Research Frontiers

FOR THE CHEMICAL INDUSTRY

report on The First Annual CHF–SCI Innovation Day Warren G. Schlinger Symposium

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Innovation Frontiers in Industrial Chemistry

A report on the First Annual
CHF–SCI Innovation Day
14 September 2004

SUMMARY

Over the past century the chemical industry has been marked by transformations related to product and process innovations, the evolution of global markets, and the expansion of regulatory mandates. Today, the chemical industry faces a unique set of challenges from the rapid emergence of new fields and the maturing of existing methods for manufacturing. Based on findings from the first annual CHF–SCI Innovation Day, which explored frontier areas for industrial chemistry, this report argues that the industry's future lies in exploring diverse areas for research and development (R&D) rather than a narrow focus. As core inventors and manufacturers of the material basis of modern life, chemical firms are uniquely positioned to avoid waves of creative destruction prevalent in other sectors. By reinvigorating R&D, developing new markets, and engaging the public in a new dialogue about the risks and rewards of emerging technology, chemical firms can promote a new wave of innovation and rejuvenate the industry.

INTRODUCTION

The chemical industry has a rich history of innovation. As the first science-based industrial sector, it pioneered new materials for a wide range of consumer products, developed new production methods, invented the corporate research laboratory, and transformed consumer culture during the past 150 years. In that time the industry underwent major transformations related to new technologies, changing markets, and shifting relationships with purchasers and the public.

While a few chemical companies can trace their lineage to the extraction of minerals and the manufacture of steel, gunpowder, and other inorganic compounds in the early nineteenth century, many firms that survive today had their origins with the mass production of synthetic organic dyes and the founding of industrial research laboratories between the 1880s and 1920s. Innovations from corporate research divisions, in turn, led to the market introduction of synthetic fabrics and new polymers in the 1930s. By the 1950s and 1960s, petrochemicals—especially plastics—heralded a third major wave of innovation. Existing firms shifted their business models to production and sales of new materials and significant new companies were created.

In recent years, however, the chemical industry has been so oriented to the manufacture of commodity products that it appears to offer little room for innovation. As electronics, biotechnology, and nanotechnology increasingly capture the public's imagination, many analysts dismiss the chemical industry as mature. From their perspective, chemical companies should focus on cutting costs and improving efficiencies in order to stay competitive. Yet historically industries that enter a mature product phase are commonly displaced by new firms offering new products or manufacturing methods. This "creative destruction," to borrow a term that the economist Joseph Schumpeter coined in the early 1940s, is a recurring pattern in modern capitalist economies.[1]

INNOVATION CYCLES

The chemical industry is acutely aware of the potential for transformational innovations coming from other materials- and science-related sectors. If chemical companies do not offer new products and manufacturing solutions in such areas as energy, biotechnology, nanotechnology, and communications, other companies will. In some cases competitors have better reputations for environmental performance and higher public opinion rankings. These reputations increasingly correlate with investor confidence and support for new initiatives. Fortunately the industry can take steps to avoid or survive historic cycles of creative destruction. As inventors, manufacturers, and suppliers of core materials to other sectors, the chemical industry occupies a unique position. By reinvigorating R&D, developing new markets, and engaging the public in a new dialogue about the risks and rewards of emerging technology, firms can promote a new wave of innovation and rejuvenate the industry.

In fact the history of the chemical industry offers important lessons in this area. Unlike other sectors chemical companies have more nimbly weathered global social transformations. One of Schumpeter's insights, further developed by the economist Gerhard Mensch, was that radical transformations are often triggered by a process of "innovation bunching."[2] Small innovations slowly accumulate over years or even decades until, in the space of one or two "radical years," minor changes are rapidly coordinated into a single network of innovations that gives birth to a new industry, leapfrogging older sectors. This process was apparent in several of the transformative innovation complexes of the late nineteenth century—communications (telephone), electricity generation and transfer, and the internal

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[1] J. Schumpeter, *Capitalism, Socialism and Democracy* (New York: Harper & Brothers, 1942), 81–87.

[2] G. Mensch, *Stalemate in Technology: Innovations Overcome the Depression* (Cambridge: Ballinger, 1979), 124–135.

combustion engine. Likewise it emerged in biotechnology and information technology in the late twentieth century and may be coalescing in nanotechnology and energy sources (especially fuel cells) today.

One of the chemical industry's great strengths in moving from one wave to the next is that it contributes many of the small innovations necessary for building and sustaining a transformational wave, but individual chemical firms rarely take a leading role in tying minor innovations together into a new sector. Advances in chemistry were crucial to the insulators and capacitors for electricity transmission; the fuels, coatings, and alloys that enabled the automobile industry; the reagents and fermentators used in biotechnology; and the silicon wafers, photoresists, and etching acids employed in microelectronics. Yet the chemical industry has not become completely tethered to any one of these sectors. It may have lost some opportunities for prestige and profit as a consequence, but it is also less vulnerable to an individual sector's eventual eclipse. Intriguingly the chemical industry has avoided the fate of the upas tree—it has never grown so large in any one area that its shade has robbed the next generation of seedlings of the sunlight necessary for growth.[3]

As a crucial adjunct to this rapidly evolving array of sectors, the chemical industry has sometimes succeeded at strategically reinvesting innovation; new solutions devised for one type of customer have become the basis for advances in other areas. This process must continue for the chemicals sector to thrive. One classic example of how to do this is Gore-Tex, the well-known manufacturer of weatherproof clothing. Today, Gore-Tex has adapted its textile innovations to the health materials market, so that it will shortly make more money putting its fabric *in* people (as part of medical implants) than *on* them (as outdoor gear).

