e-lab

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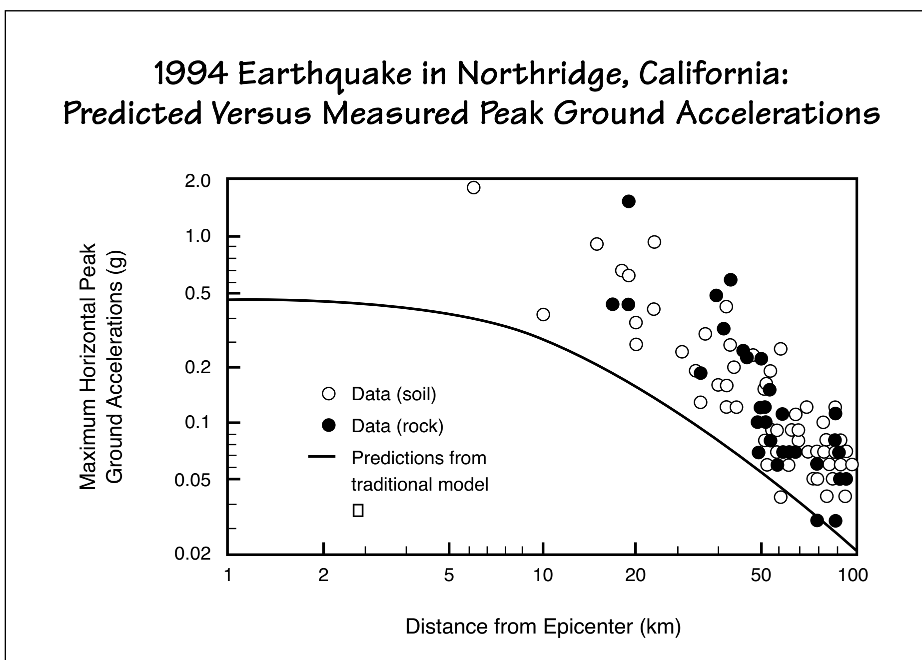
Earthquakes: How Can We Design Structures Less Likely to Fail?

During the past decade, earthquakes in California and in Japan have caused the dramatic collapse of freeways, bridges, and other structures built according to stringent earthquake-resistant design codes. A new Energy Laboratory study shows that today's building codes may be inadequate because they are based on incorrect assumptions about earthquake motions—assumptions derived when seismic data were relatively scarce. An MIT team has analyzed earthquake records gathered during the past decade and found that ground motions are more intense than previously thought possible. Moreover, they can vary substantially over short distances, producing differential motions that can endanger and even collapse large-span structures such as freeways and bridges. While theoretical simulations and scale models have been useful in earthquake engineering, they cannot accurately predict how strong ground motions cause structures to fail, hence what building codes and retrofitting techniques will prevent damage. Therefore, the MIT researchers have designed a 30-by-30-meter "shake table" that can hold a full-sized 10-story building or other large structure. Novel electromagnetic "pistons" move individual panels in the table so as to replicate the complex ground motions of an earthquake. A table-top model of the "electromagnetic seismic simulator" (EMSS) has demonstrated the feasibility of the concept. The EMSS is planned to be located at the Idaho National Engineering and Environmental Laboratory as part of a major facility for testing the responses of full-scale structures to earthquakes, wind, and aging.

Recent earthquakes in Japan and in California have been catastrophic. In 1995, an earthquake in Kobe, Japan, killed 5,500 people, injured thousands more, destroyed buildings and other structures, and caused about $200 billion in direct economic losses. In 1989 and 1994, earthquakes in California also caused widespread damage, some of it at locations 150 km from the epicenter. In all three cases, destruction far exceeded that predicted for earthquakes of such magnitudes. Damaged buildings included many that met the strictest



This figure includes 180 measurements of maximum horizontal peak ground accelerations (PGAs) taken at varying distances from the epicenter of the earthquake in Northridge, California, in 1994. The curve shows one conventional model's predictions of PGAs for an earthquake of the magnitude of Northridge. The measured PGAs generally exceed the model's predictions and show dramatic spatial variation, with neighboring points differing by as much as a factor of 5. This new understanding of earthquake ground motions confirms the critical need for updating current earthquake-resistant building codes.

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earthquake-resistant building codes in the world. Indeed, observations of the damage showed an interesting pattern: freeways, bridges, shopping malls, and parking garages—most of them built according to code—collapsed, while nearby skyscrapers and even some older, smaller buildings sustained little or no damage. Today's building codes are clearly inadequate. Revising those codes and developing techniques for retrofitting existing structures are critical before the next destructive earthquake strikes.

