Escaping the Malthusian Trap: The Haber-Bosch Process

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“ESCAPING THE MALTHUSIAN TRAP: THE HABER-BOSCH PROCESS”
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Process Paper

I chose the Haber-Bosch process as the most significant turning point in history because I was shocked by the recent milestone of the global population surpassing eight billion people. With famines a constant in world history, how could global agriculture have become so productive as to largely eliminate famines except in war-torn areas? The Haber-Bosch process made me realize how few of these eight billion people would be alive if it were not for Haber and Bosch’s achievements. This scientific and industrial process was the most significant turning point in history.

My research involved the extensive exploration of online resources, including scholarly articles and books, but especially the records of the US Patent Office now made available at https://patents.google.com/. To ensure that I gained a comprehensive understanding of the topic and to allow for more factual reporting, I visited the Library of Congress during my spring break, accessing resources not available elsewhere. Its early 20th century newspaper collection is amazing. I was surprised to find relatively few sources written in English related directly to the Haber-Bosch process. The majority of sources, especially primary sources, were written in German and therefore beyond my ability to utilize.

I developed my essay systematically by starting with the creation of a detailed outline, where I organized my key points and arguments. I transformed these bullet points into formatted sentences and coherent paragraphs. As I expanded my essay, I incorporated both primary and secondary sources to enhance my arguments. After many drafts, I refined my content and ensured the clarity of the historical narrative. I edited and proofread my essay many times to polish the final version. From there, I produced my annotated bibliography to provide context for each of my sources and composed my process paper to clarify the creative process I followed.

My historical argument centers on the premise that the Haber-Bosch process represents a crucial turning point in history. By enabling the large-scale production of ammonia-based fertilizers, this process revolutionized agriculture, spawned the Green Revolution, and addressed the pressing challenge of food scarcity. My argument also highlights how the Haber-Bosch process overcame the Malthusian trap, contributing to exponential population growth, improving living standards, and altering the trajectory of human civilization.

The topic of the Haber-Bosch process holds great significance in history for several reasons. Firstly, it alleviated food scarcity, allowing for increased agricultural productivity and sustained population growth. Secondly, it fostered the emergence of industrialized agriculture, leading to demographic shifts, economic transformations, and urbanization. Thirdly, the process stimulated further advancements in agricultural technology and sustainability, shaping the modern practices of farming, resource management, and environmental stewardship. Collectively, these aspects demonstrate the lasting impact of the Haber-Bosch process on the global population, agricultural systems, and the course of human history.

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Paper

From the Middle Ages until the twentieth century, agriculture in the world was broken. Fertile soils proved bountiful, but every harvest diminished that fertility. In the fifteenth century Europe exploded out into the world and exploited new farmlands to again delay the reckoning between population growth and diminished soil fertility. In 1798 English economist Thomas Malthus turned the reckoning into a formula: "Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio."[1] Through industrialization, the nineteenth century offered a promise of relief from this Malthusian trap, but despite its general peace and prosperity, the nineteenth century was one of famine, killing upwards of 100 million people in China, over a million in Ireland, millions in Iran and India, over a million in Ethiopia. In 1898, William Crookes, a British chemist and physicist, summarized the challenge at the British Association for the Advancement of Science. The greatest threat facing the world, he said, was that by the 1930s the world would be running out of food unless science could develop a way to produce inexpensive nitrogen fertilizer. In his address, he called it a "life-and-death question for generations to come."[2] A decade later, German scientist Fritz Haber and German engineer Carl Bosch united two of nature's simplest elements, nitrogen and hydrogen, into NH_3--ammonia fertilizer, demolishing the Malthusian trap that had plagued the world since the beginning of time. Together they welcomed the world into

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[1] Thomas Robert Malthus, An Essay on the Principle of Population (London: J. Johnson, 1798), 4, accessed June 7, 2023, https://math.uchicago.edu/~shmuel/Modeling/Malthus,%20An%20essay%20on%20the%20principle%20of%20population.pdf.
[2] William Crookes, "Address of the President Before the British Association for the Advancement of Science," Science 8:20 (October 28, 1898), 561-75.

its greatest turning point, fertilizing the world's population into unparalleled growth, rising from less than two billion in 1900 to more than eight billion people today.

