energy & environment

MIT LABORATORY FOR ENERGY AND THE ENVIRONMENT   OCTOBER 2006

Ethanol-Boosted Gasoline Engine Promises High Efficiency at Low Cost

MIT researchers have developed a concept for a half-sized gasoline engine that performs like its full-sized cousin but offers fuel efficiency approaching that of today's hybrid engine system—at a far lower cost. The key? Carefully controlled injection of ethanol directly into the engine's cylinders when there's a hill to be climbed or a car to be passed.

According to the researchers, these small engines could be on the market within five years, and consumers should find them appealing: by spending about $1,000 extra and adding a couple gallons of ethanol every few months, they will have an engine that can go as much as 30% farther on a gallon of fuel. They will have no need for expensive high-octane fuel and no worries about stringent air-pollution regulations because emissions will be as low as those from present state-of-the-art gasoline-engine vehicles.

Given the low added upfront cost and short fuel-savings payback time—three to four years at present US gasoline prices—the researchers believe that their "ethanol-boosted" turbo engine has real potential for widespread adoption. The gain in fuel economy plus the displacement of gasoline by ethanol could substantially reduce US oil consumption. For example, if all of today's cars had the new engine, US gasoline consumption of 140 billion gallons per year would drop by more than 30 billion gallons.

"Reducing US oil consumption is a daunting problem," said MIT Senior Research Scientist Daniel R. Cohn. "There's a tremendous need to find low-cost, practical ways to make engines more efficient while meeting stringent emission standards and to find cost-effective ways to use more biofuels in place of oil."

Dr. Cohn, Professor John B. Heywood, Dr. Leslie Bromberg, and their colleagues in the Laboratory for Energy and the Environment, the Plasma Science and Fusion Center, and the Sloan Automotive Laboratory have been working toward those goals. Decades of research on the spark

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Key Characteristics of Ethanol-Boosted Engine and Gasoline-Electric Hybrid
(relative to conventional gasoline engine)

	Ethanol-Boosted Engine	Gasoline-Electric Hybrid
Efficiency Gain	20%–30%	30%–40%
Extra Cost	~ $1,000	$3,000–$5,000
Technology	• Turbocharged gasoline engine • Ethanol storage • Direct injection • Reduces weight	• Gasoline engine • Electric motor • Batteries • Adds weight

MIT President Announces Energy Initiative

On September 20, MIT President Susan Hockfield announced the establishment of an Institute-wide MIT Energy Initiative (MITEI) "to address the urgent need for sustainable solutions to meet the world's energy demands." The culmination of MITEI's work will be the establishment of a new energy-focused laboratory or center that will involve researchers from all five of MIT's schools.

Over the next several years, MITEI will function as a "virtual center," reaching across the Institute to build focused multidisciplinary research programs, coordinated educational offerings, and the necessary campus infrastructure. MITEI will enhance ongoing activities while selectively and strategically building new ones, including expanded efforts to make the campus itself more energy efficient.

Director of MITEI will be Ernest J. Moniz, the Cecil and Ida Green Professor of Physics and Engineering Systems and co-director of the Laboratory for Energy and the Environment (LFEE). Robert C. Armstrong, the Chevron Professor and head of the Department of Chemical Engineering, will serve as associate director.

Professors Moniz and Armstrong will work with an Energy Council to oversee Initiative

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Ethanol-Boosted Gasoline Engine Promises High Efficiency at Low Cost

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ignition (SI) gasoline engine have achieved step-by-step increases in fuel efficiency. But a large leap has been prevented by a barrier known as the "knock limit." Changes that improve the efficiency of the SI engine tend to increase the likelihood of knock, the early spontaneous combustion of the fuel-air mixture inside the cylinder that causes a metallic clanging noise and can damage the engine.

Now, using sophisticated computer simulations, the researchers have found a way to suppress that spontaneous combustion and essentially remove the knock limit—an extraordinary achievement made even more extraordinary by the fact that they do it using a biofuel: ethanol.

Their novel SI engine concept begins with the injection of a small amount of ethanol directly into the combustion chamber, the region above the piston where fuel and air burn inside the cylinder. The ethanol enters the hot cylinder as a liquid, then rapidly vaporizes, cooling the fuel and air and making spontaneous combustion much less likely. "That's the essence of the knock suppression," said Dr. Cohn.

To quantify the effect, Dr. Bromberg developed a combined engine and chemistry computer model that can predict the impact of directly injected ethanol on the occurrence of knock. According to his analyses, with ethanol injection the engine will not knock even when the pressure inside the cylinder is three times higher than that in a conventional SI engine. The equivalent octane rating of the fuel mixture under those conditions—a measure of its resistance to knock—would jump from about 87 (that of regular gasoline) to more than 130 (above that of a high-performance gasoline racing fuel).

With knock essentially eliminated, the researchers could incorporate into their ethanol-boosted SI engine two operating techniques that help make today's diesels so efficient—but without causing the high emissions levels of diesels. First, the engine is highly turbocharged. The hot exhaust is used to compress the air entering the engine so that more air and fuel can fit inside the cylinder. The impact is increased energy release per combustion event, which means that an engine of a given size can produce more power.

Second, the engine can be designed with a higher compression ratio (the ratio of the volume of the combustion chamber after compression to the volume before). A high compression ratio gives more expansion of the burning gases each time ignition occurs, thereby getting more energy out of a given amount of fuel.

The increased turbocharging and compression ratio could increase the power of a given-sized engine by more than a factor of two. But rather than seeking higher vehicle performance—the trend in recent decades—the researchers shrank their engine to half the size. Using well-established computer models, they determined that their small, turbocharged, high-compression-ratio engine will provide the same peak power as the full-scale SI version but will be 20%–30% more fuel efficient.

But designing an efficient engine isn't enough. "To actually affect oil consumption, we need to have a lot of people want to buy our engine," said Dr. Cohn, "so our work also emphasizes keeping down the added cost and minimizing any inconvenience to the driver from using ethanol in this manner."

Although there is rapid progress in expanding the supply and distribution of ethanol, it may not be widely available at service station pumps for several years, and it may be more expensive than gasoline. To be robust to those possible circumstances, the concept provides the option to minimize the ethanol consumption. The ethanol is stored in a tank separate from the gasoline tank and injected only when the turbocharger is working hard to produce extra power, creating conditions conducive to knock. With an effective injection-control system, it should be possible to operate the engine so as to consume less than 5 gallons of ethanol for every 100 gallons of gasoline.

At that rate, drivers could add ethanol only every one to three months; and they could pump it in themselves, have it added by a service station person, or simply pour it in using one-gallon containers. The ethanol could be in the form of E85, the ethanol/gasoline mixture now being pushed by federal legislation. Running out of ethanol entirely would cause no damage, just a temporary decline in performance. Sensing a low ethanol level, the engine would automatically cut back on turbocharging, reducing the tendency to knock and allowing a cutback in ethanol use.

What about the added cost? The necessary modifications are not major. Storing the ethanol would require adding a second fuel tank or splitting the gas tank in half. A turbocharger and direct-injection system would be needed, and the small engine might have to be strengthened. Based on those changes, the researchers calculate that their engine would cost up to $1,000 more than a conventional gasoline engine.

