"[T]he power of population is indefinitely greater than the power in the earth to produce subsistence for man. Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio. A slight acquaintance with numbers will shew (sic) the immensity of the first power in comparison of the second."[1]

– Thomas Malthus, *An Essay on the Principle of Population*

At the turn of the 20th century, scientists forecast imminent worldwide starvation. In 1898, Sir William Crookes, future president of Britain's Royal Society, warned:

> My chief subject is of interest to the whole world – to every race – to every human being. It is of urgent importance to-day, and it is a life and death question for generations to come. I mean the question of Food supply....England and all civilised nations are in deadly peril of not having enough to eat.[2]

As we know now, Crookes and his peers were wrong. Even though the human population long ago exceeded the planet's natural ability to support us, our population today is four times larger, and eats on average much better, than in Crookes's day. What has made possible this unparalleled increase in population? How can we grow so much more food? This remarkable achievement can be attributed to the Haber-Bosch process. The 20th century's most consequential innovation, the Haber-Bosch process is directly responsible for keeping alive nearly half the people on Earth.[3]

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[1] Thomas Robert Malthus, "An Essay On the Principle of Population" (London: J. Johnson, in St. Paul's Church-yard, 1798), chapter 1 unpaginated. http://www.gutenberg.org/catalog/world/readfile?fk_files=1298259

[2] William Crookes, *The Wheat Problem: Based on Remarks made in the Presidential Address to the British Association at Bristol in 1898* (New York: Longmans, Green, and Co., 1917), p. 2.

[3] 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), p. 1.

All living things need nitrogen to grow, and for most plants, including crops, nitrogen is the limiting nutrient: a plant's growth is directly tied to its supply of nitrogen. Despite this great need for nitrogen, organisms can only use a tiny percentage of the planet's supply: almost all of the world's nitrogen is locked away in chemically inert nitrogen gas.[4] To get biologically usable nitrogen, the nitrogen must be "fixed." In other words, it must react with hydrogen gas and be changed into ammonia,[5] which, unlike nitrogen gas, can bond with other compounds. The problem is that very few organisms, just a few types of soil bacteria, possess the ability to fix nitrogen from the air. Even small amounts of fixed nitrogen accumulate slowly, and up until the turn of the century, human agriculture had always been faced with a shortage of usable nitrogen. It's no wonder, then, that Crookes declared, "The fixation of atmospheric nitrogen therefore is one of the great discoveries awaiting the ingenuity of chemists. ...The fixation of nitrogen is vital to the progress of civilised humanity."[6]

Crookes knew that it was only "through the laboratory that starvation may ultimately be turned into plenty,"[7] and one scientist determined to solve the nitrogen problem was the German chemist Fritz Haber. Most contemporary research focused on "burning" nitrogen out of the air – an energy-intensive process that yielded little ammonia – but Haber reasoned that the most practical way to make ammonia would be to synthesize it from its elements by mixing atmospheric nitrogen with hydrogen gas. Both gases were cheap, easy to use, and most importantly, vastly abundant.

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[4] In a basic chemical sense, "inert" means chemically unreactive. Inert gases, such as nitrogen gas, do not bond with other compounds and, therefore, have very limited value in natural settings.

[5] Ammonia used for fertilizer is used as anhydrous ammonia and should not be confused with common household "ammonia," which is ammonium hydroxide, a related compound in aqueous form.

[6] Crookes, p. 38.

[7] Ibid., p. 3.

In fact, the synthesis of ammonia from nitrogen and hydrogen gases made so much sense that it wasn't a new idea. As early as 1900, seven years before Haber started his work, another German scientist and future Nobel laureate, Wilhelm Ostwald, had tried to synthesize ammonia from nitrogen and hydrogen gases. However, Ostwald quickly discovered that the approach, seemingly so simple and practical, was more difficult than he had supposed. Breaking the extremely strong triple bond holding together nitrogen gas required intense heat on the order of 1,000° C, more than enough heat to destroy almost immediately any ammonia that had been formed.

