e-lab

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

July–September 1997

Options for Using China's Coal in Cars: A Life-Cycle Assessment

Chinese policymakers face a bewildering array of options as they consider using their vast coal deposits to fuel vehicles. Coal can be used to produce gasoline, methanol, or electricity. But each of those fuels has its advantages and disadvantages. MIT researchers and their Chinese and American collaborators have now estimated how shifting from petroleum to each coal-based fuel would change consumer costs, environmental impacts, and energy efficiency. Their life-cycle analyses included the complete history of each type of fuel and vehicle, from extraction of raw materials through production, use, and disposal. As expected, changing to any of the coal-based fuels would reduce efficiency, increase carbon dioxide emissions, and cost more. However, the added cost is a relatively small fraction of the total cost of owning a vehicle—except in the case of electricity, which is prohibitively expensive unless batteries improve dramatically. Effects on emissions other than carbon dioxide vary from fuel to fuel. This type of comprehensive assessment represents a methodology that can also be used to compare technology options in other fields.

IN THIS ISSUE

China is the world's largest coal producer. Yet in recent years this coal-rich nation has had to import petroleum, largely to fuel its rapidly growing transportation sector. Concerned about energy security, Chinese policymakers are now considering ways to use coal in place of petroleum, particularly as an automotive fuel. Processes exist for converting coal into gasoline, methanol, and electricity, any of which can run a car. The challenge is to identify the option that best meets the policymakers' three main goals: to minimize costs to the consumer, to minimize environmental damage, and to use the nation's domestic resources most efficiently. Unfortunately, no single option is the obvious winner on all fronts.

In 1996, the Chinese government initiated a study to clarify and evaluate the costs and benefits associated with the various options. Collaborating in the study were more than forty technical experts from MIT, Ford Motor Company, Tsinghua University, and several agencies of the government of the Peoples Republic of China. MIT's part of the work was coordinated by the Energy Laboratory and led by Malcolm A. Weiss, senior research staff member at the Laboratory. The Ford team was led by Walter M. Kreucher, manager, Advanced Environmental and Fuels Engineering, and the Chinese team by Qiming Zhu, professor at Tsinghua University.

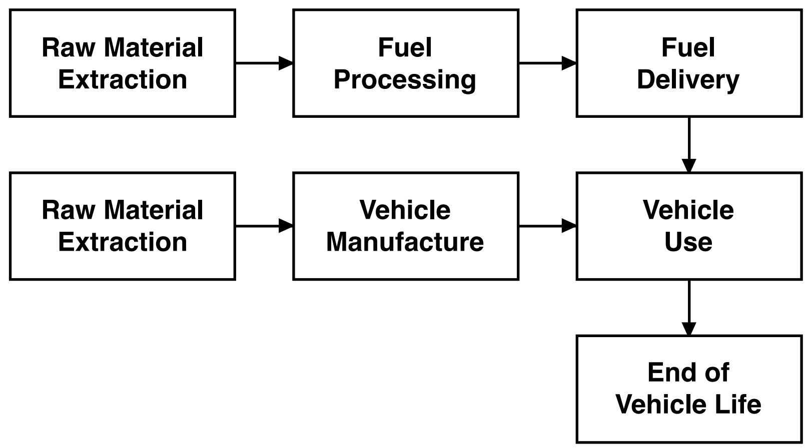
The goal of the study was not to make specific recommendations but to provide Chinese leaders with sound scientific information on the potential consequences of different approaches to using coal as an automotive fuel. The approach ultimately adopted by Chinese policymakers will, of course, take into account other societal concerns not examined in the study.

Life-Cycle Cost of Switching from Petroleum-Derived Gasoline to Other Fuels In China

Feedstock → Fuel / Cost	Petroleum → Gasoline	Petroleum → Diesel	Coal → Methanol	Coal-Bed Gas → Methanol	Coal → Gasoline	Coal → Electricity (NiMH)
Fuel Cost	Base	$(970)	$1,020	$30	$2,840	$(700)
Vehicle Cost	Base	$780	$650	$650	—	$9,650
Operational Cost	Base	—	$1,100	$1,100	—	$5,920
TOTAL	Base*	$(190)	$2,770	$1,780	$2,840	$14,870

*Total cost of base case is estimated at $40,000.

Economic, Environmental, and Energy Efficiency Assessment of Fuel Options: Major Elements Addressed in Life-Cycle Analysis



Switching from petroleum-derived gasoline to a coal-based fuel is not a simple matter. It may affect the entire history of the fuel, the car, and their use together. Therefore, the researchers performed their assessment using a technique known as life-cycle analysis. The schematic on this page shows the elements considered in the analysis. The top boxes follow the fate of the fuel—extraction from the ground, processing into a form useful in an automobile (including electricity), and delivery to the vehicle. The bottom boxes trace the vehicle's history, including extraction of the raw materials and manufacture of a vehicle suited to the fuel being assessed. The last two boxes represent the use of the fuel in the car and the disposal of the car at the end of its useful life.

To perform a life-cycle analysis of a given fuel "scenario," the researchers had to determine the economic cost, energy efficiency, and environmental impacts of each of those steps (each box in the diagram). But it is not possible to produce absolute quantitative values for all scenarios that everyone will agree on. Consider just one variable: the cost of manufacturing cars that run on methanol rather than on gasoline. Two automotive experts are unlikely to agree on the exact cost of making a gasoline car, much less the more unfamiliar methanol car. Debate will arise about even broad assumptions. (Will the cars be made in China? Will the engines be imported from Japan?) But experts can agree on *roughly* how much it costs to manufacture a gasoline car. Moreover, they can agree on generally what changes are needed to make a methanol car instead. And they can calculate how much those changes will cost or save.

