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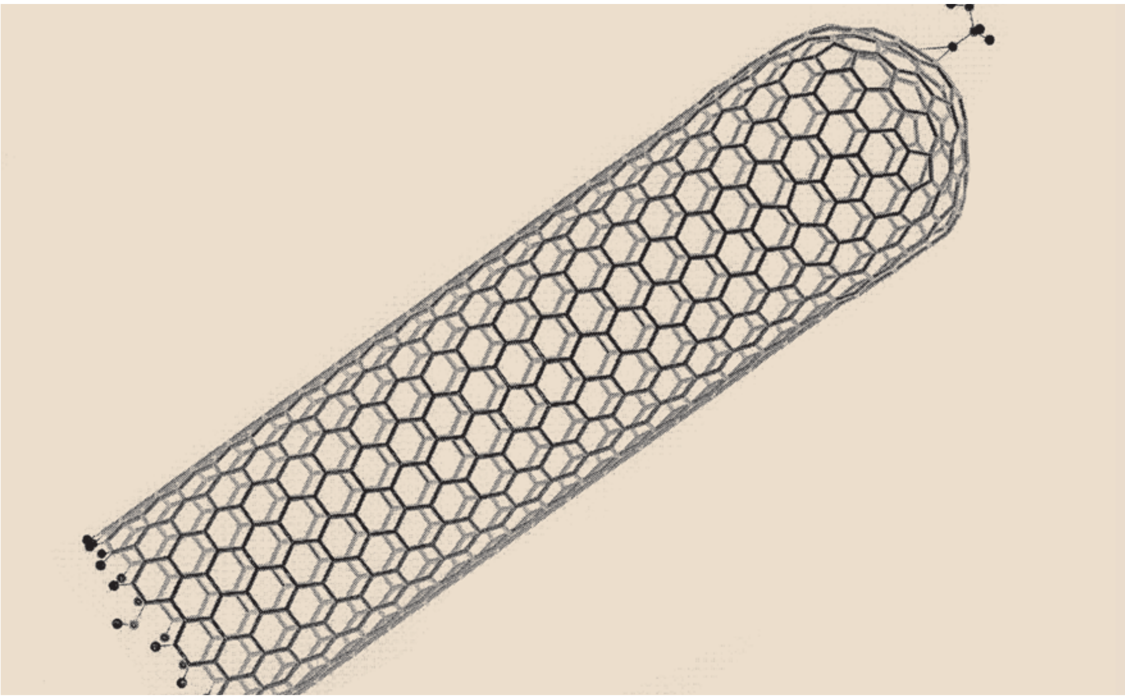
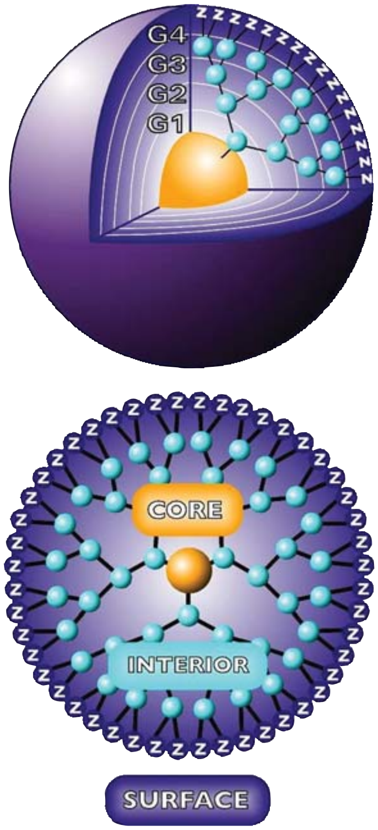
Studies in Materials Innovation

Co-Innovation of Materials, Standards, and Markets: BASF's Development of Ecoflex

Arthur Daemmrich





Chemical Heritage Foundation

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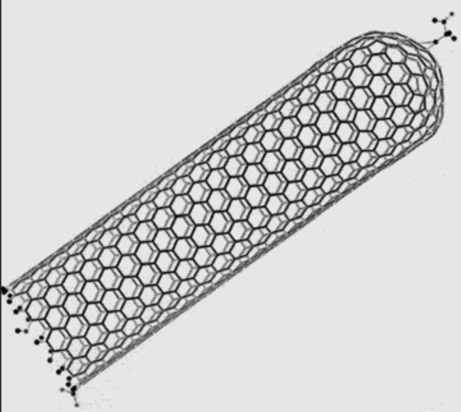

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I. SUMMARY

Product innovation in the chemicals sector today requires not just scientific and technological advances but also compliance with standards and regulations, along with marketing to sophisticated intermediate firms and end users. Yet the very novelty of new materials often means that product standards, health and safety regulations, and consumer markets are underdeveloped or absent. For new materials that offer environmental advantages over existing products, a lack of widely accepted product standards can doom market introductions.This report presents a case study of Ecoflex, a biodegradable polymer manufactured by the German chemical company BASF. The case illustrates how near-simultaneous development of the molecule, standards, and user communities distinguished Ecoflex from competitors' offerings and fostered flexible thinking about its market identity. BASF worked closely with academic scientists and standards agencies to develop measures of biodegradation, even as it synthesized and scaled up production of the new polymer. Internally, the company found it critical to have a small, focused team to develop, manufacture, and market a product whose sales had a modest impact on the overall bottom line. Externally, although BASF intended Ecoflex to be decomposed in new large-scale compost systems built in Europe during the 1990s, the company found it challenging to differentiate its product from other plastics that were separated from waste streams. Faced with possible market failure, BASF worked with its first-tier customers to develop alternative uses for Ecoflex and convince plastic-film consumers of its virtues. Overall, the case presents complexities associated with green-product introductions and suggests ways for chemical companies to overcome the inertia associated with innovations whose anticipated markets fail.

II. INTRODUCTION: POLYMERS IN PERSPECTIVE

For over a century synthetic polymers have been designed to resist nature's ravages. Measures of successful innovation in plastics have included reduced solubility, protection against breakdown by sunlight, simultaneous flexibility and hardness, and other features that extend the material's life. In recent years, however, efforts have been made to create plastics that will break down into harmless natural materials. This white paper presents a case study of the invention and development of Ecoflex as one of this new generation of biodegradable polymers.

The history of polymer research as an applied science sheds little light on the transition to degradation as a desired property, since the primary goal of researchers and manufacturers was to make materials more robust. The first commercially produced polymer was invented by John Wesley Hyatt after extensive empirical experimentation on a variety of substances. Hyatt's initial ambition was to win a $10,000 prize announced in the mid-1860s for a material that could replace the ivory then used to make billiard balls. In 1869 Hyatt created a material later called celluloid and founded a firm to commercialize his novel synthetic process. He would later develop a number of other processing methods for plastics.[1] Leo Baekeland's successful creation of a hard insulating material (Bakelite) in the early 1900s introduced the first high-temperature "thermoset" resin characterized by incredible durability. Unlike celluloid, which was made from plant-based cellulose and camphor, Bakelite was chemically synthetic, the product of a condensation reaction between phenol and formaldehyde.