The chemical industry's success with flexible, iterative, service innovations that can aid a variety of sectors is perhaps most clearly visible in the emerging area of nanomaterials. Some nanomaterials have been in widespread use for fifty or even a hundred years—e.g., carbon black particles used in car tires as a reinforcing additive and titanium dioxide used in paints and coatings. Recent innovations suggest that markets for nanomaterials will expand significantly as new properties are engineered in the next ten to twenty years. Despite much hype for revolutionary, stand-alone applications, in the short- to medium-term nanomaterials will be part of other products, not the product themselves. Thus, the road to the market for many nanomaterials will almost certainly run through the chemical industry. Researchers and managers working the intersection of nanotechnology and chemicals manufacturing, such as Bob Gower of Carbon Nanotechnologies, are acutely aware of the need for new ways to speed and streamline innovation in the chemical industry so that it can remain at the forefront in supplying nanomaterials to manufacturers.

A second, closely related advantage of the chemical industry in weathering cycles of creative destruction is that its innovations are as much *process* as *product*. Chemical firms continuously

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[3] P. Hall, "The Geography of the Fifth Kondratieff," in P. Hall and A. Markusen (eds.), *Silicon Landscapes* (Boston: Allen & Unwin, 1985), 1–19.

create new, small-scale manufacturing transformations that bridge sectors. Each new process means reorganizing how customers make products and do business. With up to two hundred years' experience in connecting customers and teaching purchasers how to use chemicals to make consumer goods, chemical companies are network builders. The sector is, in some ways, an inventor of "methods of inventing."[4] By living with and generating minor transformations in products and processes, and by continually cultivating wide networks of customers, the chemical industry is prepared to deal with revolutionary, global transformations that burst forth after the accumulation of a critical mass of minor innovations.

Process innovations bring a complex mix of tangible and intangible benefits. Proponents of green chemistry, for instance, highlight process innovation as an important site for interaction between the chemical industry and the public. Since so much of the work of chemical companies is literally and figuratively upstream from consumers, the manufacturing process is crucial to public perception of the industry. Green chemistry may eventually offer process innovations that not only save money and reduce pollution but also may enhance chemical companies' legitimacy with the public and attract the best young, environmentally aware, chemists to work in the industry.

FRONTIER AREAS FOR INDUSTRIAL CHEMISTRY

The remainder of this report outlines specific areas of innovation that will be crucial as the chemical industry continues to ride transformative waves in coming decades. The global economy is clearly in transition, and many traditional industrial sectors, regions, and production chains show signs of giving way to newcomers. Chemicals and chemical engineering will remain crucial to the new economy. Will the current chemical industry or some variant of it survive, or will an entirely new set of competitors emerge to devise solutions to new problems? As part of an ongoing search for answers to this question, the first annual Warren G. Schlinger Symposium in September 2004 explored six key areas for chemicals innovation: future energy sources, health materials, bioindustrial technologies, green chemistry, nanomaterials, and photonics and optical electronics.

Future Energy Sources

In 2003 the United States consumed over 100 quadrillion BTUs of energy, yet only 6.3 percent was obtained from renewable sources. Steady growth of energy consumption in industrialized countries and rapid expansion in developing nations will outstrip the availability of supply from conventional sources in coming decades. Without innovations in materials, technologies, and markets, experts predict a significant crisis by 2025. Researchers in the chemical industry and at start-up firms are exploring methods for generating energy

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[4] Zvi Griliches, "Hybrid Corn: An Exploration in the Economics of Technological Change," *Econometrica* 25 (1957), 501–522; A. Chandler, *Shaping the Industrial Century: The Remarkable Story of the Evolution of the Modern Chemical and Pharmaceutical Industries* (Cambridge: Harvard University Press, 2005), 41–82, 114–143; G. Meyer-Thurow, "The Industrialization of Invention: A Case Study from the German Chemical Industry" *ISIS* 73 (1982), 363–381.

using fuel cells, photovoltaics, passive solar systems, wind turbines, geothermal heat pumps, and water-powered systems. Fuel cells, integrated hydrogen energy programs, and reduced-pollution coal gasification are currently among the most promising areas for environmentally friendly, high-efficiency sources of power generation. Innovative materials are essential for success with energy sources, yet changes in company organization will likely be needed as well for the chemical industry to move from large-scale commodity production into a specialty market characterized by high rates of materials re-use.

One pressing need is for cheaper and more durable materials for proton exchange membrane (PEM) fuel-cell components. At $200/m_, the current cost of the perfluorinated ionomer material constituting the majority of the membrane electrode assembly is prohibitive; a cost threshold between $\$7/\text{m}^2$ and $\$5/\text{m}^2$ is believed to be optimal by many experts. The replacement of expensive materials cannot be based solely on technical requirements drafted by fuel-cell makers, which in the past have produced the very dependency on such materials that has inhibited fuel-cell commercialization. Even the increased volume of special-purpose membranes and sealants that fuel-cell makers would potentially consume should they engage in large-scale production would be insufficient to tempt chemical firms to invest in developing and supplying such substances. Paradoxically technology advances resulting in ever-thinner membranes lower the total volume needed, making mass production even less likely. The solution is to obtain these materials from substances *already* in volume production for other applications. One consequence of this situation may be the rise of materials suppliers as indirect arbiters of fuel-cell design.

