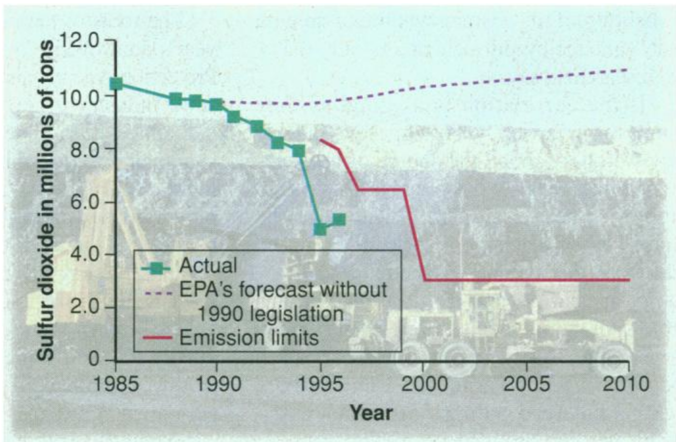
In the United States, a flexible, free-market approach has helped to curb acid rain at a bargain price. Could it work for greenhouse gases around the world?

Acid Rain Control: Success on the Cheap

Back in the 1970s, sulfuric acid seemed to be consuming the environment. Spewed from power plant smokestacks, it rained or drifted down on lakes, streams, forests, buildings, and people in ever-increasing volumes, killing fish and trees, disfiguring stone buildings, and corroding the lungs of people.

But today, after 20 years of control, acid rain is a problem on the mend. In the United States, emissions of sulfur dioxide—the chief precursor of acid rain—are down by half. The nation is on track for another round of reductions beginning in 2000, and, with some significant exceptions, lakes and forests are on the road to recovery. Perhaps even more surprisingly, U.S. acid rain control has been a bargain: The latest cost estimates are about $1 billion per year—dramatically lower than earlier forecasts of $10 billion or more, and about half as much as even the lowest estimates.



How low can you go? U.S. sulfur dioxide emissions from selected plants have already dropped below the levels required by law.

As negotiators gather this week in Buenos Aires to try to figure out how to cut greenhouse gas emissions (see sidebar), the story of U.S. acid rain control offers a case study in the successful regulation of a wide-ranging pollutant. Economists are still trying to understand just why control is proving so cheap, but they agree that at least partial credit must go to the unusually flexible U.S. regulations and their use of the free market. In the 1990 Clean Air Act Amendments, Congress told power plant operators how much to cut emissions but not how to do it, and established an emissions trading system in which power plants could buy and sell rights to pollute.

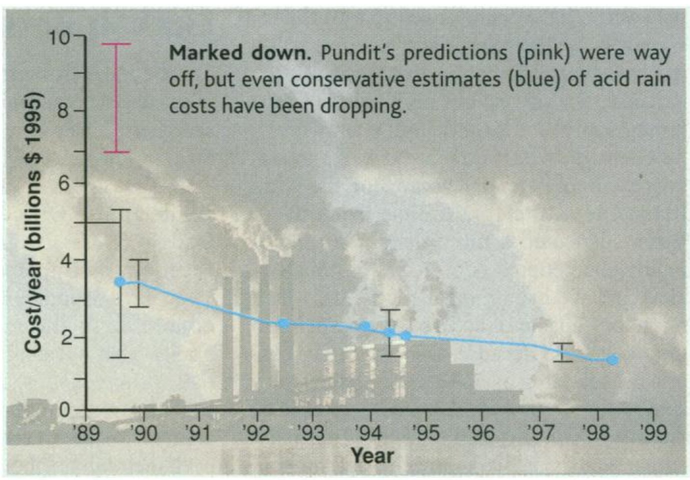
It was "a radically different way to go about environmental regulation," says economist A. Denny Ellerman of the Massachusetts Institute of Technology (MIT). "The lessons learned are pretty impressive." The United States is now trying to spread those lessons worldwide. Indeed, in Europe, where acid rain reductions appear to be more expensive than in the United States, regulators are taking a close look at the U.S. model. A flexible system of emissions trading also serves as the crux of U.S. proposals for reining in greenhouse warming—although no one is sure whether such a system can be scaled up to work across many different countries. "We proved the concept," says Joseph Kruger of the Environmental Protection Agency (EPA) in Washington, D.C. "If the acid rain program hadn't been such a success, we wouldn't be talking about trading greenhouse emissions."