Organic chemists in Germany, England, and the United States were intrigued by these inventions and carried out research leading to new theories on macromolecular structure, bonds, and the underlying process of polymerization.[2] Hermann Staudinger's explanation in the late 1920s that polymers consist of molecules linked by chemical bonds into long chains clarified what held polymers together and stimulated more systematic research into synthetics.[3]

New generations of polymers were brought to market in the 1920s, including synthetic rubber and vinyl chloride, and the 1930s, including polystyrene. Applications and consumer familiarity with plastics expanded significantly in the 1940s with the introduction

1 J. Harry DuBois, *Plastics History U.S.A.* (Boston: Cahners Books, 1972).

2 Yasu Furukawa, *Inventing Polymer Science: Staudinger, Carothers and the Emergence of Macromolecular Chemistry* (Philadelphia: University of Pennsylvania Press, 1998).

3 Philip Ball, *Made to Measure: New Materials for the 21st Century* (Princeton, NJ: Princeton University Press, 1997), 345.

of nylon. Post–World War II advances in catalysts enabled polyethylene to go from a laboratory oddity to mass production. Volume production of plastics expanded significantly as costs declined, largely from a shift from coal to oil and gas feedstocks and the discovery of catalysts critical to conversion processes.[4] By the mid-1970s polymers and plastics outsold steel by volume; today plastic has become more common in construction than steel, aluminum, and copper combined, and in food packaging it has almost entirely displaced other materials. Low weight, high durability, and ease of manufacturing and use have combined to create a global industry providing 160 million metric tons per year of packaging materials valued at over $250 billion in 2007.[5] The most widely used plastic, polyethylene, has an annual production of approximately 80 million metric tons for uses ranging from plastic bags to water pipes.

For manufacturers of most packaging, especially thin films used in plastic bags and food wrappers, the market's maturity by the early 1990s offered few incentives for innovation. A small number of high-volume producers competed primarily on price, not value-added features. Companies selling kitchen trash bags tried to differentiate their products in a crowded market through the addition of scents or greater stretch to avoid breakage, but the underlying materials were largely identical. At the same time, grocery bags and other plastics came under attack by environmentalists concerned with their overuse and inappropriate disposal. In Ireland a fifteen–euro cent tax on plastic shopping bags instituted in 2002 led to an almost immediate 90 percent reduction in their use when consumers began using cloth bags.[6] In San Francisco a 2007 ordinance mandated the use of compostable plastic, recyclable paper, or reusable bags.[7] Other cities and countries followed, including a ban on "very thin" plastic bags in China.

These regulations sought to overcome inertia in the development of "environmentally friendly" plastics in the wake of well-known failures with degradable polymers. Research in the 1970s on polyesters of 3-hydroxy acids (also known as PHAs), which are synthesized by a range of bacteria as an energy reserve and carbon source, suggested that they had properties similar to synthetic thermoplastics and elastomers. Commercial production was limited by high manufacturing costs, but the use of modified bacterial strains led to the development of the biodegradable polymer polyhydroxybutyrate, which was reformulated by Monsanto into polyhydroxyalkanoate and sold under the trade name Biopol in the late 1990s.[8] Since it was brittle, melted at comparatively low temperatures (175° C), and required a complex manufacturing process, demand for the expensive final product was very modest.[9] Since the mid-2000s a more robust version of the molecule has been

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4 Peter Morris, *Polymer Pioneers* (Philadelphia: Center for the History of Chemistry, 1986).

5 Jeffrey Meilke, *American Plastic: A Cultural History* (New Brunswick, NJ: Rutgers University Press, 1995); Society of the Plastics Industry, "Plastics Fact Sheet," 2007, available at www.plasticsdatasource.org (accessed January 2008).

6 Elisabeth Rosenthal, "Motivated by a Tax, Irish Spurn Plastic Bags," *International Harold Tribune* (2 Feb. 2008); Frank Convery, Simon McDonnell, and Susana Ferreira, "The Most Popular Tax in Europe? Lessons from the Irish Plastic Bags Levy," *Environmental and Resource Economics* 38 (2007), 1–11.

7 City and County of San Francisco, "Plastic Bag Reduction Ordinance" 81-07 (20 Apr. 2007).

8 Yves Poirier et al., "Polyhydroxybutyrate, a Biodegradable Thermoplastic Produced in Transgenic Plants," *Science* 256 (1992), 520–523.

9 Kathleen Van de Velde and Paul Kiekens, "Biopolymers: Overview of Several Properties and Consequences on Their Applications," *Polymer Testing* 21 (2002), 433–442; Giovanni Frazzetto, "White Biotechnology," *EMBO Reports* 4 (2003), 835–837.

manufactured through a fermentation process by the small firm Metabolix.

Starting in the early 1990s, research into biodegradable polymers within universities and the chemical industry brought a new generation of plastics to market intentionally designed to break down into natural products. By 2009 several new products were available to consumers, based variously on starch, polylactic acid, and modified petrochemical feedstocks.[10] In light of the growing green-product markets and concerns of environmental nongovernmental organizations and regulators with the volume of plastics in landfills and their presence elsewhere in the environment, the market appeared poised for growth. One forecast suggested that sales of biodegradable polymers would reach $200 million by 2013.[11] (See Appendix 6.1 for manufacturing volumes of biodegradable and traditional low-density polyethylene.)

[10] Eugene S. Stevens, "What Makes Green Plastics Green?" *BioCycle* 44 (Mar. 2003), 24–27; Hartmut Widdecke et al., *Bioplastics 09/10: A Global Overview* (Braunschweig, Germany: Institut für Recycling, 2009).

[11] Global Industry Analysts, "Biodegradable Polymers: Introduction, Methodology, and Product" (1 July 2007).

III. ECOFLEX INNOVATION PROCESS

Diverse political, economic, and environmental trajectories came together to stimulate research and product development of biodegradable plastics in the 1990s. After studies projected that landfills in Europe and the United States would be at full capacity in five to ten years, state and national governments began examining options for waste-to-energy, recycling, and other alternatives. With the Green Party newly represented in the German federal parliament (*Bundestag*), Germany soon took a leading position by requiring extensive recycling and waste separation. Policies coupled incentives, including new funds for research into alternative materials, with new regulations that mandated the removal of organic materials (kitchen scraps, etc.) from waste streams.[12] A 1991 law made companies responsible for recycling packaging associated with their products, and by the mid-1990s initiatives were under way in Germany and Austria to engineer systems that included the curbside pickup of waste, large-scale composting of materials, and transfer of compost to farmers and gardeners.[13] A 1999 European Union Directive mandated that member states reduce the amount of biodegradable municipal waste entering landfills by 65 percent within fifteen years.[14]

BASF, a leading chemical and plastics manufacturer, carried out a feasibility study as the European Union developed its waste policies. Findings suggested the firm could develop and manufacture new plastics useful in compost systems while also fitting with existing product lines. BASF, the Badische Analin- und Sodafabrik, was founded in 1865 as a manufacturer of synthetic indigo dyes. Within a short time the firm diversified into other organic compounds, including agricultural chemicals (fertilizers, insecticides, and pesticides), polymers, and inorganic chemicals. By the mid-1920s the firm employed 42,000 people, and its production facilities in Ludwigshafen covered over 2,700 acres. Like other German chemical firms, BASF joined cartels in the interwar period and helped create I.G. Farben, which at its peak had a controlling interest in 379 German companies and 400 foreign firms. Following World War II the firm was re-established as an independent company and switched to oil and natural gas (especially butane) as raw materials for the

[12] Motonor Yamamoto et al., "Biodegradable Aliphatic-Aromatic Copolyesters: Ecoflex," in *Biopolymers*, vol. 4, ed. Yoshiharu Doi and A. Steinbüchel (Weinheim, Germany: Wiley-VCH, 2002), 299–305; Bernd Bilitewski et al., *Waste Management* (Berlin: Springer Verlag, 1994), 1–20.

