From Air to Bread: The Haber-Bosch Process Feeds Multitude of Millions

> "The power of population is so superior to the power in the earth to produce subsistence for man..."
>
> - Thomas Malthus, Nineteenth-Century British Economist

The rise in world population during the mid-twentieth century placed a new strain on agriculture to create enough food, making it apparent that farming needed to be revolutionized to prevent starvation and famine. The development of the Haber-Bosch process, which converted air containing nitrogen gas and hydrogen to ammonia for use as a mass-produced synthetic fertilizer, transformed the global food supply, and the resultant global food production helped to sustain the increasing population. However, the nitrogen pollution caused by nitrogen not being absorbed by crops contaminated water and other resources. As a result, best management practices for nitrogen fertilization continue to be developed.

Technological advancements during the nineteenth and twentieth centuries in medical science, improved living conditions, the availability of clean water, more efficient disposal of raw sewage, and the introduction of food safety measures contributed to the global population increasing from one billion in 1825 to three billion in 1960 (Standage 227-228). New agricultural techniques relating to soil quality during the Agricultural Revolution in the eighteenth and nineteenth centuries met the need for more efficient crop placement to eliminate competition among nutrients (Standage 125). During the early twentieth century, over-farming, especially in Europe, began to deplete the soil of essential nutrients, mainly nitrogen. No major source of nitrogen existed within Europe, and most countries relied on Chilean nitrates, an extremely potent nitrogen fertilizer powder (Hager 7). William Crookes, president of the British Academy of Sciences, alerted the public of the impending nitrogen deficit and predicted that

although the population would continue to expand exponentially, available fertilizers might not last into the 1920s. Without a way to create synthetic fertilizers, the world faced starvation (Smil 58). Crookes sought solutions from the greatest minds in chemistry. As quoted in Hager, Crookes states, "It is the chemist who must come to the rescue. Before we are in the grip of actual dearth the chemist will step in and postpone the day of famine to so distant a period that we and our sons and grandsons may legitimately live without undue solicitude for the future" (9). European scientists realized that the potential existed to eradicate concerns about famine and modernize the large-scale production of food.

The key to innovations in food production lies in nitrogen, an important chemical element that is essential to life as a building block of amino acids, necessary proteins, and nucleic acids, all of which are major components in DNA and genetic material (Wolfe 44). Life forms, however, must acquire nitrogen from an outside source. Even though nitrogen comprises seventy-eight percent of the air, this inert gas cannot be used to provide the necessities of life. As a result, plants, animals and human beings require "fixed" nitrogen (Hager 6). Atmospheric nitrogen contains a triple covalent bond, making it unusable to most organisms but stable and unreactive in the atmosphere. Once broken down into an ion, it can be utilized by higher organisms. Unfarmed soil contains this form of nitrogen, which is absorbed by plants and then consumed by animals ("How Nitrogen" 45).

Because the environment produces limited amounts of fixed nitrogen, the planet cannot "fix" enough nitrogen to support billions of people without a human-made change in the nitrogen fixation process. Only two natural ways of fixing nitrogen into its usable form exist: Lightning that strikes the ground adds fixed nitrogen to the soil, and fixed nitrogen makes its way into the soil through bacteria that live on the roots of select crops (Standage 202). Rhizorbia, a bacterium

with a symbiotic relationship to such leguminous plants as peas and beans can fix nitrogen. Rotation of other crops with these plants continuously adds fixed nitrogen to the soil, but the amount of nitrogen provided by this bacterium remains inadequate to feed the global population. Farmers had long experimented with moving nitrogen throughout the soil using manures and composts, but this method was protracted and unsanitary (Smil and Christie 76). The creation of a new nitrogen source would prove to be a more efficient method (Hager xiii).

Germany, like the rest of Europe, needed to find an alternative source of nitrogen to fertilize the land, but without Chilean nitrates, its crop yield would plummet. German scientists began attempting to fix nitrogen in the lab, but this was an extremely difficult task. In 1904, chemist Fritz Haber researched the synthesis of ammonia directly from hydrogen gas and nitrogen in the air (Standage 205-207). Ammonia contains fixed nitrogen, and if it could easily be synthesized and put into fertilizers, it could transform Germany into a nitrogen exporter rather than a nitrogen importer (Stoltzenberg 80-81).

