize, Fritz Haber, Electrochemistry, Gas warfare, Nitrogen fixation.

INTRODUCTION

Chemists and chemical engineers are familiar with Fritz Haber (1868-1934) through the Haber-Bosch process for the synthesis of ammonia and the Haber rule regarding the relative stability of C-C and C-H bonds in aromatic and paraffinic compounds. Some know Haber through his contribution to chemical warfare during World War I (WWI) and the following public debate regarding participation of scientists in the developing of weapons for mass killing.

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Haber was a very versatile chemist who contributed to many areas. Here we describe his personal life and career, his scientific achievements, and, in particular, his contribution to the synthesis of ammonia and chemical warfare.

Life and career

Fritz Haber[1-4] was born on December 9, 1868, in Breslau (now Wroclaw) in lower Silesia (now Western Poland, but at the time, part of Prussia), the son of Paula and Sigfried Haber. Paula Haber died during Fritz's childbirth; nine years later Sigfried Haber married Hedwig Hamburger and had three daughters with her. Fritz's father was the owner of a company that traded on natural dyestuff, pigments, resins, linseed oil, whale oil, and industrial fats; it was one of Germany's largest importers of natural indigo.

Haber's early schooling was three years at the *Volksschule* (Common school) followed by nine years at the St. Elisabeth Gymnasium. The curriculum at the Gymnasium centered around the humanities with Latin, Greek, literature and philosophy as the main subjects. In addition, students learned a little of religion, philosophy, and natural history. So, Haber's initial education was a classical one, with emphasis on literature and philosophy. It seems that the quality of teaching at the Gymnasium and his natural interests went together because throughout his life he maintained a keen interest in the humanities and art.

In 1886 Fritz enrolled in the University of Berlin, the home of such celebrated scientists and scholars as Rudolf Virchow (physician, 1821-1902), Hermann von Helmoltz (1891-1894), August Wilhelm Hofmann (1818-1892), and Theodor Mommsen (historian, 1817-1893). The elective system of the university enabled him to take courses in several departments. He was particularly interested in chemistry and was fascinated by Hofmann's teaching, which illustrated his classes with practical demonstrations of different phenomena.

During Haber's youth it was a common practice for students to complete their studies by taking courses at several universities. So, after one semester at the University of Berlin, Haber was transferred to the University of Heidelberg where he remained for one and a half year. At

Heidelberg he attended the classes of Robert Bunsen (1811-1899) who influenced his formation strongly.

After leaving Heidelberg, Haber returned to Breslau for compulsory military service and joined the artillery regiment stationed in that city.

On October 1889 he entered Charlottenburg *Technische Hochschule.* The institution had been established in 1799 as a small trade school and had grown to become the largest engineering college in Germany. Here Haber took the course in chemical technology taught by Karl Lieberman (1842-1914), one of the co-synthesizers of alizarin. Afterwards he collaborated with Lieberman on a project related to indigo; its results were eventually published in the journal, *Berichte*[5].

In 1891 Haber was awarded his Ph.D. for a thesis concerning piperonal, a compound related to indigo[6]. He barely passed his final oral examinaiton. His examiners, Hofmann, Karl Rammelsberg (1813-1899), August Kundt (1839-1894), and Wilhelm Dilthey (philosopher, 1822-1911), wrote in their report that Haber's general thoughts were brilliant but that he was ignorant of resistance measurements of electrolytes. Little did they know how famous would Haber become in the area of electrochemistry!

In 1891 employment for a young Ph.D. scientist in Germany was limited, schools took only the best students to train for professorships. Haber had to leave Germany for employment and the business connections of his father were very helpful for this purpose. His first job was at the Leipziger distillery, located in Budapest. From there he moved to a fertilizer factory near Auschwitz in Galicia and finally to the Feldmühle textile company. In these three places he worked as an unpaid junior clerk.

In 1892 Haber entered the *Eudgenossische Technische Hochschule* at Zurich, Switzerland, as a post-doctoral student, for one semester. He picked this school in order to study under Professor George Lunge (1839-1923), who was a highly respected analytical chemist. He spent much time in Lunge's laboratory learning about textiles, bleaching, pigments, synthetic dyestuffs, inorganic technology, and metallurgy.