Ostwald had run into a dead end, but Haber, already an expert in the emerging field of physical chemistry, had a different idea to substantially improve the yield of ammonia. Knowing that pressure and temperature are inversely proportional in a chemical reaction, Haber decided to attempt the synthesis of ammonia in a high-pressure environment. Haber's new approach was an immediate success. The more he raised the pressure, the lower he could drop the temperature. The lower the temperature, the more ammonia survived the process intact.

Thanks to his innovative procedure, Haber was, by early 1908, synthesizing ammonia from the air far more efficiently than anyone had before.[8] His research started to attract attention, and in March 1908 Haber signed a contract with BASF, one of Germany's largest chemical companies. The company's in-house head of nitrogen research, Carl Bosch, soon became BASF's point-man with Haber's lab.

Still, there were obstacles to overcome. Even as Haber improved his procedure and fine-tuned his instruments, the ammonia yield, although unprecedented, remained too low for

[8] Hager, p. 81.

commercial viability. Haber then decided to tinker with the reaction's catalyst,[9] hoping to find one that would make his process efficient enough to be practical in a large-scale commercial setting.

Much as American inventor Thomas Edison tried thousands of substances for use in his incandescent light bulb, Haber tested one compound after another in the hopes of finding something that would improve the ammonia yield. Finally, after months of futile testing, Haber struck the jackpot: when nitrogen and hydrogen gases reacted in the presence of osmium,[10] the ammonia yield shot up, high enough to become commercially viable. Through a combination of brilliant scientific innovation (increasing pressure to decrease temperature, leading to higher ammonia yield) and trial-and-error persistence (finding an improved catalyst), Haber had made possible the synthesis of fertilizer from the air. The opportunities seemed boundless. *The New York Times* gushed, "The fixation of atmospheric nitrogen! The very fling and tang of this phrase holds fascination for the uninitiated. But the electro-chemical miracle is even more fascinating than it sounds."[11]

The euphoria was soon tempered when it became clear that technological innovations, on par with Haber's scientific breakthrough, would be required to mass-produce ammonia for use in synthetic fertilizer. To that end, BASF tasked Carl Bosch, their in-house nitrogen expert, with the daunting challenge of turning Haber's two-and-a-half foot high prototype into the enormous

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[9] Catalysts are frequently used in chemistry to speed up chemical reactions. By lowering the energy a chemical reaction requires to take place (the reaction's activation energy), catalysts dramatically improve reaction rate and efficiency.

[10] Osmium is a rare earth metal.

[11] Littell McClung, "Taking Nitrogen from Atmosphere; Chilean Beds Are Limited but Government Power Plant Will Produce Element Vitally Needed in the War," *The New York Times*, October 3, 1918, p. 2.

machines that would be needed to feed the world.[12] The stakes were high: unless Bosch could repeat Haber's work in an industrial setting, Haber's discovery would not feed a single person.

The work was entirely novel and almost everything had to be invented. As Bosch later remarked, "There were no examples in industry" to guide his way.[13] As Bosch quickly discovered, almost every part of Haber's model, other than the chemical reaction itself, would need to be modified. The most obvious problem was one of scale. Haber's table-top model was drilled out of solid quartz, a material strong enough to withstand the extreme temperature and pressure required for ammonia synthesis. However, it was laughably impractical for Bosch to build gigantic ammonia factories from quartz. The strongest available material was carbon steel, from which Bosch began to build test machines. But he soon ran into a major roadblock: the hydrogen gas, absolutely critical to Haber's process, was ruining the structural integrity of even the strongest steel walls. No matter what modifications Bosch and his engineering teams made to strengthen the walls, the machines always exploded within days.

Tens of thousands of man-hours later, Bosch's supervisors at BASF were growing impatient. Unless Bosch could quickly come up with a solution, Haber's scientific brilliance would never come to industrial fruition. With the fate of the project at stake, Bosch himself made an ingeniously simple breakthrough. Realizing that the hydrogen gas would attack the steel walls no matter what he did, Bosch devised a series of inner liners, which could easily be replaced, that would absorb the hydrogen's damage instead of the main steel walls. The liners were effective, cheap, and easy – and Bosch's machines stayed intact and functioning for

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[12] Hager, p. 104.
[13] Carl Bosch, "The Development of the High Pressure Method During the Establishment of the New Ammonia Industry," Nobel Lecture given May 21, 1932. http://nobelprize.org/nobel_prizes/chemistry/laureates/1931/bosch-lecture.pdf

weeks, and then months. As one of Bosch's BASF contemporaries wrote, "It was this inspiration...that made the very large scale synthesis of ammonia possible."[14] The project was back on track.