[13] David Vogel, *Trading Up: Consumer and Environmental Regulation in a Global Economy* (Cambridge, MA: Harvard University Press, 1995), 82–93; Enzo Favoino, Attilio Tornavacca, and Marco Ricci, "Recent Optimization of Schemes for Source Separation of Biowaste Taking into Account Local Conditions," ECN/ORBIT Source Separation Workshop (2003). www.webresol.org/textos/Recent%20optimisation%20of%20source%20separation%20in%20Mediterranean%20countries.pdf (accessed October 2009).

[14] Council of the European Union, Directive 99/31/EC, Article 5 (26 Apr. 1999).

manufacture of plastics and synthetic fibers. In the 1970s BASF expanded into specialty chemicals. Today the firm is a significant manufacturer of plastics, chemicals, oil and gas, performance products, agricultural products, and nutritional compounds. Characterized by a strong science and engineering culture throughout the company, BASF spent €1.35 billion on R&D in 2008 to underwrite the work of 8,900 employees. BASF has been the world's largest chemical company for decades when measured by overall sales or employee numbers, though it was only in 2007 that it overtook competitors in chemical sales alone, a lead it has maintained since.[15] (See Appendix 6.2 for BASF employee numbers and sales by division.)

Anticipating a modest initial market for biodegradable plastics that was projected to expand only slowly over time, project leaders knew that any new material would have to fit with existing manufacturing equipment. Responsible for major facilities to synthesize, package, and ship polymers in bulk, BASF's senior management was unlikely to support new pilot plants or capital investments in product-specific manufacturing equipment. But the firm did assign several people to further develop the concepts for recyclable or biodegradable plastics. Over the course of a series of brainstorming sessions that included technical experts and applications-focused staff, BASF developed the concept of a biodegradable trash bag that consumers could use in their kitchens and then place outside for curbside pickup. Specific expectations at the firm included "properties similar to polyethylene, producible using conventional starting materials available on an industrial scale, if possible with backward integration into BASF's raw materials . . . [and] utilization of existing BASF polymerization technologies/plants."[16] A small project team was in place by 1992 that included scientists assigned to synthesize and screen new molecules, engineers familiar with the company's manufacturing processes, and managers responsible for developing a marketing plan for the emerging product.[17]

CONNECTING ACADEMIC AND INDUSTRIAL RESEARCH

In a move that would eventually prove significant to the development of Ecoflex, the German federal government made new research support available to universities and corporations to stimulate the growth of "industrial biotechnology" in the early 1990s.[18] Observing low investor support for biotech initiatives other than in medicine, the government seeded a variety of new institutes and supported competitions among regions to foster biotech clusters. One recipient of grants was the restructured Gesellschaft für Biotechnologische Forschung (Society for Biotechnology Research, or GBF) at the University of Braunschweig in central Germany. The launch of GBF, previously an institute for molecular biology, signaled new research directions into applied work on fermentation and degradation. Pulling together an interdisciplinary group of chemists and

[15] Jean-Francois Tremblay, "The Chemical Company," *Chemical and Engineering News* 85 (19 Mar. 2007), 20–23; Thomas Derdak, "BASF," *International Directory of Company Histories* (Chicago: St. James Press, 1988), 305–308; C&EN, "Facts and Figures of the Chemical Industry," *Chemical and Engineering News* 87 (6 July 2009), 29–46.

[16] BASF, "Ecoflex," *BASF Research Verbund* (Ludwigshafen, Germany: BASF, 2004).

[17] Volker Warzelhan and Ursula Seelinger, interview, BASF, Ludwigshafen, Germany, 4 Oct. 2006.

[18] Christian Zeller, "Clustering Biotech: A Recipe for Success?" *Small Business Economics* 17 (2001), 123–141; Susanne Giesecke, "The Contrasting Roles of Government in the Development of Biotechnology Industry in the United States and Germany," *Research Policy* 29 (2000), 205–223.

biologists, the GBF began an extensive set of laboratory experiments on the biodegradation process.[19]

Initially, the group carried out studies that brought the analysis of composting processes from the field into the laboratory. In the past, research on compost had typically involved putting items into piles or "windrows" and taking measurements of the degradation, both visual and of volume, temperature, moisture, and other properties at regular intervals for up to six months. The GBF group developed novel protocols for biodegradation, including isolation of microorganisms, measures of enzymatic activity and biological conversion, and other changes in physical and chemical structure that could be measured in tests as short as twenty seconds in duration.[20] Initial tests based on titration (following hydrolysis in sodium chloride solution) and plating (suspending the polymer powder in the agar of a petri dish) proved challenging to replicate and standardize. However, modification of the long-standing Sturm test produced a controlled system for use with polymers that relied on CO_2 trapping to determine the degree of biological degradation.[21]

In parallel with the development of new protocols and increasingly standardized laboratory tests for biodegradation, the GBF group, led by Rolf-Joachim Müller, began testing the breakdown of a variety of synthetic plastics, as well as cellulose-, starch-, and PLA-based compounds. They obtained samples from firms across Germany and synthesized numerous propane-based compounds in their own labs. By the mid-1990s the research group was publishing a series of articles in peer-reviewed journals documenting their methods and describing the synthesis and testing of novel biodegradable compounds.[22]

When the then-Ph.D. student Uwe Witt presented some of the GBF's findings at a polymers conference in Stockholm and then at the large "K-Messe" (*Kunststoffmesse*, an annual synthetic materials trade show) in Düsseldorf, the BASF and GBF groups became aware of one another. For the Braunschweig group this connection posed both a challenge and an opportunity. BASF could supply additional materials for testing, but with its greater laboratory and legal resources the firm was moving rapidly to patent new molecules.[23] Following discussions, BASF and GBF began collaborating in the form of mutual visits, presentations, and the exchange of materials for testing. In a significant move BASF sup-

[19] Rolf-Joachim Müller, interview, GBF, Braunschweig, Germany, 27 Sept. 2006.

[20] Joseph Augusta, Rolph-Joachim Mueller, and Hartmut Widdecke, "Biologisch abbaubare Kunststoffe: Testverfahren und Beurteilungskriterien," *Chemie Ingenieur Technik* 64 (1992), 410–417; S. Urstadt et al., "Calculation of Carbon Balances for Evaluation of the Biodegradability of Polymers," *Journal of Environmental Polymer Degradation* 3 (1995), 121–131.

[21] Rolf-Joachim Müller et al., "The Development and Modification of Some Special Test Methods and the Progress in Standardisation of Test Methods in Germany," in *Biodegradable Plastics and Polymers*, ed. Yoshiharu Doi and Kazuhiko Fukuda (Amsterdam: Elsevier, 1994), 237–249.