The failure of today's building codes shows that—despite decades of research—we still do not fully understand how earthquakes affect structures. Developing such an understanding is difficult. Theoretical techniques can predict how a structure will behave during an earthquake, but only initially. Once the structure begins to deform substantially, the relationship between the imposed forces and the deformation changes, and theory fails. To gain insights, investigators have tried monitoring the behavior of a scaled-down structure placed on a shake table that replicates the ground motions of an earthquake. However, it is difficult to extrapolate findings from such tests to full scale because it is impossible to accurately scale down simultaneously all the necessary parameters (material properties, stresses, weight, and so on). Only tests with full-scale or near-full-scale structures can yield meaningful results.

For the past two years, MIT researchers have been examining the feasibility of building a shake table that could subject a full-scale building or other structure to the forces of a real earthquake. Performing the research are collaborating teams of experts in seismology; civil, electrical, and mechanical engineering; and electromagnetic energy systems. Leading the teams are M. Nafi Toksöz, professor of geophysics and director of the Earth Resources Laboratory; Professor Eduardo Kausel, professor of civil and environmental engineering; and Emmanouil A. Chaniotakis, research scientist in the Plasma Science and Fusion Center. The researchers also work with collaborators at the Idaho National Engineering and Environmental Laboratory (INEEL), the proposed location of the full-scale shake table. The table is intended to be part of INEEL's proposed "Advanced Combined Environmental Test Station" (ACETS), a grouping of facilities that will test the response of full-scale structures to three types of natural threats: earthquakes, winds (hurricanes and tornadoes), and aging due to environmental factors such as humidity, salt spray, and solar radiation.

The first step in designing a full-scale shake table is to understand the ground motions that it must replicate. Professor Toksöz and his coworkers have analyzed data on peak ground accelerations (PGAs) measured during 15 significant earthquakes worldwide. (Strong-ground-motion instruments generally measure accelerations; velocities and displacements must be calculated from the accelerations.) Their analysis led to some unexpected observations. First, the maximum PGAs in recent earthquakes were much larger than traditional earthquake models predict. Moreover, earthquakes with similar magnitudes did not necessarily yield the same ground motions. In fact, for earthquakes with similar magnitudes at similar locations, the maximum PGA varied by factors of 2 to 5. Further analysis showed an interesting trend: as the number of measurements increases for a given size earthquake, the maximum PGAs tend to be higher. There must be isolated high local motions that are identified only when sensors are highly concentrated. The components of motion were also unexpected. At some stations the vertical accelerations—usually thought to be less important—were about the same as and occasionally greater than the horizontal.

Perhaps most surprising was the dramatic variability of ground motions over small distances. Seismologists have long recognized that waves from an earthquake can get absorbed, reflected, and redirected by geologic structures within the earth, leading to a variation in surface ground motions from place to place. Examination of recent data from closely spaced sensors shows that variations up to fivefold can occur at sites as little as 100 m apart, even for locations as much as 100 km from the epicenter. Data from the 1994 earthquake in Northridge, California, shown in the figure on page 1, demonstrate some of those findings.

Such observations explain the shortcomings of current building codes during recent earthquakes. First, the ground motions were greater than expected, thus greater than the building codes are designed for. The vertical motion was significant, yet the codes focus on withstanding horizontal motions such as sliding. And most important, the measured ground motions varied over distances comparable to the "footprints" of large structures such as freeway spans, parking garages, and shopping malls. That finding could explain the widespread damage to such structures. If, for example, all the supports of a bridge move in the same direction, damage may be minimal. However, if one corner of the bridge twists or slides in a different direction from another, the likelihood of damage or collapse greatly increases.

Examining how such motions affect structures requires a shake table unlike those now available. It must be able to carry larger loads—preferably a full-scale structure—and impose stronger forces and larger accelerations with precision. Moreover, it must be able to create complicated motions, with different forces imposed at different points on the structure being tested.

Dr. Chaniotakis and his coworkers have developed a conceptual design for an electromagnetic seismic simulator (EMSS) that can meet those requirements. The EMSS is 30 x 30 meters in surface area and can hold a 10-story building weighing 1000 tons. It can operate for 30 sec and achieve an acceleration of 1 g, a velocity of 3 m/sec, and a displacement of 0.5 m. To provide spatial variability, the EMSS is not a single table but a platform made up of multiple panels that operate independently. Each panel can shift up and down and sideways, rock front to back and side to side, and twist. The basic design includes nine panels in a three-by-three array. However, the system is modular so the panels can be arranged in any pattern. For example, to test a bridge, the panels can be placed side by side to create a long platform.