A new flexibility

The prospects for economical acid rain reductions by any means looked bleak in the 1980s, says Joseph Goffman of the Environmental Defense Fund in Washington, D.C. In the late '80s, when it was thought that sulfur dioxide emissions—then totaling 25 million tons a year—would have to be reduced by 10 million tons a year, he recalls, estimates of the cost were running from many hundreds to $1000 for every ton shaved off the total, or a cool $10 billion a year. Those high prices were based on complying with the standard type of "command and control" emissions regulations, in which regulators made all the decisions. In the 1977 Clean Air Act, for example, regulators decided on a control technology—a "scrubber" that strips the sulfur dioxide from the spent combustion gases before they go up the stack—and they also decided which plants needed scrubbers.

Under a command-and-control scheme, "you've fixed the technology in place," says Goffman. "You've eliminated innovation. We did this in the '70s and '80s because that was all we knew how to do. For a while it worked well," until the easy, cheap reductions had been made. By the late 1980s, regulators had started to look for cheaper options.

When Congress contemplated the next round of emissions cuts, the $10 billion price tag triggered sticker shock. Instead of instituting ever more draconian and expensive command-and-control regulations, Congress took a new tack in the 1990 Clean Air Act Amendments: It commanded reduc-



Marked down. Pundit's predictions (pink) were way off, but even conservative estimates (blue) of acid rain costs have been dropping.

CREDITS (TOP): SOURCE: A. E. SMITH ET AL., 1998 AND D. BURTRAW, 1998; PHOTO: UNIPHOTO; (BOTTOM) SOURCE: R. SCHMALENSEE ET AL.; PHOTO: DAVID SCOTT SMITH

Pollution Permits for Greenhouse Gases?

This week, as delegates from some 180 countries gather in Buenos Aires to figure out how to reduce greenhouse gases, they will spend much of their time pondering a strategy developed to keep down the costs of acid rain controls in the United States: trading emissions coupons in a free market (see main text). Although the notion of selling permits to pollute may seem odd, its success in reducing acid rain led the Clinton Administration to press for these so-called "flexibility mechanisms." The Administration estimates that if the market operated perfectly, such trading could save around 90% of the cost of cutting greenhouse gas emissions, bringing the price down to between $14 and $23 per ton of carbon. Without trading, cutting emissions to comply with last year's Kyoto Protocol could cost the United States $54 billion to $60 billion a year, the White House says.

But despite American high hopes, experts warn that setting up an international carbon trading program will be a delicate and difficult task. "It's not a trivial extrapolation from sulfur dioxide trading. This is a tremendously difficult challenge," says Harvard University economist Robert Stavins. "There's a possibility of doing it right, but if it's done wrong, it won't save nearly what's been predicted."

The basic idea is that each country would have a sort of "checking account" of greenhouse gas emissions allowances, set as a percentage of how much it emitted in 1990. The protocol says countries can sell allowances if they have more than they need, or they can earn credits by helping reduce emissions in other countries. The United States, for example, might simply buy allowances from Russia, or it could take on a project such as upgrading coal-fired power plants in Russia in exchange for some of the Russian emissions allowances.

Keeping the accounts straight may be tricky, however. Monitoring U.S. sulfur emissions required fitting only about 110 power plants with sulfur dioxide monitors, Stavins notes. But with greenhouse gas emissions, there are "millions" of sources in more than 100 independent countries; there are at least a half-dozen important greenhouse gases; and making sure a project really results in lower emissions may be a tremendous challenge, he says.

A more political issue likely to be on the table in Buenos Aires is whether countries must make domestic cuts before they can swap permits internationally. That argument is "partly moral, partly practical," says John Lanchbery, a policy officer at the Royal Society for the Protection of Birds in the United Kingdom, as some observers believe countries won't cut at home if they can just buy their way out abroad. Some countries also argue that there should be limits on trading by Russia and Ukraine, which will get a big break because permits are set to 1990 levels, before those countries' economies—and fossil fuel use—plummeted. But "if you wanted to get the most out of trading, you would have no cap at all," Lanchbery says. A faction known as the Umbrella Group, which includes the United States, Japan, Russia, and other nations, opposes caps, while a bloc led by the European Union favors them.

