e-lab

Energy Laboratory research and related activities at the Massachusetts Institute of Technology

January–March 1997

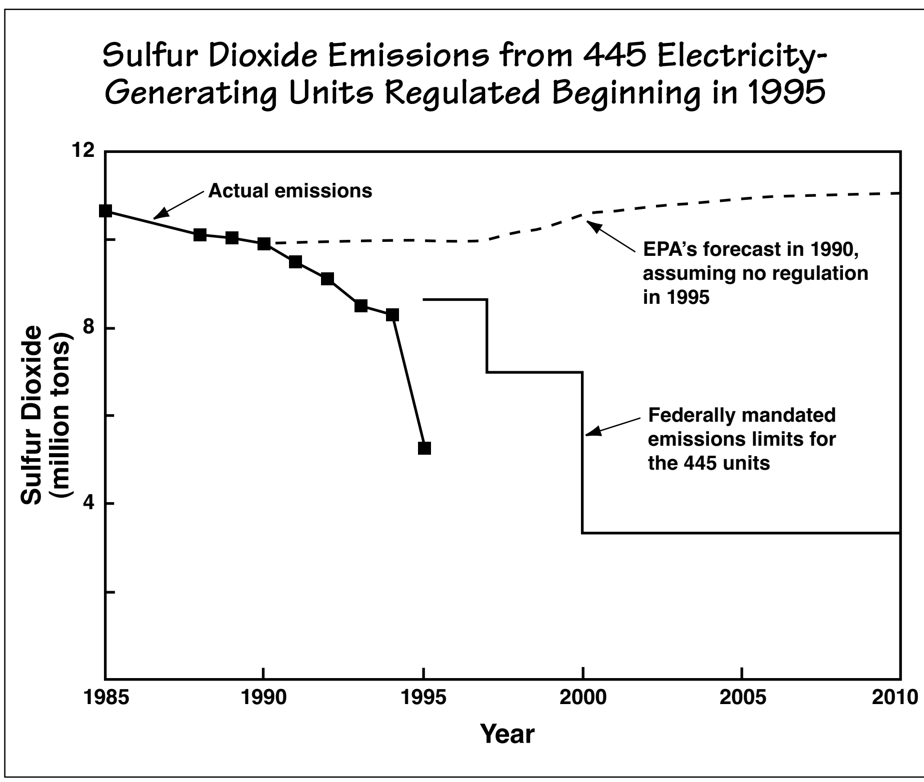
# Reducing Sulfur Dioxide Emissions Through Market-Based Regulation

**In 1995, the acid rain provisions of the 1990 Clean Air Act Amendments (CAAA) went into effect. By year's end, electric utilities had reduced emissions of sulfur dioxide ($SO_2$) far more than required by the new law. According to an Energy Laboratory analysis, the reduction was largely the result of a novel regulatory scheme that turned the right to emit $SO_2$ into a valuable commodity that could be bought and sold. Under the new law, utilities were issued a limited number of fully tradable permits to emit $SO_2$. Some utilities faced high costs to reduce emissions, so they bought permits from utilities whose costs were lower. Other utilities reduced emissions below their allowable levels, thereby freeing up permits to sell or to save for meeting tighter emissions restrictions in the future. The result was an unprecedented emissions reduction at a lower-than-expected cost. Judging by the success of this first large-scale experiment, "market-based" environmental regulation could be an effective means of controlling other pollutants, among them worldwide emissions of $CO_2$.**

## IN THIS ISSUE



Title IV of the CAAA requires that electric utilities in the United States reduce their emissions of $SO_2$ to roughly half the 1980 level, or 8.9 million tons per year—a level at which acid rain would cease to be a problem. Traditional "command-and-control" regulations would force that emissions reduction by making all electric utilities achieve a set percent reduction or meet some uniform standard and by requiring that at least some electricity-generating units install $SO_2$-removing scrubbers. If past experience is any guide, the reduction of emissions would be costly, bureaucracy and litigation would abound, and




**The solid line with data points shows actual total emissions from 445 electricity-generating units first affected by the Clean Air Act Amendments in 1995. The dashed line shows predicted emissions from those units (assuming no 1995 regulation), and the stepwise solid line shows total emissions that those units can make under the 1995 regulation. (Extra allowances were issued in 1995 and 1996 as an incentive for utilities to install scrubbers.) According to an Energy Laboratory analysis, the decline in emissions between 1990 and 1994 was largely due to cheaper low-sulfur coal from the West. However, the dramatic drop in 1995 can be attributed mostly to the new market-based, economically motivated regulatory scheme that first became effective that year.**

complete compliance would be far from assured.

Title IV takes a dramatically different approach to achieving the mandated reduction in $SO_2$ emissions. Instead of imposing a specific reduction requirement on every unit, it creates and distributes emission permits, or "allowances." Each allowance gives the holder the right to emit 1 ton of $SO_2$. The number of allowances allocated to a particular unit in a given year is determined by the product of the average amount of fuel burned between 1985 and 1987 (the "baseline") and a legislatively specified level of allowed emissions per unit of burned fuel. In Phase I, starting in 1995, 445 large units with relatively high emissions received allowances equal to 2.5 pounds of $SO_2$ per million Btu's of fuel burned during the baseline. In Phase II, starting in the year 2000, all units in the United States over 25 MWe will be issued allowances equal to 1.2 pounds per million Btu. Total emissions under all permits nationwide will equal the goal of 8.9 million tons. Under this novel regulatory arrangement, utilities must monitor $SO_2$ emissions continuously and report their measurements to the US Environmental Protection Agency (EPA). At the end of each year, utilities must turn in enough allowances to "permit" the past year's reported emissions, or face heavy fines.

For many units, the new annual emissions "budgets" are substantially below past emissions levels. To make the necessary cuts, utilities can install scrubbers, switch to lower-sulfur fuel, increase the use of non-sulfur-emitting generators, or undertake conservation measures. The approach selected is, of course, based on the relative costs of the various options. If the costs of all the options are high, a utility can continue to emit above its emissions budget by buying extra allowances from another utility. If the costs are low, a utility can cut its emissions more than required and either sell its unused allowances or "bank" them for use in the future, when standards will become more stringent and the cost of meeting them will be higher.

When Title IV was adopted in 1990, critics accused the government of granting the utilities "permission to pollute." They argued that total "compliance costs" would not be reduced because the (usually conservative) utilities would not buy and sell allowances but would simply make the necessary reductions, even at high cost. However, data from 1995—the first year in which Title IV took effect—suggest that the skeptics were wrong. Not only were compliance costs less than predicted in the affected units but the reduction in $SO_2$ emissions was dramatically more than required by law —an outcome unprecedented in the history of environmental regulation. And much of the reduction occurred at the highest-emitting plants, especially those in the heavy coal-burning states of the Midwest. The outcome has been so compelling that some people are advocating the use of "tradable allowances" for reducing other pollutants.

