The Nitrogen Bomb

By learning to draw fertilizer from a clear blue sky, chemists have fed the multitudes. they've also unleashed a fury as threatening as atomic energy

By James Worrell, David E., Marshall Jon Fisher|Sunday, April 01, 2001

In 1898, Sir William Crookes called on science to save Europe from impending starvation. The world's supply of wheat was produced mainly by the United States and Russia, Sir Crookes noted in his presidential address to the British Association for the Advancement of Science. As those countries' populations grew, their own demands would outpace any increase in production. What then would happen to Europe? "It is the chemist who must come to the rescue of the threatened communities," Crookes cried.

"It is through the laboratory that starvation may ultimately be turned into plenty."

The crux of the matter was a lack of nitrogen. By the 1840s agricultural production had declined in England, and famine would have ensued if not for the discovery that the limiting factor in food production was the amount of nitrogen in the soil. Adding nitrogen in the form of nitrate fertilizer raised food production enough to ward off disaster. But now, at the end of the century, the multiplying population was putting a new strain on agriculture. The obvious solution was to use more fertilizers. But most of the world's nitrate deposits were in Chile, and they were insufficient. Where would the additional nitrogen come from?

That question, and Crookes's scientific call to arms, would trigger a chain reaction as far-reaching as the ones unleashed at Los Alamos four decades later. Historians often describe the discovery of nuclear power as a kind of threshold in human history— a fire wall through which our culture has passed and cannot return. But a crossing every bit as fateful occurred with research on nitrogen. Like the scientists of the Manhattan Project, those who took up Crookes's challenge were tinkering with life's basic elements for social rather than scientific reasons. And like the men who created the atomic bomb, they set in motion forces beyond their control, forces that have since shaped everything from politics to culture to the environment.

Nitrogen fertilizer and air are nearly enough, by themselves, to grow any modern crop. All this plant lacks is water.
Photo by James Worrell

Today nitrogen-based fertilizers help feed billions of people, but they are also poisoning ecosystems, destroying fisheries, and sickening and killing children throughout the world. In ensuring our supply of food, they are wreaking havoc on our water and air.

Nitrogen is essential to the chemistry of life and, sometimes, its destruction. It winds its way through all living things in the form of amino acids— which are chains or rings of carbon atoms attached to clusters of nitrogen and hydrogen atoms— and it is the primary element of both nitroglycerin and trinitrotoluene, or TNT.

Nitrogen-based fertilizer is now so common, and the chemistry of explosives so well known, that any serious fanatic can make a bomb. The Alfred P. Murrah Federal Building in Oklahoma City was blown up in 1995 with nitrate fertilizer sold in a feed store, combined with fuel oil and a blasting cap.

Nearly 80 percent of the world's atmosphere is made up of nitrogen— enough to feed human populations until the end of time. But atmospheric nitrogen is made up of extremely stable N_2 molecules that are reluctant to react with other molecules. Bacteria convert some atmospheric nitrogen first into ammonia (NH_3), then into nitrites (NO_2^-) and nitrates (NO_3^-), but not nearly enough for modern agriculture. What was needed by the end of the 19th century was a way of imitating these microbes— of "fixing" atmospheric nitrogen into a chemically active form.

A few years before William Crookes gave his speech, lime and coke were successfully heated in an electric furnace to produce calcium carbide, which then reacted with atmospheric nitrogen. Crookes himself had shown that an electric arc can "put the air on fire," as he described it, oxidizing the nitrogen into nitrates. But the electricity needed for either process was prohibitively expensive. Crookes suggested the use of hydroelectric power, but only Norway had sufficient hydroelectric power, and although the Norwegians constructed a nitrogen-fixation plant, it furnished barely enough nitrogen for domestic use. The rest of Europe still faced the specter of hunger.Into this disquieting scene stepped Fritz Haber.

Haber was a young German physical chemist who renounced his Judaism to enhance his career: Academic opportunities in Germany, as in most other European countries, were limited for Jews at that time. Haber's first academic appointment after receiving his Ph.D. was as a porter, or janitor, in the chemistry department at the University of Karlsruhe. But he soon talked his way into a lectureship, and in 1898 he was appointed professor extraordinarius and was ready to begin thinking about the problem of nitrogen.