Even with a new building material in place, a mountain of other challenges remained. For instance, Bosch's teams needed to design a wholly new system of compressors, fittings, and gauges that could run for years, without breaking down, at temperatures hot enough to melt solid iron and pressures twenty times higher than those produced by locomotive steam engines. Almost none of this equipment had been conceptualized, let alone attempted to be built, before. Bosch and his assistants needed to improvise known technologies, or, as it often turned out, invent from scratch, almost every step of the way.

Despite the innumerable challenges, Bosch and his teams bested them all. By early 1911, Bosch's prototype plant at Oppau, Germany, was producing more than two tons of ammonia per day.[15] As one historian wrote about this remarkable achievement:

> Not only was Bosch able to pioneer what has become the world's most essential chemical synthesis, but he was able to turn Haber's...experimental design into a commercial success in an extraordinarily short time. In just four years the enterprise went from a 75 cm tall converter sitting on Haber's laboratory bench...to an 8 m tall converter installed at the first ammonia plant in Oppau.[16]

Thanks to Haber's scientific innovation and Bosch's technological ingenuity, the synthesis of ammonia had been perfected. Illustrating the optimism generated by the discovery, *The Washington Post* declared, "Transmutation of air into fertilizer, the erstwhile mad dream of

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[14] Dietrich Stoltzenberg, *Fritz Haber: Chemist, Nobel Laureate, German, Jew* (Philadelphia: Chemical Heritage Press, 2004), p. 100.
[15] Hager, p. 122.
[16] Vaclav Smil, *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production* (Cambridge, MA: The MIT Press, 2001), p. 84.

the twentieth-century alchemist, is now an accomplished daily miracle."[17] If anything, *The Washington Post* and others underestimated the effects of the Haber-Bosch process, which have profoundly shaped, for both good and bad, the world in which we live.

For starters, the Haber-Bosch process profoundly affected international geopolitics. Prior to the rise of cheap synthetic nitrogen fertilizers, most of the world's supply came from the nitrate mines of Chile, where nitrate exports accounted for more than half of the country's income.[18] In fact, Chile had fought a war, the War of the Pacific (1879-1884), to gain control of neighboring Bolivia's nitrate deposits. Chile's eventual victory in the nitrate war left Bolivia landlocked, causing bitterness and resentment to this day. Ultimately, Chile's gains were short-lived. After the successful commercialization of the Haber-Bosch process, Chilean nitrate exports were no longer cost-competitive with cheap synthetic fertilizer. Faced with the loss of its primary money maker, Chile's economic might and hegemony in South America declined. Germany, on the other hand, saw its power blossom. During World War I, for instance, the Haber-Bosch process allowed Germany, deprived of imported nitrates by a British naval blockade, to continue manufacturing explosives and keep fighting. Similarly, during World War II, German scientists used their knowledge of pressure chemistry, much of which had come out of the Haber-Bosch process, to create artificial gasoline, rubber, and explosives to fuel Hitler's war machine, making facilities employing Haber-Bosch techniques prime Allied bombing targets.[19] More recently, the "opening" of China in the early 1970s can be directly linked to the Haber-Bosch process. Following decades of war, China's population began to swell during the

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[17] "Fertilizer from the Air; Mad Dream of the Alchemist Has At Last Become an Accomplished Fact," *The Washington Post*, September 29, 1912, p. M4.
[18] Hager, p. 53.
[19] Trevor Evans, "The Economic War," *The Washington Post*, September 15, 1940, p. B9.