For the past year, Energy Laboratory researchers in the Center for Energy and Environmental Policy Research (CEEPR) have been examining the cost of complying with Title IV, the development of allowance markets, and the use of emissions trading. The research team includes A. Denny Ellerman, senior lecturer at the Sloan School of Management and executive director of the CEEPR; Richard L. Schmalensee, Gordon Y. Billard Professor of Management and Economics and director of the CEEPR; Paul L. Joskow, Mitsui Professor of Economics and Management; Juan Pablo Montero, PhD candidate in the Technology and Policy Program; and Elizabeth M. Bailey, PhD candidate in the Department of Economics.

To unravel the causes and costs of changing $SO_2$ emissions, the researchers used publicly available data on 1995 emissions, fuel deliveries, and investments at the 445 units affected by Phase I of Title IV in 1995. The researchers also surveyed individual utilities, soliciting information on compliance actions, costs, and allowance trading in 1995.

The figure on page 1 presents information on $SO_2$ emissions from the 445 Phase I units. The solid line with data points shows the actual aggregate emissions from those units between 1985 and 1995. The dashed line shows total emissions from those units in the absence of Title IV, as predicted by the EPA in 1990. The stepwise solid line starting in 1995 shows total emissions as mandated by Title IV. The step down in 1997 occurs because extra allowances were issued in 1995 and 1996 to encourage utilities to install scrubbers.

The decline in emissions prior to 1995—thus before the implementation of Title IV—proved to have a straightforward explanation: between 1985 and 1993, some utilities switched to lower-sulfur coal to save money. The deregulation of railroads in the 1980s drastically cut the cost of shipping low-sulfur coal from the Powder River Basin (PRB) in Wyoming. Attracted by lower prices, utilities farther east began to buy and use PRB coal, and sulfur emissions dropped. Thus, most of the reduction in emissions prior to 1993 would have occurred without Title IV.

By 1994, aggregate $SO_2$ emissions from Phase I units were already at or below the mandated cap. Nevertheless, during 1995 emissions plummeted almost 4 million tons. The researchers' analysis shows that continuing pre-1995 trends explain some of the decrease. But most of the decrease was due to Title IV. According to their calculations, fully 3.2 million tons of the decrease was the result of utilities banking allowances, that is, reducing emissions and stockpiling their allowances for future use. Of course, utilities will ultimately use those stockpiled allowances, probably after the year 2000, when more stringent emissions reductions are required.

What about the financial cost of complying with Title IV? Using data from the literature and from their survey, the MIT researchers calculated the cost of compliance, including both initial capital expenditures and annually recurring operating costs. They concluded that the 4-million-ton cut in $SO_2$ emissions observed in 1995 cost about $720 million—an estimate slightly below researchers' pre-1995 forecasts, which ranged from $800 million to $1.3 billion.

Why was the cost of reducing emissions lower than expected? About half of the reduction was achieved by using scrubbers, about half by switching to lower-sulfur fuel. The cost of switching fuels was about as anticipated. (Most utilities that switched to PRB coal did so prior to 1995.) Scrubbing costs, on the other hand, were about 40% lower than expected due to reduced operating and maintenance costs and more intensive use of the scrubbed units.

A review of the data shows that trading was more prevalent than the skeptics had predicted. Of the 8.69 million allowances issued, about 5 million were used by the utilities that received them to cover their own emissions. But about a half million were moved from an assigned unit to a different unit that would be cheaper to clean up. And 3.2 million were banked in order to reduce costs over the long term.

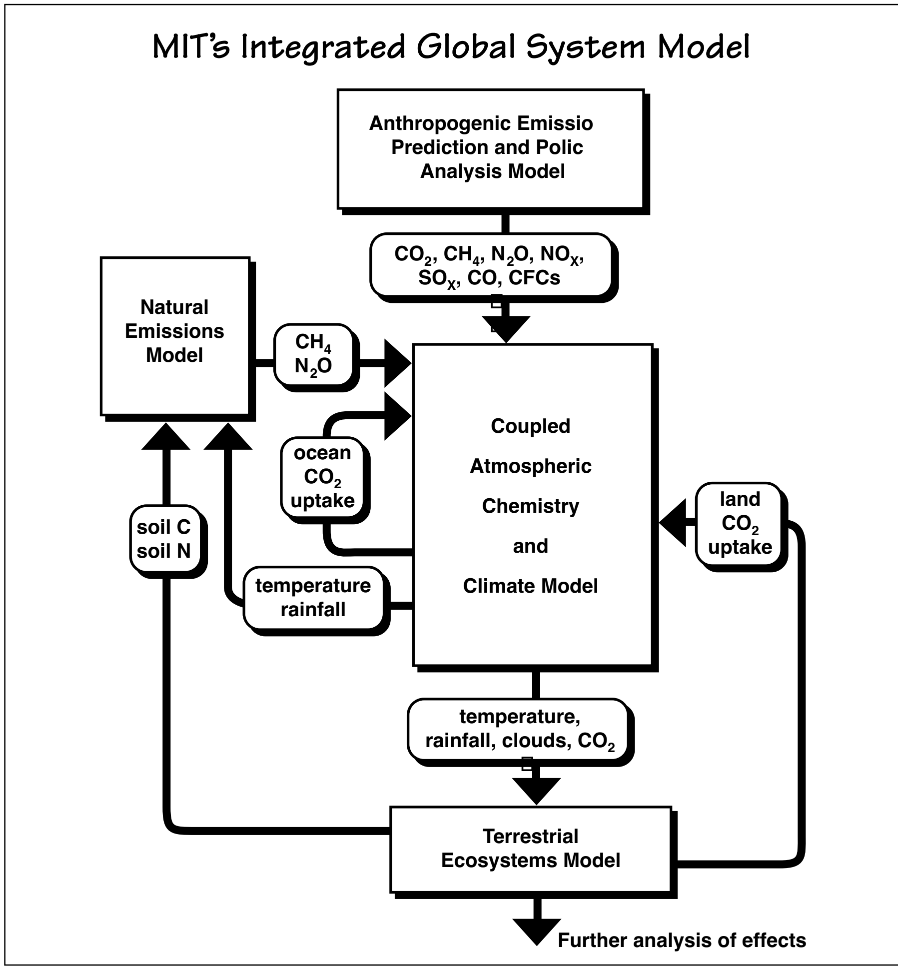
The MIT team observes that one of the most remarkable outcomes of Title IV has been the rapid evolution of a market for trading allowances. Some trading has taken place at a small annual auction administered by the EPA. But most of the trading to date has occurred privately. Because allowance trading is not hindered by government restrictions or subject to prior approvals, an effective market has developed, complete with brokers, futures, and other features typical of traditional financial markets. Thus far, allowance prices have been much lower than expected, largely because of the low cost of buying clean coal and of using already-installed scrubbers. While prices are likely to rise, utilities will almost surely continue to seek money-saving trades on the new allowance market.

