Research **Frontiers**

FOR THE CHEMICAL INDUSTRY

report on

The Third Annual CHF–SCI Innovation Day Warren G. Schlinger Symposium

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Innovation Frontiers in Industrial Chemistry

A Report on the Third Annual CHF–SCI Innovation Day 21 September 2006

SUMMARY

Competition is becoming ever fiercer in the chemical industry as new firms from such emerging economies as China and India enter the market and as technological advances, potential new regulations, and rising energy and feedstock costs shrink profit margins. Companies manufacturing commodity products are particularly vulnerable to these forces. Yet chemical firms are also discovering that cooperation, even between competitors, is necessary for meeting today's challenges. Today's market dilemmas and innovation systems are too complex for any one organization. Network building is therefore central to continued innovation. Successful networks must include competitors working in partnership. This report summarizes the third annual CHF–SCI Innovation Day and describes a variety of partnerships among chemical and materials firms that combine cooperation and competition in novel, forward-looking ways.

INTRODUCTION

Past reports in the series *Research Frontiers for the Chemical Industry* have dealt largely with the mounting interlinked pressures facing chemical firms: more evenly spread global competitiveness; consequent increased demand for and declining or uncertain supplies of oil and natural gas; anxieties about the semiconductor industry's ability to meet Moore's law and, therefore, potentially diminishing productivity gains from information technology; and global climate change, which will bring gradual shifts in weather patterns as well as sudden, turbulent weather events in the coastal regions where many of the chemical industry's facilities are concentrated.[1]

Yet over the past few years the U.S. chemical industry has been able to run in place, and sometimes to advance, in the face of these challenges. And, despite a long-standing perception that they lack innovative capacity, chemical firms have responded to this catalog of challenges in creative ways. Enormous challenges remain, but this report will outline some innovations in industrial chemistry that can be refined and extended into the future. One lesson from the recent past stands above all: when executives and researchers from chemical firms meet and talk about their plans—as they have for the past three years at the CHF–SCI Innovation Day and Warren G. Schlinger Symposium—*partnership* is the watchword of the day. It is almost axiomatic that the power of a single firm to market new products and, especially, develop new processes today is severely limited. In combination with other firms and noncorporate partners, though, chemical companies can make extraordinary strides.

This report will argue—using examples from six frontier research areas in industrial chemistry—that the only way the chemicals sector can respond to increasingly complex and intractable problems is to shift individual firms' emphasis from competition to cooperation. This shift would not mean an end to competition. In fact, chemical firms can expect a fiercer competitive environment than ever as new players emerge from all corners of the globe, as feedstocks and energy become more uncertain, and as improvements in process technology continually convert high-value specialty chemicals into lower-value commodity chemicals. It is clear, though, that for there to continue to be a chemical industry, competition must take place in an environment of deep networking and partnership. Cooperation will become the rule rather than the exception, and competition may perhaps be seen as a stylized form of cooperation.

COMPETITION MEETS COOPERATION

Even though partnerships and collaborations are the trend of the moment, it still seems paradoxical to diminish the importance of competition. After all, firms know that their survival is tied to their ability to one-up competitors through innovations in products, processes, applications, and marketing as well as through the creation of intellectual property rights to secure that innovation advantage. All medium- and large-sized chemical firms keep a focused eye on their rivals. Even among the smallest companies very few are unique suppliers of a specialty chemical, and none can count on being so forever. The competitive race—to more efficient processes, greater labor productivity, cheaper raw materials, and larger markets—structures everything that chemical firms do.

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[1] Arthur Daemmrich and Cyrus Mody, *Research Frontiers for the Chemical Industry: Report on the First Annual SCI–CHF Innovation Day Warren G. Schlinger Symposium* (Philadelphia: Chemical Heritage Foundation, 2005); Cyrus Mody and Arthur Daemmrich, *Research Frontiers for the Chemical Industry: Report on the Second Annual CHF–SCI Innovation Day Warren G. Schlinger Symposium* (Philadelphia: Chemical Heritage Foundation, 2006). These reports can be downloaded at www.chemheritage.org/pubs/innov-frontiers.pdf and www.chemheritage.org/pubs/innov-frontiers-2005.pdf.

Yet long before today's fevered talk of "networks" and "partnerships," cooperation has been a fundamental part of the chemical industry. Most firms have always seen that cooperation raises the bar for competition. Take, for instance, chemical education and the chemical industry workforce. Chemical firms, by contributing their share to such professional organizations as the American Chemical Society and the American Institute of Chemical Engineers and by participating in setting standards for chemical education, cooperatively advance the training of young chemists and chemical engineers. Of course firms compete vigorously to recruit top-shelf graduates, but collectively the firms have raised the quality of that top tier. Similar precompetitive coordination is the basis for such industrial organizations as the Society of Chemical Industry and for such sectorwide planning exercises as the International Technology Roadmap for Semiconductors and the Chemical Industry Vision2020 Technology Partnership.

Economists have long known that the distinction between competition and cooperation blurs at a sector-level scale of analysis. The return to shareholders of established firms tends to mirror strongly the return of that firm's entire industry. Up close, the picture executives see is the constant tussle between close competitors over market share; from afar the picture reveals competitors generally rising and falling together.[2] Chemical firms can take a little comfort from this; by investing in continual, incremental innovation they can hold their own and move alongside their close competitors. But they face the grim possibility that a more radical innovation from outside their sector will pull the rug from under the chemical industry as a whole.[3] As the influential Austrian economist Joseph Schumpeter put it, "Capitalist reality . . . is that it is not [price and output] competition which counts, but competition from the new commodity, the new technology, the new source of supply, the new type of organization."[4]

The chemical industry is perhaps unique in that so many of its firms, large and small, have been able to anticipate such radical disruptions and leap to the next new source of supply, manufacturing technology, commodity, or product. Think of DuPont manufacturing gunpowder and explosives in 1802 but moving over the next two centuries to lacquers and textile polymers, to nuclear materials, plastics and petrochemicals, and biotechnology and agrochemicals today. Or think of Procter and Gamble manufacturing candles in 1837 but moving since then to soap and shortening, to foodstuffs, paper products, cosmetics, over-the-counter medicines, dental care, water filtration, and so on.[5] In both cases these nimble transitions involved proliferation and change in product line as well as radical shifts in feedstocks, markets, and regulatory environments.