1960s, more than doubling between 1960 and 1970.[20] Not having access to the Haber-Bosch manufacturing process, the Chinese population quickly threatened to overgrow its food supply. By the early 1970s, food shortages menaced 800 million Chinese.[21] In 1973, China decided to open itself to Western business. Within weeks, the Chinese government's first major transaction with the West was to order 13 enormous, top-of-the-line Haber-Bosch manufacturing facilities. Within seven years, China had become the world's largest consumer of synthetic fertilizer, and today, Chinese rice fields yield twice as much grain as they did in 1973.[22]

Still, like many scientific innovations, the legacy of the Haber-Bosch process is not uniformly positive. In 1939, as the world armed for war, one scientist noted that the Haber-Bosch process had "completely revolutionized the prospect of the available supplies for fertilizers – and explosives."[23] Although he concluded that "only a small degree of sanity should be required to keep the nations from blowing themselves to pieces with explosives made from the synthetic ammonia,"[24] that clearly was not the case, and even today cheap nitrogen compounds, made in Haber-Bosch plants, continue to kill people around the world.[25] Almost as alarming, it's become increasingly clear that the Haber-Bosch process is having other, more subtle, negative effects. A recent international study concluded: "Excessive use of [nitrogen fertilizer] can lead to numerous problems directly related to human health (e.g., respiratory

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[20] Smil, p. 168.
[21] Daniel Charles, *Master Mind: The Rise and Fall of Fritz Haber, the Nobel Laureate Who Launched the Age of Chemical* Warfare (New York: HarperCollins, 2005), p. 104.
[22] Ibid., p. 106.
[23] C.C. Furnas, *The Storehouse of Civilization* (New York: Bureau of Publications, Teachers College, Columbia University, 1939), p. 146.
[24] Ibid., p. 319.
[25] Alan Cullison and Yaroslav Trofimov, "Karzai Bans Ingredient of Roadside Bombs," *The Wall Street Journal*, February 3, 2010. http://online.wsj.com/article/SB10001424052748703822404575019042216778962.html

diseases induced by exposure to high concentrations of ozone and fine particulate matter) and ecosystem vulnerability (e.g., acidification of soils and eutrophication of coastal systems)."[26]

The most obvious and important consequence of the Haber-Bosch process, though, has been the dramatic increase in worldwide agricultural production. Far from facing worldwide starvation, as Crookes predicted at the turn of the 20th century, the human population has quadrupled since 1900. Not only are more mouths being fed, but on average, humans are eating more calories and more nutritious food than ever before.[27] This enormous increase in the world's food supply can be directly tied to the Haber-Bosch process: crop yields are typically four times greater with synthetic fertilizer than if only naturally-generated nitrogen was available. In 1962, just 50 years after the discovery, some were already calling the Haber-Bosch process the "greatest single advance in the progress of mankind."[28] Norman Borlaug, one of the central figures of agriculture's "Green Revolution"[29] of the 1960s and 1970s, declared: "If the high-yielding dwarf wheat and rice varieties are the catalysts that have ignited the green revolution, then chemical fertilizer is the fuel that has powered its forward thrust."[30] Left to itself, our planet could never naturally grow enough food to support our current population. In fact, one researcher has estimated that if the Haber-Bosch process disappeared, a staggering 40 percent of the world's population would starve to death.[31]

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[26] Arvin R. Mosier, J. Keith Syers, and John R. Freney (editors), *Nitrogen Fertilizer: An Essential Component of Increased Food, Feed, and Fiber Production* (Washington, D.C.: Island Press, 2004), p. 3.
[27] Hager, p. xiv.
[28] *Agricultural Ammonia Handbook* (Memphis, TN: Agricultural Ammonia Institute, 1962), p. 3.
[29] The "Green Revolution" refers to the unprecedented harvest yields in the developing world during the second half of the 20th century due to the use of synthetic fertilizers, pesticides, and improved strains of cereal grains.
[30] Norman Borlaug, "The Green Revolution, Peace, and Humanity," Nobel Lecture given December 11, 1970. http://nobelprize.org/nobel_prizes/peace/laureates/1970/borlaug-lecture.html
[31] Smil, p. xv.