The researchers note that everyone likes some aspect of Title IV. The utilities are free to make business decisions concerning technologies, fuels, and even their allocated allowances without direction from the federal government. Government regulators are delighted because Title IV is easy to implement and the affected utilities are complying fully. (The fine for noncompliance is $2,000 plus a possible jail sentence. With allowances selling at $100 or less, the choice is clear.) And environmentalists are pleased with the complete compliance and greater-than-expected reduction in $SO_2$ emissions. Indeed, under Title IV environmentalists can influence emissions directly: they can buy allowances from utilities and "retire" them. And some groups are doing just that. At last year's annual allowance auction, a sixth-grade class from Glens Falls, New York, received an award for organizing a fund-raiser to collect money to retire $SO_2$ allowances. Their efforts raised $20,000—at the going rate, enough money to keep more than 200 tons of $SO_2$ from entering the environment next year.

*This research was supported by the National Acid Precipitation Assessment Program and the US Environmental Protection Agency. Further information can be found in references 1–5.*

# Predicting Global Climate Change: New Tools, New Insights

**A new climate-change model developed at MIT provides scientists and policymakers with an unprecedented ability to analyze potential impacts of human activities and proposed policies on the global climate system. The model simulates economic growth and associated emissions, flows of greenhouse gases into and out of land and oceans, chemical reactions in the atmosphere, climate dynamics, and changes in natural terrestrial ecosystems. It also includes previously ignored interactions among those processes—interactions that can have a substantial impact on predicted outcomes. For example, most models assume that emissions of methane and nitrous oxide from wetlands and soils are constant. But MIT simulations show that predicted rises in temperatures will cause natural emissions of those greenhouse gases to increase by 15%-60%. Other results suggest that when carbon dioxide levels become very high, the oceans may be a less effective "sink" for that gas than is often predicted. By simplifying certain components, the researchers made the model "computationally efficient" without compromising its ability to represent key climate phenomena. Performing long-term simulations and repeated runs with changed assumptions is therefore economically feasible. A series of runs using a range of plausible assumptions regarding human emissions, ocean circulation, and cloud cover suggests that predictions of temperature change are even more uncertain than generally believed. The researchers are now using the model to clarify key sources of uncertainty and to examine the effectiveness and costs of proposed policy options.**




Policies to address global climate change are the subject of much national and international debate. How serious is the climate-change problem? What level of response is appropriate? And what types of policies would be effective in alleviating any potential threat? Answering those questions is difficult because connections among human behavior, emissions, and natural systems are so complex. Emissions of greenhouse gases depend on economic, technological, and political forces. How those emissions then affect climate depends on complicated, interacting phenomena in the atmosphere, the oceans, and land ecosystems. And any change in climate in turn influences all aspects of the system. Until we better understand this elaborate global system, we cannot reliably predict the impacts of continuing human emissions, nor can we predict the effectiveness of specific policies being considered.

Much climate-change research focuses on only one discipline and one component of the global system. In contrast, MIT's Integrated Global System Model (IGSM) both describes all the components and integrates them. This inclusive approach is made possible by the interdisciplinary nature of the large research team involved. The team includes experts in economic growth, technological change, and emissions; climate chemistry and physics; and the biology of ecosystems.

The specialists are brought together by the MIT Joint Program on the Science and Policy of Global Change, which draws on two MIT centers—the Center for Energy and Environmental Policy

Research (CEEPR) and the Center for Global Change Science (CGCS). Added breadth is provided by participants from the Ecosystems Center at the Marine Biological Laboratory (Woods Hole, Massachusetts), other MIT departments, and industrial groups. Leading the effort are Ronald G. Prinn, TEPCO Professor of Atmospheric Chemistry and director of the CGCS, and Henry D. Jacoby, William F. Pounds Professor of Management and former director of the CEEPR.

In developing the IGSM, the MIT team had three goals. The model should permit researchers to examine the science of global climate change and the interactions among the many components involved. It should help clarify the effects and costs of proposed policies such as emissions quotas and taxes. And it should help investigators figure out what makes predictions of global climate change—both its magnitude and its timing—so uncertain. Many of the processes involved are not well understood, so modeling them requires making assumptions and approximations. Such uncertainty propagates through the integrated model in complicated ways, ultimately contributing to the uncertainty of the final result. The IGSM should enable scientists to identify and explore key sources of the uncertainty that now hinders both scientific understanding and policy assessment.

To perform all those functions, the IGSM must simulate a huge number of physical and chemical phenomena and track many individual chemical species, accounting for their behaviors and their impacts on climate. Moreover, its calculations must be resolved geographically. Amounts and types of emissions vary with latitude and are expected to change over time, shifting from Europe and North America to China and southern Asia during the next century. Temperatures and other climatic conditions and the nature of the earth's surface also vary with location, influencing both emissions and chemical reactions in the atmosphere. Because of such regional differences, the impacts of climate change and the effects of a given policy will differ dramatically from place to place.

After five years' work, the MIT team has developed a model that begins to provide the needed level of completeness and detail. The diagram on page 4 outlines the key models (in boxes) and information flows (in ovals) of the IGSM.

The **Anthropogenic Emissions Prediction and Policy Analysis Model** (at the top of the diagram) forecasts future anthropogenic emissions of carbon dioxide ($CO_2$), sulfur oxides ($SO_X$), nitrous oxide ($N_2O$), and other key gases. The model covers the period 1985 to 2100 in five-year steps and recognizes twelve regions of the world, linked by trade. For each region it tracks population change, technological change, economic growth, and the energy intensity of economic activity. Based on those forces, it predicts the magnitude, composition, and location of future anthropogenic emissions.

The **Natural Emissions Model** (at the left) predicts emissions from natural sources based on estimates of future temperatures, rainfall, and other climatic variables and predictions of the condition of land ecosystems, supplied by the Terrestrial Ecosystems Model (at the bottom). It recognizes different types of soils and wetlands and their geographical locations and determines the natural uptake and emission of $N_2O$ from soils and methane ($CH_4$) from wetlands.