One useful strategy may be for potential fuel-cell system customers to collaborate with government and industry in relinquishing leading-edge internal combustion engine performance as the benchmark for commercial viability and set "technological plateaus" that would freeze research on these disruptive technologies at predetermined milestones in order to hasten their production. Still, internal combustion–based sectors—particularly the automotive industry—will necessarily influence fuel-cell development especially in such areas as metal hydride systems, a technology driven by volume and weight guidelines set by the automotive industry. The case for metal hydrides depends on comparisons with compressed and liquefied hydrogen storage systems, which are lightweight and have fast response times but are also bulky and not conducive to noncylindrical tank configurations. In addition there are real and perceived safety issues with compressed hydrogen, while liquid hydrogen has limitations in storage, liquefaction, and boil off. In contrast metal hydrides store hydrogen at lower pressures and near-ambient temperatures and have the potential for higher densities than liquid-state technology. Such firms as GE Global Research are currently using high-throughput screening to isolate suitable hydrides from millions of possible compounds.

Fuel-cell firms (especially small ones) are now facing a delicate transition, from making advanced prototypes and demonstration units to marketing products. However much they might want to move toward the latter, for the time being they specialize in the former. Acquisition of the materials to make this transition possible is framed by interlocking social, political, and economic constraints. Only innovation strategies that account for social, cultural, political, and economic factors (which vary significantly by region and over time) will be successful.

For instance, a consensus is forming that stationary fuel-cell applications will be marketed before those in the transportation sector because of simpler technical and production requirements. For some firms, this market requirement means tailoring products to regional consumer cultures and existing infrastructures. Ballard Power Systems, for example, plans to enter a Japanese household market characterized by small homes and natural gas heating, factors that informed development of the 1 kW cogeneration unit the company hopes to introduce over the next several years. However, technological barriers remain. Ballard is working to improve its demonstrated 15,000-hour stationary cell lifetime to a commercial standard of 40,000 hours. In the storage sector metal hydrides are currently too heavy for light-duty vehicles but may be suitable for trucks and buses, where adoption may depend on government intervention via subsidies and fleet purchases.

Thus, there is no single material or technological solution to placing disruptive energy technologies in production. Meeting materials demands for commercialization will be an exceedingly complex task requiring all participants in the development-production chain to share a systems perspective in seeking new applications for existing volume-produced materials in hydrogen power and storage technologies.[5]

Health Materials

In recent years breakthrough innovations in medical devices, DNA-based diagnostics, and the manufacture of vaccines and therapeutics in organic systems (plants) have relied on advances in materials science and chemistry. As medical innovation continues, the need for specialty chemicals and polymers will increase, and the health-care community will rely more heavily on the chemical industry to drive the advancement of these materials. Currently the United States produces half of the world's health materials and consumes nearly 40 percent. Forecasters predict that the market for medical devices in the United States will reach $74.5 billion in 2005 and $109.5 billion by 2010.

Chemists' and the chemical industry's expertise in both process and product innovation will be crucial to meeting this market need while ameliorating troubled health-care systems. By learning the language and practices of other disciplines (e.g., botany, medicine, rural sociology, or physics), chemical industry researchers and managers can tweak familiar processes and products to speed innovation in new fields. For instance, on the process side, molecular farming (or "pharming") relies on an analogy between what (biological) plants do and what the chemical industry does. After all, both biological and chemical plants take in raw materials, pipe them to centers of production, synthesize them into complex molecules, and then transport those molecules to places where they can serve a variety of purposes:

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[5] Technological "systems" are engagingly analyzed in T. P. Hughes, *Networks of Power: Electrification in Western Society, 1880–1930* (Baltimore: Johns Hopkins University Press, 1983).

energy production and storage, communication, chemical defense, etc. Thus, molecular farming tries to incorporate crops into the manufacturing process by letting them do much of the synthesis that more traditionally engineered chemical plants are not yet able to do on large scales.

As with all challenges to chemical innovation, complex (and evolving) social, cultural, political, and economic factors are relevant to molecular farming. The field may be ready for maturity only because the decline of small farms means that agriculture—at least in North America—has mastered large-scale production in ways that make it compatible with the large-scale manufacturing of the chemical industry. With this opportunity comes a challenge: large agricultural companies like ADM stand ready to turn their farms into molecular factories and edge out traditional chemical and pharmaceutical firms with cheaper, purer, more effective products such as vaccines and industrial enzymes.

If molecular farming is a feasible innovation, the chemical industry needs to take advantage of the technique now, or someone else will. Yet the industry must be wary. The intersection of cutting-edge science and corporate agriculture produced the most intense public scientific controversy of the past decade in the debate over the use of genetically modified organisms (GMOs) in food products. One progressive way to avoid such controversy is careful, critical research in which possible dangers are thoroughly investigated and transparently dealt with, where experiments are chosen with an eye to calming public fears. For example, Barry Marrs and collaborators at the Fraunhofer Center have tried to avoid the pitfalls of GMOs by focusing on the technique of "transient gene expression," that is, exposing plants to specially constructed viruses to introduce new genes somatically, rather than permanently changing the entire genome of the plant (and all its descendants).

On the product side innovation in health materials can come from reexamining the properties of familiar chemicals through the lens of medical knowledge and adapting these chemicals to radical new applications. Some well-known materials are (with small modifications) finding new lives as contrast agents for magnetic resonance imaging (MRI) and potentially revolutionizing medicine in the process. MRI images are enhanced not by imaging the contrast agent *itself* but through the effect of the contrast agent on the water in the system. Recent advances in synthesizing contrast agents that block more water, combined with dramatic enhancements in MRI technology, allow production of images with cellular resolution (35–40 micron) over time in living subjects. This brave new world for MRI is based on contrast agents designed with high tissue/target specificity. By tagging contrast agents to activate only when particular genes or biological processes are active, researchers can now generate real time, three-dimensional, cellular-scale images of gene expression and molecular pathways. Even in its current stage this tool could be valuable both in early diagnosis of such complex diseases as cancer and Alzheimer's and in targeted delivery of drugs.