The nineteenth century was a maddeningly slow period of scientific discovery in trying to find a method to fix nitrogen into a usable form for replenishing farm fields. In 1800, thousands of years of experience showed that there were only two means of converting dinitrogen (N_2) in the atmosphere into usable nitrogen (N) that could be absorbed by plants: lightning and legumes. In 1807, Humphry Davy discovered that the electrolysis of water exposed to nitrogen in the air could produce small amounts of ammonia in a fixed form that could be absorbed by plants. He also observed that lightning could break the immensely strong triple bonds between two nitrogen atoms by raising its temperature to at least 1,832 °F. This directed scientists towards electricity as a means of producing ammonia. Electrolysis produced miniscule amounts of ammonia, however, and lightning ended up burning most of the ammonia it generated. Nevertheless, scientists began using artificial lightning in the form of an electric arc to produce ammonia. Not until the opening of the Niagara Falls hydroelectric plants in 1902 was electricity cheap enough to generate ammonia in usable quantities. Even then such ammonia was too expensive, requiring temperatures above 5,400 °F, to solve the nitrogen crisis because the resulting nitrous oxide had to be cooled immediately from 5,430 °F to less than 1,830 °F or the ammonia would decompose back in nitrogen and hydrogen gases. Nonetheless, the possibility of inexpensive ammonia production inspired Scottish-Canadian writer Robert Barr to author a fanciful short story projecting that science would take so much nitrogen from the atmosphere to produce nitrate fertilizer that it would obliterate human life in 1904.[3]

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[3] Robert Barr, "Within an Ace of the End of the World: The Scientist's Sensation," McClure's Magazine, 14:6 (April 1900), accessed July 11, 2023, https://glitternight.com/2018/04/09/within-an-ace-of-the-end-of-the-world-1900-ancient-science-fiction/.

Justus von Liebig discovered in the 1840s that plants acquired nitrogen from the atmosphere through photosynthesis but did not increase grain yields. Jean-Baptiste Boussingault discovered that legumes captured nitrogen from the atmosphere and deposited it in the soil. Hermann Hellriegel and Hermann Wilfarth followed up by identifying bacteria in the roots of legumes that fixed the nitrogen in the soil. Though great scientific discoveries, employing legumes to replenish nitrogen in the soil had only a limited impact on crop production.

Manure from animals had been used for thousands of years to return nitrogen to farm soils but was only partially effective because the animals consumed larger quantities of grasses and grains than their manure was able to fertilize. Even the best manure contained only 0.4 to 0.6 percent nitrogen.[4] Manure received a huge boost, however, when Alexander von Humboldt discovered bird guano on Peruvian islands that contained up to 14 percent nitrogen. Guano was only a short-term solution, however, because all the guano harvested in the last 50 years of the 19th century only replaced about 2 percent of the nitrogen lost through one year's crop production.[5] Farmers used slash and burn techniques that returned some nitrogen to the soil but over 90 percent of the nitrogen thus freed from trees and vegetation returned to the atmosphere from the burning.

Guano provided a brief respite from nitrogen shortages worldwide while scientists discovered other processes for producing ammonia, though none efficient enough to overcome high costs for minimal production. The destructive distillation of coal in the absence of air to produce coke released coal gas that could react with oxygen and steam to produce ammonia.

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[4] Vaclav Smil, Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production (Cambridge, MA: MIT Press, 2001), 5.

[5] Maikel Kuijpers, "The Most Important Invention of the 20th Century Keeps Us Alive . . . ," The Correspondent, October 6, 2020, 6, https://thecorrespondent.com/733/the-most-important-invention-of-the-20th-century-keeps-us-alive-but-is-killing-the-environment-the-solution-eat-less-meat.

Coal, however, contains but 1-1.5 percent nitrogen and only 12 to 17 percent of this small amount converts to ammonia. The energy expensive cyanamide process combined calcium carbide (CaC_2) with N_2 from the atmosphere at extremely high temperatures to produce calcium cyanamide ($CaCN_2$) that when heated with steam decomposed into NH_3 ($CaCN_2$ plus $3H_2$ produced $CaCO_3$ plus $2NH_3$). Reacting barium oxide with carbon and nitrogen produced barium cyanide that when heated with steam produced NH_3 and barium hydroxide (BaO plus C plus N = $Ba(CN)_2$ plus $3H_2$ produced NH_3 plus $Ba(OH)_2$). The leftover barium hydroxide ($Ba(OH)_2$), however, was extremely corrosive and highly toxic.