[22] See, for example, Uwe Witt, Rolf-Joachim Müller, and Wolf-Dieter Deckwer, "New Biodegradable Polyester-Copolymers from Commodity Chemicals with Favorable Use Properties," *Journal of Environmental Polymer Degradation* 3 (1995), 215–223; Uwe Witt, Rolf-Joachim Müller, and Wolf-Dieter Deckwer, "Biodegradation Behavior and Material Properties of Aliphatic/Aromatic Polyesters of Commercial Importance," *Journal of Environmental Polymer Degradation* 5 (1997), 81–89; Rolf-Joachim Müller, Uwe Witt, and Wolf-Dieter Deckwer, "Biologisch abbaubare Polyester-Copolymere aus petrochemischen und nachwachsenden Rohstoffen," *Fett/Lipid* 99 (1997), 40–45.

[23] GBF took out one German patent in 1995 and an international patent in 1997 on biodegradable polyesters; BASF took out numerous patents on Ecoflex, its manufacture, and applications starting in 1992. For the original patent see Deutsches Patentamt, "Biologisch abbaubare Polyester, Werkstoffe aus dem Polyester und Herstellungs verfahren" (DE 19532771A1).

plied the Braunschweig group with butane-based compounds. GBF then shifted a component of its research to testing the molecules supplied by BASF and stopped synthesizing new propane-based plastics for biodegradation tests.[24] Several years later, and after completing his doctoral degree, Witt was hired by BASF to work in manufacturing process optimization.

FROM THE LABORATORY TO THE MARKET

With a product profile defined early, BASF sent researchers to study molecular structures and the chemical literature on degradation. Team members could also draw on BASF's diverse product portfolio. Insights were drawn, for example, from discussions with scientists working on soaps and detergents, areas that historically faced more stringent environmental controls than plastics but with which polymer chemists would otherwise not typically interact. According to BASF product managers, the company put the molecular structure front and center in its innovation planning and followed a direction different from the then-prevailing approach to build polymer chains out of natural materials like starch and cellulose.[25]

One material that had received particular interest at BASF was a novel butanediol copolyester. The product that would become Ecoflex started with the insight that combining classic aromatic polyesters with biodegradable aliphatic polyesters might generate a product that would biodegrade.[26] (See Appendix 6.3 for details on the chemistry of Ecoflex.) Following extensive experimentation, BASF modified the crystalline structure of polybutylene terephthalate by incorporating an aliphatic monomer in such a way that the material properties of the polymer remained stable but it was chemically attractive to microorganisms. By 1992 the promising though still unnamed compound had undergone laboratory testing and initial compost trials at the firm to characterize its breakdown components. BASF also sponsored field tests in Kassel and other locations to evaluate how the material degraded in actual large-scale compost systems being built at the time.[27]

In addition to biodegradation tests BASF carried out a variety of other toxicology studies and environmental tests on Ecoflex and its degradation compounds. Following a set of testing protocols standardized across OECD (Organization for Economic Cooperation and Development) countries in the early 1990s, termed the screening information data set, the firm tested the toxicity to daphnia, algae, and plants.[28] In each case, test results showed no acute toxicity or accumulation of toxins at the highest tested concentrations. Using barley, tests examined mixtures of standard set 25 percent and 50 percent of com-

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[24] Müller, interview; Rolf-Joachim Müller and Wolf-Dieter Deckwer, "Biologisch abbaubare Polymere," *Ergebnisbericht 1999/2000* (Braunschweig, Germany: GBF, 2000).

[25] Warzelhan and Seelinger, interview.

[26] BASF, "Biodegradable Plastic Ecoflex," basf.com/group/corporate/en/innovations/innovation-award/2002/ecoflex, (accessed October 2009).

[27] Warzelhan and Seelinger, interview.

[28] Elsa Nielsen, Grete Ostergaard, and John Christian Larsen, *Toxicological Risk Assessment of Chemicals: A Practical Guide* (New York: Informa HealthCare, 2008), 16–19; Richard A. Becker et al., "Tiered Toxicity Testing: Evaluation of Toxicity-Based Decision Triggers for Human Health Hazard Characterization," *Food and Chemical Technology* 45 (2007), 2,454–2,469.

posted Ecoflex against the standard soil alone, and the findings showed that the blends supported greater plant mass than the control. These results were published in product brochures.[29] While not formally mandated in order to begin selling Ecoflex, BASF used this mix of toxicology and plant-tolerance testing to help advance a second-tier market for compost. Although BASF would not earn revenue in this secondary market, the firm anticipated questions that would arise regarding the final composted product and proactively tested its new material.

By 1994 BASF had filed patents on the material and was testing the manufacturing process in a pilot plant at its Ludwigshafen headquarters. The relationship with GBF that developed after the 1995 Düsseldorf trade show also furthered BASF's goal of external validation of Ecoflex's biodegradation. The firm then began scaling up production and initiated sales to companies that would make plastic bags from Ecoflex. (See Appendix 6.4 for a description of the manufacturing process.) BASF initially sold Ecoflex in the European plastics market, but the company also expected to sell its product to manufacturers in the United States and other countries. The molecule had met internal demands that it could be manufactured using existing facilities, initially between larger-volume runs of polyethylene. Once on the market the company dedicated equipment to Ecoflex through renovations to older manufacturing equipment. Nevertheless, its status at BASF was precarious, with a great deal of uncertainty over what uses to advertise and what market niche it would occupy.

Coincident with Ecoflex's market launch in 1997, the company had an internal discussion under way about strategic directions. Ultimately, BASF's leadership decided to continue its focus on supplying other manufacturers rather than seeking to brand the materials it produced and become a more direct consumer-products firm. BASF had experimented in that direction in the past (e.g., with film, magnetic tape, and audio cassettes) but now explicitly adopted the identity of manufacturer of commodity and specialty products. The company also looked at its product portfolio of over two thousand chemicals as part of the strategic analysis and decided not to trim it but instead to build smaller product teams for launches. Ecoflex served as a test case for this new approach.

Volker Warzelhan, the Ecoflex project leader, described tensions related to the new approach overall and for Ecoflex specifically as follows: "If we had used existing relationships, the BASF sales personnel would have had to make 10 customer visits to sell a single ton of Ecoflex when they could sell 10,000 tons of polyethylene with a single phone call. Ecoflex would have been dead. So we created a dedicated team."[30] With the product in hand the team had to develop a business plan within a very large firm to make and sell a small-volume product. Customers, primarily companies that would buy bulk Ecoflex and make plastic bags and films, would have to take a chance on an unproven market. BASF was one of several large firms that were creating "high-performance teams" in the mid-1990s as a means of driving innovation.[31] Whereas production was based on the use

[29] BASF, "Totally Convincing: Ecoflex" (2007); BASF, "Ecoflex: Biodegradable Plastic" (2006); these and other product brochures can be found online at: iwww.plasticsportal.com/products/ecoflex.html (accessed October 2009).

[30] Warzelhan and Seelinger, interview.

of existing infrastructure, sales were carried out through a new product team and by building new customer relationships.

A second key element in BASF's Ecoflex market introduction was for the firm to work with trade groups and associations that certify products as biodegradable. Beginning in the late 1990s a variety of organizations were formed to certify new materials, including the U.S. Composting Council, the Biodegradable Products Institute (United States), the Biodegradable Plastics Society (Japan), and others in Europe. In each case the certifying organization verifies that the company has passed biodegradation tests conducted by approved independent laboratories.[32] For BASF, certification by sectorwide logos proved important to the Ecoflex product brand. In a counterintuitive development found more generally across contemporary materials innovation, helping customers and consumers distinguish the category of "green" products from other materials has been as important, if not more important, as differentiating a specific product from its competitors. In effect BASF and other firms have found it critical to build product labels that are not unique to a single company but that span the product category in order to demonstrate the authenticity of the environmental benefits for which consumers are asked to pay a premium.