The lesson for the chemical industry, then, is to think more widely and in more spontaneous and serendipitous fashion about the uses of its products. The chemical industry possesses extensive expertise in synthesizing very complex molecules quickly, in few process steps and at large scales. Creative uses of classes of molecules, such as contrast agents, can rapidly open up large areas of research and manufacturing to the industry. The barriers in product application innovations are cognitive as much as societal or regulatory. Contrast agent research allows doctors, biologists, and chemists to *see* the world much differently than they ever have before. Getting people accustomed to this new vision—or, more generally, to new uses for old products—will take some effort.

The effort is clearly worth it, though. The backdrop for process and product innovations in health materials is the cripplingly rapid rise in the cost of health care. The chemical industry has the know-how to slow or even reverse that rise. New ways to think about the pathways for production of pharmaceuticals can dramatically lessen the manufacturing costs of drugs. New ways to think about the products the chemical industry already makes can allow us to make diagnoses earlier (before symptoms even appear in blood-based tests) and more accurately (reducing the 20 percent of hospital fatalities that are caused by medical error). These and other advances are within reach of the chemical industry even today, yet they are also within sight of other, competing sectors. Nimble navigation of potential barriers (regulatory, social, and cognitive) will be necessary to keep the chemical industry ahead of the game.

Green Chemistry

Green chemistry represents a significant advance for chemical science and manufacturing. Rather than focusing on the control and cleanup of waste and hazardous materials, this field redesigns industrial products and processes to reduce the quantity of material inputs and minimize environmentally detrimental outputs. When successfully implemented, green chemistry generates advances in environmental protection at low cost and with net economic gain. Over the past decade breakthroughs have been made in the use of nonhazardous solvents, reactants, and catalysts, as well as in bio-based processes. These innovations are providing chemical companies with business opportunities in both traditional and new markets. Green chemistry is also attracting young scientists to industrial chemistry, since it offers original solutions to environmental concerns.

In 2003 the chemical industry spent $14.3 billion for environmental health and safety, using innovation and production models that resolve environmental concerns at very late stages in development. Green chemistry (as defined by the Twelve Principles of Green Chemistry) offers the chance to reduce that expenditure by bringing environmental considerations into the very first steps of innovation and production.[6] This has the added advantage of shortening time to market as well. Yet green chemistry has long been dogged by suspicions that it is an immature, uneconomical field. One sign that this is changing is the founding of graduate programs specifically in green chemistry. The University of Massachusetts at

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[6] See the EPA Green Chemistry Web site www.epa.gov/greenchemistry/ or the American Chemical Society's Green Chemistry Institute Web site, www.chemistry.org/portal/a/c/s/1/acsdisplay.html?DOC=green chemistryinstitute\index.html.

Lowell, for instance, has recently founded a Ph.D. program in the field. Over one hundred students have now completed the program, which consists of three components: research (done in a holistic and multidisciplinary manner), education and outreach, and industrial collaboration. These students have been at least as successful as others in finding employment, belying the idea that industry will be reluctant to hire students trained in this way.

Still for green chemistry to mature and become more viable, it needs new tools, that is, more solvents and processes that can substitute for hazardous pathways traditionally used in the chemical industry. As such tools are developed and implemented, institutional support for green chemistry will likely grow. For instance, Joseph DeSimone and his colleagues at the University of North Carolina have developed a new process for polymerization of tetrafluoroethylene and comonomers (Teflon) that avoids the use of such controversial surfactants as C-8. Using this new process DuPont was able to construct a plant that was 20 percent less expensive to build and 20 percent cheaper to operate, thereby avoiding the loss of jobs to overseas sites. Other tools may grow out of small, almost grass-roots changes in commercial practices. For example, DeSimone has developed and helped commercialize a dry-cleaning process that eliminates the use of perchloroethylene. In the United States dry-cleaning is a $24 billion business with over 100,000 machines, 90 percent of which use perchloroethylene. A new line of dry cleaners called Hangars has started 100 franchises that use carbon dioxide rather than perchloroethylene. Supporters of green chemistry have secured small-business loans for dry cleaners to promote greener laundry.

Significant barriers do exist for the implementation of green chemistry–based processes. Competing business interests have retarded the growth of carbon dioxide–based dry cleaning. Even in markets without such competing interests, customers may not approve of change in product properties that result from a switch to green chemistry–based processes. Still the U.S. chemical industry must be ready to act or someone else will; given the potential for saving money at all points of the innovation and production process, American companies must be wary of falling behind Japanese and European firms that may already be required by law to conduct green chemistry research.

Bioindustrial Technologies

Technologies to apply living organisms to chemical manufacturing processes have made major advances in recent years. Biotechnology has been used in the chemical industry to produce PLA polymers, 1,3-propanediol, and ascorbic acid from corn sugars and starches. Bio-based techniques are being used to create specialized enzymes that synthesize chemicals without fermentation. Genetically modified plants, protozoa, and algae can now produce novel resins and polymers. Based on biotechnology's potential to reduce harmful waste and emissions, decrease dependency on nonrenewable raw materials, lower operating costs, and facilitate the production of complex specialty chemicals, some analysts predict that these new technologies will affect 10 to 20 percent of total chemical industry revenues by 2010. Much research in this area aims to achieve sustainability with new bio-based technologies.

