# Arsenal Of Chemistry: The Haber Bosch Process and the Great War

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*Fritz Haber's Nobel Prize diploma for the fixation of nitrogen*

Though the First World War culminated in unprecedented industrialized destruction, its foundations were rooted in scientific achievement, without which the Great War, or 'the chemists' war' would have been comparatively brief and innocuous. The sheer carnage of this total war generally precludes any discussion of its origins beyond nationalism and political revanchism, favoring intrigue over logistics to the detriment of this inflection point. Yet even when drastic improvements in the capacity and efficiency of warfare are acknowledged as prime factors of its protraction the study of this scientific coup is limited to the role of machine guns and poison gas— myopically favoring symptoms to causes. The field of applied chemistry predicated the modernization of warfare by removing one of nature's fundamental limiting factors, access to fixed nitrogen, with the Haber-Bosch process. Patented in 1908 and awarded the Nobel Prize a decade later, the Haber-Bosch process provided Germany with a uniquely domestic source of nitrates uninhibited by the allied blockade, enabling the simultaneous production of guns and butter[1] that led to four years of war. Following the war the United States Congress declared that "the present European war could not have been possible, in so far as least as Germany was concerned, had it not been for the modern inventions [Haber-Bosch process] making it possible to extract nitrogen from the air."[2] While the Allied Powers capitalized on the extensive, far-flung resources of their colonies, Germany mobilized her academia to compensate for disadvantages in men and materials, proving the integral role of science in a war increasingly defined by attrition.

Germany's scientific resources played a key role in industrialization prior to the war; the dye industry in particular demonstrates the early advantages of chemical engineering to industrial production. The discovery of synthetic indigo by the German conglomerate Badische Anilin- und Soda-Fabrik, or BASF,[3] late in the 19th century quickly led to market dominance by corporations which had created industrial laboratories. By 1913 German firms controlled 85% of world market shares in dyes and pharmaceuticals,[4] 'tolerating' Britain's domestic chemical industry to monopolize one of the worlds most profitable enterprises.[5]

Critical to the success of German firms was their investment of significant profits into universities and research laboratories, reinforcing the bond between scientific advances and an educated workforce. By investing heavily in mutually reinforcing fields like dyes, chemicals and pharmaceuticals individual German firms were able to carve out distinct markets and research programs, rapidly outperforming foreign rivals. BASF and its domestic competitors vertically

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[1] The term 'guns and butter' refers to the product possibility frontier demonstrating a country's opportunity cost in gearing its economy towards either defense or humanitarian goods. The choice between these goods was mutually exclusive while nitrates were scarce, but with the advent of nitrogen fixation the opportunity cost for each good diminished considerably. The term was coined in direct reference to the nitrogen fields of the Chinchas Islands, as an argument for isolationist, anti-war sentiments prohibiting America's entry into WWI. See Vaclav Smil, *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production* (Cambridge: MIT Press, 2001).

[2] Senate Report No. 69th-119 (1925), 4.

[3] BASF was one of the first companies to use coal tar for synthetic dye, and played a leading role in developing applied science laboratories.

[4] Arora Ashish, *Chemicals and Long-Term Economic Growth: Insights from the Chemical Industry* (New York: Wiley, 1998), 31.

[5] L. F. Haber, *The Chemical Industry, 1900-1930: International Growth and Technological Change* (Oxford: Clarendon, 1971), 147.

integrated their production through competition, rapidly outpacing foreign firms and accruing peerless expertise in complex operations. This marked advantage in human resources and industrial science, critical to the development and adoption of the Haber Bosch process, was fundamental to German industry while the rest of the world struggled to accumulate the intellectual and industrial resources required to support chemical industries.[6]

This thesis will demonstrate the centrality of the Haber-Bosch process to Germany's military capacity during the First World War, as nearly half of all her munitions were derived from the process, a technological advantage without which the German war effort would have succumbed to embargo. The birth of modern industrial chemistry during the Great War is one of the most decisive yet neglected developments in the history of warfare, comparable to mastery of nuclear fission. Indeed the creation of nuclear weapons during World War II stands upon the proverbial shoulders of the Haber-Bosch process, capitalizing on the marriage of industry and professional research that presages the phenomena of "the industrial-military complex and 'Big Science'...'a kind of Manhattan Project before its time'."[7] Historiography of Haber-Bosch process remains the single greatest blind spot in contemporary comprehension of the First World War, as Germany's scientific prowess trumped economic sanctions to achieve parity and eventual superiority in the procurement of munitions. It is my assertion that the Haber-Bosch process enabled Imperial Germany to sustain war efforts more effectively than the combined capacities of her European opponents, waging wholesale industrial warfare despite international embargo.

Historiography of the Haber-Bosch process itself is relatively sparse; most astonishingly it is completely absent from the vast majority of historical literature on the First World War, including most works dedicated to scientific and economic aspects. Among the primary sources true to the topic of nitrogen fixation there are Haber's own works, including his Nobel Prize acceptance speech and his address to The Franklin Institute in 1924 concerning *The Practical Results of the Theoretical Development of Chemistry*.[8] A propaganda pamphlet distributed by Dresdner Bank in New York circa 1916 titled *Germany's Economic Forces During the War* cites "nitrogen drawn from the air" as one of the key industrial developments granting Germany a competitive edge in the war,[9] a salient fact broadcast internationally yet somehow unacknowledged during and after the conflict. The United States Senate proved one of the few sources of credible, incisive debate and patent regulation on the Haber-Bosch process, with three reports: *The Nitrogen Situation of 1924*, *Majority and Minority Reports on the Muscle Shoals Inquiry of 1925*, and the *1936 Munitions Industry Report,*[10] proving practically invaluable.

A few biographies of Fritz Haber and Carl Bosch, as well as scientific literature on the establishment of Germany's chemical industry provide context for the breakthroughs in synthetic products and the opening of the Kaiser Wilhelm Institutes. Among the most useful biographies were *Master Mind: The Rise and Fall of Fritz Haber* by Daniel Charles[11] and *The Alchemy of Air*

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6 Ashish, *Chemicals and Long-Term Economic Growth*, 31.

