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Green chemistry

John C. Warner*, Amy S. Cannon, Kevin M. Dye

*Center for Green Chemistry, University of Massachusetts-Boston, 100 Morrissey Boulevard,
Boston, MA 02125-3393, USA*

Abstract

A grand challenge facing government, industry, and academia in the relationship of our technological society to the environment is reinventing the use of materials. To address this challenge, collaboration from an interdisciplinary group of stakeholders will be necessary. Traditionally, the approach to risk management of materials and chemicals has been through inerventions intended to reduce exposure to materials that are hazardous to health and the environment. In 1990, the Pollution Prevention Act encouraged a new tact-elimination of hazards at the source. An emerging approach to this grand challenge seeks to embed the diverse set of environmental perspectives and interests in the everyday practice of the people most responsible for using and creating new materials—chemists. The approach, which has come to be known as Green Chemistry, intends to eliminate intrinsic hazard itself, rather than focusing on reducing risk by minimizing exposure. This chapter addresses the representation of downstream environmental stakeholder interests in the upstream everyday practice that is reinventing chemistry and its material inputs, products, and waste as described in the "12 Principles of Green Chemistry".

Keywords: Green chemistry; Pollution prevention; Benign by design; Reducing intrinsic hazard

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1. A grand challenge

There is a grand challenge facing government, industry, and academia in the relationship of our technological society to the environment—Reinventing the

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* Corresponding author. Present address: Green Chemistry Program, School of Health and the Environment, University of Massachusetts Lowell, 3 Solomon Way, Suite 4, Lowell, MA 01854, USA. Tel.: +1-978-934-4543; fax: +1-978-934.

E-mail address: john_warner@uml.edu (J.C. Warner).

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Use of Materials (National Research Council, 2001). Addressing this challenge will require grounding in the insights, desires, and uncertainties of an interdisciplinary group of stakeholders. Input from state and private research investment organizations, policy makers and risk managers, business leaders and consumers, and the scientists, designers, and engineers that serve these interests must all be engaged. Practitioners of Environmental Impact Assessment (EIA) seek to accommodate this breadth of stakeholder interests. Heretofore, the approach to risk management of materials/chemicals has been articulated in intervention approaches intended to reduce exposure to materials that are hazardous to health and the environment. In 1990, the Pollution Prevention Act encouraged a new tact-elimination of hazards at the source.

An emerging approach to this grand challenge seeks to embed the diverse set of environmental perspectives and interests in the everyday practice (Heiskanen, 2001) of the people most responsible for using and creating new materials—chemists. “This role for chemistry is not generally recognized by government or the public. In fact, chemicals, chemistry, and chemists are actually seen by many as the cause of the problems” (Clark, 1999). Indeed, the chemical industry releases more hazardous waste to the environment than any other industry sector, and more in total than is released by the next nine sectors combined (Anastas and Warner, 1998).

The approach, which has come to be known as Green Chemistry,[1] intends to eliminate intrinsic hazard itself, rather than focusing on reducing risk by minimizing exposure. This chapter addresses the representation of downstream environmental stakeholder interests in the upstream everyday practice that is reinventing chemistry and its material inputs, products, and waste. Guidelines on adoption of this approach is portrayed in the “12 Principles of Green Chemistry” (Anastas and Warner, 1998).

Green Chemistry is diffusing throughout the chemical industry (SIC 28, NAICS 325), and includes use and development of new substances and processes that impact other sectors such as agriculture, healthcare, automotive, aerospace, energy, electronics, and advanced materials. Key questions for the reader are: “can Green Chemistry incorporate the breadth of environmental interests far upstream from EIA’s normal points of intervention? (McDonald and Brown, 1995)”; “does Green Chemistry accommodate or anticipate the interests of EIA sufficiently?”; and “what are the prospects for the relationship of EIA and Green Chemistry?”.

2. Emerging trends

The role of Green Chemistry is intimately related to broad emerging trends in policy, regulations and incentives, industry initiatives, and science and

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[1] “Green Chemistry” is also referred to as “Sustainable Chemistry” as well as previous related terms such as: “environmentally benign synthesis”, “benign by design” and “clean chemistry”.

professional developments involved in reinventing the use of materials. Understanding the challenge and prospective impact of Green Chemistry depends on some familiarity with the context of its adoption and practice. This section outlines the scale of R&D in the chemical industry, the dynamics of chemical innovation, and the interplay of industry, government, and professional societies and NGOs.

The chemical industry accounts for 7% of global income, 9% of global trade, US$1.5 trillion in sales in 1998, with 80% of world output produced by 16 countries. Production is projected to increase 85% by 2020 compared to 1995 levels, roughly in pace with GDP growth, but at twice the per capita intensity. There will be strong market penetration by countries other than these 16, especially in commodity chemicals (OECD, 2001). Over the past half century, the largest growth in volume of any category of materials has been in petrochemical-based plastics; and in terms of revenue—pharmaceuticals have surged over the past two decades. Overall production is shifting from a predominance of commodity chemicals to fine/specialty chemicals and those for the life sciences. In the U.S., the chemical industry contributes 5% of GDP, 12% of the value added to GDP by all U.S. Manufacturing and is the nation's top exporter (Lenz and Lafrance, 1996).

The prospective practice of Green Chemistry is primarily in R&D, including scale-up. R&D investment in the chemical industry is about 5% of gross output (Rao et al., 1999). Total R&D spending doubled between 1987 and 1997. Investment in R&D of chemicals, which is predominantly funded by corporations, is at or near the top of the list of all industries, for all categories (Landau and Rosenberg, 1991). Green Chemistry can also be employed in other industries regarding materials.

Much of the chemical industry is capital-intensive, based on economies of scale, and thus large companies are typically slow to convert to new technologies. The dynamics of advance in the chemical industry, as for non-assembled products in general, is dominated by increasing scale, reducing costs, and increasing demand that spurs process innovation rather than breakthrough product innovations. The Federal portion of R&D funding is crucial to advance of Green Chemistry as much of private funding is directed to incremental advance of existing approaches.

The pattern of process innovation is punctuated by occasional discontinuities of enabling technology followed by long periods of incrementalism (Utterback, 1996; Stobaugh, 1988). Process innovation in the chemical sector is often risky, expensive, difficult, requires a broad combination of skills, and takes a long time (Freeman, 1986). In order to frame expectations regarding the adoption rate of Green Chemistry, at an industry level, the comparative rates of evolution of industries are insightful. One of the fastest evolving industries is personal computers with a product technology changeover of less than 6 months and a process technology cycle of 2–4 years; semiconductors are 1–2 and 3–10 years, respectively. At other end of the spectrum is the petrochemical industry with a new product technology cycle of 10–20 and 20–40 years for major process change. The pharmaceutical industry stands midway with a product cycle of 7–15 years and process cycle of 5–10 years (Fine, 1998).