At that price, car buyers would likely find the new engine economically appealing. As shown in the table on page 1, the ethanol-boosted engine could provide efficiency gains comparable to those of today's hybrid engine systems for less investment: a typical hybrid costs $3,000 to $5,000 extra. The hybrid uses a small conventional engine, but when extra power is needed, it relies on batteries hooked to an electric motor—devices that add both cost and weight. Ethanol boosting actually reduces weight relative to a conventional gasoline engine by reducing the size of the engine and adding almost nothing. "From this perspective, we think it is a more elegant way to use a small engine than a hybrid is," said Dr. Cohn.

Encouraged by their modeling results, the researchers decided that the quickest way to get their engine to market would be to team up with experts in the automotive industry. In spring 2005, they formed their own company, Ethanol Boosting Systems LLC; and they are now working to test and develop the new concept. If all goes as expected, vehicles with the new engine could be on the road within five years.

Dr. Cohn believes there are few practical options to radically improve engine fuel efficiency in the next few decades. "The only near-term ones on the table are the gas-electric hybrid and the turbo diesel, which has emissions problems," Dr. Cohn said. "We're adding a third one, which we think is the most economically attractive while still meeting the stringent emissions requirements—and it encourages the use of alternative fuels."

The impact on ethanol's attractiveness as an alternative fuel could be significant. Ethanol clearly has value as a replacement for gasoline. For example, simply using ethanol to displace 5% of the gasoline used in today's US vehicles—as the ethanol-boosted engine would—could save about 8 billion gallons of gasoline per year. Using ethanol in this new engine would improve the benefits dramatically: the researchers estimate that ethanol's energy value increases by a factor of four because a small amount of it makes the use of a large amount of gasoline significantly more efficient. The ethanol could thus provide large petroleum savings. ■

Daniel R. Cohn is a senior research scientist at the Laboratory for Energy and the Environment and head of the Plasma Technology Division at the Plasma Science and Fusion Center (PSFC). John B. Heywood is the Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory. Leslie Bromberg is a principal research engineer and group leader in the PSFC. Further information can be found in references 1 and 2 (see the Publications and References section).

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activities, coordinate with existing energy activities across the Institute, and guide the development of relationships with other institutions, industry, and government agencies.

Plans for MITEI reflect the recommendations of the Energy Research Council (ERC), an Institute-wide group of faculty convened by President Hockfield in June 2005 to help MIT understand how best to tackle the world's energy challenge. The ERC was co-chaired by Professors Moniz and Armstrong and solicited input from faculty, staff, and students as well as alumni and key industry leaders.

The report of the ERC, released at the widely publicized Energy Forum in May 2006, calls for MIT to undertake a broad initiative to address the science, technology, policy, and systems design required to meet the global energy challenge. The ERC identified numerous energy-related endeavors already under way in many departments, labs, and centers (including the LFEE), many of which can serve as seeds for programs of enhanced scope and impact. The report recommended a phased implementation, building up research and educational activities involving current and new faculty and broadening efforts at improving campus energy management—referred to as "walk-the-talk."

"Organizationally, the scope and reach across the Institute of the new center are unprecedented, so careful planning and coordination are required at many levels of the MIT administration," said Vice President for Research and Associate Provost Claude R. Canizares, to whom MITEI will report. Among the requirements will be significant new resources including funding, space, and equipment.

During this semester, MIT will announce the membership of the Energy Council, which will draw on all five schools and will work with MITEI's

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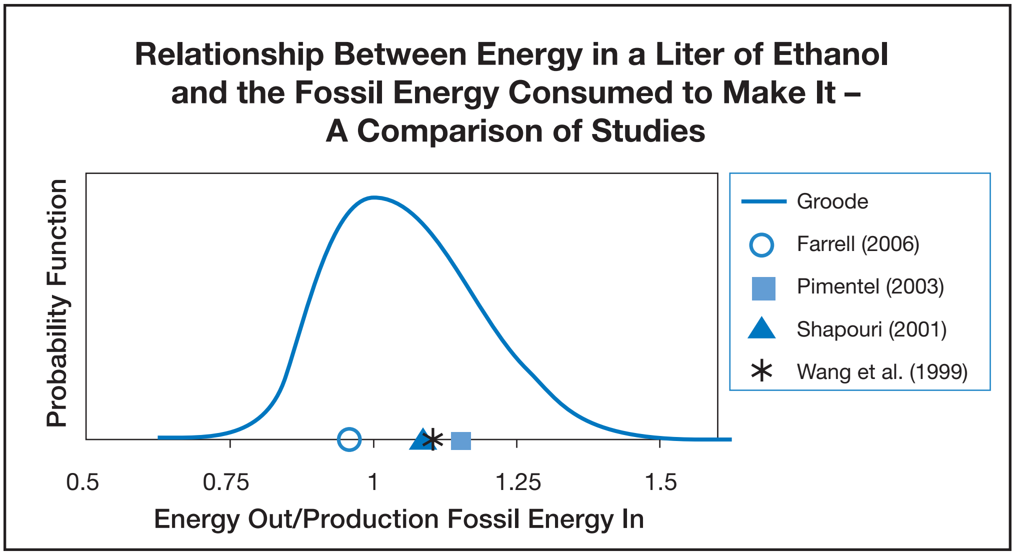
Fueling Vehicles with Ethanol: Calculating Impacts on Energy Use and Emissions

Controversy over the benefits of using corn-based ethanol in vehicles has been fueled by studies showing that converting corn into ethanol may use more fossil energy than the energy contained in the ethanol produced. A new MIT analysis shows that the energy balance is so close that the details of an analysis determine whether ethanol ends up a net energy winner or loser. Regardless of the energy balance, replacing gasoline with corn-based ethanol does significantly reduce oil consumption because the conversion process requires little petroleum. Further MIT analyses show that making ethanol from cellulosic sources such as switchgrass has far greater potential to reduce fossil energy use and greenhouse gas (GHG) emissions.



MIT researchers compared three studies of corn-based ethanol that (in their published form) came out with opposing answers on whether corn-based ethanol provides more or less energy than is contained in the fossil fuels used in making it. In the comparison, the three studies plus the MIT analysis were all limited to the same inputs (for example, the energy used to run tractors but not to manufacture them). The MIT results appear as a curve showing a range of values with the probability of each. With differences in assumptions removed, the studies all generate results close to 1. (Note: all studies are cited as references in Alexander E. Farrell et al., "Ethanol can contribute to energy and environmental goals," Science, *v. 311, 27 January 2006.)*

The Bush administration is pushing the use of ethanol as a domestically available, non-petroleum alternative to gasoline. But most US ethanol is now made from corn, and growing corn and converting the kernels into ethanol consume a lot of energy—comparable to what is contained in the ethanol produced. Making ethanol from corn stalks, other agricultural wastes, and wild grasses would consume less energy, but the technology for converting them to ethanol may not be economically viable for another five to ten years.

Does using corn-based ethanol in place of gasoline actually make energy consumption and GHG emissions go up, as some researchers claim? Why do others reach the opposite conclusion? And how much better would ethanol from "cellulosic" feedstocks such as switchgrass be?

To answer those questions, graduate student Tiffany A. Groode, supervised by Professor John B. Heywood, performed her own study. Using a technique called life cycle analysis (LCA), she looked at energy consumption and GHG emissions associated with all the steps in making and using ethanol: growing the crop, manufacturing and applying fertilizer, running farm machinery, shipping the crop to the processing plant, and converting it into ethanol. She limited energy sources to fossil fuels, including those used to generate any electricity consumed. Finally, she accounted for the different energy contents of gasoline and ethanol. Pure ethanol carries 30% less energy per gallon, so more is needed to travel a given distance—a difference that is factored into her calculations.