7 John Cornwell, *Hitler's Scientists: Science, War, and the Devil's Pact* (New York: Viking, 2003): 54.

8 Fritz Haber, *Practical Results of the Theoretical Development of Chemistry* (Philadelphia: Franklin Institute, 1924), 1-13.

9 *Germany's Economic Forces During the War* (New York: Dresdner Bank, 1916), 3.

10 United States Senate Report No. 68th-88 (1924). See also United States Senate Report No. 69th-119 (1925) and United States Senate Report No. 74th-944 (1936).

11 Daniel Charles, *Master Mind: The Rise and Fall of Fritz Haber, the Nobel Laureate Who Launched the Age of Chemical Warfare* (New York: Gale Ecco, 2005), 4.

by Thomas Hager, which document the efforts of Fritz Haber and Carl Bosch within the context of First World War.[12] *Enriching the Earth* by Vaclav Smil sets the standard for a worldly biography still intimately connected to the contemporary issues of synthetic nitrates.[13] In John Cornwell's *Hitler's Scientists* the link between Haber's research and the birth of industrial giant IG Farben are succinctly demonstrated.[14]

Though biographies provided insight into the human aspect of the process, those works analyzing the Haber-Bosch process in terms of economics and science furnished more concrete data, like *Prometheans in the Lab* by Sharon Bertsch McGrayne.[15] *Chemicals and Long Term Economic Growth* by Ashish Arora (et al) details the inception of the chemical industry and its utility in peace and war.[16] Some works on the economic aspect of the war provided critical data, *The First World War and the International Economy* by Chris Wrigley details the finance of international finance and embargo[17] while *Army, Industry and Labor in Germany, 1914-1918* by Gerald Feldman discusses the domestic economic conditions that Germany faced through the war.[18] In *With Our Backs to the Wall: Victory and Defeat in 1918*, David Stevenson focuses on various forces of industry to reinforce the popular notion that ultimately superior industrial capacity led to allied victory,[19] yet production of nitrates is barely noted. The dismal failure of all belligerents to form coherent fiscal policy is a core tenet of *Financing the First World War* by Hew Strachan,[20] a large topic sub-divided by country in Stephen Broadberry and Mark Harrison's *The Economics of World War One*.[21] In *Frontline and Factory: Comparative Perspectives on the Chemical Industry at War, 1914-1924* chapters by Jeffrey Allan Johnson and Roy MacLeod provided analysis of Germany's 'dual use' chemical industry as it transitioned to wartime manufacturing.[22] The 'controlled implosion' of international finance is the topic of *Planning Armageddon* by Nicholas Lambert,[23] which greatly improves (and compromises) the validity of Norman Angell's monumental *The Great Illusion: A Study of the Relation of Military Power to*

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[12] Thomas Hager, *The Alchemy of Air: A Jewish Genius, a Doomed Tycoon, and the Scientific Discovery That Fed the World but Fueled the Rise of Hitler* (New York: Harmony Books, 2008), 4.

[13] Smil, *Enriching the Earth Food Production*, 61.

[14] John Cornwell, *Hitler's Scientists: Science, War, and the Devil's Pact* (New York: Viking, 2003), 25.

[15] Sharon B. McGrayne, *Prometheans in the Lab: Chemistry and the Making of the Modern World* (New York: McGraw-Hill, 2001), 58-78.

[16] Ashish Arora, Ralph Landau, and Nathan Rosenberg, *Chemicals and Long-Term Economic Growth: Insights from the Chemical Industry* (New York: Wiley, 1998), 27.

[17] Chris Wrigley, *The First World War and the International Economy* (Cheltenham, UK: E. Elgar, 2000), 4.

[18] *Army, Industry, and Labor in Germany, 1914-1918* (Princeton: Princeton University Press, 1966), 7.

[19] D. Stevenson, *With Our Backs to the Wall: Victory and Defeat in 1918* (Cambridge: Harvard University Press, 2011).

[20] Hew Strachan, *Financing the First World War* (Oxford: Oxford University Press, 2004).

[21] Stephen Broadberry and Mark Harrison, *The Economics of World War One* (Cambridge: Cambridge University Press, 2005), 43.

[22] Jeffrey A. Johnson and Roy M. MacLeod, *Frontline and Factory: Comparative Perspectives on the Chemical Industry at War, 1914-1924* (Dordrecht: Springer, 2006), 20.

[23] Nicholas A. Lambert, *Planning Armageddon: British Economic Warfare and the First World War* (Cambridge: Harvard University Press, 2012), 11.

*National Advantage*, a prewar best- seller which sought to demonstrate the impossibility of sustained war between European belligerents.[24]

Studies of Germany's industrial productivity became prevalent after the war as victorious allied historians and generals attempted and failed to document the factors favoring Germany's industrial capacity. The most splendid failure of this genre is *The Triumph of Unarmed Forces* by rear-admiral M. Consett, which cites the painstaking reconstitution of animal fats as a key element of Germany's munitions program while the Haber-Bosch process is entirely neglected.[25] Consett was not alone in his misconceptions; practically all of the literature on the Great War dismisses the influence of the Haber-Bosch process.

This thesis is divided into three sections demonstrating the importance of the Haber-Bosch process. Section one, Chemistry's Finest Hour, explores the international effort to synthesize nitrogen from the atmosphere and the primacy of the Haber-Bosch process among the many contending patents, the success of which fostered the creation of industrial laboratories and the rapid ascent of applied science in Germany. The second section, The Synthesis of War, focuses on the chemical industry's pivotal role in munitions production during the Great War, with the Haber-Bosch process nullifying international embargo and outperforming the combined Allied chemical industry. The concluding section discusses the impact of munitions production on attritional warfare, comparing Germany's domestic synthetic nitrogen production to the Allies' resources. In the conclusion I reaffirm my thesis while arguing that previous attempts to analyze the Haber-Bosch process have only contributed to its misunderstanding and disregard.