While there is a substantial concentration of production by large multinational firms, producing some chemicals in volumes of millions of tons per year, over 95% of the 50,000 chemicals made in the U.S. are produced by companies with fewer than 50 employees (Synthetic Organic Chemical Manufacturer's Association, 2000), and mostly less than 1000 tons per year (OECD, 2001). There are roughly 3000 chemical companies in the U.S. (1750 in industrial chemicals, 1225 in pharmaceuticals) and about 6000 companies producing other chemical products. In the U.S. Chemical Industry, there are about 89,000 R&D chemists, engineers and technicians focused on innovation (Lenz and Lafrance, 1996). The context of R&D and innovation in chemistry can be seen as benefiting from huge economic drivers, leveraged by a fairly small number of people, with diverse opportunities in small-scale initiatives (Poliakoff et al., 2002).

The theory and practice of Green Chemistry is associated (in concept) with a reorientation in the paradigm for conducting science-based investigations—that is 'use-inspired basic research[2] (Stokes, 1997)—the pursuit of fundamental understanding motivated by a practical problem. Green Chemistry can be viewed as "work that locates the center of research in an area of basic scientific ignorance that lies at the heart of a social problem".[3] Some people view Federal R&D support for the national goal of sustainable development as having little such capacity.[4] Furthermore, private investment in R&D has become dominant (about 65%), and its interest seems to some to be shifting increasingly to "work conducted to achieve practical benefits without consideration of advancing the frontiers of knowledge" (National Research Council, 1999; Rosenbloom and Spencer, 1996). This perception has led to a drive for the formation of Government–Industry Partnerships (Weisner, 2003).

This partnering mode of R&D on use-inspired research, with respect to Green Chemistry, is particularly strong in development of bioproducts (Paster et al.,

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[2] CHEMRAWN—Chemistry Research Applied to World Needs, a program of the International Union of Pure and Applied Chemistry was formed in 1975. The IUPAC Working Party on "Synthetic Pathways and Processes in Green Chemistry" was founded in 1997 with the first results presented in 1999.

[3] Gerald Holton, as quoted by Donald Stokes in "Completing the Bush Model: Pasteur's Quadrant", p. 9 in "Science the Endless Frontier 1945–95: Learning from the Past, Designing for the Future," conference, December 9, 1994, Center for Science, Policy, and Outcomes, Columbia University, New York. http://www.cspo.org/products/conferences/.

[4] Thomas Kalil, A Broader Vision for Government Research, Issues in Science and Technology, Spring 2003, National Academy of Sciences. Kalil was deputy director of the White House National Economic Council during the Clinton Administration and is now the special assistant to the chancellor for science and technology at the University of California Berkeley.

2003). The large scale of this collaboration seeks "market transformation" from a petrochemical-based to carbohydrate-based chemical economy. Chemicals derived from biomass are as yet generally more expensive to produce than petrochemicals. However, there are breakthroughs that illustrate Green Chemistry Principle #7 [Renewable Feedstocks].

By the 1980s, it was estimated that modern industrialized countries devoted 1–2% of GDP to prevention and reduction of pollution (Kates, 1986). By the mid-1990s, all private sector pollution abatement and control expenditures, across OECD countries, generally amounted to between 0.5% and 0.9% of GDP (OECD, 1998), about 1.5% of GDP in the U.S. (OECD, 1996; Arnold, 1999). Yet, already by the 1970s, it was estimated that the social cost of coping with technological hazards in the U.S. was 7–12% of GDP with about half devoted to hazard management and the remainder incurred as damages to people, material, and the environment (Kates, 1986; Tuller, 1984). It is not unusual for chemical companies to be spending as much on abatement and control as on R&D. Thus, the chemical industry has a substantial economic interest in Green Chemistry to ameliorate downstream costs.

"Qualitative shifts in the conjuncture of key actors in the organizational field, dominant institutional beliefs, and organizational practices" in the history of corporate environmentalism in the chemical industry can be viewed as four periods: Industrial Environmentalism (1960–1970), Regulatory Environmentalism (1970–1982), Environmentalism as Social Responsibility (1982–1988), and Strategic Environmentalism (1988–1993) (Lounsbury, 1999; Hoffman, 1997). It remains to be seen if Green Chemistry is considered as an indicator of a fifth phase, yet to be identified. The emergence of EIA overlaps with the latter phases of institutionalization of environmental concerns within the chemical industry (McDonald and Brown, 1995).

To a large extent, Green Chemistry addresses the long-run, social purpose of EIA in an anticipatory fashion, both in synthesis and applications as well as investigations of fundamental phenomena. The evolution of societal concerns regarding toxicity and environmental effects are embedded in a set of guiding principles of Green Chemistry for the practicing chemist. Chemists must address the challenge. It has been posed as a scientific challenge in chemical process research—in alternative feedstocks, alternative solvents, and alternative synthetic pathways.

3. The transformational power of Green Chemistry

The new style of thought that seeks to accommodate environmental stakeholder interests in the model of 'doing science' is articulated in "The 12 Principles of Green Chemistry." The diffusion of the 12 Principles into practice is seen in a growing body of case studies internationally. First, we turn to a consideration of the role of chemists practicing Green Chemistry.

In contrast to many previous initiatives, which were confrontational amongst government, industry, NGOs, and insurance companies, Green Chemistry is seen by some as a cooperative (Woodhouse and Breyman, 2000) enterprise. The EPA and American Chemical Society began recognition of industry and academic achievements through the Presidential Green Chemistry Challenge in 1996.

There are roughly three million chemists in the world, producing about 570,000 to 700,000 papers, roughly three quarters of which report on some 900,000 to 1.3 million new chemical substances (excluding biosequences), each year (Schummer, 1997).[5] As of 1990 there were about 70,000 chemical substances in commercial use with estimates from 200–300 to 500–1000 being added each year. A very startling observation is the doctoral training of chemists typically does not require a single course on toxicology, nor distribution requirements in environmental sciences.[6] A chemist may produce several thousand new substances in their career, and have little knowledge about their potential hazard or potential interaction with other materials in the environment. Introducing toxicological competence and ecosystem awareness regarding chemical life cycles is a key component of ‘greening’ education in chemistry.