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[2] Richard N. Foster and Sarah Kaplan, *Creative Destruction: Why Companies That Are Built to Last Underperform the Market—and How to Successfully Transform Them* (New York: Doubleday, 2001).

[3] Clayton Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Allston, MA: Harvard Business School Press, 1997).

[4] Joseph A. Schumpeter, *Capitalism, Socialism, and Democracy* (New York: Harper, 1942; repr. 1978), 84.

[5] The DuPont and Procter and Gamble examples are drawn from Schlinger Symposium presentations by Keith Grime, David Anton, and Uma Chowdhry.

Such transitions are hardly painless, but they cannot be avoided. If a first glance at the big economic picture shows established firms rising and falling with their industries, a second glance shows that new entrants usually outperform the industry for a while—until their competitive advantage fades and their new ideas become routine. Companies that continually reinvent themselves—and are in some sense perpetual new entrants—hold a permanent edge over competitors. The problem, as outlined in the second *Research Frontiers for the Chemical Industry* report, is that today's technological systems have become so complicated and entrenched, with so many organizations tied to them, that few firms can reinvent themselves on their own. The semiconductor industry, for instance, is so well road mapped that no company can single-handedly reinvent microelectronics; similarly oil and natural gas are so critical for energy and feedstocks that only industry-wide (or cross-sector) cooperation can bring alternatives to the fore.

Some blending of cooperation and competition is quite old, but this report suggests the chemical industry is entering a new phase of cooperative activity. From 2004 to 2005, for example, partnerships between pharmaceutical and biotechnology firms alone shot from $11 billion to $15 billion.[6] More significantly, companies today look well beyond firm-to-firm partnerships. Think, for instance, of the evolution in patient activism since the late 1970s. Doctors and pharmaceutical firms once regarded patients' groups with suspicion, but today those groups are seen as important partners for biomedical research and development.[7] Even very traditional chemical firms have shifted over the past decade to a more cooperative model of R&D. The production of new ideas was once seen as an entirely in-house activity. Research labs were large, well-manicured places, often in lush settings "protected" not only from the prying eyes of competitors but from the distractions of manufacturing and marketing as well. Innovations were almost always envisioned traveling through a single firm's "pipeline": basic research, then applied research, then development, then manufacturing, then marketing.

Today other models of innovation are ascending, and most of them emphasize cooperation and sharing—even among competitors—rather than secrecy and absolute in-house control. Increased global competition and today's faster movement of information and goods provide firms with the means and motivation to make each dollar spent on R&D generate tangible revenue. Realizing revenue from R&D is fundamentally a three-part process. First, in-house barriers are made permeable so that the company's own discoveries can be made relevant to all its product lines rather than just the corporate unit that commissioned a particular piece of research. Second, large firms must realize that while their researchers are capable of dramatic discoveries, a large company's strength usually lies in taking smaller firms' inventions and turning them into technologically superior, marketable innovations. Large firms must therefore build very deep networks to draw in knowledge, to create partnerships, and to harness small-firm ingenuity to large-firm know-how.

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[6] Rick Mullin, "The Partnership Push," *Chemical and Engineering News* 84:10 (2006), 21–27.

[7] Steven Epstein, *Impure Science: AIDS, Activism, and the Politics of Knowledge* (Berkeley: University of California Press, 1996); Rick Mullin, "Patient Activism," *Chemical and Engineering News* 84:25 (2006), 42–43.

Third, every R&D dollar yields something, even if it is not something the firm itself can use. Intellectual property can return value to the firm if it is channeled to the right partner—and that partner may even be a competitor. Large firms need customers for discoveries they cannot commercialize themselves just as much as they need suppliers of breakthroughs that enable the products they do bring to market. Building deep, collaborative R&D networks will generate revenue by fostering the flow of intellectual property in both directions.

FRONTIER AREAS FOR INDUSTRIAL CHEMISTRY

Competition necessitates cooperation; cooperation in turn raises the standard of competition. But neither competition nor cooperation is an undifferentiated category. Many kinds of each exist, and firms need to be able to fine-tune the character of both their competitive and cooperative relationships to meet specific objectives. No single firm can overcome the nearly intractable problems facing the chemical industry; firms that succeed will be those that develop large heterogeneous networks of partnerships and information sharing. Traditional partnerships—with government agencies, with suppliers, with smaller start-ups—are necessary but no longer sufficient. Today firms must consider the merits of counterintuitive forms of cooperation—with consumers; with (sometimes skeptical) nongovernmental organizations (NGOs), professional societies, and unions; and with competitors. In a very real sense even the natural world is coming to be seen as a valued partner in R&D.

As part of an ongoing effort to understand new forms of innovation in the chemical industry, the third annual Warren G. Schlinger Symposium explored six key areas: sustainable chemistry and engineering, renewable chemical feedstocks, chemistry of energy sources, meeting global water needs, electronic materials, and health materials.

Sustainable Chemistry and Engineering

The movement toward sustainable chemistry and engineering nicely illustrates the complexity and heterogeneity of the cooperative relationships chemical firms need to overcome today's challenges. As the United Nations defines it, *sustainability* is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[8] That is, the move toward sustainability constitutes a recognition that today's resource users have been outcompeting future resource users for access to oil, gas, clean air, clean water, and so on for some time now. To prevent such competition present societies must find ways to use, without using up, our natural resource base. As Paul Hawken, author of *The Ecology of Commerce*, puts it, sustainable industry means "taking nothing from the Earth that is not renewable, and doing no harm."[9]

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[8] Gro Harlem Brundtland et al., *Our Common Future: World Commission on Environment and Developmen*t (Oxford: Oxford University Press, 1987), 43.
[9] Paul Hawken, *The Ecology of Commerce: A Declaration of Sustainability* (New York: Harper Business, 1994).

Obviously firms cannot enter into formal partnerships with either future generations or the earth itself, but it may be helpful to think in such terms. For instance, to be sustainable firms will need to zero out a balance sheet of inputs and outputs from and to the earth's biosphere. No more of the earth's crust and no more artificial substances should wind up in the biosphere without firms eliminating some equivalent irruption of lithosphere or pollution. Fortunately, as we will see further in the next section, the biosphere can offer a kind of payment. Bio-prospecting for pharmaceutically active molecules has long depended on maintaining a diverse, sustainable biosphere; now "bio-inspired" chemistry and engineering are taking root in such areas as electronic materials, health materials, energy, building materials, and eco-friendly consumer goods.

