New Simulation Tool for Designing Cleaner Diesels

The fuel-efficient diesel engine may face a bleak future unless engineers can dramatically reduce its particulate emissions to meet likely future regulations. Low-cost solutions may emerge if engineers can rethink engine and fuels technologies in tandem, tailoring the fuel properties to the engine design and vice versa. To help them achieve that match, Energy Laboratory researchers are formulating a simulation tool that will predict the effects of changes in both engine design and fuel composition on emissions and efficiency. The simulation generates equations that describe chemical reactions occurring throughout the combustion chamber and links them to reflect the interdependency of chemical composition, flows, and temperatures in adjacent regions. Representing all the molecular species in a combustor would require thousands of chemical models, so the simulation instead deals with “functional groups”—groups of atoms that always act as a unit and are building blocks for many types of molecules. Most important, the simulation uses “adaptive chemistry,” a novel concept that involves using the simplest possible chemical model to analyze a given region. Based on numerical analysis, the simulation determines which species and reactions are important in a region and which ones it can leave out. (For example, why examine reactions involving fuel molecules in areas where no fuel remains?) This approach simplifies the computational task without sacrificing accuracy. While much work remains, the new simulation may one day reveal ways to fine-tune a variety of combustion devices and their fuels for cleaner operation, perhaps without major financial investment.

The diesel vehicle is one of our most promising transportation technologies. It offers high fuel economy and low emissions of carbon dioxide. But whether it can meet future regulatory limits on other emissions, notably particulates and nitrogen oxides, is questionable. Changing the chemical composition of diesel fuels will not dramatically reduce emissions, largely because modern engines are designed to burn diesel fuels that vary widely in composition. But burning a well-defined diesel fuel in a specially tailored engine could bring large reductions in...
emissions without sacrificing efficiency. However, to achieve those advances, engineers need a better fundamental understanding of combustion and of the interplay between engine design and fuel properties.

For the past three years, Professors William H. Green and Paul I. Barton have been developing a tool that will help designers of diesel engines—and related devices such as burners and furnaces—foresee how proposed changes in equipment design and fuel composition will together affect efficiency and emissions. Their goal is to formulate a computer simulation that, given a specific engine design, fuel composition, fuel-air ratio, and other starting conditions, can calculate what reactions occur, what products form, how those products then react and interact, and what emissions ultimately go out the tailpipe. Defining all the necessary equations by hand would be impossible. Combustion in engines typically involves thousands of molecules that are chemically reacting while being influenced by flowing fluids and changing temperatures and pressures. Therefore, the researchers are working to make their computer simulation automatically perform as much of the job as possible.

Already they have made significant strides toward a better simulation tool than those now available. One big advance is a new computer algorithm that can construct a “reaction mechanism,” a list of equations that describe the behavior of a given material under well-defined operating conditions. To compute the many rate parameters and physical property values required, the algorithm deals not with individual molecular species but rather with different types of functional atomic groups that tend to behave as a unit. This approach has several advantages. There are fewer distinct functional groups than molecules inside a combustor, and many of the functional groups prevalent in fuel molecules do not chemically react with one another. Some functional groups act as “conductors,” meaning that electrons can move into and out of the group. If two conducting groups are next to each other and one changes chemically, the other will be affected. Thus, the simulation must treat those two functional groups together, first calculating the reactions of the individual functional groups and then calculating the subsequent interactions that occur between the two.

In hydrocarbon fuels, however, many of the functional groups are simple combinations of hydrogen and carbon that instead act as “insulators.” Electrons do not pass into and out of them. As a result, groups separated by insulators can be treated separately. The presence of many insulating groups in hydrocarbon fuels thus simplifies the modeling task. To perform an analysis, the simulation tool uses a library of reaction rules to define mechanisms for specific functional groups under specific conditions. With each mechanism, the simulation provides the appropriate rate constant (how quickly the starting material disappears) and the relevant thermochernistry (heat consumed or produced by the reaction). Rate constants for some reactions have been measured directly. In other cases, the simulation must estimate the rate constant using quantum chemical calculations and other advanced theoretical methods. The results are added to the library of information accessible by the simulation.

