Feeding a Hungry World: The Triumph of Synthetic Fertilizers

Travis P. Hignett Memorial Lecture

September 16, 2009

Muscle Shoals, Alabama (U.S.A.)

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Prepared by
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Fourth Travis P. Hignett Memorial Lecture

The Travis P. Hignett Memorial Lecture Series was initiated during 1994 by IFDC to honor a distinguished chemist, chemical technologist and developer, author, and administrator. Mr. Hignett (1907-89) received global recognition for his many accomplishments in the fertilizer world over a period of some 50 years. After a 35-year career with the Tennessee Valley Authority, Hignett served as a special consultant at IFDC for more than a decade. Often referred to as the "Father of Fertilizer Technology," Hignett held 15 patents and was the author of approximately 150 publications. He received a number of awards, including the Francis New Memorial Medal from the Fertiliser Society of London in 1969. This lecture series is being sponsored by the Hignett Memorial Fund, which was established in 1987 to honor Mr. Hignett.

Feeding a Hungry World: The Triumph of Synthetic Fertilizers[1]

Thomas Hager

I first want to say a few words about Norman Borlaug. In addition to being a Nobel laureate and a great humanitarian, Dr. Borlaug was a long-time board member of IFDC and a previous Hignett Lecturer. His dedication to and success in developing high-yield strains of wheat and rice helped to create what is now called the "Green Revolution," in the 1970s and 1980s. Maximizing those yield increases required more than new strains of cereal crops. It is important to remember as well that Dr. Borlaug's Green Revolution also depended on the discovery I will talk about today: the development in 1909 of an effective method to produce synthetic fertilizers. Dr. Borlaug was straightforward in noting the interdependence of these two developments: the creation of higher-yielding crop strains and the synthetic fertilizers to feed them. We all owe Norman Borlaug a debt of thanks.

Dr. Norman Borlaug

I believe that the development of a cost-effective way to make synthetic fertilizers ranks among the most important scientific developments of the past two centuries. This is because, put simply, it is keeping alive more than two billion people (and, by some estimates, even more, perhaps one-half of the people alive on earth today). About half the nitrogen atoms in your body come from synthetic fertilizers. Much of the work carried out here at the TVA, and certainly much of the work done at IFDC involves synthetic fertilizers and the role that they play in agriculture today in the world.

Dr. Norman Borlaug

[1]Travis P. Hignett Memorial Lecture, IFDC, September 16, 2009, Muscle Shoals, Alabama.

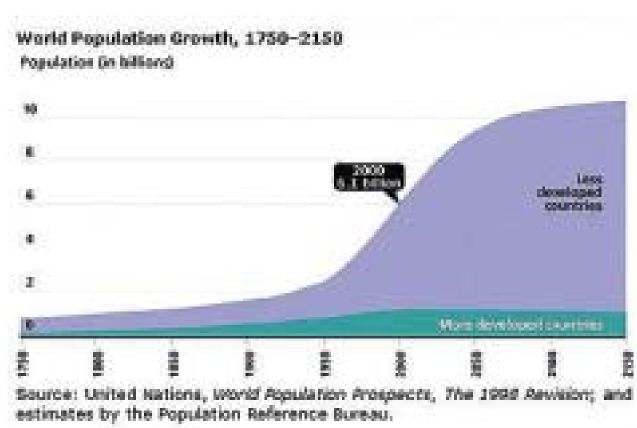
Today I will take you back to the beginnings of this vital technology. I want to start with an admission: I am not a scientist. Many people in this auditorium today are scientists. Many of the people I will be talking about during my lecture are scientists. But I am not. I am a journalist. I am a writer. I have training in science, but I do not do research. What I do is tell stories. And the stories I will tell today are some of the best I've ever come across.

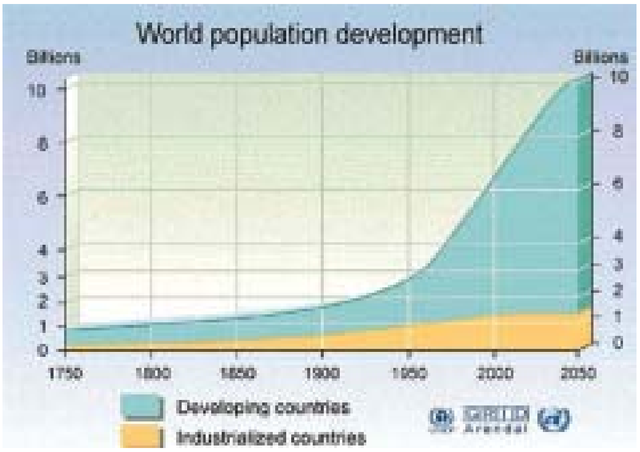
Some 200 years before Dr. Borlaug we had the Reverend Dr. Thomas Malthus. Many of you know Malthus by name. He was the fellow credited with the idea that populations rise at a geometric rate while food production rises much more slowly – in other words, two parents have, say, four children, those four have eight, and the eight have 16 (the usual sort of progression there). The standard graph of population growth looks like a hockey stick, rising slowly at first, then rapidly. We are in the middle of population growth that is almost vertical. Food production, on the other hand, goes up in bits and pieces, a field at a time. As a result, Malthus foresaw, growing populations will outstrip their food supplies. When that happens, people begin to starve.

Dr. Thomas Malthus

Malthus's reasoning was perfectly logical. His mathematics was correct. Populations generally have risen in the geometric pattern he predicted. The only problem is that his predictions of starvation did not come true. This is because – and this would have astonished Malthus – food production has kept pace with population. This happened first because, from the late 1700s through the mid-1800s, vast new areas of the earth came under the plow: the Great Plains of the United States, the steppes of Russia, and large grain-growing regions in Australia, among other places. The dramatic increase in rich, arable land helped produce enough grain to stave off mass starvation until the beginning of the twentieth century.