After this short academic stint Fritz Haber joined his father's organization but not for long. A cholera epidemic affected the port of

Hamburg, the only effective treatment was use of calcium hypochlorite, a product sold by Haber's business. Fritz Haber speculated that the epidemic would spread before physicians could geographically isolate it and talked his father into buying large quantities of hypochlorite in anticipation of big sales. But this turned out to be a very bad guess, the epidemic was isolated and the Habers were left with huge stocks of the chemical. Sigfried Haber became very angry and advised his son to retire to the academic world.

Without alternative Haber returned to academy and joined the staff of the University of Jena as an assistant to Ludwig Knorr (1859-1921). Knorr was a well-known chemist who had synthesized antipyrine and done important work on the phenomenon of tautomerism and alkaloids. Knorr was not particularly impressed by Haber's work and this resulted in Haber moving again, this time to the *Karlsruhe Technische Hochschule* as an assistant to professor Hans Bunte in the Department of Chemical and Fuel Technology.

Under Bunte's guidance Haber began to study the thermal cracking of hydrocarbons. He adopted hexane for an exhaustive study as typical higher paraffin and also because of its relation to benzene. He made a detailed analysis of all the products of the cracking reaction and concluded that the thermal stability of the carbon-carbon bond was stronger than that between carbon and hydrogen in aromatic compounds, and weaker in aliphatic compounds (*Haber's rule).* All his results were published in 1896 as a book entitled, "Experimental Studies on the Decomposition and Combustion of Hydrocarbons"[7]. The publication of this book led to his appointment as *privatdozent* at Karlsruhe, an unpaid position that allowed the carrier to lecture to students with students' fees as compensation.

At Karlsruhe Haber was introduced to the new rapidly growing area of physical chemistry, particularly electrochemistry. His first research was on the electrochemical reduction of nitrobenzene[8] where he demonstrated that the reducing power of a cathode depended on its electrical potential, and that, varying the potential determined the nature of the product; a higher potential was equivalent to a more active reducing agent. He also studied the electrolysis of hydrogen chloride[9] and discovered that at high

current density cathodes of platinum became coated with the finely divided metal.[10] Haber and Bredig explained the pulverization phenomenon by the formation of an alloy of alkali metal with the cathode metal. Haber studied the electrochemical phenomena that took place in fuel cells and discovered a reversible oxygen electrode that he applied in gas cells for the study of high-temeprature oxidation reactions[11]. He also proposed an equation to calculate the force of oxidation-reduction changes.

Haber also studied the nature and rate process of the reversible oxidation/reduction of the hydroquinone/quinone system, although he did not emphasize its applicaiton to the measurement of the hydrogen ion concentration. It was Einar Bülman who used Haber's results to develop this electrode as an indicator of hydrogen ion activity. Haber's studies on phase-boundary potentials led him to develop the glass electrode for measuring hydrogen-ion activity.

All his results led him to publish the book, *Outline of Technical Electrochemistry on a Theoretical Basis*[12]. This book was an important factor in his promotion in 1898 to associate professor (*extraordinarius*). Beginning his career as an organic chemist he now made his way in electro and physical chemistry.

In 1901 Haber married Dr. Clara Immerwhar, also a chemist. A year later their son Hermann was born. After Clara's death in 1915 he married Charlotta Nathan in 1917 and with her had a daughter Eva, born in 1918, and a son Ludwig Fritz, born in 1921. Haber divorced Charlotta in 1927.

As a consequence of his extraordinary achievements in electrochemistry the Wurzburg convention of the Bunsen Society in 1902 selected Haber as an expert to observe and report on the technical and educational progress of the United States. Haber stayed in the US for sixteen weeks, visited eleven universities and representative chemical factories. He found the training for chemists to be superficial. The editors of *Electrochemical Industry* wrote that Haber's report was one of the "ablest and most complete papers that have been published on the subject, and is extremely suggestive on account of many remarks of a critical and general nature"[13]

After his return to Germany Haber devoted himself to a wide variety of research projects. Among them, the iron plates used in the printing of bank notes, and corrosion of underground gas and water pipes due to stray currents emitted from the direct current used for operating streetcars[14]. His first patent was for a technique for staining cotton and other fibers with chromium[15].