But conditions are not the same everywhere inside an operating engine. In some regions, cold fuel is entering; in others, hot fuel is burning; in others, soot is forming. The chemical composition and the temperature and pressure therefore differ at different locations and different times. And when conditions are different, even the same materials may react in different ways. One set of reactions may be important at high temperatures, a different set at low temperatures.

Therefore, the researchers couple their chemical simulation with an analysis of how air and fuel move and how conditions vary from place to place as ignition occurs and burning progresses. They use an approach called finite element modeling. They subdivide the entire combustion chamber into tiny cubes, each with its own local temperature, pressure, flow patterns, and species concentrations. Based on starting information about the fuel and air mixture and operating conditions, the simulation calculates all reactions of every species at every time step within every cube inside the engine. Moreover, the calculations for various cubes are linked, as the starting composition and conditions in one cube depend on the outcome of processes that have just occurred in neighboring cubes.

Not surprisingly, in most realistic situations this approach turns out to be computationally unmanageable. Simulating one combustion event (from ignition to burnout) requires analyzing the reactions and interactions of a thousand species within several thousand cubes at a million time steps—a job that would make even a supercomputer crash. One can make some progress by adjusting the number of time steps and the number of cubes, but one hits a limit. The chemistry happens so fast that one cannot use longer time steps or larger cubes and still get reasonable accuracy. Leaving out certain species or reactions is a possibility. Most simulations analyze...
processes in every cube using a single large chemical model that can handle all species and all conditions. Some modelers reduce the computation time by leaving out reactions they assume to be slow or species that appear sparse or of little practical concern. But such omissions can be risky. Under certain conditions those deleted reactions or species may be important.

Professors Green and Barton reduce the computational overload by taking a novel approach: rather than using the same model to analyze all cubes, they use different models in different cubes. For example, where ignition is occurring, the chemistry is very complicated. The models for cubes in that region therefore contain many species and reactions. Where fuel is burning, the chemistry is simpler; fewer species and reactions need to be monitored. And in cubes where exhaust is forming, the models need not try to track fuel molecules because there are none.

Their approach, called adaptive chemistry, involves simply deleting reactions and species in cubes where prevailing conditions make those reactions and species negligible. And rather than do this adapting by hand or based on assumptions, they have the simulation determine numerically which species are important and which are not within different cells. The diagram on page 1 shows that process for a single cube in a single time step. A is a chemical species that is involved in some reaction that produces B. The simulation calculates a rate constant for that reaction at the prevailing temperature and pressure. Since that rate is high, B can form quickly; and the simulation includes it in the model. A is also involved in a reaction that forms the species X. Following the same procedure, the simulation determines that X forms at a low rate, so it excludes X from the model (assuming that it finds no other reactions forming X at an appreciable rate). The simulation next examines the reaction by which B forms Y. Again the rate is low, so Y is also excluded from the model. If in some other cube conditions are different and one of the excluded species forms at a high rate, the simulation recalculates the entire system with that species included.

Developing a workable system of models may take several hundred iterations, but the researchers have proved mathematically that there always will be a final solution because the list of species and reactions will never be infinite. In the end, each cell has its own chemical model that includes only the species and reactions that are important for those conditions at that time and place. Unnecessary computations are thus avoided whenever possible without loss of accuracy.

The researchers are continuing to develop and refine various aspects of their simulation to make it more accurate as well as more efficient. They are also calculating and measuring rate constants for more reactions and adding them to the simulation library. They are working to incorporate flow-modeling techniques that will better reflect the turbulence typical of combustion systems. And they are considering the challenges involved in working with more complicated fuels. Thus far, their work has focused on diesel fuel made from natural gas using the Fischer-Tropsch process. This pure, highly paraffinic fuel is simple to model and promises low emissions if matched with an appropriately designed engine. The simulation task will be harder with standard diesel fuel, which is far more variable and contains a huge number of different species. Another challenge will be tracking all of the intermediate species involved in the growth of giant soot particles. The ability to model particulate growth is important because particle size distribution may directly affect the potential health impacts of emissions.

