The Slow Birth of Green Chemistry

Government funding, public concern, and tantalizing research problems may finally coax mainstream chemists into lending their skills to environmental protection

Chemistry may have endowed humanity with the menagerie of compounds that comprise the modern material landscape, but it has also landed the world in an unholy environmental mess. "Whether you are talking about oil spills, or landfills, or ozone holes...or any [human-made] environmental problem that has ever occurred, it comes from chemistry," says Kenneth Hancock, director of the National Science Foundation's chemistry division. Now, says Hancock, it's up to chemists to get us out of the mess. "Any solution that you will devise will come from chemistry."

There's a sense of urgency in Hancock's tone, because the subfield of chemistry that will provide those solutions is having a troubled birth. He's referring not to pollution cleanup, a longstanding effort that draws heavily on the skill of analytical chemists, but to something more fundamental: redesigning commercially important chemical processes and products or inventing new ones to prevent environmental harm in the first place. Hancock's call to action is echoed in a spate of government reports and in funding programs recently inaugurated by the National Science Foundation (NSF) and the Environmental Protection Agency (EPA). The chemical industry, trying to survive in an environment-conscious world, is also committed to learning how to mend its ways (see box on this page). But academic chemists, who in the past have been eager to push the bounds of chemistry into other fields such as biology and materials science, have been slow to respond to the environmental wakeup call.

Frontiers in Chemistry

Science's look at research horizons in chemistry begins on page 1552. In a companion effort, the News Department profiles a subdiscipline defined not by a research focus but by a goal—making chemistry environmentally benign.

As regulatory and industry efforts expand from merely cleaning up pollution to preventing it in the first place, though, environmental chemistry is finally entering the mainstream. Lured by increased government and industrial funding and by the intellectual challenges of the new subdiscipline, a cadre of chemists is now aiming to rethink some of the central processes of industrial chemistry in the name of environmental soundness. Among their goals are to replace organic solvents with water-based ones, substitute environmentally benign reaction ingredients for catalysts that involve toxic heavy metals, and design products to make them easy to recycle or safely discard (see box on page 1540). Quantitative appraisals of how far the subdiscipline has progressed are hard to come by, but Hancock goes so far as to suggest that it could change chemistry as dramatically as biochemistry did 40 years ago and as materials science has in more recent decades.

Can the Chemical Industry Change Its Spots?

Just before 1:00 A.M. on 3 December 1984, the worst industrial accident in history began. Uncontrolled emission of lethal gas from a Union Carbide pesticide plant stalked the slummy streets of Bhopal, India, killing thousands and maiming hundreds of thousands of people. That dreadful night and its hellish aftermath sealed the already grim public image of the chemical industry as a threat to health and the environment—but it also helped seal the industry's determination to change that image.

Nearly a decade later, the chemical industry's counteroffensive is in full swing. The Chemical Manufacturers Association (CMA), which represents most of the chemical producers in the United States, heralds the new corporate philosophy with a trademarked credo—Responsible Care. Its 10 guiding principles and six management practices include an agenda for preventing accidents, guidelines for informing the public and responding to its concerns, and a program for preventing pollution by reducing waste and modifying processes, products, and facilities.

There's a heavy veneer of PR over the whole enterprise, and that raises the suspicions of some environmentalists; Fred Millar of Friends of the Earth, for example, calls the movement "a velvet glove over an iron fist." But other observers are impressed with the signs that the chemical industry is genuinely eager to improve its environmental record. According to statistics, mostly from government sources but compiled by the CMA, the industry as a whole reduced its emissions to air, land, and water by 41% between 1987 and 1991, while overall production increased by more than 10%. Capital expenditures for pollution control and abatement in 1991 amounted to about $2.4 billion, the CMA estimates. Not all of this is voluntary, of course; existing regulations and the expectation of tighter ones have provided plenty of incentive.