In 1905 Fritz Haber published his book, *Thermodynamics of Technical Gas Reactions*[16] and dedicated it to his wife Clara for "her silent cooperation".

In 1906 Haber was named a full professor at Karlsruhe as well as director of the Electrochemistry Institute, in replacement of Max Le Blanc (1865-1941) who had moved to Leipzig to work with Willhelm Ostwald (1853-1932; 1909 Nobel Prize in Chemistry).

Haber's relations with certain colleagues were not always the best; the worst problems occurred with Walter Nernst (1864-1941; 1921 Nobel Prize winner in chemistry), as described below. They came to an understanding near the end of 1933. Other problematic relations were with Karl Bosch (1874-1940; 1931 Nobel Prize winner in chemistry) also involved in the nitrogen-fixation achievement; with Karl Correns (1864-1933, botanist and geneticist); and Otto Warburg (1874-1940; 1931 Nobel Prize winner in medicine). On the other hand Haber always had a very good relation with Albert Einstein (1879-1955; 1921 Nobel Prize winner in physics), Vladimir M. Ipatieff (1867-1952), Herbert Freundlich (1880-1941), James Franck (1882-1964; 1925 Nobel Prize winner in physics), Friedrich Epstein (murdered in a concentration camp), Max Born (1882-1970; 1954 Nobel Prize winner in physics), and Richard Willsttätter (1872-1942).

In 1903, Haber had applied for a vacant post of professorship at Stuttgart. He was a third choice, with two less distinguished, less accomplished, and less talented scientists being given preference. Jewish ancestry could have been the reason he was not selected. After this event he converted to Protestantism. Haber had never been a real adherent of the Jewish faith. He had not been reared as a Jew, although his two wives were Jewish. His father never insisted on Jewish customs in his home. At his time German Jewry tended to be more German and less Jewish. Many

of Haber's friends were Jewish and although some found baptism helpful on the road to success they kept the problem of negating their past[1]. Anyhow, Haber could not guess that thirty-years later the same Germans that had hailed his success would remind him of his Jewish roots and force his exile.

In January 1933 the National Socialist Party came to power in Germany. In the coming months the reaction of scientists was varied. Psychologist Wolfgang Köhler (1887-1967) came to class meetings saying "Heil Hitler". some Nobel Prize winners like Johannes Stark (1874-1957; 1919 Nobel Prize winner in physics) and Philipp Lenard (1862-1947; 1905 Nobel Prize winner in physics) joined the Nazi Party early.

In April 1933 Nazi laws were enacted forbidding the employment of Jews in government establishments, except in some circumstances like having participated in WWI. Later, legislation was hardened and Jewish academics were purged, Haber prepared for emigration. Germany had returned him to the past, from the German Haber to the Jew Haber. Haber sent his resignation letter on April 1930 and asked to be released of his post on October the first; the resignation was accepted much to Haber's surprise. Beginning May 1933, Haber spent a large portion of his time finding suitable positions for his staff.

It is known that Haber would have preferred to go to Switzerland for language and health reasons, but he received no invitaion. Haber received an invitaiton to the Cambridge laboratory of William J. Pope (1870-1939) and left Germany for good. His stay in Cambridge was short because ill-health and the climate depressed him.

On January 26, 1934, Haber went to Switzerland for a short vacation and to visit his sister. He made a short detour to Locarno, to visit with Chaim Weizman (1874-1952), a Zionist leader who eventually would be elected as the first President of Israel. Both represented opposing perspectives of Jews. One, Haber, became a German nationalist; the other, Weizman, became a Jewish nationalist. The former gave up Judaism to be a German; the latter, although he had British citizenship, gave his first loyalty to Judaism. Weizman had already offered Haber a position at the

Daniel Sieff Research Institute[17] in Palestine, but according to Goran[1] Haber declined the invitation, saying that his acceptance will signify his tacit approval fo Zionism. In his book *'Trail and Error*[18]' Chaim Weizman claims that Haber accepted his proposition and requested resting for some time in Swtizerland before moving to Palestine.