A large portion of publications in chemistry represent intermediate findings that serve the interests of chemists themselves in furthering their craft. As the above numbers indicate, most new substances are never commercialized. Nor are applications the primary interest of the majority of work of synthetic chemists. While chemical R&D accounts for one of every eight U.S. Patents (Lenz and Lafrance, 1996), the ratio of patents to new publications has slightly been increasing to about 20–25%, while the ratio of patents to new substances has been steady at about 16% for three decades. Although there is a growing rhetorical emphasis on applied research, only a quarter of these publications are concerned with eventual applications (Schummer, 1997). Half of publications in chemistry are concerned with improving synthetic capacities—that is synthesis is both the means and the ends, and the purpose of producing most new substances is towards synthetic capacity, not end-use applications, as an end purpose. Over the past decade, the number of scientific publications explicitly invoking the term “Green Chemistry” have grown exponentially to a few thousand and increasing at a rate of several hundred per year.[7] To a large extent, the emergence of literature driven by the 12 Principles is creating the knowledge base and tools to transform the craft of chemistry.

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[5] Joachim Schummer, Ethics of Chemical Synthesis, HYLE—International Journal for Philosophy of Chemistry, Vol. 7, No. 2, 2001, pp. 103–124. Citing J. Schummer, Scientometric Studies on Chemistry I: The Exponential Growth of Chemical Substances, 1800–1995, Scientometrics, 39, 1997, 107–123; Scientometric Studies on Chemistry II: Aims and Methods of Producing New Chemical Substances, Scientometrics, 39, 1997, 125–140; and CAS Statistical Summary, Columbus/Ohio, 2001.

[6] It is believed by the authors that the PhD Program in Green Chemistry at the University of Massachusetts is the first doctoral program in chemistry to require competence in toxicology.

[7] Based on bibliometric data searching on the phrase “Green Chemistry” in Scifinder Scholar.

“The 12 Principles of Green Chemistry” have been embraced by professional societies of chemistry and are flown as a banner on websites worldwide. Some sociologists of science and communications consider adoption of such environmental messages as a matter of corporate identity (Coupland, 2003), yet indicating a supportive environment for the craft. Standard bearers of “The Principles” lead the movement on the front lines of research, education, in incentive and research programs of the EPA, NSF, DOE, and USDA, and most importantly in the daily operations of company laboratories. At stake is a battle for the hearts and minds of a comparatively small number of individuals that perhaps exert more power with respect to the future of materials than any government, corporation, or market can muster. The source of their power is in the daily thought process that chooses how they are going to proceed when they arrive for work in the morning and in their reflection on the world they will leave their descendants when they go home at night. “. . .chemists and chemical engineers must accept the important challenges that they alone can meet” (Committee on Challenges for the Chemical Sciences in the 21st Century, 2003).

When we think of power, one is inclined to invoke a military metaphor. The analogy of Green Chemistry as campaign captures the vigor of the pursuit, the magnitude of the stakes, the criticality of the transformation, and the fervor of the dialectic amongst the outspoken poles in ideologies. Yet, the greatest insight from an analogy or metaphor is often found in where its use breaks down. The 12 Principles of Green Chemistry can be seen as a constitution that must be grasped willingly by the practicing chemist. Those that grasp it will want to bear it as their standard. The battle has no enemy in the list of decision-making entities listed in the first paragraph—their disparate interests can be viewed as equally legitimate and urgent (Mitchel et al., 1997), they are all stakeholders (Post et al., 2002). The battle as yet has comparatively few weapons. Prospective tools will primarily be forged by the recently converted in a manner specific to their own field in which they are often the primary subject authority. What is the nature of power of the practicing chemist?

From the perspective of Agency Theory, a chemist typically does not have institutional authority, nor do they directly control capital investment, nor are they generally in a position to reward or punish the superstructures encompassing their labs (Jensen and Meckling, 1976). From the perspective of Resource Dependence Theory, chemists do not explicitly control the resources on which the production regime in which they are embedded depends (Pfeffer and Salancik, 1978). Occasionally, the findings of a chemist can lead to a conversion of resource dependency. The prospect of a large-scale shift from the dependence of the chemical industry on petrochemicals to renewables is a key principle in Green Chemistry. However, owing to the capital intensity of the industry, and to the intermittent nature of such substantial breakthroughs, wholesale shifts in resource dependency are sporadic and infrequent. “In high-tech as well as in low-tech industries, an unkind Providence seems to have ordained that commercial success is likely to favor particularly the possessors of a varied assortment of grubby skills" (Landau and Rosenberg, 1991). Chemists generate options for these small incremental advances. A chemist's authority over incremental advances stems from their dominion over their own professional practice, the conduct of work in their laboratories, and the ingenuity of their innovation. Authorization of commercialization of a chemist's results, which involves EIA, is far downstream from their work. Indeed EIA interests are more immediately addressed by Chemical Engineers and process specialists—which have a parallel movement in "Green Engineering" (Allen and Shonnard, 2001).

In this regard, a Green Chemist's power could be seen, from the perspective of Transaction cost theory[8] (Williamson, 1975a,b; Jones and Hill, 1988), as stemming from a combined effect of four factors. One is a chemist's upstream autonomy in daily practice in a high number of low cost transactions, which constitute the large bulk of the types of small incremental innovations that seem to matter most in the industry. The second is the high leverage the results of a chemist's work have downstream in scale-up, in resource use, and in environmental effects. It is an adage of product development that the cost of a change in product or process increases an order of magnitude each stage along the value chain from R&D, to scale-up and product release to the market. Third, Green Chemistry acts to ameliorate exposure of corporations to risk, litigation, negative societal or consumer reactions, and government intervention. These events, while infrequent, have extremely high transaction costs—even if successful for the corporation. Fourth, an increasing number of corporations are discovering that to a large extent, enacting the Principles of Green Chemistry strengthens their business and improves profits. This dynamic mirrors the counterintuitive dynamic that was observed in the Total Quality Movement (TQM). Prior to the demonstration of success of TQM in many industries, it was presumed that improving quality came at a high cost. But what was found in many industries is that improving quality tends to drive down cost and reducing cycle time tends to improve quality.

The prospect for Green Chemistry as a new means of business improvement is illustrated by the growth in the applicant pool for the Presidential Green Chemistry Challenge, which requires that the implementation of environmentally better chemistry is done in such a fashion that it makes good economic sense. Taking a broad view, the seeming constraints imposed by Green Chemistry are projected by adherents. That are likely to help force the launch of a new wave of innovation in the industry. Let us now consider the transformational effect of one winner of the President's Green Chemistry Challenge.

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[8] Power is accorded to those actors, whom, even in small numbers, can significantly affect the transaction costs of the coordination and structure of carrying out an organization's mission.

