Green Chemistry

Does green chemistry represent the logical next step in chemical product development?

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I. Introduction

The current status of chemistry in society is a dichotomy of perceptions. The scientific sector hails accomplishments while a growing number of people fear and avoid chemicals whenever possible. Neither of these perspectives can factually capture the full vision of chemistry because of its complexity in understanding its characterization, interaction and manipulation of matter (Anastas, 1998). Although these concerns will not be resolved any time soon, green chemistry offers an alternative to current practices. This report addresses whether green chemistry is the next logical step in chemical product development.

II. Defining Green Chemistry

Green chemistry is an approach that provides a fundamental methodology for changing the intrinsic nature of a chemical product or process that is inherently of less risk to human health and the environment (Anastas, 1998). Different to current chemical practices, green chemistry incorporates pollution prevention practices in the manufacture of chemicals. Green chemistry attempts to address problems of sustainability by dealing with fundamental problems such as toxicity, renewability and global impact by designing and redesigning matter at a molecular level. "Green chemistry addresses hazards, whether physical (flammability, explosivity), toxicological (carcinogenicity, endocrine disruption), or global (ozone depletion, climate change) as an inherent property of a molecule. Therefore the hazard can be addressed through appropriate design of the structure and its associated physical/chemical properties at the molecular level." (Anastas, 2003).

Green chemistry is part of a growing industrial sector of worldwide “green” activity; green chemistry or environmentally benign chemistry is not a new branch of chemistry but a philosophy combining critical elements which is essential for conserving the environment (Greenscope). Emerging in the early 1990’s in response to the Pollution Prevention Act of 1990, green chemistry was developed through the EPA’s Office of Pollution Prevention and Toxics

(OPPT), by designing research grant programs and recognition awards for industry (Green, EPA website). In *Green Chemistry: Theory and Practice (1998)*, authors Paul Anastas and John C. Warner further define green chemistry as the "utilization of a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacture and application of chemical products." These principles adopted by the US EPA are the following:

<u>12 Principles of Green Chemistry</u>

1. **Prevent Waste –** Design chemical syntheses to prevent waste, leaving no waste to treat or clean up.
2. **Design safer chemicals and products –** Design syntheses to be fully effective, yet have little or no toxicity.
3. **Design less hazardous chemical syntheses –** Design syntheses to use and generate substances with little or no toxicity to humans and the environment.
4. **Use renewable feedstocks** – Use raw materials and feedstocks that are renewable instead of depleting. Renewable feedstocks are often made from agricultural products or are the wastes of other processes; depleting feedstocks are made from fossil fuels, or are mined.
5. **Use catalysts, not stoichiometric reagents –** minimize wastes by using catalytic reactions. Catalysts are used in small amounts and can carry out a single reaction many times. They are preferable to stoichiometric reagents which are used in excess and work only once.
6. **Avoid chemical derivatives –** Avoid using blocking or protecting groups or any temporary modifications if possible. Derivatives use additional reagents and generate waste.
7. **Maximize atom economy** – Design Syntheses so that the final product contains the maximum proportion of the starting materials. There should be few if any wasted atoms.
8. **Use safer solvents and reaction conditions –** Avoid using solvents, separation agents, or other auxiliary chemicals. If these chemicals are necessary, use innocuous chemicals.
9. **Increase energy efficiency –** Run chemical reactions at ambient temperature and pressure whenever possible.
10. **Design chemicals and products to degrade after use –** Design chemical products to break down to innocuous so that they do not accumulate in the environment.
11. **Analyze in real time to prevent pollution –** Include in-process real-time monitoring and control during syntheses to minimize or eliminate the formation of byproducts.
12. **Minimize the potential for accidents –** Design chemicals and their forms (solid, liquid or gas) to minimize the potential for chemical accidents including explosions, fires, and releases to the environment.

Why Has Green Chemistry Gained Attention?