A major challenge was finding a means of moving the panels. Existing shake tables are generally driven by hydraulics—a method that does not yield the precision and flexibility needed for the large, "articulated" shake table. The MIT researchers have come up with a novel solution: they use "actuators" driven by electromagnets. Drawing on their experience with using very large magnets in fusion energy experiments, Dr. Chaniotakis and his colleagues in the Plasma Science and Fusion Center designed an actuator for the EMSS that consists of two magnets. One is a stationary hollow cylinder; the other is a rod inside the cylinder that moves up and down like a piston. Current passing through the outer cylinder generates a magnetic field. Current flowing through the central rod interacts with the magnetic field, generating a force that causes the rod to move. By altering the polarity, the researchers can make the rod go up and down. The result is a large, well-controlled force capable of moving a heavy weight. In the EMSS design, several actuators are placed on each panel, oriented in different directions. By controlling the magnetic fields in the individual actuators, the researchers can make a given panel move in all directions. Taken together, the panels can simulate the complex ground motions measured during earthquakes. Altering the pattern of motion requires changing the way electric power flows to the system—a far simpler task than changing hydraulic fluid flows.

Computer simulations prepared by Professor Toksöz and his seismology team provide extensive details on the motions resulting from earthquakes. However, performing a shake-table test requires knowing how those relatively large-scale motions translate into forces exerted on a single structure. Professor Kausel and his coworkers have therefore performed simulations that describe the propagation of seismic waves through the ground and the differential motions they create at points on the surface—points that may be only a few meters apart, thus within the footprint of a sample structure being tested on the EMSS. Other analyses examine further refinements and adjustments that are needed. For instance, as an experiment begins, a massive structure being tested will initially resist moving. Once moving, it will have a tendency to vibrate at a certain frequency or even to tip over. Indeed, the structure could begin to move the table rather than vice versa. Professor Kausel has calculated the components of such "feedback effects" that would not occur in natural systems and has defined the forces needed to offset them.

The researchers have now performed several computer simulations to evaluate the performance of the EMSS. In one simulation they modeled a full-scale 10-story building using the real signal of the Kobe earthquake. In the simulation, the EMSS consists of nine panels arranged in a square configuration. Each panel is 10 x 10 meters and is driven by three electromagnetic actuators, one vertical and two horizontal. Using their computer models, the researchers calculated the forces that the simulator must provide at the base of the building to reproduce the Kobe earthquake signal. The simulation showed that the EMSS is capable of delivering the needed forces. The calculated power and energy requirements are comparable to those used in today's fusion experiments. In fact, as designed, the power system for the EMSS can satisfy the requirements of other facilities at the ACETS site, in particular, the facilities to test the response of structures to high winds like those during hurricanes.

Because of the novel nature of the EMSS, Dr. Chaniotakis and his team have designed and built a table-top seismic simulator to demonstrate certain principles inherent in the full-scale concept. The table-top simulator is 1 meter by 1 meter and has four rectangular panels, each driven by two electromagnetic actuators. The panels move independently, though thus far only in the horizontal direction. The size of the simulator and the forces it creates are relatively small, yet the simulator demonstrates the general design of the full-scale EMSS and the spatial variability and fidelity that can be attained. Because of its modular nature, the table-top model can be disassembled and moved for demonstration purposes. Indeed, during the summer of 1996 the researchers took it to INEEL, where it operated well with a scale-model structure placed on its platform.

An important practical question is how the EMSS will affect the region around it. The researchers estimate that operating the table will produce forces equivalent to those of a magnitude 4.5 earthquake. The geology at INEEL would seem capable of handling such a disturbance: layers of hard basalt are interspersed with layers of soft volcanic ash that are ideal for damping seismic motion. Using two numerical methods and descriptions of the INEEL site geology, the MIT researchers determined that most of the ground motion caused by the shaking of the table would be confined to a small region close to the EMSS.

In the coming months, the MIT teams will continue working on various aspects of the EMSS. Tasks include adding vertical motion to the table-top model and developing a half-scale prototype of the actuator included in the conceptual design. The teams will continue to refine their computer simulations of the operation of the EMSS and the interactions between a sample structure, the table, and the ground beneath. They will investigate the feasibility of scaled-down experiments to examine certain aspects of the shake-table operation. They are also considering a "hybrid" method of seismic testing potentially applicable to the design of the EMSS. The method calls for using not only the shake table but also independent force actuators placed directly on the structure to provide further forces, perhaps in the vertical direction. The two methods would create motions of different frequencies, further increasing the accuracy with which the EMSS could replicate actual seismic signals.