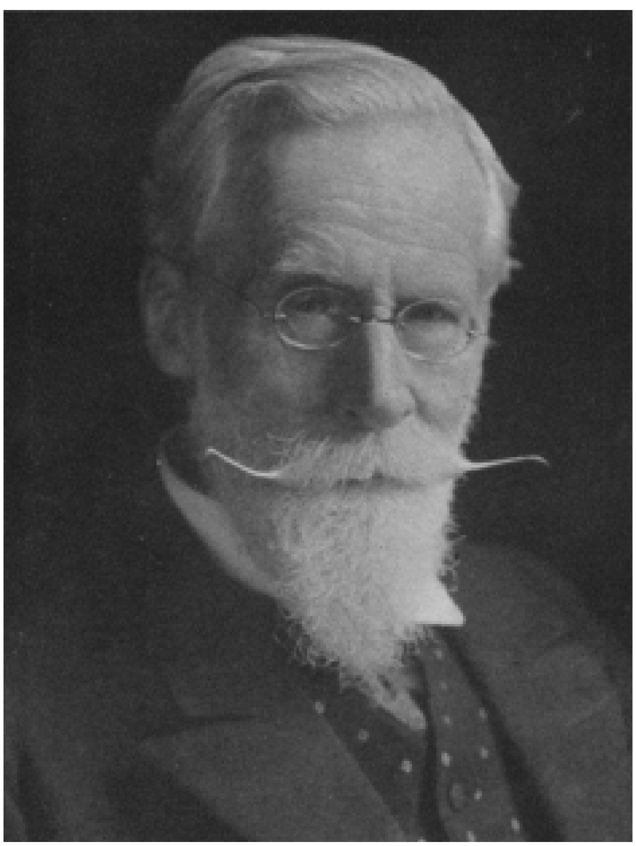
It was then that Sir William Crookes came along. In 1898 Crookes, a British chemist and physicist, was elected president of the British Scientific Association. The organization counted among its members many the brightest scientific minds of the time. Crookes was him-





self an eminent researcher, discoverer of the element thallium and inventor of "the Crookes Tube," a predecessor to the cathode ray tubes used in old-fashioned televisions. He was, in 1898, newly knighted and at the peak of his professional life.

But he was also an independent-minded fellow. In his first address as President of the association, he decided to shake things up a bit. Presidential talks of the day



Sir William Crookes

were usually long, dry recitations of the successes of British science and the achievements of British scientists. Crookes didn't want to give that kind of speech.

Instead, he began his address to a hall filled with the cream of British science in evening attire, with a flat statement: "England and all civilized nations," he said, "stand in deadly peril."

The hall grew quiet. Then he told them why. It was because, he said, Malthus, after a century and a half, was about to be proven right. The world's population, which in 1898 was around one billion people, was rising at a dramatic rate. Recent advances in medicine, public hygiene and public health were driving down mortality rates. The Industrial Revolution had spurred the explosive growth of cities, and farmers had begun migrating to urban areas. At the same time, all the earth's largest and most accessible arable areas were already being farmed. There were no more Great Plains.

There was only one reason people had not begun starving already, Crookes said: fertilizer. Humans were increasingly reliant on fertilizers to boost crop yields. For millennia farmers had used manures and composts to enrich their fields, as well as burnt bones, fish carcasses, kelp, blood, urine, and any of a hundred other substances that could boost fertility. In the 1840s a trade blossomed in bird guano from a few arid islands off the coast of Peru. This was, for two decades, the most important, richest fertilizer on Earth. It was full of both nitrogen and phosphorus. It was worth a fortune. A war was fought over it. It did not take long to strip a million years accumulation from the Peruvian rocks, and despite scouring the world, no sources of similar quality were ever found again.

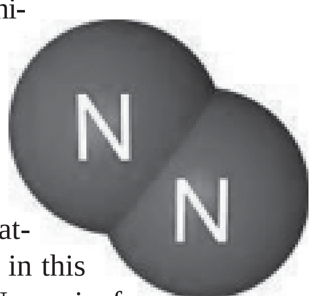
The agricultural world turned to another massive source of fertilizer found in the driest place on earth, the Atacama Desert of South America. The rocks there were laced with a natural layer of sodium nitrate, an effective source of nitrogen for plants. Millions of tons of it were mined and shipped to Europe and America. By Crookes's time, the richest deposits were already gone. Estimates were being made of how long the remaining nitrate would last.

Crookes explained this to his audience, and then offered his own estimates, indicating that by the 1930s or 1940s the world was going to start running out of South

American nitrate. When that happened cereal yields (especially wheat) would begin to decline, and populations would begin starving.

The answer to this catastrophe, he told his rapt audience, was chemistry. What nature could not provide, scientists would have to synthesize. The key, he said, was to find a way to make synthetic fertilizer.

And he knew where it had to come from. We are sitting in the middle of it. This auditorium is full of fertilizer. The air around us is almost 80 percent nitrogen, the most important elemental component of mixed fertilizers. The problem is that nitrogen in the air does us no good at all. No plants can use it. No animals, either. We breathe it in and out all day without using a single molecule. This is because atmospheric nitrogen exists in this form, called dinitrogen, or N_2, a pair of nitrogen atoms bound together with a triple covalent bond, one of the strongest chemical bonds found in nature. It's extraordinarily hard to break them apart. But they have to be broken apart to make the nitrogen available for biological processes.



Very few things in nature can tear dinitrogen apart. One of them is a bolt of lightning. The electric charge in a lightning bolt is powerful enough to break up the dinitrogen around it, and some of the freed nitrogen atoms quickly combine with other chemical components in the air, creating an array of chemical compounds that living creatures can use. The process is called nitrogen fixation.

Lightning bolts, however, don't fix very much nitrogen. Far more important are these organisms. The little nodules on these roots are full of nitrogen-fixing bacteria, microscopic creatures that have figured out how to break dinitrogen apart at room temperature using enzymes – a very clever trick that today's scientists are having a hard time duplicating. Plants cannot pull this off; only bacteria can. Often these nitrogen-fixing bacteria will enter into a symbiotic relationship with plants, as they are in these nodules, trading fixed nitrogen to the plants in exchange for plant-created nutrients like sugars. Peas, beans, soybeans, and legumes in general, have this power, as do clovers and other types of plants that farmers learned long ago to use in crop rotations. They provide a natural means of putting usable nitrogen back in the soil.

These two sources, lightning and nitrogen-fixing bacteria, created virtually all of the nitrogen available for growing crops in Crookes's day. Over eons they slowly stocked the Earth's storehouse. Once fixed, the nitrogen could be passed from molecule to molecule, organism to organism, from the air to soils, soils to plants, plants to animals. The plants and animals died and rotted and some of the nitrogen went back into the air, some ended up in water, some in soil, some to other living things, creating the complex web we call the nitrogen cycle.

The problem for farmers was that there was never enough of it. Despite all of their manuring schedules and crop rotations, their careful composting and application of South American nitrates by the ton, crop yields were just barely keeping up with a fast-growing population. When the nitrates were gone, the game would be over.

Crookes, in his speech, laid down a challenge to chemists. He asked them to find a way to use modern science to find a way to make synthetic fertilizers, harvesting it from the air, by the ton, economically. He made it clear that humanity's continued progress depended on it.

There were reporters in the audience; his words were carried by newspapers around the world, and his speech became a sensation. It was something like the Global Warming of its day. A number of scientists accepted his challenge and went to work. Some were interested in doing good for humanity, of course, and solving the problem of world hunger. Some were drawn by the chance for fame. Others were lured by money, because whoever found a way to fix nitrogen in bulk would have a corner on the world fertilizer market and would become very wealthy. Not all scientists are altruists!

