Straw-Based Insulation for Pakistan: Addressing the Needs of Developing Regions

In remote, mountainous regions of northern Pakistan, buildings are typically made of uninsulated stone or cement block. Wood and other fuels are scarce, and indoor temperatures in winter are frequently only a few degrees above those outdoors. A straw-based insulation developed by Energy Laboratory researchers in MIT's Building Technology Program could help boost those temperatures while saving fuel. Drawing on a technique developed by ICI Polyurethanes, the researchers place milled straw inside a tumbler with a central nozzle that sprays fine droplets of an adhesive onto the tumbling straw. Once coated, the straw is removed, placed in a frame, and pressed and heated. The straw boards produced can be installed on interior walls; and they have the insulating value of expanded polystyrene, the only other rigid insulation available in Pakistan. Half the cost of polystyrene, the straw insulation could be made in local factories using local materials, simple machinery, and little energy. Only small amounts of adhesive would have to be imported. Case studies at four Pakistani schools show that installing straw insulation could cut energy requirements by half or more. The methods developed here could be applied in many developing areas using straw or other available waste materials.

Three years ago, a team of Energy Laboratory researchers in MIT's Building Technology Program went to northern Pakistan to help villagers determine how to upgrade their homes, schools, and other buildings. Based on surveys of occupants and measurements taken in buildings, the team made a simple recommendation: install insulation. Most A classroom in Dahnyore High School in Gilgit, a town in mountainous northern Pakistan. The uninsulated cement block construction is typical of buildings in this region and does little to protect inhabitants from the cold temperatures of winter. Energy Laboratory researchers have developed straw-based insulation that can be made locally and installed on the interior of such buildings, helping to keep temperatures up while saving scarce firewood and other fuel.
of the buildings have walls of uninsulated stone or concrete block—materials that provide little protection against the cold temperatures of winter in this mountainous region. People burn firewood for heat, but wood is scarce and indoor temperatures are often only a few degrees above those outdoors. Indeed, schools become so cold that they are unusable for several months in the winter. Adding insulation would both improve living conditions and conserve scarce resources.

While the researchers’ recommendation was straightforward, carrying it out was not. The stone or concrete walls of the local buildings are a single layer with no interior cavity, so using loose fill insulation is not feasible. The only option is rigid insulation that can be fitted or retrofit on interior walls, where it would be protected from the harsh weather. Rigid expanded polystyrene insulation is available in more developed areas of Pakistan and could be trucked to these remote villages, but the cost would be high.

The researchers—Leon R. Glicksman, Leslie K. Norford, Joseph A. Charlson, Henry S. Harvey, and Gregory P. Sullivan—therefore set out to develop boards or panels that could be made on-site from waste (or near-waste) materials by the local people using simple machinery and little energy. As their primary material, the researchers selected straw, a wheat-threshing by-product that is abundantly available at little cost in Pakistan. Straw has long been used worldwide in construction, generally in compressed form as structural boards. However, making a straw-based board that is both strong and insulating posed new challenges. Straw fibers conduct heat more readily than air does, so insulating value will be highest if the board contains little straw and lots of air, preferably trapped in tiny pockets so it cannot circulate and transfer heat. But the insulating board must also be strong enough to support itself during construction and to resist damage at its surface—requirements best fulfilled by using more straw and less air. The challenge, then, is to create a straw board that has low enough density to be a good insulator but high enough density to be sufficiently strong—all at an acceptable cost.

Guided by theoretical models, the researchers considered various ways of making insulation from straw. One approach is to mix straw with an adhesive (glue) to make a pulp feedstock. The result would be a strong, homogeneous board—but without the optimal distribution of air pockets and straw fibers. The researchers therefore tried shredding the straw in a hammer mill, spraying or foaming adhesive onto it, and then forming the final shape. But when the amount of adhesive used was low enough for costs to be acceptable, the samples produced were fragile and flaky.

The problem was uneven distribution of the adhesive; some areas received clumps of adhesive and other areas none at all. To solve that problem, the researchers turned to a technique developed by ICI Polyurethanes for spreading fine layers of adhesive onto particles. The shredded straw is placed in a large tumbler. A fine nozzle at the center of the tumbler sprays tiny droplets of a high-performance ICI adhesive, methane di-isocyanate (MDI), into the tumbler straw. The straw, now coated with a fine layer of adhesive, is removed from the tumbler, placed into a framework, and pressed while being heated.