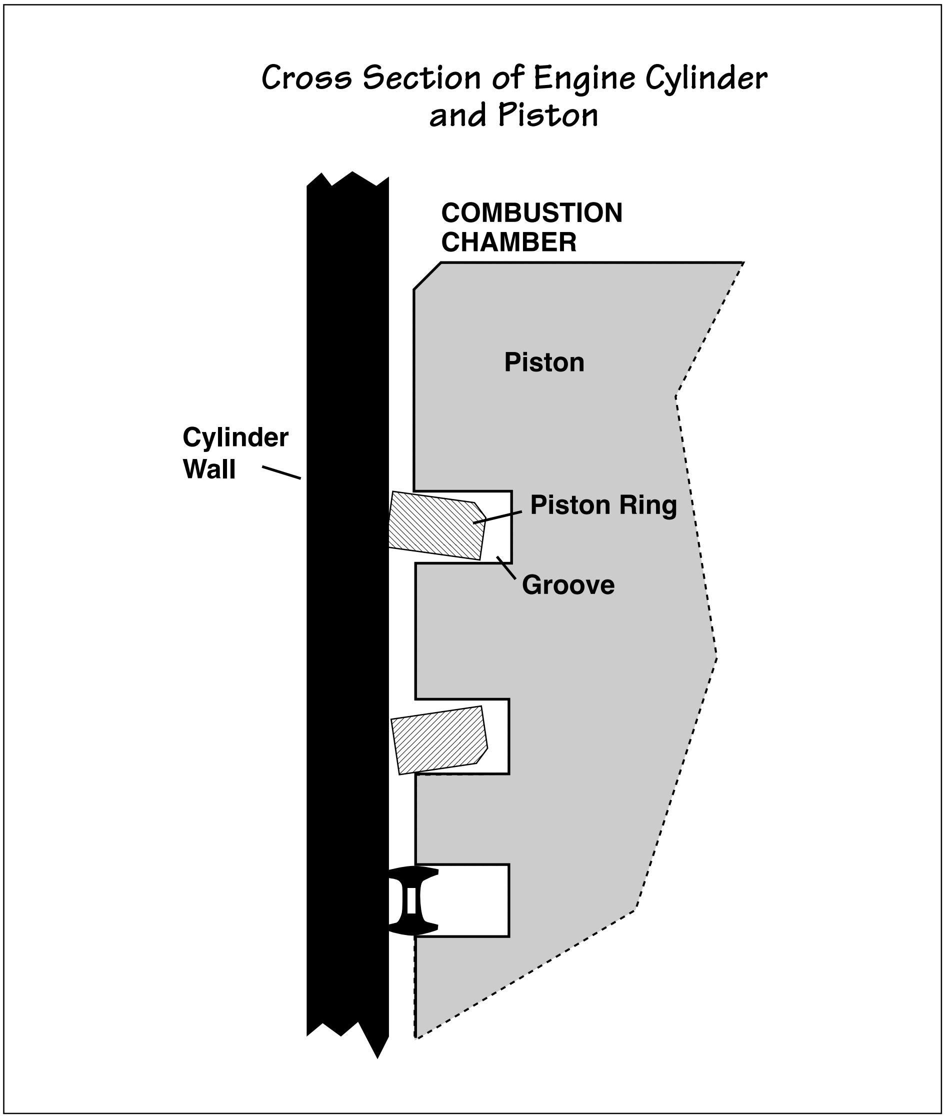
This research was supported by the University Research Consortium of the Idaho National Engineering and Environmental Laboratory. Further information can be found in references 1 and 2.

Improving Piston Engines Through Better Ring Design

A major challenge for designers of internal combustion engines is how to seal shut the "combustion chamber" at the top of the cylinder while the piston is moving up and down. Three rings are mounted on each piston and extend to the cylinder wall to form a seal. But as the piston moves, the rings shift in ways that can contribute to three major engine problems: friction, wear, and oil consumption. A detailed model developed by Energy Laboratory researchers can help engine designers identify new piston and ring designs that will reduce those problems. For a given engine design and operating conditions, the model describes how the rings move, how much friction and wear occur as they encounter other metal surfaces, and how much lubricating oil escapes into the combustion chamber, especially when the rings become unseated. Experimental studies have verified the model's ability to predict ring and oil film behavior. Using the model, the MIT researchers have defined a new friction-reducing shape for the grooves in which the rings are mounted. They have also identified a type of ring behavior that may contribute significantly to oil consumption—a behavior that can be altered by changing the shape of the rings.