While most studies follow those guidelines, she added one more feature: she incorporated the uncertainty associated with the values of many of the inputs. Following a methodology developed by recent MIT graduate Jeremy Johnson, she used not just one value for each key variable but rather a range of values along with the probability that each of those values would occur. In a single analysis, her model runs thousands of times with varying input values, generating a range of results, some more probable than others.

Based on her "most likely" outcomes, she concluded that traveling a kilometer using ethanol does indeed consume more energy—and as a result generate more GHGs—than traveling the same distance using gasoline. However, further analyses showed that several factors can easily change the outcome, rendering corn-based ethanol a "green" fuel.

One such factor is the much-debated co-product credit. When corn is converted into ethanol, the material that remains is a high-protein animal feed. One assumption is that the availability of that feed will enable traditional feed manufacturers to produce less, saving energy; ethanol producers should therefore get to subtract those energy savings from their energy consumption. When Ms. Groode put co-product credits into her calculations, ethanol's life-cycle energy use became lower than gasoline's.

Another factor that influences the outcome is which energy-using factors of production are included and excluded—the so-called system boundary. A study performed by Professor David Pimentel of Cornell University in 2003 includes energy-consuming inputs that other studies do not, one example being the manufacture of farm machinery. His analysis concludes that using corn-based ethanol yields a significant net energy loss. Other studies conclude the opposite.

To determine the importance of the system boundary, Ms. Groode compared her own analysis, the study by Pimentel, and three other reputable studies, considering the same energy-consuming inputs and no co-product credits in each case. The outcome appears in the figure on page 4. Her own results appear as a curve showing a distribution of possible values. Interestingly, the other groups' results all have a value close to 1.

"The results show that everybody is basically correct," she said. "The energy balance is so close that the outcome depends on exactly how you define the problem." The results also serve to validate her methodology: results from the other studies fall within the range of her more probable results.

Another factor that influences the outcome—and raises considerable concern—is the region of the United States studied. In her initial study, Ms. Groode used data from Iowa, the country's top corn-producing state. Even so, corn-based ethanol was not a clear winner on the fossil energy front. In subsequent analyses she looked at Nebraska and Georgia, states that require more fertilizer and irrigation to produce corn. Analyses for those states concluded that corn-based ethanol is not a green alternative, even when co-product credits are included.

Growing more corn may not be the best route to expanding ethanol production. Other options include using corn stover, the plants and husks that are left on the field, or growing an "energy crop" such as switchgrass. While corn kernels are mostly starch, corn stover and switchgrass are primarily cellulose. Commercial technologies to make ethanol from cellulose are not yet available, but laboratory and pilot-scale tests are generating useful data on processing techniques. So how do cellulosic sources measure up in terms of saving energy and reducing GHG emissions?

Using her methodology, Ms. Groode has now performed an initial analysis of switchgrass and (again drawing on Dr. Johnson's work) corn stover. The figure below shows the fossil energy required to produce a liter of ethanol from corn kernels, corn stover, and switchgrass. Fossil energy consumption is far lower with the two cellulosic sources. Farming corn stover requires energy only for harvesting and transporting the material. (Fertilizer and other inputs are assumed to be associated with growing the kernels.) Growing switchgrass is even less energy intensive. It requires minimal fertilizer; its life cycle is about ten years, so it need not be replanted each year; and it can be grown almost anywhere so transport costs can be minimized. And converting the cellulosic sources to ethanol is likely to require little or no additional energy input. The processing waste can be burned to generate enough heat and electricity to run the processing plant—perhaps with some leftover electricity to sell to the power grid.

Of course, energy is not the only resource used in making biomass-based ethanol. It also requires land. As a sample scenario, Ms. Groode used her model to examine how much land would be needed to replace 25% of total gasoline consumption projected for 2035. Using corn kernels as the source would require double the amount of

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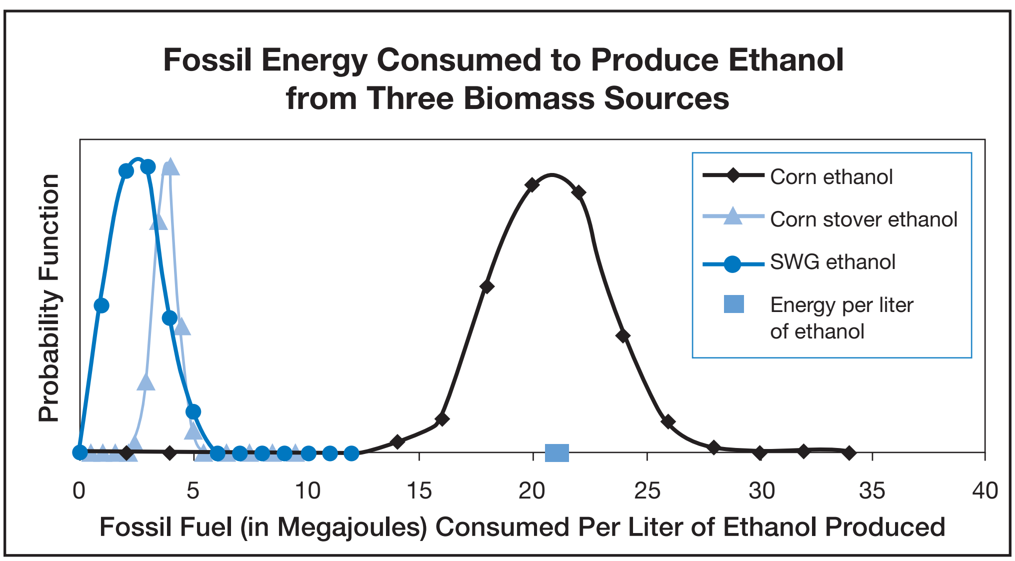

This figure shows the fossil energy required to make a liter of ethanol from corn kernels, corn stover, and switchgrass. Energy consumption is far lower with the stover and switchgrass, but the technology to convert such cellulosic sources to ethanol is still under development. (A liter of ethanol contains 21 megajoules of energy.)

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land currently devoted to growing corn. Using switchgrass would require the same amount of land as now used to grow corn—but not in the same location. Switchgrass could be grown on land not suitable for food crops. Competition for high-value agricultural land would not be an issue.

Ms. Groode and Professor Heywood now view the three sources as a continuum. In the future, cellulosic sources such as corn stover and ultimately switchgrass can provide large quantities of ethanol for widespread use as a transportation fuel. In the meantime, ethanol made from corn can provide some immediate benefits. For example, the corn-to-ethanol conversion process consumes relatively little petroleum, so using corn-based ethanol in place of gasoline reduces oil consumption. (The process does, however, consume considerable amounts of natural gas—a fuel that the US is importing in increasing quantities.) Vehicles that can run on corn-based ethanol are already commercially available. And perhaps most important, the availability of corn-based ethanol is helping consumers make the transition from familiar oil-based fuels to something new.