4. An illustrative case in Green Chemistry

Argonne National Laboratory Energy Systems Division (ANL) won the 1998 President's Green Chemistry Challenge in the Alternative Solvents/Reaction category.[9] Potential substitution of Green/Bio-Based Solvents is foreseen for up to 80% of the 30 billion pounds of environmentally damaging solvents employed in the world. It is interesting to note that this effort did not win for creating a new solvent. Their product is Ethyl Lactate,[10] known for years as a technically effective alternative solvent and approved by the FDA for use in food. Until this innovation, Ethyl Lactate has been too expensive to employ as an alternative solvent. ANL's breakthrough transformed the economics of producing Ethyl Lactate that allows it to compete with existing solvents. The ANL team's primary breakthrough was developing a cost-cutting manufacturing process[11] based on new membrane technology that enabled more cost effective separation and purification techniques. ANL did it in a fashion that is more environmentally benign and this case is judged to illustrate most of the 12 Principles of Green Chemistry.

- The process eliminates salt waste (gypsum) and undesirable by-products achieving Principle 1 Prevent Waste.
- The process innovation demonstrates Principle 2 Atom Economy in that undesirable by-products are avoided, much more of the input materials are incorporated in the final product, and
- ANL's synthetic process minimizes the use of ethanol and the need to distill it and keeps the alcohol in the reaction system reducing the risk of fire or explosion—fulfilling Principle 3 Less Hazardous Synthesis.
- Ethyl Lactate is non-toxic and therefore a good example of Principle 4 Safer Chemicals,
- Their innovation provides an option for users to address Principle 5 Alternative Solvents.
- The use of catalysis and the membrane separations technology enables the reaction to consume 90% less energy than traditional processes fulfilling Principle 6 Energy Efficiency.
- This process for Ethyl Lactate is carbohydrate rather than petrochemical-based, using corn for example. It therefore demonstrates Principle 7 Renewable Feedstocks.
- The process illustrates Principle 9 in its use of catalysis for cracking the carbohydrates.

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[9] The process developers also won the Discover Award for Technical Innovation by Discover Magazine, and Rathin Datta, the lead Chemical Engineer on the project was previously honored with the Ernest W. Thiele Award of the Midwest AIChE for his pioneering research in metabolic engineering of anaerobes.

[10] Also known as Lactate Ester, Lactic Acid Ethyl Ester, and Ethyl 2-hydroxypropionate.

[11] Argonne National Laboratory Press Release, "Award-winning process makes low-costs environmentally friendly solvents", March 25, 1999.

- Ethyl Lactate is biodegradable. It hydrolyses into ethyl alcohol and lactic acid—common constituents of food. Thus the end product builds in Principle 10 Design for Degradation.
- The handling of the end product is less dangerous than most other solvents. Therefore it illustrates Principle 12 Accident Prevention.

This case is also indicative of success in government–industry partnering, winning an award for Excellence in Technology Transfer from the Federal Laboratory Consortium for Technology Transfer. NTEC Versol (renamed Vertec Biosolvents) licensed the Ethyl Lactate process patent from ANL in 1999, obtained venture capital, and signed agreements with Archer–Daniels–Midland to jointly develop and commercialize Versol Ethyl Lactate. They diversified the product line for specific applications combining it with other solvents derived from soy, citrus, and pine.[12] Vertec then engaged a consortium with ANL, UCLA, the California Energy Commission and other companies to develop waste rice straw as another renewable feedstock. ANL has also created a Midwest Consortium for Bio-Based Products and Bioenergy with surrounding universities, DOE labs and the Department of Agriculture.

5. The principles of Green Chemistry

The Principles of Green Chemistry have been distilled from a diverse set of practices and emerging research. They can be viewed as imperatives or directives that address alternative starting and target materials, alternative reagants and solvents, catalysts, and improved processes and process control.

In the following briefs of each principle a representative case study is summarized that illustrates an individual principle particularly well. It is acknowledged that each case typically adheres to more than one principle. Broader implications regarding each principle are highlighted.

5.1. Prevent waste

It is better to prevent waste than to treat or clean up waste after it is formed.

The old adage: “An ounce of prevention is worth a pound of cure” applies here. Green Chemistry is pollution prevention at the molecular level. Regard-

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[12] Vertec scientists then discovered that blending ethyl lactate with a commonly available soy methyl ester, methyl soyate, improved the properties of both and patented it as Vertec Gold and Ink Zapper in 2000. In 2002, they combined it with de-limonene (VertecBio Citrus) launching VertecBio Gold. In 2003 they combined with pine oil launching VertecBio Elpine. These products will face increasing competition from Purac (Netherlands) as it enters the U.S. market with products already established in the European context—Purasal Purasolv EL and Purasolv EHL.

less of the scale, using benign and safe materials and processes is always going to be beneficial. At the laboratory research level, the costs of disposal of hazardous spent materials usually exceeds the per volume price of the raw materials as input. At the manufacturing scale, the costs to remain within legal emission levels and the associated costs to monitor and document these levels become quite high. In every scale, the potential liability of mishap looms ever present.

Pfizer won the 2002 Alternative Synthetic Pathway Award of the Presidential Green Chemistry Challenge for their re-design of the manufacturing process for Sertraline, the active ingredient in Zoloft®, the world's most widely prescribed antidepressant. By reassessing their manufacturing process, they were able to design their reactions to be more efficient by eliminating many materials that were not incorporated into the final product. The change resulted in eliminating approximately 700 metric tons of waste per year. Realization of Principle 1 makes "environmentally sensitive production technologies better investments than waste treatment technologies" (Geiser, 2001). The waste to product ratio is highest in fine chemicals and pharmaceuticals portions of the chemical industry (Sheldon, 1994). Thus the case draws attention to the significant opportunity for preventing waste as a means of increasing profit margin in these growth areas of the chemical sector.

Evolution of related institutional initiatives foster a supportive context for Green Chemistry. Principle 1 also can be seen as an extension of "elimination of muda" at the heart of the Total Quality Management movement of the 1980s. The TQM, environmental, and health and safety movements were well formalized in ISO 9001[13] (launched in 1987), ISO14001 (Block, 1997) (launched in 1995–1996) and OHSAS 18001(based on British Standard launched in 1996 launched 1999–2000), respectively. In the chemical industry, these are now incorporated in ISO 14001-RC, under the Responsible Care program. (launched in 1985 in Canada, 1988 in the U.S. and advancing from 6 countries in 1992 to 47 countries today). Many adopters report savings mainly in waste and emissions minimization (Scott, 1999). Green Chemistry is an initiative of individual chemists and their associations whereas Responsible Care is industry led. Rohm and Haas, another winner of the Challenge, speaks to the need for programs and policies that promote Green Chemistry within the Responsible Care framework especially when faced with the challenged of immediacy of results (Reinert, 2001).