## I. Chemistry's Finest Hour

3 H2 + N2 → 2 NH3 Painted on a cloud in the corner of Fritz Haber's Nobel Prize diploma is this deceptively simple equation.[26] It represents one of mankind's greatest triumphs in his attempt to imitate the workings of nature, a building block of life that perplexed the greatest minds of the early 20th century. To fully appreciate the benefits of nitrogen fixation it is necessary to understand the context in which the Haber-Bosch process was developed.

The element nitrogen was discovered in the 18th century by Daniel Rutherford when lab tests combusting atmosphere left behind substantial amounts of an unknown gas, later identified as nitrogen, now known to comprise approximately four fifths of the earth's atmosphere.[27] This abundant store of nitrogen is as plentiful as it is troublesome, although we breathe nitrogen it remains inert— chemically isolated and stubbornly resistant to change. Atmospheric sources of nitrogen were left practically irrelevant as a consequence of the seemingly insurmountable barriers to procurement, especially in relation to the bounty of readily available 'fixed' nitrogen forming on the earth's surface. Naturally occurring nitrogen is most commonly found in saltpeter, a compound consisting of nitrates fused with potassium, a catalyzing process that occurs in two

[24] Norman Angell, *The Great Illusion: A Study of the Relation of Military Power to National Advantage* (London: W. Heinemann, 1910), 2.

[25] M. W. W. P. Consett, *The Triumph of Unarmed Forces: An Account of the Transactions by Which Germany during the Great War Was Able to Obtain Supplies Prior to Her Collapse under the Pressure of Economic Forces* (London: Williams and Norgate, 1923), 3.

[26]"Nobel Diploma" *Nobel Prize Committee,* <http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1918/haber-diploma.html>

[27] Antoine Laurent De Lavoisier, *Elements of Chemistry* (Gale Ecco: 2010)

radically different climates. Saltpeter forms in dark, damp caves and cellars where it crystalizes on walls, allowing it to be harvested locally in small quantities. The second source of natural saltpeter is bountiful but relatively inaccessible, forming mountains of nitrates along the arid deserts of western South America, namely "the Chinchas Islands, a sprinkling of rocks six miles off the coast of Pisco, Peru, which constituted, in 1850, acre for acre, the most valuable real estate on earth."[28] These obscure islands only entered onto the world stage by chance after they were sought out by the great naturalist Alexander von Humboldt, who heard rumors of powerful fertilizer used to grow crops in the searing deserts of South America. His determination to understand the chemical basis of these claims led him to further analyze the saltpeter, identifying its high levels of urea and phosphates (the basis for its potency as a fertilizer) at the turn of the 19th century. This critical breakthrough would not be capitalized on for another quarter century, until imperiled agronomic productivity prompted a revolution in agriculture. The discovery of Chilean nitrates would remain unexploited for decades before reemerging as the temporary guarantor of food security, and by extension civil society at large.

Europe was no stranger to famine by the 19th century, as ever increasing populations threatened to outstrip their narrow agricultural base the danger to governments took a political dimension, and guaranteeing the public health became intimately tied to the survival of the regime. In 1848 the 'year of revolutions' shook Europe's power structure to the core, when the scarcity of basic food staples led to price increases and subsequent violent uprisings among the urban and rural peasants.[29] This was due to a *moderate* decrease in the food supply which increased prices, making Malthusian predictions of famine even more threatening:

> While every man felt secure that all his children would be well provided for by the general benevolence, *the powers of the earth would be absolutely inadequate to produce food for the population which would inevitably ensue*; that even if the whole attention and labor of the society were directed to this sole point, and if . . . the greatest possible increase of produce were yearly obtained; yet still, that the increase of food would by no means keep pace with the much more rapid increase of the population.[30]

These dire predictions were amplified in the scientific community by Sir William Crookes, whose inaugural speech as the president of the British Academy of Science awakened Europe's community of scientists to their new challenge.[31] Recognizing the 'stubborn facts' that the world's arable land had already been claimed and that efficient cultivation was western society's only recourse, Crookes identified the creation of artificial fertilizer via atmospheric nitrogen as the greatest technological challenge facing humanity.[32] The only means of fortifying exhausted farmland was nitrogen-rich fertilizer and with single greatest source of nitrogen sequestered in the atmosphere, all that remained was to chemically alter or 'fix' the ubiquitous element.

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[28] Thomas Hager, *The Alchemy of Air: A Jewish Genius, a Doomed Tycoon, and the Scientific Discovery That Fed the World but Fueled the Rise of Hitler* (New York: Harmony, 2008), 27.

[29] David Parker, *Revolutions and the Revolutionary Tradition: In the West 1560-1991* (London: Routledge, 2000), 114.

[30] T. R. Malthus, *An Essay on the Principle of Population* (Harmondsworth: *Penguin*, 1970), 56, emphasis added.

[31] Hager, *The Alchemy of Air,* 9.

[32] Ibid.

Germany's motivation to find a replacement for Chilean nitrates also rested upon the calculations of national security, as international disputes increased the frequency and impact of 'gunboat diplomacy'[33] which threatened to flare into full-scale war. During the Agadir crisis Germany's interjection into French colonial affairs severely impacted her economy, as other powers reprimanded her for threatening European peace and trade relations.[34] This market shock, a portent of economic destabilization experienced during the First World War, eventually convinced the government to seek a peaceful conclusion, though the incident only amplified public support for martial adventurism. The powerful combination of saber-rattling and increased military spending only fueled nationalist sentiments, reinforcing mutual distrust among the great powers and further threatening the Reich's tenuous supply of nitrates, already recognized as "a nightmare scenario in which a British naval blockade of Germany would cut the flow of nitrate from South America, cripple German farms, starve German citizens, and silence German guns."[35] Nationalism had compromised Europe's fragile peace, only Germany's chemists could free the state from dependence on foreign nitrates.