Predictions of anthropogenic and natural emissions (resolved by latitude) feed directly into the **Coupled Atmospheric Chemistry and Climate Model** (at the center). The climate portion of this integrated model simulates global climate dynamics including critical physical processes such as radiation and convection and the effects on those processes of all significant greenhouse gases and a variety of aerosols (suspended particulate matter, the most important being sulfate aerosols resulting from $SO_X$ emissions). It also includes the crucial role of ocean circulations, which can remove both heat and $CO_2$ from the atmosphere. It differentiates between climate dynamics over land and ocean at each latitude. An interactive atmospheric chemistry submodel includes more than 50 chemical reactions and recognizes 25 chemical species. The passage of $CO_2$ into and out of the ocean is also calculated. Based on temperatures and other outputs of the climate model, the chemistry submodel determines the formation and destruction of important greenhouse gases and aerosols and feeds the predictions back into the climate model.

Finally, the **Terrestrial Ecosystems Model** predicts how changes in climate and atmospheric composition will affect the state of terrestrial ecosystems—one measure of the potential impact of global climate change. The model, developed by collaborators at the Marine Biological Laboratory, simulates fundamental biogeochemical processes in 18 terrestrial ecosystems around the world and makes monthly estimates of key carbon and nitrogen fluxes. The predicted uptake of $CO_2$ by land ecosystems feeds back into the chemistry submodel, and predicted soil compositions become inputs for the Natural Emissions Model.

The IGSM thus simulates all the relevant processes and feedbacks among them. And it can do so quickly—an important feature for scientific studies and policy assessments, which may require repeated runs using different variables and simulating extended periods of time. A traditional model may take months even on a supercomputer to simulate climate change over a century. The IGSM incorporates carefully chosen simplifications that make it much faster. For example, in initial tests the coupled chemistry/climate model—which considers latitude and altitude but not longitude—performed simulations twenty times faster than did more complicated models that also consider longitude. Yet the climate change patterns predicted by the two types of models were similar. And despite the simplifications, the coupled chemistry/climate model reproduces the major features of today's climate reasonably well, including seasonal variations.

Already the researchers have identified some feedbacks that have important impacts but are not addressed by other models designed for policy studies.

• **Climate feedbacks on natural emissions:** Results show that land ecosystems play an important role in taking up carbon and emitting $CH_4$ and $N_2O$. Further, interactions between the coupled models show that those fluxes are significantly altered by changes in climate and in atmospheric $CO_2$. For example, predicted increases in temperatures and precipitation will substantially increase natural emissions of $CH_4$ and $N_2O$. Indeed, the increase in natural emissions of $N_2O$ may be as large as the increase in human emissions of that gas. Assuming that natural emissions are constant—as do most models now used in policy discussions—is therefore wrong and leads to significant underestimates of the future roles of those gases.

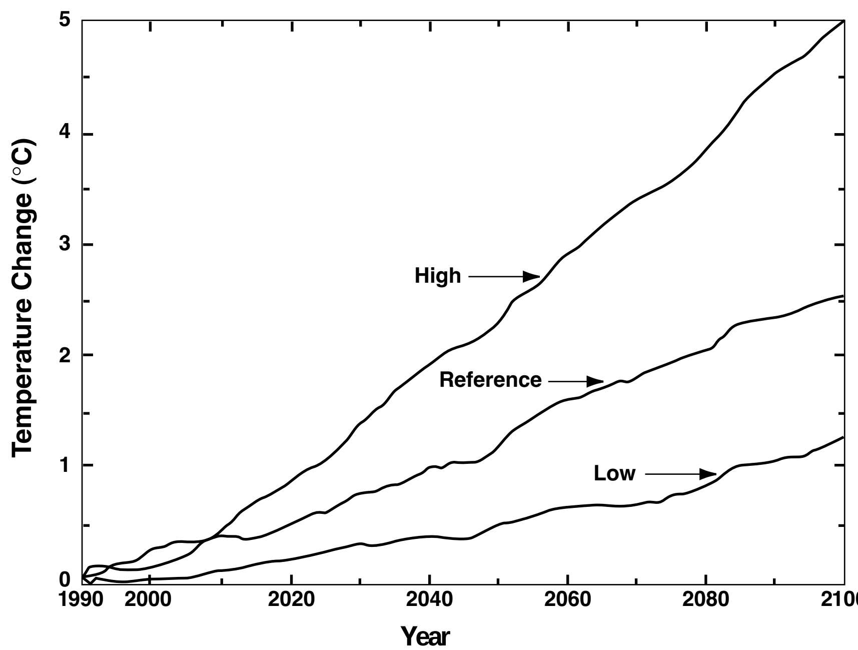
• **Removal of sulfate aerosol:** Among the emissions from coal-burning power plants are sulfate aerosols that remain suspended in the atmosphere. While aerosols are troublesome pollutants, they play a positive role in terms of climate change: they reflect incoming sunlight back to space, thereby cooling the earth. Model results suggest that aerosols may not be as abundant in the future as is generally assumed, as $SO_X$ control schemes are put in place and as more aerosols may be washed out of the atmosphere by climate-change-induced increases in future precipitation.

• **Ocean uptake of carbon:** Oceans are known to be an important sink for $CO_2$, but here again traditional climate models generally omit an important feature: the effect of the ocean's pH on $CO_2$ uptake. Rather than assuming a given pH that remains constant, the ocean submodel in the IGSM explicitly predicts the ocean's pH. As levels of $CO_2$ in the ocean increase, the water becomes more acidic; and as acidity increases, the water's capacity for holding $CO_2$ decreases. Total carbon uptake by the ocean thus decreases. This more realistic approach yields significantly different oceanic carbon uptake rates over the next century than do simpler schemes.

The researchers have also begun examining sources of uncertainty by performing a series of sensitivity studies. For example, they have tested the effects of using different values for input parameters influencing three key components of climate change: anthropogenic emissions, ocean circulation, and climate sensitivity. All three are potentially important but not well understood. The level of anthropogenic emissions depends on hard-to-predict factors such as population growth and technological change. The behavior of the ocean is not well understood, yet the rate at which surface waters circulate to the ocean depths is critical. The more rapid the circulation, the more quickly heat and $CO_2$ will be removed from the atmosphere, slowing warming. The third parameter—climate sensitivity—indicates how much warming will occur for given levels of $CO_2$ and other greenhouse gases in the atmosphere. One of the most uncertain factors affecting climate sensitivity is cloud cover. Clouds reflect incoming sunlight, so their presence lowers the temperature. But they also redirect outgoing infrared radiation back to the earth's surface, thereby raising the temperature. The net impact is highly uncertain.