In explaining why the Haber-Bosch process ranks as the most consequential invention of the 20th century, one scientist has written:

> What is the most important invention of the twentieth century? Aeroplanes, nuclear energy, space flight, television and computers will be the most common answers. Yet none of these can match the synthesis of ammonia from its elements. The world might be better off without Microsoft and CNN, and neither nuclear reactors nor space shuttles are critical to human well-being. But the world's population could not have grown from 1.6 billion in 1900 to today's six billion without the Haber-Bosch process.[32]

Others, too, recognized the importance of the discovery. In 1918, Fritz Haber was awarded the Nobel Prize in chemistry for his synthesis of ammonia, an "exceedingly important means of improving the standards of agriculture and the well-being of mankind."[33] Nor did Carl Bosch's work go without notice. In 1931, Bosch too was awarded the Nobel Prize in chemistry for his role in making a "technical advance of extraordinary importance" and his "tremendous step" in industrializing Haber's work.[34]

The Haber-Bosch process has irrevocably changed the world. No other invention has affected more people. This incredible innovation, scientifically discovered by Fritz Haber and made industrially feasible by Carl Bosch, fully deserves to be considered one of mankind's most significant and enduring accomplishments.

Word count: 2,498

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[32] Vaclav Smil, "Detonator of the population explosion," *Nature*, July 29, 1999, p. 415.
[33] Å.G. Ekstrand, "Presentation Speech," given June 1, 1920. http://nobelprize.org/nobel_prizes/chemistry/laureates/1918/press.html
[34] W. Palmær, "Presentation Speech,"given December 10, 1931. http://nobelprize.org/nobel_prizes/chemistry/laureates/1931/press.html

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Primary Sources

Agricultural Ammonia Handbook. Memphis, TN: Agricultural Ammonia Institute, 1962.

This basic factbook, designed to educate American farmers about the benefits of ammonia fertilizer in an agricultural setting, was produced by the Agricultural Ammonia Institute in 1962 and showed me how much of a boon the Haber-Bosch process was considered to be for farmers.

Borlaug, Norman. "The Green Revolution, Peace, and Humanity." Nobel Lecture given December 11, 1970. http://nobelprize.org/nobel_prizes/peace/laureates/1970/borlaug-lecture.html

Norman Borlaug was awarded the Nobel Peace Prize for his work "to provide bread for a hungry world." The Nobel Lecture he gave upon receipt of his award credited Haber and Bosch for their role in making the Green Revolution possible. This lecture illustrated the continuing importance of the Haber-Bosch process and its role in influencing the Green Revolution of the late 20th century. The website is the official site of the Nobel Foundation and the official repository of all information related to the Nobel Prize.

Bosch, Carl. "The Development of the High Pressure Method During the Establishment of the New Ammonia Industry." Nobel Lecture given May 21, 1932. http://nobelprize.org/nobel_prizes/chemistry/laureates/1931/bosch-lecture.pdf

This is the lecture Carl Bosch gave in 1931 upon receiving the Nobel Prize in Chemistry. It provided me with concrete examples of how Bosch's technological ingenuity allowed him to overcome major obstacles during his quest to industrialize Haber's work. Because Bosch, like Haber, published in German, this speech was a rare English-language primary source from Bosch detailing his work. The website is the official site of the Nobel Foundation and the official repository of all information related to the Nobel Prize.

Browning, Philip. "The Conservation of Phosphates in the Urine." In *Original Communications, Eighth International Congress of Applied Chemistry, Washington and New York, September 4 to 13, 1912*." Concord, NH: Rumford Press, 1912, p. 41.

In researching Haber and Bosch's work, I came across these proceedings from a 1912 international chemistry symposium. Reading through the section on agricultural chemistry, I found several examples of other scientists working on creating synthetic fertilizer compounds. I was particularly struck by the creativity, and perhaps desperation, of this scientist who was working on techniques to develop fertilizers from urine: "Should the time arrive when the mineral supply of phosphatic material threatens to be exhausted, possibly the public urinals of our larger cities might utilize this reaction to keep up the supply."

Crookes, William. *The Wheat Problem: Based on Remarks made in the Presidential Address to the British Association at Bristol in 1898*. New York: Longmans, Green, and Co., 1917.http://books.google.com/books?id=DiVBAAAAIAAJ&printsec=frontcover&dq=crookes+wheat&ei=-x2PS-7IA4WGyQTG0v2kBQ&cd=1#v=onepage&q=&f=false

Sir William Crookes was president of the British Association, a group founded as a more modern response to the Royal Society. Crookes was one of many prominent turn-of-the-century scientists who forecast imminent worldwide starvation. Crookes's speech showed me just how seriously scientists were taking the threat of starvation. Unfortunately, there is only one library copy of this book in the United States, which is in Indiana. I used a digitized version of the complete book available through Google Books.