Then there's the Clean Development Mechanism (CDM), a complicated and controversial plan to help curb emissions in developing countries. This is an effort to plug what many see as a big gap in the Kyoto protocol: At present it doesn't set any emissions caps for developing countries. Under the CDM scheme, developed countries could earn credits by setting up emissions-reduction projects in developing countries—converting an Indonesian coal-fired power plant to natural gas, for example. But it will be a challenge to prove that countries aren't earning credits for "projects" that would have happened anyway. "It becomes a much squishier story," says Michael Toman of Resources for the Future, a think tank in Washington, D.C.

Also to be worked out, says Annie Petsonk of the Environmental Defense Fund's Washington, D.C., office, is how to punish countries that don't meet their emissions targets. "We don't have the equivalent of the Seventh Fleet to hammer them into compliance," she says. The proponents of flexibility mechanisms are leaning toward a system in which permits would lose some value if the selling country exceeds its targets.

Beyond the permit question, other major issues at Buenos Aires are expected to be whether developing countries should commit to voluntary emissions reductions, and how to account for carbon dioxide "sinks," such as replanted forests (*Science*, 24 July, p. 504). But no decisions on this issue will likely be made until the Intergovernmental Panel on Climate Change, the scientific group whose findings led to the treaty, issues a report on sinks in May 2000, says Alden Meyer, director of government relations at the Union of Concerned Scientists. And as with flexibility mechanisms, the main outcome of Buenos Aires will likely be to set up working groups to hammer out issues over the next few years, says Meyer, who concludes: "We don't expect the drama of Kyoto, but there should be progress forward." **–JOCELYN KAISER**

tions but let power plant operators figure out the cheapest way to control emissions. The reductions were to come in two steps. Starting in 1995, 110 mostly coal-burning plants out of thousands in the country—then emitting about 4 pounds of sulfur dioxide per million British thermal units (mBtu) of heat—would be cut back to only 2.5 pounds/mBtu. In Phase II, starting in 2000, more plants are to fall under the plan and emissions will be tightened to 1.2 pounds/mBtu. The total release expected in 2010 is 8.95 million tons per year, a reduction of 10 million tons per year from the amount projected to be released without controls.

Congress made the rules even more flexible by authorizing a limited number of emission allowances, "right-to-pollute" coupons that could be bought, sold, or saved. Such trading with a cap on total releases means emitters are "strictly accountable for the end result," says Kruger, "but they have flexibility in the way they get there."

Cost and effect

But as the final Clean Air Act Amendments neared passage in 1990, just how much money the new rules would cost was a matter of sharp debate. At the high end, some lobbyists, columnists, and industry advertisements were touting vaguely documented figures of "$3 billion to $7 billion per year, with the price tag rising to $7 billion to $25 billion by the year 2000," according to environmental policy analyst Don Munton of the University of British Columbia. The lower end of these estimates compares with the estimated cost of simply putting scrubbers on the 50 dirtiest plants. That was thought to cost $7.9 billion per year, according to a 1983 Office of Technology Assessment study, or $11.5 billion per year, according to an industry study (figures in 1995 dollars).

More rigorous cost projections came in lower. These generally fell within the range of a 1990 study for the EPA made by ICF Inc. of Fairfax, Virginia, that found annual costs (in 1995 dollars) could be as low as $1.9 billion per year through to the 2010 goal or as high as $5.5 billion per year. But the lower figures were not widely believed at the time. When EPA testified to Congress just before passage that the annual cost in 2010 could be roughly $4 billion, notes Kruger, "we were roundly criticized for being overly optimistic."

It turns out that those figures weren't optimistic enough. Two groups of economists—Dallas Burtraw and colleagues at the Washington think tank Resources for the Future (RFF) and Anne Smith of Charles River Associates in Washington, D.C., Jeremy Platt of the Electric Power Research Institute (EPRI) in Palo Alto, California, and Ellerman—have recently compared those early analyses with actual costs. In 1996, after the first 2 years of the Phase I limits, emissions from participating power plants dropped to 5.4 million tons, 35% below the legal limit for those plants of 8.3 million tons. And it was done at a cost of about $0.8 billion per year, according to two independent estimates by Ellerman and by Curtis Carlson and colleagues at RFF.