The figure above shows the effect on temperature predictions of using different "reasonable" assumptions about the underlying input parameters. The middle curve—the reference case—represents the outcome using assumptions consistent with estimates from the Intergovernmental Panel on Climate Change (IPCC). The higher curve reflects a carbon-intense world, a slowly overturning ocean, and high positive feedback because of water vapor and cloud behavior. The lower curve reflects a cleaner world, a faster ocean overturn, and lower cloud feedback. The amount of temperature change predicted for the year 2100 varies from a little over 1°C to about 5°C—at the high end, enough to raise sea level significantly, to shift

**Changes in Global-Average Temperature as Predicted by MIT's Integrated Global System Model**




**Predicted changes in global-average temperature as calculated by the new Integrated Global System Model (see ref. 10 in the publications list). The three curves result from using differing assumptions about three uncertain components of the integrated system: anthropogenic emissions, ocean circulation, and cloud cover. The reference case is based on estimates from the Intergovernmental Panel on Climate Change. The other curves use estimates that are at the high and low ends of the range of "plausible" values. Thus, the uncertainties associated with just those three parameters cause a 4°C variation in predicted temperature change by 2100.**

agricultural regions, and to cause other ecological and economic changes. The IPCC recently provided a range of estimates of temperature predictions from 1°C to 3.5°C by 2100. But that summary was based on a compilation of results from a variety of climate change models. If the results from a single model—the IGSM—can vary by that much and more, the IPCC range is apt to be too narrow.

The researchers are now continuing to refine the IGSM. They are improving its ability to track factors such as energy prices, resource depletion, and levels of stratospheric ozone (another greenhouse gas). They are developing a model that can predict future distributions of potential croplands under various climate-change scenarios. They are modifying the submodel for terrestrial ecosystems so it can operate simultaneously and interactively with the chemistry/climate model (rather than iteratively, as it has in the past). And they are examining the costs and impacts of proposed policy options such as restricting emissions and stabilizing atmospheric concentrations of $CO_2$ at particular levels. New work focuses on the potential impact on global warming of proposed restrictions on $SO_X$ emissions aimed at reducing local and regional air pollution. Coal-burning electric utilities may use scrubbers to remove $SO_X$ from their stack gases yet leave levels of $CO_2$ emissions unchanged. In the absence of the cooling aerosols, any potential global warming will progress more quickly. Using the IGSM, researchers are quantifying such effects so that policymakers can assess the trade-offs involved when considering potentially conflicting local, regional, and global policies.

*This research was supported through the MIT Joint Program on the Science and Policy of Global Change by the US Department of Energy, the National Science Foundation, the US National Oceanic and Atmospheric Administration, the US Environmental Protection Agency, the Royal Norwegian Ministries of Industry and Energy and Foreign Affairs, and a group of corporate sponsors from the United States, Europe, and Japan. Further information can be found in references 6–17.*

# News Items

On January 28, the **Electric Utility Program** (EUP) held a one-day **workshop** entitled "**The 'State of the Debate' on Electromagnetic Fields (EMF)**." An opening session considered how recent reports, scientific studies, siting efforts, and legal actions have influenced the current debate about EMF exposure and its perceived health implications. James C. Weaver, senior research scientist in the Harvard-MIT Division of Health Sciences and Technology (HST), and Timothy E. Vaughan, postdoctoral associate in HST, then discussed their current research on biophysical mechanisms and described their future plans. A final discussion focused on how to pursue research in this area so that results can contribute to a more rational debate regarding the potential impacts of EMF. The workshop served as a kickoff event for a new **consortium-funded project.** This project focuses on identifying which types of field exposures and biophysical mechanisms can or cannot cause molecular change. If certain mechanisms can be ruled out as avenues for possible health effects, then future EMF research efforts can be better directed, and uncertainties and controversy regarding the rancorous EMF debate can be reduced. Current sponsors are Allegheny Power System, Electricité de France, Ontario Hydro Technologies, and Southern California Edison Company.

On January 29 and 30, the **EUP** held its **annual planning meeting**, entitled "**The Role of Knowledge-Based Research in a Competitive Electric Industry.**" The general focus was on how to facilitate basic, or "knowledge-based," research given the new competitive and global nature of the electric utility industry. Individual sessions considered four topics: power systems and equipment, the implications of the climate-change debate for the electric industry, combustion and emissions research, and corporate and industry research. A poster session allowed EUP members to learn more about specific research activities under way at MIT. Attendees included 20 representatives from the electric utilities, industry, the Electric Power Research Institute, and the US Department of Energy plus more than 30 MIT researchers. A recurring theme of the meeting was how to promote dialogue among the EUP's members and MIT researchers. Discussion is continuing on how to modify the structure of the EUP so it will better serve the utility industry's changing needs. One option is to enable companies to concentrate their interactions with MIT in areas relevant to their redefined corporate functions and responsibilities.

The **Joint Program on the Science and Policy of Global Change** held its **eleventh Global Change Forum** in Cambridge, Massachusetts, on January 29–31. The theme of the forum was "**The Berlin Mandate: Progress, Prospects, and Aftermath**." The Berlin Mandate represents a significant step toward defining international agreements addressing carbon dioxide emissions under the United Nations Framework Convention on Climate Change. The forum opened with an evening keynote address by Dr. Jerry Melillo, White House Associate Director for the Environment. Sessions on the following day were devoted to interpreting the results of the Berlin Mandate process as of January 1997; the likely effects of proposals under consideration by the Ad Hoc Group on the Berlin Mandate; greenhouse policy architecture and institutions; and lessons learned from sulfur trading that can be applied to carbon policy. The final day began with a panel discussion in which invited presenters commented on the process by which competing interests might be reconciled on the road to the Third Meeting of the Conference of the Parties (COP-3). Dr. Robert Watson, director of the World Bank and chair-elect of the Intergovernmental Panel on Climate Change, presented a talk in the closing session on the broader, long-term significance of COP-3. About 110 representatives from industry, government, and academia participated in the forum. The **twelfth Global Change Forum** will be held in

Boston on September 29–October 1. The Joint Program's first **Special Regional Forum on Global Change** will be held in Riyadh, Saudi Arabia, on June 24–25. The theme will be "**The Role of Developing Countries in the Climate Issue**."