A number of researchers felt that the only way to make synthetic fertilizer was to burn it out of the air with an artificial lightning bolt. In the USA one of Thomas Edison's former assistants, a young man named Charles Bradley, patented a machine to do just that. Bradley and his partner, a man named Lovejoy, tried to catch lightning in a bottle with a sort of Rube Goldberg contraption with one big metal cylinder spinning inside another, wired for high-voltage, creating a series of high-intensity electrical arcs as contacts whizzed by one another. The machine required so much electricity that they had to build it near Niagara Falls, site of the only cheap bulk voltage in America. By blowing air through their miniature lightning bolts, they created a significant amount of fixed nitrogen. Unfortunately, much of it was in the form of nitric acid, which corroded their wiring and ruined their efforts. After a few years they had to give up.

Niagara Falls

In Norway, Sven Birkeland, a Norwegian researcher, attacked the problem. Birkeland was a brilliant chemist and physicist who was also something of an eccentric. He spent much of his time trying to figure out what the Northern Lights were made of. He needed money for his investigations, and in order to make it, he decided to go into the synthetic fertilizer business. He found a way to take an electric arc and put magnets around it so that the arc spread out and made sort of a circle of flame – a six-foot wide disc of high-intensity energy. By blowing air through the flame, nitrogen could be burned out.

Birkeland was a better engineer than Bradley and Lovejoy had been, and he actually got his system to work. It also required a huge amount of electricity to make those flames, so he teamed up with a business-

Sven Birkeland

man in Norway who traveled from farm to farm and bought waterfalls from the farmers. They had a stock of waterfalls. They ended up building a plant that worked and then they built a bigger one in the side of a mountain, using water from a mountain lake piped through a tunnel in the mountain to generate electricity. They figured out how to solve the acid problem and made a lot of fixed nitrogen in the form of calcium nitrate, which was marketed as Norwegian saltpeter. But it was not a perfect system. The process was very expensive. It used enormous amounts of electricity. The machinery to build the plant was costly and finicky.

Keeping the flames going was difficult. It was something that could be scaled up to factory size but it was so expensive that the fertilizer it made was too costly for farmers to use. The search went on.

It continued here at Muscle Shoals, Alabama. An entrepreneur named Frank Washburn came here because it looked like a good place to build a dam to generate electricity, which he needed to make fertilizer through a system called the cyanamid process. It works through a series of chemical reactions that involve lime and atmospheric nitrogen and high-intensity heat. Washburn wanted to build a dam across the river here and make Muscle Shoals the center of cyanamid production in the United States. He couldn't put together the funding so he went back up to Niagara Falls, got his electricity there, and started a company called American Cyanamid, another early maker of fertilizer.

The problem with cyanamid is that the end product is not very desirable from a farmer's standpoint. It is a sort of dusty black stuff that's hard to apply to fields, difficult to transport, and can be caustic on the skin. It could also have some unfortunate effects on soil chemistry. So it wasn't a popular fertilizer. But at least Washburn had a system that showed some promise.

All of these efforts were going on right around 1900. But no one had found a perfect answer – the systems were unreliable, or too expensive, or made an unsatisfactory product.

There was, at least in theory, an entirely different way to fix nitrogen, but it was thought to be so difficult that few researchers took it seriously. This is the formula for the method. N_2 – that's dinitrogen – is broken apart, and the atoms combine with hydrogen to make NH_3, which is ammonia. The chemists in the room are probably very familiar with this formula. It's a way to get fixed nitrogen without burning it out of the air. People had known about this reaction for probably 100 years by the time Crookes gave his speech.

$$N_2 + 3H_2 \rightleftharpoons 2NH_3$$

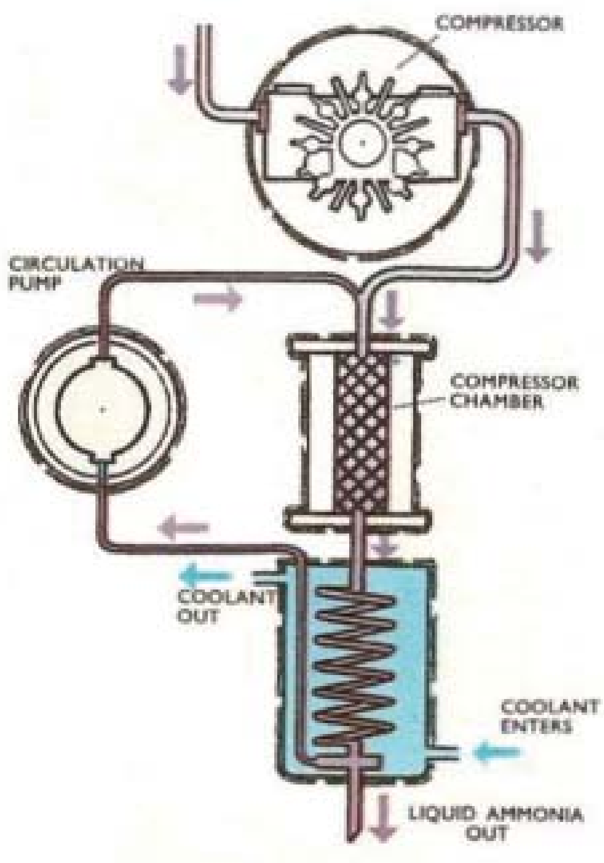
The problem was dinitrogen. It still had to be ripped apart, which meant high heat. And the heat required to make that happen, to make the reaction go, would decompose any ammonia that formed, turning it back into the starting materials. This reaction, like all chemical reactions, can go either way – back, forward. At high heat you wouldn't gain anything. From a theoretical standpoint it was fruitless to pursue the problem. Nobody could see how to make it work. With the exception of a couple of fellows in Germany, no one was looking at it seriously.

And Germany is where we go next. This is Wilhelm Ostwald. He was in 1900 perhaps the most famous chemist in Germany – and Germany at that time was the center of the chemical universe. The best chemists were trained in Germany. Every serious chemistry student wanted to go to Germany. If Germany was the Emerald City for chemists, Ostwald's lab was the Wizard's palace. He decided that he could make the ammonia reaction work, for the good of Germany (which needed synthetic fertilizers to ensure its agricultural and military future), for the good of science, and for the good of Wilhelm Ostwald. He was ready for a triumph that would make money. He was a professor and he didn't want to be a professor. He wanted

Wilhelm Ostwald

to be a bit wealthier. So he decided to build a machine to make ammonia.