"I view corn-based ethanol as a stepping-stone," said Ms. Groode. "People can buy flexible-fuel vehicles right now and get used to the idea that ethanol or E85 works in their car. If ethanol is produced from a more environmentally friendly source in the future, we'll be ready for it." ■

Tiffany Groode received her master's degree from the Department of Mechanical Engineering in May 2004; she is now a PhD candidate in the same department. John B. Heywood is the Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory. Jeremy Johnson received his PhD from the Department of Chemical Engineering in 2006. This research was supported by BP America, Inc. Further information can be found in reference 3 (see the Publications and References section).

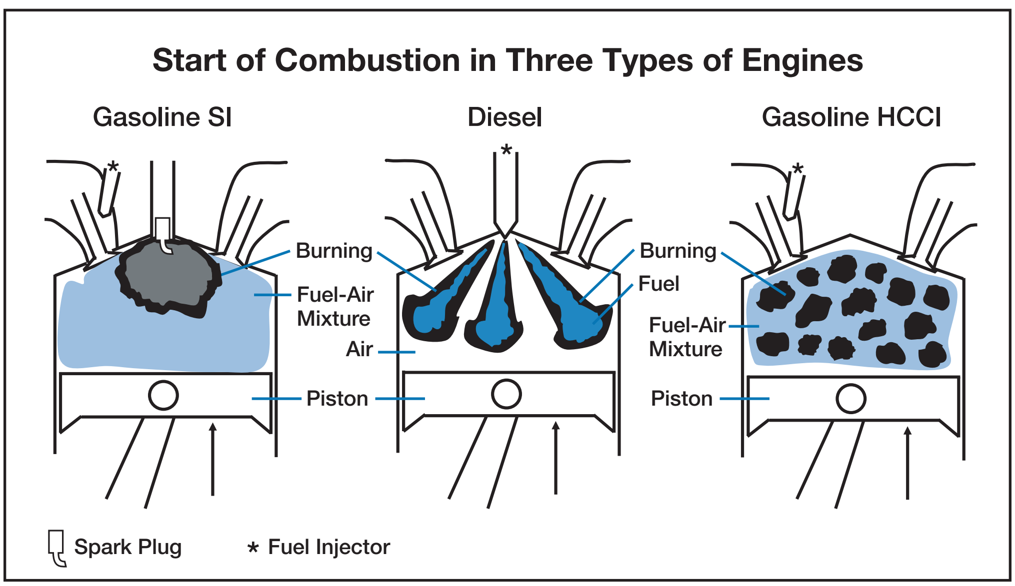
Gasoline Engines: Spark-Free, Fuel-Efficient Operation

MIT researchers have demonstrated a method whereby ordinary spark-ignition (SI) engines can, under certain driving conditions, move into a spark-free operating mode that is more fuel efficient and just as clean. If all goes well, the mode-switching capability could appear in production models within a few years, improving fuel economy by several miles per gallon in millions of new cars each year. Parallel theoretical studies are focusing on expanding the time the engine can spend in the more-efficient mode.

Many researchers are studying a new way of operating an internal combustion engine known as "homogeneous charge compression ignition" (HCCI). Switching an SI engine to HCCI mode pushes up its fuel efficiency. But it doesn't always run. The problem stems from the very features that make it efficient and clean.

In an HCCI engine, fuel and air are mixed together and injected into the cylinder. The piston then compresses the mixture until spontaneous combustion occurs (see the figure below). The engine thus combines fuel-and-air premixing (as in an SI engine) with spontaneous ignition (as in a diesel engine). The result of that combination is the HCCI's distinctive feature: combustion occurs simultaneously at many locations throughout the combustion chamber.

That behavior has advantages. In both the SI engine and the diesel engine, burning begins locally—with a spark in the former and with fuel injected into hot, compressed air in the latter. In those engines, the fuel must burn hot to ensure that the flame spreads rapidly through the combustion chamber before a new "charge" enters. In an HCCI engine, there is no need for a quickly spreading flame because combustion occurs throughout the combustion chamber. As a result, combustion temperatures can be lower, so emissions of nitrogen are negligible (in some designs,

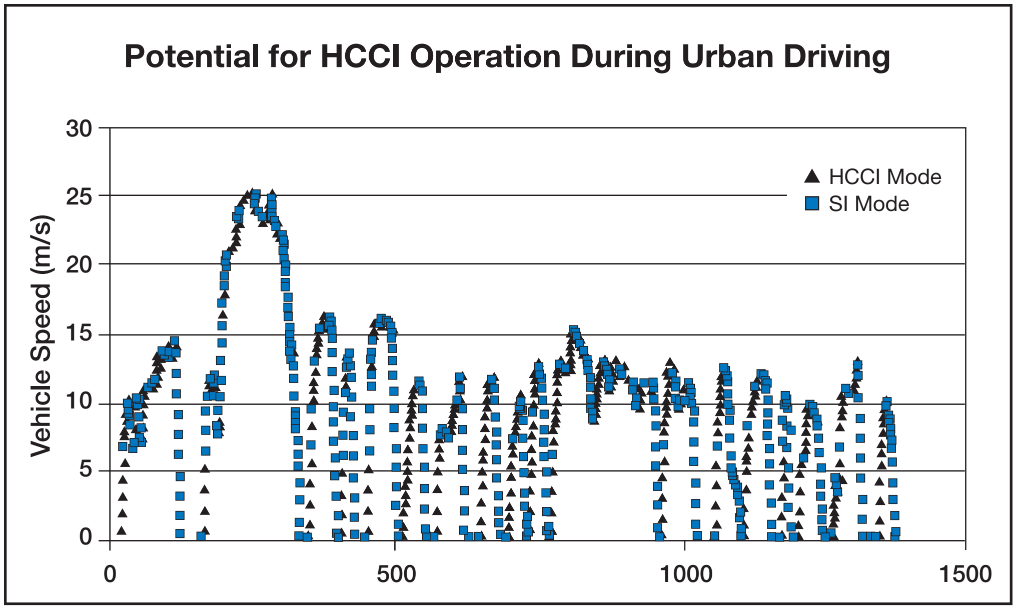


In a gasoline spark-ignition engine (left), combustion begins when a mixture of fuel and air is ignited by the spark plug. In a diesel engine (center), combustion begins when fuel is injected into hot, highly compressed air. In both cases, ensuring that the resulting flame spreads rapidly is a concern. In a homogeneous charge compression ignition engine (right), well-mixed fuel and air are compressed until combustion occurs at multiple points throughout the combustion chamber. Flame expansion is not a concern—but without a spark or fuel injection to start the process, timing is tricky.

making the catalytic converter unnecessary). The fuel is spread in low concentrations throughout the cylinder, so the soot emissions from fuel-rich regions in diesels are not present. Perhaps most important, the HCCI engine is not locked into having just enough air to burn the available fuel, as is the SI engine. When the fuel coming into an SI engine is reduced to cut power, the incoming air must also be constrained—a major source of wasted energy. The HCCI is free from that constraint.

However, as with most promising engine technologies, there's a catch. The HCCI engine has no external method of ignition—no spark as in the SI engine, no injection of pure fuel as in the diesel. As a result, controlling exactly when ignition occurs is difficult. And if it does not begin when the piston is positioned for the power stroke, the engine will not run right. "It's like when you push a kid on a swing," said Professor William H. Green, Jr., who directs MIT research on the HCCI engine. "You have to push when the swing is all the way back and about to go. If you push at the wrong time, the kid will twist around and not go anywhere. The same thing happens to your engine."