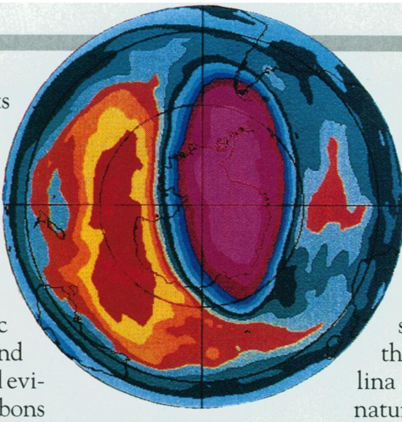
Still, Responsible Care "is not just smoke and mirrors," says William Glaze, chairman of the department of environmental sciences and engineering at the University of North Carolina and editor of *Environmental Science and Technology*. In an editorial last October in *Chemical & Engineering News*, Michael Heylin, the publication's long-time editor, went even further, hailing Responsible Care as a sign that "the chemical industry has finally changed its mindset."

It took some major jolts to bring about that change, notes Bruce Smart, a former industry executive, now a senior fellow at the World Resources Institute. "A series of events in the 1980s [including the Bhopal tragedy in 1984 and the discovery of an ozone hole over Antarctica in 1986] jarred lots of chemical companies into seeing their own future as endangered." In addition, a shift in the regulatory focus from "end-of-the-pipe" thinking toward preventing pollution led many companies to realize that reducing waste and preventing pollution in the first place makes environmental compliance much easier, reduces cleanup headaches, and can save money all along the line. It took until last April, though, before the industry had fully articulated and approved the Responsible Care program.

Responsible Care, say industry spokespeople, simply codifies efforts they were already making. One rough indicator of the headway is the 41% drop in emissions between 1987 and 1991. And some companies report achieving more dramatic cuts in

One chemist who responded early to the new challenge is Gary Epling of the University of Connecticut, who is developing ways of replacing toxic, metal-based catalysts with clean, sunlight-driven reaction centers. Epling says he's not surprised that his fellow chemists haven't shown much enthusiasm for environmental chemistry: Historically, if you had a great idea about cleaning up a chemical process or preventing pollution, he says, "you didn't have a prayer of getting it reviewed" or funded by the academic chemistry establishment. He and his colleagues blame an image problem. Environmental chemistry was linked to the pollution control philosophy of the 1970s and '80s, which focused on tracking, recycling, or detoxifying contaminants—problems of limited interest to all but a few academic chemists.

Such environmental problems as identifying, mapping, and quantifying hazardous materials like polychlorinated biphenyls (PCBs), dioxins, or heavy metals have been the bailiwick of a clique of analytical chemists who develop the tools and methods needed to do such monitoring. (One joke even had it that all environmental problems could be made to disappear by killing off the analytical chemists.) Chemistry and the environment also intersected in a few other academic venues such as civil engineering, forestry, agriculture, oceanography, and geology departments, where researchers trace how manmade pollutants migrate through water systems and the natural world. But mainstream chemists paid little attention to their colleagues' forays, says Epling.


MARK MARTEN/NASA/PHOTO RESEARCHERS

The ozone hole. Chemistry made it; will chemistry be able to mend it?

Take their reaction in 1974, when atmospheric chemists Sherwood Rowland and Mario Molina reported evidence that chlorofluorocarbons (CFCs)—whose apparent inertness, lack of toxicity, and low cost had made them big-business, vast-volume wonder chemicals—were destroying stratospheric ozone molecules. "We encountered much more skepticism than belief" from fellow chemists, recalls Molina, now at the Massachusetts Institute of Technology (MIT).

Soft science?

Underlying this reaction, Molina surmises, was a discipline-wide chauvinism about environmental research: "Historically, environmental science was discredited...because people working in that field usually were not the ones making contributions to the academic [chemistry] community." Regardless of the research's actual quality, many chemists saw it as soft, minor-league science, compared to their own hard, detailed work on chemical synthesis, catalysis, and reaction mechanisms, for example. To William Glaze, editor of *Environmental Science and Technology* (*ES&T*) and chairman of the department of environmental science and engineering at the University of North Carolina in Chapel Hill, that was a natural response to the descriptive quality of much environmental research.