Green chemistry has gained so much attention due to the continuous debate of the exact nature of the environmental hazards that have been generated as a result of the release of various synthetic chemicals into the environment. Because of the uncertainties in toxicological data remain unresolved – exposure, fate, and transport, these concerns add firewood to the debate. The solution rests on allowing the uncertainties to continue paralyzing the risks posed on human health and the environment; or, as adopted by those pursuing green chemistry, accepting the fact that chemicals cause some risks to human health and the environment; and through fundamental breakthroughs in chemical methodologies, both technically and economically viable, then the chemical community should pursue it (Anastas, 1998).

Types of Green Chemistry Being Practiced

In reviewing case studies of companies pursuing green chemistry, we observed three main ways that companies practiced green chemistry: (1) as a systems approach, (2) for discovering alternatives to synthetic pathways of chemicals, and (3) for environmental conservation. The overlying factor which encouraged companies to continue practicing green chemistry was the reduction in raw material, manufacturing and waste disposal costs, and the reduction of risk analyses when factoring in overall costs; making the new practice a more efficient method for companies.

Green chemistry as a systems approach – Principle 7 supports this method by encouraging companies to maximize the incorporation of all materials. By designing chemical syntheses to function in a non-linear method, chemicals are recycled in the reactions. They are longer lasting and produce less if any waste. Principle 5 encourages the use of catalytic reactions. Catalysts are the mechanisms that get the reaction to go, they facilitate a transformation without being completely used up and they can be recycled into a new reaction.

Green chemistry as deriving alternatives to synthetic pathways of chemicals – The focus of this method is to reduce wastes and use softer chemicals less harmful to human health and the environment. The 'yield' part of chemical reactions rarely factor in the effectiveness or efficiency of synthetic reactions. Often the reactions will yield 100% of the desired product, but produce more waste in mass or volume than the product. Principle 3 encourages using alternative chemicals that produce less waste and are benign to the environment which reduce hazards.

Green chemistry as a form of environmental conservation – All of the principles point to this much needed initiative. Worldwide poor water quality and shortage from inefficient use of water are indicators of our environment's state of health. Environmental conservation is an intrinsic benefit in green chemistry. Companies that practice green chemistry for other reasons are happy to recognize that they are being environmental stewards, although this method is rarely the priority in practicing green chemistry, since not all the right incentives are in place to create urgency in conserving the environment. Green chemistry is also a cost effective approach – Principles 1, 4, 9, 12 encourage energy saving methods and waste treatment reduction as well as reduction of fines due to accidents.

III. Major Players

There are many stakeholders involved in the use and development of Green Chemistry. The most prominent among them include industry (chemical manufacturing as well as consumption), scientific and professional organizations, academia/research fields, non-profits, businesses, government, and consumers/general public. All play roles in bringing a different piece of the puzzle to further green chemistry, as well as affect each other's capacity to do so. In the current stage of Green Chemistry's development/use there are different ways each can assist its future success.

Industry: The U.S. chemical industry is the world's largest producer of chemicals (367.5 billion shipped in 1995), and represents 10% of all U.S. manufacturing (IUPAC). However, according to Dr. Edward Woodhouse (an RPI professor invited to testify before Congress on Green Chemistry), the U.S. industry is globally the least progressive. While speaking for the encouragement of Green Chemistry, Dr. Woodhouse notes that as other countries move ahead with this benign-by-design chemistry, the U.S. increases its “commercial risk of waiting to act” by not breaking into the market early.

Some in industry are aware of this opportunity for progress, and Steven Bradfield, VP of Environmental Development at Shaw Industries requested of Congress the opportunity for industry to have a voice in helping to guide the GC agenda. There is some sense of responsibility in his comments as he notes, “When a company achieves this sustained level of success we are expected to provide leadership”. Industry is eager to get behind Green Chemistry, both wanting to help guide the process as well as be assisted by other stakeholders.

In addition to the manufacturing sector, industry that uses chemicals has expressed interest in Green Chemistry. According to Dr. Lauren Heine of ZeroWasteAlliance, IKEA has adopted GC principles in some of its manufacturing and even stated “What we are measuring at the cash register is the rate at which we are transforming resources into waste”. Nike is also making use of GC technology, the website discusses “product life cycle” in recycling shoe parts, and has posted a job ad for a Director of Sustainable Production Chemistry, who is required to actively seek out GC applications. Large corporations such as Patagonia, 3M and Dow chemical also currently use GC technology.