Principle 1 also reflects a key theme of the international, UNEP Cleaner Production initiative, formally launched in 1989. While the statement of Principle

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[13] American Society for Quality, ISO 9001: 2000 Guidelines for the Chemical and Process Industries, ASQ, Donald Singer, A Laboratory Quality Handbook of Best Practices and Relevant Regulations, ASQ, 2001. ASQ Chemical and Process Industries Division, Chemical Interest Committee, Quality Assurance for the Chemical and Process Industries, A Manual of Good Prcatices, 2nd Edition, ASQ, 1999.

1 for Green Chemistry may seem broad in its language, Clean Production has a much broader intent and impact, not only as a technology promoter but as a managerial catalyst and paradigm reformer."[14] A chemists enactment of Principle 1 can be viewed on a continuum of measures "Waste Disposal, Pollution Control, Recycling, Waste Minimization, Pollution Prevention, Cleaner Production, Industrial Ecology, Sustainable Development" (Hammer, 1996). "Green Chemistry" was coined just over a decade ago in the context of Pollution Prevention. The Clean Production movement builds upon the international conventions and national policy spheres. Even Clean Production is viewed by some as being subsumed in Sustainable Development that is more comprehensive in its concern with systems, social equity, and consumption.[15] Green Chemistry is an essential underpinning to these broader initiatives but its focus is on creating technology options and new scientific insight.

5.2. Atom economy

> Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.

This is a restatement of atom economy as defined by Barry Trost (1991). We have relied on the learning of nearly 100 years of synthetic organic chemistry to build our "toolbox" of synthetic transformations. These reactions have been designed within the framework of "make the product at whatever the cost". One often sees "modifications" of previously reported reactions that report increased yield. At one level this looks quite promising. But when one looks closer at the underlying chemistry and tallies the materials input of the transformation, you see an actual increase in non-incorporated atoms into the final product. One must do an accurate analysis of efficiency. If an existing reaction provides a 75% yield with modest by-products, and an alternative synthesis achieves a significantly higher yield but also reduces the atom economy by a larger amount, then the initial reaction might prove more environmentally responsible.

In 1997, the BHC won a Green Chemistry Challenge Award for developing a way to make Ibuprofen in a significantly more efficient and more environmentally friendly manner. The new process uses fewer materials, has a much higher atom economy (99% with the recovery of an acetic acid by-product) and creates almost no waste (the waste that is made is recycled into the process). Ibuprofen manufactured via the BHC process is marketed under brand names such as Advil™ and Motrin™.

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[14] Comments of Ken Geiser at the First International Pollution Prevention Summit.

[15] Comments of Ken Geiser cited in Canada Hosts First International Pollution Prevention Summit, in Industry and Environment, Volume 24, Nos. 1–2, January–June 2001, United Nations Environment Programme, p. 25.

Most Organic Chemistry textbooks do not address Atom Economy as a necessary component to understanding reactions. Revamping the curriculum is being spearheaded first by the introduction of new laboratory experiences that do, as distributed by the American Chemical Society.

Achievement of 100% Atom Economy generally implies higher yield which is a driver of profitability. Note that neither of the first two principles implies that the transformed synthetic method is not hazardous.

5.3. Less hazardous synthesis

> Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

When one looks solely at the product of a chemical transformation, what is often seen is the proverbial "tip of the iceberg". In a multistep reaction sequence, or sometimes even a single step process, "hidden" in its synthetic history often lurk quite hazardous and toxic reagents. Manufacturing and engineering procedures ensure that contamination from these process do not appear in the final product. But the process itself still presents a number of hazards. Redesigning existing transformations to incorporate less hazardous materials is at the heart of Green Chemistry.

Lilly Research Laboratories won a Green Chemistry Challenge Award in 1999 for the redesign of the synthesis of an anticonvulsant drug candidate, LY300164. This pharmaceutical agent is being developed for the treatment of epilepsy and neurodegenerative disorders. The first step in the new synthesis utilizes the yeast *Zygosaccharomyces rouxii* in a novel three-phase reaction system, allowing for the removal of organic reaction components from the aqueous waste stream. A second key step in the synthesis was a selective oxidation using compressed air, which eliminated the use of chromium oxide, a possible carcinogen, and preventing the generation of chromium waste. Significant environmental improvements were realized upon implementing this less hazardous synthetic strategy. Roughly 34,000 l of solvent and 300 kg of chromium waste were eliminated for every 100 kg of LY300164 produced. Only three of the six intermediates generated were isolated, limiting worker exposure and decreasing processing costs. The synthetic scheme proved more efficient as well, with percent yield climbing from 16% to 55%.

In contrast to Principle 3, which is concerned with synthetic methods, Principle 4 focuses on products.

5.4. Safer chemicals

> Chemical products should be designed to preserve efficacy of function while reducing toxicity.

In the pharmaceutical industry, this is referred to as the efficacy/toxicity ratio. Obviously, it is important to achieve certain chemical performance in our final product. It is often the unintended side reactivity of that comes back to haunt us such as the carcinogenic red dyes, endocrine disrupting plasticizers, and ozone depleting refrigerants. The chemical community has become quite sophisticated in identifying specific mechanisms of action for a variety of negative endpoints. We need to train synthetic chemists to appreciate these mechanisms better.

The World Wildlife Foundation (WWF) currently has a campaign to phase out the use of anti-fouling agents on ships. Large ships traditionally have used chemicals called organotin compounds to prevent accumulation of barnacles and marine plants which increase drag. They write, "Organotin compounds—such as TBT—are considered to be amongst the most toxic chemicals ever released into the marine environment. Even when present in the marine environment at very low concentrations, they have been shown to produce demonstrable negative impacts upon marine life."[16] Rohm and Haas has developed a non-toxic alternative, replacing the Organotin compounds with a product called Sea-Nine™, a Green Chemistry Challenge Award winner in 1996. This product degrades quickly in the environment and does not bioaccumulate. It also has no chronic toxicity to the surrounding marine life.

Over the past few decades, control of the chemical industry has evolved from regulation and litigation to a diverse set of instruments[17] including information disclosure and incentives (Anderson, 2001). Yet even today only 55% of chemicals on the Toxic Release Inventory list have full testing data. Of the 3000 high production volume chemicals (more than 1 million lb/year) 43% have no testing data on basic toxicity and only 7% have a full set of basic test data.[18] For 38,000, of the more than 45,000 chemicals listed by the EPA, fewer than 1000 have been tested for acute effects and only about 500 have been tested for cancer-causing, reproductive, or mutagenic effects.[19] What would it cost to fill all basic screening data gaps in high volume chemicals? It would cost only US$427 million, just 0.2% of the sales revenue of the top 100 chemical companies.