Though Germany's status as the rising industrial power of Europe was imperiled by the growing scarcity of organic nitrates she was uniquely positioned to capitalize on her preeminent industrial and scientific resources to solve this issue. Both France and Britain possessed vast colonial empires, sources of raw materials for their industries and markets for finished products which gradually came to dominate their industrial capacity. Germany had no profitable colonies to speak of, but what she lacked in resources was actively compensated by technological prowess in the burgeoning field of industrial chemistry, exemplified by the development of the synthetic dyes.[36]

One of the first breakthroughs in applied chemistry was pivotal in transforming the dye industry— a market dominated by British and French firms whose access to indigo plantations frustrated German competitors. Beginning in the mid-19th century, German firms started experimenting with coal products to replace organic dyes, discovering a wide variety of colors and hues which could be derived synthetically at a fraction of the cost.[37] Success fueled further endeavors and before long the process of identifying and patenting these lucrative chemicals gave rise to fledgling industrial science labs. BASF was one of the first companies to hire professional chemists and devote significant resources to its industrial laboratory, intent on being the first company to synthesize indigo. Guided by a young technical director named Heinrich von Brunck, BASF instigated a race between German firms to recruit renowned chemists and establish large-scale, competitive laboratories. These well financed laboratories rapidly diversified into niche industries including pharmaceuticals, photographic chemicals, and agriculture.[38]

Although synthetic indigo was Brunck's immediate goal it eluded BASF for decades, prompting the company to restructure its manufacture of chemicals to in-house production while expanding the range and quantity of chemicals in its repertoire. This seemingly inconsequential

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[33] Henry Kissinger, *Apolitical Doomsday Machine: European Diplomacy Before the First World War* (New York: Simon & Schuster, 1994), 168-200.

[34] Ibid.

[35] Hager, *The Alchemy of Air,* 78.

[36] Kissinger, *Apolitical Doomsday Machine,* 168-200.

[37] Haber, *The Chemical Industry*, 123-124.

[38] Sharon Bertsch McGrayne, *Prometheans in the Lab: Chemistry and the Making of the Modern World* (New York: McGraw-Hill, 2001) 64.

decision ensured the complete vertical integration of Germany's chemical industry before such a concept had even emerged; out of competitive necessity the German dye industry had invented the nascent chemical company. Recognizing that BASF's industrial capacity increasingly relied on the efficiency of its machines, Brunck "paid attention to the required engineering as well as the chemistry, seeing the two as inextricable, pioneering the field of chemical engineering before people ever used the term", and had composed the world's single largest staff of chemists by 1899.[39] In 1897 BASF finally perfected the synthesis of indigo from coal, and by 1904 German firms were exporting 9,000 tons of synthetic indigo a year, collapsing the British and French indigo industries to monopolize international dye markets.[40] Once the pinnacle of imperial aspirations and an enviable source of revenue, colonies quickly forfeited their economic preponderance to the new synthetic products that Germany was inventing. The 'king of dyes' had transformed BASF into the king of chemical engineering and Brunck into the CEO of the world's most powerful chemical corporation.[41]

Such was the state of German industry and chemical engineering when Fritz Haber began his monumental effort to 'fix' atmospheric nitrogen. Unlike most classically trained chemists, Haber began his professional academic career at a humble technical school, the Karlsruhe Institute of Technology, a new type of university which combined education and applied research rather than focusing on 'pure' research. While this did not provide him with the same credentials as many of his peers, it afforded him the opportunity to teach industry-specific courses and apply his restless mind to various practical issues. Haber sought out complex industrial problems and attacked them from different angles, applying theoretical concepts to study mechanical problems like Karlsruhe's corroded water and gas mains, relentlessly developing and applying theoretical chemistry until "he had contributed basic scientific insights to almost every area of physical chemistry."[42] The importance of hands-on education to Haber's research methodology is hard to quantify, though his time at Karlsruhe undoubtedly provided him with the perfect opportunity to immerse himself in the field of applied chemistry and raise his brazen curiosity to the level of academic rigor.

In 1902 Haber was chosen to lead a five-month fact finding mission to the United States by the German Electrochemical Society, where he toured numerous industrial plants and educational programs like the Rockefeller and Carnegie Institutes. Entranced by these sprawling, well-funded institutes, Haber lectured on the benefits of such scientific meccas when he returned home, convinced that Germany required the same infrastructure to support its industrialization. The most immediate benefit of Haber's trip was that it further honed his capacities as a specialist in the merging fields of mechanical and chemical engineering, marking him as one of the world's foremost experts. In light of his unique qualifications, Haber was hired in 1905 to determine the feasibility of synthesizing ammonia from atmospheric nitrogen. Rather than launch himself into a frenzy attempting to find the miracle combination of elements as his peers had, Haber approached the problem as he had taught himself to, with both the chemical process and engineering requirements in mind.[43]

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[39] Haber, *The Chemical Industry*, 31.

[40] Dunikowska, Magda, and Ludwik Turko, *Fritz Haber: The Damned Scientist,* (Angewandte Chemie International Edition, 2011), 1-17.

[41] Ibid.

[42] McGrayne, *Prometheans in the Lab*, 50-60.

[43] Haber, *The Chemical Industry*, 87.