Thus bioindustrial processes should be tailored to the three "legs" of sustainability: greater functionality, lower cost and investment, and a smaller environmental footprint.

Of course neither sustainability nor bioindustrial technology is entirely new. Bio-based materials have been used in the chemical industry for many years, for example, in processes that convert cellulosic materials into a variety of products. New research at Dow and elsewhere is expanding the use of cellulosic materials as backbones for long-chained molecules. Not only is there an abundance of these materials in our environment, but their unique structures and properties can be utilized to synthesize highly specialized molecules. Other firms are investigating how to turn traditional agricultural products (or by-products) such as soybean oil and chicken feathers into chemical feedstocks. The technology needed to create a potentially enormous bioindustrial technology market exists today. To innovate in this market, however, requires that companies prove that their bio-based technologies outperform traditional products. Unless the wider public comes to demand bio-based products even in the face of higher prices and lower quality, chemical companies will need to radically improve cost and performance of these materials. So far, except where the consumer is the government, marketing products as bio-based has not provided an advantage.

Another challenge lies in adapting the large and complex petrochemical infrastructure as a support system for bio-based technology. Shifting the mindsets of the major players in such an established and influential industry is daunting and may not be accomplished without significant disruption. The petrochemical industry may be persuaded by younger generations of consumers, many of whom support making industrial manufacturing more environmentally friendly.

Even here challenges remain. Although the products of bio-based technology originate from naturally "recyclable" materials, after processing these materials may lose some of their ability to biodegrade. Synthesizing molecules to be better performing, stronger, and longer lasting may result in products that are difficult to dispose of, thereby reversing the environmental benefits of using bio-based materials. Ironically, designing bio-based materials to capture public enthusiasm may undermine the goal of creating demand from industry, since the properties each are looking for are not always complementary (e.g., rapidly biodegradable versus stable and long lasting). At the same time there is no governmental regulation to force research on the life cycle of bio-based products—companies like DuPont choose to study these issues voluntarily.

As in molecular farming, bioindustrial technology raises important issues surrounding the relationship between the chemical and agricultural industries. If bio-based technology becomes an important manufacturing tool, will large chemical companies own and operate farms? How will the use of corn and soy as chemical feedstock affect the supply for consumption? As it appears now, using bio-based feedstocks, especially corn, will not have a negative effect on the food supply. Moreover, as the industry grows, chemical companies will depend more on biomass (stalks, leaves, etc.) than on the edible portions of the crops.

Even at maximum production chemical companies will not overtake the agricultural industry nor displace the farmer. Instead, farmers will have the opportunity to become more entrepreneurial, perhaps forming collaborations with chemical companies. Chemical companies that own seed companies or have established ventures with agricultural businesses will be at a definite advantage if crops become the primary feedstock for chemical manufacturing. For example, if farmers purchase seeds from DuPont subsidiary Pioneer Hi-Bred International to produce crops for DuPont's chemical business, DuPont will have boosted its seed business while providing a feedstock for its chemical business.

For the bioindustrial sector to flourish the nation's dependency on petroleum will need to be modified. While bioindustrial research continues to produce molecules and materials that are proven functional replacements for many traditional oil-based products, the demand is not evident at this point. Many scientists in the chemical industry are relatively unconcerned, however, because they are confident that rising oil and natural gas prices will continue to drive bioindustrial business, eventually forcing the public to make the transition. When government, industry, and the public accept the reality of this crisis, the chemical industry will be able to build the support system needed to make bioindustrial technology a sustainable business.

Nanomaterials

There has been much hype about the novelty of nanotechnology in recent years, and expectations are running high for breakthrough products in such diverse areas as microrobotics, manufacturing, and health care. Yet chemists have worked on nanoscale materials for at least a century. Current nano concepts may lay the groundwork for a new industrial revolution, but to succeed the field will need to focus on the core chemistry of such nanomaterials as dendrimers, nanotubes, nanopowders, and quantum dots. Practical applications will likewise necessitate successful scale-up from the laboratory to mass production.

Clearly the chemical industry possesses a vast well of expertise that should be crucial in making nanomaterials marketable. As Bob Gower of Carbon Nanotechnologies puts it, "No area of technological innovation has greater potential to transform the chemical industry—and society more broadly—than nanotechnology. No industry is better positioned to exploit the revolutionary potential of nanotechnology than the chemical industry. If the chemical industry does not step up to the plate and change its approach to innovation, however, others will get there first."[7]

The ability to manipulate matter at the nanoscale offers tremendous opportunities for technological change and industrial application. Exploiting such innovations will require skills that range from innovative idea development and testing to intellectual property protection, process and product development, safety, market development, initial sales,

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[7] Bob Gower, "Innovation and Opportunity in the Chemical Industry," (Keynote Address, Innovation Day, CHF, Philadelphia, 14 September 2005).

scale-up, and capital investment. Though start-up companies will undoubtedly help push development in this area, the skills and the human and financial resources to apply them successfully lie with the mature firms that make up the chemical industry. Yet without the discipline and entrepreneurial activity to take advantage of their competitive edge, the chemical industry will lag, not lead, the nanotechnology revolution.