Crookes' "life and death question" would remain unanswered until July 2, 1909, when Fritz Haber successfully synthesized ammonia from elemental nitrogen and hydrogen, and until Carl Bosch made Haber's process commercially viable in the next six years. Haber did not start in a vacuum, however, as in 1884 William Ramsay and Sydney Young had produced small amounts of ammonia by mixing nitrogen and hydrogen in the presence of an iron catalyst at 1,470 °F. In 1900 Wilhelm Ostwald added pressure to the Ramsay-Young technique, but ended his research into this promising method when another scientist determined that Ostwald's small amounts of ammonia were not the result of nitrogen fixation from the atmosphere, but rather nitrogen released from impurities in the iron catalyst.[6]

Four years later, the Austrian Chemical Works in Vienna contracted with Fritz Haber (1868-1934), a German expert in thermodynamics, electrochemistry, and gas reactions, to pursue the production of ammonia. Rather than employing the Edisonian method of testing thousands of compounds, processes, and procedures, Haber chose to use the scientific method of researching gas equilibria pioneered by German chemist Walter Nernst. Instead of trying to produce

[6] Smil, Enriching the Earth, 62-64.

ammonia by combining hydrogen and nitrogen, Haber began in reverse, subjecting ammonia produced by traditional methods to heat and catalysis, causing it to decompose into hydrogen and nitrogen gases. He then unsuccessfully tried to recombine the two elements using heat and various catalysts. Failure nevertheless taught him that lower temperatures and circulating the gases to achieve better contact with the catalyst might promise more efficient ammonia production. Quitting the project in frustration, Haber returned to ammonia production seeking vindication after fellow German scientist Walter Nernst challenged Faber's reputation by demonstrating that Faber's results were incorrect.[7]

Haber and assistant Robert Le Rossignol designed a small-scale (5 x 30 inches) high pressure compressor, achieving the merging of hydrogen and nitrogen with an 8 percent yield at 1,100 deg F, a never-before-achieved 2,900 pounds per square inch of pressure, and manganese and nickel catalysts. The Badische Anilin und Sodafabrik Factory (BASF), frustrated with the great costs of its electric arc production of ammonia, funded continued Haber/Le Rossignol research based on their 8 percent yield success. A redesigned apparatus achieved even higher pressures and added the ability to cool the resulting ammonia rapidly to prevent decomposition. On October 13, 1908, Haber filed a patent for his new process (German patent no. 235421, issued June 8, 1911). Continued research showed that better catalysts such as osmium and uranium raised the ammonia yield to 10 percent at the relatively low pressure of 1,450 psi and temperature of 930 deg F.[8]

On July 2, 1909, Haber demonstrated his apparatus to BASF, which immediately assigned chemist/engineer Carl Bosch (1874-1940), an expert in catalysis and fertilizer

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[7] Smil, Enriching the Earth, 69-72.

[8] Smil, Enriching the Earth, 73-82.

production,[9] to turn Haber's laboratory achievement into a practical, efficient method of ammonia production. His challenges were legion. Hydrogen and nitrogen under high temperature and pressure attacked the carbon in his high-carbon, high-strength steel reactor tubes, leading to large explosions. Bosch solved the problem by adding soft, low-carbon steel liners to the reactors.[10] Haber's osmium and uranium catalysts, rare and expensive, were unusable on an industrial scale. Bosch constructed 30 small reactors patterned after Haber's model to run 6,500 tests on over 2,500 potential catalysts, finally settling on magnetite composed of aluminum, potassium, calcium, and magnesium oxides.[11] He had to design and build the largest compressors in the world. For cheap nitrogen, Bosch utilized an existing method of fractional atmospheric distillation. For cheap hydrogen, he developed an original method of heating coal over an iron and chromium oxide catalyst.[12] Finally, he developed an innovative method for oxidizing ammonia into nitric acid (HNO_3) to produce fertilizer.[13] Production began at BASF's Oppau factory on May 18/19, 1910. By 1914, production had increased to 22 tons per day. When World

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[9] Carl Bosch, "Production of Commercially-Pure Nitrates," US Patent No. 1,115,164A, October 27, 1914 (filed June 22, 1909).

[10] Carl Bosch, "Apparatus for Working with Hydrogen under Pressure," US Patent No. 1,188,530A, June 27, 1916 (filed February 5, 1912); and Carl Bosch, 'Process of Working with Hydrogen under Pressure," US Patent No. 1,086,130A, February 3, 1914 (filed June 5, 1913).

[11] Carl Bosch, Alwin Mittasch, "Catalytic Production of Ammonia," US Patent No. 1,225,755A, May 15, 1917 (filed November 18, 1911); and Carl Bosch, Alwin Mittasch, Hans Wolf, Georg Stern, "Catalytic Agent for Use in Producing Ammonia," US Patent No. 1,148,570A, August 3, 1915 (filed December 24, 1910).

[12] Carl Bosch, Wilhelm Wild, "Process of Producing Hydrogen," US Patent No. 1,113,097A, October 6, 1914 (filed October 29, 1913).