[31] Steven C. Wheelwright and Kim B. Clark, *Revolutionizing Product Development: Quantum Leaps in Speed, Efficacy, and Quality* (New York: Free Press, 1992); ibid., *The Product Development Challenge: Competing through Speed, Quality, and Creativity* (Cambridge, MA: Harvard Business School Press, 1995).

[32] "Certifying Bioplastics Compostability," *BioCycle* 47 (May 2006), 44.

IV. STANDARDIZATION AND UNRULY MARKETS

The development of formal technical standards for what counts as biodegradation was critical to the marketing of Ecoflex. Standards for biodegradable plastics ultimately served to define a boundary separating different materials based not on their source (petrochemicals versus starch or other plant-based materials) but on their environmental fate. As companies selling a variety of "green" or "natural" products have discovered, issues of product authenticity can become critical stumbling blocks in consumer purchasing decisions. One successful response has been to work with national or international standards agencies to define terms like *organic* or *biodegradation*; another was to develop voluntary certification schemes.[33] For BASF, involvement with the technical standard-setting process was an opportunity to add value to Ecoflex, both by giving it external verification as biodegradable and as a way to distinguish it from competing high-volume production plastics.

SEQUENTIAL STANDARDIZATION

Overlapping, even redundant standards and certification schemes emerged in the wake of criticisms in the early 1990s that manufacturers were making unverified claims of biodegradation. Drawing the attention of government officials in the United States and Europe, such practices as including a small amount of starch in polyolefins—which resulted in their disintegration but not chemical conversion to soil—led to legal actions against firms for making false claims.[34] It also prompted companies to focus on finding a scientific definition for biodegradation that would stand up to legal or regulatory challenge. While the U.S.-based American Society for Testing and Materials (ASTM) was the first to publish biodegradation test methods, its 1996 standard did not differentiate between physical and chemical degradation.[35] As a result purchasers remained uncertain

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[33] Michael E. Conroy, *Branded! How the "Certification Revolution Is Transforming Global Corporations* (Gabriola Island, British Columbia: New Society Publishers, 2007), 1–26; Kristoffer Whitney, "Sun and Earth and the 'Green Economy': A Case Study in Small-Business Innovation," Chemical Heritage Foundation Studies in Materials Innovation (Philadelphia: Chemical Heritage Foundation, 2009); Susan Leigh Star and Martha Lampland, "Reckoning with Standards," in *Standards and Their Stories: How Quantifying, Classifying, and Formalizing Practices Shape Everyday Life*, ed. Martha Lampland and Susan Leigh Star (Ithaca, NY: Cornell University Press, 2009), 3–24.

[34] Ramani Narayan, "Impact of Government Policies, Regulation, and Standards Activities on an Emerging Biodegradable Plastics Industry," in *Biodegradable Plastics and Polymers*, 261–270.

[35] ASTM, "D6002-96 Standard Guide for Assessing the Compostability of Environmentally Degradable Plastics" (West Conshohocken, PA: ASTM International, 1996); Catia Bastioli, *Handbook of Biodegradable Polymers* (London: Rapra Press, 2005), 162–169.

about which plastics counted as compostable, and new products had no way of competing with existing materials. An initiative begun in 1992 by the Deutsches Institut für Normung (DIN) ultimately served as the central site for defining compost standards. A key question for the German group early on was whether breakdown as occurs to plastics from sunlight would count as biodegradation. Has a material that is chemically the same but broken down into tiny particles undergone biodegradation? Or does a specific chemical reaction have to occur, and if so, how should it be measured? Standard setters in the initial instance included some representation from DIN as the administrative body but were primarily made up of a network of academic scientists from Germany, other countries in Europe, the United States, and Japan. This group of experts soon focused in on laboratory outcomes, specifically the chemistry of the compost and measuring CO_2 output rather than measuring compost volumes or debating what physical properties were desired in the final compost.

The German standard DIN V 54900 was initially written with the GBF group in a leading role and then was adopted more widely across Europe through EN 13432 and influenced revisions to ASTM standards.[36] The final 1997 DIN standard classified a compound as biodegradable if it converted to carbon dioxide, water, and biomass via microbial action. The key metric for producers was the conversion of 90 percent of the organic carbon to CO_2 in less than 180 days. Ecoflex achieves this in 80 days. Providing an example of how technical standards can diverge from everyday experience, wood and most tree leaves would not be certifiable as biodegradable under this standard, since they compost too slowly.

By 1998 international standards imposed the additional requirement that the resulting compost be able to support plant life. Specific standards for test methods, paper coatings, and other materials followed and set additional technical requirements regarding commercial composting conditions.[37] The shift from ASTM and DIN to negotiations on international standards was dominated by industry, and involvement of the original small academic community declined. Expertise with new materials was increasingly found in industry, not in academic centers, and firms, including BASF, sought implementable standards for biodegradation on a large scale.

Ecoflex also fulfills similar requirements set out by a variety of emerging voluntary certification schemes, including Japan's GreenPla system for testing and certification, the U.S.-based Biodegradable Products Institute and the U.S. Composting Council, and the Belgian "OK Compost" certification and labeling system. Ecoflex also complies with European Union and international food-wrapping requirements. For BASF each of these certifications required paying fees to support external laboratory analysis of the material and the administrative costs of the certification organizations. In exchange the company could use certification logos in advertising and on product-information brochures. The credibility of Ecoflex—understood by BASF product managers as key to its marketing—was underpinned by involvement with both standards agencies and voluntary certification schemes.

[36] Deutsches Institut für Normung, "DIN V 54900: Testing of the Compostability of Plastics" (Berlin: Deutsches Institut für Normung, 1997).

[37] David Riggle, "Moving towards Consensus on Degradable Plastics," *BioCycle* 39 (Mar. 1998), 64–70.

By the end of 1998 Ecoflex appeared poised for growth. A breakthrough article by the GBF group had described the significance of chemical structure rather than origin for biodegradation.[38] Government policies were driving the construction of new large-scale compost facilities and the separation of waste streams. Standards and certification schemes were in place, expanding their reach into the industry and promoting awareness among downstream plastic-bag and thin-film producers that new products were available. For an emerging network of scientists, polymer product managers, and compost facility advocates, a collaborative product ontology had emerged. Innovation, according to these supporters of biodegradable plastics, was based on technology transfer and the sharing of samples, synthesis methods, and testing procedures among academic and industrial organizations.

CONSUMER RESISTANCE AND MARKET REPOSITIONING

BASF developed a market analysis in the early 1990s for Ecoflex built around changing rules for garbage collection and waste management in Germany, Austria, and elsewhere in Europe. Following BASF's original plan Ecoflex would be integrated with new large-scale compost systems. Under a German national and E.U.-wide mandate, communities set up systems to collect kitchen, restaurant, and grocery-store waste, then compost it and distribute the usable final product to farmers and back to consumers. With landfill-space projections showing shortages within two decades and public concerns with the environment translating into behavioral changes, these systems offered efficiency gains over individual compost, especially for people with no yards or only small gardens.