Prior to Haber, scientists had tried unsuccessfully to create ammonia (Stoltzenberg 80-81). Haber initially struggled to find the right temperature and pressure conditions (Haber, "Synthesis"). Finally, Haber discovered that at about 1,000° C, the hydrogen and nitrogen atoms would bond, but the extreme heat almost immediately disintegrated the compound, which contained only about one hundredth of one percent of ammonia. Haber became discouraged in his attempt to synthesis ammonia, but criticism from Walther Nernst, a rival chemist, sparked his resolve (Charles 84-85).

Nernst had developed a heat theorem, the third law of thermodynamics, and predicted how much ammonia Haber should have been able to yield (Standage 207-208). Nernst advised Haber that his numbers were wrong and that he planned to recreate the experiment and report his

own findings at a conference of chemists to contradict Haber's results and affirm the correct method to synthesize ammonia (Haber, "Synthesis"). The public insult infuriated Haber, who repeated his experiment and obtained an ammonia yield much closer to what Nernst had predicted. Haber altered some conditions of his experiments, and the results represented a marked change in nitrogen fixation and ammonia synthesis (Charles 85-87).

Haber, who was on the verge of making a significant scientific breakthrough, would soon reach a defining moment in large-scale food production. He predicted that if he doubled the pressure in his reaction chamber, decreased the temperature to about 600° C, and modified his catalyst to include uranium, his output would achieve an ammonia yield of eight percent (Standage 208). However, his equipment proved incapable of withstanding such high pressure. Carl Engler, an academic mentor to Haber, introduced him to Badische Anilin and Soda-Fabrik (BASF), the leading German chemistry company at the time. Engler also was a member of the board of directors of the company. BASF was trying to synthesize ammonia, albeit through different methods, but with little success. BASF agreed to fund Haber's experiments, provided that he reported all results to the company. With this new funding, Haber built an apparatus that could endure double the pressure of normal atmospheric pressure. Additionally, the new device contained a cooling chamber that eliminated the risk of destroying the manufactured ammonia. Haber's altered experiment ultimately produced commercially useful synthetic ammonia (Stoltzenberg 86-87).

Haber improved his experiment to create an ammonia yield of ten percent, a result much higher than anything BASF had generated. One of BASF's representatives was Carl Bosch, a senior chemist who had worked extensively with nitrogen. Bosch believed that Haber's device required steel modifications to support the mass synthesis of ammonia (Charles 93-94). Bosch's

first reactors, about four times the size of Haber's, had failed after eighty hours of work, but they were still considered a major accomplishment. Bosch redesigned the steel tubes to provide additional support, developed new safety valves to relieve the pressure on the machine, and improved the heat exchange systems to reduce the energy required for the process. By 1912, Bosch was constructing larger devices that used nitrogen from the air and hydrogen extracted from coal to fuel the process and create more than a ton of ammonia per day (Bosch). The Haber-Bosch process, the industrialization of synthetic ammonia, had become a reality.

Haber's seminal scientific breakthrough and Bosch's efforts to mass-produce ammonia revolutionized food production. The initial plant opened in Oppau, Germany, in 1914 and produced 20 metric tons of ammonia and 36,000 tons of fertilizer per day (Standage 209-211). Haber and Bosch won the Nobel Prize in chemistry for their contributions to ammonia synthesis and the invention and development of chemical high-pressure methods, respectively. Together, Haber and Bosch transformed agriculture and reduced concerns about a potential famine in Germany ("Two German" 10). However, the Haber-Bosch process also would profoundly impact food production with respect to worldwide population growth.

Although not abrupt, subsequent reactions to the Haber-Bosch process confirmed the significance of this historic breakthrough. BASF commissioned the construction of an additional ammonia synthesis plant in Leuna, Germany. In response, production rates continued to flourish (Bosch). Industrialization of the process occurred during World War I, and Germany's synthesized ammonia went towards chemical weaponry and the maintenance of nitrogen-rich soil without the need to import fertilizer, subsequently prolonging the war for Germany (Pearce). Bosch continued to refine the process, and the usage of synthesized ammonia rose until it

overtook Chilean nitrates in the 1930s. The Haber-Bosch process was accepted and used globally after WWI, bringing benefit to soils outside of Germany (Smil 105-107).