Phase I was expected to be cheaper than later reductions, but estimates of the long-term costs through 2010 have also been dropping (see graph, p. 1024). By 1995, ICF's estimate for the EPA had dropped to $2.5 billion per year. EPRI's 1997 estimate was down to $1.6 billion to $1.8 billion per year, and Carlson and colleagues' 1998 estimate is $1.0 billion—a far cry from many earlier estimates and below EPA's early projections.

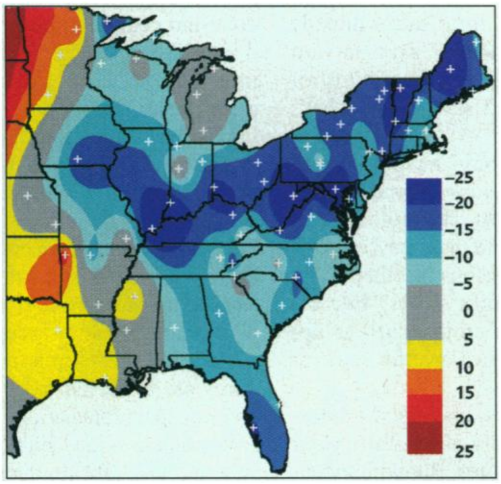
Why is acid rain reduction so economical, at least so far? Economists are still exploring the answer, but they agree that the biggest advantage was the overall flexibility of the program, which allowed power plants to exploit unexpected opportunities. The emissions trading system has been just one factor in this flexibility, these analysts conclude, but its impact is likely to grow in the years ahead as reductions become increasingly harder to achieve.

The chief benefit of the trading system is that it puts free market forces to work, economists explain. "It's very much like [the way] a bank operates," says Ellerman. Emitters have a checking account system, and the EPA limits the amount of "currency" in the system. Everyone is free to find the best buy in emissions reduction as long as they don't "overspend" their allowances. "You no longer have a bureaucratic nightmare" like that of command and control, he says.

The allowance system broadens a power plant operator's options. An operator might install a scrubber—the cheapest available, as there are no regulations on types of scrubbers—or perhaps switch from a coal supply high in sulfur to a low-sulfur one, whatever option is cheaper per ton of emission reduction. Because allowances can be bought and sold, emissions can be cut wherever it's cheapest to do so—even at another company's plant in a different state. Each emitter just needs enough allowances to give to the EPA at the end of the year to cover the tons released. If a plant emits fewer tons than allowed, it can save leftover allowances for later.

Trading has saved money, reducing costs by perhaps 30%, according to Burtraw and others, but it's by no means an ideal system. "The trading program has worked well, but I wouldn't say it has worked perfectly," says Burtraw. Although increasing, trading has been light and largely limited to swaps between plants within the same company, perhaps because state regulatory commissions new to the system didn't steer utilities to the lowest cost option allowed by outside trading.

For the most part, economists suspect that the trading system hasn't come up to speed because operators have had a choice of other unexpectedly inexpensive options. For one thing, "scrubbers turned out to be a lot cheaper than people thought," says Ellerman. New instrumentation and controls reduced staffing requirements, and units fitted with scrubbers are in use more often than expected, reports economist Richard Schmalensee and his MIT colleagues. And although relatively few trades actually occur, the trading system reduces overall scrubber costs by doing away with the need for backup scrubbers: If a scrubber goes down, plant operators can buy allowances to cover the added emissions. Overall, Schmalensee found, the cost of scrubbing in phase I has been 40% lower than estimated in 1990.



Sweeter rain. Thanks to controls, precipitation in much of the east is less acid, as seen in the percent change from 1983 to 1994.

More unexpected savings came from fuel switching. Much of the Appalachian and Midwestern coal that fed the plants of the Ohio Valley—the biggest source of sulfur dioxide in the country—had a sulfur content of several percent. By switching to coal containing 1% sulfur or mixing low- and high-sulfur coal, plant operators could avoid scrubbers. In 1990, most observers believed that fuel switching would be limited. They expected that burning fuel with 1% sulfur would damage hardware—a prediction not borne out by experience—and that the price of low-sulfur coal would rise once the Clean Air Act upped demand.