In other words the chemical industry is working toward an understanding of nature as a collaborative partner in technology transfer. We can now see that for some applications biological factories can produce chemicals that are more efficient, cheaper, cleaner, and of better quality than those produced by traditional facilities. Such companies as DuPont, for example, are working on "metabolic engineering"—programming cells via genetic manipulation to manufacture high-value products. Of course the biosphere will often require a third party (probably from the biotech industry) to facilitate its partnership with a chemical firm.[10] In this case metabolic engineering could be commercialized only through a partnership among DuPont, Genencor, and Tate & Lyle, resulting in a $100 million plant in Loudon, Tennessee, that produces corn-based 1,3-propanediol.

The motivation for this and similar projects is not just an altruistic reduction in competition with future generations (who after all cannot pay the present back in real time). Metabolic engineering also offers firms like DuPont a competitive advantage today. The Loudon plant, for instance, provides a 40 percent savings in energy over non-bio-based facilities. Out of concern for both shareholder profit and environmental sustainability, therefore, DuPont has set a goal for 2010 to derive 25 percent of its revenues from nondepletable raw materials, to obtain 10 percent of the energy it uses from renewable sources, and to reduce its greenhouse emissions by 65 percent relative to 1990 levels. Partnerships are critical to meeting those goals: with firms that will use DuPont's bio-based materials (e.g., Mohawk Industries, a flooring manufacturer); with raw materials and energy firms (e.g., with BP to make bio-butanol); with government labs (e.g., the Department of Energy's National Renewable Energy Laboratory), academia (e.g., the Michigan Agricultural Experiment Station), and even DuPont's agricultural subsidiaries (e.g., Pioneer Hi-Bred) to discover new routes to and uses for biomaterials.

Both small companies and industry giants face risks in taking a sustainable approach; not all attempts to replace traditional manufacturing will yield increased profits. Large or small,

[10] Anthropologist Bruno Latour has written provocatively about viewing the natural world as an intentional agent with whom humans can bargain and form partnerships. See Bruno Latour, *The Pasteurization of France,* trans. Alan Sheridan and John Law (Cambridge, MA: Harvard University Press, 1988), and *Politics of Nature: How to Bring the Sciences into Democracy*, trans. Catherine Porter (Cambridge, MA: Harvard University Press, 2004).

though, no single firm can shoulder the risks alone. Some level of industry-wide cooperation is needed before firms can move on to the competitive stage of letting market forces decide which approach to sustainability is best. Companies, universities, and professional societies, among other institutions, need to restructure chemical education to give chemists and engineers the tools to develop sustainable products and processes and to promote cognizance of sustainability issues among the wider public. At the same time companies, governments, and NGOs need to cooperate to develop metrics and rewards for sustainable manufacturing that will help incubate unproven methods over the short term so that down the road more sophisticated methods will allow sustainable chemistry to compete successfully with traditional manufacturing.

Renewable Chemical Feedstocks

Three key research areas in developing such sustainable approaches are feedstocks, energy, and water use. Of these, feedstocks perhaps present the greatest paradox to the chemical industry: chemical firms possess the most know-how for developing new raw materials as alternatives to oil and natural gas, but they probably hold the least leverage in implementing that know-how. In other words chemical firms are practically the only organizations that understand the chemical pathways from any raw material to a finished product, yet their relationship to those raw materials puts them in a precarious position. Chemical firms are either petrochemicals companies that own the raw material (oil and natural gas) to which they are tied by almost a century of institutional entrenchment or they are nonpetro firms dependent on other industries—energy, biotech, agriculture—to supply their raw materials.

Thus renewable feedstocks could represent a radical competitive threat to some of the largest firms in the chemical industry, the kind of fundamental shift in technological platform that, as Schumpeter noted, occasionally sweeps whole sectors aside. Or new feedstocks could offer chemical firms the opportunity to change directions once again and gain the advantages inherent to new entrants to an industry. Either way chemical firms will always need some kind of feedstock; the secret will be to make feedstock suppliers as dependent on chemical knowledge as chemical firms will be on the feedstocks they supply.

The chemistry of renewable feedstocks is extraordinarily complicated. It is becoming clear that simplistic direct attempts to substitute renewables—especially those derived from a single crop—are at least as environmentally unsustainable as dependence on oil and natural gas. For example, Brazil has been experimenting with ethanol from sugarcane for more than thirty years; the country has replaced gasoline with ethanol in 20 percent of national transport fuel use, thereby making the nation nearly energy independent, reducing costs, and lowering pollution levels in big cities. Yet smoke from the slash-and-burn agriculture used to grow sugarcane has made pollution levels worse in Brazil's rural areas. On a global scale Brazil's ethanol program is almost certainly unsustainable. Since road transport accounts for less than 10 percent of global greenhouse gas emissions while deforestation and agriculture together account for more than triple that, the Brazilian program's benefits in decreased auto emissions are more than erased by the intensive agriculture and deforestation needed to supply enough sugarcane as the raw material.

Even if the simple solutions were not so counterproductive, they would not move the chemical industry much closer to independence from oil. Certainly no single biofuel could unseat oil and gas; as a recent study showed, "the entire effect of corn ethanol in 2012 will be less than the effect of inflating properly the U.S. passenger car tires."[11] If all the land in the United States on which corn is currently grown were used for ethanol, it would replace only 12 percent of the nation's gasoline demand; if all U.S. soya production were converted to diesel, it would meet only 6 percent of demand.

Again, even if these land use and food availability issues could be solved, complications would abound. Because oil is so chemically complex, it yields a large number of intermediate feedstocks. No bio-based feedstock can cover that range of molecules on its own. As Rich Chapas of Battelle put it in his Schlinger Symposium talk, "Globally there's no shortage of hydrocarbons, only a shortage of high-quality hydrocarbons." A variety of renewables—each associated with a different region—will therefore need to be combined. In the first stage a combination of various grains, sugar, and oilseeds will likely be used: corn and soybeans from North America; sugarcane from South America; wheat, sugar beet, canola, and sunflower from Europe; physic nut and pongamia from India; and oil palm from Southeast Asia. As the chemistry improves, ligno-cellulosic sources will enter the mix: miscanthus, switch grass, willow, poplar, and so on. Even more advanced chemistry conducted in multifaceted collaborations (such as a current partnership among Battelle/Pacific Northwest National Laboratory, Cargill, and ADM) may yield complex molecules from such exotic sources as bioengineered fungi.