Future regulatory limits on particulate emissions from diesels are not yet set. Epidemiological data suggest that particulates in diesel exhaust harm human health, but toxicologists cannot yet explain exactly how the damage occurs. As a result, there is much controversy about whether particulates from diesels are actually responsible for the observed health problems. Professor Green believes that confirming and clarifying the relationship between particulate emissions and health may take a long time. Meanwhile, engine designers may be able to ensure the future of the diesel by simply preventing particulates from forming. And having the ability to understand exactly how fuels and engines work together may point to cost-effective changes that could achieve that goal.

William H. Green is an assistant professor of chemical engineering. Paul I. Barton is an associate professor of chemical engineering. This research is funded by ABB Alstom Power, the US Department of Energy, and the US Environmental Protection Agency. Further information can be found in references 1 and 2.
When fuel and air burn inside an internal combustion engine, deposits form on the walls inside the cylinders—a real headache for engine designers. The coated walls trap heat inside the cylinder, and the increased temperatures that result affect emissions and impede changes that could increase fuel efficiency. A new Energy Laboratory model may help designers bring about changes in fuels or engines that will discourage deposit formation. The numerical model simulates the chemical reactions that produce deposit “precursors”; the processes that carry those precursors to the wall; and the condensation, evaporation, and chemical interactions that occur at the wall. Using models of precursor-forming reactions designed to bracket real-world engine and fuel conditions, the simulation generates results that are consistent with deposit growth observed experimentally. The results also suggest that the only way to stop precursors from landing on the wall is by preventing their condensation. Raising the wall temperature would prevent condensation but would defeat the overall goal of keeping cylinder temperatures down. The MIT student performing the research is now gathering precise data on precursors and their behavior by using the model plus measurements taken in a specially designed low-pressure flame. With sufficient data, the model may help designers identify practical strategies for keeping the precursors from forming in the first place.

Surfaces inside internal combustion engines are dirty. Wherever fuel or fuel-and-air mixture comes into contact with a surface, deposits form. Fuel additives help keep some areas clean, but deposits persist on surfaces inside the combustion chamber. And those deposits have significant effects. The deposit layer on the cylinder wall prevents the coolant that runs through the engine from bringing down the temperature inside the cylinder. Due to the increased temperatures, parts of the fuel-air mixture may ignite before the flame front reaches them, causing the engine to “knock.” Another effect of the raised temperatures is increased production of pollutants such as nitrogen oxides inside the engine cylinder. Engineers minimize both of those problems by keeping the compression ratio of the engine relatively low—an approach that brings down fuel efficiency.

While engine experts understand the problems caused by combustion chamber deposits, they do not fully understand how those deposits form. As a result, finding ways to change fuels or engines to prevent deposition formation is difficult, at best. To help in that effort, Mr. Christopher J. O’Brien has spent the past two years investigating chemical and physical processes inside engine cylinders. The work was formulated under the direction of Professor Simone Hochgreb and now involves several colleagues in the Sloan Automotive Laboratory, which is directed by Professor John B. Heywood. Although this work focuses on wall deposits inside gasoline engines, the approach and analytical techniques involved are similar to those used by Professors William H. Green and Paul I. Barton in analyzing the performance of diesel engines (see previous article). The two research groups are planning closer collaboration in the future.

The figure on page 5 shows the many processes involved in the buildup of deposits inside cylinders. The dashed line near the top of the figure shows how the temperature inside the cylinder varies with distance from the wall as the flame approaches. Well away from the wall, the temperature is high and normal combustion chemistry proceeds. The lightweight molecules that form are highly volatile, that is, they evaporate readily. They are therefore not prone to condensing on surfaces (should they encounter any). However, as the flame nears the wall, it cools; and in this moderate-temperature region, partially burned fuel components turn into heavier, less volatile species (step 1 in the figure). Low-volatility species tend to condense readily and evaporate with difficulty, so if they land on the cold wall they are likely to stay there. They are therefore the deposit precursors of concern.