[13] Carl Bosch, "Production of Commercially-Pure Nitrates," US Patent No. 1,115,164A, October 27, 1914 (filed June 22, 1909); Carl Bosch, Alwin Mittasch, Christoph Beck, "Manufacture of Oxids of Nitrogen," US Patent No. 1,207,706A, December 12, 1916 (filed February 25, 1915); and Carl Bosch, Alwin Mittasch, Christoph Beck, "Manufacture of Oxids of Nitrogen," US Patent No. 1,207,707A, December 12, 1916 (filed February 25, 1915)

War I erupted that year, BASF diverted ammonia/nitric acid production to explosives production.[14]

The Haber-Bosch process facilitated the industrial production of agricultural fertilizers, leading to substantial improvements in global crop yields. Studies estimate that the number of humans supported per hectare of arable land increased from 1.9 to 4.3 persons between 1908 and 2008 due to the application of nitrogen fertilizers. Nitrogen application accounted for about half of crop yield increases during that period.[15] Ammonia-based fertilizers were the major factor in increasing the world population while also improving food security, eliminating famine except in war-torn areas, and launching Norman Borlaug's Green Revolution of the 1960s and beyond.[16]

Bosch's collaboration with Haber in scaling up the Haber process was a crucial partnership that revolutionized the production of ammonia. Bosch's profound expertise in chemical engineering, industrialization, and catalysis played a vital role in optimizing the process for large-scale production. Evidence from Bosch's patents, filed with the US Patent Office, demonstrates his significant contributions. In his patents, Bosch outlined key advancements, including the design of high-pressure equipment, utilization of iron catalysts, and specific operating conditions to enhance the reaction efficiency and yield of ammonia. These innovations allowed for the successful implementation of the Haber process on an industrial level. The patent documents from the US Patent Office serve as a testament to Bosch's instrumental role in

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[14] Carl Bosch, Alwin Mittasch, "Process of Producing Ammonia and Aluminium Compounds," US Patent No. 1043798A, November 12, 1912 (filed July 7, 1910); Carl Bosch, Alwin Mittasch, "Production of Ammonia," US Patent No. 1,158,167A, October 26, 1915 (filed November 18, 1911); Carl Bosch, "Process of Producing Ammonia," US Patent No. 990,191A, April 18, 1911 (filed March 2, 1908); and Smil, Enriching the Earth, 84-102.

[15] J. W. Erisman, "How a Century of Ammonia Synthesis Changed the World." Nature Geoscience 1 (2008): 636–639. https://doi.org/10.1038/ngeo325.

[16] Norman Borlaug, The Green Revolution, Peace, and Humanity," Nobel Lecture, December 11, 1970, accessed July 16, 2023, https://www.nobelprize.org/prizes/peace/1970/borlaug/lecture/.

optimizing the Haber process, transforming Haber's ammonia synthesis into ammonia production.

The effects of the Haber-Bosch process on agricultural productivity were transformative. With the availability of synthetic nitrogen fertilizers, crop yields increased significantly. The Haber-Bosch process enabled the mass production and accessibility of nitrogen fertilizers, leading to global increases in food production. Providing a means to address nutrient deficiencies in soils and promote vigorous plant growth resulted in higher yields and improved food security. Regions previously limited by low agricultural productivity and struggling to feed their populations suddenly had access to a reliable and abundant source of nitrogen fertilizers. This breakthrough played a significant role in improving nutrition levels and mitigating food shortages on a global scale.

Haber-Bosch has also caused demographic changes worldwide. The availability of abundant and affordable food supplies has contributed to a rapid increase in population growth. Access to more food has decreased infant mortality and increased life expectancy as population numbers surged. Population growth has challenged resource allocation, as the demand for land, water, housing, clothing, and energy have grown to sustain expanding populations. Population growth also has put pressure on social infrastructure, healthcare systems, and urban development. Fertilizers have raised concerns about their environmental impact. The runoff of nitrogen-based fertilizers contributes to water pollution and eutrophication, where excessive nutrients cause harmful algal blooms and the depletion of oxygen in water bodies. Fertilizer use also impacts soil health, altering microbial ecosystems and reducing fertility in the long run. In response to these challenges, the Green Revolution emerged as a movement to develop sustainable agricultural practices focused on improving crop yields through the use of highyielding varieties, mechanization, and advanced irrigation techniques. Its goal was to balance the need for increased food production with environmental conservation and sustainability. The Green Revolution, based primarily on the mass employment of nitrogen fertilizers, had a significant impact in boosting agricultural productivity, particularly in developing countries, and helped alleviate food scarcity in many regions.

By providing a reliable and abundant source of nitrogen, the Haber-Bosch process revolutionized agriculture: increased crop yields, improved food security, agricultural expansion into marginal unproductive lands, and the ability to sustain a growing global population. Moreover, the Haber-Bosch process paved the way for further advancements in agricultural technology and sustainability, spurring research and innovation in crop breeding, irrigation techniques, pest management, and precision agriculture. These advancements have continued to enhance productivity, resource efficiency, and environmental stewardship in modern agriculture. Sustainable practices such as conservation agriculture, organic farming, and precision farming have emerged, aiming to minimize environmental impacts while maximizing yields.