But environmental chemistry doesn't have to be limited to issues such as tracking contaminants, says Hancock; they're largely a reflection of yesteryear's focus on pollution abatement and remediation. To chemists, says Hancock, those buzz words conjure moving dirt with heavy machinery, not synthesizing molecules or uncovering precise reaction mechanisms with elegant experimental protocols. "If cleaning up is what it is all about, then academic chemists are not interested," adds Princeton University chemist Thomas Spiro, who teaches a course on environmental chemistry.

That has slowly been changing as both regulatory agencies and industries, driven by economic realities and the broader philosophy embodied in the notion of "sustainable development," shift their sights from mere

---

specific kinds of emissions: Monsanto, still one of the nation's largest emitters of toxic chemicals, for example, boasts that it has cut its toxic air emissions from U.S. plants by nearly 90% since 1987. Though much of this decrease was forced by regulations, some reductions go beyond compliance. For example, since 1987, the company has cut air emissions of trichloroethylene, considered one of the most hazardous chemicals by EPA, by 75%, already surpassing the voluntary goal of a 50% reduction by 1995 that EPA proposed in its so-called 35-50 toxics reduction program.


MONSANTO

Taking responsibility. Equipment that recovers cyclohexane, a volatile industrial solvent.

Part of that kind of progress comes from plant shutdowns. But increasingly, the emissions cuts reflect practices such as recovering and recycling raw ingredients, using less material to begin with, and applying innovative chemistry and engineering. Louis Hegedus of W.R. Grace & Co., which makes catalysts, polymers and other products, cites one example: "Our manufacturing operations are all involved in programs to replace hydrocarbon solvents [from petroleum] with aqueous [water-based] ones." At 3M, employees found that a mild, citric-acid based solution washes copper sheeting used for making circuit boards just as well as the acid solution that had been standard—a substitution that has eliminated 40,000 gallons of hazardous waste per year. And scientists from Monsanto will report later this month at the American Chemical Society that they have developed a way to replace phosgene—a toxic chemical used for making many products including polyurethanes and chemical weapons—with carbon dioxide.

None of this comes cheap. For example, *Chemical & Engineering News* reported last December that Monsanto had spent $100 million since 1988 on projects to reduce its toxic air emissions. Glaze notes that one very large company, which he would not name, spends seven times that much on cleanup alone.

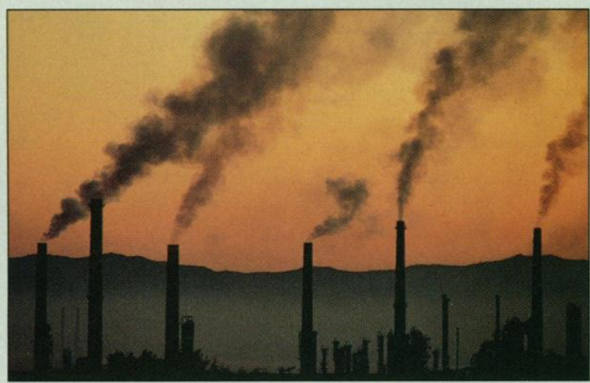
To Millar, of Friends of the Earth, all that isn't enough to cover what he sees as the industry's ongoing sins. He suspects that a touted component of the Responsible Care initiative, the panels meant to keep communities informed about the chemical processing being done in their neighborhoods, actually serves industry more than the public. And the industry as a whole is still reluctant to drop environmentally harmful practices, he says. "The change we see from these companies is when we force them to do something with laws."

The Environmental Defense Fund, a moderate environmental group, agrees, in the words of staff attorney Kevin Mills, that "a lot still needs to happen." He says his organization will take the industry's slogan, "Don't trust us, track us," quite seriously. But he thinks environmentalists should welcome the industry's hints of green. "We could be looking at something very powerful."

–I.A.