On September 11–12, the **MIT Japan Program** in collaboration with **MIT's Industrial Liaison Program** will present a symposium entitled "**Securing Asian Energy Investments: Geopolitics and Implications for Business Strategy**." The development and growth of Asian countries spur their need for energy sources. Meeting that need demands a critical interrelation of finance, ecology, territory, technology, and trade. In the process of creating electric power, these forces also create opportunity. The symposium at MIT will address questions about the increasing Asian energy demand, the manner in which that demand will be met, the environmental and geopolitical impact, and the opportunities for and roles of foreign corporations. Speakers will include John Deutch, former head of the US Central Intelligence Agency; David Jhirad, Deputy Assistant Secretary for International Energy Policy Trade and Investment; Katsuhiko Suetsugu, Director-General, Asia-Pacific Energy Forum; and Richard Samuels, head of MIT's Department of Political Science and director of the MIT Japan Program. To receive a brochure describing the symposium call 617-258-9419 or write to Conferences, MIT Industrial Liaison Program, E38-568, 77 Massachusetts Avenue, Cambridge, MA 02139-4307. To access information via the World Wide Web, type http://ilp.mit.edu/ and click on "Conferences." The cost of the seminar is $650 ($375 for nonprofit/government attendees, free for ILP members).

The **1997 Merit Award of the Society of Toxicology** has been presented to **Dr. Mary Amdur** in recognition of her distinguished career in toxicology. Dr. Amdur was a leader of Energy Laboratory research from 1975 until 1986, when she retired from MIT. In conferring its most prestigious award, the society states: "Dr. Amdur is a distinguished toxicologist who has had a profound effect on the development of the field of toxicology for more than four decades. Her impact on toxicology is perhaps most evident when one considers her contributions to the scientific foundation of our knowledge of air pollution in the workplace and environment." She is particularly cited for her contributions to our understanding of the adverse effects of sulfuric acid mists and mixtures of gases and particles in the lung—the focus of her research at the Energy Laboratory. Her work has played a major role in the establishment of air pollution standards.

A team of faculty and staff from the Energy Laboratory, the Technology and Policy Program, and the Department of Nuclear Engineering is now presenting a new **interdepartmental graduate course on sustainable energy** to a class of 35 students from various technology and policy backgrounds. Many of the students provide international perspectives that lead to cross-cultural interactions and stimulating debates on various topics. During the next year the course developers plan to refine the course and develop a textbook and other educational materials. This and other environment-related courses have resulted from an MIT initiative to develop new educational materials and programs that will change the knowledge base and attitudes of students regarding energy technology and policy issues.

## PUBLICATIONS AND REFERENCES

The following publications of Energy Laboratory and related research were released during the past period or are cited as references in this issue. An order form for reports from the **MIT Joint Program on the Science and Policy of Global Change** is available by request to the MIT Joint Program on the Science and Policy of Global Change, Publications, Room E40-271, Cambridge, MA 02139-4307, tel.: 617-253-7492; fax: 617-253-9845; e-mail: tzh@mit.edu. **MIT theses** may be ordered from the Library Document Services, MIT, Room 14-0551, Cambridge, MA 02139-4307. Other publications may be ordered from Energy Laboratory Publications, MIT, Room E40-441, Cambridge, MA 02139-4307, *only* if a price is assigned and *only* if prepaid by check payable to "MIT Energy Laboratory." Prices are postpaid surface mail. For air delivery, add 15% to US, Canada, and Mexico, and 30% elsewhere. A list of publications is available on request.

### Reports and Working Papers

Bailey, E. *Allowance Trading Activity and State Regulatory Rulings: Evidence from the US Acid Rain Program*. March 1996. Working Paper No. MIT-CEEPR 96-002WP. 28 pages. $10.00 **(Ref. 1)**

Dixit, A., R. Pindyck, and S. Sodal. *A Markup Interpretation of Optimal Rules for Irreversible Investment*. February 1997. Working Paper No. MIT-CEEPR 97-002WP. 15 pages. $10.00

Ellerman, A., and J. Montero. *Why Are Allowance Prices So Low? An Analysis of the $SO_2$ Emissions Trading Program*. February 1996. Working Paper No. MIT-CEEPR 96-001WP. 27 pages. $10.00 **(Ref. 2)**

Joskow, P., and R. Schmalensee. *The Political Economy of Market-Based Environmental Policy: The US Acid Rain Program*. March 1996. Working Paper No. MIT-CEEPR 96-003WP. 93 pages. $12.00 **(Ref. 3)**

Joskow, P., R. Schmalensee, and E. Bailey. *Auction Design and the Market for Sulfur Dioxide*. August 1996. Working Paper No. MIT-CEEPR 96-007WP. 46 pages. $10.00 **(Ref. 4)**

Montero, J. *Volunteering for Market-Based Environmental Regulation: The Substitution Provision of the $SO_2$ Emissions Trading Program*. January 1997. Working Paper No. MIT-CEEPR 97-001WP. 37 pages. $10.00 **(Ref. 5)**

**Other Publications**

Ahmad, B., and P. Barton. "Homogeneous multicomponent azeotropic batch distillation." *AIChE Journal*, v. 42, no. 12, pp. 3419–3433, December 1996.

Binello, E., S. Shortkroff, A. Jones, C. Viveiros, A. Ly, C. Sledge, A. Davison, R. Shefer, and J. Yanch. "Research in boron neutron capture synovectomy." Presented at Society of Photo-Optical Instrumentation Engineers International Conference on Neutrons in Research and Industry, Crete, Greece, June 9–15, 1996. *SPIE Proceedings Series*, v. 2867, pp. 68–71, 1997.

Bryden, K., and J. Ying. "Synthesis and structural characteristics of mechanically alloyed nanostructured palladium-yttrium." *Materials Science Forum,* v. 225–227, pp. 895–900, 1996.

Carroll, J. *Organizational Learning Activities in High Hazard Industries: The Logics Underlying Self-Analysis*. MIT Sloan School of Management Working Paper No. 3936. January 1997. 37 pages. Available from MIT Sloan School of Management Publications, Room E56–290, Cambridge, MA 02139-4307

Eckaus, R., H. Jacoby, A. Ellerman, W. Leung, and Z. Yang. "Economic assessment of $CO_2$ capture and disposal." *Energy Conversion and Management*, Elsevier Science Ltd., 1997. **(Ref. 6)**

Ellerman, A. "The competition between coal and natural gas." *Resources Policy*, v. 22, nos. 1/2, pp. 33–42, 1996.