Germany, which was fighting another world war in 1944, was more concerned about war efforts than population growth and would wait until after the war to experience major agricultural and population advancements. Ammonia synthesis would be repeated by other organizations all over the world, and other nations soon began to produce nitrogen fertilizers (Standage 213-214). However, increased nitrogen yield to normal crops caused the seeds to outgrow the stalks; as a result, plants collapsed under the amplified weight of the nitrogen yield. The Haber-Bosch process now required a more durable crop to accommodate the increase in nitrogen absorption. In response, farmers began to plant "dwarf" plants to ensure the effective application of new fertilizers and maximize crop production. Dwarf plants have shorter stalks, require less energy to grow and can support larger seeds (Anderson 240).

Fertilizers developed from the breakthrough Haber-Bosch process had the potential to increase worldwide crop yields, but it would take an innovator's initiative to globalize this new knowledge. Norman Borlaug, an American agronomist, guided the development of dwarf plants and oversaw the spread of this agricultural improvement to such famished and impoverished countries as Mexico, India and Japan. Borlaug was sent to Mexico in 1944 on behalf of the Rockefeller Foundation, which had been established to challenge the economic, social, medical, and environmental problems of humankind, to improve crop yields and reduce dependency on grain imports (Standage 214). He worked extensively to develop wheat varieties resistant to stem rust, a disease that weakened the stems of wheat and had destroyed almost half of Mexico's wheat harvest. He cross-bred local wheat crops until he produced a plant that was resistant to stem rust and could produce a forty percent higher crop yield (Shenker 18). This stunning

increase in food production became known as the Green Revolution. Borlaug subsequently educated farmers around the world about the potential to breed plants to produce higher yields (Sterba 23). Influenced by mass-produced synthetic nitrogen fertilizers created by the Haber-Bosch process, the Green Revolution became instrumental in reducing hunger worldwide (Degregori 503).

By 1970, the Green Revolution and the Haber-Bosch process had critically impacted global food production by helping it to keep pace with population growth (Conway 269). Borlaug received the Nobel Prize for his efforts in leading the Green Revolution and powering the effort to end global famine (Anderson 240). Borlaug's techniques had taught the world to feed itself. However, Borlaug readily admitted that his work would not have been possible without the Haber-Bosch process (see fig.1). He states, "If the high-yielding dwarf wheat and rice varieties are the catalyst that have ignited the Green Revolution, then chemical fertilizer is the fuel that has powered its forward thrust" (Borlaug). The Green Revolution caused an eight-fold increase in the usage of synthetic nitrogen fertilizers, which eventually would feed at least three billion people (Pearce). Created by the Haber-Bosch process, synthetic fertilizers eliminated the potential for catastrophic global famine, but this watershed in human history also resulted in unanticipated consequences.

World Population and Ammonia Production

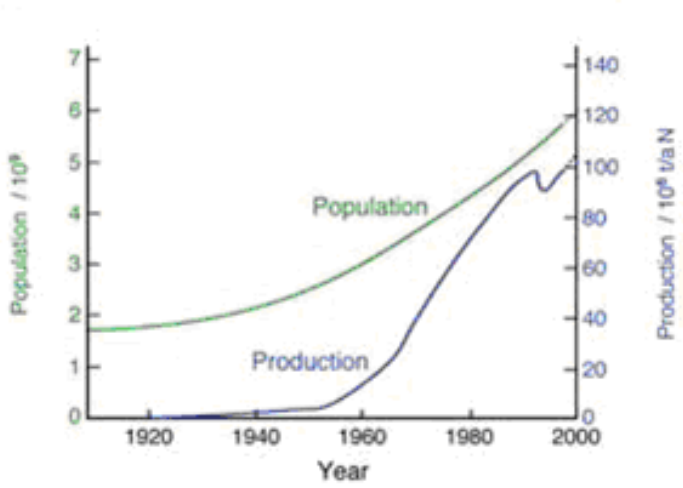


Fig. 1. World population growth and production of ammonia during the 20th century. Ertl, Gerhard. "Reactions at Surfaces: From Atoms to Complexity." 8 Dec. 2007. *Nobelprize.org*. Web. 23 Jan. 2012.