Making Molecules Without the Mess

Environmental chemistry has been slow to green the groves of academia (see main text). But the pace is quickening thanks to a new awareness of the challenges to be found in designing environment-friendly chemical processes, together with a modest funding boost. Here are a few of the projects, funded through new programs initiated by the National Science Foundation and the Environmental Protection Agency, that are seeding this new subfield of chemistry.



WEINBERG/CLARK/THE IMAGE BANK

Smoke signals. Academic researchers are heeding them.

■ **Turning off the heavy metal.** Catalysts are credited by some with the very existence of a chemical industry. But they also often enclose some nasty secrets: toxic metal atoms, including mercury and silver, that become hazardous waste when the catalysts lose their effectiveness and are discarded. Gary Epling and his colleagues at the University of Connecticut are looking for a benign alternative: dye molecules that can capture energy from sunlight or some other cheap light source and then drive reactions that are standard in the agrichemical and pharmaceutical industries.

■ **Bugs over benzene.** The basic ingredient of many industrial chemicals, including hydroquinone, a photographic developing agent, and benzoquinone, a common ingredient for industrial chemicals, is benzene. But this versatile petrochemical is also a carcinogen and a polluter. For making hydroquinone and benzoquinone, at least, there's a benign alternative: quinic acid. And John Frost and colleagues at Purdue University may have derived an equally benign route for making it: They've genetically engineered a bacterium that can produce the substance by digesting glucose, a.k.a. sugar.

■ **Kicking the organic solvent habit.** Plenty of industrial chemical reactions now happen in organic solvents, among them chlorofluorocarbons, benzene, and carbon tetrachloride—all of which have such environmental downsides as toxicity or damage to the stratospheric ozone layer. For at least one major class of industrial reactions, there may be a gentler substitute. James Tanko of Virginia Polytechnic Institute and State University and an associate are eyeing supercritical carbon dioxide—carbon dioxide in a netherworld between the liquid and gaseous states. They think it could do the job for reactions known as halogenations, in which chlorine or fluorine, say, replaces one or more of the hydrogens on a hydrocarbon as a first step in the manufacture of hundreds of products, including drugs and polymers.

■ **Cutting pollution by design.** When hundreds or thousands of pounds of different chemical ingredients get mixed in huge vats, sent down pipes, treated with gases, heated, cooled, and otherwise pummeled into new ingredients or products, waste and pollution have lots of opportunities to rear their ugly heads. Chemical engineer W. Harmon Ray at the University of Wisconsin is developing computer modeling methods aimed at helping chemical companies design the safest and most efficient processes and operating conditions while minimizing pollution.

■ **Writing and painting with light.** When ink and other coatings dry, puffs of a volatile solvent such as methylene chloride can escape into the air, making infinitesimal contributions to global warming. Infinitesimal, that is, until the amount of escaping solvent is summed over large-scale operations such as coating photographic paper or running printing presses. Alec Scranton and colleagues at Michigan State University hope to turn down the heat with solvent-free inks and coatings. Based on molecules known as vinyl ethers, the inks would cure when exposed to ultraviolet light, which would cause the vinyl ethers to polymerize—link together into long, durable chains.

Multiply these kinds of efforts enough times and transfer them to manufacturers, and industrial chemistry might eventually be able to deliver the goods without the grime.

–I.A.

pollution abatement to pollution prevention. The trend is opening a whole new realm of issues in environmental chemistry that are challenging enough to hold the interest of academic chemists. "Environmental chemistry is finally becoming recognized for the sophisticated subject that it is," Glaze says. Deciphering how CFC substitutes dodge the chemical pathways that result in ozone destruction requires first-rate atmospheric and surface chemists; finding viable, cleaner-burning liquid fuels relies on the particular rigor of physical chemists; developing microbial chemical-making methods to bypass more toxic traditional ones leans on the knowledge of bioorganic and bioinorganic chemists.