In 1903 Adolf Frank and Nikodem Caro patented one the first moderately successful process for extracting atmospheric nitrogen, refereed to as the Cyanamide process.[44] The Cyanamide process required large amounts of electricity to produce meager amounts of nitrogen, and would be replaced by the Haber-Bosch process in Germany—an inestimable advantage during the war. Nitrogen could also be siphoned from the waste products of coal burning facilities, the only readily available source of nitrogen for many countries apart from imported Chilean nitrates. Although both of these processes were patented before the Haber-Bosch process they were completely insufficient as sources of nitrates, and even if they did not have serious shortcomings the Haber-Bosch process was "so much cheaper than the Cyanamide process that many great foreign companies are [circa 1925] transforming their old factories to adopt this new Haber-Bosch process."[45] While the retrofitted coal plants did indeed produce decent quantities of nitrates, reaching a peak of 700,000 tons in Germany,[46] production was entirely contingent on the consumption rate of the plant. Nitrates harvested as the runoff from coal plants were an intermittent and unreliable source of nitrates, especially at a time when coal power was being challenged by oil. Both of these methods were put into production- the Frank-Caro process before there was any competition, and coal siphoning method in factories that could afford to retrofit. Neither was practical as an industrial process though, and imports of Chilean nitrates were not challenged. Research on nitrogen fixation was increasing as demand grew, but efficient synthesis would require the knowledge of multiple disciplines working in concert.[47]

Competition to synthesize ammonia was tremendous. When one of Haber's chief critics derided his results as "erroneous," the slight caused him considerable anxiety, forcing the self-taught chemist to painstakingly compare test methods in an effort to vindicate his methods.[48] Not only did Haber soundly reaffirm his methodology, but the comparison proved immeasurably valuable as it prompted Haber to adopt high-pressure gasses in his experiments. As perhaps the world's first true chemical engineer, Haber understood that the application of increased pressure to chemical reactions presented a new tool in the chemical manipulation of elements: increased pressure allowed for lower temperatures and greater force to break the stubborn N2 bond. In order to increase the maximum pressure of his test machine, Haber hired Robert Le Rossignol, a young engineer whose ingenuity and aptitude for manipulating machinery mirrored the uncanny instincts of his superior.[49] Their partnership proved hugely successful; Haber experimented with the chemical composition of tests and Le Rossignol designed ingenious new fittings and valves to increase pressure inside the reactor. Together their machine yielded ever increasing amounts of pure ammonia directly from the atmosphere. At this point Haber realized that he required the resources of a major company in order to move his experiment from the laboratory to the industrial scale—a risky transition that required immense financial support and keen understanding of nitrogen fixation's potential.

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[44] Gerald D. Feldman, *Army, Industry, and Labor in Germany, 1914-1918* (Princeton, NJ: Princeton UP, 1966), 45-56.

[45] Senate Report No. 69th-119 (1925) 638.

[46] Ibid, 850.

[47] Gerald D. Feldman, *Army, Industry, and Labor in Germany, 1914-1918* (Princeton, NJ: Princeton UP, 1966), 35-44.

[48] McGrayne, *Prometheans in the Lab*, 60-65.

[49] Ibid, 60-72.

In 1908 BASF hired Fritz Haber to perfect the fixation of ammonia from the atmosphere, a decision that would lead to one of the most spectacularly successful commercial ventures in history. Once Haber and Le Rossignol acquired BASF's resources their incremental successes began to increase in frequency, leading to record-setting pressure levels in the machines. Pressure, they both came to realize, was the key to efficient synthesis. In "an elegant study of thermodynamics", Haber and Le Rossignol determined that isolated hydrogen and nitrogen molecules would only remain combined as ammonia molecules "under extraordinarily harsh conditions: temperatures of 200°C (390°F) and atmospheric pressure 200 times stronger than normal [atmospheric pressure at sea level]".[50] At even higher pressures the temperature required for the reaction of ammonia and its catalysts decreased, improving yields substantially. During their first months at BASF, Haber and Le Rossignol had decreased the operating temperature of their machine from 1000°C to 600°C (~1832°F to ~1112°F), and discovered successful catalysts in osmium and uranium. Their next challenge was to turn their table-top machine into a full-sized model, but scaling a high-pressure model to industrial size would inevitably multiply minor mechanical issues.[51]

The task of appraising Haber's machine for use on an industrial scale was assigned to Carl Bosch, a young engineer whom BASF had recently employed to test another method of nitrogen fixation. Bosch's rigorous trial of this rival method of nitrogen fixation determined that impurities in the catalyst were responsible for its limited success, much to BASF's disappointment. Bosch had demonstrated great aptitude and skill in analyzing and identifying the process's failures, a penchant for technical scrutiny and exhaustive examination which solidified his place as BASF's unofficial chief of trials. When Haber submitted to BASF that his process was ready for full-scale trials, Bosch was assigned the task of determining its efficacy.[52]

At this point the history of nitrogen fixation transitioned from chemical engineering to industrial manufacturing, as Fritz Haber's epochal discovery grew into Carl Bosch's industrial juggernaut. Both halves of the Haber-Bosch partnership deserve credit for turning this multifaceted experiment into one of the most stable and long-lasting chemical process in existence. After years of steady development the scientific basis of Haber's work was prepared for industrial augmentation, and one of the first steps was to identify a readily available catalyst. The first effective catalyst Haber discovered was osmium, an extremely rare element which BASF had quietly purchased the entire world's known supply of, amounting to a few hundred pounds, upon Haber's request.[53] The other viable catalyst, uranium, was equally insufficient in quantity to support long-term ammonia synthesis. What Bosch eagerly awaited was a cheap alternative that would provide the last piece of the scientific puzzle, enabling industrial-scale manufacture of ammonia to proceed unimpeded.