His trick was to say okay, the heat part doesn't work out but if I add pressure to the mix then we can do more. He was working with gases – nitrogen gas and hydrogen gas – and all chemists knew that with any gas, the same number of molecules will fill the same amount of space, the same volume. If you squeeze that volume down, push the molecules closer together, you tend to push reactions toward the direction that has fewer molecules in it because they don't want to get all that close together. So, he thought, well look, you're starting with one molecule of N_2 and three molecules of hydrogen (that's H_2), making four molecules on the starting side of the equation, but on the product side there's two molecules of ammonia. So you're turning four molecules of feedstock gases into two of ammonia. If you want to push the reaction toward the two-molecule side, he reasoned, you need to squeeze it. So he started running gas experiments under pressure. He built a little tabletop machine where he used the bicycle pump to pump up some pressure, and he put in some



nitrogen and some hydrogen and he heated it up and tried to make ammonia. Ultimately, it didn't work. There's a longer story there; we don't have time for it today. But the great Ostwald failed and he failed very publicly. He was humiliated by his failure to do it so he dropped the whole project. And those who were watching said, well, if Ostwald can't do it, nobody can.

However, his work did spur a bit of interest in the ammonia reaction. Some chemists thought, "Well maybe I can get an interesting conference paper out of this. We can't make ammonia, really, but we could study the dynamics of that reaction and see where heat is released and where heat is…and we might learn something useful." The number-two man in Ostwald's lab, a brilliant chemist named Walther Nernst, started doing studies on just how H_2 and N_2 join together to make ammonia, and what the energetics were like. It was mainly theoretical work. And Nernst started talking about his results.

There was another fellow in Germany who had competed with Nernst to be Ostwald's assistant. Nernst won the competition; the other guy lost and went off to a sort of a minor professorship in a university in southern Germany. Here is the man who lost the assistantship. This is Fritz Haber. He had set his heart on becoming Ostwald's assistant and it burned him up that he didn't get it. So he watched what Nernst was doing. And he didn't believe that Nernst's ammonia results were right. Haber started doing his own experiments on ammonia and got a different set of results. The two men fought publicly in meetings, attacked each other's data – one of these little scientific spats that didn't seem to mean much, except to Fritz Haber. He was a very prideful man and a great German chemist, but he was also Jewish. He had converted to Christianity as many Jews did in Germany, but he was barred regardless from a number of positions because of his Jewish heritage. He was thin-skinned, and particularly sensitive about any questioning of his scientific work. Nernst, during this time, attacked his results, Haber felt insulted, and he threw himself into ammonia research as a result.

Fritz Haber

Haber and a talented assistant – a fellow named Robert Le Rossignol – started playing around at higher and higher pressures. Instead of using a bicycle pump, they invented machines that could pump up pressures higher than anything laboratories had ever achieved before. They built new kinds of compressors and fittings. The pressures they were using were intense enough to explode any metal container, so they ran experiments in hollowed-out quartz crystals. They found that the higher they pushed the pressure, the lower they could drop the temperature of the reaction. The lower the temperature, the more ammonia they got. That was encouraging. They experimented with a third factor beyond temperature and pressure, using a catalyst to spur the reaction along. This was an idea that Ostwald had used as well: Running the ammonia reaction in the presence of certain metal catalysts, it turned out, could push the reaction toward the production of more ammonia.

So they played with various combinations of catalyst, heat, and pressure. And in 1909 – let's see, this would be 11 years after Crookes laid down his challenge – Haber and Le Rossignol placed a very rare metal catalyst in their reaction chamber. It was called osmium. Osmium was one of the hardest-to-find metals on Earth. Only a couple of hundred pounds of it were available on Earth. But Haber had worked with it in some past work on electrical lights, so he had some around the lab, they tossed it in the reaction chamber to see what would happen, and suddenly the amount of ammonia being produced shot up. They repeated their experiments, and as long as osmium was in the middle of all that hot pressurized gas, they created a lot of ammonia. They set to work figuring out ways to further boost the yield of ammonia by cooling it quickly when it was formed, so that it wouldn't decompose back into the starting gases, and then improved ways to gather it. They invented ways to recirculate the hot nitrogen and hot hydrogen starting gases, putting them through the reaction over and over and over, also increasing the yield of ammonia.

This is the machine that they invented. This is a museum recreation of the Haber device and you can see at the bottom the little belt-driven thing. That's a compressor for building up pressure. I believe the reaction chamber is the large tube on the left and inside of that would have been an apparatus for both holding the heat and for having the high-pressure gases inside of a quartz crystal and then a variety of fittings and valves and gauges to feed the gases in, to cool the system, to recirculate the gases, to pull the ammonia out. It's a complicated little machine. And it is little: It fits on a tabletop. In their first experiments, they would run it for an hour and harvest maybe 20 drops of ammonia. It doesn't seem like much, but it was historic. It showed that it could be done. One scholar later compared the historic importance of those few drops to the Wright Brothers first flight at Kitty Hawk.

Haber knew he had made a valuable breakthrough, and approached BASF, at that time the biggest chemical company in Germany, to get more funding. BASF, of course, still exists and is extremely active, a very innovative company. It had started as maker of clothing dyes. But by 1909 it was expanding its reach into other kinds of chemical products. BASF had been looking for a way to fix nitrogen because the company could see big money there. Haber brought his breakthrough idea to BASF expecting riches in return, but the company's directors, especially their research director, said there is no way it was going to work at an industrial scale because the pressures required were too high. The pressures Haber was working at were similar to those found a mile under the surface of the ocean, the sorts that crush submarines.

The BASF research director said, well, look, there is no large container that can hold that pressure. You might be able to use a little quartz crystal in a tabletop machine but if you try and make a factory, you won't find quartz crystals that big. The pressures required were too intense, and so was the heat: Temperatures in the Haber machine would turn iron red hot. No factory-sized machine like this has ever been built, he said, and nothing will ever be built. Don't invest.

There was only one person at BASF who reviewed Haber's technique and thought it might work, and here he is: Carl Bosch. Bosch was a talented young chemist at BASF, only 34 or 35 when Haber walked in the door with his idea, but Bosch knew something that the other people at the company did not know. He had been raised in Germany by a father who was a plumbing supply-maker, a fellow who knew how to make and weld metal pipes that would hold water under pressure. Bosch had been very interested in metals as a young man. He had planned at one point to become a metallurgist but decided on chemistry instead. As a result, he was a rare find: a chemist who knew a lot about making things out of metal. He listened to Haber's ideas, thought about the pressures and temperatures, factored in what he knew about the strength of metals, and told his bosses that he thought he could make the process work at an industrial level.

The BASF directors let him have a shot at it. It was a gamble, but the potential payoff was too great to miss. No firm had ever tried to do what the Haber process demanded: high-pressure, high-temperature, continuous-flow industrial chemistry. It would involve inventing totally new devices, new solutions, and new techniques. Thanks to Bosch's optimism, BASF created a contract with Haber, purchasing rights to Haber's basic ideas and any resulting patents. In exchange they paid Haber a cut of the potential profits from making synthetic ammonia – from making ammonia out of air.