Such collaborations among organizations within a nation or region will be necessary to bring renewables into the energy and chemicals infrastructure. More vexing, though, is the level of international cooperation required. Some regions have near monopolies on nonrenewables: coal in the United States, India, China, Russia, and Australia; oil in the Middle East and parts of the United States, Africa, South America, and (with difficulty) Canada; natural gas in the Middle East and parts of the United States and the former Soviet Union. These nations must be convinced that renewables are not a threat to their economic base and that in fact some portion of revenues from nonrenewables is wisely spent on researching and building a renewable infrastructure. Climate change caused by emissions from nonrenewables will after all affect everyone (though it will not affect everyone equally). Moreover, if predictions of reserves are accurate, these economies need to prepare for a time when nonrenewables have

[11] Evidence supporting the claim about tire inflation can be found in Tad W. Patzek, "The Real Biofuel Cycles: Online Supporting Material for Science Letter," 11 July 2006, petroleum.berkeley.edu/patzek/BiofuelQA/Materials/RealFuelCycles-Web.pdf. Patzek's original letter to the editor was published in *Science* 312:23 (June 2006).

run out—at current rates of consumption, as soon as 41 years for oil, 60 years for gas, and 166 years for coal.[12]

At the same time different regions will eventually have near monopolies on different feedstock crops. As with nonrenewables supply and demand will be only partially collocated; many of the highest-quality hydrocarbons will come from tropical regions where demand is currently low. In the past competition among nations with complex economies over resources from their colonies and client states continually triggered political, environmental, and public health crises. The potential clearly exists for history to repeat itself. If nations with high rates of energy consumption rush to replace their dependence on oil with dependence on renewables, demand for feedstock crops will skyrocket. A rise in demand could promote wholesale deforestation and monocropping, as has already begun to happen with oil palm in Indonesia.[13]

In the Indonesian case environmental destruction from planting oil palm was the direct result of subsidies from the Netherlands (Indonesia's former colonial power) intended to promote alternative feedstocks. If the past two centuries are a guide, such inducements from industrialized nations for their current or former colonies to become dependent on a high-value monocropped resource will almost certainly lead to increased greenhouse emissions (see Brazil above), famine (e.g., the Irish potato famine of 1846–1847 or the Bengali famine of 1943), and autocratic corruption (see almost any small, oil-rich developing economy of the past hundred years).[14] To prevent such disasters and make the transition to renewables sustainable will require intense collaboration among all wealthy economies and between the hydrocarbon hungry and the potentially hydrocarbon rich.

Chemistry of Energy Sources

Fortunately the chemical industry may well hold the keys to such sustainable collaboration, at least in the vital area of alternative energy. Nearly half of all greenhouse contributions comes from the need for heat and electricity; around 13 percent comes from transportation, which conceivably could be re-engineered as an electricity-generation problem as well. Bio-based feedstocks will clearly be important for chemical manufacturing, but for energy generation they have severe drawbacks. Alternative energy sources that create electricity without burning a fuel will be much cleaner and more efficient. Hydrothermal power, windmills, tidal power, and nuclear power all have their advocates (and opponents). But solar energy—cheap, clean, abundant, and steady (at least in some parts of the world)—probably

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[12] The assumption that consumption rates will not rise seems unlikely given rising demand in China, India, and other emerging economies.

[13] Elisabeth Rosenthal, "Once a Dream Fuel, Palm Oil May Be an Eco-Nightmare," *New York Times*, 31 January 2007, Section C.

[14] Amartya Sen, *Poverty and Famines: An Essay on Entitlement and Deprivation* (Oxford: Clarendon Press, 1981). A similar point about monocropping and the failings of overly rationalized large-scale projects can be found in James C. Scott, *Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed* (New Haven, CT: Yale University Press, 1998).

has the most potential. And generating electricity from solar energy is fundamentally a materials problem. From the photovoltaic materials that capture solar energy to the transmission lines that move it from solar "farms" to the batteries that store that energy until it is needed, a raft of new materials will be needed to make solar energy viable.

The good and bad news is that solar power technology has a long history. The photovoltaics industry arguably dates back to 1953 and the invention at Bell Labs of a 6 percent–efficient silicon-based solar cell. Within a few years NASA and the U.S. Department of Defense had latched onto the solar cell as a nearly unique way to generate electricity in space. Today governmental customers with high-end uses continue to be an important driver for research on both photovoltaics and advanced batteries and fuel cells. Since the 1970s photovoltaics have also been commercialized for ordinary terrestrial consumers, but buildings that incorporate solar panels are still an uncommon sight. Mass commercialization remains elusive.

A similar problem applies to advanced batteries. While this report's readers are probably familiar with rechargeable long-life lithium-ion batteries for cell phones, laptop computers, digital cameras, and so on, the potential uses for this technology are much more ambitious. For instance, nickel-metal hydride batteries are the current energy storage technology for hybrid vehicles; lithium-ion batteries would in theory have a much higher energy density and would therefore make such cars cheaper and more efficient. For now formidable barriers prevent lithium-ion from replacing nickel-metal hydride for automotive applications. In particular, abuse tolerance and safety problems are not well controlled. If those issues are ironed out, however, conservative estimates suggest that by 2014 more than 1.8 million hybrid vehicles will be sold every year and more than 1.4 million of them will use lithium-ion technology.

Such estimates allow us to see our long-range but not our short-term energy future. The energy infrastructure of today is characterized by relatively centralized energy production; by dependence on energy assets that are largely located in politically unstable regions, are responsible for global climate change, and are finite both in annual production and total reserves (i.e., each year's pie is no bigger even though there are more mouths to feed and we know that someday there will be no pie at all); and by immense inertia (after all it took sixty years to electrify all of the United States, and in the thirty-five years since the first oil crisis alternative energy sources have only slowly crept forward). We can see, though not in detail, what the energy infrastructure of fifty years from now will look like: a multitude of energy sources, probably led by solar energy, that are generated at many more points than today, transmitted nearly without loss, and stored in advanced batteries so as to be available when and where needed. But every attempt to move toward this future energy infrastructure has ended in a cul-de-sac: advanced fuel cells that only NASA will buy, high-temperature superconductors for power lines that (despite vast promises) still will not carry a reasonable amount of current, and solar panels that only a few especially eco-conscious consumers are willing to use.