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[16] World Wildlife Foundation http://www.panda.org.

[17] A delineation of such instruments in the European context, which many believe is more robust than that in the U.S., is found in: European Environment Agency, Environmental Agreements, Environmental Effectiveness, Environmental Issues Series No. 3, Vol 1, EEA, Copenhagen, 1997, Fig. 1, p. 18.

[18] EPA, Chemical Hazard Data Availability Study: What do we really know about the safety of High Production Volume Chemicals?, EPA's Baseline of Hazard Information that is Readily Available to the Public, EPA Office of Pollution Prevention and Toxics, Washington, DC, April 1998.

[19] Elfren Sicango Cruz, Leave Our Children a Living Planet, Business World, in The Environment in the News, UNEP, November 11, 2003.

Still the goal of Green Chemistry is to eliminate use of such hazardous substances such as ANL did with Ethyl Lactate, an option for enacting Principle 5.

5.5. Safer solvents and auxiliaries

> The use of auxiliary substances (e.g. solvents, separation agents, etc.) should be made unnecessary wherever possible and, innocuous when used.

Often one has a form of "chemical tunnel vision" when designing synthetic transformations. We follow the electron flow of various reagents, anticipating mechanistically, the series of bond forming and bond breaking reactions that will occur in the process of synthesis. But what is often seen as an inconsequential afterthought is reaction and purification media that will be used. Elegant chemistry that requires high dilution in chlorinated solvents can be quite problematic. Chromatographic separations using enormous amounts of elution solvent can be the single largest environmental impact of a transformation.

In 1996 Dow Chemical won a Green Chemistry Challenge Award for developing an alternative method for making styrofoam that does not use CFCs (ozone depletors). Traditional blowing agents used to manufacture polystyrene (Styrofoam) have been associated with ozone depletion, global warming, and smog. The new method uses carbon dioxide (CO_2) and is completely non-toxic. The CO_2 used is the by-product of existing commercial and natural sources, therefore it does not contribute to a net increase of CO_2 in the atmosphere. Current applications include thermoformed meat, poultry and produce trays, fast food containers, egg cartons, and serviceware.

About 3.8 million tons of solvents are used in the U.S. each year. Solvents (typically petroleum-based) are employed as cleaning agents for electronics, printing, and textiles and are included in products such as adhesives, paints, and coatings. Many solvents have been implicated in environmental damage such as ozone depleting chlorofluorocarbons and trichloroethane, smog producing Volatile Organic Compounds, and ground-water polluting trichloroethylene. Some solvents are implicated in human health effects and are in EPA's list of toxic materials such as ethylene glycol ethers, chloroform, benzene, xylene, carbon tetrachloride, and toluene. Others are implicated in long term carcinogenicity such as methylene chloride. And many are flammable and/or corrosive and thus of concern to OSHA.

As noted above, ANL's process innovation to reduce the cost of Ethyl Lactate could help supplant 25–80% of current solvent usage. This large market opportunity is attracting new entrants. Cargill Dow's innovation of polylactic acid, taken here to illustrate Principle 7 in production of bio-based plastics, is also poised with an alternative synthetic route from lactic acid to Ethyl Lactate. Purac, of The Netherlands, the world's largest producer of lactic acid, is forging U.S. market entry and engaging in U.S. consortia.

Recall that ANL’s process innovation in solvents make Ethyl Lactate an economically viable alternative in large part because it saved energy.

5.6. Energy efficiency

> Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.

Chemical reactivity is obviously governed by the laws of thermodynamics and kinetics. Every transformation requires an input of energy to overcome the activation energy of the transition state. Highly exothermic reactions must be cooled in order to be controlled. These energy inputs can amount to a substantial component of the overall environmental “footprint” of a transformation. New transformations must be designed to work within more readily accessible energy limits.

Pollution reduction has been achieved through the use of catalytic technologies in the generation of clean fuels and chemicals. However, traditional preparation of the catalysts used generate large amounts of wastewater, utilize large amounts of energy and oftentimes generate nitrate and sulfate emissions which contribute to acid rain. Sud-Chemie, has developed an efficient method for manufacturing catalysts to be used in the generation of clean fuels and chemicals that has drastically decreased the amount of water and energy utilized. The new process also reduces emissions down to just pure water vapor and a small amount of CO_2. This technology won a Green Chemistry Challenge Award in 2003.

The U.S. Chemical Industry consumes roughly seven quadrillion BTUs of energy annually (Chemical Manufacturers Association, 1998), about 25% of all U.S. manufacturing energy use. About half of the energy-material use is as feedstock. The industry is the largest consumer of natural gas, 10% of total domestic consumption, and about 7% for petroleum. These energy expenditures represent about 9% of chemical product value (Energetics, 2000). The oil shock of 1973 launched aggressive energy management, housekeeping programs, operating practices, and improvements in process and equipment design in the industry. These low-cost, high-return investments reduced the amount of energy used per unit output by 39% (Chemical Manufacturers Association, 1998). These types of gains have quiesced and with comparatively low energy prices since the late 1980s as a disincentive to further investment, improvements in efficiency have remained relatively flat. Just 30 major chemicals loose almost a quadrillion BTUs every year due to process inefficiencies. A major area of opportunity for energy efficiency is in improved catalytic processes[20] (Principle #9). Another area of opportunity is in further waste minimization (Principle #1). About US$2

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[20] Pacific Northwest National Laboratory, Top 50 Commodity Chemicals: Impact of Catalytic Process Limitations on Energy, Environment, and Economics, 1995.

billion of energy used as feedstock in those 30 major chemicals is converted to waste. A focus on Principle 1 would also ameliorate end-of-pipe waste treatment and disposal which are energy-intensive.

Towards these ends, an example of collaborative, cost-shared, government laboratory–industry R&D and commercialization partnering, focused on energy efficiency in the chemical sector, is the Department of Energy's Chemicals and Forest Products Industries of the Future initiative. It prioritizes needs, as expressed in industry roadmaps, for more energy efficient technologies in Reaction Engineering and New Process Chemistry such as catalytic oxidation, as well as new separations technologies.[21] Another effort involving the collaboration of a government agency and a professional association provides decision support tools for improving efficiency via chemical engineering.[22]

The chemical industry accounts for about 7% of world energy use but has achieved energy efficiency gains over the past 15 years that have stabilized CO_2 emissions even though world output doubled in this period (OECD, 2001). However, the rate of production in countries that employ less-efficient technologies will increase over the next 20 years. While contributing just 4% of overall emissions of CO_2 the chemical industry is a major industrial emitter by comparison to other industries, and emissions may again surge as the industry grows in countries that are more dependent on coal. A major opportunity in Green Chemistry to get carbon out of the atmosphere is the focus of Principle 7.