Cullison, Alan and Trofimov, Yaroslav. "Karzai Bans Ingredient of Roadside Bombs," *The Wall Street Journal*, February 3, 2010. http://online.wsj.com/article/SB10001424052748703822404575019042216778962.html

This article, written just recently, describes Afghanistan's ban of ammonium nitrate fertilizers in order to deny potential explosives to insurgent organizations, and showed me how inexpensive Haber-Bosch compounds continue to kill people even in today's age of high technology.

Ekstrand, Å.G. "Presentation Speech." Given June 1, 1920. http://nobelprize.org/nobel_prizes/chemistry/laureates/1918/press.html

Å.G. Ekstrand gave this speech about Fritz Haber in presenting him for the Nobel Prize in Chemistry and explained the rationale behind Haber's selection as the Nobel committee's recipient of the Chemistry prize in 1918. The website is the official site of the Nobel Foundation and the official repository of all information related to the Nobel Prize.

Evans, Trevor. "The Economic War," *The Washington Post*, September 15, 1940, p. B9.

During World War II, Germany's Leuna factory, which produced synthetic oil using a variant of the Haber-Bosch process, was one of the most well-defended sites in Western Europe. This article, which is an interview with British Minister of Economic Warfare Hugh Dalton, describes Dalton's elation at the British bombing of Leuna. The Germans, however, repeatedly rebuilt Leuna during World War II. Although British, and later American, bombers reduced Leuna to 15 percent production by war's end, today it remains one of the world's largest chemical plants.

"Fertilizer from the Air; Mad Dream of the Alchemist Has At Last Become an Accomplished Fact," *The Washington Post*, September 29, 1912, p. M4.

This article illustrated for me how importantly the American government viewed the Haber-Bosch process and how much value Americans placed on getting their own Haber-Bosch technology.

Furnas, C.C. *The Storehouse of Civilization.* New York: Teachers College, Columbia University, 1939.

This book, written in 1939 by a scientist from Yale University, showed me how critically important the Haber-Bosch process was believed to be less than 30 years after Haber and Bosch's work. It also, rather naively, predicted that the Haber-Bosch process would be "an unmixed blessing." (p. 320)

Haber, Fritz. "The Synthesis of Ammonia From Its Elements." Nobel Lecture given June 2, 1920. http://nobelprize.org/nobel_prizes/chemistry/laureates/1918/haber-lecture.pdf

Fritz Haber's Nobel Lecture, delivered in conjunction with his receiving the Nobel Prize in Chemistry in 1918, gave me valuable insight into Haber's research that ultimately produced the synthesis of ammonia. Because Haber, like Bosch, published in German, this speech was a rare English-language primary source from Haber expounding on the details of his experimentation. The website is the official site of the Nobel Foundation and the official repository of all information related to the Nobel Prize.

Malthus, Thomas Robert. "An Essay On the Principle of Population." London: J. Johnson, in St. Paul's Church-yard, 1798. http://www.gutenberg.org/catalog/world/readfile?fk_files=1298259

Today, Thomas Malthus's views on the limits of human population are widely considered to be wrong, but in his day, Malthus was extremely influential. Without the Haber-Bosch process, however, Malthus may well have been correct. Malthus's best-known work, "An Essay on the Principle of Population," describes his reasoning as to why human population would be checked by insufficient food resources. I was able to find his original essay on Project Gutenberg, a digital archive of culturally significant books in the public domain.

McClung, Littell. "Taking Nitrogen from Atmosphere; Chilean Beds Are Limited but Government Power Plant Will Produce Element Vitally Needed in the War." *The New York Times*, October 3, 1918, p.2.

I used this article to better understand American efforts to use Haber-Bosch technology to create explosives for the war effort during World War I, as Germany was doing.