Gaseous flows and diffusion inside the cylinder move the newly formed deposit precursors both toward the wall and away from it (step 2). Some of them reach the cylinder wall, where various processes add to and deplete the deposit. At the surface of the deposit layer, precursors condense and evaporate as temperatures and pressures inside the cylinder change (step 3). Within the deposit, condensed species chemically react to become part of the deposit, and species already in the deposit are removed by chemical processes such as oxidation and
gasification and by mechanical processes such as abrasion and flaking (step 4). After a few hundred hours of engine operation, the net effects of the formation and removal processes yield a deposit with a fairly stable thickness.

Within this array of complicated processes Mr. O’Brien sees several possibilities for interfering with the buildup of deposits. Keeping the precursors from diffusing to the wall after they form—step 2 in the figure—would be extremely difficult. Two other approaches seem more promising. By changing fuel composition or engine operating conditions, designers might be able to prevent the precursors from forming (step 1), or they might be able to keep them from depositing on the wall (steps 3 and 4).

To investigate those possibilities, Mr. O’Brien is working to clarify the processes that take place in the moderate-temperature region of the cylinder close to and at the wall. Developing the needed detailed understanding experimentally would be difficult: in an operating engine, pressures are high and everything is changing rapidly. He therefore began by developing a numerical model that could help in the investigation.

Combustion models exist that describe the behavior of a stationary flame under constant conditions. However, Mr. O’Brien needed a model that would describe what happens to a moving flame close to the cylinder wall using complex chemical systems. Based on available models of flame chemistry, he formulated a numerical model that can follow the flame as it travels through the region of interest. Given starting conditions and a description of the fuel,
the model calculates chemical reactions, flows, temperature, pressure, and other important variables for a given position of the flame. It then moves forward one time step and, based on outputs from the first calculations, performs the same calculations, yielding information for a subsequent position along the flame’s travels. At the wall, the model calculates condensation, evaporation, and reactions between the deposit layer and the gases in contact with it. By performing a series of calculations for sequential time steps, the model produces a complete description of what happens as the flame enters at the edge of the area being simulated, propagates across that area, and hits the cold wall.

In theory, the model is capable of simulating all the reactions that take place inside a deposit-producing engine. However, there are several practical problems. A real flame involves hundreds of species and thousands of reactions; running a simulation would require weeks of computer time and would produce masses of data. Therefore, Mr. O’Brien tracks only about thirty key species in his model. To that simplified flame chemistry he adds a single reaction by which a selected component in the fuel can form a deposit precursor. But another problem arises. While the chemistry within a hot flame has been experimentally defined fairly well, reaction rates and other key data are not available for the precursor species formed in the moderate-temperature region.

Despite the lack of data, Mr. O’Brien has already performed simulations based on a series of reasonable assumptions about the behavior and nature of precursors; and the results have been valuable, both in validating the model and in establishing the relative importance of certain processes. His assumptions concern two variables critical to deposit build-up. The first is reaction rate, that is, how rapidly the precursor forms from the fuel as a function of temperature and other conditions. In different runs, Mr. O’Brien assumes reaction rates that range from so slow that none of the precursor forms to so fast that the precursor is abundant. The second variable is the volatility of the precursor that forms. (Again, the lower the volatility, the “stickier” the species at the wall.) In various runs, he assumes a range of volatilities based on physical properties observed experimentally with real fuels. The series of simulations based on the various assumptions generates a range of feasible values for how much of the precursor forms, how much reaches the wall, and how much condenses and forms a deposit.

Certain sets of assumptions describe quite closely the behavior and nature of selected components in real fuels that researchers elsewhere have tested in experimental engines. An opportunity arises, therefore, to assess the performance of the model by comparison to experimental observations. Because experimental equipment and procedures vary so widely, Mr. O’Brien focuses on comparing trends. For example, how does the thickness of the deposit vary with fuel concentration or with operating conditions? The simulation results show the same trends as those reported in experiments using comparable materials.