Carl Bosch

While the initial idea was to make fertilizer from ammonia – and that was a huge market by itself — the people running BASF also knew that ammonia could be a feedstock for other things. Atmospheric nitrogen fixed into other molecules, like ammonia, nitrates, or nitric acid, also can be used to make explosives. TNT is trinitrotoluene – and the nitro part comes from fixed nitrogen. Gunpowder is made with saltpeter, a nitrate-containing compound. Anybody who could make fertilizer could also make explosives, a fact that made Haber's discovery even more important, and potentially far more profitable.

Bosch got to work. He turned out to be a good choice for the project: quiet, determined, smart, and very skilled at organizing research efforts. He built teams, organized research into new catalysts, plant engineering, heat and pressure control, and within three years after Haber first squeezed out a few drops of ammonia, Bosch had scaled up his method to the size of a small factory. His teams discovered a cheap, reliable, stable new iron-based catalyst to replace osmium. They improved the methods of re-circulating gases and refrigerating the results.

Most important, they figured out how to make a metal reactor chamber that would hold the necessary pressures. It involved a thick cylinder of steel with a soft iron liner in it. It took years, and the solution of innumerable technical difficulties. Every step along the way, test vessels were blowing up. They had to encase things in concrete blast walls because the machines were blowing up so often. It was an enormously expensive process. But Bosch and his teams figured out answers for every problem, scaling the process up to bigger and bigger machines. Soon, instead of the table top model, they had reactor chambers that were eight feet high and could produce ammonia by the kilo. Then they were twenty feet high, producing ammonia by the ton.

This was a revolutionary moment in human history. The Haber-Bosch system, as it is called now, used far less energy than the competing methods, Birkeland's flaming discs or Washburn's cyanamid process. The Haber-Bosch reaction creates a certain amount of heat on its own, which is used to preheat the gases, lowering energy costs. They worked continuously, day and night, gases in, ammonia flowing out.

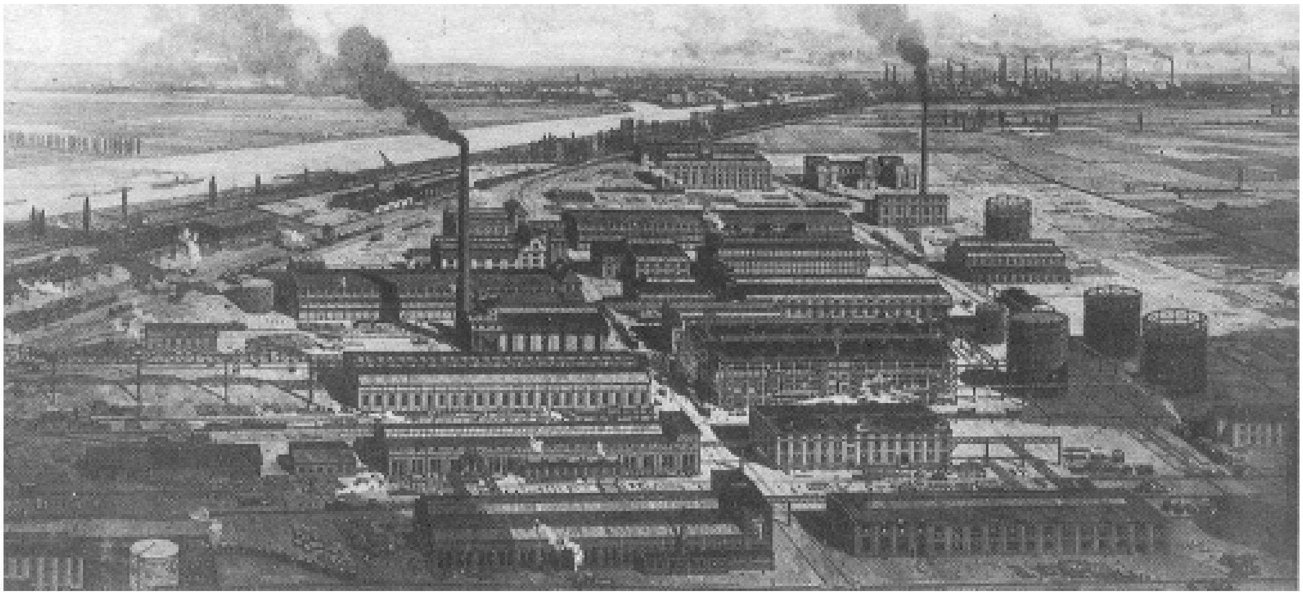
In the fall of 1913, the world's first Haber-Bosch factory opened. It was called Oppau, and it looked like this (see next page). That is the Rhine River on the left. It is Haber's tabletop machine basically, scaled up by Bosch to the size of a small town. It was enormously successful. The ammonia it produced was shipped out on those railway lines that you see along the river, and by boat. This was game-changing technology. The company started selling ammonia-based fertilizers globally and money started to pour in. Soon BASF was the wealthiest chemical company in the world. Carl Bosch rose up the ladder to a point where he was not only in charge of this factory and others they were planning, but was also doing field experiments on fertilizer applications to find the best formulations. He created test gardens and a fertilizer research facility. Bosch eventually became head of BASF.

And what happened to Fritz Haber? He took his cut of the income from his invention and became a very wealthy and very famous chemist. He was named to head his own research institute in Berlin.

Everything was looking great. And then, World War I started.

This is a day in 1914 (see photo on next page) in Munich when Germany announced that it was going to war. The Oppau plant that we just looked at had been running for less than three years. The people who ran Germany understood that not only did their people now have a way to make their own fertilizer and hence their own food – so they were independent of the world fertilizer trade system, Germany could make its own food – but also that they had virtually unlimited access to explosives. Germany was free to make war. Here in the crowd of people in a square in Munich you can see a little circle around a fellow who was in the crowd when World War I was announced. That is the young Adolf Hitler.

The Haber-Bosch plant at Oppau was turned into a gunpowder factory. Several historians have estimated that Haber-Bosch had a significant effect on the war, allowing Germany to feed its people, make explosives, and fight for years longer than it would have without the technology. Without Haber-Bosch, the war would have been over a couple of years earlier. Haber, who thought of himself as an ideal German, spent the war years inventing ways to kill soldiers with poison gas.