Working with ICI personnel, the MIT research team produced samples of straw insulation with varying densities and adhesive contents. Thermal and structural tests showed that samples with densities of 128 kg/m³ and 160 kg/m³ and adhesive contents as low as 2–4% by weight are insulating and strong. The sample boards have insulation ratings of R4 and R3 per inch, respectively—values typical of the better air-based insulations such as expanded polystyrene, fiberglass, and cellulose. (Modern insulation can have R values up to 7 per inch, but they contain a low-conductivity gas rather than air—not an option here.) The sample boards are stronger in compression than widely used boards such as expanded polystyrene and rigid fiberglass; and the higher-density samples have a bending strength equal to that of extruded polystyrene, a material used in forming concrete foundations and placed under footings. Removing fine particles before processing the straw would further increase the compressive and bending strength of both boards without affecting their thermal resistance.

Economic analyses showed that the straw insulation would cost less than half as much as the polystyrene insulation would cost for a given insulating value. Moreover, unlike the polystyrene insulation, the straw insulation could be made in local facilities using local materials. Only the MDI adhesive would have to be imported. Although MDI is a relatively expensive adhesive, the small amount used makes the purchase cost tolerable for many applications. And the shipping cost for only the MDI adhesive will be much lower than that of a finished insulation product such as polystyrene since shipping costs are largely based on volume.

To assess the energy savings from using the insulation, the researchers surveyed and then simulated energy performance at four Pakistani schools with different designs and wall constructions. Energy use was based on a target temperature of 17°C (63°F). The efficiency of wood stoves was estimated to be 50%; infiltration rates were estimated from measured air tightness and available wind-speed data; and classroom occupancies noted in the site surveys were incorporated into the simulations. The simulations included an uninsulated base case and a series of scenarios in which insulation was placed on various external walls, internal corridor walls, and ceilings.

The figure on page 3 shows the estimated energy needs at one building of the Ahmedabad School, located in the Hunza Valley of Pakistan’s Northern Areas. The building includes three classrooms, one office, and a hallway. Comparison of the insulation scenarios with the uninsulated base case shows that applying insulation could reduce...
To determine potential energy savings from using straw-based insulation, the researchers simulated energy performance at a school in northern Pakistan with and without insulation. The simulations include the current uninsulated base case plus five scenarios in which insulation is placed on specific walls (external and internal) and on the ceilings. In all cases the insulating value is assumed to be R10. As these data show, insulating external walls as well as ceilings can bring dramatic reductions in consumption of heating energy, which is normally supplied by firewood.

The calculated payback period for the straw insulation varies from school to school. Depending on the school and the insulation scenario selected, the cost of buying the necessary insulating board is offset by savings from reduced firewood purchases in 3 to 8 years. The cost of attaching the insulation to the stone or concrete walls and giving it a plaster finish coat—in both cases using special methods developed by the MIT researchers—lengthens the payback period. Considering the cost of the insulation plus labor and materials for installing it, the payback period ranges from 4 to 11 years. Comparable values for the polystyrene insulation are almost twice as long. Comparing the use of straw as insulation with its use as a fuel to heat the building, the payback of the insulation in energy savings is less than one year.

While results thus far are promising, more work is needed to make the straw insulation a practical option for the people of northern Pakistan. Given added financial support, the researchers would next develop a low-cost tumbler and an MDI sprayer that could be used inexpensively and safely in Pakistani villages. They would perform field tests of the new insulation to assess its installed thermal and structural performance and its long-term durability. And they would continue theoretical and experimental work to improve the insulation itself.

In the longer term, the processes used for shredding the straw, applying the binder, and forming the strong, porous boards could be used with other feedstocks—indeed, with whatever low-value fibrous materials are available in a given region. Thus, locally made, inexpensive insulation could become available in other parts of the developing world, improving living standards while reducing energy use and related environmental and climate effects.