Anyhow, in route to southern Switzerland, Haber had a heart attack and died in Basle on 30 January 1934. He was just over 65.

Many learned societies in Germany planned to commemorate the first anniversary of his death but were warned by the Minister of Education not to do so because the governemnt would see it as a challenge to the National Socialist state. Notwithstanding the ultimatum, more than five hundred scientists, soldiers, industrialists, and teachers, gathered in Dahlem to pay tribute to Haber. Max Planck (1858-1947; 1918 Nobel Prize in physics) opened the services with the Nazi salute and said that Haber would retain in the annals of science, as in the history of the Kaiser Wilhelm Institute, a place of honor[1].

A memorial service was also held in Palestine with the opening of the Haber library in the Daniel Sieff Institute (donated by Haber).

The fortieth anniversary of the founding of the Institute was observed on what would have been Fritz Haber's eighty-fourth birthday, December 9, 1952. A memorial plaque was dedicated and placed on the stairwell of the main building. The inscription of the tablet reads:

HABER

> will live in history as the brilliant discoverer of the method of combining nitrogen with hydrogen which is the basis of the technical fixation of atmospheric nitrogen, as the man who created, as was stated at his receipt of the Nobel Pize, "an exceedingly important means of advancing agriculture and the welfare of mankind", who obtained bread from air, and won a triumph "in the services of his country and all mankind."

In 1968 at the formal ceremony to commemorate the centenary of the birth of Haber, there was an incident in the lecture theater of the Unviersity of Karlsruhe. Two young men appeared on the rostrum and unfurled a banner with following legend:

Feier für einen Mörder

Haber = Vater des Gaskriegs[19]

There was a brief, complete silence, the youths disappeared as suddenly as they had come[4].

Scientific Work

We will now describe in some detil the contributions of Haber to the synthesis of ammonia and chemical warfare.

The ammonia synthesis

All living matter contains considerable amounts of chemically combined nitrogen, which is essential for the growth of living organisms. Animals cannot assimilate free nitrogen from the air and depend upon plants for their supply. Most plants, apart from legumes cannot assimilate free nitrogen and get their nitrogen from the soil in the form of nitrates, ammonium salts, or other nitrogen compounds arising from the decay of living matter.

The first nitrogenous fertilizer to be imported into Europe was *guano*, hardened bird's droppings from islands off Peru, followed by sodium nitrate, mined in Chile, and supplemented by-product of ammoniacal solutions and ammonium sulfate from the carbonization of coal in gas works and coke ovens. In 1900 Chile provided two thirds of the fertilizer nitrogen used around the world, and in 1913 Germany took about one-third of the total Chilean production.

By the end of the nineteenth century the demand for fertilizer nitrogen was beginning to outstrip supply and the need for man to devise methods of fixing atmospheric nitrogen was recognized and emphasized. In September 1898, Sir William Crookes (1832-1919), in his presidential address to the British Association for the Advancement of Science, warned that supply of fixed nitrogen for agricultural purposes was rapidly reaching a point where it was insufficient to support an ever increasing population. he said that "the fixation of atmospheric nitrogen is one of the greatest discoveries awaiting the ingenuity of chemists."

Within a few years, three different processes for the fixation of nitrogen were in commercial operation and adequate supplies of fertilizer nitrogen were assured.

In 1895 Frank and Caro were able to fix atmospheric nitrogen by the reaction of calcium carbide with nitrogen

$$CaC_2 + N_2 = CaCN_2 + C \qquad (1)$$

Commercial operation started in 1915. In this process calcium carbide was heated to 1000°C in a stream of nitrogen to give calcium cyanamide, which reacted with water to give ammonia and calcium carbonate. Although the formation of calcium carbide from calcium oxide and carbon required temperatures as high as 2300 K, the overall power necessary for this fixation process was only one quarter of that required by the arc process.