As with much else in the transition to sustainable industry, the way forward in alternative energy must begin with a reconceptualization of the biosphere as a cooperative partner. Alternative energy should present numerous benefits to the environment. As they would with any business partner, chemical firms need some standardized metric for understanding how much the biosphere has benefited from their research. Obviously the biosphere cannot pay anything directly in return, but such a metric will allow governments, NGOs, and trade associations to provide a clearer system of incentives and rewards. And nature does offer a technology transfer as payment; after all, organic plants still outperform almost all solar cells. Fundamental, long-term research aimed at understanding the electron physics and biochemistry of how plants convert and store solar energy should provide the blueprints for a first generation of bio-inspired solar cells. These devices will almost certainly have fragile components with short life spans, but once they are on the market, an incremental pathway of development will have opened up—rather like Moore's law in the microelectronics industry—by which small-scale materials improvements (chemical firms' forte) will eventually lead to widespread commercialization of cheap, reliable, long-life solar cells.

Meeting Global Water Needs

In many ways the chemical industry's relation to water ties together the themes discussed thus far. Like the global energy supply, the global water supply is clearly amenable to improvement through the development and commercialization of advanced materials. Indeed some of these materials—for example, advanced membranes—may provide a common technology base for water filtration and energy storage. Like new feedstocks, though, the way forward with water is dismayingly opaque and will require a complicated combination of progress in international law, diplomacy, and economics alongside new chemistry. The technological problem is roughly analogous; just as the issue with feedstocks was not the availability of but the quality of hydrocarbons, the pressing global water problem is not availability (oceans cover more than 70 percent of the earth's surface) but quality (fresh water covers only 1 percent of the globe). To the extent that new feedstocks will depend on globalized, intensive agriculture even in water-poor regions, the two problems are tightly linked. In general the issues we have identified at the core of a sustainable chemical industry—feedstocks, energy, and water—are so intertwined that progress can happen only if information flows across disparate parts of the industry and collaborations are built among the various units of firms dedicated to solving these problems.

One enlightening way to think about this is to see sustainability as a problem of managing supply and demand. Right now a substantial demand for more sustainable industry exists among citizens, as measured directly through polls and indirectly through the rhetoric of politicians, contributions to environmental NGOs, and box-office receipts (and Oscar recognition) for such films as *An Inconvenient Truth*.[15] Yet, as consumers, those same citizens have been much slower to demand "green" products. Even the most successful enviro-

[15] Claudia H. Deutsch, "Take Your Best Shot; New Surveys Show That Big Business Has a P.R. Problem," *New York Times*, 9 December 2005, Section C.

friendly products, such as Toyota's hybrid vehicle lines, still occupy niche markets that are unlikely to replace conventional products any time soon. When they view the choice purely in economic terms, consumers will generally demand sustainable solutions only if it means an immediate or medium-term reduction in cost.

Many sources can be identified for this mismatch between what citizens and consumers demand. Chemical firms' tendency to view consumers as a finite resource over which to compete with other firms rather than as a body of reasonable, potentially well-informed partners is one critical driver. However, models do exist for treating consumers as active partners. Specialty chemical companies—as we will see in the next section—have long thrived on intense dynamic cooperation with customers, in which information moves quickly and both client and patron are involved in design of the final product. But this type of cooperation has been a much more unconventional model when dealing with a mass consumer market. Fortunately, today new information technologies are making this model more viable, as evidenced by growing corporate interest in the open-source movement.[16]

The exact mechanics of treating the wider public as an informed, engaged partner have yet to be worked out, especially in the chemical industry. But water quality and availability issues are perhaps the critical area where chemical firms can and must work closely with consumers to point patterns of both supply and demand in a sustainable direction. Fortunately, chemical firms can move stepwise in that direction. Water has become in some sense a specialty chemical, and the specialty chemicals business model can provide first steps to new water supply innovations. Chemical firms are both suppliers and users of advanced water purification technologies, and ultrapure water is a critical resource in such sectors as pharmaceuticals and electronics, where close partnerships between manufacturers and suppliers are already the norm. Chemical companies are well along in developing new reverse osmosis and nanofiltration membranes, such new antiscalant technologies as dendrimer "hosts" for dissolved ions, and new sensors for detecting biological contaminants. Given that water is transported, stored, used, and disposed of differently by different customers, the units developing these technologies will have to work closely with users—including other units within the same firm—to design the right solution.

Once such technologies have been proven for industrial users, an innovation road map will be needed to adapt them for individual or small-scale consumers. For instance, one of the greatest water quality problems today is the lack of small, cheap treatment technologies that can be easily transported into regions with needs both acute (e.g., areas hit by a hurricane or a tsunami) and chronic (e.g., water-stressed areas of Africa and Asia). Even if the commercial market for such technologies is soft, many firms will have no choice but to subsidize their commercialization. Coca-Cola, for example, has recognized that it needs to have factories in water-scarce areas; that water is a sensitive issue everywhere and that adverse headlines about water quality and access affect profits; and that, therefore, in regions where it uses water, the

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[16] See, for example, Lego's close involvement with customers in developing its Mindstorms product line. Brendan I. Koerner, "Geeks in Toyland," *Wired* 14.02 (2006).

company needs to do its best to use less water and make more and better water available to the local community.

Some solutions to this challenge will be relatively straightforward and painless. Dow found that a single plant's program to find and fix leaks led to a savings of $135,000 per year and 13,000 gallons of water per minute. In most cases, though, very little fat exists in industrial chemical processes, even in water budgets. Firms will have difficulty freeing up more water on their own. As this report has argued throughout, the pain of reducing water use must be ameliorated through strong, diverse partnerships. In confronting water issues firms need to find international NGOs to identify and communicate local and regional needs and breakthrough efficiency opportunities. Coca-Cola has developed an exemplary program to supply safe water to primary schools in Kenya. Success in this program—and in making the program visible—was possible only through collaboration with Global Water Challenge, CARE Kenya, Millennium Water Alliance, the Kenyan Ministry of Water and Irrigation, and local communities throughout the country. Such collaborations are complex and challenging, but many firms will soon find business impossible without them.