The search for a replacement catalyst required a different approach than that of Haber and Le Rossignol, analyzing thousands of materials demanded a much higher volume of tests. Bosch appointed Alwin Mittasch the task of finding a suitable catalyst, without which the entire project was in jeopardy. The appointment of Mittasch bears some of irony; he was one of the few engineers who accompanied Bosch to Haber's first demonstration of the machine, which blew a gas-

[50] McGrayne *Prometheans in the Lab*, 64-67.
[51] Ibid, 65-72.
[52] Hager, *The Alchemy of Air,* 72-99.
[53] Ibid, 72-90.

ket and had to be jury-rigged on the spot. Though Carl Bosch left the laboratory early convinced of its failure, Mittasch remained to see the machine in action—a stay of execution which saved the Haber-Bosch process. As the head of his own department, Mittasch displayed remarkable ingenuity by designing his own catalyst test machines to heat and pressurize each material, allowing him to conduct several tests concurrently, expediting the project. These machines played a dual role in determining catalysts while also stress testing new components; whenever a test machine failed the wreckage was analyzed to improve the next model, incrementally improving them as a system of stress testing crucial components emerged.[54] By this method, new valves, pumps, and other devices were further improved during the search for catalysts, providing crucial data on components subjected to previously unobserved temperatures and pressures. Over several weeks a combination of cheap and effective catalysts were identified, complimenting a final cocktail of ingredients that "opened a new era in catalytic chemistry, with an emphasis on promoters rather than pure elements".[55] When it was over, Mittasch had completed more than 20,000 tests in a few weeks, literally setting the industry standard for materials testing, and arriving at a combination of catalysts including iron, aluminum, calcium and potassium— a recipe virtually unaltered to this day.[56] Mittasch's frenzied screening of catalysts and promoters provided a glimpse of the scientific methodology he and Haber would leave in their wake, highly efficient with ever greater impacts upon society at large.

By 1911 BASF had a full-scale prototype of the Haber-Bosch machine producing more than a ton of ammonia a day, with plans to create an industrial park capable of rapidly converting the ammonia into various forms of nitrate for farmers, its intended purpose. Before the process was scaled to industrial production Bosch had formed such extensive research teams that he reasoned "It is probably true to assert that such numbers [of scientists] have never before been engaged on one single problem."[57] It was certainly the largest scientific endeavor of its time, openly acknowledged as a precursor to the Manhattan Project of the Second World War. Haber had invented, and Bosch had constructed the most technologically complex machine to date, fulfilling the promise that science would alleviate the looming threat of famine. What they could not predict was the incredible effect their work would have on the coming war, "it would be very difficult for an inventor to stop at being a benefactor of mankind. No society can restrict, or could have restricted, a new, promising technology to serve peaceful development only. . . ".[58]

## II. The Synthesis of War

For the first few months of 1914, Carl Bosch had been overseeing the construction of a new ammonia factory in the city of Oppau, intent on bringing the Haber-Bosch process into full production. BASF wanted to capitalize on their advantage as the sole owner of the Haber-Bosch process the same way they had with their wildly successful synthetic dyes, by rapidly scaling their production to outperform the inferior processes of their competitors.[59] All of BASF's in-

[54] Hager, *The Alchemy of Air*, 101-105.
[55] Ibid, 101-110.
[56] Hager, *The Alchemy of Air*, 107.
[57] Cornwell, *Hitler's Scientists*, 54.
[58] Dunikowska, *Fritz Haber: The Damned Scientist*, 14-17.
[59] Feldman, *Army, Industry, and Labor in Germany*, 41-48.

vestments in research and equipment would be paid back with dividends, and Europe would never fear famine again.

However, all of BASF's plans would have to be put on hold. In July of 1914 the assassination of Archduke Franz Ferdinand of Austria quickly led to the declaration of war between Europe's great powers, all of whom rapidly mobilized for what was assumed to be a quick and decisive conflict. The possibility of a lengthy war was inconceivable to all parties, the feasibility of war itself was even doubted for a number of reasons. One of the best-selling books of the day, Norman Angell's *The Great Illusion,* made the assertion that a continental war was highly unlikely due to the economic cohesion of European states, none of which would prosper from capturing the others' territory or resources.[60] Angell denounced conflict between states, alleging:

> [international conflict] belongs to a stage of development out of which we have passed, that the commerce and industry of a people no longer depend upon the expansion of its political frontiers; that a nation's political and economic frontiers do not now necessarily coincide; *that military power is socially and economically futile, and can have no relation to the prosperity of the people exercising it*; that it is impossible for one nation to seize by force the wealth or trade of another — to enrich itself by subjugating, or imposing its will by force on another; that in short, war, even when victorious, can no longer achieve those aims for which people strive[61]

Angell's reasoning may seem faulty in hindsight, but for a nation like Germany, trade provided a huge portion of national and personal wealth, without which a war theoretically could not be funded. The procurement of staple foods also weighed heavily on calculations of war, as all of the great powers relied on importation of food to satisfy their growing populations, a critical fact which Malthus cited.[62] These facts of national survival, driving Germany's utilization of science to unprecedented economic prosperity, could not compete with allure of nationalism. By August 1914 all of Europe was at war, though *industry* would displace nationalism as the barometer of victory.

Germany's victory plan relied on rapid mobilization, enabling her to capture Paris and secure the western front before turning to deal with the monolithic power of Russia. The German general staff's obsession with a quick war, based on the vaunted theories of field marshal Alfred von Schlieffen, failed to account for the possibility of a lengthy war, and plans for the continued production of munitions were non-existent. Indeed, Germany only had enough ammunition on hand to wage war for approximately six months—a striking lack of organization and foresight that became apparent as the intensity of fighting and daily ammunition expenditure increased exponentially.[63] At the outset of the war German war planners had estimated that twenty nine kilotons of fixed nitrogen would make enough gunpowder to supply the military for one year of warfare. The following year, the imperial army was expending that amount every ten weeks.[64] The rate of expenditure continued throughout the war, surpassing all expectations and transform-

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[60] Norman Angell, *The Great Illusion: A Study of the Relation of Military Power to National Advantage*, (New York: G.P. Putnam's Sons, 1913) 11.

[61] Angell, *The Great Illusion*, 9, emphasis added.

[62] Ibid, 6-13.

[63] Feldman, *Army, Industry, and Labor in Germany, 1914-1918*, 50-52.

[64] Hager, *The Alchemy of Air,* 138.

ing the conflict into a war of production. Angell had been incorrect about the ability of European states to sustain internecine warfare but his estimation of the damage to the belligerents' economy was correct, after a year of war Germany's exports had nearly halved and her ability to import food and war munitions was severely compromised.[65] If Germany was to sustain war industries she desperately required a domestic source of nitrates to feed and arm herself.