In 1905, Kristian Birkeland and Sam Eyde, in Norway, started commercial production of nitric oxide, NO, by passing air through an electric arc, drawn to a sheet of flame in an electromagnetic field, with temperatures at about 3000°C. The reason for using an electric arc was that the thermodynamic equilibrium concentration of nitric oxide was extremely low at atmospheric temperatures. To obtain an appreciable amount of nitric oxide it was necessary to heat up the air to temperatures above 3000°C. In the arc a small portion of the nitrogen in the air reacted with oxygen to yield about one to two percent of NO. In order to prevent a reversal of the reaction, the gas was cooled rapidly to 600°C, at which temperature the nitric oxide reacted with more oxygen, forming NO_2. The NO_2 was then absorbed in water forming a nitric acid solution. The nitric acid was then reacted with calcium hydroxide to form calcium nitrate containing about thirteen percent weight nitrogen, known as *Norge saltpeter.* Eventually the consumption of electricity, and hence the cost of production, were so high that the Birkeland-Eyde process became obsolete.

The Birkeland-Eyde process was developed further by other groups, such as *Badische Anilin und Soda Fabrik* (BASF) in Germany. It was through this process that Haber had his first connection with this chemical company. Haber had studied the oxidation of nitrogen in an electric arc and had proposed a mechanism[20] where it was shown that the concentration of

nitric oxide in the stationary state was greater than in the equilibrium one. The excess amount decomposed on the removal of the electric field, thus high yields could be obtained by rapid quenching the mixture after the arc.

The fixation of atmospheric nitrogen through both the electric arc and calcium cyanamide routes required large amounts of electrical energy and were replaced before long by the direct synthesis of ammonia from its elements,

$$N_2 + 3H_2 = 2NH_3 \qquad (3)$$

developed in Germany between 1905 and 1913, by a process that has become known as the Haber-Bosch process.

In 1904, the Margulies brothers of Vienna, asked Haber to study the formation of ammonia from the elements. Haber tried several methods of obtaining ammonia and initially did not succeed and this brought an end to the support from Margulies[21].

By the time Haber initiated his measurements on the equilibrium of the system N_2-N_2-NH_3, many attempts had already been made to study the synthesis and decomposition of ammonia. The most famous are probably those performed in 1901 by Henry-Louis Le Chatelier (1850-1936). Le Chatelier obtained a patent for the direct combination of hydrogen and nitrogen and claimed that higher pressures, upto 100 bar, would facilitate the reaction. However, he was obliged to stop his high-pressure experiments because of an accidental explosion in which one of his assistants was killed.

Haber started his work on measurement of the equilibrium using iron as a catalyst at temperatures around 1300 K and atmospheric pressure. He knew that higher pressures would give higher yields of ammonia, but the measurements at atmospheric pressure could be carried more simply. Together with Van Oordt they measured the yield in a wide range of temperatures and found that it decreased from 98.5% at 300 K to 0.012% at 1400 K. Walter Nernst (1864-1941; 1921 Nobel Prize winner in chemistry), professor of physical chemistry at the University of Berlin, examined Haber's report and claimed that his results were erroneous and set out to establish the correct figures[22]. Nernst was also intent in increasing the yield

of ammonia. Nernst and his students conducted experiments with pressures in the range 30 to 75 atm and temperatures from 1000 to 1300 K. Their data was consistent with those calculated from the heat theorem, and inconsistent with those reported by Haber. After Nernst reported his results to Haber by letter in 1906, Haber repeated his experiments and again obtained figures about 50% higher than Nernst's.

The two conflicting views of two of the most famous German professors led to a hot discussion during the 1907 meeting of the *Deutsche Bunsen Gesellschaft* (Bunsen Society). Upon his return to Karlsruhe Haber focused his attention on the ammonia synthesis. His collaborator was Robert Le Rossignol who had received his training under William Ramsay (1852-1916; 1904 Nobel Prize winner in Chemistry). Haber and Rossignol repeated their experiments at higher pressures and their new results confirmed the previous ones. Eventually it was found that the difference in interpretation between Nernst and Haber was due to Nernst using the wrong value of the specific heat of ammonia, which had never been measured accurately at high temperatures.