Despite the monumental impact of the Haber-Bosch process, the world-changing nature of its development was not immediately recognized by contemporary newspapers and media. The outbreak of World War I contributed to its lack of recognition. Monumental historical moments like July 2, 1909, are occasionally overlooked.

The Haber-Bosch process stands as a monumental turning point in history, revolutionizing agriculture and society. Its long-term impact has been profound, providing a reliable source of nitrogen fertilizers that have fueled increased crop yields, improved food security, and sustained a growing global population. This process not only enabled the expansion of agricultural practices into previously unproductive areas but also catalyzed further advancements in agriculture. Despite the initial lack of recognition by contemporary media, the Haber-Bosch process laid the foundation for transformative developments in crop breeding, irrigation techniques, precision agriculture, and especially the Green Revolution of the 1960s and 70s. Addressing future challenges such as climate change, resource limitations, and shifting dietary preferences presents opportunities for additional innovations in sustainable food production, surely based on nitrogen fertilizer. By embracing resilient agriculture, efficient resource management, and innovative solutions, agriculture will continue to nourish the global population. The profound and enduring impact of the Haber-Bosch process will continue to serve as a catalyst for change in global agriculture and as a cornerstone of modern food systems.

The Haber-Bosch process was the greatest turning point in history, taking a planet that could not support two billion people without massive famines in 1900 and transforming it into a planet supporting eight billion people and beyond without the constant threat of famine. The Bible's Book of Revelation identified the Four Horsemen of the Apocalypse. One down, three to go.[17]

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[17] Apocalypse (Revelation), 6:1-8 NIV.

ANNOTATED BIBLIOGRAPHY

PRIMARY SOURCES

Bosch, Carl. “Apparatus for Working with Hydrogen under Pressure.” US Patent No. 1,188,530A, June 27, 1916 (filed February 5, 1912). https://patents.google.com/patent/US1188530A/en?oq=US1%2c188%2c530A. Bosch’s patent describes the method he developed for preventing hydrogen from reacting with the carbon-rich steel of his reaction cylinders under high pressures. His solution was to use dual-layer cylinders--one layer was carbon steel and the other had little carbon. Patents such as this one are very valuable in highlighting the processes engineers such as Bosch used in commercializing such an important scientific breakthrough.

Bosch, Carl, Alwin Mittasch, Hans Wolf, Georg Stern. “Catalytic Agent for Use in Producing Ammonia.” US Patent No. 1,148,570A, August 3, 1915 (filed December 24, 1910). https://patents.google.com/patent/US1148570A/en?oq=US1148570A. I used this patent to help learn about Bosch’s ideas for the production of ammonia, and especially the use of a catalyst in the synthesis. Specifically, the patent refers to the creation of thousands of reactions to test potential catalysts, finally settling on magnetite composed of aluminum, potassium, calcium, and magnesium oxides.

Bosch, Carl and Alwin Mittasch. “Catalytic Production of Ammonia.” US Patent No. 1,225,755A, May 15, 1917 (filed November 18, 1911). https://patents.google.com/patent/US1225755A/en?oq=US1225755A. I used this patent to learn more about the key role of metallic catalysts in the production of ammonia. Specifically, the patent refers to the creation of thousands of reactions to test potential catalysts.

Bosch, Carl. “The Development of the Chemical High Pressure Method during the Establishment of the New Ammonia Industry.” Nobel Lecture. May 21, 1932. https://www.nobelprize.org/uploads/2018/06/bosch-lecture.pdf. Bosch exhaustively reviewed the many challenges he had to overcome in creating a method of producing commercial quantities of ammonia using Haber's process. Bosch in receiving the Nobel Prize was much more gracious than Haber in recognizing the vital role his colleagues played in his success.

Bosch, Carl, Alwin Mittasch, Christoph Beck. “Manufacture of Oxids of Nitrogen.” US Patent No. 1,207,706A, December 12, 1916 (filed February 25, 1915). https://patents.google.com/patent/US1207706A/en?oq=US1207706A. This patent details the development of Bosch’s innovative method for oxidizing ammonia into nitric acid (HNO_3) to produce nitrate fertilizer.

Bosch, Carl, Alwin Mittasch, Christoph Beck. "Manufacture of Oxids of Nitrogen." US Patent No. 1,207,707A, December 12, 1916 (filed February 25, 1915). https://patents.google.com/patent/US1207707A/en?oq=US1207707A. This patent details the development of an innovative method for oxidizing ammonia into nitric acid (HNO_3) to produce nitrate fertilizer. It is very similar to Patent No. 1,207,706A, but goes into further detail describing the machinery and process behind the manufacture.