As engineers try to improve today's internal combustion engine, an important place they look is inside the cylinder. Some 8% of the fuel used in automotive engines is consumed by friction related to the moving pistons. Altering the piston's design and behavior to reduce friction could improve fuel efficiency and reduce the rate at which engine components wear. In-cylinder refinements could also reduce oil consumption, making possible the use of less viscous oils—a change that would itself reduce friction throughout the engine. However, making such improvements is difficult because it requires changing the "microgeometry" of the engine, that is, the details of how the components inside the cylinder are designed and the precision with which they fit together. Given the subtlety of the changes to be made and the complexity of today's engines, engine designers must rely on computer models to test the impact of proposed changes.

In past work, Dr. Victor W. Wong, principal research scientist in the Energy Laboratory and lecturer in the Department of Mechanical Engineering, and collaborators from MIT's Sloan Automotive Laboratory and Nissan Motor Company developed a model that is now helping engine designers reduce one counterproductive type of piston behavior: "piston slap." As a piston moves up and down inside its cylinder, it also shifts from side to side, sometimes hitting one side of the cylinder wall with a hard slap. Such slapping of the piston on the cylinder wall generates noise, increases friction, and reduces fuel economy; and it can also damage the engine. For a specified engine design and operating conditions, the MIT model determines the piston's behavior within the cylinder, including where and how hard the piston



A schematic cross section of the wall of an engine cylinder, piston, and the three rings that are mounted in grooves on the piston to close the gap between the piston and the cylinder wall. A new Energy Laboratory model describes how the piston rings move within their grooves as the piston goes up and down and how their movements affect friction, wear, and oil consumption.

slaps and the amount of friction that results (see *e-lab*, January–March 1996).

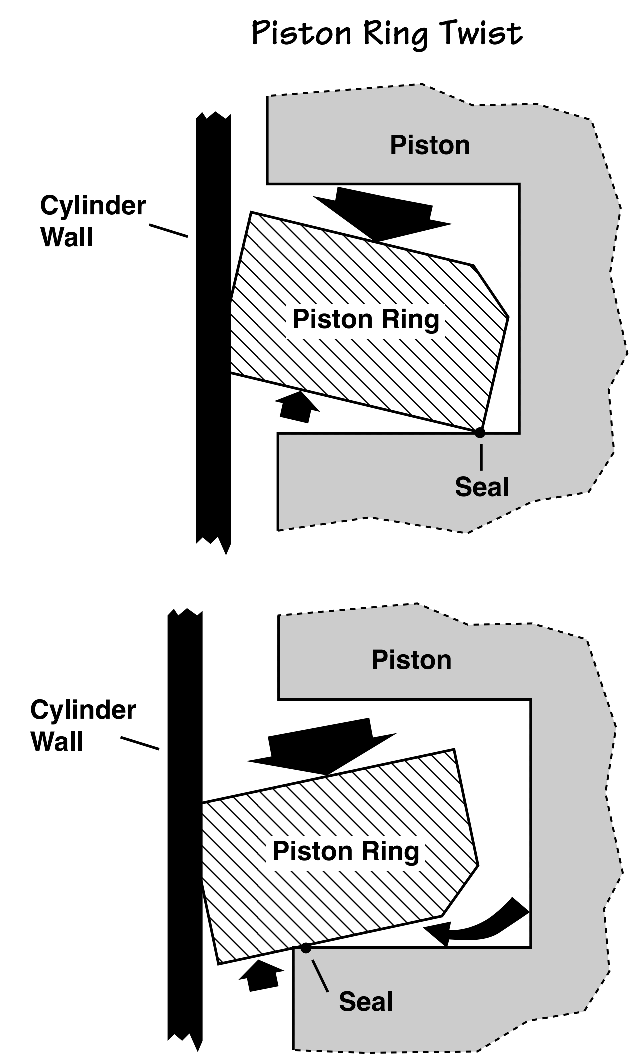
Now Tian Tian, a recent PhD graduate in the Department of Mechanical Engineering, Remi Rabute of Dana Corporation, Dr. Wong, and Professor John B. Heywood, Sun Jae Professor of Mechanical Engineering, have developed a model that focuses on an even more detailed engine component: the piston rings. In a typical engine, three metal rings are mounted on each piston (see the figure to the left). Each ring extends to the cylinder wall and slides along a film of lubricating oil on the wall as the piston moves up and down. The top ring seals shut the chamber above the top of the piston where combustion occurs, creating the high pressures needed to push the piston down. The second and third rings primarily control the flow of lubricating oil along the cylinder wall.