A critical component of this program was to turn compost into both a civic duty and a form of commodity exchange. In effect the system operates partly as driven by regulation but also driven by communal norms of separating trash before putting it on the curb. However, as the compost systems were put into place, compost engineers found that some people did not separate their waste in as disciplined a way as the experts envisioned. As a result, compost facilities found it necessary to separate a variety of unwanted materials from desired streams, including metals, glass, and various plastics.

To BASF's disappointment and despite branding efforts, compost facilities could not differentiate an Ecoflex bag from another plastic bag that would not degrade in compost. Facilities thus built large fans to blow lightweight materials like plastic bags out of the waste stream before it began to compost (see Appendix 6.5). These plastics were then separated and either sent to plastics recycling facilities or to landfills. In landfills Ecoflex does not break down in the same way as in large-scale compost facilities. However, like other biodegradable plastics—including those based on starch and polylactic acid—Ecoflex needs to be removed from recycling processes that convert plastic bottles and packaging into such products as carpeting and polyester fibers or back into containers.[39] Rather than fitting a niche with precision, Ecoflex faced a significant roadblock as a result of unruly consumer behavior and compost-facility removal of plastics from the degradable waste stream.

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[38] Uwe Witt et al., "Biodegradable Polymeric Materials: Not the Origin, but the Chemical Structure Determines Biodegradability," *Angewandte Chemie International Edition* 38 (1999), 1,438–1,442.

[39] Elizabeth Royte, "Corn Plastic to the Rescue?" *Smithsonian* (Aug. 2006), 84–88.

In the face of this challenge BASF reoriented its marketing to focus on two different kinds of end users. In addition to focusing on supermarkets and individuals buying plastic bags the firm built sales among farmers who used plastic sheeting to prevent weed growth and trap moisture in the soil. A second market emerged among organic-food packagers who were willing to pay a premium to promote packaging along with their specialty produce. Farmers can plow the sheeting back into the field after harvest and allow it to compost naturally over time. It will not break down in the short timeframe of a sophisticated compost facility, but it does decompose over four to six months. Likewise food packaging will break down, though over a longer timeframe in large landfills.

Today Ecoflex is used to produce compost bags for organic waste (as originally envisioned), mulch films, orientated films, transparent or cling films for food wrapping, and coatings for paper plates and other products. An emerging use is to improve starch products, either by coating starch-foam food packaging or by blending the two materials to make them resistant to grease, moisture, and temperature variation. In 2006 BASF announced that Ecoflex would be used by Zerust Consumer Products to manufacture plastic compostable bags called Great Green Earth bags. These are sold directly to consumers with a one-year shelf life and the assurance that they will break down in normal landfill conditions.

By fall 2007 BASF began actively advertising Ecoflex to the U.S. market, including in magazines like *Newsweek* and *Harvard Business Review*. One goal of this campaign was a broader corporate branding endeavor to raise visibility of the company as providing environmental solutions. Ads thus depicted plastic bags arranged as petals of an open flower with the following caption: "Environmentally friendly plastic bags are a beautiful thing. Ecoflex, one of the latest breakthroughs from BASF, is a biodegradable plastic that can be used in bags and packaging. It's shelf stable for one full year, then completely decomposes in compost within a few weeks."[40] But Ecoflex also showcases a long-term product strategy at BASF. Even if the specific uses BASF currently advocates for Ecoflex fail to develop into major markets, the company is laying the groundwork for a future competitive position when polyethylene plastic bags are restricted or banned more widely than at present.[41]

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[40] This advertisement was run in a variety of print and electronic magazines. See, for example, "BASF: The Chemical Company," *Harvard Business Review* 85 (Oct. 2007), 11.

[41] Warzelhan and Seelinger, interview.

V. FINDINGS

The invention, development, and marketing of Ecoflex offer novel insights into the green-product innovation process. Advocates and critics of the need to transition to a green economy have offered quite different, though largely ungrounded, assertions of whether environmentally sustainable products necessitate novel innovation pathways, can overcome regulatory and institutional inertia, and will be viable once on the market. Without regulations that put a cost on previously free environmental externalities, such as discarding plastics into landfills, a critical market-pull feature is absent from green-product innovation. Likewise, without standards and certification schemes that verify to consumers that products meet the claims of manufacturers, plastics with very different environmental life-cycle and consumer lifestyle features are compared solely on the basis of price. Michael Porter and Claas van der Linde noted in 1995 that "properly designed environmental standards trigger innovations that lower the total cost of a product or improve its value."[42] But a view nonetheless persists that the choice for consumers—and consequently for manufacturers—is between ecology and economy. Neither mandates for composting, standards defining biodegradation, nor the advances in chemistry that produced polybutylene adipate-co-butylene terephthalate account fully for the existence of the material product called Ecoflex. Its development instead illustrates the coevolution of a product, standards, and the market. No one of the three is static, and the successful innovation pathway engaged the firm in areas far afield from the laboratory without losing a critical link back to R&D.

GREEN-PRODUCT STRATEGY

Actively creating markets rather than waiting for consumer demand to attract new products has become integral to product innovation in a wide array of business sectors. For the chemical industry, green products offer both challenges and opportunities. Shepherding products to market that will have modest impact on the bottom line requires a flexible corporate innovation strategy, often in the face of contrary economics. Furthermore, in the case of Ecoflex and products like it, companies need to integrate the final material with waste management and product life-cycle systems that are external to the firm. In many cases the product development process involves working with a novel mix of local and regional government officials in addition to standards agencies and private certification schemes.

[42] Michael Porter and Claas van der Linde, "Green and Competitive," *Harvard Business Review* 73 (Sept. 1995), 120–134.

Two other points about company strategy follow from the Ecoflex case. First, on a sector-wide level the chemical industry can play an active role in developing new systems for recycling. There are significant business opportunities in product life-cycle management, and chemical firms have the scientific expertise, laboratories, and test facilities to advance businesses oriented to the breakdown of consumer products after their use. In the Ecoflex case, however, municipal facilities proved resistant to putting biodegradable waste bags into the compost because they could not mechanically distinguish them from other plastics. In this specific product life cycle, and in many others like it, either all plastic bags become biodegradable or manufacturers and government together must develop a mechanism to categorize them that works with large facilities and does not require hand sorting.

Second, at BASF the product-development strategy for Ecoflex was a component of longer-term planning in the green-product category. The company avoided a technological lock for manufacturing because it did not build new plants with major sunk costs. Building on Ecoflex, BASF launched Ecovio in early 2006, which blended Ecoflex with corn-based polylactic acid. The company strategy was clear from how Ecoflex product managers described their thinking about green-product markets: "It is critical that we understand these markets. And it is much easier to position our company and build up the market if we are in it."[43] BASF was unwilling to lose money on Ecoflex but also knew that in an emerging market for green products flexibility would be key to the development of future products. A lesson from the Ecoflex case thus holds that when designing the first product in a new area, firms should not make large capital investments but should develop flexible teams for future products that may have different market dynamics among downstream customers, consumers, and recycling or composting facilities.

ANTICIPATORY ECONOMICS

Even though the chemical sector has great potential to innovate new green products, firms face the reality of pipeline or stage-gate management decisions that may weed out precisely those products that offer novel properties to meet emerging market needs. Anticipation of economic returns—and of how the green economy will develop as an integrated whole—shapes decisions along the entire innovation chain. BASF nearly closed down the biodegradable-plastics project at an early stage when considering a plant-based polymer. With known high raw-material costs the unknowns of the degradable plastics market proved too high a threshold to cross. Following the invention of a butane-based polymer, however, the firm could take risks in the expectation that the economics of its sources would hold relatively constant, while it had potential upside gains for sales of the final material.