At this point supply management blurs into demand management. The chemical industry has generally focused on developing such new supply technologies as advanced membranes, antiscalants, and sensors. Yet the need to visibly protect water supplies requires firms to engage on the demand side as well. The obvious place to start, of course, is with their own demand. Dow, for example, currently uses 900 billion pounds of water per year for 120 billion pounds of products; 70 percent of that water is treated and discharged after one use. One of several sustainability goals the company set for the decade ending in 2005 was a 50 percent reduction in the amount of wastewater generated per pound of product. In the end Dow's reductions were closer to 40 percent, but it was a very ambitious objective requiring organizational and technological innovations that will continue to benefit the company.

The next step in meeting global water needs requires chemical firms to be active partners with the public to manage consumer demand. Consumer-oriented chemical firms already guide public demand through marketing, though their marketing strategies are usually meant to increase demand for a company's products. The trick now is to apply the same combination of marketing and technological innovation to reduce demand for water (and energy and nonrenewable feedstocks) to sustainable levels. Simply presenting sustainable products alongside conventional, less eco-friendly products and allowing the market to decide which is better will not solve the problem. Both the economics and the marketing of that recipe ensure that consumers will continue to choose the conventional, unsustainable product.

For instance, Procter and Gamble launched a cold-water detergent, Tide Coldwater, in 2005. This product is clearly a laudable attempt to use new chemistry and new marketing to manage consumer demand for energy use toward a more sustainable level; it helps move the public's demand (as citizens) for an eco-friendly industry in line with the same public's demand (as consumers) for low-cost products. Yet Tide Coldwater entered a marketplace with a rich, complicated history. At the turn of the last century chemical companies specializing in consumer products (such as Procter and Gamble) made common cause with the politicians, journalists, reformers, and intellectuals of the Progressive movement to promote the idea that cleanliness and morality were two sides of the same coin. It is a tribute to the success of that conjoined marketing campaign and political movement that Americans wash themselves and their clothes as often—and buy as many personal care products—as they do.[17] By partnering with broader social movements in the past, chemical firms helped create the conditions that now make it difficult for such eco-friendly products as Tide Coldwater to gain traction.

Industry-wide, consumer demand for limited resources must be high enough to be economically sustainable but low enough to be environmentally sustainable. This point cannot be reached if chemical firms treat consumers as yet another limited resource over which to compete. Strong partnerships are necessary—with competitors, with government, with NGOs, and with local communities—to turn the mix of marketing and innovation around so that demand for nonrenewable resources can plateau rather than rise to the breaking point. Past experience shows that chemical firms can be nimble in working with broader social movements and can reap substantial economic gains from doing so. The cost is a significant change in the way firms do business. But when social movements succeed, firms that change to accommodate them outcompete firms that do not adapt. Sustainability as a social movement is probably here to stay. Firms that make common cause with sustainability's precepts and promoters now will likely adapt better to the competitive environment of the future.

Electronic Materials

Sustainability will be a crucial objective for all materials firms in the near future. Even in the electronics industry—traditionally noted neither for belching smokestacks and reeking effluent streams nor for particular concern for the environment—sustainability (particularly around water use) has become an integral part of the industry road map.[18] Sustainability, however, will have a different emphasis for the electronics sector than for other materials industries. If we take the definition of John Elkington, cofounder of SustainAbility, *sustainability* is "triple bottom line" accounting: requiring organizations to commit simultaneously to economic, environmental, and social benefit.[19] Previous sections of this report focused on the intersection of economic and environmental benefit. The final topics, electronic materials and health materials, also require environmentally focused

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[17] Daniel Eli Burnstein, *Next to Godliness: Confronting Dirt and Despair in Progressive Era New York City* (Urbana, IL: University of Illinois Press, 2006); Susan Strassner, *Never Done: A History of American Housework* (New York: Pantheon Books, 1982).

[18] The industry's targets, however, indicate little sense of urgency.

[19] This is in contrast to a traditional business focus on the single bottom line of economic success. See John Elkington, *Cannibals with Forks: The Triple Bottom Line of 21st Century Business* (Stony Creek, CT: New Society Publishers, 1998).

manufacturing innovation, but their more pressing problems lie at the intersection of economic and social benefit.

If we restrict our focus to the single bottom line of profits, we see that the microelectronics industry, more than any other materials sector, has recognized the need for the kinds of partnerships this report recommends. The technology of scaling electronic components down in size (and upward in complexity) in accordance with Moore's law is now so baroque as to require the coordinated participation of hundreds of organizations. The number of breakthroughs needed for every advance in miniaturization is continually growing. Take, for instance, the evolution of photolithographic materials. Fifteen years ago a photoresist sat directly on top of the substrate that was to be patterned; light shone threw a pattern cut into a mask and onto the resist, which underwent a chemical change in the areas exposed to light, thereby affecting those regions' resistance to acid etching. The pattern on the mask could therefore be directly etched into the substrate.

As the patterns got smaller, though, normal photoresists proved too blurry. By 2000 the system had evolved such that the photoresist sat on a layer of bottom antireflective coating (BARC). Today photolithography requires a stack of advanced materials: a top antireflective coating on top of a photoresist on top of BARC on top of a chemical vapor deposition hardmask on top of an underlayer. Each of these new materials is in turn extraordinarily complex and requires new chemistry both to synthesize and to understand its interactions with the other materials in the process. Any new material must be integrated into a pre-existing, intricate, hierarchically organized system. For example, it was well known that the switch from aluminum to copper interconnects in integrated circuits would lead to 10 to 20 percent faster integrated circuits. But it took twenty years—ten involving intensive work—to bring this innovation about, because the changeover in this one process step required the modification of some twenty-five other steps.

Each process step is associated with a different complex of firms—of materials and equipment suppliers, chip manufacturers, and the electronics firms that incorporate those chips in their products. And since each process step ramifies through so many other steps, the success of the whole enterprise depends critically on the coordination of large numbers of companies. This industry is built on collaborative activity; firms continually have to work with partners several steps up and down on the value chain to achieve the desired effect. This type of collaboration is achieved through several organizational tools, most notably the International Technology Roadmap for Semiconductors.

Yet such road maps are purely instrumental and technology oriented. They show the industry how to get to a certain size transistor and a certain complexity of chip, but they fail to show what such a chip is good for or what possibilities lie on roads not shown on the map. This narrow focus may leave substantial markets untapped. Therefore, some firms with experience in electronic materials are beginning "off-road" exploration. One potentially vast area is so-called printed electronics. Unlike their silicon counterparts, devices made from printed electronics would not necessarily be *micro*electronics (indeed, some have named this field *macro*electronics); that is, the emphasis would be less on reducing size and more on reducing production overhead. Silicon microelectronics enables unbelievably cheap cost per transistor. Yet the cost of building a fab to make such transistors doubles, in accordance with Rock's law, every four years. (A new competitive fab costs around $6 billion today).[20] Printed electronics, however, could enable the construction of fabs with very low overhead. Fabs for printed electronics could be built from the manufacturing tools of other industries (such as the publishing industry). Ultimately, commercial electronic devices could even be printed using desktop inkjet printers.