5.7. Renewable feedstocks

> A raw material of feedstock should be renewable rather than depleting wherever technically and economically practicable.

The chemical industry's reliance on petroleum-based feedstocks must be addressed. The timeline for depletion might be debatable; nevertheless, long-term sustainable alternatives must be identified. Agricultural-based feedstocks offer promise as the isolation and purification technologies improve.

Cargill Dow LLC was founded in 1997, which they claim to be "the first company to offer a family of polymers and intermediates derived entirely from annually renewable resources with the cost and performance necessary to compete with petroleum-based materials." They commissioned a key plant in 2001 that in 2002, won a Green Chemistry award for developing materials out of poly-lactic acid (PLA), from biomass, a renewable resource. PLA is made from lactic acid, which is generated from biomass through a natural fermentation

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[21] DOE Industrial Technologies Program, Office of Energy Efficiency and Renewable Energy, Chemicals and Forest Products Industries of the Future, Program Announcement, Issued 12/15/2003.

[22] Department of Energy Office of Industrial Technologies and the American Institute of Chemical Engineers, The Chemical Industry Tools CD: Resources for Energy Efficiency and Cost Reduction, DOE/GO-102002-159.

process. PLA is used in Nature Works™ products such as clothing and plastic packing materials. Not only are the products made from renewable resources, but they are also capable of being completely recycled or even composted after use.

Cargill Dow signed a distribution agreement with Ashland Specialty Chemical in 2002. Cargill Dow competes with Purac of The Netherlands in PLA and faces their competition as they move into lactate solvents—as well as with Vertec Biosolvents (ANL case above). Cargill Dow is also a participant in an Industry/Government Partnership in the Office of Industrial Technologies, Industries of the Future Programs with the Department of Energy. Lactic-acid-based biodegradable polymers will remain more expensive than commodity polymers in the near future. The increasing concentration of government leveraged R&D, an emerging market, and the emerging competition cited above will likely drive those prices down.

Another Principle that tends to drive down manufacturing cost is the elimination of unnecessary intermediate products.

5.8. Reduce derivatives

> Unnecessary derivatization (blocking group, protection/deprotection, and temporary modification of physical/chemical processes) should be avoided whenever possible.

Synthetic organic chemistry achieved breathtaking success in the middle of the 20th century. Elegant multistep syntheses were designed that employed increasingly clever "protecting groups" that would temporarily block the reactivity of a specific functional group until a very specific second reagent was introduced to remove it. While these classic syntheses will ever remain testaments to the history of organic synthesis, it must be acknowledged that from an environmental impact perspective, the use of blocking groups is less acceptable that syntheses that are designed not requiring them.

The properties of materials are based on how molecules interact with each other and with their surrounding environment. Molecules of interest (with a certain activity) are traditionally manipulated by covalently changing the "topography" of the molecule in order to change the physical properties. This covalent derivatization generally involves many synthetic steps using exotic (and possibly toxic) reagents, therefore creating waste and unwanted byproducts. A great deal of research has been done to understand the non-covalent, intermolecular, tendencies of molecules and therefore design molecular systems using the natural processes of molecular recognition and self assembly (Warner, 1998; Cannon and Warner, 2002). This has been termed noncovalent derivatization and is inherently more benign than traditional covalent methods.

Three winners of the President's Green Chemistry Challenge Award acknowledge fundamental academic contributions that provide options for users to enact Principle 8, which all leverage new catalyst technology. A 2001 winner, Quasi-Nature Catalysis invented by Chao-Jun Li at Tulane University, enables “natural” catalytic reactions that are aqueous and at ambient conditions. It will help replace traditional use of transition metal catalysts in pharmaceuticals, fine chemicals, petrochemicals, agricultural chemicals, polymers, and plastics. A 2003 winner, lipase catalysts for polymerizations, developed by Richard Gross of Polytechnic University, eliminates the need for protecting/deprotecting groups and solvents as well as enabling milder reaction conditions.

Gross’s advanced was based on enzymes in living organisms. Li indicates the similarity of his invention to enzymatic reactions in biocatalysts, biodegradation, photosynthesis, nitrogen fixation and digestions. The theme of bioinspired research, (also called biomimetics, bionics, biognosis) the “abstraction of good design from nature” underlies many advances in Green Chemistry—especially in catalysis.

5.9. Catalysis

> Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

In order to make transition state energies more accessible in a chemical transformation, the use of catalysts can be quite beneficial. There are countless examples of stoichiometric reactions that might have catalytic alternatives. Provided the catalyst employed is not orders of magnitude more toxic than the stoichiometric reagents they replace, their use will be quite beneficial.

In 1999 the Academic Award in the Green Chemistry Challenge was given to the Collin’s group for the design of a benign oxidation catalyst called TAML™. TAML™ catalysts are non-toxic iron-based catalysts that are being used to clean up wastewater streams in the pulp and paper industry. Environmental benefits include decreased energy requirements, elimination of chlorinated organics from the waste stream, and decreased water usage. The catalysts are also completely degradable into benign components. TAML™ Oxidant Activators provides an option for low temperature, chlorine-free means of bleaching important to both the Pulp and Paper industry as well as household laundering. They are currently being investigated as oxidation catalysts for many purposes involving wastewater treatment.

Catalysis is a major focus of international research, a joint pursuit of industry and professional associations, as articulated for example in Catalysis Roadmaps of the U.S.,[23] Germany, Japan, and The Netherlands.

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[23] American Chemical Society, American Institute of Chemical Engineers, Chemical Manufacturers Association, Council for Chemical Research, and Synthetic Organic Chemical Manufacturers Association, Technology Vision 2020: The U.S. Chemical Industry, ACS, Washington, DC, 1996.

5.10. Design for degradation

> Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products.

The earth's natural environment is full of ecological cycles where the waste of one process becomes the feedstock of another. In society's quest for durable and stable materials, in the past we have designed materials that are robust and resist entering into any degradative cycle. But perhaps we have become "too good" at it. Landfills across the planet are filling up with more and more material that will not undergo any form of degradation. We must better understand these cycles and incorporate them into the design of future materials so as to give us strong stable materials that are around for as long as they are needed and no longer.