Leon R. Glicksman is a professor of building technology. Leslie K. Norford is an associate professor of building technology. Joseph A. Charlson, Henry S. Harvey, and Gregory P. Sullivan received their SM degrees from the Department of Architecture in June 1997, February 1997, and June 1995, respectively. This research was supported by ICI Polyurethanes; the American Society of Heating, Refrigerating, and Air-Conditioning Engineers; and the Aga Khan Housing Board for Pakistan. Further information can be found in references 1–3.
New vehicles with direct-injection spark-ignited (DISI) gasoline engines offer high power and fuel efficiencies fully 30% higher than those of conventional gasoline engines. The high efficiency of DISI engines stems from their ability to run “fuel lean,” that is, with a lower fuel-to-air ratio than used in conventional engines. Smooth ignition, however, requires a relatively “fuel-rich” mixture. The challenge in DISI engines is therefore to capitalize on the lean part while ensuring a strong fuel-air mixture at the spark plug. To provide adequate fuel vaporization and transport to the ignition source, many designs use high-pressure fuel injectors that provide swirl to the liquid fuel as it enters the combustion chamber, creating a hollow cone of droplets that stays airborne long enough to vaporize. However, Energy Laboratory experiments in a transparent test engine show that the injected fuel may not always form a hollow cone. When fuel temperatures are high or pressures in the combustion chamber are low, the hollow cone can become filled in and more jet-like—especially when the burning mixture contains components with low boiling points, as does gasoline. The researchers’ explanation? When the mixture enters the combustion chamber, the low-boiling-point components suddenly vaporize with enough force to shatter the liquid film. The tiny droplets that result are sucked into the center of the disintegrating hollow cone. The MIT research findings should help engine designers optimize the geometry of the combustion chamber to ensure complete vaporization and easy ignition under all engine conditions.

In a conventional spark-ignition engine, fuel is injected into a hot holding area, the “intake port,” before it enters the combustion chamber (the area inside the cylinder above the piston, where combustion occurs). As a result, much of the incoming fuel is vapor and thus easily ignited when the spark plug fires. However, the fuel may not fully vaporize in the intake port; and it may not completely mix with the air inside the cylinder before the spark plug fires. Conventional spark-ignition engines therefore need extra fuel to ensure ignition—a requirement that significantly reduces fuel efficiency.

Today’s new DISI engines are designed to solve those problems. Liquid fuel is injected directly into the combustion chamber. By carefully designing the injector and the shape of the combustion chamber and top of the piston, designers induce flows that push the injected fuel toward the spark plug but along an indirect route that provides time for the liquid to vaporize. The injected mixture thus becomes “stratified”: it is fuel-rich near the spark plug for easy ignition and fuel-lean elsewhere inside the combustion chamber. The direct-injection approach thus permits overall fuel-lean operation for high efficiency as well as other advantages including smooth acceleration, high maximum power, and potential emissions benefits.

Several companies have now introduced DISI models, with considerable fanfare about their high efficiency and other attributes. Yet research on this emerging technology continues. At MIT, Energy Laboratory researchers led by Simone Hochgreb have been investigating basic processes that may interfere with vaporization and stratification under some conditions, with potentially serious negative impacts. Incomplete vaporization can mean incomplete combustion, unburned fuel, and high emissions of hydrocarbons and particulate matter. And unsuccessful stratification can mean that the mixture near the spark plug is not sufficiently fuel rich for ignition.

Designing a system that will prevent those outcomes is tricky. Putting the injector near the spark plug ensures sufficient fuel for ignition, but the fuel does not have time to vaporize completely and tends to foul or wet the spark plug. A new approach is therefore to place the injector and spark plug farther apart. The three drawings in the figure on page 5 show a concept implemented by Mitsubishi. First the fuel enters the combustion chamber. Then it impinges on the top of the rising piston and begins to vaporize. Finally, it arrives at the spark plug in time for firing. Unusual piston-head contours and special injectors help to create tumbling or swirling flows that carry the injected fuel along the desired pathway.

Developing all the details of such a system has required decades of theoretical and experimental work. Yet one aspect of direct-injection operation may have received short shift. How does the fuel travels inside the combustion chamber depends on the precise nature of the spray as it enters. How many droplets are there, how big are they, and how do they behave? Current designs are based on answers to those questions gathered in bench-scale equipment operated at room temperature. But the hot, high-pressure environment of the combustion chamber may change that picture. Professor Hochgreb, Brad VanDerWege, and Michael Shelby have therefore been working to define the physical characteristics of the incoming fuel spray in an operating engine. They perform their experiments inside a transparent single-cylinder test engine consisting of a square piston that moves within a square “cylinder” with parallel glass walls that serve as windows for optical access (see e-lab, July–September 1994). To observe the entering spray, they use a technique called planar laser-induced fluorescence (PLIF). A laser beam is focused through a third, small quartz window. The burning mixture is
“doped” with a compound that fluoresces in the laser light. The intensity of the fluorescence indicates the concentration of the dopant in liquid and vapor form. By creating an illuminated plane with the laser, the researchers can take photographs of the fuel’s location as the engine operates.