Even discounting for hype, this revolution does hold significant promise. The U.S. government estimates nanotechnology will be a $1 trillion industry by 2020. Through the 21st Century Nanotechnology Research and Development Act, federal grants will run to $4 billion over the next four years for nanoscale science and engineering, and Japan and Europe will each invest comparable amounts. Fortunately the chemical industry is already positioning itself to take advantage of this new research through the *Chemical Industry R&D Roadmap for Nanomaterials by Design*, which emphasizes a strategy based on materials manufacturing and processing, characterization tools, modeling and simulation, and basic ideas.[8]

Most federal funding will be directed to academic research. To bring new nanomaterials to market will require constructing new ways to organize linkages between corporate and academic institutions and new ways to spin innovations from one domain to the other. Chemical firms and universities will need to collaborate in new ways, perhaps by focusing corporate research to meet short-term financial accounting constraints, while increasing corporate sponsorship of academic chemistry for innovations with a ten-year or greater pipeline to market.

Somewhat surprisingly the overlap between traditional chemistry and nanotechnology may represent a significant barrier to the chemical industry's activity in this area. Many chemists are skeptical of the need for a new field of nanotechnology, since their firms have been producing tons of "nanomaterials" for almost a century. One way for companies to bring the traditions of chemistry together with the freshness of nanotechnology may be to see the development of nano as a two-stage process. The first stage will involve modification and enhancement of existing products, followed (perhaps much later) by introduction of next generation technologies. Viewed this way, nanotechnology may be invigorating, rather than disruptive, for the chemical industry.

As in all innovation areas, though, nanotechnology will need to show firm evidence of its advantages over existing processes and products—particularly in cost versus performance. It is currently unclear whether nanotechnologies can generate either sufficiently inexpensive materials or sufficiently high value so that customers would be willing to pay elevated prices. Moreover many nanotechnologists worry that, even if such benefits emerge, nanotechnology will face similar levels of public concern and possible backlash as genetically modified crops.

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[8] Chemical Industry Vision2020 Technology Partnership, *Chemical Industry R&D Roadmap for Nanomaterials by Design: From Fundamentals to Function* (Chemical Industry Vision2020 Technology Partnership, 2003), www.chemicalvision2020.org/pdfs/nano_roadmap.pdf.

Already toxicological studies that show potentially harmful environmental and health effects are generating some public outcry.

Photonics and Optoelectronics

Chemists, physicists, and materials scientists working in the photonic and optoelectronic fields during the past three decades have contributed to lasers, fiber optics, and digital cameras, displays, and storage media. Research today is oriented to such innovative and varied applications as advanced waveguide technologies for routing optical signals in new ways; organic light-emitting diodes for displays; optoelectronic devices that can integrate multiple functions on a single substrate or chip; and, ultimately, the photonic analog of today's solid-state electronic transistors. Leading-edge industrial and academic research in this field will find applications in information technology, medicine, sensors, displays, consumer electronics, and other areas. As these applications develop, chemical and materials science companies are realizing the benefits of orienting R&D to optoelectronic and photonic materials and devices.

A consensus has emerged that the boom-and-bust cycles of the past decade have left the optoelectronics industry in need of radical restructuring to reinvigorate itself and become profitable. Less clear, though, is where the impetus for this restructuring will come from or what shape it will take. One option would be for the government to fund a reorganized infrastructure, as in Korea, Japan, and China. The need for a government role is driven by the fact that start-up companies and venture capital firms have not been able to fill the niche left by the collapse of Bell Labs (long a leader in optoelectronics), largely because innovation in this area requires long-term commitments and large teams. In its heyday Bell Labs was often viewed by government, industry, and academia as a *de facto* national laboratory, mandated by AT&T's special position as a large regulated monopoly. Thus one possibility would be for government to provide the long-term, high-quality specialized resources once found at Bell Labs, as it is doing in nanotechnology through the founding of nanoscale science and engineering centers on university campuses.

Another hoped-for driver for optoelectronics would be the discovery of a "killer application" that would attract the patronage of a large company such as Intel, Sony, or Apple. Indeed, a common refrain is that optoelectronics needs bigger, rather than more, firms, as there are currently too many small players in telecommunications, leading to short, unsustainable product development timetables. Another possibility would be to develop an industry-wide consortium, on the model of Sematech in the microelectronics industry, that would set standards and map out developments. The optoelectronics industry badly needs standardization and road maps to grow to the $20 billion level believed to be needed for a self-sustaining, continually reinvesting sector.

Given the need for a reorganization of optoelectronics activity, the chemical industry has an exciting opportunity in two different roles: either in providing much-needed new materials or, higher up the value chain, in devising, manufacturing, and even marketing end-user-driven high-profile applications. In materials there is a pressing need for ways to integrate optoelectronics with more traditional silicon devices. Intel, among others, has quite reasonably bet that optoelectronics will never be reliable, functional, and cost-efficient until optoelectronic materials can be married with the massive knowledge, skill, and industrial infrastructure surrounding silicon. This marriage could take a variety of forms—silicon as a light emitter and modulator, germanium and gallium arsenide lasers laid on silicon through heteroepitaxy, and nano particles to increase refractive index without increasing scattering are but three proposed examples. Low-cost disposable optoelectronics will also be crucial, which may indicate a role for the plastics industry in polymer waveguides and low-cost polymer lasers or for other chemical firms in manufacturing filters and bandgap materials from block copolymers or signal switching devices from liquid crystals.