According to Professor Green, ignition timing in an HCCI engine depends on two factors: the temperature of the mixture and the detailed chemistry of the fuel. Both are hard to predict and control. Outdoor temperatures can vary dramatically from place to place and at different times of day. Also, the temperature inside the engine now depends on how the engine was running a few seconds ago. And gasolines can differ considerably in different regions of the country and at different times. So engine manufacturers are concerned. While the HCCI engine performs well under controlled conditions in the laboratory, what will happen in the real world, where temperatures and fuels vary?



This figure shows an engine switching between SI and HCCI modes during a simulated drive of almost 25 minutes in an urban setting. The driving speeds are defined by the Federal Testing Procedure. The HCCI mode would operate during 40% of the overall cycle, improving fuel economy by several miles per gallon. (Source: Morgan Andreae, PhD thesis, 2006, Ref. 4.)

Professor Green, Professor Wai K. Cheng, and their colleagues in the Sloan Automotive Laboratory and the Laboratory for Energy and the Environment have been working to answer those questions.

Much of their research has taken place in a Mazda engine provided by Ford and modified so that it can run in either HCCI or SI operating mode. For the past two years, graduate students Morgan Andreae and John Angelos have been studying the engine's behavior as the inlet temperature and type of fuel are changed. They used more than a dozen gasoline samples provided by BP that span the range of available commercial gasolines. For each temperature and fuel combination, they tested the engine at various speeds and levels of power output to determine when the engine could operate in the HCCI mode.

Not surprisingly, the range of conditions suitable for HCCI operation is far smaller than the range for SI mode. Under conditions replicating rapid acceleration or idling, the experimental HCCI engine tended to fire too early, too late, or not at all. But it worked well at partial load, such as during gradual acceleration or whenever the gas pedal is depressed just partway—a time at which the SI engine is particularly inefficient because the incoming airflow must be throttled.

What about the effects of temperature and fuel type? Variations in temperature had a noticeable but not overwhelming effect on when the HCCI mode worked. Fuel composition had a greater impact, but it was not as much of a showstopper as the researchers expected. Controlling operation may be possible using refined or adapted versions of the fuel sensors now used in flexible-fuel vehicles. But ensuring optimal performance

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may require the development of standards for certifying specific fuels as HCCI appropriate (analogous to octane ratings for gasolines).

Guided by their engine tests, the researchers have developed an inexpensive technique that should enable a single engine to run in SI mode but switch to HCCI mode whenever possible. A simple temperature sensor determines whether the upcoming cycle should be in SI or HCCI mode (assuming a constant fuel). If the choice is HCCI, the exhaust valve closes a little early to trap some of the exhaust inside the cylinder. The hot exhaust pushes up temperatures in the next cycle, encouraging the spontaneous combustion critical to HCCI operation. Engine experiments confirm that retaining varying amounts of exhaust is an effective means of manipulating the timing of combustion.

"This is the kind of technology that, once you figure out how to do it correctly, you could spend less than $500 per car and put it into mass production easily in just a few years," said Professor Green. "It's not drastically changed. It's not a gas turbine or a fuel cell or a battery—it's still a car engine."

To estimate potential fuel savings from the mode-switching scheme, Mr. Andreae determined when an SI engine would switch into HCCI mode under simulated urban driving conditions (specifically, the Federal Testing Procedure used to calculate the fuel economy of all production vehicles). His results are shown in the figure on page 7. During times of gradual acceleration, HCCI mode prevails. During deceleration and idling, SI mode takes over. Over the whole simulated trip, HCCI mode operates about 40% of the time.

Based on such information, the researchers estimate that the increase in fuel efficiency would be a few miles per gallon. "That may not seem like an impressive improvement," said Professor Green. "But if all the cars in the US today improved that much, it might be worth a million barrels of oil per day—and that's a lot."

The researchers are working to expand the range of operating conditions in which HCCI will work. They have developed new computer simulations that track both chemical reactions and heat transfer and are now examining HCCI engine behavior at both extremes—the "low-load limit" (with very little fuel) and the "high-load limit" (with a lot of fuel). Of particular interest is exactly how HCCI ignition fails at those extremes. "When you get close to the boundaries of where you can operate, you can get all kinds of really strange things happening," said Professor Green. "But we might be able to control some of those things if we really understood them—and then we could push the boundaries a little farther."

With a more detailed understanding of the fundamentals, they plan to refine their control system for switching modes and also identify fuel compositions that enable greater use of the fuel-efficient HCCI mode. ■

William H. Green, Jr., is an associate professor in the Department of Chemical Engineering. Wai K. Cheng is a professor in the Department of Mechanical Engineering. Morgan Andreae received his PhD from the Department of Mechanical Engineering in 2006. John Angelos is a PhD candidate in the Department of Chemical Engineering. *This research was supported by Ford Motor Company and the Ford-MIT Alliance, with additional support from BP.* *Further information can be found in references 4–6 (see the Publications and References section).*

MIT President Announces Energy Initiative

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director and associate director to implement the research, education, and on-campus initiatives.

Various task forces will also be set up. An Energy Education Task Force will coordinate MIT's energy-related educational offerings and recommend new subjects from the undergraduate to the graduate level. An Energy Management Task Force will draw on research and educational activities to help improve campus energy efficiency. Work on MIT's physical plant takes on special importance in light of plans for substantial campus construction and renovation. In addition, a number of faculty task forces will be organized to advance major interdisciplinary research thrusts within MITEI.

Finally, an External Advisory Committee of leaders from industry, academia, and government will provide guidance, advice, and direction as MITEI's activities evolve.

In a letter to the MIT community, President Hockfield reiterated the ERC's assertion that "the need for workable energy options is perhaps the greatest single challenge facing our nation and the world in the 21st century." She went on to say, "Many members of our community are already at work on energy issues, producing significant breakthroughs; their contributions will have even greater impact as parts of a coherent answer to the world's energy problems."

Announcements about the new initiative and a copy of the ERC report can be found at web.mit.edu/erc/. ■

Auto Expert Offers Practical Advice on Saving Fuel

People are often surprised to hear that it will take decades for new technology to have any real impact on our staggering consumption of fuel for personal transportation, Professor John B. Heywood told the audience at an MIT Energy Club seminar in spring 2006.

But they're also surprised at some seemingly minor changes in their own behavior that can make a difference right away, noted Heywood, the Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory.

Based on population and economic growth, by 2050 there will be three times as many cars, vans, pick-up trucks, and SUVs as there are now—some 2 billion worldwide. At today's level of fuel consumption per car, that's just not feasible.

"To offset the increase in number of cars, we really need to cut fuel use per vehicle by a factor of three or four," Heywood said.

Technology can help. "Evolutionary improvements" in the technologies we know—for example, more efficient engines and transmissions and lighter, more streamlined designs—can make changes that add up significantly. More "radical transitions" might involve vehicles running on biofuels and fuel cells and hydrogen.

But it'll be a long time before new technologies significantly reduce overall fuel consumption. Heywood looked carefully at the sequence of steps required: develop the technology until it's market competitive, start manufacturing and selling the improved vehicle, and get enough of them on the road to make a difference. (Previous research suggests that "making a difference" will occur when those vehicles are responsible for about one-third of total miles driven.)