Bosch, Carl. "Process of Producing Ammonia." US Patent No. 990,191A, April 18, 1911 (filed March 2, 1908). https://patents.google.com/patent/US990191A/en?oq=US990191A. This patent refers to the process that Bosch used (based on Haber's work) to produce ammonia. It also details the factory in which production took place--production began at BASF's Oppau factory on May 18/19, 1910, and by 1914, production had increased to 22 tons per day.

Bosch, Carl, Wilhelm Wild. "Process of Producing Hydrogen." US Patent No. 1,113,097A, October 6, 1914 (filed October 29, 1913). https://patents.google.com/patent/US1113097A/en?oq=US1113097A. This patent was used to support claims of Bosch's process of producing hydrogen cheaply and efficiently. He developed an original method of heating coal over an iron and chromium oxide catalyst, and this reinforces the idea of using many different catalysts throughout the process (catalysts being one of Bosch's many specialties).

Bosch, Carl, Alwin Mittasch. "Production of Ammonia." US Patent No. 1,158,167A, October 26, 1915 (filed November 18, 1911). https://patents.google.com/patent/US1158167A/en?oq=US1158167A. This patent refers to the process that Bosch used (based on Haber's work) to produce ammonia. It also details the factory in which production took place--production began at BASF's Oppau factory on May 18/19, 1910, and by 1914, production had increased to 22 tons per day.

Bosch, Carl. "Process of Working with Hydrogen under Pressure." US Patent No. 1,086,130A, February 3, 1914 (filed June 5, 1913). https://patents.google.com/patent/US1158167A/en?oq=US1158167A. Bosch's patent describes the method he developed for preventing hydrogen from reacting with the carbon-rich steel of his reaction cylinders under high pressures. His solution was to use dual-layer cylinders--the outer layer was carbon steel to provide great strength and the inner layer was reduced carbon steel that could be easily replaced. Patents such as this one are very valuable in highlighting the processes engineers such as Bosch used in commercializing such an important scientific breakthrough.

This patent is highly similar to US Patent No. 1,188,530A--yet this one explains the process in less detail.

Bosch, Carl. “Production of Commercially-Pure Nitrates.” US Patent No. 1,115,164A, October 27, 1914 (filed June 22, 1909). https://patents.google.com/patent/US1158167A/en?oq=US1158167A. I used this patent source to prove that Bosch was instrumental in the scaling and development of the Haber-Bosch Process. The fact that he had extensive experience synthesizing fertilizers (Commercially-Pure Nitrates) proves that he was instrumental in the creation of a process to synthesize ammonia.

Crookes, William. “Address of the President Before the British Association for the Advancement of Science.” Science 8, No. 200 (October 28, 1898): 561-75. https://www.jstor.org/stable/1627238. Crookes was a highly respected British chemist and physicist who had invented the vacuum tube and radiometer and discovered the element thallium. His call to action in 1898, identifying ammonia fertilizer as the key to “the fate of continents” inspired Haber and many other scientists to pursue the synthesis of nitrogen and hydrogen.

“Fame's Pathway.” Bellingham Herald 20, Number 219 (November 27, 1910) 4. I searched dozens of digitized historical newspapers in the University of North Carolina Wilmington Randall Library and the Library of Congress, including such leading sources as the Los Angeles Times, New York Times, Washington Post, Chicago Tribune, Atlanta Constitution, Wall Street Journal, and Scientific American but could find no references to Haber’s discovery. This article in the Bellingham Herald was one of only two references I could find.

Foreign Agricultural Service, U.S. Department of Agriculture. “Impacts and Repercussions of Price Increases on the Global Fertilizer Market.” June 30, 2022. https://www.fas.usda.gov/data/impacts-and-repercussions-price-increases-global-fertilizer-market. Fertilizer expenses account for 20 percent of all farm operating costs, 36 percent for corn, and 35 percent for wheat. The Russian invasion of Ukraine has created shortages in what was already a limited supply of fertilizer for world farms. This study projects significant price increases, dramatic cost increases in food products, and resulting spot food shortages around the world.

Haber, Fritz, and Robert Le Rossignol. “Production of Ammonia,” US Patent No. 971,501A, September 27, 1910 (filed August 13, 1909). https://patents.google.com/patent/US971501A/en?oq=US971501. The patent describes in general terms the successful production of ammonia at a relatively low temperature, high pressure, and high speed by passing nitrogen and hydrogen over an osmium catalyst, claiming a yield of 8 percent. Haber's claim relied on the original use of a heated osmium catalyst, pressure above 100 atmospheres. With a truly minimal description, the patent clearly spelled out the keys to ammonia production.