In the initial sea battle of the war, a German flotilla cut Allied access to the Chinchas Islands, the Allies major source of nitrates, critically threatening their ability to wage war. With one minor skirmish of the coast of South America Germany had severed the enemy's greatest source of nitrates, as an American observer stated, "to strike at the source of allied nitrate supply was to paralyze the armies in France. The destruction of a nitrate carrier was a greater blow to the allies than the loss of a battleship".[66] Thus, the critical importance of nitrates production was understood through the absence of the only reliable source, belatedly prompting both sides to reappraise their tenuous means of production. Ironically, attempts to inform the German officer corps of the extreme utility of domestic fixed nitrogen plants had been ignored, despite glaring necessity, due to the military's focus on a rapid war.[67] Haber and several leading chemists argued that a domestic source of nitrates would prove critical to the prosecution of any war, but efforts to convince military planners of this looming catastrophe failed.[68] Despite this initial mistake Germany was still far ahead of her adversaries, possessing the largest and most sophisticated chemical industry in the world.

Germany possessed two major processes for producing the required nitrates: the common Cyanamide process, and the newly-minted Haber-Bosch process. The only reason the German government even entertained the idea of the inferior and more expensive Cyanamide process was because tit produced pure calcium Cyanamide which was easily converted into various nitrates including gunpowder, while pure ammonia required another step to arrive at the same point. A method of turning ammonia into white salt (or saltpeter) was already known, but it would be costly to retrofit existing plants to incorporate this last step, BASF's ammonia factories were designed to produce mountains fertilizer in peacetime, not munitions in war.[69]

Bosch's proposal to the German war ministry was radical: he asked them to fund another plant to process the ammonia being produced at BASF's largest plant at Oppau, further promising that production of white salt would begin within six months.[70] Haber was assigned the task of garnering political support for the venture, dining with politicians and boasting about the efficiency of his process. There was a substantial financial incentive for Haber as he pocketed a few dollars for every ton of ammonia produced by BASF, before long he had brought most of government officials to his side. Bosch's gamble paid off, and a deal known as the Saltpeter Promise was signed, guaranteeing the delivery of five thousand tons of white salt per month, expanding to over seven thousand in the future. The plant worked ceaselessly, all day every day without exception, with production only pausing to replace worn parts. In fact the plant at Oppau was so efficient that within a matter of weeks the war ministry asked BASF to expand its operations,

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[65] Chris Wrigley, *The First World War and the International Economy*, (Cheltenham: E. Elgar, 2000), 3.

[66] Hager, *The Alchemy of Air,* 141.

[67] Feldman, *Army, Industry, and Labor in Germany, 1914-1918*, 48-52.

[68] Jeffrey Allan Johnson and Roy M. MacLeod, *Frontline and Factory: Comparative Perspectives on the Chemical Industry at War 1914-1924,* (Dordrecht: Springer, 2006), 4.

[69] Johnson and MacLeod, *Frontline and Factory*, 7-11.

[70] Ibid, 12.

offering to fund a facility more than twice the size of Oppau. It would be massive, and it would be exorbitantly expensive, but it would grant Germany the unique position of being the only nation on earth self-sufficiently producing all of its own nitrates.[71]

Haber's departure from BASF coincided with the construction of the Leuna Works,[72] he moved on to his infamous work in the realm of poison gas, while Bosch oversaw the creation of the world's most complex factory. Every system and component would be designed as large and efficient as BASF's engineers were willing to build it, and as quickly as possible. Bosch considered the Leuna Works his crown jewel and raced to complete its construction in time to impact the war, which was turning in favor of the Allies with the entrance of the United States. He oversaw every detail of its design and construction which took a mere seven months to complete—an incredible feat in itself considering the massive shortages of labor in Germany at the time. Only one year after groundbreaking the Leuna Works began shipping explosives to the front, with output rising drastically from 36,000 tons per year to over 160,000 tons by the end of the war.[73] The Leuna Works had transformed BASF from a dye company into a munitions cartel; it was larger than any automotive plant and used technology so advanced that no other country could replicate it.

With the Leuna Works providing massive quantities of nitrogen to the German army there was finally enough for agricultural use, a critical field of the war effort long neglected. Nitrogen critical to the productivity of German farms had been diverted to industry since the outbreak of the war, leading to diminished harvests. By the end of the war Germany was only producing foodstuffs at 57% capacity compared to 1914.[74] As the Leuna Works shouldered an increasing portion of war production the nitrogen of Cyanamide plants were diverted to the agricultural sector, "In this manner the development of the Haber-Bosch process between 1915 and 1918 enabled Germany to continue the war at home and at the front."[75] The reallocation of nitrogen to agriculture would not be enough to prevent Germany's capitulation, though the efficiency of nitrogen plants using the Haber-Bosch process was a clear advantage contrasted with reliance on Chilean nitrates.

By the end of the Great War Germany's munitions production had outpaced every adversary. BASF's two facilities at Oppau and Leuna accounted for fully half of all munitions production between them, as one industrialist noted, "without this contribution, the war would undoubtedly have ended sooner."[76] The Haber-Bosch process significantly reduced the cost of munitions while drastically increasing production, a major factor in Germany's economic competitiveness during the war. While all nations suffered a loss of productivity German only spent an average of 40% of its national income on the war effort, as compared to 50-60% in Britain and even higher rates among other nations.[77] While Britain and France relied on colonies to prop up their war economies Germany had constructed the largest factory on earth to domestically synthesize all of her nitrates, a feat recognized by the US congress in its 'Nitrogen Report':

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[71] Johnson and MacLeod, *Frontline and Factory*, 11-15.

[72] Located in the town of Leuna, the factory became known as the Leuna Works.

[73] Johnson and MacLeod, *Frontline and Factory*, 11-13.

[74] S. N. Broadberry and Mark Harrison, *The Economics of World War I* (Cambridge: Cambridge UP, 2005), 46.