PYROCOOL developed a non-toxic, completely degradable fire-extinguishing and cooling agent. Traditional extinguishers have utilized halogens, ozone-depleting chemicals, or fluorinated materials that leak into the environment harming aquatic systems and contaminating water supplies. The PYROCOOL extinguishers replace the traditional extinguishers that are just as effective in putting out fires and does not deplete the ozone layer or persist in the environment. This product won a Green Chemistry Challenge Award in 1998.

5.11. Real-time analysis for pollution prevention

> Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

There are two aspects of this principle—time and materials. Real-time analytical techniques must be developed for use in large-scale manufacturing processes. If better, more responsive monitors can be designed, then the use of "just-in-time" reagents and techniques can be employed that will minimize the environmental toll. Also there is a need to improve analytical techniques to consume less materials. New chromatographic methods that use less solvents or do not require complex mixtures of solvents need to be developed.

Analytical chemistry has played an essential role in organic synthetic chemistry, helping to understand what is happening within reactions and also helping to identify and characterize isolated compounds. Traditional analytical chemistry, while being an integral part of chemistry, has also involved excessive solvent usage, high-energy requirements and often large sample sizes. Process analytical chemistry has recently shifted towards smaller, more precise instrumentation and in-line analysis, which has helped decrease the solvent usage and therefore drastically decrease waste.

Quantitative determinations of contaminants and pollutants in the environment are another important aspect of analytical chemistry. Dr. Albert Robbat, Jr. of Tufts University has developed analytical methods for hazardous waste sites that enable quick and easy determinations and assessments. By designing mobile systems, the measurements can be made on-site and in a fraction of the time regular methods require. This also allows for a reduction in the amount of waste generated in operating the instruments (Mauro et al., 2000; Simpson et al., 1999; Robbat et al., 1998, 1999).

5.12. Inherently safer chemistry for accident prevention

> Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions, and fires.

Often missing in discussions of Green Chemistry are the physical hazards of explosion and fire. The issues of environmental impact and human toxicity can sometimes dominate the agenda. It is important to recognize that chemistry has developed a complex mechanistic understanding of physical hazard and it is possible to use these learning in the design of future materials.

Novel solvents called ionic liquids are being developed by a number of research groups in Green Chemistry (Rogers and Seddon, 2003a,b). Ionic liquids are liquids composed of ions, which have a very low vapor pressure and therefore are virtually non-volatile. They are being used for a number of purposes including as alternative solvents in organic synthesis (Wasserscheid and Welton, 2003) and as a media to dissolve cellulose to be used for materials (Swatloski et al., 2002). Ionic liquids can be used to replace flammable and potentially explosive organic solvents, therefore drastically reducing the potential for accidents.

Analysis of the Risk Management Plans database, initiated under Rule 112(r) of the Clean Air Act Amendments, indicates there are about 300–400 chemical accidents per year in the U.S. resulting in over US$1 billion in damage (Kleindorfer et al., 2000). The use of catalysts, alternative solvents, less hazardous and lower energy reactions, production of safer chemicals, and preventing production of waste should act to drive this rate down in the long run.

6. The prospective relationship of EIA and Green Chemistry

Green Chemistry could be viewed as a design hub standing midway between the societal purpose directly engaged by EIA at the point of deployment and the evolving science base of alternative approaches to chemistry ‘deployed’ in journals, conferences, and lab notebooks. The results of Green Chemistry are typically far upstream from EIA activities, yet, act to generate alternatives and increase options with respect to EIA's interests in the long run. EIA can help to clarify environmental, societal, and economic benefits of these resulting clean production options. EIA could be employed as part of a priority setting framework for Green Chemistry in R&D investment and in operational improvement targets of Green Chemistry initiatives in a corporation. Both Green Chemistry and EIA can be viewed as collaborative learning processes and as barometers of progress in learning by agencies and corporations in the relationship of the chemical industry to the environment. Both the EIA and Green Chemistry fields also are still in the midst of theory building.

There are significant differences between Green Chemistry and EIA that make them complementary. There is major difference in the timing of their respective interventions. A Green Chemistry innovation would typically not come into the purview of an EIA practitioner for years. Whereas operationalization of Green Chemistry can be taken as a matter of professional ethics, of an individual practitioner, EIA is typically conducted in a much larger arena, in the realm of pluralist ethics. Green Chemists would typically not engage the public in the normal course of their work whereas broad stakeholder engagement is a mantra of EIA. Some Green Chemists do engage the public in educational settings, especially via the introduction of new laboratory experiences. But a chemist is not likely to be engaging the public in the midst of their development work. In fact, most of the work in progress could not be disclosed to the public prior to the securing of appropriability via patents, or it may be kept as a trade secret as is common in process-based industries.

The scale of EIA versus Green Chemistry interventions is different by orders of magnitude in terms of cost, number of people engaged, and frequency. EIAs are infrequent for a company in comparison to the daily decision-making in a lab. So too there is a comparative limitation of EIA in working on small projects while most of Green Chemistry happens in very small projects of incremental improvement, most of the time.

While the purview of Green Chemistry initiatives may look at opportunities in an overall regime of production and use, the practice of Green Chemistry is typically dealing with small pieces of a large system, one at a time. In contrast, EIA is deliberately more systemic in conduct. The trends of implementation of Green Chemistry are towards the lab level with increasingly critical consideration of finer points, whereas a major trend for EIA is to the strategic and international levels. The transnational aspect of Green Chemistry is primarily in publications. To some extent, the more successful Green Chemistry is, the less need there will be for EIA in the long run in the chemical sector (although that is a long way off.) There is also a contrast in the leverage of EIA and Green Chemistry on technological change. EIA acts as large, long-term stimulus to prompt society, government, and corporations to improve technology with respect to the environment. Green Chemistry in the best case is changing technology on a daily basis, and the improvement in approach is in large part the journey of the individual practitioner.

EIA is an impetus for more robust up-front planning and design and its insights and frameworks will find their way into the toolbox of the chemist, eventually. Ideally, Green Chemistry would operationalize and integrate some form of EIA in decision-making at the lab level. As yet there are limited tools for doing this. Green Chemistry has a more operational basis whereas EIA is more concerned with ends, thus there certainly seems to be the prospect of their complementarity. Green Chemistry can learn from EIA in making its decisions more transparent to executives, and making the decision-making itself more accessible. Green Chemistry can learn from the practice of EIA to increase transparency in substantiating selection of alternatives, especially with respect to incremental improvements, on a less arbitrary basis. Eventually, Green Chemistry will benefit from EIA techniques in having more quantitative comparisons for lab level decision making. This type of link will likely be in the form of Life Cycle Analysis.

So too, Green Chemistry's insights and expert systems will likely be incorporated into LCA tools alongside the criteria, priorities, and decision making processes of EIA.

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