**NEW AND RENEWED PROJECTS, JANUARY – MARCH 1997**

| Topic | Donor or Sponsor | Investigators (*Department*) |
|---|---|---|
| GIFTS AND CONTRIBUTIONS | | |
| CEEPR membership | Amoco Foundation, Inc.; Asea Brown Boveri, Ltd.; British Petroleum International Ltd.; Chevron Corp.; Cyprus Amax Coal Sales Co.; Statoil | |
| EUP membership | Consol; Tokyo Electric Power Co., Inc. | |
| Energy Laboratory | Asahi Chemical Industry America, Inc.; Hitachi Plant Engineering and Construction Co., Ltd. | |
| NEW PROJECTS | | |
| Review of Longer Term Scenarios for Development and Deployment of Climate-Friendly Technologies | NEDO | E. Drake<br>H. Herzog<br>*(Energy Laboratory)* |
| CONTINUING PROJECTS | | |
| Airborne Organic Compounds: Sources, Transformation and Control (in collaboration with New Jersey Institute of Technology and California Institute of Technology) | US Environmental Protection Agency (EPA) | J. Howard<br>*(Chemical Engineering)* |
| Markers for Emissions from Combustion Sources | above | J. Vander Sande<br>*(Materials Science and Engineering)* |

Feehery, W., and P. Barton. “A differentiation-based approach to dynamic simulation and optimization with high-index differential-algebraic equations.” Chapter 21 in *Computational Differentiation: Techniques, Applications, and Tools*, M. Berz, C. Bischof, G. Corliss, and A. Griewank, eds. Society for Industrial and Applied Mathematics (SIAM): Philadelphia, Pennsylvania, 1996.

Glicksman, L., L. Norford, G. Okutan, and K. Holden. “Scale model studies of displacement ventilation.” *ROOMVENT ’96*, 5th International Conference on Air Distribution in Rooms, Yokohama, Japan, July 17–19, 1996.

Glicksman, L., and P. Noymer. “Measurements of cluster-wall contact times in a scale-model circulating fluidized bed.” *Proceedings of the 1996 Mechanical Engineering Congress and Exposition: The Winter Annual Meeting of ASME*, Atlanta, Georgia, November 14–22, 1996.

Herzog, H., E. Drake, and E. Adams. *$CO_2$ Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change*. US Department of Energy White Paper prepared under DOE Order No. DE-AF22-96PC01257, January 1997. 66 pages. $12.00

Herzog, H., J. Tester, and M. Frank. “Economic analysis of heat mining.” *Energy Sources*, v. 19, pp. 19–33, 1997.

Hytros, M., J. Chun, R. Lanza, and N. Saka. “A solidification front monitor for metal casting.” *Proceedings of the 1996 Mechanical Engineering Congress and Exposition: The Winter Annual Meeting of ASME*, Atlanta, Georgia, November 14–22, 1996.

Hytros, M., I. Jureidini, D. Kim, J. Chun, R. Lanza, and N. Saka. *A Computed Tomography Sensor for Solidification Monitoring in Metal Casting*. Presented at TMS (The Metallurgical Society) Conference, Orlando, Florida, February 1997. 9 pages. $10.00

Jacoby, H., E. Eckaus, A. Ellerman, R. Prinn, D. Reiner, and Z. Yang. *$CO_2$ Emissions Limits: Economic Adjustments*

**NEW AND RENEWED PROJECTS, CONTINUED**

| Topic | Donor or Sponsor | Investigators (*Department*) |
|---|---|---|
| Direct Treatment of Uncertainties in Mathematical Models of the Transport and Fate of Airborne Organics | above | G. McRae *(Chemical Engineering)* |
| Modeling Gas-Phase Chemistry and Heterogeneous Reactions of Polycyclic Aromatic Compounds | above | J. Howard *(Chemical Engineering)* |
| Deposit Effects: Buildup on Engine of Hydrocarbon Emissions | above | J. Heywood *(Mechanical Engineering)* V. Wong *(Energy Laboratory)* |
| Chemical Kinetic Modeling of Products of Incomplete Combustion in Spark-Ignition Engines | above | S. Hochgreb *(Mechanical Engineering)* |
| Studies of Specific Topics Regarding the Interrelationship Between Energy and the Environment: Replacement of Coal-Fired Power Plants | US EPA | A. Ellerman *(Sloan School of Management)* |
| A Collaborative Program of Research in Engineering Sciences (with Idaho National Engineering and Environmental Laboratory) | US Department of Energy | D. Hardt *(Mechanical Engineering and Laboratory for Manufacturing and Productivity)* |
| Fundamentals of Elastic-Plastic Fracture: Three Dimensional and Mechanistic Modeling | above | D. Parks *(Mechanical Engineering)* |
| Experimental Investigation of the Fuel Distribution in Gasoline SI Engines | Sandia National Laboratories | S. Hochgreb *(Mechanical Engineering)* |
| Consortium on Lubrication in Internal Combustion Engines | Shell Oil Co. | V. Wong *(Energy Laboratory)* J. Heywood *(Mechanical Engineering)* |

*and the Distribution of Burdens.* MIT Joint Program on the Science and Policy of Global Change, Report No. 9, Revised November 1996. **(Ref. 7)**

Jacoby, H., R. Schmalensee, and D. Reiner. *What Does Stabilizing Greenhouse Gas Concentrations Mean?* MIT Joint Program on the Science and Policy of Global Change, Report No. 14, November 1996. **(Ref. 8)**

Jureidini, I. *A Design for a High Energy X-Ray Computed Tomography Sensor for the Study of Solidification Fronts in Aluminum*. SM Thesis. MIT Department of Nuclear Engineering, Cambridge, Massachusetts, 1997.

Lee, D., and S. Hochgreb. *Hydrogen Autoignition at Pressures Above the Second Explosion Limit (0.6–4.0 MPa).* Prepared for Western States Section/ The Combustion Institute 1997 Spring Meeting, Livermore, California, April 14–15, 1997. 31 pages. $10.00

Lienhard, J., and D. Napolitano. "Thermal stress limits of plates subjected to extremely high heat flux." *Proceedings of the ASME Heat Transfer Division*, D. Wroblewski, et al., eds., American Society of Mechanical Engineers, New York, 1996. *HTD*, v. 333, pp. 23–35, 1996.

Liu, Y. *Modeling the Emissions of Nitrous Oxide ($N_2O$) and Methane ($CH_4$) from the Terrestrial Biosphere to the Atmosphere.* MIT Joint Program on the Science and Policy of Global Change, Report No. 10, August 1996. **(Ref. 9)**

Mitton, D. "Hazardous waste destruction by supercritical water oxidation." *New England Science Teachers Working to Promote Science Literacy*, v. 8, no. 1, p. 22, August 1996.