[75] Haber, *The Chemical Industry*, 202.

[76] Broadberry, and Harrison, *The Economics of World War I,* 42.

[77] Broadberry, and Harrison, *The Economics of World War I,* 45.

> The World War brought home to all the belligerent nations the danger of relying on the Chilean nitrate supply for a material so intimately related to national security, and the remarkable achievement of Germany in arriving at independence of the Chilean supply through intensive development of her air-nitrogen industry during the war . . . [and the] *inestimable value* of [fixation plants] as a unit in our national defense equipment . . . it is without the shadow of a doubt of greatest importance to hold this great nitrogen-fixing capacity in readiness."[78]

German Industry had not only weathered the Great War but as the armistice was signed in 1918 it stood stronger and potentially more profitable than ever, due largely to the preeminence of the Haber- Bosch process. With the close of the war the mystery of German industry was fast becoming the topic of international scientific and industrial communities, which had stolen patents for the Haber-Bosch process but were unable to replicate its success. US government reports openly acknowledge the superiority of the Haber-Bosch processes to organic nitrates and the inferior processes the Allies relied on, congressional hearings on the wartime chemical industry note:

> in a memorandum . . . found in the du Pont Co. files, the military advantage inherent in the explosives capacity of the great German chemical combine — I.G. Farben — was throughout to be comparable to 'a large, rapidly mobilizable force, or a large number of guns, or a fleet'.[79]

German monopolies of synthetic nitrates were a threat not only to Allied economic policy after the war but in future wars as well, acknowledging the strategic advantage of centralized, domestic nitrates production. The senate committee believed that "there could be no complete disarmament [of Germany] without control of the chemical industry," a fact uniting the Allies in breaking BASF's monopoly on the Haber-Bosch process.[80]

The economic potency of the Haber-Bosch process trumped the strategic implications so recently acknowledged by the United States Senate. Finances were thought to be the determining factor of the war's viability, in fact Angell had based most of his assumptions on the belief that countries required international trade to prosper and maintain armed forces. This notion was disproven at length, as the war stretched on for 4 years the authority of finance was replaced with that of industry. Somehow this single aspect— the economic superiority of the Allies and the United States in particular— is held to be the determining factor of the entire war, although most reports (including the US Senate) reaffirm that finance was a relatively minor concern. Each country had only to manage internal finances in order to procure weapons as debt would be paid after triumphal victory. As Strachan argues, "what mattered was the ability of industry to produce armaments . . . the monetary implications of the war were therefore postponed until after its conclusion".[81] Nitrogen fixation had supported Germany during the war, in peace this signal industrial advantage would determine both the economic and martial strength of states.

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[78] Senate Report No. 69th-119 (1925), emphasis added.
[79] Johnson and MacLeod, *Frontline and Factory,* 255.
[80] Senate Report No. 69th-119 (1925).
[81] Strachan, *Financing the First World War,* 11.

## III. Conclusion

By underestimating the importance of the Haber-Bosch process our understanding of WWI reverts to a facile narrative: that the entire conflict was merely disastrous miscalculation, or industrialized folly. Even historical accounts of Haber's life and the marvel of scientific engineering manage to discount the impact of synthetic nitrogen, dismissing decades of scientific breakthroughs as an extended precursor to all-important war. As author Daniel Charles states:

> Even Haber's most important technological triumph, the ammonia factories that delivered munitions to German soldiers and fertilizer to German farms, is in hindsight *of deeply ambiguous significance. Those factories didn't change the outcome of the war, but prolonged it by three years*, piling horror on top of horror. That brutality bred more brutality[82]

Some revisionist historians like Charles, keen to reiterate the bathos that dominates most scholarly writing on the Great War, maintain that the only lesson to be learned from the conflict is the hubris of war. This is much more than scholarly negligence; linking the importance of the Haber-Bosch process to Germany's eventual defeat in the war is reductio ad absurdum, or reduction of a major argument to absurd standards. It is clear that although several authors do recount the development of the Haber-Bosch process it remains to them an oddity at best, simply another story of scientific genius stranded at a time history devoted solely to the bemoaning of conflict.

The implications of the Haber-Bosch process are tantalizing and practically disregarded, with particular reference to how it prolonged the Great War, enabled industrialized total war, and led to other inventions like poison gas. The timely discovery of the Haber- Bosch process allowed Germany to mitigate the effects of the international embargo that threatened her food security and access to Chilean nitrates. As Chris Wrigley, a Great War economist noted, "a major lesson of the First World War was the extent to which industrialized states could be self-sufficient if public policy prioritized achieving this."[83] Germany's production of gunpowder surpassed the production of guns before the end of the war, alleviating one of the greatest bottlenecks of the conflict. How could this feat possibly be misconstrued as insignificant when it singularly sustained one of longest and bloodiest wars in history?

Haber's breakthrough discovery of nitrogen fixation was "a powerful exemplar for the notion that science was value-free, neutral, apolitical: the scientist discovered the laws of nature and invented applications; the good and evil perpetrated by those applications was on the conscience of others"[84]. The Haber-Bosch process was a prodigious yet discreet force throughout the war, too broad and all-encompassing to be counted among the wonder weapons it supplied. The fixation of atmospheric nitrogen shortly before the war granted Germany the ability to domestically sustain its war effort while nations relying primarily on foreign nitrates struggled to supply their forces. This competition between each nation's chemists and industrialists was far more relevant to ultimate victory than timetables; one determined the ability to wage and sustain war, the

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[82] Daniel, *Master Mind*, 183.
[83] Wrigley, *The First World War and the International Economy*, 9.
[84] Cornwell, *Hitler's Scientists*, 55.

other scrutinized the efficiency of deployment. By ascribing the horror of the Great War to nationalism and folly we naively disregard the role of chemistry, conflating the efficacy of applied science with politics and violence. Focusing on the war's futility to the exclusion of all other factors is a simplistic, satisfying hubris which must be rectified.

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