Haber, Fritz, and Robert Le Rossignol. "Production of Ammonia," US Patent No. 1,202,995A, October 31, 1916 (filed August 13, 1909). https://patents.google.com/patent/US1202995A/en?oq=US1202995. This patent, filed at the same time as the original patent, sought to provide greater detail about the Haber process. It moved beyond the original osmium catalyst, thereby providing patent protection for the process using any catalyst. It added that passing the nitrogen and hydrogen over the catalyst multiple times under pressure increased the yield. This patent also offered a path to increased efficiency by using the hot gases leaving the catalyst to preheat the new hydrogen and nitrogen entering the process so as not to waste the heat. This more expansive patent was probably based on the realization that huge profits could be had through the process. Haber and Le Rossignol also filed and received additional patents on modified explanations of the Haber process, including numbers 999,025, 999,191, and 1,006,206 as Haber tried to cover all aspects of his discovery to prevent others from exploiting it.

Haber, Fritz. "The Synthesis of Ammonia from Its Elements." Nobel Lecture. June 2, 1920. https://www.nobelprize.org/uploads/2018/06/haber-lecture.pdf. In his Nobel lecture, Haber reviewed the great need for ammonia fertilizers and covered some of the difficulties he faced in synthesizing nitrogen. Haber mentioned Bosch only twice while mentioning Le Rossignol four times. Fortunately, the Nobel Committee recognized Bosch for his role by awarding him the 1931 Nobel Prize in Chemistry.

Jones, Grinnell. "Nitrogen: Its Fixation, Its Uses in Peace and War." The Quarterly Journal of Economics 34, Number 3 (May 1920): 391-431. https://www.jstor.org/stable/1883359. Jones, a Harvard scientist, reviewed the efforts of the United States government during World War I to commit $20 million ($587 million today) to build nitrogen fertilizer plants to replace German sources that were inaccessible during the war because of the British blockade of German exports. The American Chemical Company improved the Haber-Bosch process and thereby avoided any patent violation. The blockade also forced America to search for alternative sources of fertilizers, primarily Chilean nitrate. Jones also identified the importance of the Haber process to the production of nitric acid needed to produce explosives for the German war effort.

"Organic Nitrogen." The Oregonian 29, Number 30 (July 24, 1910), 6. I searched dozens of digitized historical newspapers in the University of North Carolina Wilmington Randall Library and the Library of Congress, including such leading sources as the Los Angeles Times, New York Times, Washington Post, Chicago Tribune, Atlanta Constitution, Wall Street Journal, and Scientific American but could find no references to Haber's discovery. This article in The Oregonian was one of only two references I could find.

SECONDARY SOURCES

Colussi, J., G. Schnitkey and C. Zulauf. "War in Ukraine and its Effect on Fertilizer Exports to Brazil and the U.S." Farmdoc Daily 12, no. 34, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, March 17, 2022. https://farmdocdaily.illinois.edu/2022/03/war-in-ukraine-and-its-effect-on-fertilizer-exports-to-brazil-and-the-us.html. This web article focuses on the risks associated with disruptions in the world's fertilizer trade. Russia, as the world's largest exporter of fertilizers, has been hit by sanctions that disrupt its exports, leading to higher prices, shortages, and reductions in the export of agricultural commodities by the United States and Brazil, the world's top food exporters.

Erisman, J. W. "How a Century of Ammonia Synthesis Changed the World." Nature Geoscience 1 (2008): 636–639. https://doi.org/10.1038/ngeo325. Erisman looks at the impact of Haber's discovery 100 years later, emphasizing the overwhelming dependency of the world today on the Haber-Bosch synthesis of nitrogen and the "cascade of environmental changes" it initiated. Erisman estimates that 44 percent of the world's population is fed by nitrogen fertilizers. He also projects their continuing impact on the world through 2100 when nitrogen fertilizer from the Haber-Bosch process will be supporting 15 billion people in a nitrogen-saturated planet of polluted air, reduced biodiversity, increased human health risks, and increased greenhouse gases.

Galloway, J. N., et. al. "Nitrogen Cycles: Past, Present, and Future." Biogeochemistry 70 (2004): 153-226. This article estimates that an amazing 40 percent of the nitrogen fertilizer lost to the environment decomposes back to unreactive atmospheric dinitrogen. The remaining 60 percent, however, ends up polluting water supplies, promoting algal blooms, and damaging terrestrial biodiversity. It tracks reactive forms of nitrogen on a global scale from 1860 to the early 1990s.