However, as the piston goes up and down, the rings move around in their grooves. If the rings no longer seal the combustion chamber, gases can flow around the rings, and lubricating oil can leak into the combustion chamber and subsequently burn. The movement of the rings also affects friction and wear: despite the layer of lubricating oil, the rings inevitably come in direct contact with metal surfaces, particularly the surfaces of their grooves in the piston. The wear that results can significantly alter the shapes of both the rings and the grooves. Engine designers control ring behavior by making the rings different sizes and shapes or by cutting tiny notches out of them. But a design that provides a tight seal when new may lose its effectiveness over time as the rings and grooves wear.

The new MIT model predicts not only how the rings move within their grooves for a given piston and ring design but also how that motion affects oil consumption, friction, and wear. To determine the motion of the rings, the model calculates all the forces acting on each ring. It determines the forces due to the piston's motion within the cylinder, including the effects of slap (as described by the piston-slap model) and inertial forces that arise when the piston reverses direction and the rings tend to keep going (much as a passenger jerks forward when a train stops suddenly). The model determines how the rings bend and twist and calculates the forces that tend to bring them back to their original positions (like coil springs). It also calculates the behavior of the oil films on the cylinder wall and in the ring-grooves—films measured in thousandths of millimeters—and the effects on the rings of interacting with those films. It calculates when the rings come into direct contact with other metal surfaces and the forces that result. And it tracks how gas pressures change in the spaces above, below, and between the rings and the net forces on the rings resulting from those pressures.

Based on all the forces, the model calculates precisely how each ring moves as the piston travels up and down inside the cylinder. The model predicts both how the ring moves up and down within its groove and how it twists—a feature that makes the simulation realistic and the model valuable for practical engine studies.

The figure to the right shows two examples of how a ring can twist and the implications for engine operation. The drawing on the top shows a ring twisted so that it forms a seal at the bottom surface toward the inside of the groove. When the pressure of the gases above the ring is high, the force downward on the ring is strong and the seal is tight. In the drawing on the bottom, the ring tilts so that the seal is at the outer edge of the groove. The high-pressure gases can



These drawings show examples of how a piston ring can twist within its groove. (Tops of pistons are at tops of drawings.) In the top drawing, high-pressure gases above the ring create a strong downward force, and the ring forms a tight seal with the bottom of the groove. In the bottom drawing, the gases can flow below the ring and press upward. The downward pressure on the ring is not as strong, and the ring is more likely to lift off the surface of the groove. The new MIT model predicts how the piston rings will twist under specified conditions, where and how much friction and wear will occur, and how much gas and lubricating oil will flow into and out of the combustion chamber above when the ring lifts off the groove.

now flow below the ring and press upward. The net downward pressure on the ring is not so high, increasing the likelihood that the ring will lift off the surface of the groove as the piston moves.

Having calculated each ring's detailed movements, the model then determines what those movements mean for engine operation. For example, it calculates how much of the high-pressure combustion gases or unburned fuel/air mixture escapes from the combustion chamber when a ring lifts off its groove. It also predicts the flow of gases through the tiny gap between the two ends of the ring. (A ring is not a continuous circle but rather has an opening that allows it to be mounted on the piston.) It then determines the effect of such gas flows on the layer of lubricating oil. As the gases jet through a small opening, they pick up lubricating oil from adjacent surfaces. If the gases escape downward, the oil simply returns to the crankcase to be recirculated. However, during some parts of the piston's travels, the pressure is higher below the rings than above, and gases escape upward. In that case, the entrained lubricating oil blows into the combustion chamber, where it vaporizes and burns up. The model calculates the oil losses that result.

The model also predicts how the ring's position will affect friction and wear. If the ring-groove contact occurs at a single point (as in both drawings), the layer of lubricating oil tends to be pushed aside. Metal-to-metal contact occurs, and friction and wear are high. If the ring lies flat on the bottom of the groove, the lubricant is better able to keep the ring off the surface; and friction and wear are lower. The model predicts where contact occurs, what the contact pressure is, and how much wear results. Finally, the model calculates how the friction and the gas and oil flows contribute to the forces that determine the movement of the rings.