For each technology, Heywood added up the time required for all the steps to occur. His conclusion? It will take two decades before "moderately improved vehicles" will make a noticeable difference—and some 50 years before the much-touted hydrogen fuel-cell vehicle will be out in force.

"I'm not saying that hydrogen is a waste of time, but don't expect it to have a serious impact in a decade," he warned. "People who are working on it seriously estimate that only between 2015 and 2020 will we really know whether it's a market-competitive technology."

So is it realistic to think about quartering the petroleum used per vehicle in the next few decades? Heywood says maybe. He has a list of 12 potential measures and notes that a 20% gain in six of them would do the trick.

Six of the measures on his list involve the evolutionary and radical approaches to improving new vehicles. But the other six focus on cutting fuel use in today's overall fleet—changes that can have an impact soon.

Some are obvious. Commute with a friend. Take the subway. Don't insist on owning a car that accelerates like a Ferrari. But even "driving less aggressively" makes the list. By no longer rushing through that yellow light or darting in front of that other driver, we can cut the gas we use by up to a third.

"None of these measures alone is going to save us from our appetites," Heywood said, "but lots of them together could."

He stressed that the key is for each of us to take responsibility. He told the audience how he trained himself to turn off the light whenever he leaves a room. Each time he reminded himself, "By turning the light off, there's less carbon dioxide going into the atmosphere that'll be around for a hundred years."

"We've got to take that same sort of personal commitment and attitude into our car-buying habits and our driving behavior," he said. ■

Various Factors That Affect Fuel Consumption

Opportunities to Impact Total In-Use Vehicles:

1. Encourage/enforce less-aggressive driving behavior
2. Increase vehicle occupancy on substantial fraction of trips
3. Reduce mileage driven per person per year
4. Use biomass-based fuels to substitute for petroleum-based fuels
5. More effective transportation system management
6. Increase public transportation utilization

Opportunities for Impact through Improving New Vehicles:

1. Shift the vehicle performance/fuel economy trade-off towards lower fuel consumption
2. Improve vehicle maintenance, lubricants, and tire pressure and reduce parasitic loads
3. Buy and use lighter-weight, "less big" vehicles
4. Implement more efficient engine, drive train, and vehicle technologies
5. Develop and implement use of hydrogen with fuel-cell-powered vehicles
6. Use electricity with advanced batteries to reduce petroleum consumption

News

AltWheels caravan presents cars of the future

Some of the hybrid, flexible fuel, and other vehicles on display near MIT's Stata Center as part of the fourth annual AltWheels Festival. Photo: Stephen Connors, LFEE.

On Thursday, September 21, a caravan of 46 vehicles powered by alternative fuels, hybrid power trains, and other innovative automotive technologies pulled into MIT's Stata Center amphitheater. Among them were hydrogen-fueled cars and buses, an antique Stanley Steamer, a motorcycle with a passenger seat made from a diner's counter stool, and a biodiesel tanker with a bucolic scene painted on the side.

The caravan and reception that followed—hosted by MIT's Laboratory for Energy and the Environment (LFEE) and Environmental Programs Office (EPO)—were the highlight of a week of alternative transport activities.

The fourth annual AltWheels Festival was an all-volunteer, multiday, multivenue event designed to raise public awareness of commercially available vehicles that provide alternatives to the fossil-fuel-powered automobile. The caravan was preceded by a weekend-long symposium at the Museum of Science and kicked off three days of displays, demonstrations, and activities at Boston City Hall Plaza and the Larz Anderson Auto Museum in Brookline, Massachusetts.

"Even though the price of fuel dropped 20¢, there's a need for this," MIT Chancellor Phillip L. Clay told the crowd of drivers, inventors, and curious onlookers. "With Ford and others, MIT works hard with industry to advance fuel and energy research. This caravan represents the work of many at MIT."

Professor John B. Heywood, director of the MIT Sloan Automotive Laboratory, said he's been involved in the automotive field "a long time, but it's never been this lively and exciting."

As the Hood blimp circled overhead, a crowd milled around the vehicles. Many looked fairly ordinary but ran on ethanol, hydrogen, compressed natural gas, electricity, or diesel- or gasoline-hybrid systems. Others would look out of place on a city street. For example, there was the Moonbeam, a tiny three-wheeled contraption built from secondhand motorcycle parts that gets up to 100 mpg and fulfills 90% of its owner's travel needs. Retired electrical engineer David K. Nergaard drove his 1922 Stanley Steamer, a steam-powered vehicle that attracted a covey of MIT students who peered at its parts as they puzzled out its principles. And there was the Honda FCX, powered by PEM fuel cells and provided by the New York Office of General Services Clean Fueled Vehicle Program. Although not surprising in outward appearance, the FCX—one of about 20 of its kind in the world—is valued at roughly $1,000,000, though it can be leased for just $500 per month.

Our environmental problems, Heywood said, boil down to this: "There are too many of us, we use too much stuff, and we use it in damaging ways." The range of alternatives to typical gas-guzzling vehicles is now wide enough to help people make personal choices "about how we live and how we drive. We can drive small and light," Heywood said. "We can use less stuff and use it less damagingly."

Subsequent speakers at the event included Simon Pitts, executive director of the Ford-MIT Alliance; Scott Griffith, CEO of ZipCar; James W. Hunt, chief of environmental and energy services for the City of Boston; David Cash, director of air, energy, and waste policy at the Massachusetts Executive Office of Environmental Affairs; Massport CEO Tom Kinton; and Alison Sander, founder of the AltWheels Festival.

The vehicles in the caravan were a small preview of those presented at the AltWheels Festival that followed at Boston City Hall Plaza and then at the Larz Anderson museum. More than 100 vehicles were exhibited, including models available now and in the future, along with displays by public transportation providers, transportation organizations, and alternative-energy providers. In addition to transportation options, this year's AltWheels Festival featured environmental organizations, bike and walk groups, educational institutions, and others along an "Energy Freedom Trail."

One of 30 Ford Focus fuel cell vehicles running on hydrogen that are now in fleets around the United States, Canada, and Europe. Photo: Stephen Connors, LFEE.

The two-day Alternative Transportation Symposium, held the previous weekend, featured industry leaders and other transportation and energy experts discussing future vehicles and fuels (including technologies on display during the festival); incentives for using fuel-efficient and renewable-fuel vehicles; sustainable urban design; ride sharing and mass transit; and sustainable-transportation innovations.

For more information, visit the AltWheels website at www.altwheels.org. ■

Cambridge-MIT Institute inaugurates energy security center

In mid-November 2006, the Cambridge-MIT Institute will officially launch the Centre for Energy Security (CMI-CES), an organization focusing on regional and global security challenges and other long-term energy-related issues. The new Centre is the product of a two-year dialogue with stakeholders on the topic of energy security and UK competitiveness.

Professor David H. Marks, co-director of MIT's Laboratory for Energy and the Environment (LFEE) and a US representative on the CMI-CES planning team, observed, "The essential elements of energy security in the UK are equally important in other nations; CMI-CES research will have global relevance."

Jointly housed at MIT and Cambridge University, the Centre will serve as a focal point for research, dialogue, and outreach among representatives from industry, government, and academia. Stephen R. Connors, director of the Analysis Group for Regional Energy Alternatives at the LFEE, is also a member of the planning group.