Johnson, Benjamin. Making Ammonia: Fritz Haber, Walter Nernst, and the Nature of Scientific Discovery. New York: Springer, 2022. Johnson's book tracks the many scientific discoveries in the years before Haber that led up to Haber's discovery. It gives proof of Isaac Newton's famous quotation: "if I have seen further, it is by standing on the shoulders of giants."

Kuijpers, Maikel. "The Most Important Invention of the 20th Century Keeps Us Alive but Is Killing the Environment. The Solution? Eat Less Meat." The Correspondent. October 6, 2020. https://thecorrespondent.com/733/the-most-important-invention-of-the-20th-century-keeps-us-alive-but-is-killing-the-environment-the-solution-eat-less-meat. Kuijpers traces the evolution of fertilizer through history; a history of shortages eventually solved by the Haber-Bosch process. When the first farmers planted seeds, they trapped humanity into the nitrogen cycle. He states bluntly that "nitrogen is life," declaring that the Haber-Bosch process was the most important invention of the 20th century. Ammonia fertilizers have so many negative effects, Kuijpers argues, that only significant decreases in meat consumption can reduce their impact.

Ornes, Stephen. "Green Ammonia Could Produce Climate-Friendly Ways to Store Energy and Fertilize Farms." PNAS 118 (December 1, 2021). https://doi.org/10.1073/pnas.2119584118. Ornes offers yet another potential use of ammonia from the Haber-Bosch process as a fuel. Critically, ammonia burns with releasing carbon and therefore might be an answer to what Ornes calls "the globe's massive carbon emissions conundrum." The Haber-Bosch process, however, releases hydrogen from fossil fuels, adding carbon dioxide to the atmosphere. Scientists are currently working on ways to produce "green" ammonia that will make the Haber-Bosch process obsolete. Most focus on extracting hydrogen from water instead of coal and natural gas. Ornes acknowledges, however, that until these technologies become practical, the world is stuck with Haber-Bosch.

Smil, Vaclav. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. Cambridge, MA: MIT Press, 2001. The best source I found on the Haber-Bosch process being the greatest turning point in human history. Smil makes his viewpoint clear in his introduction: "The Haber-Bosch process was the greatest turning point in history since the invention of agriculture 12,000 years ago." He takes the long view, beginning with an explanation of the nutritional needs of humans and of the physical difficulties in splitting nitrogen molecules into nitrogen atoms. Smil traces the many developments and discoveries that preceded Haber's work and commits hundreds of pages to describing Haber's discovery and Bosch's inventions step by step as well as their importance to the 20th and 21st century world. Smil is Distinguished Professor Emeritus in the Faculty of Environment at the University of Manitoba.

Smil, V. "Nitrogen Cycle and World Food Production." World Agriculture 2 (2011): 9-13.
https://www.vaclavsmil.com/wp-content/uploads/docs/smil-article-worldagriculture.pdf. Smil focuses on the environmental impact of nitrogen fertilizers, stating bluntly that nitrogen's "incessant reuse makes life on Earth possible."

Stoltzenberg, Dietrich. Fritz Haber: Chemist, Nobel Laureate, German, Jew. Philadelphia:

Chemical Heritage Press, 2004. This source is the only full-length biography of Haber in English. It is replete with scientific jargon and highly technical explanations that limit its usefulness. It served, however, as a great source for checking dates and the technical details of the Haber-Bosch process.

Witschi, Hanspeter. "Fritz Haber: December 9, 1868-January 29, 1934." Toxicology 149 (2000): 3-15. https://doi.org/10.1016/s0300-483x(00)00227-4. This short biography of Haber expanded my knowledge of Haber to include his wartime involvement in the development of explosives and poison gases for the German war effort and his postwar problems with the new Nazi, anti-Jewish government of Germany.

Wood, Johnny. "Why We Need More Ammonia to Feed the World." September 14, 2021. https://spectra.mhi.com/why-we-need-more-ammonia-to-feed-the-world. Using United Nations sources, Wood describes large-scale ammonia production facilities under construction in the United States, China, Russia, and India--the largest consumers of nitrogen fertilizers. He projects a growing inequality between producing and consuming nations.

Wyer, Katie E., David B. Kelleghan, Victoria Blanes-Vidal, Gunther Schauberger, and Thomas P. Curran. "Ammonia Emissions from Agriculture and Their Contribution to Fine Particulate Matter: A Review of Implications for Human Health." Journal of Environmental Management 323 (2022): 1-13. https://doi.org/10.1016/j.jenvman.2022.116285. This article presents current data on the dangers of airborne ammonia fertilizer to human health. Most previous research has focused on the danger ammonia fertilizer presents to the environment. This article extends this danger to human health.