And Hancock and his colleagues in the federal science policy fraternity are taking steps to speed the birth of this new subdiscipline. Last year Henry McGee, NSF's director of the Division of Chemical and Thermal Systems (which includes chemical engineering) teamed up with Hancock and the nonprofit Council for Chemical Research to initiate their research program on the topic, called Environmentally Benign Chemical Synthesis and Processing. In launching it, McGee and his colleagues were careful to disavow the "move-the-dirt" image that still often pops into many chemists' minds when they hear "environmental science." In italic type and appropriately green ink, the program announcement stresses that "this initiative addresses concerns in pollution prevention and reduction, not concerns in waste treatment."

Pertinent projects, some of which received their first funding last year—a total of $950,000—run the gamut from developing more selective catalysts that reduce waste while improving product yields, through new and cleaner reactions to replace existing ones that require toxic feedstocks or solvents, to new processes that minimize or eliminate the production of hard-to-entrap aerosol particles that contribute to air pollution.

Still, environmental chemistry's pariah status has haunted the program. In its maiden year, only a handful of chemists came forward with proposals. (The turnout was better among chemical engineers.) The poor showing from chemists proper is not for lack of interest, insists Epling: Environmental chemists, he says, simply don't think of the chemistry-related divisions of NSF—the wellspring of funding for mainstream chemistry—as a likely source of money for environmental projects. After all, EPA received plenty of proposals for its related, one-time only program called The Chemical Design Project. But EPA had only enough money to grant about $50,000 each to a half-dozen environmental chemists, says Joseph Breen of EPA's Office of Pollution Prevention and Toxics (formerly just the Office of Toxics). This year, NSF and EPA decided to join forces by signing an agreement to collaborate. "We had more money, and they had more of a constituency," Hancock says. "It's a mutual love affair," he says, which he expects will yield more and more environmental chemistry.

The color of money

If a soon-to-be-released NSF report titled "Challenges and Opportunities in Environmental Chemistry" has any impact, the greening of academic chemistry's research culture should accelerate markedly in coming years. A draft of the report obtained by *Science* reads like a call to arms to chemists. "To meet the challenge—to understand the environment in all its chemical complexity, and to minimize the environmental impact of chemical technology—will require the best minds in chemical science," the draft states. Among the general challenges described in the report: finding cleaner combustion processes that extract more automotive miles out of fossil fuel while generating little or no smog-producing nitrogen oxides; designing polymers and other materials with "molecular suicide switches" so that microbes might better be able to degrade them after their useful lifetimes; finding CFC replacements; and developing catalysts that can destroy chlorocarbons such as PCBs. To support all this, the 16-member panel that prepared the report recommends establishing a federally funded $30-million-a-year Environmental Chemistry Initiative to fund at least 100 individual investigators, up to 10 problem-focused groups, and up to four national research centers.

But a new national infrastructure for environmental chemistry by itself won't be enough to overcome the old aversion to green. The environmental movement is barely 20 years old, and chemistry's culture can be slow to change. Plenty of chemists studied biological molecules even in the 19th century, for example, but it took the discovery of the structure of DNA in the 1950s to spur the culture change that has made biochemistry part of chemistry's everyday lexicon.

In the case of environmental chemistry, generational change may prove the key impetus, Spiro says. One telling sign comes from the American Chemical Society's division of education. They recently approved an "environmental track" for undergraduate chemistry curricula. And Spiro of Princeton and Molina of MIT report that students have been pushing faculty to get more environmentalism into courses. "The tail has been wagging the dog," Spiro says. Or, to put it another way, some green seedlings may soon be overshadowing chemistry's old growth.