In a recent report to the UK Department of Trade and Industry, the planning team defined the Centre's objectives. The goals are to reduce the exposure of the UK economy to the dynamics of international fuel supply chains while helping the nation realize its long-term social and environmental goals.

Investigators have identified three components key to a successful energy security strategy for the UK. First, the efficiency of energy services must be greatly improved. Second, the nation must diversify its energy resources. Third, the UK must modernize its energy infrastructure. These approaches will both improve energy security and reduce greenhouse-gas production to meet Kyoto and post-Kyoto targets.

UK members of the CMI-CES planning team are Dr. Hugh Aldridge, CMI director for industry, and Dr. William Nuttall, course director in technology policy at the Judge Business School at Cambridge University.

Through the Cambridge-MIT Institute, MIT and Cambridge University collaborate on research and education initiatives to enhance competitiveness, productivity, and entrepreneurship in the UK economy. ■

By Teresa Hill, Laboratory for Energy and the Environment

Education Update

Summer course on energy and climate focuses on lighting efficiency

Lighting is the most visible use of energy in our daily lives and the potential source of significant energy savings at institutions such as MIT. Thus, it was appropriate for students in MIT's summer short course on energy and climate to undertake a lighting audit to make their global lessons concrete.

The course, "Energy and Climate: Toward Sustainable Systems," provided undergraduates from institutions across the eastern United States with an intensive one-week introduction to global energy and climate challenges. MIT researchers led discussions on the benefits and drawbacks of conventional fuel supply, on climate change as one of the key challenges of fossil fuel use, and on potential solutions such as increased energy efficiency and new energy-production technologies. The capstone of the course was "Lightspotting," the lighting-audit project that provided students with analytical skills that they could take back to their home campuses.

"The Lightspotting project engaged students in active learning about lighting as a component of campus energy management," said Dr. Amanda Graham, education program manager for the Laboratory for Energy and the Environment (LFEE) and one of the organizers and instructors of the course.

Armed with light meters, measuring tapes, and their own powers of observation, students analyzed designated common areas, classrooms, offices, and athletic facilities at MIT. In each space, they observed the installed lighting and

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Education Update

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measured the actual light shed. They then compared their findings to recommended lighting levels specifically suited to particular tasks and spaces. Finally, they designed retrofit plans using the best and most cost-effective energy-efficient light fixtures and bulbs. Their ultimate recommendations incorporated not only energy efficiency but also human comfort, aesthetics, and cost.

They presented their results to a panel of lighting and MIT campus experts: Ronald Adams, senior electrical engineer of MIT Facilities; Steven Lanou, MIT deputy director of sustainability initiatives; Marilyne Andersen, assistant professor of architecture and an expert in daylighting; and Ira Rothman, a consultant at the Reflex Lighting Group, Inc., in Boston.

Their recommendations included a retrofit of an elevator lobby in which many different types of scattered fixtures would be replaced by fewer, more energy-efficient fluorescent lamps focused on the elevator space and adjusted by a daylight sensor. Students estimated that the new lighting would pay for itself in energy savings within five years. Another recommendation was simply to remove bulbs from fixtures in a conference room that had excessive lighting.

Course instructor and project reviewer Mr. Lanou said, “These data will be useful to the Institute’s ongoing efforts to improve campus energy management.” The Environmental Programs Office and the Department of Facilities have taken all recommendations under consideration.

This practical experience rounded out a week of presentations from MIT experts. For example, Professor Kerry Emanuel explained the factors driving climate change; Dr. John Parsons provided an introduction to energy economics; Mr. Howard Herzog discussed technological, economic, and social aspects of carbon sequestration; and Professor David Marks described the current state of global energy systems. Dr. Richard Sears, LFEE visiting scientist from Royal Dutch Shell, discussed the role of oil in our energy infrastructure; and Ross Gelbspan, journalist and author, proposed a global energy strategy to use market incentives to speed a transition away from fossil fuels.

Course participants Mai Kobayashi and Francesca Hernandez examine a 400-watt high intensity discharge (HID) metal halide lamp. MIT currently has this type of lamp in many of its athletic facilities. The benefit of the lamp is high lumen output, energy efficiency, and low maintenance. The bulb lasts approximately 25,000 hours. Photo: Amanda Graham, LFEE.

Francesca Hernandez, a fourth-year landscape architecture student at Ball State University in Muncie, Indiana, said she signed up for the class because she hoped it would help round out her understanding “of the innate connections between energy demand and climate change.” Hernandez, who hopes to work one day as a consultant in ecological design and engineering, said she walked away from the experience with “a renewed sense of hope that solutions to the issue of global warming can and will be found.” ■

By Beth Conlin, Education Program Coordinator, Laboratory for Energy and the Environment, and Deborah Halber, MIT News Office Correspondent

First Martin UROP reports from the field

In spring 2006 the LFEE announced that the Martin Foundation, Inc., would provide new support for MIT undergraduates involved in sustainability research through MIT’s Undergraduate Research Opportunities Program (UROP). Each “Martin UROP” would collaborate with a Martin graduate fellow (see box on page 13) and a faculty supervisor on a sustainability-related research project. In the article that follows, the first Martin UROP, Maggie Avener, describes her research experience working with Martin Fellow Anne Lightbody in a constructed wetland in Georgia during summer 2006.

Specially constructed wetlands are sometimes used in place of storm-water treatment plants to remove pollutants from water. Typically, engineers design wetlands with uniform vegetation so that the water flows through at a slow, steady rate and remains long enough for the vegetation to take up nitrogen, phosphorus, and other contaminants, reducing them to safe levels. However, even in carefully designed wetlands, there are often channels with little or no vegetation where fast-moving water “short-circuits” the wetland. Empirical evidence suggests that digging a transverse deep zone across the wetland helps to decrease the effect of such short-circuiting on contaminant removal.

To investigate the phenomenon, in spring 2006 I began working with [Martin Fellow] Anne Lightbody at MIT’s Ralph Parsons Laboratory to simulate flow through constructed treatment wetlands. We built a physical model of a wetland in a flume that was about 1.2 meters wide and 7 meters long. We used arrays of wooden dowels elevated on wooden boxes to simulate vegetation. Spaces without dowels simulated channels in the direction of the flow, and spaces without boxes simulated deep zones across the flow. We used fluorescent dye to observe the flow patterns in the model basin. We released dye at the upstream end of the channel and measured the dye concentration across the downstream end (beyond the deep zone) with a fluorometer. We also measured flow velocity at specific points across the channel.

To validate our laboratory model, we wanted to run large-scale field experiments paralleling those we had done in the lab. Supported in part by the Martin Family UROP funds and Anne’s travel funding from the Switzer Foundation, we spent the month of July performing experiments in a constructed treatment wetland in Augusta, Georgia. The Augusta wetlands provided an ideal research setting as they had been built with transverse deep zones, which were proving very effective.

At a constructed water-treatment wetland in Georgia, Martin UROP Maggie Avener prepares to tow a pump across a vegetated area, releasing dye into the water. By tracing the movement of the dye, the researchers could identify channels in which the water moves too quickly for the vegetation to remove contaminants effectively and could observe the mixing patterns when those channels leave the vegetation. Photo: Anne Lightbody, MIT.