Interestingly, the simulation results also yield unexpected insights into what happens at the wall. Engine experts have a number of theories about how precursors stick. Some believe that they simply condense, like water vapor condensing out of the air. Some believe that various chemical processes are involved. And others are convinced that the surface roughness of the wall is a key factor. Mr. O’Brien’s analyses suggest that simple condensation is the primary mechanism for deposit formation. Simulations that include only condensation at the wall produce estimated deposit growth rates that match experimental observations.

That outcome is bad news for engine designers. While condensation is well understood, defining a practical strategy to prevent it inside an engine cylinder is difficult. Increasing the wall temperature would work nicely—but the main goal of preventing deposits is to keep temperatures low to inhibit knock and limit nitrogen oxides formation. Since keeping the precursors from reaching the wall and condensing seems unlikely, attention must focus on preventing the precursors from forming in the first place.

The MIT model could provide valuable insight into how to alter fuel composition to keep sticky precursors from forming—if data were available on reaction rates and other details involved in precursor formation. Mr. O’Brien is now gathering the needed data and observing deposit behavior using an experimental apparatus that he designed and built during the past year. Rather than trying to replicate engine conditions, he uses a low-pressure, steady-state flame and then
turns to the numerical model, which can simulate a wide range of conditions. Thus, based on measurements taken in the simple experimental environment, the model can calculate flows, deposit growth rates, and so on under actual engine conditions.

To simulate the cylinder wall, Mr. O'Brien uses a flat copper plate that is water-cooled from below. A mixture of fuel and air blows up through small holes in the plate and ignites above it. A stationary probe gathers samples within the flame. The speed of the fuel-air mixture and the pressure of the vessel determine how far above the plate the flame rests and how much it is cooled by the plate. By moving the plate closer to and farther from the probe, Mr. O'Brien can gather samples at different locations within the flame, thereby investigating processes that occur at varying distances from the cylinder wall. Samples are analyzed on-site and also in the Analytical Chemistry Laboratory of the Center for Environmental Health Sciences, which is headed by Dr. Arthur Lafleur and has sophisticated instrumentation and techniques for looking at such materials.

Thus far, Mr. O'Brien has performed preliminary experiments with propane and air flames. Although such flames do not create deposits, results have been encouraging. In particular, experimental measurements of concentrations of carbon monoxide, carbon dioxide, and hydrogen at various locations match predictions generated by model simulations under comparable conditions. The next step is to add—one at a time—fuel components such as benzene, toluene, and other species known to cause deposits. Tests with other fuel components may lead to identification of not-yet-recognized precursor species.

Mr. O'Brien is far from tackling the complex chemistry of real flames. He will need a detailed database on all the chemical species and how they interact with each other. For now, he is just trying to establish the building blocks underlying the complex combustion process. But those building blocks may be all the automotive and fuel companies need to design practical strategies for dealing with deposits, especially if the sticky precursors form from a few reactions early in the burning and cooling process. Already Mr. O'Brien has provided his model to several automobile and oil companies for review. With additional data on precursors and their behavior, Mr. O'Brien hopes that the model will enable engine experts to identify a series of changes in fuels and engine operating conditions that will not only control deposits but also reduce emissions and increase efficiency.