The researchers therefore performed their assessment as a comparative analysis. They assumed as their base case a Ford Escort fueled by petroleum-derived gasoline, equipped with an emission-control catalyst, and operating for 12 years. (Catalysts are not used in China now because unleaded gasoline is not generally available. Both are expected to come into widespread use by the year 2000.) They then estimated the performance measures of interest: the cost to the consumer, the environmental impacts, and the energy efficiency associated with each step in the diagram. For each coal-based scenario they determined how each of those three measures would change from the base case, first within each step and then cumulatively. They thus ranked the options relative to the base case and relative to one another on each of the performance measures.

The analysis focused on fuel options of particular interest to the Chinese participants. It considered two petroleum-based fuels—gasoline (the base case) and diesel—and three coal-based fuels—gasoline, electricity, and methanol. For each coal-based option, they made certain assumptions.

- Gasoline: Coal can be converted into gasoline by indirect liquefaction (the solid coal is converted to a gas and the gas to a liquid) or by direct liquefaction (the solid coal is converted directly to a liquid). The analysis assumed indirect liquefaction using the Fischer-Tropsch technique. Direct liquefaction is also of interest and will be analyzed in a future supplement to the study.
- Electricity: The impacts of choosing electricity depend critically on the future cost and efficiency of batteries for electric vehicles. Those factors are highly uncertain. Therefore, the evaluation included battery technologies ranging from today's conventional lead-acid battery to a highly efficient battery representing the long-term goal of the US Advanced Battery Consortium. The main focus was on a medium-term technology, the nickel metal hydride battery (NiMH).
- Methanol: The vehicle assumed for this scenario was a "flexible-fuel" vehicle that operates on 85% methanol and 15% gasoline. Dedicated methanol vehicles would be feasible only when methanol is widely available throughout China. The main fuel-processing technique assumed was advanced technology involving coal gasification, then methanol synthesis. Several other minor potential sources of methanol were also considered, the most

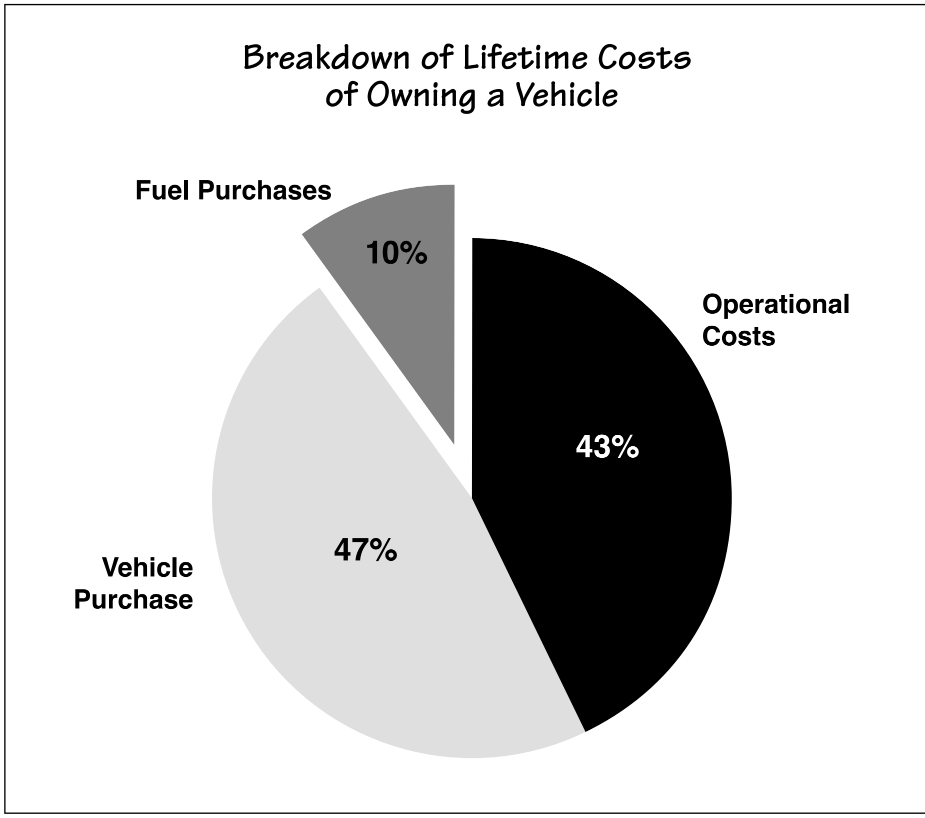
important being methanol made from methane gas that can be drawn from cracks in coal beds. While "coal-bed gas" could produce relatively little methanol nationwide, it could be an important supplementary source of methanol in certain regions.

All the data used in the study are intended to reflect conditions in China, which often differ from corresponding conditions in the United States. Chinese participants in the study provided data on costs, air emissions, and energy efficiency for each fuel scenario. Ford developed data for vehicle manufacturing and operation. The analyses were performed using a variety of existing spreadsheet-based models and computer simulations, specially tailored for this life-cycle analysis.

Chinese policymakers are concerned about energy efficiency not only because they do not want to waste resources but also—perhaps more importantly—because energy efficiency can affect both economic cost and environmental impacts. The most direct effect of energy efficiency is on emissions of carbon dioxide (CO_2): the more efficient a fuel scenario, the lower its emissions of CO_2.

To determine the energy efficiency of each fuel scenario, the analysis tracked energy input versus energy output in each step of the life-cycle diagram. Converting coal to automotive fuels is inefficient, so the lifetime energy efficiencies of all the coal-based scenarios are lower than those of the petroleum scenarios (both gasoline and diesel). Electricity does best of the coal-based scenarios because of the higher efficiency of operating electric vehicles. But that advantage is offset by the inefficiency of generating electricity from coal.