Applications of such cheap circuits currently on the market include printed batteries, printed photovoltaics, e-ink printed displays, printed lighting, and radio-frequency identification devices for tracking goods. Once again further development of such applications will require extensive inter- and intrafirm collaboration. Some collaboration will be among traditional chemical companies with expertise in electronic materials. For instance, Motorola has been developing printed electronics since 2000 through a collaboration in which Dow Corning and Xerox (two experienced photoresist manufacturers) supply the metal and dielectric "inks" and Motorola supplies the semiconductor "ink" and printing process. Such traditional partnerships are necessary but not sufficient for achieving printed electronics' potential. The next step for Motorola, therefore, was to partner with large-scale printing houses—the kinds of firms that print mass-circulation newspapers—to figure out how to rapidly produce square kilometers of printed circuits.

Printed electronics synthesize two wildly divergent worlds, microelectronics and graphic arts printing, in order to create unheard-of media (e.g., animated newspaper ads or newspapers that broadcast information to nearby cell phones). This technology is a new paradigm for innovation in microelectronics. Of course, the current paradigm, miniaturization of silicon-based electronics on the path of the International Technology Roadmap for Semiconductors, will continue to be vital to economic growth. But this report upholds printed electronics as an exemplar of the kinds of opportunities that can be created by stepping back from road maps and looking around for unconventional partnerships.

Health Materials

Sustainability, electronics, and health materials offer interesting contrasts. For the complex of issues around sustainability—particularly alternative energy and renewable feedstocks—the eventual outcome for the chemical industry is somewhat clear: greater diversity of feedstocks and energy sources is essential. But no consensus has been reached on how to get there. In electronic materials both outcome and path have been hammered out in great detail—perhaps too great, since many opportunities will be discovered only by wandering off the path. In health materials neither the outcome nor the path is clear. Different firms will

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[20] Michael Kanellos, "Soaring Costs of Chipmaking Recast Industry," *c|net News*, 22 January 2003. As Hector Ruiz, CEO of Advanced Micro Devices, puts it in this article, "Outside of Intel, I don't know who could [build a fab] alone. There has to be a coalition."

likely go their own directions. With sustainability and electronic materials some industry-wide coordination will be inevitable, but with health materials the need for consensus is less apparent.

Historically, chemical firms have been active inventors and producers of pharmaceuticals and materials used in health care. Such firms as Dow and BASF had large health operations in the 1960s and 1970s. More recently, such partnerships as DuPont Merck Pharmaceutical Company (founded in 1991) were not uncommon. With the demise of the integrated "life sciences" company in the mid-1990s, however, chemicals and health materials separated. In recent years renewed innovation in the area and the attraction of high profit margins have prompted chemical companies to take a new look at health materials. Unlike in the past, each company seems to have a very different business model and strategy for its involvement in the area.

Forgoing coordination in the health-materials sector involves risks. Unlike in the electronics field, where the greatest risk lies in not being the first company to market the next advance along Moore's curve, in the health sector the greatest risks may lie in bringing products to market before their properties are fully known. In the United States pharmaceuticals and health materials are a source of costly litigation, as in the recent case of cox-2 inhibitors. Globally publics can mobilize quickly, as in the genetically modified organisms debate, if they see potential health risks in the manufactured molecules that they eat, breathe, or are prescribed. Chemical firms venturing into the health materials market must know that they may receive unwelcome attention. Partnerships with firms or organizations that are well established in health care will almost certainly be necessary in navigating this tricky terrain.

At the same time the American health system is likely moving toward dramatic changes that will open new opportunities for the chemical industry. In other sectors—for example, energy and renewables—chemical firms may be vulnerable to competitors from outside their industry. In the health sector the chemical industry may be the one to offer new, disruptive technologies. The need for some disruption is clear. The United States now spends 16 percent of its gross domestic product on health care compared with a global average of 9.3 percent. Japan, a comparable economy, offers superb health care with only 6.2 percent of gross domestic product. The United States spends about $4,600 per capita on health care compared with only $2,000 in Western Europe, yet Western Europe has 3.5 physicians per 1,000 people and the United States has only 2.7. Hospital stays in the United States average 7 days compared with 8.3 in Western Europe and a staggering 39.8 in Japan.

These numbers paint a crude picture, but they do show U.S. citizens spending more and getting less in health care. Given the size of the American health care system, any increase in efficiency, however small, could multiply into large savings. For instance, some ninety million surgical procedures are performed in the United States every year. The savings from even slight improvements to surgical procedures that reduce complications, hospital stays, or physician time would be tremendous. Fortunately the chemical industry has a long history of developing materials that enable such small, continuous improvements in efficiency.

Medicine is essentially about manipulating a very specific set of materials—those found in or in contact with the human body. Chemical companies, with their materials expertise, have a unique advantage in creating new materials to add to medicine's toolkit. This advantage can be leveraged, however, only through partnerships with organizations that have other forms of medical expertise.

For instance, half of all litigation surrounding health materials is for patent infringement—a necessary evil perhaps. The other half, though, is for health lawsuits. This latter half can be mitigated only through early and active communication with the U.S. Food and Drug Administration during product development, combined with a massive battery of tests conducted at multiple centers. In the past the need to build such an extensive wall of legal protection would have discouraged companies like DuPont and 3M from exploring health-materials products; in particular, such firms rarely entered the clinic to see how doctors would actually use their products. Today, though, the benefits of watching prototype products in use outweigh even the extensive risks. DuPont has a major commitment to create new clinical applications. By giving materials to doctors and then following up, the company learns of serendipitous new uses for its medical (and sometimes nonmedical) products. Similarly 3M works hard to find "dentist leaders" who can give advice to the company while also drawing their colleagues' attention to the applications of new products (in a specialized professional language that 3M itself could not hope to speak). Moreover, 3M researchers routinely staff sales booths, work with focus groups to better understand dentists' needs, and welcome dentists into their research labs to provide advice at the bench.