That hasn't happened yet, thanks to developments that, at least initially, were unrelated to acid rain control. Low-cost, low-sulfur fuel had been available in the West for some time, notably in the Powder River Basin of Wyoming; the expense in the 1970s was in getting the coal to the East, where the big markets were. Then the Staggers Act of 1980 largely deregulated railroads. Coal transportation costs have fallen 35% since the 1980s, notes Burtraw. By 1990, the amount of low-sulfur coal burned had doubled, but the implications for acid rain control were underappreciated by most policy-makers and power plant operators, says Munton. In fact, Smith and her colleagues say, because plant operators shied away from the unknowns of the fuel-switching option in favor of more familiar scrubbing, phase I reductions cost significantly more than they had to.

Although these external factors rather than trading have apparently dominated savings in phase I of acid rain control, most observers credit the innovative flexibility of the Clean Air Act Amendments with letting this mix of solutions develop. Once Congress gave plant operators complete freedom to cut emissions, "all the compliance vendors—low-sulfur fuel suppliers, scrubber manufacturers, and natural gas producers, for example—had to compete very hard to win," says Goffman. "The more choice you give to more people, the better the outcome." Burtraw agrees that "a big thing about the trading program is the flexibility that allows firms to take advantage of changes in prices and technology."

How that flexibility will work out in phase II remains to be seen, as there are new uncertainties in the offing. EPA is considering restrictions on fine atmospheric pollutant particles, some of which form from sulfur dioxide. Reduction of greenhouse emissions could also shrink sulfur emissions, if the United States adopts energy-conservation or fuel-switching measures. But the prospect of unknown steps has the power industry worried, says Platt.

Meanwhile, Europeans have also been successful in reducing their sulfur dioxide emissions, halving them between 1980 and 1993, says EPA international liaison Rhona Birnbaum. But they have not fully embraced trading. Instead European countries have adopted diverse approaches ranging from limited trading to pure command-and-control regulations. No one has calculated the costs of this mixed approach to date, but estimates for Europe's ambitious 2010 goals—to cut sulfur emissions damaging sensitive ecosystems by 60%—are quite high: about $1100 per ton of sulfur dioxide, according to Mary

SOURCE: JAMES A. LYNCH/PENN STATE UNIVERSITY

Saether of the European Union in Brussels. As a result, Europeans are showing increasing interest in American-style allowance trading. "People come to the United States and want to know how this works and how it is generalizable," says Burtraw.

He notes that the United States succeeded in making the concepts of trading and flexibility hallmarks of the Kyoto agreement to reduce greenhouse gas emissions. And some of the solutions might be similar to those used in the acid rain case: As producers switched to low-sulfur coal, so they might switch to natural gas, which produces less warming per unit of energy produced. Technology and efficiency improvements, particularly in developing nations, might be a relatively cost-effective way to reduce greenhouse gas emissions.

But the parallels are not perfect, Ellerman cautions. For starters, it's not clear that a trading system will work with a half-dozen greenhouse gases, where trades among different industries and across the world would be required. And a key factor in the greenhouse case is the stringency of the emission cap—the final figure of allowable emissions. If it's too low, flexibility is reduced along with the price competition it encourages. As Ellerman and his colleagues have written, emissions trading "is not a panacea that inevitably makes costs of emissions control simply disappear into thin air." But for reining in pollution without choking industry, it looks like a good place to start.

–RICHARD A. KERR

CANCER RESEARCH

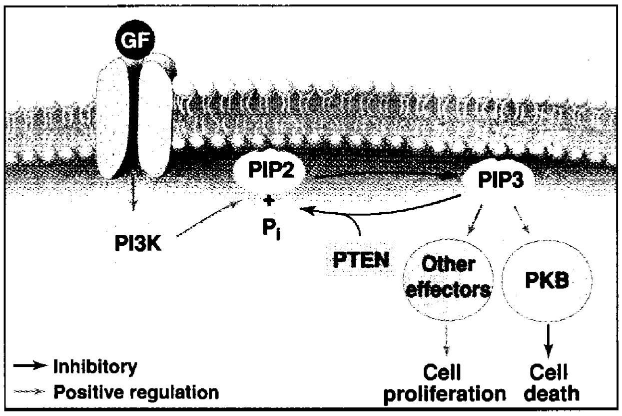
A Surprising Function for the PTEN Tumor Suppressor