In contrast to energy efficiency, cost plays a direct and important role in deciding the attractiveness of the options. The analysis focused on cost to the consumer. What would switching to coal mean for the owner's out-of-pocket expenses during the lifetime of the vehicle? The expenses included no government-imposed taxes or fees, and



This figure shows the relative importance of the three major components of the consumer's total cost of owning a car. This cost breakdown is for a "flexible fuel" vehicle burning a blend of 85% methanol and 15% gasoline, but it is typical for all of the fuels in the study. Operating costs include insurance, maintenance, license and registration fees, parking, and finance charges. The cost of fuel represents the smallest part of the total lifetime cost of the vehicle.

costs incurred in different years were not discounted.

A consumer's total cost consists of three components: buying the car, buying fuel, and operating the car. (Operating costs include insurance, maintenance, license and registration fees, parking, and finance charges on car loans.) The table on page 1 shows how each of those components differs from the base case for each scenario, yielding a life-cycle cost differential to the consumer.

As shown in the table, the consumer's expenditure on fuel varies dramatically from scenario to scenario. However, the cost of buying fuel is a small part of the total lifetime cost associated with having a car. As shown in the pie chart above, buying fuel is only about 10% of the total cost, with the remainder split about equally between buying the car and operating it.

The total incremental costs for the non-electricity coal-based scenarios do not differ greatly—from one another or from the gasoline base case. The distributions of costs among the three components differ, but the bottom line is about the same: having a (non-electric) coal-fueled car costs $2000–3000 more than having a conventional petroleum-fueled car. That added cost, spread over the 12-year lifetime of the car, is relatively small: the total cost of a conventional petroleum vehicle is estimated at $40,000, so the variation is only about 5%.

The outcome is quite different with the electric option. Assuming an electric car with an NiMH battery, the consumer pays $700 *less* for fuel than in the base case. But that saving is offset by dramatically higher costs to buy and operate the vehicle. Overall, the consumer will pay close to $15,000 more to own and drive an electric car—a substantial increase, even spread over 12 years. And despite the high cost, the consumer will still get a car with the power and range limitations that make electric vehicles unmarketable today. Analyses of the other battery options show that the cost of switching to electricity is comparable to that of the other coal-based options only if batteries meet the Battery Consortium's long-term goals for cost and storage capacity.

Comparing the environmental effects of the different scenarios is more complex. Again, the analysis looked at emissions during the processing of the fuel and the manufacturing of the vehicle as well as "on-road" vehicle emissions, based on a standard urban driving cycle defined by the US Environmental Protection Agency. The table on this page presents detailed results for key pollutants. (The values are absolute rather than comparative to show which emission levels and changes are large enough to be of concern.)

A few generalizations can be made. Coal-bed gas is the winner in most areas—not a surprise, as starting with methane gas is always cleaner than starting with either coal or oil. As already stated, all of the coal-based options generate more CO_2 than the petroleum-based options do. Thus, the switch from petroleum to any of the coal-based fuels would further increase China's already substantial contribution to greenhouse gas emissions.

As for the other emissions (most of whose impacts are regional or local), the outcome varies from pollutant to pollutant, with no one scenario being the across-the-board winner. For example, methanol from coal generates lower sulfur dioxide and nitrogen oxides emissions than do the petroleum-to-gasoline base case and the coal-based options, but it produces lots of carbon monoxide. Electric power beats all the other options (coal and petroleum alike) on carbon monoxide and hydrocarbons, but it generates the most sulfur dioxide. Petroleum-based diesel does well in most categories but has high emissions of nitrogen oxides and particulate matter. Only gasoline from coal is relatively straightforward: it is among the worst on almost all emissions. With its high cost and high CO_2 emissions, it ranks low in the overall assessment.

The researchers did not expect to find a best option. They intended only to quantify the trade-offs for the Chinese policymakers. They do, however, emphasize that the findings depend on many assumptions. For example, if the cost of oil was higher than they assumed or if the cost of manufacturing vehicles for the coal-based fuels was lower, the economic viability of all the coal-based options would improve. They also caution that other factors must be examined. For example, for each scenario they estimated water require-

Life-Cycle Emissions Using Various Petroleum- and Coal-Based Automotive Fuels

kilograms per vehicle

Feedstock → Fuel / Emission	Petroleum → Gasoline	Petroleum → Diesel	Coal → Methanol	Coal-Bed Gas → Methanol	Coal → Gasoline	Coal → Electricity (NiMH)
Carbon Dioxide	59000	50000	76000	45000	87000	63000
Sulfur Dioxide	210	200	160	60	240	620
Nitrogen Oxides	90	130	60	50	110	70
Carbon Monoxide	140	110	330	60	110	30
Hydro-carbons	90	60	60	40	90	10
Particulate Matter	5	20	10	5	20	7

ments but not whether those requirements could be met. Land use has yet to be addressed, and a detailed examination of the technical feasibility of each option is needed. Nevertheless, the results thus far should provide a useful foundation for Chinese policymaking.

Another important contribution is the analytical methodology itself. The computer models developed are simple, flexible, and transparent so that users can easily make clear and consistent comparisons of the impacts of different technology options and can readily see the results of changing underlying assumptions such as the cost of oil. This type of life-cycle analysis can also be used in other areas in which the technology options are many, their impacts are uncertain, and their costs and benefits are variable.

This research at MIT was supported by the Ford Motor Company. Further information can be found in reference 1.