Fuel is injected through a high-pressure, swirl fuel injector. The injector is designed to create relatively small droplets that vaporize quickly and to give rotational movement to the fuel so it enters as a wide, hollow cone rather than a narrow, focused jet that would quickly reach the opposite wall. A thermocouple measures temperature in the cylinder head near the tip of the injector—an approximate measure of the temperature of the incoming fuel.

Early tests involved burning iso-octane, a component of automotive fuel, and acetone, a lower-boiling-point compound that fluoresces. The results were unexpected. The PLIF photos on page 6 show cross sections of the incoming spray at two inlet fuel temperatures (30°C and 90°C) and at three combustion chamber air pressures (0.3, 0.6, and 0.9 bar). (Conditions are described in terms of the air pressure inside the intake manifold, which delivers air to the combustion chamber at a controlled pressure. In this case, the manifold air pressure is roughly equal to the combustion chamber air pressure.) Each image was taken when the piston was halfway up the cylinder. The top left image, taken at 30°C and 0.3 bar, shows the expected hollow-cone structure—the structure observed in bench-scale, cold equipment. But in the lower left image, taken at the same pressure but at 90°C, the hollow-cone shape disappears. At the two higher pressures, the cone is again visible; but it is still somewhat disrupted at the higher temperature. Thus, when the temperature is high or the pressure is low, the fuel spray can take on a distribution that is not what designers have in mind as they optimize their direct-injection geometry and flows.

Because PLIF does not differentiate between vapor and liquid, the researchers could not directly determine the physical form of the material in the center of the cone. Is acetone vapor being entrained, or are acetone droplets also being brought in? To find out, they turned to a diagnostic technique called Mie scattering, in which a light shining on a cloud of material scatters wherever droplets are present. Those experiments confirmed that the material filling the cones does include droplets. Moreover, theoretical analysis based on the scattering images suggests that the mean droplet diameter in the case of the filled cone is roughly half the mean droplet diameter in the case of the cold hollow cone.

The researchers believe that their unexpected observations are caused by a process they call “disruptive vaporization.” Acetone boils at about 56°C, compared to 99°C for iso-octane. As the fuel enters the hot combustion chamber, the more volatile acetone suddenly vaporizes, with enough force to shatter the rest of the mixture into small droplets. The large droplets that form initially have sufficient momentum to follow their own trajectory; they are unaffected by airflows and create the hollow-cone

Injecting fuel directly into an engine’s combustion chamber poses two challenges: giving the fuel droplets time to vaporize and getting most of the fuel to the spark plug in time for ignition. The drawings to the right show Mitsubishi’s solution. Fuel is injected relatively far from the spark plug as the piston rises. Flows inside the chamber carry it to the top surface of the piston and then up to the spark plug. The relatively long pathway and the hot environment ensure that most of the fuel will be vapor when ignition occurs.
According to that theory, disruptive vaporization would be less likely with compounds that are less volatile, that is, that have higher boiling points (at normal pressure). To test that idea, the researchers performed experiments with two other fluorescing dopants: 2-butanone, which boils at 80°C, and 3-pentanone, which boils at 102°C. The array of photos on page 7 were taken during tests at 90°C. (The acetone results are repeated for comparison.) Clearly, the higher the boiling point of the dopant, the less disrupted the cone is.

Based on their experimental results and theoretical modeling, the researchers can estimate when disruption will occur. Their estimate is based on the “bubble point,” the temperature at which bubbles start to form in a multicomponent fuel because the lightest component is beginning to vaporize. According to their analysis, when the temperature of the fuel is about 20°C above the mixture’s bubble point, vaporization will be vigorous enough to affect the structure of the spray, disrupting the hollow-cone structure. In the images on page 7, significant disruption is evident when the difference between the bubble point and the fuel temperature (shown as ΔT) exceeds 20°C.