Anticipating how regulatory changes will shape markets is an additional critical dimension to innovation management. In the case of Ecoflex, biodegradable plastics received a significant nudge from government regulations, ranging from mandates for composting to laws that require manufacturers to pay for the ultimate disposal of their products after consumer use.[44] Yet building a business around anticipated regulations with a tight cou-

[43] Warzelhan and Seelinger, interview.

[44] Diane Greer, "Plastics from Plants, Not Petroleum," *BioCycle* 47 (June 2006), 33–35.

pling of product to mandated behaviors involves significant risk. The expectation of a smooth flow from household to waste pickup to compost facility was part of the initial Ecoflex product identity within BASF and enabled its champions to keep it going in the face of concerns about the anticipated modest market size. Though Ecoflex's development was not driven by an existing market with clear needs, the knowledge that waste would be ever more stringently regulated in Germany and elsewhere made for a realistic goal of capturing value from a biodegradable plastic. While the final market evolved in unanticipated ways, the product narrative that held through its development process coupled regulation, consumer behavior, and market dynamics in a coherent way.

Overall, market considerations are important to companies from the very start of R&D projects. Though poorly understood in the innovation-management literature, firms like BASF are engaging in a significant form of economic modeling.[45] By anticipating market share at an early stage of the research and product-testing process and by engaging in activities ranging from standards setting to lobbying for or against regulations, firms actively construct the market dynamics their products enter. This anticipatory strategy suggests the need for diverse perspectives within the firm, especially at chemical companies dominated by a culture of chemistry and engineering. The Ecoflex case moreover indicates that companies will benefit from sharing market projections with scientists and other team members throughout the innovation process.

MODELING USES AND USERS

As the primary upstream originators of commodity products that are reformulated by a long chain of downstream companies before reaching consumers, chemical companies have long operated with several degrees of separation from end users. Firms regularly face the threat of product displacement when consumer preferences change. Unlike consumer product firms that operate closer to users, however, chemical companies have difficulty identifying changing consumer preferences. For retailers, it makes little difference who supplies the plastic bags used at checkout; for chemical companies it is critical. But to understand the customer of your customer is a challenge. BASF nevertheless successfully developed a product that consumers collecting food and other biodegradable waste at home would buy. However, the operators of compost facilities—not customers, but significant "users" of Ecoflex—had a negative impact on the product. While a great deal of effort went into modeling uses for the product during its innovation, BASF's flexibility about alternative uses once it was on the market proved critical. Such expanded uses as for farm fields, various forms of food packaging, and the blended product Ecovio came at least partly from user communities. Thus Ecovio, a controlled blend of Ecoflex and starches, was developed after BASF observed its customers making various mixtures. Though scientists and engineers at BASF initially resisted the concept of a blended Ecoflex and starch plastic because of concerns with its stability (blends could melt at

[45] Abagail McWilliams, Donald Siegel, and Patrick Wright, "Corporate Social Responsibility: Strategic Implications," *Journal of Management Studies* 43 (2006), 1–18; David Brock, "Patterning the World: The Rise of Chemically Amplified Photoresists," Chemical Heritage Foundation Studies in Materials Innovation (Philadelphia: Chemical Heritage Foundation, 2009).

temperatures as low as 50° C), further discussion with customers and surveys of users led the company to develop Ecovio.

At present, and in all probability with greater intensity in the future, consumers can learn about the source, manufacturing chain, and ultimate fate of products and packaging. The long-standing invisibility of the chemical industry to most consumers that resulted from few, if any, products carrying the brand names of BASF, Dow, DuPont, or others has been superseded by traceable production chains and consumer interest in the environment. To chemical companies, innovation historically was about the molecules (their technical sophistication or production process) and the diversity of uses that downstream purchasers developed for novel materials. Now firms like BASF must add attention to diverse product uses and the environmental fate of their materials to the innovation process. Opportunities abound for novel products that break down in predictable ways.

Summing up, the innovation pathway described here for Ecoflex does not fit neatly with long-standing models of a linear path from laboratory to market or even with innovation network analyses that map connections among diverse scientists.[46] For the product Ecoflex a co-innovation of the material, standards and certifications, and the market for biodegradable plastics were critical. The failure of Ecoflex to align neatly with industrial-scale compost systems shows a lapse in the theory that product testing and standardization alone build markets. But flexibility at the firm with regard to uses and users helped avoid failure for the product; instead a more diverse range of applications and formulations suggest Ecoflex will remain a significant product in the new biodegradable-plastics market.

[46] James Fleck, "The Structure of Technological Evolutions: Linear Models, Configurations, and Systems of Development," in *The Science-Industry Nexus*, ed. Karl Grandin et al. (Sagamore Beach, MA: Science History Publications, 2004), 229–256; Stephen Kline and Nathan Rosenberg, "An Overview of Innovation," in *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, ed. Ralph Landau and Nathan Rosenberg (Washington, D.C.: National Academy Press, 1986), 275–306; Mark B. Myers and Richard S. Rosenbloom, "Rethinking the Role of Industrial Research," in *Engines of Innovation*, ed. Richard S. Rosenbloom and William J. Spencer (Boston: Harvard Business School Press, 1996), 209–228.

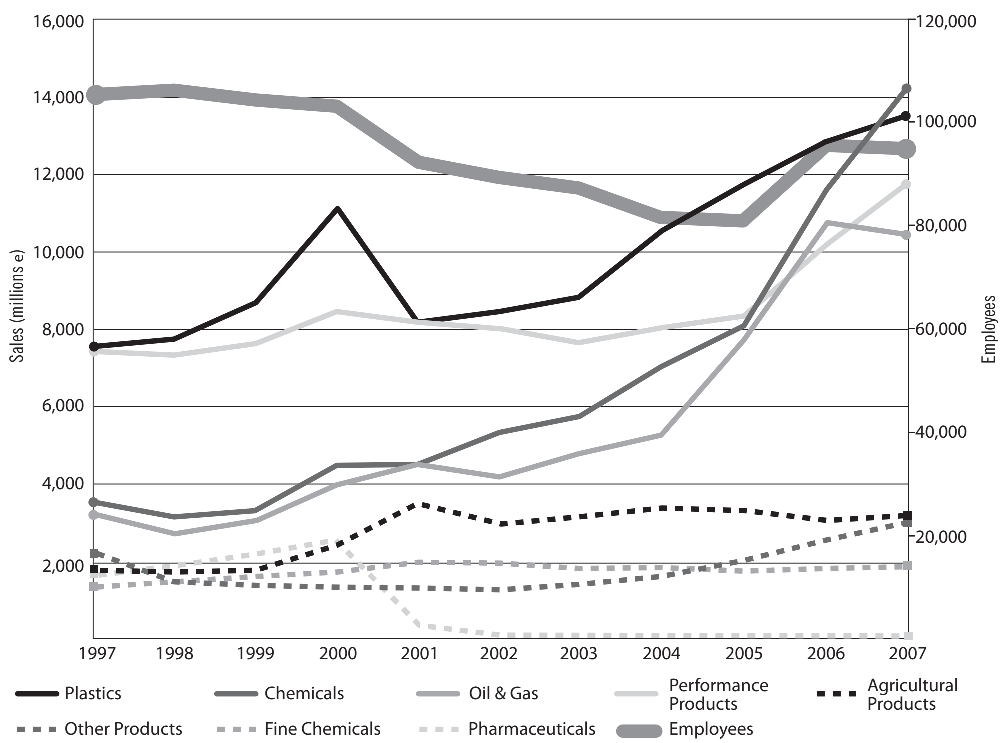
VI. APPENDIXES

1. BIODEGRADABLE PLASTICS AND LDPE MANUFACTURING VOLUMES

(Millions of pounds)	2000	2005	2010 (est.)
Application			
Packaging	33	53	83
Compost bags	23	48	95
Other uses (medicine, agriculture, coatings)	5	13	28
Material			
Polystyrene replacements	23	35	53
Polyester-starch blends	15	33	68
Polylactic acid (Natureworks)	12	23	45
Biodegradable polyesters (Ecoflex)	9	18	33
Others (PHB and related)	2	5	8
Traditional low-density polyethylene (LDPE)	39,683	38,008	47,950