Christopher J. O'Brien is a PhD candidate in MIT's Department of Mechanical Engineering. Simone Hochgreb was an associate professor of mechanical engineering through 1998. She is now at the Combustion Research Facility of the Sandia National Laboratories. John B. Heywood is Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory. Arthur L. Lafleur is associate director of the Center for Environmental Health Sciences. This research was supported by the MIT Engine and Fuels Consortium, which now includes DaimlerChrysler, ExxonMobil, Ford Motor Company, General Motors Corporation, Shell, and Volvo Car Corporation. Publications are forthcoming.
Seven companies have become charter members of the Energy Laboratory’s new industrial consortium focusing on carbon sequestration (see page 12 of e-lab, January–March 2000). The companies are American Electric Power, BP Amoco, Ford Motor Company, General Motors, Norsk Hydro (Norway), Texaco, and TotalFinaElf (France). The membership represents most of the key sectors of the energy industry: oil and gas, electric power, and transportation. Howard J. Herzog, director of the new “Carbon Sequestration Initiative” and a principal research engineer in the Energy Laboratory, is now discussing possible membership with additional companies, including those in the coal industry. Additional information about the consortium can now be found on the World Wide Web at <http://web.mit.edu/sequestration/>. The site provides a brief overview of the technology, a prospectus describing the objectives and activities of the consortium and member benefits, and contact information. Also included are selected articles prepared by Energy Laboratory researchers that will provide additional information about various aspects of sequestration. The consortium is part of the Energy Laboratory’s Energy Choices Program, a major initiative launched in 1997 that focuses on finding ways to meet the expanding demand for energy services worldwide while reducing greenhouse gas emissions.

On June 21–23, the Joint Program on the Science and Policy of Global Change held its sixteenth Global Change Forum in Berlin, Germany, titled “Key Non-Linearities and Uncertainties in Climate Policy.” Topics included ocean response and the stability of the thermohaline circulation; aerosols and clouds; the response of the terrestrial biosphere; integration of components into overall uncertainty analysis; emission control decisions under uncertainty; and progress of the climate negotiations and expectations for the sixth Conference of the Parties to the UN Framework Convention on Climate Change (COP-6). The keynote address was given by Rainer Baake, State Secretary, the Federal Environment Ministry (Germany). Meeting participants included about 100 representatives from industry, government, and academia, worldwide.

On June 20–21, the Energy Laboratory hosted the Annual Technical Review Meeting of the MIT/Idaho National Engineering and Environmental Laboratory (INEEL) Collaborative Program of Research in Engineering Sciences. At the meeting, MIT and INEEL researchers discussed their ongoing projects with the program’s outside technical advisory committee. Current collaborative projects focus on developing new techniques for predicting fractures in welded structures and on understanding the physics of metal transfer in gas metal arc welding, with the objective of developing advanced intelligent welding machines. MIT principal investigators are Professor Thomas W. Eagar of the Department of Materials Science and Engineering and Professors Frank A. McClintock and David M. Parks of the Department of Mechanical Engineering. The program, funded by the US Department of Energy, Office of Science, Basic Energy Sciences, was initiated in 1985 in response to a federal call for closer collaboration between national laboratories and universities. The MIT/INEEL collaboration has provided opportunities for productive synergies that are difficult to develop in other programs. The INEEL provides well-qualified staff and sophisticated and expensive experimental facilities, and MIT provides researchers and graduate students with different perspectives, talents, and new ideas. In addition, both the INEEL and MIT draw on their close ties to the private sector to engage industrial collaborators. The annual review of the program by outside experts ensures productive collaboration, relevance to important industrial needs, and technology transfer.

János M. Beér, Professor Emeritus of Chemical and Fuel Engineering, has been reappointed to the National Coal Council (NCC) by the Secretary of Energy, Mr. Bill Richardson. The NCC is a Federal Advisory Committee to the Secretary of Energy. Its purpose is to advise, inform, and make recommendations to the Secretary of Energy on matters relating to coal as an energy carrier. The NCC has published several technical reports on scientific and engineering aspects of clean coal utilization. The most recent report is entitled “Research and Development Needs for the Management of Carbon Dioxide.” Professor Beér has served as a member of the NCC since 1993. For more information about the NCC, go to <www.nationalcoalcouncil.org> on the World Wide Web.
During the past six months, researchers in the Energy Laboratory's Analysis Group for Regional Electricity Alternatives (AGREA) have traveled to China, Mexico, and Switzerland to meet with collaborators in projects designed to help those countries evaluate potential strategies for dealing with complex energy and environmental issues. Directed by Mr. Stephen R. Connors, an Energy Laboratory staff member, AGREA performs scenario-based multi-attribute trade-off analysis to assist stakeholders in comparing the potential impacts of various options for dealing with energy and environmental issues of local, regional, and global importance. Ongoing "integrated assessment" projects move beyond traditional energy planning to incorporate life cycle assessment, risk assessment, atmospheric science, and analysis of public health impacts, all with the goal of helping local and regional decisionmakers make more informed choices. Meetings such as those in China, Mexico, and Switzerland are a critical component of the research, as they permit AGREA and its collaborators to interact directly with local decision-makers and stakeholders. Such interactions ensure that the analyses are responsive to local needs and constraints and that the information generated flows to those who can best use it.