The development of synthetic fertilizers responded to the demand to increase food production to keep pace with population growth, but environmental concerns also emerged, one of which was nitrogen pollution. Ammonia volatizes, or evaporates, out of soil and into the atmosphere, negatively affecting air quality. If extra ammonia remains in the soil, the nitrogen in the compound can leak into groundwater and lead to major health concerns, including cancer and the inability of the blood to carry oxygen (Foster). Overabundance of nitrogen stimulates algae growth, increasing toxins and decreasing dissolved oxygen in water. This overabundance of algae can kill aquatic plants and animals, and create a dead zone (Buchsbaum).

Excess nitrogen in the soil can exacerbate global warming. Of the 80 million tons of nitrogen fertilizer spread on soil yearly, only 17 million tons are absorbed into food (Pearce). Nitrogen can be converted to greenhouse gases when warm temperatures coexist with inadequate

amounts of oxygen in the soil, such as after a rainstorm. The rain causes these gases to escape from the soil and contribute to the destruction of the ozone layer, subsequently escalating global temperatures (Stoner). Other problems with the manufacture of synthetic fertilizers include the rising cost of oil, an essential component needed to fuel the Haber-Bosch process. As oil prices rise, fertilizer production and sale prices also rise (Neurath 145-147).

Efforts continue to use best management practices to reform the use of nitrogen fertilizers and lessen the impact of nitrogen pollution. One such practice is the monitoring of the amount and rate of nitrogen fertilizer applied to crops (Foster). Additional measures to decrease excess nitrogen in the soil include the use of cover crops and rotating crops, both of which require different amounts of nitrogen for optimal yield. Cover crops such as wheat and rye capture residual nitrogen, which would be carried away by groundwater or would evaporate into the atmosphere, and use it for growth and nutrition (Buchsbaum). With respect to crop rotation, a corn crop, for instance, uses nitrogen inefficiently and must be rotated with another crop, such as a legume, which uses nitrogen more effectively by taking excess nitrogen out of the soil and reducing pollution (Drinkwater and Snapp 170). Finally, the development and use of synthetic nitrogen fertilizers cannot feed the entire world efficiently because of continuing problems with food distribution in parts of Africa, Asia, and so on. Even though enough food is produced to feed the entire world, poverty, inefficiencies of market and transportation systems, and unpredictable prices hinder people's efforts to feed themselves ("Inadequate Food").

The Haber-Bosch process, which converted air containing nitrogen gas and hydrogen to ammonia for further use as a mass-produced synthetic fertilizer, became one of the most important discoveries of the 20th century. According to Smil, the Haber-Bosch process is "the single most important change affecting the world's population - its expansion from 1.6 billion

people in 1900 to today's 6 billion - would not have been possible without the synthesis of ammonia" (xiii). This ammonia synthesis process transformed the world's food supply, and the resulting global food production has helped to sustain the rapidly increasing population. Indeed, Thomas Malthus underestimated the power of science and the power of man. The Haber-Bosch process remains a scientific breakthrough that has had far-reaching significance in allowing Earth to support its burgeoning human population.

Annotated Bibliography

Primary Sources

Anderson, Alan, Jr. "The Green Revolution Lives." *New York Times* 27 Apr. 1975: 240. *ProQuest Historical Newspapers*. Web. 23 Jan. 2012.

In this article, Norman Borlaug discusses the Green Revolution in response to advances made by the Haber-Bosch process. It explains what he hoped to accomplish and the efforts he made to decrease famine.

Borlaug, Norman. "The Green Revolution, Peace, and Humanity." 11 Dec. 1970. *Nobelprize.org*. Web. 22 Jan. 2012. <http://www.nobelprize.org/nobel_prizes/peace/laureates/1970/borlaug-lecture.html>.

Borlaug's Nobel lecture discusses his work with dwarf plants and nitrogen-based fertilizers. Millions of people have benefited from Borlaug's advances in agriculture. His lecture explains his work and the effects of the Haber-Bosch process.

Bosch, Carl. "The Development of the Chemical High Pressure Method during the Establishment of the New Ammonia Industry." 21 May 1932. *Nobelprize.org*. Web. 26 Nov. 2011. <http://www.nobelprize.org/_prizes////lecture.pdf>.

Bosch's lecture tells of his work of ammonia synthesis. It provides scientific explanation of the industrialization, or mass production, of the Haber process, which then became known as the Haber-Bosch process.