Chemical companies' materials expertise does not guarantee they can cut through the health-care sector's shortcomings. The size of market opportunities will vary enormously depending on how health-materials products are coordinated with the interests of the field's diverse set of actors. If the chemical industry's advanced materials are seen to benefit one group (e.g., insurance companies) at the expense of others (e.g., patients or medical professionals), the chances of successful commercialization will plummet.

Moreover, the baggage chemical firms bring with them occasionally amplifies controversial currents already swirling within the health-care sector. For instance, many chemical firms already worry about public anxiety over possible toxicological risks from engineered nanoparticles. Since almost all biological materials have a complicated nanostructure, any good bio-inspired health material will as well; such companies as 3M, with health nanomaterials on the market, have already noted the incendiary potential for public skepticism toward new drugs and medical devices to link up with possible public fear of nano-contamination. 3M's wariness is justified, though its fears may never become reality; the public could just as easily conclude that "bio-inspired" is a positive characteristic synonymous with "natural." Navigating between such positive and negative outcomes will require deep and varied interactions with many different parties to health care.

COLLABORATIVE OPEN INNOVATION

Modern materials are getting more complex, and the processes for making them are getting much more complex. Today's materials are made through more steps, from more feedstocks, with less water and energy, using ideas from more fields. Value chains, road maps, intellectual property, life-cycle analyses—these and other signposts map out increasingly complicated manufacturing and a more convoluted innovation process. This rising complexity has meant a shift, accelerating over the past decade, to a more open, collaborative innovation model. Firms are less insistent that the only innovations they can trust are those developed in-house. Partners, even competitors, are now indispensable sources of (and clients for) innovations.

The notion that R&D needs to be opened up and that the burdens of innovation are lightest when shared is becoming a new orthodoxy in the chemical industry. This report takes this orthodoxy one step further in encouraging chemical firms to think imaginatively about how and to whom to open up their innovation process for partnership. Other chemical firms will continue to be the most obvious partners; firms from nearby sectors—or sectors that are pulled into proximity—will be next (agriculture, health, electronics, even media). Partnerships between smaller ventures and established firms often allow for creative leveraging of intellectual property and manufacturing capability; these collaborations are not unproblematic, but they can offer such dramatic advantages that larger companies may want to create them artificially by establishing "start-ups" within the boundaries of the firm.

New management techniques, especially those that take advantage of new information technologies, will be needed to forge and maintain such firm-to-firm partnerships. This report, however, encourages an even more expanded notion of collaboration. The same information technologies make it possible to continuously bring in advice and ideas from, among others, patients and consumers, different units within the firm, alumni of the company, and independent inventors. Indeed many sectors of the public now demand greater transparency and involvement in innovation. Firms can only help themselves by developing strategies (based largely in new information technologies) for working with the public and its representatives, including both governments and NGOs.

It is crucial to remember, though, that collaborations are a learned activity and that firms and individuals will improve in that activity with experience. As collaborations become more widespread, the industry should develop standard tools to aid this activity, such as standard contracts and other legal documents for sharing of intellectual property and financial rewards. Successful collaborations usually blur the lines between technical and business considerations and need to be managed by personnel with both kinds of expertise. Where possible, firms should leverage external signposts to coordinate both collaboration and competition. Such signposts include industry road maps, technology standards, new regulations, and the pull of a single powerful customer.

Finally, this report makes the somewhat counterintuitive suggestion that firms consider collaborations with entities not traditionally thought capable of entering into partnerships. In particular firms should strike deals that mutually benefit the company and the earth's biosphere. This recommendation is decidedly rooted in old-fashioned pragmatism rather than a romanticized holism. Seeing the biosphere as a partner can potentially bring in new bio-inspired innovations, increase public trust, inspire a new generation of industry researchers, increase efficiency, mitigate environmental and public health disasters that—as Hurricane Katrina showed—often affect the chemical industry more than other sectors, and lay the material basis for the continuation of the industry well into the future.

This report cannot yet fully lay out the particulars of partnership with the biosphere—an oft-repeated but ill-sketched trope of the Schlinger Symposium. At the least, though, firms can begin to move in this direction by expanding the disciplinary core of their research teams to include molecular biologists, toxicologists, environmental chemists, environmental economists, and environmental sociologists. These people can speak for the biosphere: by pointing out where nature can be a source of innovation, by developing metrics for "balancing the books" between industry and environment, and by getting firms to reduce not just the time needed to bring a product to market but also the time needed to make that product's manufacture sustainable.

Schedule of Events
Warren G. Schlinger Symposium
21 September 2006

9:00 a.m. **Opening Plenary: "Creative Destruction: Understanding the Dynamics of Disruption and Innovation"**
Sarah Kaplan, Wharton School, University of Pennsylvania

10:00 a.m. **Breakout Sessions**

Renewable Chemical Feedstocks
Moderator: John M. Vohs, University of Pennsylvania
Speakers: Alan D. Baylis, Nuvistix Innovation
Richard Chapas, Battelle Memorial Institute

Sustainable Chemistry and Engineering
Moderator: Paul Clark, NOVA Chemicals
Speakers: Michael D. Bertolucci, Interface Research Corporation
David Anton, DuPont

Electronic Chemicals
Moderator: Cathie Markham, Rohm and Haas Electronic Materials
Speakers: Robert Wisnieff, IBM
Marc Chason, Motorola

Chemistry of Energy Sources
Moderator: Miles Drake, Air Products and Chemicals
Speakers: Rakesh Agrawal, Purdue University
Khalil Amine, Argonne National Laboratory

Health Materials
Moderator: Uma Chowdhry, DuPont
Speakers: George Kodokian, DuPont
Sumita B. Mitra, 3M Company

Meeting Global Water Needs
Moderator: Jim Alder, Celanese
Speakers: Steven Gluck, The Dow Chemical Company
Paul Bowen, Coca-Cola

11:45 a.m. **Luncheon and SCI Gordon E. Moore Medal Ceremony**
Lecture by Jonathan McConnachie, recipient of the 2006 Moore Medal

2:00 p.m. **Breakout Sessions (see above)**

4:00 p.m. **Closing Plenary**
Moderator: Cyrus Mody, Chemical Heritage Foundation
Speakers: Klaus Heinzelbecker, BASF
Frankie Wood-Black, ConocoPhillips
Madeleine Jacobs, American Chemical Society