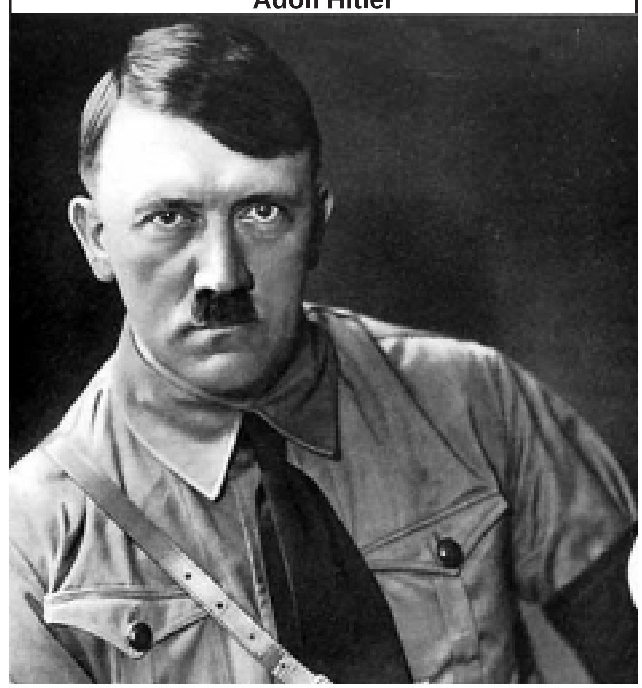
Die Ammoniakfabrik der BASF in Oppau. Gemälde von Otto Bollhagen, 1914. Ludwigshafen, Unternehmensarchiv BASF

Eventually the war did end, however, and Adolf Hitler came to power in the decades following. During the 1920s, Bosch concentrated on protecting his technology – keeping the Allies from discovering the secret of fixing nitrogen – and expanding it. His people found a way to use high-pressure chemistry to make methanol in bulk, and then began exploring the idea of making synthetic gasoline from coal.

Hitler, too, had a keen appreciation of technology. He had great plans for Germany, and gasoline and explosives were central to his vision. He arranged government support for BASF's costly synthetic gasoline venture. There are strong links, in case you didn't notice, between politics, economics, war-making and the fertilizer industry. These things are inextricably tied at this point in history.

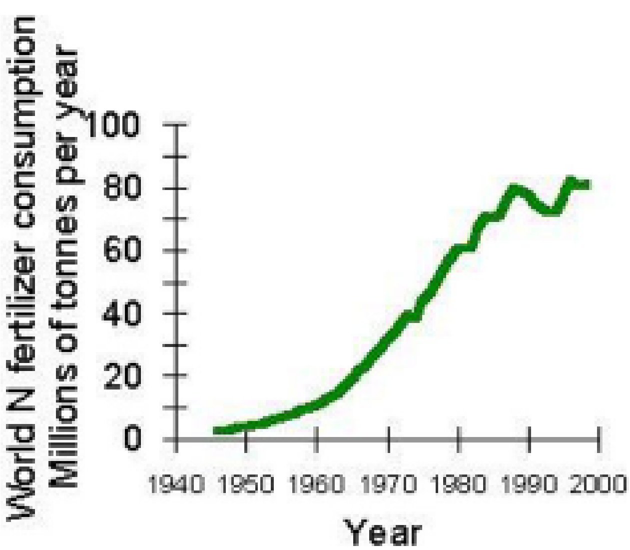
Bosch, however, was an anti-Nazi, and despised Hitler. The one time the two of them sat down to talk, Bosch tried to convince Hitler that he should not levy exclusion laws against the Jews because so many Jewish scientists were important to Germany's well-being. And as soon as Bosch said that, Hitler hit the roof, pounding his knee and yelling. Bosch was escorted out of his office. Within a few years, Hitler succeeded in removing Bosch from power. The Nazi Party essentially took over BASF, which by that time was part of a huge conglomerate of chemical companies called IG Farben. IG Farben became Hitler's war laboratory – a very

Adolf Hitler



unfortunate turn of events. Farben fertilizer helped stave off hunger in Germany. Farben explosives armed German troops. Farben gasoline – they did succeed in making synthetic gasoline by the ton – fueled Hitler's armies and air force.

Carl Bosch and Fritz Haber had intended to feed the world. It is a great irony that they made possible the rise of Hitler, who used their factories to fuel his armies during World War II.

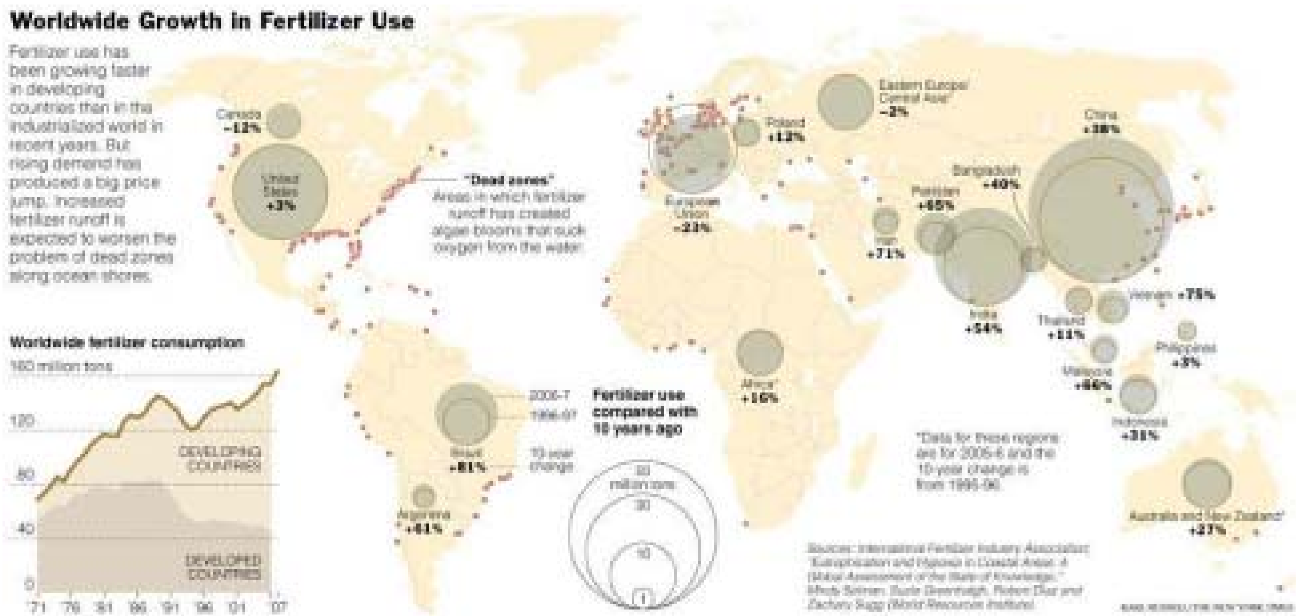


After the war was over, Haber-Bosch technology returned to its original aim: the production of synthetic fertilizer. This is a graph of nitrogen fertilizer consumption in millions of tons per year starting in 1940. You can see an enormous increase in the past 60 years in the use of nitrogen fertilizers. Their use has changed the way the world farms.

Haber-Bosch technology has continued to improve in efficiency, although the basics are the same (including the catalyst, which is basically the same one Bosch's teams found a century ago). Here is a fairly modern plant in Malaysia.