Buchsbaum, Andy. "Nutrient Pollution." *Congressional Testimony* (Oct. 2011). *eLibrary*. Web. 4 Oct. 2011.

This testimony offered by Mr. Andy Buchsbaum, regional executive director of the Great Lakes Natural Resources Center to the Senate Environment and Public Works

Subcommittee on Water and Wildlife, emphasizes how nitrogen pollution is one of the most significant threats to waters throughout the world. Mr. Buchsbaum is actively involved in reform efforts by introducing best-management practices in nitrogen fertilization.

Ertl, Gerhard. "Reactions at Surfaces: From Atoms to Complexity." 8 Dec. 2007. *Nobelprize.org*. Web. 23 Jan. 2012. <http://www.nobelprize.org/_prizes////_lecture.pdf>.

This Nobel lecture contains useful information and a graph comparing world population and ammonia production. This lecture also provides information about the application and significance of the Haber-Bosch process.

Haber, Fritz. "The Synthesis of Ammonia from its Elements." 2 June 1920. *Nobelprize.org*. Web. 26 Nov. 2011. <http://www.nobelprize.org/_prizes////lecture.pdf>.

Haber's lecture describes ammonia synthesis and its impact on the world from Haber's point of view.

- - -. *Thermodynamics of Technical Gas-Reactions*. New York: Longsman, Green, 1908. *archive.org*. Web. 26 Nov. 2011.

This extensive report provides detailed information about the scientific process of ammonia synthesis. Written by Haber, these lectures were initially intended to advise his colleagues about his chemical experiments.

"Says Man May Live on Thousand Years." *New York Times* 22 Sept. 1924: 9. *ProQuest Historical Newspapers*. Web. 23 Jan. 2012.

The newspaper article describes the historical perspective prior to Haber's invention. His view suggests that world population would outpace food production. Haber briefly explains how he believed his process would prolong humankind's existence.

Sheeran, Josette. "Global Food Crisis." *Congressional Testimony* (May 2008). *eLibrary*. Web. 6 Jan. 2012.

The testimony provided by Josette Sheeran, executive director of the World Food Progamme United Nations to the Senate Foreign Relations Committee, highlights the benefits of the industrialization of ammonia synthesis and how the Haber-Bosch process and the Green Revolution assist her efforts as executive director in combating the global food crisis.

Shenker, Israel. "'Green Revolution' has Sharply Increased Gain Yields but May Cause Problems." *New York Times* 22 Oct. 1970: 18. *ProQuest Historical Newspapers*. Web. 23 Jan. 2012.

Shenker describes the impact of the Green Revolution on world hunger and also explains the drawbacks of the Revolution. The article explains that the Green Revolution is a direct result of the Haber-Bosch process on the world population.

Sterba, James P. "The Green Revolution hasn't Ended Hunger." *New York Times* 15 Apr. 1973: 23. *ProQuest Historical Newspapers*. Web. 23 Jan. 2012.

Sterba describes the Green Revolution, what it attempts to accomplish, and how it relates to and benefits from the Haber-Bosch process.

Stoner, Nancy K. "Nutrient Pollution." *Congressional Testimony* (Oct. 2011). *eLibrary*. Web. 4 Oct. 2011.

The testimony by Nancy K. Stoner, acting assistant administrator for Water for the United States Environmental Protection Agency (EPA) to the Senate Environment and Public Works Subcommittee, discusses the efforts of the EPA to improve water quality as a result of excess nitrogen in the environment consequential of the Haber-Bosch process.

"Two German Chemists Share Nobel Prize; Make Ammonia from Air, Gasoline from Coal." *New York Times* 13 Nov. 1931: 10. *ProQuest Historical Newspapers*. Web. 23 Jan. 2012.

This article announces that Bosch is to receive the Nobel Prize for his work on the large-scale production of ammonia. It also briefly explains the process in easily understood terms.

Secondary Sources

"Agency Claims U.S. Streams, Groundwater Remain Harmed by N, Other Nutrients." *Corn and Soybean Digest*. 04 Oct. 2010. *eLibrary*. Web. 6 Jan. 2012.

This article discusses water pollution caused by an abundance of nitrogen in the water. The excess nitrogen is run-off from highly based nitrogen fertilizers created by the Haber-Bosch process.