Meetings in March and June of this year in China have brought together researchers and stakeholders of the China Energy Technology Program (CETP), part of MIT's Alliance for Global Sustainability (a joint program involving MIT, the Swiss Federal Institutes of Technology, and the University of Tokyo). The CETP is looking at a broad range of electricity alternatives for Shandong Province, located in Eastern China. Sponsored and coordinated by ABB, the effort includes MIT and collaborators at the Swiss Federal Institutes of Technology (Zürich and Lausanne), the Paul Scherrer Institute, and the University of Tokyo as well as participants from Chinese universities, environmental and economic development ministries, and the local power company. Shandong faces numerous challenges. It needs both advanced generating technologies and alternative fuel supplies. (It now relies almost exclusively on coal.) Moreover, any policies must also support the region's continuing economic growth, improve air quality and water use, and meet other environmental constraints. AGREA therefore collaborates closely with other teams that perform life cycle assessment, risk assessment, energy-economic modeling, and decision support.

Meetings held in January at MIT and in June in Mexico brought together participants of the Integrated Program on Urban, Regional, and Global Air Pollution. In this program, AGREA's trade-off analysis takes into account not only electricity supply and demand but also household, commercial, and industrial energy uses and emissions from transportation. The initial case study focuses on the Mexico City Metropolitan Area and also involves atmospheric modelers, who are looking at the unique meteorology of Mexico City, and public health researchers, who are exploring the impacts of poor air quality on Mexico City's inhabitants. The Mexico City project is led by MIT Institute Professor Mario Molina and involves a multidisciplinary team from MIT and Harvard as well as representatives from many local and state-level agencies and six universities in Mexico. The Mexico City project was initiated by MIT under the Consortium for Environmental Challenges.

A recent series of meetings with Swiss colleagues focused on disseminating results from a three-year project exploring electricity alternatives for Switzerland. This program, also part of MIT's Alliance for Global Sustainability, demonstrates the types of results achievable with integrated assessment. The analyses point to the need to better balance electricity supplies from Swiss nuclear and hydropower sources with supplies from sources in Western Europe, especially as the European electricity market becomes more competitive. In addition, Switzerland—like many industrialized nations—will need to rethink how it acquires and uses energy to meet day-to-day needs, as current levels of energy intensity cannot be sustained if targets for greenhouse gas emissions reductions set forth in the Kyoto Protocol are to be met. This assessment confirms and quantifies the challenges involved in meeting those targets.

AGREA and its research colleagues are identifying new areas of research whereby cost-effective options for reducing emissions can be identified and communicated to decisionmakers.
The following publications of Energy Laboratory and related research were released during the past period or are cited as references in this issue. 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 E40-473, 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. Publications marked by an asterisk (*) can be found or are forthcoming on-line via the following addresses:

Energy Laboratory:

Center for Energy and Environmental Policy Research:
http://web.mit.edu/ceepr/www/

Joint Program on the Science and Policy of Global Change:
http://web.mit.edu/globalchange/www/

Instructions for ordering paper copies of the reports and working papers are also available at the above listed sites or by telephoning 617-258-0307 for Energy Laboratory publications, 617-253-3551 for Center publications, and 617-253-7492 for Joint Program publications.

Reports and Working Papers


Other Publications


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### NEW AND RENEWED PROJECTS, APRIL–JUNE 2000

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