–Ivan Amato

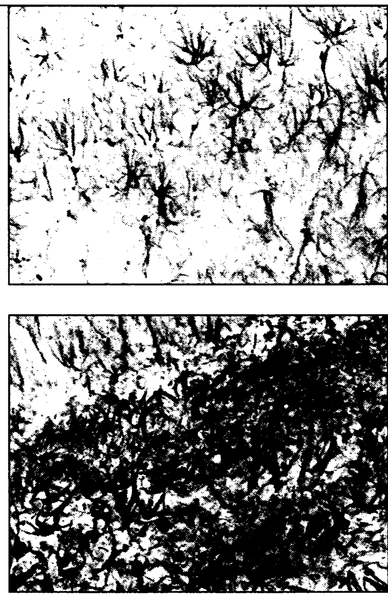
NEUROTOXICOLOGY

New Marker for Nerve Damage

When rats are fed a certain nerve-damaging chemical, they waltz in circles in their cages, performing a grotesque imitation of Fred Astaire dancing with his shadow. But the effects of the chemical, β,β-iminodipropionitrile (IDPN), are not limited to the brain centers that control movements. Neurotoxicologists have recently discovered that IDPN is toxic to nerve cells in the cerebral cortex and other brain areas where it had not been previously thought to act. This surprising finding is among the first fruits of a new type of biochemical assay that uses a biological marker to detect neurological damage. The new technique is causing much excitement among toxicologists because it's the first tool to be developed in years that can help scientists screen chemicals for neurotoxic effects in animals.

As a report from the National Research Council pointed out last year, there's a great need for such a screen; an estimated 70,000 chemicals in commercial use haven't yet been tested for neurological effects (*Science*, 28 February 1992, p. 1063). To help remedy that situation, the Environmental Protection Agency (EPA) last year began recommending that companies include the new assay, which measures the levels in brain of a protein called glial fibrillary acidic protein (GFAP) in the batteries of animal tests they use to assess the potential health effects of commercial chemicals. And Monsanto and Eastman Kodak recently began to move in that direction by assigning staff to explore the use of the assay in their in-house testing programs. "It's premature to use it routinely as a screen," says Monsanto neurotoxicologist Abby Li. Nevertheless, she says it holds great promise as a measure of damage to the central nervous system. Eventually, neurotoxicologists hope, the GFAP assay may also provide insights that can help them develop "biomarker" assays of, for example, blood, urine, or cerebrospinal fluid that can help them determine whether people have suffered damage from neurotoxicants.

Research on the GFAP assay dates back to work done in the mid-1980s by neurotoxicologist James O'Callaghan and colleagues at EPA's lab in Research Triangle Park, North Carolina. Aware that brains cells known as astrocytes grow larger in response to neurological damage, the EPA group looked to see if any of the astrocyte protein concentrations went up in brain tissue from mice and rats exposed to neurotoxicants. Among the substances they tested were the recreational drug methamphetamine and the environmental pollutant methylmercury, and they also looked at the effects of other insults to the brain, such as stab wounds. The result: GFAP levels increased in precisely those brain areas thought to be damaged by the chemicals. Even more intriguing, O'Callaghan says, is the recent finding that the GFAP assay can detect nervous system damage missed by standard histological screens. Although researchers suspected, for example, that IDPN damages the olfactory bulb of rats, they could find no damage with a variety of standard assays. But when they measured GFAP, they found that this region had indeed sustained damage. (The results were published in the December issue of the *Journal of Pharmacology and Experimental Therapeutics*.) Another surprise was the finding, in press in the same journal, that IDPN was doing major damage to the cerebral cortex.



JAMES O'CALLAGHAN

Bad sign. GFAP staining picks up 10 times more astrocytes after neurotoxicant damage *(below)*.

Neurotoxicologists now hope that the GFAP results can help them find a similar human biomarker that would reveal exposure to neurotoxicants. Currently they have only a handful of such biomarker assays, including the test for elevated blood lead levels and another that measures blood concentrations of the enzyme acetylcholinesterase, which decreases after exposure to organophosphate pesticides. But researchers would like more generic biomarkers that could pick up damage from a wide range of chemicals. Because the brain is a complex melange of cell types and neurotransmitters that neurotoxicants can damage in many ways, that could be a problem. "It's not going to be easy to develop generic markers for broad classes of neurotoxicants," cautions Hugh Tilson, director of EPA's neurotoxicology division. Nevertheless, the GFAP work indicates that it can be used to detect damage from different chemicals. So, Tilson says, it may well be possible to push the field in that direction.

–Richard Stone