The researchers have verified their model using three experimental approaches. They have measured the thickness of the oil film using the laser fluorescence technique they developed a decade ago (see *e-lab*, April–June 1987 and October 1989–March 1990). The experimental measurements confirm the model's ability to predict the behavior of the oil film, which is a critical input to other calculations. In other experiments the researchers mounted probes on the cylinder wall in an operating engine and measured the pressure between the wall and the piston, in particular, in the spaces above and below the top piston ring. Pressures predicted by the model match the measured pressures well—an indirect indication that the model correctly simulates the behavior of the ring and the resulting flows of high-pressure gases from one space to another. Finally, the researchers have verified the model's ability to predict wear by measuring the shapes of the rings and the grooves when they are new and after hours of operation. Tests show that the regions of the grooves where the contact pressure is highest according to the model correspond to the regions where the actual erosion of material is greatest in the experimental engine.

The researchers have now used the model in several practical studies. One focus has been reducing wear. Model simulations show that the contact pressure, hence wear, peaks at one area on the groove's bottom surface when combustion is occurring. Using the model, Dr. Tian and Mr. Rabute showed that cutting the groove at a specific angle produces a lower, more uniform contact pressure all along the bottom of the groove. Not surprisingly, the shape of that angled groove corresponds closely to the profiles of worn grooves measured in long-term engine tests.

The model has also enabled the MIT researchers to clarify and quantify a potentially important source of oil consumption. Under certain conditions, when the piston moves upward, the top ring scrapes oil off the cylinder wall and pushes it along. When the piston moves downward, a ring of oil is left behind, some of which vaporizes and burns. According to the model, such ring "up-scraping" can deposit significant amounts of oil. Precisely how much depends on how the piston is tilted and how the ring is twisted within its groove. Further analysis should identify ring designs that will reduce this oil-consuming behavior.

Finally, the researchers are using the model to examine a troublesome phenomenon known as "ring flutter." Under certain operating conditions, a ring moves rapidly up and down in its groove, never staying at the top or the bottom, sometimes for an extended period of time. The seal between the ring and the groove is never tight, so the leakage of gas and entrained oil is extremely high. Using the model, the researchers are defining the exact conditions that lead to flutter and are exploring changes in piston and ring design that may prevent it, thereby reducing oil consumption.

This research was supported by the Energy Laboratory's Consortium on Lubrication in Internal Combustion Engines, whose members are Dana Corporation, Shell Oil Company, Renault, and Peugeot PSA. Further information can be found in references 3–6.

News Items

On April 3–4, the **Center for Energy and Environmental Policy Research** held its **spring workshop**. Topics included energy futures, forwards, and arbitrage; particulate and ozone standards; evidence concerning the location of hazardous waste dumps in relation to income and minority status; possibilities for tax reform that would include an environmental double dividend; the evolution of the European natural gas market; and problems in implementing independent system operators (ISOs) in a deregulated electricity market. Guest speakers were Mujid S. Kazimi, MIT professor of nuclear engineering and head of the Department of Nuclear Engineering, who discussed disposition of Russian weapons-grade plutonium; and Paul R. Krugman, MIT professor of economics, who made remarks about the role of ideas in public policy. The workshop was attended by about fifty people from industry, academia, and government, both national and international.

On May 29, researchers from MIT and McGill University and representatives from the electric utilities, industry, and regulatory agencies attended a kick-off workshop for a **new consortium** entitled "**Transmission Provision and Pricing Under Open Access**." In the newly deregulated electric power system, all participants must have "open access" to transmission services in real time. With support from the consortium, MIT and McGill researchers are examining some of the serious questions that arise. For example, what is the best technical means of providing fair access to transmission services, given generation and demand uncertainties, potential shortages in transmission capacity, and the need to maintain system reliability? How can transmission services be priced equitably? And what incentives can be provided to encourage transmission suppliers to upgrade and expand their systems as needed? The consortium is led by Dr. Marija Ilic of MIT's Department of Electrical Engineering and Computer Science and Dr. Francisco D. Galiana of McGill University's Department of Electrical Engineering. Current sponsors of the consortium are Allegheny Power, Edison Electric Institute, and the Electric Power Research Institute.