Gasoline itself is, of course, an extremely complex mixture that contains thousands of compounds with widely varying boiling points. Using PLIF to understand the fate of injected gasoline is difficult because only very heavy compounds in the mixture fluoresce. Mr. VanDerWege therefore created a simplified “surrogate” gasoline. He combined just five compounds with different volatilities to form a mixture that has the same distillation curve (mix of boiling points) that gasoline does. The compounds do not fluoresce, so they will not show up in a PLIF image—a feature that Mr. VanDerWege used to his advantage. In a series of experiments, he replaced three of the compounds (one at a time) with fluorescing dopants that have similar boiling points. The resulting PLIF images show where compounds with different volatilities go after they leave the injector.

The results were consistent with the disruptive vaporization theory. As temperatures go up and pressures go down, the heavier compounds remain in the hollow-cone structure while the lighter compounds fill in the middle. When temperatures are sufficiently high and pressures sufficiently low, the cone structure is replaced by a relatively straight jet. Even so, the more- and less-volatile components are separated, with the lighter materials in the center and the heavier ones more spread out.

The MIT researchers’ findings are significant for designers of DISI engines.
Effect of Dopants with Different Volatilities on Fuel Behavior

Dopant:
- Acetone ($T_b = 56^\circ$C)
- 2-butanone ($T_b = 80^\circ$C)
- 3-pentanone ($T_b = 102^\circ$C)

Intake Manifold Air Pressure

These images show the behavior of iso-octane plus three dopants with different boiling points ($T_b$) as the mixtures are injected into the firing test engine. Fuel temperature at injection is constant at 90°C. The heavier dopants tend to stay in the cone-shaped structure except at the lowest air pressure. Calculations suggest that the cone structure is disrupted when the difference ($\Delta T$ in these images) between the bubbling point (the temperature at which the lightest component begins to vaporize) and the fuel temperature is greater than about 20°C. Under those conditions, the lightest component vaporizes with enough force to break the rest of the mixture into tiny droplets, which are pulled into the center of the disintegrating cone.

Given the observed effects of temperature and pressure, designers must find new ways to control the motion of smaller fuel droplets and more abundant vapor—a different task than influencing the large droplets they expected. On the other hand, the new insights may lead to novel design approaches. After all, smaller droplets vaporize more quickly than large ones. Disruptive vaporization could thus be an advantage. All in all, the findings from MIT provide designers of DISI engines with new food for thought.

Simone Hochgreb is an associate professor of mechanical engineering. Brad VanDerWege is a PhD candidate in the Department of Mechanical Engineering. Michael Shelby received his SM degree from that department in June 1997. This research was supported by the US Department of Energy. Additional support came from Zexel, Inc., and from the Energy Laboratory’s Engine and Fuels Research Consortium, whose members are Chrysler Corporation, Ford Motor Company, General Motors Corporation, Mobil Corporation, Peugeot SA, Renault SA, Shell Oil Company, and Volvo Car Corporation. Further information can be found in references 4 and 5.

News Items

Richard L. Schmalensee, director of the Center for Energy and Environmental Policy Research (CEPR), has been named the seventh dean of the Sloan School of Management. Professor Schmalensee is the Gordon Y Billard Professor of Economics and Management at Sloan. His research focuses on industrial organization, regulation, and managerial economics; environmental policy; and electric utility industry structure and regulation. He is a noted expert on emissions trading and issues of global change. He served on the Council of Economic Advisers in the White House under President George Bush and also on the Environmental Protection Agency’s Environmental Economic Advisory Committee, chairing its Advisory Council on Clean Air Act Compliance Analysis.

On November 19–20, the CEEPR held its fall workshop. Topics included experience with new electricity markets in California and the Midwest; the long-term evolution of energy prices; technology in climate change policy; coal productivity; nitrogen oxides emission reduction and trading under Title IV; and carbon dioxide/energy income elasticities. Attendees included 77 representatives from industry, government, and academia. Guest speakers were James M. Poterba, Mitsui Professor of Economics at MIT, who discussed the changing composition of retirement saving in the United States, and Kevin Cook of the US House Commerce Committee, who discussed energy and environmental issues in the 106th Congress.