Sources: Kevin Fitzgerald, "The Global Market for Biodegradable Polymers," available at www.ptonline.com/articles/06confex06.html (accessed August 2009); *Chemical Week*, "Product Focus: LDPE," various years.

2. BASF EMPLOYEES AND SALES BY PRODUCT CATEGORY



Source: BASF, "Annual Report," various years, nominal.

3. CHEMISTRY OF ECOFLEX

Ecoflex is a biodegradable aliphatic-aromatic copolyester, which means the material is a combination of two different polymer classes: aliphatic and aromatic polyesters. Aliphatic polyesters, while biodegradable, have physical properties, including low melting points, that preclude their use in most commercial settings. Aromatic polyesters, however, have high melting points (above 200° C) but typically are not biodegradable. Scientists combined polymers from each of the two classes to create Ecoflex, which is biodegradable and has physical properties, including a melting point between 110° and 120° C, that make it suitable for diverse applications.

The trade name Ecoflex refers to the compound polybutylene adipate-co-butylene terephthalate (PBAT), which is obtained by polycondensation of 1,4-butanediol with adipic acid and terephthalic acid. Ecoflex is also termed a BTA-copolyester (for the combination of 1,4-butanediol, terephthalic acid, and adipic acid).

Ecoflex is composed of a random distribution of aromatic and aliphatic units. The structure above features the aromatic poly(butylene terephthalate) units (PBT) on the left and the aliphatic poly(butylene adipate) units (PBA) on the right. As the fraction of aromatic units increases, melting temperature increases, but the biodegradation rate decreases. Through extensive testing BASF scientists found that a fraction of terephthalic acid between 35 and 55 mol-percentage results in a flexible and stable product that biodegrades completely.

4. MANUFACTURING ECOFLEX

BASF primarily sells Ecoflex in pellet form to firms that make consumer plastics, though it has the capacity to produce films at its Ludwigshafen, Germany, site and elsewhere. A variety of Ecoflex products are available; the major ones are Ecoflex F, which is used for flexible-film applications, and Ecoflex S, which is a base material for use in blends. Blending Ecoflex with other materials provides specific desired properties, such as transparency, stiffness, or impermeability. Ecoflex typically is converted into its final consumer application through a blown-film process, which involves extruding melted plastics through a slit and blowing it vertically into a thin-walled tube. The blown film can then be used either in tube form (e.g., cut and sealed at one end to form plastic bags) or sheet form.

Ecoflex also can be produced by chill-roll extrusion, which involves stretching and cooling melted plastic on the surface of a long roll. The fact that Ecoflex-based thin films use traditional manufacturing processes means that Ecoflex can be used at any plant designed for the manufacture of low-density polyethylene (LDPE) and can be used with LDPE printing machinery.

BASF's Ecoflex production facility in Ludwigshafen, Germany, has an annual capacity of 8,000 metric tons, and the company opened a new plant with an annual capacity of 6,000 metric tons in Schwarzheide, Germany, in 2006.

5. METHODS AND ACKNOWLEDGMENTS

This case was written as part of a project to analyze contemporary materials innovation. Initiated in 2006, the CHF Gore Innovation Project is compiling case studies across an array of materials innovation in the chemical and molecular-science industries. The project has three primary goals: first, to improve understanding of the materials innovation process in order to help industry leaders organize their firms for successful innovation and for technology managers to learn from the recent past; second, to test the fit of academic theories on innovation with empirical research and to develop new conceptual frameworks for innovation management; and third, to offer insights to government regulators and nongovernmental organizations as they call for innovations that generate social and environmental benefits as well as economic growth. Ecoflex was chosen as a case study within the project based on its alignment along a set of variables that influence new product innovation. Specifically, it offered a case of a product developed by a large, publicly traded, vertically integrated firm that acts as a supplier of producer goods (not a direct consumer-products firm); operates in a regulated environment; and has a large R&D organization with connections to academic and government labs.

Research and analysis for the case was conducted using methods common to the historical and policy sciences, including gathering and analyzing published technical journals, policy papers, press reports, and company marketing and promotional literature, as well as interviews with Rolf-Joachim Müller at the Gesellschaft für Biotechnologische Forschung in Braunschweig and Volker Warzelhan and Ursula Seelinger at BASF.

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7. ABOUT THE ROBERT W. GORE MATERIALS INNOVATION PROJECT

Begun in 2006, the Robert W. Gore Materials Innovation Project, conducted by the Chemical Heritage Foundation's Center for Contemporary History and Policy, aims to illuminate the diverse contributions of materials innovation within the broader process of technological development in the contemporary age. Conceived as a three-year project, it documents, analyzes, and makes known the immense benefits of materials innovation through its white paper series, Studies in Materials Innovation, and public symposia.

The Gore Innovation Project is made possible by the generous financial contribution of Robert W. Gore, chairman of W. L. Gore & Associates.

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HYUNGSUB CHOI
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About the Chemical Heritage Foundation

The Chemical Heritage Foundation (CHF) fosters an understanding of chemistry's impact on society. An independent nonprofit organization, we strive to

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- Highlight chemistry's role in meeting current social challenges; and
- Preserve the story of chemistry across centuries.

CHF maintains major collections of instruments, fine art, photographs, papers, and books. We host conferences and lectures, support research, offer fellowships, and produce educational materials. Our museum and public programs explore subjects ranging from alchemy to nanotechnology.

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The Center for Contemporary History and Policy offers historically grounded perspectives on issues related to the molecular sciences and technologies. The center's programmatic initiatives draw on diverse historical and contemporary source materials to provide knowledge, perspective, and advice to stakeholders from industry, academia, government, and citizen groups.

About the series

Studies in Materials Innovation examines the dynamic process of conception, development, manufacturing, marketing, and regulation of new materials innovations in the contemporary world. Each case study in the series will focus on a particular materials innovation based on in-depth research, making explicit the lessons for researchers, research managers, and policy makers.

About the author

Arthur Daemmrich is an assistant professor in the Business, Government, and the International Economy Unit at Harvard Business School (HBS) and a faculty member of the HBS Healthcare Initiative. His research examines science, medicine, and the state, with a focus on advancing theories of risk and regulation through empirical research on the pharmaceutical, biotechnology, and chemical sectors. Daemmrich has published on regulation and innovation as well as science, technology, and business policy. He holds a Ph.D. from Cornell University and a B.A. from the University of Pennsylvania.

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