More broadly, however, the chemical industry can bring its traditional knowledge of how to supply materials to other industrial sectors into its role in optoelectronics. Optoelectronic components will clearly find dramatic uses in many of the sectors where chemical firms already provide materials; chemical firms are well placed to identify, develop, and manufacture new applications that heighten the value of optoelectronics to those sectors. In the entertainment industry, for instance, optoelectronics can help satisfy consumer demand for high bandwidth, high-quality digital video interfaces. In the automotive industry optoelectronics can be used for optical interconnects ("drive by wire") as well as for new types of information displays. Obviously telecommunications will continue to be a major sector, with the potential of achieving low-cost video communication anywhere, anytime, for anyone. The biomedical industry, too, is keen for new kinds of displays, as medicine becomes an even more information- and image-intensive field than it now is. Finally optoelectronics *may* provide the change of paradigm long dreamed of for the microelectronics industry—with a shift away from ever denser chips to more parallel processing (or some combination of the two).

COMMONALITIES ON THE RESEARCH FRONTIER

The chemical industry is at the threshold of a fourth major innovation wave since its emergence in the mid-nineteenth century. Unlike previous turning points that were characterized by a single major product type—dyes, synthetic fibers, or plastics—current opportunities are spread across a broader spectrum of emerging areas. If the industry is to ride this wave, rather than be overwhelmed by it, chemical firms will need to understand what is common to emerging areas and what is distinct about each of them. Understanding why some areas move faster than others and assessing what market potentials are opened by technology advances will help firms choose where to invest resources.

Historical perspective suggests that innovative firms can be captured by their success; a mix of narrowing technological advances and high profitability make it difficult for firms to prepare for disruptive change.[9] Unfortunately neither managerial experience nor case histories provide a clear map to navigating through the current innovation wave. Industry-transforming events happen far enough apart in time that few current executives can apply personal lessons from, for example, the introduction of plastics and other petrochemicals. Innovations, or bundles of innovations, are transformative when they present radical shortcuts through the usual way of doing things. Thus lessons of past transformations must be carefully adapted to the current wave, and firms must be willing to discard trusted knowledge if it is not relevant to new circumstances. Creative destruction, as Schumpeter noted in 1942, is by its nature chaotic and hard to predict, especially in terms of timing and magnitude.

For industry leaders and technology managers, a new set of analyses needs to combine the attention to detail found in sociology with economists' understanding of markets and business sectors. Innovation Day offers an important data set for understanding research frontiers and their potentially transformative influence. As it is further developed in coming years, Innovation Day's Warren G. Schlinger Symposium will form the basis for a new set of case studies that can help managers assess the kinds of innovations now critical to the chemical industry's future.

Based on the first Innovation Day, we can identify two seemingly opposed features that help to frame and characterize frontier research. First, speakers and audience members at Innovation Day frequently evoked a sense of decline, crisis, and decay in the chemical industry. Based largely on external portents of disaster, this aspect of the industry today can provide ground rules of sorts for a research frontier, making clear the urgent need for a radically new way of doing things. Green chemistry, for instance, offers not just a way to deal with a looming environmental crisis but may also help demonstrate the chemical industry's commitment to better corporate citizenship and help solve the chemistry profession's demographic crisis brought on by a failure to attract younger practitioners.

Similarly, research in biomaterials and future energy sources is grounded in fears of declining petroleum reserves, health materials work taps into front-page narratives of an impending health-care disaster, while nanotechnology and optical electronics are heralded as possible answers to the inevitable demise of Moore's law. Narratives of impending doom, of course, are easily exaggerated and can be countered with alternative data and interpretations. Gloomy predictions of the end of Moore's law go back almost as far as the law itself; in microelectronics, science and technology always seem about to hit a limit, yet miniaturization has continued to accelerate for almost five decades. Likewise, fears of energy supply shortages have been around for over a century, and a long succession of "future" energy sources have been promoted as the solution. As *The Economist*, among others, has recently

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[9] C. Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Boston: Harvard Business School Press, 1997), 3–110.

pointed out, "for the past half century, fusion advocates have claimed that achieving commercial nuclear fusion is 30 years away."[10]

Even though catastrophic narratives are fallible, they are still a powerful way to foster a new technology. Alarm can open opportunities for new technology to be adopted more quickly and for companies to take risks. At the same time, continual alarm can lead to a loss of legitimacy, particularly if events show that crises are not as imminent or as severe as alarmists claim. This dilemma opens a space, we believe, for analyses of recent history to supplement chemical industry strategy. Contemporary history is a resource like any other for firms that are positioning themselves before the next innovation wave; firms that can back their pronouncements and decisions with sophisticated recent historical studies will stand a better chance of carving a niche for their innovations.

The second feature—intriguingly a mirror to the declensionist narratives—that defines frontiers and plays a critical role in industry business decisions is an optimistic view that technology and experience will come to the rescue just when they are needed. Innovation waves can be triggered by real or perceived crises, but they cannot move forward if no innovations are deemed relevant to those crises, or if the innovation area is not yet ready for commercialization. Thus many of the areas addressed during Innovation Day are beginning to attract significant discussion because participants feel these fields are only now mature enough to become frontiers. Maturity seems to be marked by a number of signs, each of which calls for further investigation; green chemistry, for instance, is now mature because sustainable graduate programs have been established in the area; nanomaterials are reaching maturity because there is coherent federal support and a mix of markets and venture capital underwriting of activities in the area; fuel cells and a few other future energy sources are deemed mature because they have moved past the "proof of concept" phase into a period of developing lower-cost manufacturing methods.

Firms can stake their claims to frontier research through a clever pairing of these two kinds of narratives: a story of impending crisis and a story of technological solutions ready just in time. Yet such pairings are often fragile; even if consensus is forged that there is a crisis (for instance, in health care), people may not be able to agree that a particular research frontier is the solution. Indeed, in health care, the costs of implementing new technologies may contribute to the financial crisis plaguing the system. In other cases—nanotechnology being perhaps the most prominent—a research frontier may be widely regarded as valuable and interesting, yet there is little consensus on what, if any, crisis it will solve.