Much of our initial research focused on finding short-circuiting channels cutting across deep zones in three distinct “cells”—areas of the wetland divided by earthen berms. We identified some channels by eye (duckweed covering the water surface parted in areas of faster flow) and characterized them by measuring flow velocity across their widths and at various depths. We also performed tracer studies with dye. We would traverse a shallow area upstream of a deep zone, pumping dye into the water as we walked at a steady pace. After completing the release, we would drive our boat across the deep zone, continuously measuring the downstream dye concentration with a fluorometer. In August, we returned to MIT and began to analyze our data.

Although our analyses are not yet complete, we have already observed a few trends. For example, the distribution of dye in the deep zone correlates strongly with wind conditions. On calm days, we saw the dye in the short-circuiting channels both enter and exit the transverse deep zone in distinct clouds, with relatively little dispersion. On windy days, we saw the dye mix entirely over the width and depth of the deep zone before it reached the downstream end. We also found that the amount of water short-circuiting through channels varies from one wetland cell to another. According to our preliminary estimates, the fraction short-circuiting was about 10% in one cell and as little as 3% in another.

Results from the field experiments revealed trends similar to those we saw in the lab, encouraging follow-on studies of our model basin in more detail and in new configurations. On a personal level, I not only learned a great deal about designing wetlands for contamination cleanup but also gained valuable experience in conducting both laboratory and field experiments. As a result of my summer experience, I believe I could now design and run a large-scale tracer study myself. ■

By Maggie Avener, MIT ’07

New Martin Fellows named

In late September, 20 MIT graduate students were inducted into the Martin Family Society of Fellows for Sustainability for the academic year 2006–2007. The new Fellows come from the Engineering Systems Division, the Sloan School of Management, and 11 academic departments and programs within the schools of Engineering; Science; Architecture and Planning; and Humanities, Arts, and Social Sciences.

Their activities span a wide range of topics including renewable energy technologies, green architecture, green chemistry, responses to climate change, sustainable business practices, environmental cooperation and negotiation, water resource availability, prevention and control of worldwide epidemics, and sustainable energy solutions for the developing world.

The Martin Family Society was established at MIT in 1996 by Lee ’42 and Geraldine Martin to foster graduate-level research, education, and collaboration on issues relating to sustainability. It supports and connects MIT’s top graduate students in environmental studies and fosters opportunities for them to collaborate on multidisciplinary research on complex environmental problems.

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

Inquiries can be sent by e-mail to thill@mit.edu for LFEE publications, canes@mit.edu for CANES publications, bubluski@mit.edu for CEEPR publications, and tzh@mit.edu for Joint Program publications. To obtain a copy of an MIT thesis, in paper or electronic format, go to http://libraries.mit.edu/docs/theses.html.

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NEW AND RENEWED PROJECTS, MARCH–SEPTEMBER 2006

Topic	Donor or Sponsor	Investigators *(Department)*
GIFTS, CONTRIBUTIONS, AND MEMBERSHIPS		
Environmental Fellowship Group Network and Mentoring for Sustainability	Martin Foundation	D. Marks *(Laboratory for Energy and the Environment)*
The Future of Coal: An Interdisciplinary MIT Study	Pew Charitable Trust Foundations	E. Moniz *(Laboratory for Energy and the Environment)*
2006 Summer Symposium: Air Quality Symposium on Vehicles, Traffic, and Transportation	American Chemistry Council; Electric Power Research Institute; The Mickey Leland National Urban Air Toxics Research Center; Mid-Atlantic Regional Air Management Assoc.; Molina Center for Energy and the Environment; National Commission on Energy Policy; New York State Energy Research and Development Authority; Northeast States for Coordinated Air Use Management; PSEG; Sunoco, Inc.; US Environmental Protection Agency	D. Marks *(Laboratory for Energy and the Environment)*
Center for Energy and Environmental Policy Research membership	Alstom Power; Aramco Services Co.; BP International; Constellation; EnBW Energie Baden-Wurttemberg AG; ENEL SpA; Essent Nederland BV; Omel, SA; MVV Energie AG; Petroleo Brasileiro SA; Shell International Ltd.; Swedish Energy Agency	J. Parsons *(Sloan School of Management)*
NEW PROJECTS		
Dynamic Simulation and Optimization of Nuclear Hydrogen Production Systems	US Department of Energy – Idaho Falls	P. Barton *(Chemical Engineering)*
Cyprus Institute Program for Energy, Environment and Water Resources	Cyprus Research and Educational Foundation	E. Moniz *(Laboratory for Energy and the Environment)*
Strategy Development for a Transition to Hydrogen Fuel Cell Vehicles	Shell International Exploration and Production, Inc.	J. Sterman *(Sloan School of Management)*
Metropolitan China: Clean Transportation Energy Futures	Alliance for Global Sustainability International	P. Zegras *(Urban Studies and Planning)*
GIS-CrossCut-MIT	Electric Power Research Institute	H. Herzog *(Laboratory for Energy and the Environment)*
Development of a Bayesian Method for the Detection of Nuclear Proliferation	Battelle Energy Alliance, LLC	M. Golay *(Nuclear Science and Engineering)*
Computer Analysis of Fuel Cycle Alternatives to Support SINEMA	Battelle Energy Alliance, LLC	M. Kazimi *(Nuclear Science and Engineering)*

NEW AND RENEWED PROJECTS, CONTINUED

Topic	Donor or Sponsor	Investigators *(Department)*
NEW PROJECTS continued		
Before a Transition to Hydrogen Transportation	CONCAWE	J. Heywood *(Mechanical Engineering)*
Before a Transition to Hydrogen Transportation	ENI SPA	J. Heywood *(Mechanical Engineering)*
RENEWED PROJECTS		
Energy Choices: Carbon Sequestration Initiative	Alstom Power Inc.; American Petroleum Institute; Electric Power Research Institute; ExxonMobil; Marathon Oil; Saudi Aramco; Schlumberger Water Services (NEW MEMBER); Southern Co. Services Inc. (NEW MEMBER)	H. Herzog *(Laboratory for Energy and the Environment)*
Engine and Fuels Research Consortium	General Motors Research Laboratories	J. Heywood *(Mechanical Engineering)*
Oil and Lubrication Research Consortium	Dana Corp.	J. Heywood *(Mechanical Engineering)*
Low-Ash Engine Emissions Consortium	Cummins; Lutek, LLC; Komatsu (NEW MEMBER); Sud-Chemie, Inc.	V. Wong *(Laboratory for Energy and the Environment)*
Before a Transition to Hydrogen Transportation	Shell International Exploration and Production, Inc.	J. Heywood *(Mechanical Engineering)*
Optimal Production and Planning of Smart Gas Systems	Shell International Exploration and Production, Inc.	P. Barton *(Chemical Engineering)*
Uncertainty Analysis of Distributed Parameter Models	Shell International Exploration and Production, Inc.	G. McRae *(Chemical Engineering)*
Data Assimilation in Reservoir Engineering	Shell International Exploration and Production, Inc.	D. McLaughlin *(Civil and Environmental Engineering)*
GM/MIT Materials and Manufacturing Systems Analysis Collaborative Research Laboratory	General Motors Corporation	J. Clark *(Materials Science and Engineering)*
Eco Efficient Supply-Chain for End-Of-Life Electronics	Hewlett-Packard	R. Kirchain *(Materials Science and Engineering)*

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Nancy W. Stauffer, editor

ISSN 1550-008X

2006-2

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