Haber and Rossignol[23-25] found that they could obtain an 8% yield by performing the synthesis at 200 atm and 600°C. After extensive search they also found that uranium and osmium were better catalysts than iron. Eventually BASF took a license of Haber's patents[26-27] and agreed to pay him a flat sum for every kilogram of ammonia sold. Carl Bosch (1874-1940; 1931 Nobel Prize winner in Chemistry) an industrial chemist working for BASF would eventually find a better catalyst for the reaction (iron promoted by alumina and potash), and design the equipment for carrying out the synthesis of ammonia at high pressure and high temperature.

Haber's ammonia synthesis became the solution to nitrogen shortage and the almost ruin of Chile's nitrate industry.

BASF had a great deal of confidence on the ammonia synthesis - they sold their arc process interests in Norway soon after obtaining the Haber patents. In 1910 they constructed a pilot plant at Ludwigshafen and there they solved three major difficulties: (a) building a reactor strong enough to withstand high pressures and temperatures, (b) overcoming the danger

of serious explosions and, (c) finding satisfactory catalysts. Purification of the reacting gases proved to be a major portion of the cost. At first, about 75% of the total production expenses went into the preparation of mixtures of hydrogen and ammonia. In 1905 BASF began to build an ammonia synthesis plant at Oppau, in 1913 the plant initiated operations with an initial output of about 7,000 ton fixed nitrogen/year. During the war production rose to about 60,000K ton fixed nitrogen/year. In 1918 the Haber process provided Germany with more than 200,000 ton fixed nitrogen/year[1].

The Oppau plant used hydrogen produced by the water shift reaction

$$CO + H_2O = CO_2 + H_2 \qquad (2)$$

Nitrogen was obtained originally by the liquefaction of air, but this process was soon replaced by the reaction of air with red hot coke to produce *producer gas* , a mixture of 60% N_2 and 40% CO.

As a closing remark we can mention that the world annual production of ammonia is well in excess of 180 million ton/year and virtually all of this ammonia is produced from a mixture of nitrogen and hydrogen over a promoted iron catalyst operating at elevated temperature and pressure. Over 90% of the ammonia produced is used as a fertilizer, principally in the form of urea or ammonium nitrate.

Haber received many decorations and honors for his contribution to German industry and the war effort. He was appointed Knight of both classes of the Iron Cross and Knight of the Kaiser House Order of Hohenzollern Swords. He was given the Order of the Crown Third Class and an autographed portrait of Wilhelm II. The Grand Duke of Baden presented him with a First Order Red Cross as well as knighthood in a regal order. He was made an honorary fellow of the Bayer Academy of Sciences in Munich and also of the Prussian and Gottingen Academies. Honorary doctorate degrees were conferred upon him by Gottingen University, the University of Wittenberg, and the Karlsruhe Engineering College.

Nitrogen fixation was but an episode in the controversy between Nernst and Haber. They became growing scientific adversaries, each one

wanting to be the number one physical chemist, and a struggle for the center position in the scientific world.

The ammonia synthesis brought new offers. The Auergeellschaft wanted him as director of research. When this did not materialize, the owner of the company, Leopold Koppel, offered to help build the *Kaiser Wilhelm Institut für Physikalische Chemie und Elektrochemie* (Kaiser Wilhelm Institute for Physical Chemistry and Electrochemistry) on the one condition that Fritz Haber be its head. Haber accepted. The Institute was built at Dahlem, a former farm belonging to the royal family, and inaugurated in 1912[1].

One of the first research projects at Dahlem was undertaken at the request of the Kaiser Wilhelm II. He wanted a good indicator for firedamp gas. Germany's huge coal production was always endangered by this menace. The miner's safety lamp was not reliable, it could also lead to an explosion. The solution developed by Haber was a whistle that produced distinctive beats when blown with air containing up to 5% firedamp. Before being used, one side of the whistle was filled with ordinary air, mine air filled the other side. If methane was present, beats could be heard when the whistle was blown. These increased in rapidity with larger concentrations of firedamp. At the explosive limit there was a characteristic thrill[28].

Haber continued to devote his energies to Germany during the early postwar period. He suggested acetylene, produced from coal, as a substitute for gasoline to aid Germany's petroleum shortage[29]. In 1919 he helped organize technicians and engineers for public service. The men were trained to operate utilities in the event of a strike.