In many cases transformative innovations come where the rhetoric of a particular crisis is flexible enough to temporarily accommodate many different solutions. In normal circumstances solutions will be offered by a variety of firms within a *single* industry, and ordinary market forces will identify which solution is satisfactory to most people. But in a frontier area, solutions can be offered by firms across a wide range of industries.

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[10] "Fusion Power: Nuclear Ambitions," *The Economist* (2 July 2005), 71.

Competition was, indeed, a recurring theme of Innovation Day. In almost all the panel discussions warnings were repeated that if the chemical industry does not come up with innovations, other industries will.

Frontiers, by their very nature, are open-ended; no one knows exactly where the boundaries will eventually be drawn and what industries will eventually sit side-by-side as neighbors. This is in marked contrast to more ordinary circumstances, where "boundary work" involves tinkering with or maintaining distinctions between fields that are already known to have some relation to each other.[11] In a frontier situation various industries jockey to decide what, if any, relation they will have when the frontier closes, whether collegial, competitive, customer-client, or some mix of the three. This can then be a time of creative destruction. The frontier opens, firms and industries lose the security of knowing they are relevant to a particular area, and clever inventions can be sped through the industrial innovation pipeline.

The frontier holds a strong attraction, particularly in the United States, where a frontier mythology was long central to national self-image. In a global era such myths have a currency that pushes beyond national borders. Indeed the globalization of commerce indicates that the last frontiers left are not geographically unexplored territory but symbolic areas of unexplored intellectual or entrepreneurial activity. Research frontiers present an opportunity to remake old rules and expand horizons; in the chemical industry's case, the challenge is to transform its traditional research and manufacturing methods for emerging twenty-first century environments.

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[11] T. Gieryn, *Cultural Boundaries of Science: Credibility on the Line* (Chicago: University of Chicago Press, 1999), 1–35.

SCHEDULE OF EVENTS

Warren G. Schlinger Symposium
14 September 2004

8:00 A.M. **Plenary Session 1: Opening Keynote Address**

Bob Gower, Carbon Nanotechnologies

9:30 A.M. **Breakout Sessions**

Future Energy Sources
Moderator: Paul Clark, NOVA Chemicals
Speakers: Job Rijssenbeek, GE Global Research
Charles Stone, Ballard Power Systems

Health Materials
Moderator: Mani Subramanian, The Dow Chemical Company
Speakers: Barry Marrs, Fraunhofer CMB
Thomas Meade, Northwestern University

Bioindustrial Technologies
Moderator: Ray W. Miller, DuPont
Speakers: John Klier, The Dow Chemical Company
Richard Wool, Cara Plastics

Green Chemistry
Moderator: Jim Alder, Celanese Chemicals
Speakers: Joseph DeSimone, University of North Carolina
John Warner, University of Massachusetts Lowell

Nanomaterials
Moderator: Miles Drake, Air Products and Chemicals
Speakers: Arthur B. Ellis, National Science Foundation
Robert Kirschbaum, DSM Venturing

Photonics and Optoelectronics
Moderator: Gary Calabrese, Rohm and Haas Company
Speakers: Stan Lumish, JDS Uniphase
Lionel “Kim” Kimerling, MIT

11:45 A.M. **Luncheon and Gordon E. Moore Medal Ceremony**

Lecture by George Barclay, recipient of the 2004 Moore Medal

1:30 P.M. **Breakout Sessions (see above)**

3:30 p.m. **Plenary Session 2: Panel Presentation and Open Discussion on the Frontiers of Chemical R&D**

Moderator: Parry Norling, CHF
Speakers: Jim Alder, Celanese Chemicals
Paul Clark, NOVA Chemicals
Miles Drake, Air Products and Chemicals
Ray W. Miller, DuPont
Mani Subramanian, The Dow Chemical Company
Gary Calabrese, Rohm and Haas Company

About Innovation Day

The chemical industry faces many challenges and opportunities at the start of the twenty-first century, including the rapid emergence of new fields and the maturing of existing methods for research and manufacturing. Only a renewed focus on innovation will harness promising technologies and spur industry growth. To promote early career innovation, the Chemical Heritage Foundation (CHF) and the Society of Chemical Industry (SCI) jointly organize an annual Innovation Day, consisting of the Warren G. Schlinger Symposium, Gordon E. Moore Medal presentation, and Perkin Medal award ceremony. The Schlinger Symposium brings together promising early career scientists and technology leaders from across the chemical industries to focus on frontiers of chemical R&D. Plenary and breakout sessions are oriented to areas where the chemical industry interfaces with other emerging business sectors. In combination with the medal ceremonies, the Schlinger Symposium offers attendees the opportunity to learn about cutting-edge science and technology, exchange ideas with peer industrial researchers and entrepreneurs, and prepare to be innovation leaders.

About the Chemical Heritage Foundation

The Chemical Heritage Foundation (CHF) serves the community of the chemical and molecular sciences, and the wider public, by treasuring the past, educating the present, and inspiring the future. CHF maintains a world-class collection of historical materials that document the history and heritage of the chemical and molecular sciences, technologies, and industries; encourages research in CHF collections on topics of strategic interest to CHF; and carries out a program of outreach and interpretation in order to advance an understanding of the role of the chemical and molecular sciences, technologies, and industries in shaping society. CHF's Center for Contemporary History and Policy conducts research, publishes reports, and organizes conferences that bring long-range perspectives to bear on topics in risk, regulation, innovation, and industrial research.

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