Haber began by considering the possibility of converting atmospheric nitrogen to ammonia directly by reacting it with hydrogen. Previous experimenters had found that the reaction would take place only at high temperatures— roughly 1,000 degrees Celsius— at which ammonia was known to break down instantly. But Haber's own experiments confirmed that he could transform only about 0.0048 percent of the nitrogen into ammonia in this way. Moreover, a comprehensive investigation of thermodynamic theory confirmed what he had long suspected: that ammonia could be produced in large quantities only under high pressure— higher than was then attainable, but not impossibly high. The problem now became one of finding the right balance between pressure and temperature to get the best results, and of finding a catalyst that might allow the pressures to be brought just slightly back down into the realm of commercial possibility.

After a long search Haber found the element uranium to be just such a catalyst, and with a few further technical refinements he was able to produce nearly half a liter of ammonia an hour. Best of all, the process required little energy, and this obscure metal, having no other commercial use, was cheap.

The company Badische Anilin-& Soda-Fabrik (BASF) sent the chemist Alwin Mittasch and the engineer Carl Bosch to Haber's laboratory for a demonstration. And, of course, everything went wrong. Haber begged them to stay while he fiddled with the apparatus. Time went by, and Bosch left. Then, just as Mittasch was preparing to leave, the ammonia began to drip out of the tubing. Mittasch stood and stared, and then sat down again, deeply impressed. By the time he left, the ammonia was flowing freely.

It took another three years for the company's engineers, led by Bosch, to scale up the experiment to commercial levels, but by 1912 the Haber-Bosch process was a viable means of producing fertilizer. Haber and Bosch would later receive Nobel prizes for their efforts, the threat of famine was averted, and the world lived happily ever after. Well, not quite.

Kaiser Wilhelm II's Germany in the early 1900s was the most powerful state in Europe, with the strongest army, the greatest industrial capacity, and a patriotic fervor to match. The Germans wanted their "rightful place" in the world order, yet their country could not grow except at the expense of someone else's borders. Nor could Germany fulfill her ambitions through colonization— most of the undeveloped world had already been claimed.

With no room to grow, or even stretch, the kaiser's fancy turned to thoughts of war. Three inhibitions, however, held him back. The first was the problem of nitrogen for fertilizer, since in these first years of the century Haber had not yet begun his work. Germany was the world's largest importer of Chilean nitrates, and without a constant infusion of fertilizer, its poor, sandy soils got worse every year. The second problem was again lack of nitrogen, this time for explosives. The third problem was Britain's Royal Navy, which ruled the seas. If Germany were to start a war, the Royal Navy would cut off its supply of nitrates from Chile, and the population would slowly starve while the armed forces ran out of explosive shells and bombs.

How wonderful for the kaiser, then, was Fritz Haber's invention of industrial nitrogen fixation. In one stroke Germany would be able to produce all the fertilizer and explosives it needed— provided the war didn't last too long. In 1913 the first nitrogen-fixing plant began operations at Oppau. A year later, Austria's heir to the throne, Archduke Franz Ferdinand, was assassinated in Sarajevo. Germany soon pushed Austria to declare war and loosed its own troops both east and west.

Nitrogen makes up nearly 80 percent of Earth's atmosphere, yet 20th-century Europeans nearly starved for lack of it
Photo by James Worrell

World War I ended four years later with the establishment of Soviet Russia and the collapse of Germany, leading directly to the rise of Nazism with all its horrors and to World War II. None of this could have come about without the discovery of commercial nitrogen fixation. In trying to save Europe, Fritz Haber came close to destroying it.

And in trying to feed humankind, we may yet starve it. Civilization's bloodiest century, sent on a rampage by nitrogen's emancipation, has passed into history. But the paradox of nitrogen remains. First it was all around us and we couldn't use it. Now we know how to use it, and it's suffocating us.

The planet's 6 billion humans (and counting) rely more than ever on fertilizer to augment the natural nitrogen in soils. In fact, we now produce more fixed nitrogen, via a somewhat modified Haber-Bosch process, than the soil's natural microbial processes do. Farmers tend to apply more fertilizer rather than take a chance on less, so more nitrogen accumulates than the soil can absorb or break down. Nitrates from automobile exhaust and other fossil-fuel combustion add appreciably to this overload. The excess either gets washed off by rainfall or irrigation or else leaches from the soil into groundwater. An estimated 20 percent of the nitrogen that humans contribute to watersheds eventually ends up in lakes, rivers, oceans, and public reservoirs, opening a virtual Pandora's box of problems.