One way thought by Haber to pay the Allies reparation demanded from Germany at Versailles was extraction of gold from the bottom of the sea. The basic idea had already been proposed by Svante Arrhenius (1859-1927; 1903 Nobel Prize winner in chemistry). Haber became convinced that the wealth in seawater could pay the Allies. He based his plans on a number of supposedly reputed analyses, which eventually proved to be wrong, the gold content of the oceans was actually one-thousandth of the supposed value. Haber abandoned the project in 1926, after costly experiences and deep disappointment.

Chemical warfare

Work at the Institute was greatly disorganized during the first week of WWI. Haber volunteered for service and was refused. Nernst was asked to suggest chemical agents which could be included in sharpnel and shell. He proposed using dianisidine chlorosulfonate, which causes violent sneezing, but is otherwise inoffensive, and xylyl bromide, a tear producer. After these two agents proved ineffective the request was passed to Haber. The war had reached a stalemate, with both parties holding their position in trenches. The German High Command thought that the only way to decide the struggle was to spread a chemical agent that would drive the enemy out of the trenches, forcing the resumption of open warfare. The enemy was to be overcome by the chemical, but advancing troops were not to be hindered. This idea did not prosper and was substituted by the one of a mass discharge of irritant gas from cylinders. Haber realized the value of chlorine. Within two months field experiments were performed to determine the proper humidity and wind conditions; weather of the wrong kind was found capable of making poison gas useless.

On April 22, 1915, the deadly chemical was emitted about the sector near Ypres. Nearly an entire divison of Allied troops suffocated in agony. Fifteen thousand casualties were counted; one third was fatal. Haber advocated massive gas attacks but his advice was discarded by the military. Haber had said: "Every new weapon is capable of winning a war. It was against the soul of the soldier, not the body. New weapons break his morale because they are something new, something he has not experienced, and something that he fears. Every change in sensation transmitted by smell and taste troubles the mind with fresh anxieties of unknown effects and further strains the soldier's power of endurance at the very moment when his entire mental energy is required for battle."

Almost the same pattern followed the introduction of mustard gas. Haber directed research seeking to learn the toxic effects of poison gas. Experimentation with laboratory animals indicated that the most toxic gas was phosgene (prepared by reacting chlorine with CO over a charcoal catalyst). Lewisite (2-chlorovinyldichloroarsine, discovered by W. Lee Lewis

in 1918), and mustard gas (dichlorodiethyl sulfide) showed similar toxicity and chlorine the weakest poison.

Gas actually proved to be a weak weapon. The 125,000 tons of gas used by both sides during the war caused less than 5% of the total casualties. Haber's son, Ludwig Fritz, discussed this fact in depth in his book[4] quoting the estimates of every country that participated in WW1. The total casualty estimates varied between 880,000 to 1,300,000. There is no way of knowing how many soldiers were killed by gas because no accurate records were kept on the actual cause of death of the fatalities.

The story of warfare is largerly one of imitation: During WWI the Germans usually led and the Allies followed. Miscalculations, technical failures, and inertia on both sides handicapped or delayed the most effective deployment of gas weapons[4]. But gas was an unconventional weapon without precedent. There ws no theory, no body of knowledge, nothing apart from science fiction, about what could be achieved by gas.

The report of a British Mission appointed to visit German chemical factories after the war pointed out that the key to Germany's war production of explosives was Haber's process for the production of ammonia from atmospheric nitrogen. Without such a process Germany[30] could not have made the nitric acid required for the explosives program, nor obtained fertilizers for food production, and it is probable that she could not have continued the war after 1916. The resources of the German dye industry were of no less military importance. Most of the gases employed towards the end of the war were complex organic substances

The report concluded with the statement that military operations of any country without a well-developed organic chemical industry will be severely handicapped.

Haber's role in gas warfare resulted in family tragedy. His wife Clara was deeply affected by her husband's role in warfare. She regarded poison gas not only as a perversion but also as a sign of barbarism. She pleaded with her husband to forsake poison gas, but her efforts did not succeed. The events caused her such an anxiety and depression that eventually she committed suicide.