The **proceedings of the Third International Conference on Carbon Dioxide (CO_2) Removal**, hosted by the Energy Laboratory and held on the MIT campus on September 9–11, 1996, is now available. The proceedings contains 111 papers focusing on methods for capturing and disposing of power plant emissions of CO_2, a gas that is expected to be the largest single contributor to potential global warming. The first section of the proceedings contains papers from five invited speakers who provided a context for the conference. The remaining sections focus on CO_2 separation and recovery, geological storage, ocean storage, chemical utilization, biological utilization, and additional topics including economics, fuel cycle analysis, policy and implementation issues, and comparisons with other mitigation options. Guest editor of the proceedings is Howard J. Herzog, chair of the conference organizing committee and principal research engineer in the Energy Laboratory. The Energy Laboratory is selling a limited number of copies at a price below the publisher's list price. They are available on a first-come, first-served basis, with a limit of three copies per customer. The price (including shipping and handling) is $90 for North American orders and $105 for international orders. Orders should be prepaid by check or money order (made out to the MIT Energy Laboratory) and mailed to Mary Gallagher, MIT Energy Laboratory, Room E40-473, Cambridge, MA 02139-4307, USA. Questions may be sent to Ms. Gallagher at marygal@MIT.EDU or by fax to 1-617-253-8013. Information on ordering directly from the publisher can be found on the World Wide Web at <http://web.mit.edu/energylab/iccdr3/order.html>.

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. 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.

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NEW AND RENEWED PROJECTS, APRIL – JUNE 1997

Topic	**Donor or Sponsor**	**Investigators (*Department*)**
GIFTS AND CONTRIBUTIONS		
CEEPR membership	Electric Power Development Co., Ltd.; Exxon Education Foundation; The Kansai Electric Power Co., Inc.; Vattenfall AB	
Joint Program on the Science and Policy of Global Change (new members)	American Automobile Manufacturers Association; Atlantic Richfield Company; G. Unger Vetlesen Foundation; Mobil Corporation; Shell International Petroleum (The Netherlands)	
EUP membership	Tokyo Electric Power Co., Inc.; US Department of Energy	
Energy Laboratory	The Anne H. Foster Trust	
Sloan Automotive Laboratory–Unrestricted Grant for Hybrid Vehicle Research	Ford Motor Co.	J. Heywood *(Mechanical Engineering)*

Morosan, F., and M. Kazimi. *Multi-attribute Analysis of Alternatives for Hanford Tanks Remediation System*. Nuclear Fuel Cycle Economics and Environmental Management Program Report No. MIT-NFC-TR-002, February 1997. 142 pages. $17.00

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Peralta, N. *The Process of Fuel Transport in Engine Oil.* MS thesis, MIT Department of Mechanical Engineering, Cambridge, Massachusetts, May 1997.

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NEW AND RENEWED PROJECTS, CONTINUED

Topic	**Donor or Sponsor**	**Investigators (*Department*)**
Sloan Automotive Laboratory–Unrestricted Grant for Fuels Research	YPF SA-Tecnologia Aplicada	J. Heywood *(Mechanical Engineering)*
Discretionary Gift	Generalitat de Catalunya	J. Tester *(Energy Laboratory and Chemical Engineering)*
NEW PROJECTS		
Characterization of Oil Consumption and Correlation with Lubricant Behavior and Design Parameters in Piston-Ring Pack of a Modern Passenger Car	GIE PSA Peugeot Citroen	V. Wong *(Energy Laboratory)* J. Heywood *(Mechanical Engineering)*
Laminar Flame Propagation in a Stratified Charge	Exxon Research and Engineering Co.	W. Cheng *(Mechanical Engineering)*
Assessment of Compliance Costs of Emissions Trading under Title IV of the Clean Air Act	US Environmental Protection Agency	A. Ellerman *(Sloan School of Management)*
CONTINUING PROJECTS		
Renewable Energy for Transportation and Rural Development: Biomass Pyrolysis Oil Utilization in Diesel Engines	Lockheed-Martin Energy Systems, Inc.	S. Hochgreb *(Mechanical Engineering)*

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

Tian, T. *Modeling the Performance of the Piston Ring-Pack in Internal Combustion Engines*. PhD thesis, MIT Department of Mechanical Engineering, Cambridge, Massachusetts, June 1997. **(Ref. 3)**

Tian, T., B. Noordzij, V. Wong, and J. Heywood. *Modeling Piston-Ring Dynamics, Blowby, and Ring-Twist Effects*. Presented at the 18th Annual Fall Technical Conference of the American Society of Mechanical Engineers, Internal Combustion Engine Division, Fairborn, Ohio, October 20–23, 1996. 14 pages. $10.00 **(Ref. 4)**

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