"Carl Bosch Biography." *Nobelprize.org*. Nobel Media, 2011. Web. 26 Nov. 2011. <http://www.nobelprize.org/_prizes////.html?print=1>.

This biography of Carl Bosch provides insight into his rise in the chemistry world. It explains how Bosch contributed to the Haber-Bosch process and the advancements that could not have been made without him.

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

This book describes Haber's life. It includes Haber's motivations and insights while he was developing his ammonia synthesis process.

Clark, Jim. "The Haber Process." *Chemguide*. Jim Clark, 2002. Web. 6 Nov. 2011. <http://www.chemguide.co.uk///.html>.

Clark provides an in-depth explanation of all scientific aspects of the Haber-Bosch

process and exactly what must be done in order to synthesize ammonia. This source also presents a chart that shows the flow scheme of the process.

Conway, Gordon. "Presidential Address: The Food Crisis." *Geographical Journal* (Sept. 2008): 269. *eLibrary*. Web. 6 Jan. 2012.

The journal article discusses how hunger continues to be a long-term problem facing the world. Even with Haber-Bosch ammonia synthesis and nitrogen fixation, the exponentially increasing world population may prove difficult to sustain in terms of food production.

DeGregori, Thomas R. "Green Revolution Myth and Agricultural Reality?" *Journal of Economic Issues* 38 (June 2004): 503. *eLibrary*. Web. 6 Jan. 2012.

DeGregori compares the benefits and disadvantages of the Green Revolution and its impact on hunger and pollution. In addition, it affords a detailed description of how nitrogen-based fertilizer is created through the Haber-Bosch process.

Drinkwater, L. E., and S. S. Snapp. "Nutrients in Agroecosystems: Rethinking the Management Paradigm." *Advances in Agronomy* 92 (2007): 163-186. Print.

In this source, the authors include information about how the agricultural system needs to be reformed with the use of nitrogen fertilizers created by the Haber-Bosch process.

"The Fate of Nitrogen in Grain Cropping Systems: A Meta-Analysis of 15N Field Experiments." *Ecological Applications* (2007): 2167-2184. Print.

This extensive journal provides information regarding the pollution of the planet caused by nitrogen fixation, such as the Haber-Bosch process. It also offers some useful graphs and figures that show the rate of pollution.

Foster, Shelby. "Re: Research Questions." Message to Mr. Charlie White. 17 Jan. 2012. E-mail.

My e-mail interview with Mr. White, Pennsylvania State University Extension associate, Sustainable Agriculture, focused on how excess nitrogen impacts the environment and current practices to reform the fertilization process to avoid further nitrogen pollution.

Hager, Thomas. *The Alchemy of Air*: *A Jewish Genius, a Doomed Tycoon, and the Discovery that Fed the World but Fueled the Rise of Hitler.* New York: Three Rivers Press, 2008. Print.

Hager's book about Haber and Bosch provides information on the ammonia synthesis process. It also explains the pollution created by the process.

"How Nitrogen Came to Life." *Max Planck Research* (2004): 44-49. *Max-Planck Gesellschaft*. Web. 24 Jan. 2012.

This source, from a German journal that extends from a German research institute, explains the importance of nitrogen in the world with respect to soil, plants and animals.

"Inadequate Food Distribution Systems." *Mission 2014*. Massachusetts Institute of Technology, n.d. N. pag. Web. 1 Apr. 2012. <http://12.000.scripts.mit.edu/mission2014/problems/inadequate-food-distribution-systems>

This source provides information about why famine still exists, even though enough food is produced to feed the entire world. Poverty and corruption affect the ability of people to acquire the food that they need.

Kiewitz, Susanne. "The Highs and Lows of a Scientific Genius." *Max Planck Research* (Apr. 2011): 94. *Max-Planck-Gesellschaft*. Web. 7 Jan. 2012.

This summary of the triumphs and downfalls of Fritz Haber's scientific career contains information about the creation of the Haber-Bosch ammonia synthesis process.

Malthus, Thomas. *An Essay on the Principle of Population*. London: Electronic Scholarly Publishing Project, 1998. 4. *Electronic Scholarly Publishing*. Web. 8 Feb. 2012. <http://www.esp.org/books/malthus/population/ malthus.pdf>

This book contains an essay written by Thomas Malthus, an economist who predicted that food supply could not keep pace with population growth. This quote was used as an introduction to the paper.