Algae, like all living organisms, are limited by their food supply, and nitrogen is their staff of life. So when excess nitrogen is washed off into warm, sunlit waters, an algal bacchanalia ensues. Some species form what is known as a "red tide" for its lurid color, producing chemical toxins that kill fish and devastate commercial fisheries. When people eat shellfish tainted by a red tide, they can suffer everything from skin irritation to liver damage, paralysis, and even death. As Yeats put it, "the blood-dimmed tide is loosed."

Algal blooms, even when nontoxic, block out sunlight and cut off photosynthesis for the plants living below. Then they die off and sink, depleting the water's supply of oxygen through their decomposition and killing clams, crabs, and other bottom dwellers. In the Baltic Sea, nitrogen levels increased by a factor of four during the 20th century, causing massive increases in springtime algal blooms. Some ecologists believe this was the main cause of the collapse of the Baltic cod fishery in the early 1990s.

Every spring, the same process now creates a gigantic and growing "dead zone" one to 20 yards down in the Gulf of Mexico. The Mississippi and Atchafalaya rivers, which drain 41 percent of the continental United States, wash excess nitrates and phosphates from the farmlands of 31 states, as well as from factories, into the Gulf. The runoff has created a hypoxic, or deoxygenated, area along the coast of Louisiana toward Texas that has in some years grown as large as New Jersey. This area supports a rich fishery, and dire consequences similar to those in the Baltic Sea can be expected if nothing is done. So Haber's gift of nitrogen was not entirely a boon in the area of food: It increased food production on land, but now it threatens our supply of food from the sea.

Four years ago the Environmental Protection Agency formed a task force of experts to address the dead-zone problem. Their final plan of action, submitted in January, calls for increased research, monitoring, education, and more planning. Above all, the plan proposes incentives for farmers to use less fertilizer. But the addiction will be hard to break. Unlike nuclear energy, nitrogen fertilizer is absolutely necessary to the survival of modern civilization. "No Nitrates!" and "Fertilizer Freeze Forever!" are not viable slogans. At the end of the 19th century there were around 1.5 billion people in the world, and they were already beginning to exhaust the food supply. Today, as the population surges past 6 billion, there is no way humanity could feed itself without nitrogen fertilizers. As Stanford University ecologist Peter Vitousek told us recently, "We can't make food without mobilizing a lot of nitrogen, and we can't mobilize a lot of nitrogen without spreading some around."

Algal blooms are just one of the many disastrous side effects of runaway nitrogen. In Florida, for example, nitrogen (and phosphorus) runoff from dairies and farms has sabotaged the native inhabitants of the Everglades, which evolved in a low-nutrient environment. The influx of nutrient-loving algae has largely replaced the gray-green periphytic algae that once floated over much of the Everglades. The new hordes of blue-green algae deplete the oxygen and are a less favorable food supply. So exotic plants such as cattails, melaleuca, and Australian pine have invaded the Everglades. Just as shopping-mall and subdivision developers have paved over most habitable land to the east and south, these opportunists have covered the native marshes and wet prairies where birds once fed. Beneath the surface, the faster-accumulating remains of the new algae have almost completely obliterated the dissolved oxygen in the water. Few fish can survive.

Nitrogen also contaminates drinking water, making it especially dangerous for infants. It interferes with the necessary transformation of methemoglobin into hemoglobin, thus decreasing the blood's ability to carry oxygen and causing methemoglobinemia, or blue baby syndrome. The EPA has named nitrates, along with bacteria, as the only contaminants that pose an immediate threat to health whenever base levels are exceeded, and increasingly they are being exceeded. According to a 1995 report by the U.S. Geological Survey, 9 percent of tested wells have nitrate concentrations exceeding the EPA limit; previous studies showed that only 2.4 percent of the wells were dangerous.

Beefing up agriculture not only contaminates our water, it corrupts the air. As fertilizers build up in the soil, bacteria convert more and more of it into nitrous oxide (N_2O). Nitrous oxide is best known as "laughing gas," a common dental anesthetic, but it is also a powerful greenhouse gas, hundreds of times more effective than carbon dioxide, and a threat to the ozone layer. Like a Rube Goldberg contraption designed to create and foster life on Earth, our ecosphere can apparently withstand little tinkering. Bend one little pole the wrong way, and the whole interlocking mechanism goes out of whack.