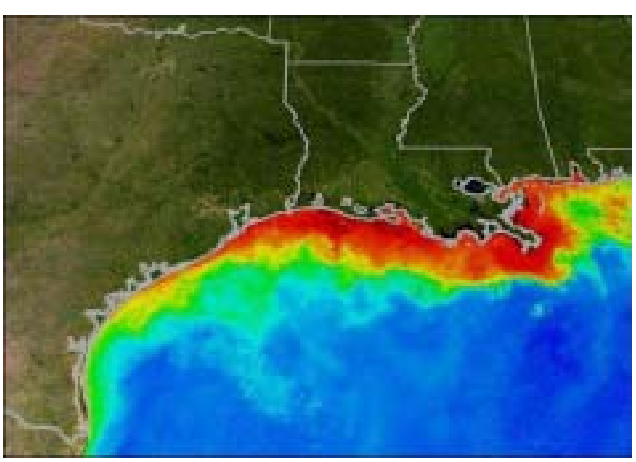
Synthetic fertilizer is changing the Earth – not just how we farm, but the very biosphere in which we live. In the past 100 years, Haber-Bosch technology has doubled the amount of fixed nitrogen on the globe. Human activity now equals the importance of nitrogen-fixing bacteria and lightning. We have, as a species, "greened" the Earth in a way that would not have been dreamed of a century ago. Synthetic fertilizer is keeping alive more than two billion people today. Half the nitrogen in your body is synthetic; it came out of a factory. This industry has made possible incredible population growth and ensured a degree of prosperity that no one would have thought possible with six billion people on Earth.

This graphic (see next page) from the *New York Times* demonstrates that along with the great triumph comes a negative side as well. It shows fertilizer use compared to 10 years ago. The sizes of the circles show growth or decrease in use. The interesting things to me



are the little red squares you see in coastal areas. Those are dead zones, areas in which the oxygen level is so low that most marine life cannot survive. The oxygen level is low in great part because plants are scavenging the oxygen out of the water. Those plants, in turn, are fed to one degree or another by synthetic nitrogen. This is the result of farmers applying nitrogen fertilizers to their fields, half of which, on average, goes into the crops, and half of which does not. Much of that goes into groundwater. The groundwater gets contaminated with nitrates; it ends up in rivers, and where the rivers empty into the oceans you end up with dead zones.

Other factors are at play; synthetic nitrogen isn't 100 percent of the story of dead zones, but it is an important player. These zones are increasing in number and in size, and you can see where they are – mostly in Western Europe (that group of red dots around the Baltic), and the east coast of the United States. Those are the places where we have historically seen the heaviest uses of synthetic nitrogen. The worst is down in the Gulf of Mexico, where the Mississippi and Atchafalaya river systems empty into the Gulf. These river systems drain some of the richest and most heavily fertilized farmland in the world. The dead zone in the Gulf is now roughly the size of New Jersey, and grows a little each year.



Let me end by returning to the prophecy made by Sir William Crookes in 1898. Thanks to Haber-Bosch and the Green Revolution, we have as a species managed to sidestep his prediction of doom. Today, we face another challenge, just as serious, just as difficult. We will need to find ways to feed an additional three billion people in the next fifty years, with diets richer on average than today's. Crookes pointed people toward a technological solution. He thought the answer was chemistry and he was right: chemists figured out an answer very quickly.

Our challenge differs in scope. It seems to me as an observer of this field that the work that groups like IFDC are doing is essential because it recognizes that this is no longer simply a technological issue. This is a human issue. It cuts across science and technology, culture and cultural history, questions of national identity, international relations, politics, agriculture, big business and money.

Our challenge today is much more difficult because it will require more than a single quick fix. We will not solve it with another Haber-Bosch machine. What I see is the necessity for a broad-based, all-encompassing effort that works on a number of approaches at once to ensure that the seed and the nutrients and the water and the quality of soils, the roads and marketing systems, governmental controls and subsidies, wars and crises — all of these factors are approached jointly in terms of providing adequate nutrition. That is the challenge today.

It is going to require a lot of talent. But you know talented people appeared when they were needed 100 years ago, and I think we have a room full of talented people today, and a world full of talented people beyond these walls. I expect success. I'm an optimist by nature but I will tell you I am heartened by what I've heard here and what I continue to hear in other places about making that effort.

Thank you very much for your attention.

Question and Answer Session

Dr. Amit Roy — Thank you very much Tom. I suspect you are going to entertain some questions?

Thomas Hager — Yes, if people have questions, I'd be happy to answer them.

Audience Member — Thank you very much. My question is about the very early stages…and the availability of purified gases for the various experiments.

Thomas Hager — You know, I didn't have time to go into everything. That was a huge technical issue. The availability of purified gases – nitrogen and hydrogen – for this process, as everyone who is associated with the industry understands, is a tremendous ongoing issue and a very important part of the process. Haber and Bosch faced it as well. Haber didn't have much of an issue with it because he only needed small quantities. Bosch figured out new systems for making purified gases. He got his nitrogen by freezing it out of the air and then distilling it. So he would take frozen air and distill the nitrogen out of it and then scrub it. The hydrogen they got first from the electrolysis of water. That was the first system that was used. Because when you take H_2O and run some current through it, you break the hydrogen and oxygen apart. You can capture the hydrogen – again, a difficult process, scrubbing involved. And that was among the challenges that they had. Nowadays, hydrogen comes from natural gas primarily. The big plants that produce fertilizer today get the hydrogen… You know, nitrogen is cheap, nitrogen is in the air all around us, it doesn't cost anything. But the hydrogen is expensive, as it turns out, because you need a lot of it. You need three atoms of hydrogen for every atom of nitrogen to make ammonia (NH_3). So you need a lot of hydrogen. It comes today primarily from natural gas. The Haber-Bosch process, the Haber-Bosch plants around the world burn somewhere around two or three percent of all the natural gas on Earth. One percent of all the energy on Earth goes to run those plants. So, it still isn't cheap.

Audience Member — I'm always fascinated by some of the opposing views of science, the steady accumulation of knowledge, the other being more like the revolutionary anomaly of osmium, is it steady accumulation or a bit of both?

Thomas Hager — Yeah, that's a good question; let me repeat it for those that didn't hear the entire question. The question is, "Is this an example of the steady accumulation of scientific insights over time or is it one of these revolutionary moments?" I think it's both. It is certainly the case that Haber was standing on the shoulders of giants, as they say. Everyone who does scientific work benefits from the scientific work that was done before. The knowledge base that you go in with depends on what other scientists have done. They have done very hard work so you can do your work. Well, Haber was the same way. He benefited from a knowledge of gases, pressures and catalysts that was done by a number of other people, including Ostwald. It should be remembered also that Ostwald had the right idea. Ostwald was working with the right system; he just didn't get it going. So Haber had his moment. The discovery of osmium as a catalyst simply showed that a catalyst was important, because they discarded osmium very quickly after that. So there was that combination of hard work, long preparation, deep history but then boom, it comes together in a person, in an individual, and it can come together in an odd way and Haber's story is an odd story. Unfortunately, it has a sad ending. Haber died a broken man. When Hitler came to power, Haber was stripped of his research institute because he was Jewish and he died in exile literally broken-hearted very shortly thereafter. So I hope that answers your question. .