Palmær, W. "Presentation Speech." Given December 10, 1931. http://nobelprize.org/nobel_prizes/chemistry/laureates/1931/press.html

Professor Palmær gave this speech about Carl Bosch in presenting him for the Nobel Prize in Chemistry in 1931 and explained the rationale behind Haber's selection as the Nobel committee's recipient of the Chemistry prize in 1931. The website is the official site of the Nobel Foundation and the official repository of all information related to the Nobel Prize.

Secondary Sources

Bown, Stephen R. *A Most Damnable Invention: Dynamite, Nitrates, and the Making of the Modern World.* New York: St. Martin's Press, 2005.

This book, focusing primarily on the Haber-Bosch process's darker role – facilitating the mass production of explosives – provided me with a helpful look at the U.S. government's efforts to acquire Haber-Bosch technology during World War I.

Charles, Daniel. *Master Mind: The Rise and Fall of Fritz Haber, the Nobel Laureate Who Launched the Age of Chemical Warfare.* New York: HarperCollins, 2005.

This book did an excellent job illustrating Haber's life after his discovery of ammonia synthesis. Intensely loyal to Germany, in peace and in war, Haber's contributions were outweighed by his Jewish ethnicity when the Nazis came to power. He was ultimately forced into exile from the country on whose behalf he had worked so hard.

"Fritz Haber." http://www.chemheritage.org/classroom/chemach/gases/haber.html

This biography of Fritz Haber, provided by the Chemical Heritage Foundation, gave me a basic overview of Haber's professional career and the underlying chemical principles behind Haber's discovery.

Hager, Thomas. *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.

Hager's book sparked my initial interest in the Haber-Bosch process and remained my most valuable secondary source throughout my research. Hager's book provided me with important details of both Haber's scientific innovation and Bosch's technological ingenuity, along with the context needed to fully understand the importance of their work.

Leigh, G.J. *The World's Greatest Fix: A History of Nitrogen and Agriculture.* New York: Oxford University Press, 2004.

This comprehensive look at nitrogen's role in international agriculture, both historical and current, gave me useful background information on how the Haber-Bosch process has affected the global nitrogen cycle.

Mosier, Arvin R., Syers, J. Keith, and Freney, John R. (eds.) *Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment*. Washington, D.C.: Island Press, 2004.

A publication of SCOPE (the International Council for Science's Scientific Committee on Problems of the Environment), this set of essays and studies examined how nitrogen fertilizer has affected our world. In particular, this source helped me to understand how nitrogen fertilizers can negatively impact the environment and human health.

Smil, Vaclav. "Detonator of the Population Explosion." *Nature*, Vol. 400, July 29, 1999, p. 415.

This article, which appeared in the prestigious science journal *Nature* in 1999, explained why the Haber-Bosch process should be considered the most important innovation of the 20^{th} century.

Smil, Vaclav. *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production.* Cambridge, MA: The MIT Press, 2001.

Smil's comprehensive analysis of the Haber-Bosch process's impact on global agriculture gave me important statistics to support my thesis that the Haber-Bosch process has had a major role in shaping worldwide population patterns.

Stoltzenberg, Dietrich. *Fritz Haber: Chemist, Nobel Laureate, German, Jew.* Philadelphia: Chemical Heritage Press, 2004.

This biography of Fritz Haber, written by a chemist who attended Karlsruhe Institute of Technology, the institution where Haber made his breakthrough discovery, gave me a valuable look at Haber's complex personality.

"The Tragedy of Fritz Haber."
http://www.npr.org/programs/morning/features/2002/jul/fritzhaber/

This is a companion resource to an NPR special, based on Daniel Charles's work, that ran in 2002. It gave me an especially interesting look at how the Haber-Bosch process continues to affect society. This article profiled nitrogen pollution caused by inexpensive fertilizer generated by the Haber-Bosch process.

Zmaczynski, Raymond. "The Effect of the Haber Process on Fertilizers."
http://www.princeton.edu/~hos/mike/texts/readmach/zmaczynski.htm

This website, written by a researcher associated with Princeton University, gave me historical context on Haber's work by discussing other contemporary ways of obtaining nitrogen-based fertilizers.