Using Optical Fibers to Monitor the Health of Concrete Structures

Bridges and other reinforced concrete structures inevitably crack before they fail. To look for cracks, owners of such structures perform periodic visual inspections—a technique that is both expensive and unreliable. Energy Laboratory and Brown University researchers are now developing a sensor that can automatically monitor concrete structures for cracking. The sensor involves an optical fiber placed on or within the concrete structure. When a crack forms, the fiber bends and light rays passing through it escape. By analyzing reductions in the light signal, the sensor indicates not only the existence of new cracks but also their sizes and locations. The sensor can detect multiple cracks all along the length of the fiber—a major advantage over other sensors being developed, which typically monitor only what happens at a particular point. Both laboratory experiments and computer simulations demonstrate the capabilities of the new sensor. Other experiments show that wrapping optical fibers around a rod produces a crack sensor that can be embedded into buried structures such as barriers for hazardous waste containment. In related work, the researchers are using chemical deposition techniques to produce optical fiber sensors that can detect strain (stretching or shortening) at a local point on a concrete structure under stress. The novel strain sensor is highly sensitive and a fraction of the cost of optical strain sensors produced by conventional means.

Optical Sensor for Detecting Cracks

A good way to monitor the condition of bridges and other reinforced concrete structures is to look for cracks. For example, the advent of widely opened cracks (several millimeters or more) after an earthquake indicates severe damage and urgent need for repair. Smaller cracks can also cause problems. Over time, water and road salt can seep in and corrode the reinforcing steel bars embedded in the concrete, shortening the lifetime of the structure. To prevent such damage, bridge owners are required by law to inspect their bridges every other year. At present, the only means of inspection is by looking. An inspector climbs over the bridge, examining the top, sides, and bottom for cracks—a method that is time-consuming, expensive, and unreliable because some cracks are missed. For buried concrete structures such as underground containers, there are no reliable techniques for detecting cracks.

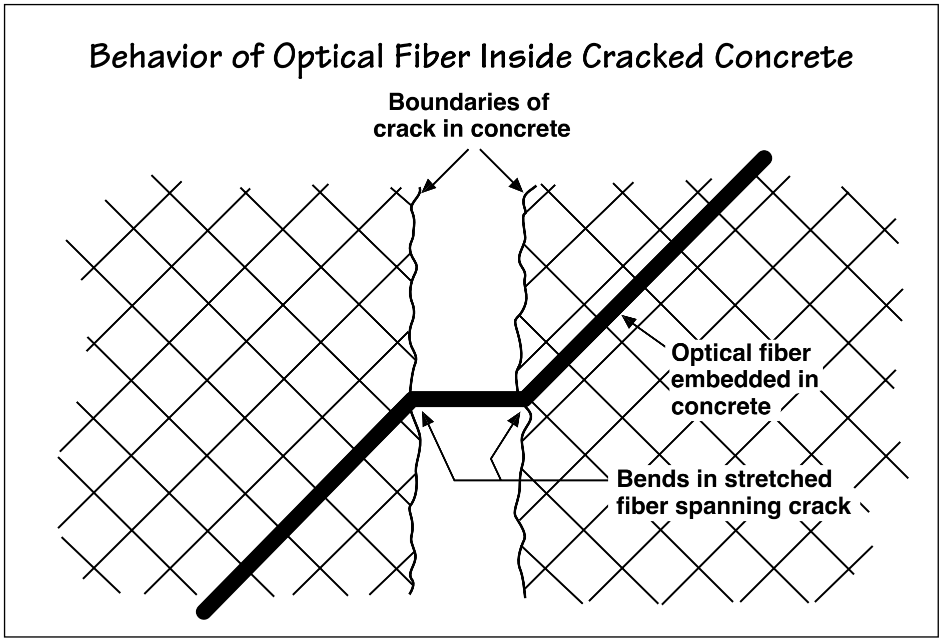
Various researchers have worked to develop sensors that can automatically detect and monitor cracks in concrete. Approaches have involved transducers, optical fibers, and other devices. But the sensors produced have limited usefulness largely because they can only detect cracks that run through them. In other words, they must be placed precisely where cracks will appear—something that no one can predict.

Now Christopher K.Y. Leung, associate professor of civil and environmental engineering at MIT, Theodore F. Morse, professor in the Division of Engineering at Brown University, and their teams of researchers have used optical fibers to develop a sensor that can detect cracks anywhere along the entire length of the fiber, not limited to a single spot. The only information needed is the general area that is vulnerable and the probable orientation of cracks—factors that often can be predicted. For example, bridges crack because downward pressure causes the surface of the bridge to compress and the bottom to stretch. Since concrete is strong under compression but weak under tension, cracks will tend to form on the underside of the bridge, running crosswise.

Key to the sensor is how a beam of light traveling down an optical fiber behaves when the fiber bends. An optical fiber is a solid glass structure consisting of two parts: a core surrounded by a cladding that has a lower refractive index. (Refractive index is a measure of how fast light travels through a material.) When a fiber is straight, a light ray travels down it by reflecting off first one side of the core and then the other. But when the fiber is bent, some of the light will hit the outside of the core at an angle such that it will not all reflect. Some of it will pass through, escaping from the fiber.

Based on years of work in the field of composite mechanics, Professor Leung and his colleagues knew that if a fiber is embedded in a material and a crack opens along the fiber, the fiber stretches in order to span the new crack. But as shown in the figure on this page, it must also bend twice, once on each side of the crack, unless the crack intersects the fiber at exactly a right angle. Thus, the intensity of light passing through a fiber embedded in a concrete structure will remain essentially constant unless a crack occurs. Then the fiber will bend, and the amount of light transmitted will abruptly drop.