Audience Member — If you had $100 million to spend on this problem, how would you spend it?

Thomas Hager — Getting some more $100 millions. I'd get like $100 billion. This is a question for Dr. Roy, not me. I observe and report history. I'm really not good at prognostications. But, you know, as I mentioned at the end of the speech, this is such a wide-ranging issue now. It goes into so many areas, all of which need to be addressed in some way that I don't think that there is one place I would put it, you know. You have to throw it at a dozen places. Ask Dr. Roy.

Audience Member — I would suggest that water is the big problem because if you put a lot of nutrients into the water, they end up in the Gulf of Mexico or the Chesapeake Bay. If we could keep the nutrients from getting into the water, then there would be less pollution.

Thomas Hager — And that's a very good point. The question is about water pollution and nutrient loss through leaching fertilizers from fields. You know, one thing that IFDC is doing and has been very active in, I know, is developing application procedures that minimize loss that way. If you can get the nutrients to plants and nowhere else, that's the ideal. You want to grow crops. You don't want to pollute the water. That is a technological question – finding delivery systems and formulations that allow maximum plant uptake and minimal pollution. Do you want to say anything about that, Amit?

Dr. Amit Roy — Well, essentially it actually comes down to how do we improve the efficiency of nitrogen fertilizer use and that's a challenge which TVA has addressed and we continue to address in our work. And that's the challenge for the future. And when you look at the nitrogen side, you know it's such an energy-dependent product and I want to say that we use one ton of urea as the most common nitrogen fertilizer, it takes the energy contained in four barrels of oil. And fertilizers are only 30 percent efficient; 70 percent is lost. So if you can improve that efficiency factor to something that will move along in the right direction.

Thomas Hager — You know, in Crookes' day, the issue was a production question in how we produce the fertilizers and now we are dealing with not only the other variables but also with the whole delivery system; the question of how you put the fertilizer on the field. Because we've got fertilizer now and we can make more. It is energy-intensive. It takes a lot of energy. One place I'd throw money for research, for instance because I'm a microbiology trainee, I would do what a number of agricultural microbiologists are doing. I would try and figure out how to make nitrogen fixers out of a whole bunch of crops, not just peas and beans. I know that's genetic engineering on a scale that a lot of people don't like to hear about, but from what I know about microbiology, I'd go that route. If you can get natural nitrogen fertilizer production from a microorganism and you can have a wheat plant do what a pea plant does for nitrogen fixation, I'd be very interested in seeing what would happen with that. Because if you get the plants to produce it themselves, perhaps that would solve part of the problem. But that's just my microbiology bias.

Audience Member — What about other reasons for famine?

Thomas Hager — The question basically is reasons for famine that don't have to do with the availability of fertilizer, essentially, if I'm getting that right. You know, what else goes on to create famines besides not having enough fertilizer. Well, certainly, it's seed and soil and water and all of those other things. It's also, as I'm learning, the availability of an economic system that will support the farmers and so on. So it's much more complex now than just fertilizer. Fertilizer is just one part of a much larger equation. That's the simple answer.

Audience Member — This is not a question; it's more a comment. You mentioned the year 1909 and September 16, 1909, was 100 years ago. It's a good point to know that we are talking about exactly 100 years ago.

Thomas Hager — That's a very good point. The comment was that this is the 100th anniversary of the Haber-Bosch discovery. It happened in 1909. The first demonstration was July but we're pretty close, a couple of months ago. This is the 100th birthday of the work of Haber and Bosch and look what happened in just 100 years. Any other questions before we close it? No. Then I want to thank you very much. Thank you, Dr. Roy, for hosting me. Thank you all.

Dr. Amit Roy — One other comment I wanted to make is the book I referred to – *The Alchemy of Air* – I would encourage all of you to read that because what Tom has presented essentially traces that whole development process except that he has left out a few other things that you will find very interesting. The book is a fascinating, interesting "read" and I encourage you to find a copy

Thomas Hager

Thomas Hager is the author/co-author of 12 books. His latest book, *The Alchemy of Air,* recounts how Dr. Fritz Haber and Dr. Carl Bosch, recipients of the Nobel Prize in Chemistry, changed history with perhaps the most significant invention of the 20th century. According to Hager, "Two men found a method in 1909 to turn air into bread… my book is the first to describe in detail the work of these pioneers, who developed a method to pull nitrogen out of the air and put it into fertilizers for growing food." According to the *Washington Post Book World*, the book is "a Faustian tale of pride, vanity and ambition…Haber and Bosch are fascinating if troubled personalities, brought by Hager compellingly to life."

According to the Portland *Oregonian,* Hager's book is "a page-turner...it make[s] the scientific process as suspenseful as a good whodunit," while *Discover* magazine states, "this scientific adventure spans two world wars and every cell in your body." *The Alchemy of Air* was a finalist for the National Academies Communication Award and was listed among the "Best Books of the Year" by Kirkus Reviews. It was also chosen a Borders' "Original Voices" selection.

Hager's efforts include three books about Linus Pauling and his work; Hager has also written text for several Linus Pauling websites. He has had more than 100 medicine and science articles published in periodicals ranging from *Readers Digest, Self* and the *Wall Street Journal* to *Cardio,* the *Journal of the American Medical Association* and the *Medical Tribune*. He has appeared on C-Span's BookTV and been interviewed on National Public Radio.

Our Daily Bread is the title of Hager's next book, which he is co-writing with Dr. Amit Roy, IFDC president and chief executive officer. The book is about the coming world food crisis and how it can be prevented in ways that also improve soil and food quality.

Thomas Hager was raised in and around Portland, Oregon. He earned a master's degree in medical microbiology and immunology from the Oregon Health Sciences University and a second master's in journalism at the University of Oregon.

He worked as a freelance medical writer, a contributor to *American Health* and as a West Coast news correspondent for the *Journal of the American Medical Association* before getting into editing and publishing. He was the founding editor of a scientific trade publication, and for 10 years he edited the *Oregon Quarterly*, the state's oldest and largest circulation magazine. He also held the position of director of communications and marketing at the University of Oregon, where he restarted the University of Oregon Press.

He and his wife, author Lauren Kessler, have three children and live near Eugene, Oregon, home of the University of Oregon, where he is an adjunct professor. Hager and his family have a blog where they describe their efforts to rehabilitate a 70-year-old house and cut their energy use by 80 percent. That is the amount required to get an average American down to a globally sustainable level.

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