The PTEN protein apparently exerts its effects by removing a phosphate from a lipid in one of the cell's key growth control pathways

Last year, cancer researchers welcomed the discovery of the *PTEN* gene with great enthusiasm. Not only was it a new tumor suppressor, one of the growing number of genes whose loss or inactivation contributes to cancer development, but it appeared to be quite an important one: *PTEN* mutations have been linked to a variety of common human cancers, including breast, prostate, and brain cancer (*Science*, 28 March 1997, p. 1876). And unlike some tumor suppressor genes whose functions were complete mysteries when they were first discovered—the two breast cancer genes are examples—*PTEN*'s structure provided an intriguing clue to how the protein might suppress tumor cell growth.

The early reports suggested that PTEN might be a tyrosine phosphatase, an enzyme that strips off phosphate groups attached to tyrosine residues in other proteins. The idea made sense because several oncogenes, which can lead to cancer when inappropriately activated, work by attaching those phosphate groups in the first place, thereby revving up the signaling pathways that tell cells to divide. A protein phosphatase might then be expected to reverse those growth-stimulatory effects. Indeed, cancer researchers had long expected that one or more of the enzymes would prove to be tumor suppressors, but before PTEN's discovery, they had not found any that seemed to fit the bill. Now, a flurry of new papers is showing that they are only half right about how PTEN works.

The enzyme is a phosphatase—but its target is apparently not a protein. Instead, it's a fatty molecule, or lipid, that's tucked into the cell membrane—a completely new kind of target, as far as tumor suppressors are concerned. "It's kind of ironic," notes Ben Neel of Beth Israel Deaconess Medical Center and Harvard Medical School in Boston. "Many of us went into the protein tyrosine phosphatase field looking for tumor suppressors. We finally find a tumor suppressor that looks good—and it turns out to be a lipid phosphatase."



Putting the brakes on. PTEN may inhibit cell growth by removing a phosphate from PIP3, thereby blocking its growth-stimulatory and apoptosis-blocking effects.

ILLUSTRATION: K. SUTLIFF

The target lipid, called phosphatidylinositol-3,4,5-trisphosphate—PIP3 for short—is a key component of one of the cell's major growth control pathways, acting both to stimulate cell growth and to block apoptosis, a form of cell suicide that can keep damaged cells from proliferating. By stripping away one of PIP3's three phosphates, it appears, PTEN reins in the growth pathways and allows cell suicide to proceed, keeping cell populations in check.

Conversely, loss of *PTEN* during tumorigenesis presumably keeps the PIP3 pathway inappropriately activated, allowing the mutated cells to grow unchecked when they should die. "I think the results are fascinating," says cancer gene expert Bert Vogelstein of Johns Hopkins University School of Medicine in Baltimore. "The new data on lipids dramatically change our perspective and should open up new vistas in the study of oncogenesis."

What's more, knowing that PTEN suppresses proliferation by interfering with the PIP3 pathway may aid the development of treatments for cancers in which *PTEN* is mutated. Such therapies might also control cancers in which the PIP3 pathway is overactive for other reasons. It might be possible, for example, to design drugs that work by blocking critical steps in the pathway.

The first inkling that PTEN might be a lipid phosphatase came in work reported last spring by Jack Dixon, Tomohiko Maehamahis, and their colleagues at the University of Michigan, Ann Arbor. Because the structure of PTEN resembles that of known tyrosine phosphatases, researchers looking for its targets first concentrated on phosphorylated proteins. But Nick Tonks of Cold Spring Harbor Laboratory in New York, a pioneer in the phosphatase field, says that they "had trouble finding any [protein] substrate that made biological sense."

Instead, Tonks and his postdoc Mike Myers found that PTEN preferentially strips phosphate groups from synthetic peptides that carry an unusual number of negatively charged, highly phosphorylated amino acid residues. Such sequences don't occur naturally in any proteins known to be phosphorylated by tyrosine kinases. But the finding prompted both Tonks and Dixon to look at other negatively charged molecules found inside the cell, including phospholipids.

The search paid off: In the 29 May issue of the *Journal of Biological Chemistry*, Dixon's team reported that, in test tube stud-