A loss in signal thus indicates the formation of a crack—but not its location. To determine location, the sensor borrows a technique from the communications industry that involves measuring not the "forward" signal but "backscatter." As light passes through an optical fiber, a small amount is reflected back-



This drawing illustrates the concept underlying a novel sensor for detecting cracks in concrete structures, developed by researchers at MIT and Brown University. An optical fiber is embedded in or attached to a concrete structure. As long as the optical fiber is straight, light travels through it without escaping. But when a crack opens anywhere along the fiber, the fiber will stretch and bend to span the crack without breaking (as shown above). At the bend, some of the light passing through the fiber will escape. By monitoring and analyzing the behavior of the backscattered light, the new sensor can detect not only the formation of cracks but also their locations and sizes (see article).

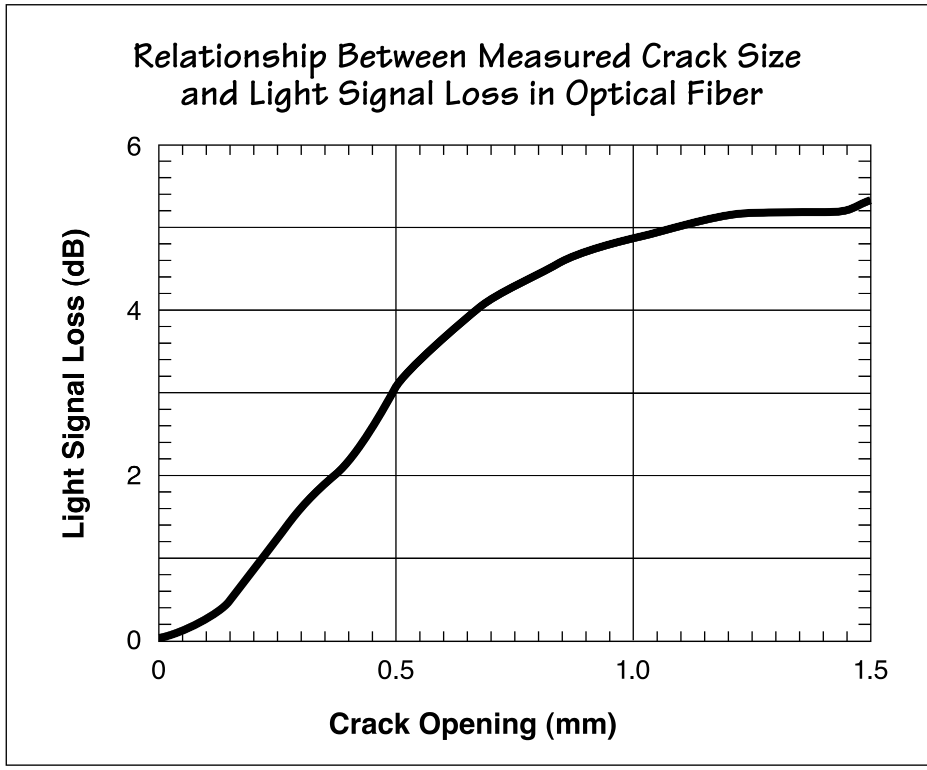
wards by nonuniformities in the glass structure. A bend in the fiber likewise reduces the backscattered signal. By feeding in quick pulses of light and monitoring the backscattered signal as a function of time, the researchers can calculate (based on the speed of light in the glass) where the loss, hence the crack, has occurred and how large the crack is. Based on subsequent losses in the signal, they can identify and locate additional cracks along the same fiber.

Optimizing the sensitivity of the optical sensor is critical. A submillimeter crack must produce a drop in intensity large enough to detect. But if that drop is too large, a few small cracks or even a single large one will reduce the signal so much that additional changes, thus additional cracks, cannot be detected. The sensitivity of the sensor depends on many parameters, including the size and mechanical and optical properties of the fiber, the thickness and stiffness of the protective plastic coating around the fiber, and the fiber layout in the structure. Achieving an optimal design by trial and error is thus impractical. Therefore, the researchers have developed a computer model that helps. Predictions from the model show good qualitative agreement with results from preliminary experiments with cracks in an epoxy block in which fibers were embedded.

Another challenge is how to use the sensor on concrete structures that are already in place. Since embedding fibers in existing structures is impractical, the researchers have developed a technique for mounting them on surfaces. They enclose the fiber in a thin polymeric sheet and glue the sheet tightly onto the concrete—tightly enough that when the concrete cracks the sheet will also crack rather than peel away. The fiber, on the other hand, is loosely attached inside the sheet so that it will slide, stretch, and bend rather than break when a crack opens.

The researchers have performed a series of experiments that demonstrate the feasibility of that technique. They glue a polymeric sheet containing the optical fiber to the bottom of a beam specimen. They then cut a notch across the specimen so the crack position is known, and they place an instrument across the notch to measure the opening directly. When a load is applied to the beam, the instrument reading and the intensity of light passing through the fiber are both recorded.

The figure to the right shows the results as a plot of light signal loss versus crack opening. Signal loss is clearly detectable at crack openings below 0.2 mm. The loss steadily increases as the crack grows until the crack reaches about half a millimeter. As the crack opens further, the loss grows more slowly and then levels off at a crack width of about 1 mm. At that width a relatively long expanse of the fiber extends straight across the crack. Since losses occur only where the fiber bends, further expansion of the opening causes little additional



In laboratory tests, the researchers have demonstrated the feasibility of their new optical fiber crack sensor. They attach the sensor to a sample beam, pulse light into the fiber, and measure the intensity of the forward signal as a crack opens, spanned by the fiber. This figure shows the loss in the signal versus the width of the crack (as measured directly). These results confirm that formation of a crack produces a measurable loss in signal. Moreover, the magnitude of the loss correlates with crack size for cracks below a millimeter in width. Above a millimeter, exact size is irrelevant because all cracks should be repaired.

loss—an advantage, as the formation of a single large crack will not necessarily mean a total loss of signal.