Mass-produced Nitrogen made modern warfare possible. What other explosions lie ahead?
Photo by James Worrell

Scientists around the world are working to reverse the effects of eutrophication, as the introduction of excessive nutrients is called. But while fuel-cell car engines and other advances loom in the near future, and chlorofluorocarbons have largely been replaced with safer chemicals, there is no such substitute for nitrogen. "An enormous number of people in the underdeveloped world still need to be better fed," says Duke University biogeochemist William Schlesinger, "particularly in India and Africa. When they come online agriculturally, sometime in the next 50 years, at least twice as much nitrogen will be deployed on land each year."

Improving the management of fertilizer is one good way to decrease runoff. If we can better understand exactly when crops need to absorb nitrogen, farmers can learn to apply fertilizer sparingly, at just the right time. "When application and uptake are coupled," says Schlesinger, "it minimizes the amount of runoff." In some watersheds like the Chesapeake Bay, farmers have reduced their nutrient runoff voluntarily. In other areas, farmers haven't had a choice: When the Soviet Union and its economy collapsed, fertilizer was suddenly hard to come by near the Black Sea. As a result, the hypoxic zone in the Black Sea shrank appreciably.

Another, less drastic strategy for reducing the use of nitrogen is called "intercropping" and goes back to Roman times. By alternating rows of standard crops with rows of nitrogen-fixing crops, such as soybeans or alfalfa, farmers can let nature do their fertilizing for them. Intercropping could be a godsend to the developing world, where fertilizer is hard to come by. The difficulty is devising new plowing schemes, and farmers, like everyone else, are reluctant to abandon tried-and-true methods. But even successful farmers in the United States might be convinced. Aside from protecting the global environment— a somewhat intangible goal— intercropping could save them money on fertilizer. And farming areas are often most affected by groundwater contaminated by nitrates.

Other researchers are developing natural processes to clean up our mess. Just as some bacteria can draw nitrogen from the atmosphere and expel it as nitrates, others can consume nitrates and expel nitrogen molecules back into the air. Denitrifying bacteria are too scarce to clean up all nitrogen pollution, but they could be used much more extensively. For example, some farmers in Iowa and near the Chesapeake Bay drain their fields through adjacent wetlands, where denitrifying bacteria are common, so that excess nitrogen is consumed before it reaches streams, rivers, and bays.

Biologists willing to brave a slippery slope might want to go further, adding denitrifying bacteria to soil or water contaminated with nitrates. In the last few years several bacterial strains that might be useful have been identified. Why not genetically modify them to do exactly what we want? To anyone familiar with the ravages of invasive species worldwide, the danger is obvious.

Genetically modified microbes would have to be spread over large areas, making them hard to monitor. And in developing countries, where the need is greatest, there are few experts to do the monitoring.

The specter of genetically engineered bacteria spreading beyond the targeted regions, and mutating into new strains, brings to mind a picture of biogeochemists in the 22nd century looking back on the halcyon days when people still had the luxury of worrying about nitrogen. Fritz Haber couldn't have imagined that he was altering Earth's environmental balance when he thought to heat up uranium, hydrogen, and air at high pressure. If we're not careful, our attempts to rectify that balance will only trigger another, even more destructive chain reaction.

Haber's uranium was Oppenheimer's uranium in more ways than one.

A Short, Salient History of Nitrogen

1910 Kaiser Wilhelm II wants Germany to expand but lacks the necessary fertilizer and explosives for war. The missing ingredient: nitrogen.

1912 A brilliant young chemist named Fritz Haber discovers the keys to mass-producing nitrogen: high pressure and a uranium catalyst.

1956 Nitrogen-based fertilizer production is growing exponentially. In Minnesota, models in fertilizer sacks pose on a production line.

1980 Over the next decade, more man-made fertilizers, like this nitrogen-phosphorus-potassium mix, will be put on crops than were used in previous human history.

1995 The Alfred P. Murrah Federal Building in Oklahoma City is destroyed by a bomb made mostly of ammonium nitrate and diesel-fuel oil, killing 168 people.

2001 The Florida Everglades are slowly being choked by vast algal blooms as dairies and farms send their nitrogen- and phosphorus-rich runoff into the swamps. Native species such as periphyton, adapted to water with fewer nutrients, are being displaced by exotic plants such as cattails, melaleuca, and Australian pine.