Mancus, Philip. "Nitrogen Fertilizer Dependency and its Contradictions: A Theoretical Exploration of Social-Ecological Metabolism." *Rural Sociology* (June 2007): n. pag. *eLibrary*. Web. 14 Dec. 2011.

In this article, Mancus discusses the reform of the world after the industrial synthesis of ammonia through the Haber-Bosch process. It depicts how people have become increasing dependent on the process in order to survive.

Neurath, Paul. *From Malthus to the Club of Rome and Back: Problems of Limits to Growth, Population, Control, and Migrations*. Armonk: M.E. Sharpe, 1994. Print.

This source contains valuable information about events, such as the Industrial Revolution that have affected population growth. It also provides information about problems with reform related to rising oil prices.

"New Chemicals: Ammonia." *Making the Modern World*. The Science Museum, 2004. Web. 6 Nov. 2011. <http://www.makingthemodernworld.org.uk//the_second_industrial_ revolution/.ST.01/?scene=5>

This website offers information about how nitrogen was introduced to crops prior to the Haber- Bosch process. In addition, it conveys how Carl Bosch became involved by industrializing the process that Haber invented.

Pearce, Fred. "The Nitrogen Fix: Breaking a Costly Addiction." Environment 360. Yale, 5 Nov. 2009. N. pag. Web. 1 Apr. 2012. <http://e360.yale.edu/feature/the_nitrogen_fix_breaking_a_costly_addiction/2207/>.

This source provides valuable information about Germany's lack of nitrogen prior to World War I and how the nation would have fared without the development of the Haber-Bosch process.

Pietschmann, Catarina. "Gerhard Ertl." *Max Planck Research* (Jan. 2008): 74-78. *Max-Planck-Gesellschaft*. Web. 7 Jan. 2012.

This article from a German research institute speaks of the work that Gerhard Ertl conducted with the Haber-Bosch process by realizing the necessity of using an iron oxide catalyst.

Ribaudo, Marc, et al. "Nitrogen in Agricultural Systems: Implications for Conservation Policy." *Economic Research* 127 (Sept. 2011): 1-27. Print.

This journal by Ribaudo includes many useful graphs and charts that make the effects of the Haber-Bosch process easily understood. Moreover, it includes significant information about nitrogen fixation and pollution.

Smil, Vaclav. *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production*. Cambridge: MIT Press, 2004. Print.

Smil relates the Haber-Bosch process to world population growth and explains how the process affected food production. Furthermore, it presents interesting insight about the process as the most important of recent centuries.

Smil, Vaclav, and Bryan Christie. "Global Population and the Nitrogen Cycle." *Scientific American* (July 1997): 76-81. *eLibrary*. Web. 14 Dec. 2011.

This article is co-written by Vaclav Smil, a prominent author about the Haber-Bosch ammonia synthesis process. It directly relates the process to the huge increase in the world population.

Standage, Tom. *An Edible History of Humanity*. New York: Walker & Company, 2009. Print.

In this book, Standage relates food production to the Haber-Bosch process. In addition, it links the process to the Green Revolution and includes the negative effects on the environment. Lastly, the source includes information on Norman Borlaug and his work with the Green Revolution.

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

Haber's biography provides information about his life and scientific career. It explains Haber's motivation to study ammonia synthesis and the initiative to create the world-changing process.

Townsend, Alan R., and Cheryl A. Palm. "The Nitrogen Challenge." *Bioscience* (Nov. 2009): 822. *eLibrary*. Web. 6 Jan. 2012.

This journal discusses the timely necessity of a nitrogen fixation process in the early twentieth century and Haber's beginning work with the process.

"The Tragedy of Fritz Haber." npr, 2012. Web. 6 Nov. 2011. <http://www.npr.org///////>.

Although this source provides some information on how the Haber-Bosch process benefits agriculture, it additionally gives insight on how it has caused mass amounts of pollution.

Wolfe, David. "Out of Thin Air." *Natural History* 110 (Sept. 2001): 44. *eLibrary*. Web. 6 Jan. 2012.

Wolfe explains the necessity of the Haber-Bosch process to a growing population. It also goes into significant detail about the conditions and materials needed for Haber's process.