The researchers are using a similar concept to develop optical fiber sensors that can be installed in buried structures formed *in situ*. Of particular interest are protective barriers around hazardous waste sites. The Idaho National Engineering and Environmental Laboratory (INEEL) is developing a way to build a structure around buried waste. They drill closely spaced holes around and under the waste and then inject columns of grout. The grout penetrates the soil and forms a continuous wall and bottom. Such a structure will effectively contain any hazardous waste that moves outward—unless the structure develops cracks.

The MIT researchers are designing a sensor for detecting cracks in such structures. The new sensor is a rod wrapped with optical fibers and inserted into the holes before the grout is injected. Cracks in a column generally run crosswise, the result of the column's having been bent. The optical fibers are therefore wrapped around the rod in a spiraling fashion so cracks will intersect them at an angle and be detected. Monitoring of backscattered light will again indicate the formation and location of cracks so that failing sections can be regrouted. Using an experimental sensing rod cast into a mortar beam, the researchers have demonstrated the crack-sensing ability of their new device.

Optical Sensor for Monitoring Strain

In related work, the researchers are using optical fibers to detect another worrisome behavior in concrete structures: when stressed, structures may stretch rather than crack. A measure called strain expresses the fractional change in the length of a concrete structure due to stress. Detecting strain is vital in critical members such as prestressed concrete sections. But developing an effective strain sensor is difficult, in part because small changes are difficult to detect and even a small change in overall length may be important structurally.

One method of detecting strain uses a fiber made up of alternating segments of glass (or other materials) with differing refractive indexes. When white light, which contains many wavelengths, passes through such a fiber, some of each wavelength is reflected from the interfaces between the segments. But a narrow band of wavelengths is reflected more intensely than other wavelengths are, and the particular band of "peak reflectivity" depends on the spacing between the interfaces. If the fiber is attached to an underlying structure that stretches, the fiber will also stretch. The thickness of the alternating segments will change, so the spacing between the interfaces will change. The wavelength at which peak reflectivity occurs will then shift, and the shift can be measured. Such a fiber is an ideal strain sensor. Since changes in temperature will alter the thickness of the segments through thermal expansion or contraction, the fiber also serves as a temperature sensor. Indeed, a separate, uncoupled fiber must be used along with the strain sensor so that temperature effects on the sensor can be quantified and separated from the strain effects.

A major challenge with this approach has been how to create the segments with differing refractive indexes. The standard technique uses high-energy lasers and is very expensive. Professor Leung, Professor Brown, and their coworkers are developing a novel method that is potentially much cheaper. They use chemical deposition techniques to deposit thin layers of silicon nitride and silicon-rich silicon nitride—materials with different refractive indexes—onto the tip of the fiber. By stacking up forty alternating layers they focus the reflected light to a narrower and narrower band of wavelengths, thereby making the sensor sensitive to smaller and smaller changes in the spacing of the layers. Experiments on a layered optical fiber embedded in a polymer specimen show that the system behaves as predicted in its responsiveness to strain and temperature.

The most promising way to use this layered-tip fiber on an existing structure is to glue the fiber firmly onto a steel strip and then glue the steel strip onto the concrete section under strain. In that design, the strain over the length of the steel strip is transmitted directly to the fiber tip and detected. Results to date suggest that this novel strain sensor should be able to measure changes in length smaller than a thousandth of a millimeter.

This research was supported by the University Research Consortium of the Idaho National Engineering and Environmental Laboratory. Further information can be found in reference 2.

Special Reports

PCAST Energy Recommendations Go To Clinton

On September 30, the President's Committee of Advisors on Science and Technology (PCAST) delivered to President Clinton its report *Federal Energy Research and Development for the Challenges of the 21st Century*. More than 20 high-level executives from universities, companies, government, foundations, and other organizations served on the committee, among them Charles M. Vest, president of MIT. Jefferson W. Tester, H.P. Meissner Professor of Chemical Engineering and director of the Energy Laboratory, served as Dr. Vest's deputy.

The study was undertaken in response to President Clinton's request for recommendations on how to ensure that the United States has a national energy R&D portfolio that addresses its energy and environmental needs for the next century. A cover letter transmitting the report to President Clinton notes that the country's economic prosperity, environmental quality, national security, and world leadership in science and technology all require improving our energy technologies. Of particular concern is the development of technological options that will permit significant reductions in greenhouse gas emissions at the lowest possible economic, environmental, and social cost. An enhanced national R&D effort is needed to provide such improvements.

Accordingly, the report recommends an increase, over a five-year period, of about $1 billion in the Department of Energy's annual budget for R&D on applied energy technology. As shown in the table, spending (in constant dollars) would go from about $1.3 billion in FY 1997 to about $2.1 billion in FY 2003.

Recommended DOE Budget Authority for Applied Energy Technology R&D

in millions of constant 1997 dollars

	FY 1997 Actual	FY 1999	FY 2001	FY 2003
Efficiency*	373	584	695	755
Fission	42	63	91	102
Fossil	365	360	391	371
Fusion	232	237	262	281
Renewables	270	451	559	559
TOTAL	**1282**	**1695**	**1998**	**2068**

*End-use efficiency, which may appear as "conservation" in many budget documents.

The largest shares of the increase would go to R&D on energy efficiency and renewable energy technologies. R&D on nuclear fusion and fission would also receive increased funding. Spending on fossil-fuel technologies would stay roughly constant, but the composition of the R&D supported would change in favor of longer-term opportunities including fuel cells and carbon-sequestration technologies. In constant dollars, the average real growth rate between FY 1997 and FY 2003 would be 8.3% per year. The proposed total for FY 2003 would return DOE's real level of effort in applied energy technology R&D to about where it was in FY 1991 and FY 1992.