This family tragedy was accompanied also by academic criticism and condemnation in the countries at war with Germany. During 1914-1918, enemy censure was to be expected. When Haber and Karl Bosch received the Bunsen Medal, the editors of Industrial and Engineering Chemistry made censorious comments. They called for careful consideration of admittance into the good fellowship of science of all the evil scientists of Germany, especially those responsible for poison gas. Haber was not the only one censored scientist. After the United States entered the war, the American Chemical Society revoked the honorary membership status from Ostwald and Emil Fisher (1877-1947).

Haber's criticism and condemnation continued after the end of the war. His leading role in chemical warfare lead to his isolation from the international scientific community for several years. Many people, among them Ernest Rutherford (1871-1937; 1908 Nobel Prize winner in chemistry), continued to censure Haber for years.

Honors

As mentioned above, Haber received many honors in Germany for his efforts during the war. After the war he was also awarded many others in Germany and abroad: President of the German Chemical Society (1923); Honorary Doctor of Agriculture degree from the Berlin Agricultural School; the Wilhelm Eimer Medal of the Lower Austrian Business Society; and the Goethe Medal awarded by the President of Germany. He was made advisory editor of the *Biochemisches Zeitschrift* and was a member of the editorial board of the *Zeitschrift für Elektrochemie.* He was on the board of directors of IUPAC from 1929 to 1931. In 1931 he became an honorary member of the *Société Chimique de France,* of the Chemical Society of England, and of the Society of Chemical Industry of London. In 1932 he was appointed honorary member of the Academy of Science of the USSR, as well as of the United States Academy of Sciences. In 1932 the American Academy of Arts and Sciences awarded him the biennial Rumford prize. Haber was also made a member of the International Red Cross.

Haber's name was proposed for the 1918 Nobel Prize in chemistry. In the first round of meetings, the Chemistry Prize Committee was unable to reach a decision. One member argued that the Haber-Bosch process was

still secret, which was against three principles of the Nobel Foundation. Another member considered that the fixation of atmospheric nitrogen had prolonged the war and on those grounds Haber should be disqualified. No criticism of chemical warfare was recorded. There was also the question to what extent Haber had been assisted by Le Rossignol, Alwyn Mittasch (1869-1953), and Bosch. In November 1919 the same commitee reversed its decision, and without dissent awarded the chemistry prize to Haber.

Fig. 1 Stamp issued by Sweden in 1978, in honor of Fritz Haber, winner of the 1918 Nobel Prize in Chemistry.

Because of his work with poison gas, Haber's is the only Nobel Prize winner in science that has ever been contested. Frenchmen offered the 1919 awards, declined the honor of participating in the ceremony, rather than be in the same company with their former enemy.

The Chemical Society of London expelled Haber because of his connection with chemical warfare but later re-admitted him. After his death the Society invited J. E. Coates[2], a former student of Haber, to give the Haber Memorial Lecture in 1937. Coates was careful and conscientious. Through interviews and correspondence, he gathered a mass of personal impressions so that he was able to appreciate Haber's commitment to chemical warfare, which, however awkward, had to be presented to a large audience of British chemists. Coats was troubled: Haber had broken the rules of war and though not guilty in any legal sense, had acted in a way that many perceived as going against custom and morality. Thus he could be held "responsible for gas warfare".

An appropriate epilogue is a quote from the presentation speech to the Nobel Prize: "Geheimrat Professor Haber. This country's Academy of Sciences has awarded you the 1918 Nobel Prize for Chemistry in recognition of your great services in the solution of the problem of directly combining atmospheric nitrogen with hydrogen. A solution to this problem has been repeatedly attempted before, but you were the first to provide the industrial solution and thus to create an exceedingly important means of improving the standards of agriculture and the well-being of mankind. We congratulate you on this triumph in the service of your country and the whole of humanity. Please, accept now your Prize from the President of the Nobel Foundation."

Conclusion

As we have seen, Haber started his career in organic chemistry and then shifted to electrochemistry and physical chemistry. Although self-taught, he made significant contributions towards establishing the modern science of these fields. He was instrumental in bringing German science to an unparalleled level. His personal contribution to chemical warfare, although terrible in result, must be judged against the political background of the time, as well as what other countries and their scientists did in the same direction then and in later years.

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