Mitton, E., E. Han, S. Zhang, K. Hautanen, and R. Latanision. *Degradation in Supercritical Water Oxidation Systems*. Presented at the Supercritical Fluid Extraction Symposium, American Chemical Society Spring National Meeting, New Orleans, Louisiana, March 24–28, 1996. 14 pages. $10.00

**NEW AND RENEWED PROJECTS, CONTINUED**

| Topic | Donor or Sponsor | Investigators (*Department*) |
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| Sloan Lab Consortium | Ford Motor Co. | J. Heywood *(Mechanical Engineering)* |
| Development and Application of Biophysical Mechanism Theory: Ruling Out Electric and Magnetic Field Exposure Conditions | EUP: Electricité de France; Ontario Hydro Technologies; Southern California Edison Co. | J. Weaver *(Harvard-MIT Division of Health Sciences and Technology)* |

*Note: CEEPR = Center for Energy and Environmental Policy Research*
*EUP = Electric Utility Program*

Mitton, D., P. Marrone, and R. Latanision. "Interpretation of the rationale for feed modification in SCWO systems." *Journal of the Electrochemical Society*, v. 143, no. 3, pp. L59–L61, March 1996.

Mitton, D., S. Zhang, E. Han, J. Cline, K. Hautanen, and R. Latanision. *An Assessment of Corrosion and Failure Mechanisms in Supercritical Water Oxidation Systems*. Presented at the 13th Annual ICC (International Combustion Council) Congress, Melbourne, Australia, November 25–29, 1996. 8 pages. $10.00

Mitton, D., S. Zhang, K. Hautanen, J. Cline, E. Han, and R. Latanision. *Evaluating Stress Corrosion and Corrosion Aspects in Supercritical Water Oxidation Systems for the Destruction of Hazardous Waste*. Presented at NACE International Conference "Corrosion 97," New Orleans, Louisiana, March 9–14, 1997. Paper No. 203. 6 pages. $10.00

O'Brien, C., and S. Hochgreb. *Thermodynamic Analysis of Fuel Processing.* Prepared for Western States Section/ The Combustion Institute 1997 Spring Meeting, Livermore, California, April 14–15, 1997. 14 pages. $10.00

Prinn, R., H. Jacoby, A. Sokolov, C. Wang, X. Xiao, Z. Yang, R. Eckaus, P. Stone, A. Ellerman, J. Melillo, J. Fitzmaurice, D. Kicklighter, G. Holian, and Y. Liu. *Integrated Global System Model for Climate Policy Assessment: Feedbacks and Sensitivity Studies*. MIT Joint Program on the Science and Policy of Global Change, Report No. 7, March 1997. **(Ref. 10)**

Renslo, A., R. Weinstein, J. Tester, and R. Danheiser. *Concerning the Regiochemical Course of the Diels-Alder Reaction in Supercritical Carbon Dioxide*. Accepted for publication in *Journal of Organic Chemistry*. 1997. 12 pages. $10.00

Schmalensee, R. *Greenhouse Policy Architectures and Institutions.* MIT Joint Program on the Science and Policy of Global Change, Report No. 13, November 1996.

Sokolov, A., and P. Stone. *Description and Validation of the MIT Version of the GISS 2D Model.* MIT Joint Program on the Science and Policy of Global Change, Report No. 2, May 1995. **(Ref. 11)**

Sokolov, A., and P. Stone. *A Flexible Climate Model for Use in Integrated Assessments.* MIT Joint Program on the Science and Policy of Global Change, Report No. 17, March 1997. **(Ref. 12)**

Sokolov, A., and P. Stone. *Global Warming Projections: Sensitivity to Deep Ocean Mixing.* MIT Joint Program on the Science and Policy of Global Change, Report No. 11, September 1996. **(Ref. 13)**

Sun, T., M. Fokema, and J. Ying. "Mechanistic study of NO reduction with methane over $CO^{2+}$ modified ZSM-5 catalysts." *Catalysis Today*, v. 33, nos. 1–3, pp. 251–261, 1997.

Tester, J., H. Herzog, C. Peterson, and R. Potter. *The Impacts of Reservoir Performance and Drilling Costs on the Commercial Feasibility of Geothermal Energy Production*. March 1997. Accepted for publication in *GRC Bulletin*. 11 pages. $10.00

Tian, T., R. Rabute, V. Wong, and J. Heywood. *Effects of Piston-Ring Dynamics on Ring/Groove Wear and Oil Consumption*. Presented at 1997 Society of Automotive Engineers International Congress and Exposition, Detroit, Michigan, February 1997. SAE Paper 970835. Available from SAE, Inc., 400 Commonwealth Drive, Warrendale, PA 15096-0001.

Trudeau, M., M. Braunovic, K. Bryden, and J. Ying. "Fretting studies of nanocrystalline Pd, Pd-Ag, and Pd-Y films." Holm Conference Proceedings, *Electrical Contacts – 1996,* Montreal, Canada, 1996, pp. 393–394, 1996.

VanDerWege, B., and S. Hochgreb. *Application of Shear Plate Interferometry to Jet Diffusion Flame Temperature Measurements.* Prepared for Western States Section/The Combustion Institute 1997 Spring Meeting, Livermore, California, April 14–15, 1997. 11 pages. $10.00

Xiao, X., D. Kicklighter, J. Melillo, A. McGuire, P. Stone, and A. Sokolov. "Linking a global terrestrial biogeochemical model and a 2-dimensional climate model: implications for the global carbon budget." *Tellus*, in press, 1997. **(Ref. 14)**

Xiao, X., J. Melillo, D. Kicklighter, A. McGuire, P. Stone, and A. Sokolov. *Relative Roles of Changes in $CO_2$ and Climate to Equilibrium Responses of Net Primary Production and Carbon Storage of the Terrestrial Biosphere*. MIT Joint Program on the Science and Policy of Global Change, Report No. 8, June 1996. **(Ref. 15)**

Xiao, X., J. Melillo, D. Kicklighter, Y. Pan, A. McGuire, and J. Helfrich. *Net Primary Production of Terrestrial Ecosystems in China and Its Equilibrium Responses to Changes in Climate and Atmospheric $CO_2$ Concentration*. MIT Joint Program on the Science and Policy of Global Change, Report No. 12, October 1996. **(Ref. 16)**

Yang, Z., R. Eckaus, A. Ellerman, and H. Jacoby. *The MIT Emissions Prediction and Policy Analysis (EPPA) Model*. MIT Joint Program on the Science and Policy of Global Change, Report No. 6, May 1996. **(Ref. 17)**

Yanch, J., R. Shefer, and E. Binello. "Design of low-energy neutron beams for boron neutron capture synovectomy." Presented at Society of Photo-Optical Instrumentation Engineers International Conference on Neutrons in Research and Industry, Crete, Greece, June 9–15, 1996. *SPIE Proceedings Series*, v. 2867, pp. 31–40, 1997.

Ying, J., and A. Tschope. "Synthesis and characteristics of nonstoichiometric nanocrystalline cerium oxide-based catalysts." *Chemical Engineering Journal*, v. 64, no. 2, pp. 225–237, 1996.



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