The report also addresses other issues including commercialization strategies, coordination of applied energy technology programs and fundamental research programs, increased emphasis on international aspects of its energy R&D portfolio, and changes that will improve DOE's management of its R&D. The committee recommends that the Secretary of Energy be designated the national leader and coordinator for developing and carrying out the national energy strategy and that the President communicate clearly to the public the importance of energy and energy R&D to the nation's future.

The executive summary of the PCAST report can be accessed on the World Wide Web at <http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html>.

Energy Laboratory's "Low-NO_X" Burner Now in Commercial Use

In the early 1990s, Energy Laboratory researchers designed a new industrial burner that could burn fossil fuels with much lower emissions of nitrogen oxides (NO_X)—precursors of acid rain and smog—than produced by conventional burners used by industry and the electric utilities. Commercial units based on that design and developed by ABB-Combustion Engineering Inc. (ABB-CE) are now being used at an industrial boiler burning oil and gas and at an electric utility boiler burning coal. At both sites, installation of the new burners on existing boilers proved fast and simple; NO_X emissions are now below the emission standards; and combustion efficiency is higher than before the retrofit. Additional installations are expected, including several at industrial and utility sites overseas.

The Radially Stratified Flame Core (RSFC) burner was designed by Majed Toqan, then principal research engineer at the Energy Laboratory and now with ABB-CE, and a team of researchers led by Janos M. Beér, professor of chemical and fuel engineering, emeritus (see *e-lab*, April–September 1992). Their design was based on a decade's fundamental and experimental research on "staged combustion," a process in which fuel is burned in two stages. In the first stage, the flame is fuel rich (oxygen deficient) and the temperature is high. Under those conditions, nitrogen coming out of the fuel converts to innocuous molecular nitrogen rather than to NO_X. However, some fuel remains unburned. Therefore, the second, lower-temperature stage is fuel lean, with abundant air that ensures that remaining combustibles burn up.

The conventional approach to implementing this concept is to create the two stages in separate regions of the combustion chamber by injecting air at several locations. But that approach creates practical problems, including the need to install air-injection ports along the combustion chamber. The RSFC burner instead uses "internal staging," a process in which all the combustion air is supplied through a single burner. The design of the fuel-injection and air-inlet nozzles produces a combination of combustion air swirl and delayed fuel mixing that creates fuel-rich and fuel-lean zones within a single flame. Injecting air downstream is therefore unnecessary. In tests in the Energy Laboratory's pilot-scale Combustion Research Facility, the RSFC burner reduced NO_X emissions by up to 90% burning natural gas, 70% burning pulverized coal, and 80% burning heavy fuel oil.

The RSFC is under exclusive license to ABB-CE. Based on mathematical modeling and experimental studies carried out at MIT, researchers at ABB-CE Services Inc., assisted by the ABB Power Plant Laboratory and members of the original MIT team, scaled up and developed the design to a commercial product. The results demonstrate the ability of MIT researchers to generate a novel concept based on fundamental studies, design and test a device based on that concept, and then work with a company to refine and adapt the device to make it flexible, reliable, and suited for use in commercial settings.

The MIT work was sponsored by ABB-CE, Babcock and Wilcox, Eniricerche SpA, ENEL SpA, Electric Power Research Institute, Empire State Electric Energy Research Corporation, Florida Power & Light Company, Southern California Edison Company, Southern California Gas Company, and the US Department of Energy.

News Items

A **ceremony and press conference** were held on July 14 in the Great Hall of the People in Beijing to announce the findings of the study, "**Economic, Environmental, and Energy Life-Cycle Assessment of Coal Conversion to Automotive Fuels**." The study involved life-cycle analyses to assess the effects on consumer cost, environmental impacts, and energy efficiency of switching from petroleum-based gasoline to coal-based fuels including methanol, gasoline, and electricity. (See the article on page 1 for additional details.) The event was covered by about 40 press agencies and TV stations and attended by 75 Chinese government officials and representatives. Speeches were given by John McTague, vice president for technical affairs, Ford Motor Company; Vaughn Koshkarian, vice president, Ford Motor Company, and president, Ford Motor (China) Ltd.; Xu Guanhua, vice chairman, State Science and Technology Commission of China; and Peng Zhigui, vice governor, Shanxi Province. Representing MIT at the ceremony was J. David Litster, vice president for research and dean for graduate education. Undertaking this project was one of the recommendations resulting from a 1995 workshop in which more than a hundred technical and policy experts from China and the United States considered ways to support China's ninth five-year plan for the development of China's automotive industry.

The **second annual review meeting** of the **University Research Consortium (URC) of the Idaho National Engineering and Environmental Laboratory (INEEL)** was held on July 29–30 in Idaho Falls, Idaho. Investigators from 21 universities in 15 states described progress on each of the 42 research projects now being funded by the URC. The primary purpose of the meeting was to report and evaluate progress on each of the projects. In addition, the meeting permitted faculty, industry, and INEEL experts to meet in an informal setting, encouraging new collaborations for additional work that may further the missions and business objectives of INEEL. The two days were organized into 12 review sessions, each covering two to four projects on a common topic in one of the consortium's three focus areas: advanced systems engineering, nuclear engineering, and environmental and ecological engineering. Each session had an evaluation panel consisting of university faculty and INEEL technical staff knowledgeable in the subjects presented. The review sessions were planned and organized by MIT, and MIT faculty chaired most of the panels. More than 200 people attended the meeting.

The **Joint Program on the Science and Policy of Global Change** held its first **Special Regional Forum on Global Change** in **Riyadh, Saudi Arabia**, on June 23–24. This forum, organized in collaboration with the Cooperation Council for the Arab States of the Gulf (GCC), the King Abdul Aziz City for Science and Technology (KACST), and the Saudi Arabian Oil Company (Aramco), focused specifically on climate change issues and policy negotiations relevant to oil exporting countries. About 70 people attended, representing major international oil concerns, with the majority of participants drawn from the Arab States. Speakers from MIT, industry, and the Saudi government gave presentations focusing on the science of global change, possible economic and ecosystem effects of climate change, economic and trade impacts of control policies, the role of oil producers in the global climate change negotiations, and other topics.