Professor of Civil and Environmental Engineering Herbert H. Einstein has received the Müller Award from the International Society for Rock Mechanics (ISRM), a professional society with 5,500 members from 42 nations. Professor Einstein, who received the award “in recognition of his distinguished contributions to the profession of rock mechanics and rock engineering,” will deliver the Müller Lecture at the 1999 ISRM Congress in Paris. Professor Einstein participates in Energy Laboratory research on geengineering for energy recovery and is associated with the National Advanced Drilling and Excavation Technologies Program.
SPECIAL REPORT:
Electric Utility Program Refocuses, Disbands

This fall—aafter a twenty-year run—Professor Jefferson W. Tester, director of the Energy Laboratory, and Mr. Stephen R. Connors, director of the Electric Utility Program (EUP), decided to disband the EUP. In recent years, rapid changes in regulation of electric industries in many regions have led to a dramatic shift in how electric utilities view research, especially in a collaborative academic environment. Utilities have become less able to pursue collaborative research as time horizons have shortened and some vertically integrated companies have restructured.

While the EUP will no longer officially exist, the Energy Laboratory continues to be active in several areas of electric industry research. Mr. Connors continues to direct the Energy Laboratory’s Analysis Group for Regional Electricity Alternatives (AGREA), which currently is developing energy assessment models to explore cost-effective low-emissions energy strategies in Switzerland, Japan, and China. (Look for a description of these research initiatives and their latest results in an upcoming issue of e-lab.) Mr. Connors is also assisting Dr. Marija Ilić with her latest research consortium, “New Concepts and Software for Competitive Power Systems,” and Dr. James Weaver with his continuing research on biophysical mechanisms associated with electromagnetic field exposure.

The EUP began in the mid-1970s and over the years provided an international group of electric utilities, power equipment manufacturers, and related companies with workshops, research, and analysis relating to combustion, environmental performance, transmission and distribution, and—in later years—competition-oriented topics. From 1984 through 1996 the EUP had more than two dozen members from the United States, Canada, France, Germany, Sweden, Italy, Spain, Venezuela, Japan, Taiwan, and South Korea. More than a hundred workshops and conferences were held.

Although the restructuring of electric industries was well under way in other countries by 1994, it was not until the submission of deregulation legislation in the United States (California in particular) that the EUP began to see significant shifts in member participation and support for collaborative research. As electric utility research departments were significantly reduced—and in some cases eliminated—we recognized that basic research was shifting to technology providers. Therefore, we decided that it would be more productive to pursue more narrowly focused collaborations such as Dr. Ilić’s research on open access transmission and the Energy Laboratory’s Energy Choices Program (including AGREA), led by Dr. Elisabeth M. Drake. We plan to develop new research initiatives as opportunities arise.

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 E40-473, Cambridge, MA 02139-4307, only if a price is assigned and only if prepaid by check payable to “MIT Energy Laboratory.” Prices are postpaid surface mail. For air delivery, add 15% to US, Canada, and Mexico, and 30% elsewhere. A list of publications is available on request.

Publications marked by an asterisk (*) can be found on-line via the following addresses:

Energy Laboratory:
http://web.mit.edu/energylab/www/
Center for Energy and Environmental Policy Research:
http://web.mit.edu/ceepr/www/
MIT Joint Program on the Science and Policy of Global Change:
http://web.mit.edu/globalchange/www/

Instructions for ordering paper copies of other Center and Joint Program publications are also available at those sites or by telephoning 617-253-3551 for Center publications and 617-253-7492 for Joint Program publications.

Reports and Working Papers


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- Development of Boron Neutron Capture Synovectomy for the Treatment of Rheumatoid Arthritis: INEEL URC, J. Yanch *(Nuclear Engineering)*
- Center for Airborne Organics 1998 Summer Symposium: Costs and Benefits Estimation in Air Quality Regulations: California Air Resources Board, J. Howard *(Chemical Engineering)*
Performance of Exterior Envelopes of Buildings III, Clearwater Beach, Florida, December 7–11, 1998. 20 pages. $10.00 (Ref. 3)

Herzog, H. Ocean Sequestration of CO₂—An Overview. Presented at the Air and Waste Management Association Conference on Global Climate Change, Washington, DC, October 13–15, 1998. 8 pages. $10.00*


VanDerWege, B., and S. Hochgreb. The Effect of Fuel Volatility on Sprays from High-Pressure Swirl Injectors. Presented at the Twenty-Seventh International Symposium on Combustion, University of Colorado at Boulder, August 2–7, 1998. Publication no. 2E08. 12 pages. $10.00 (Ref. 5)

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