The **Energy Laboratory** is a key player in a new **strategic partnership** between **MIT and the University of Alaska** that will promote the development of appropriate technology for application in remote and complex regions such as Alaska. A major goal is to develop technologies that will make possible smaller-scale forestry, mining, and other industries that will create jobs and develop resources in remote areas while having minimal impact on the environment. Initial projects identified include timber-based products that could be economically developed on a small scale, mini-mining using local energy sources, and energy product and utilities development technology suited to use on a small scale in various remote environments. Forestry provides a good example of the concept. In much of Alaska, forestry is not economical because shipping low-value logs and wood chips from remote areas is prohibitively expensive. But with an appropriate small-scale chemical reactor, local employees could convert small amounts of wood and fiber to high-value plastics or chemicals, which could then be shipped. Capital investment would be small, permitting such operations to compete on price with larger-scale manufacturers. Under the strategic partnership, faculty at MIT and the University of Alaska will collaborate in seeking research funding from the government and industry and in performing research projects, which will benefit students at both institutions. The program will be governed jointly by a coordinating committee made up of three representatives from each university. The MIT representatives are Thomas W. Eager, POSCO Professor of Materials Engineering and head of the Department of Materials Science and Engineering; Jefferson W. Tester, H.P. Meissner Professor of Chemical Engineering and director of the Energy Laboratory; and Robert A. Brown, Warren K. Lewis Professor of Chemical Engineering and dean of the School of Engineering. Executive director of the program is Daniel I. Fine, research associate in the Department of Materials Science and Engineering.

PUBLICATIONS AND REFERENCES

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

Reports and Working Papers

Montero, J.-P. *Optimal Design of a Phase-in Emissions Trading Program with Voluntary Compliance Options*. July 1997. Working Paper No. MIT-CEEPR 97-004WP. 24 pages. $10.00

Other Publications

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NEW AND RENEWED PROJECTS, JULY–SEPTEMBER 1997

Topic	**Donor or Sponsor**	**Investigators *(Department)***
GIFTS AND CONTRIBUTIONS		
CEEPR membership	British Petroleum; New England Power Service Co.; Petroleos de Venezuela SA; Shell Oil Co. Foundation	
Joint Program on the Science and Policy of Global Change	Texaco	
NEW PROJECTS		
Center for Airborne Organic Compounds Symposium (July 1997)	Exxon Co., USA; Ford Motor Co.; Northeast States for Coordinated Air Use Management; Pennsylvania Power and Light Co.; US Dept. of Transportation	J. Howard *(Chemical Engineering)*
Sustainable Electric Strategies for the 21st Century	Alliance for Global Sustainability	S. Connors *(Energy Laboratory)*
Geographic Integration of the Western US Electricity Market	CEEPR	P. Joskow *(Economics)*
Energy Prices, Investment, and Environmental Policy	CEEPR	R. Pindyck *(School of Management)*
Embodied and Disembodied Technological Progress in US Coal Mining: Modeling the Diffusion of Longwall Mining	CEEPR	A. Ellerman E. Berndt *(School of Management)*

Lee, D., and S. Hochgreb. *Hydrogen Autoignition at Pressures Above the Second Explosion Limit (0.6-4.0 MPa)*. *International Journal of Chemical Kinetics*, forthcoming. 34 pages. $10.00

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NEW AND RENEWED PROJECTS, CONTINUED

Topic	**Donor or Sponsor**	**Investigators *(Department)***
Public Oil Wealth and Government Behavior	CEEPR	J. Poterba *(Economics)*
Semiparametric Analysis of Energy and Environmental Impacts	CEEPR	T. Stoker *(School of Management)*
Halocarbon Project: Experiments Involving Halogenated Compounds in Supercritical Water	Halocarbon Products Corp.	J. Tester *(Energy Laboratory and Chemical Engineering)*
Chemical Process Models for Supercritical Water Oxidation of Toxic Organic Materials	CFD Research Corp.	H. Herzog W. Peters *(Energy Laboratory)* K. Smith *(Chemical Engineering)*
CONTINUING PROJECTS		
Airborne Organic Compounds: Sources, Transformation and Control (in collaboration with New Jersey Institute of Technology and California Institute of Technology)	US Environmental Protection Agency	J. Howard *(Chemical Engineering)*
Detailed Mechanics and Models for PAH Formation (new project)	above	W. Green *(Chemical Engineering)*
Laboratory Studies of Intermediate Steps in the Atmospheric Oxidation of Organic Compounds	above	M. Molina *(Mechanical Engineering)*

NEW AND RENEWED PROJECTS, CONTINUED

Topic	Donor or Sponsor	Investigators *(Department)*
Investigation of the Formation of Particulate Matter in Spark Ignition Engines	above	S. Hochgreb (*Mechanical Engineering*)
Markers for Carbonaceous Emissions from Combustion Sources	above	J. Vander Sande *(School of Engineering)*
Oil and Gas Policy Office Project	US Department of Energy–Boston	E. Drake *(Energy Laboratory)*
Economic Modeling of Heat Mining Worldwide from Hot Dry Rock Geothermal Reservoirs (new project)	above	H. Herzog *(Energy Laboratory)*
Sloan Lab Consortium	Shell Oil Company	J. Heywood *(Mechanical Engineering)*

Note: CEEPR = Center for Energy and Environmental Policy Research

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Massachusetts Institute of Technology
Energy Laboratory
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