Industry can significantly affect the success of GC by choosing to implement it. Hopefully this will happen naturally as Green Chemistry is recognized for better processes, less waste, less cost and less risk to health and the environment. It cannot make the switch on its own, and needs the cooperation of other stakeholders discussed below.

Scientific/Professional Organizations: There are many scientific organizations citing an affiliation with Green Chemistry in some form. The most prominent are the International Union for Pure and Applied Chemistry (IUPAC), the Council for Chemical Research (CCR), and the American Chemical Society (ACS).

IUPAC has articulated its role as “a leading and internationally representative scientific body” and in 1996 established a working party on synthetic pathways and processes in green chemistry. IUPAC sees itself in the position to be useful for standardization and definition of various aspects of GC, in addition to helping to define the general concept in order to help attract leading scientists to the field. Also, IUPAC is an international coordinator of educational programs, and has issued a call for partnership between government, industry and academia in order to establish a curriculum and infrastructure for GC. The organization went so far as to create a “technology roadmap” for the industry, with attention to supply chain/technology management, efficiency in raw material usage, and reusing and recycling materials. IUPAC also has the distinction of having organized at least 13 international conferences pertaining to GC in the years 1996-2001.

The Council for Chemical Research counts in its membership representatives of industry, academia (including Cornell University), government, and a majority of the “chemical research enterprise”. It has a $7 billion Research and Development budget and was founded in order to further cooperation in research, hoping to exemplify collaboration “across discipline, institution and sector boundaries in order to benefit society”. CCR seems to have more modest programs specifically focused on green chemistry.

The American Chemical Society is a professional organization with 159,000 members at all degree levels and in all fields of chemistry. It might be said to be associated with GC superficially. Dr. Woodhouse states, “Professional associations such as the American Chemical Society and the American Institute of Chemical Engineers are rhetorically supportive of chemical greening, and even have a few modest programs, but they are not doing much at present to actually inflect the trajectories of their mainstream members”.

It seems that organizations such as these have a great capacity to serve as coordinators and information disseminators for Green Chemistry efforts due to their significant access to many sectors, but they differ greatly from one another in degree of rising to the challenge.

Academia/Research: John Warner of the University of Massachusetts criticizes the current status of chemistry educational programs and opportunities in the U.S., stating that "About half of U.S. chemistry departments still require PhD students to pass a qualifying exam in a foreign language, but not one requires equivalent proficiency in toxicology" (Woodhouse 2004). Dr. Woodhouse also noted that chemists are not required to obtain professional licensing and can be employed without it. The licensing that does exist has not changed significantly in the past 10 years, so it does not reflect the advances made in the field of Green Chemistry.

There are 2 notable programs focused on Green Chemistry in the University setting, at the University of Scranton and University of Massachusetts. The University of Scranton has collaborated with the Green Chemistry Institute (discussed later) in order to assess the economic and environmental benefits for US industries of adopting green chemistry processes and products. Faculty members have developed GC modules for specific chemistry courses that can hopefully be shared with other universities.

The University of Massachusetts offers a PhD in Environmental Sciences with a green chemistry track. It is the first such program in the world and focuses on practical skills and tools, and prepares students for conventional chemistry jobs in many fields.

The University of York hosts the Green Chemistry Network, which was created to help chemical companies and chemists by sharing best practice, enabling the transfer of green technology, and providing data to demonstrate that industry can save money by adopting green practices. The Network also envisions green issues eventually forming the underlying principles of chemistry courses. The Network has created a GC database linked to overseas networks, and through it organizes conferences, makes educational materials available and awards prizes for researchers and companies.

Perhaps one benchmark of green chemistry's progress towards firmly establishing itself in academia is the scientific journal *Green Chemistry*, first published in 1999. Cornell University subscribes to this journal.

As for Cornell's standing with green chemistry, in 2001, a Cornell researcher also discovered a protein that won the Presidential Green Chemistry Award (Chronicle, 2001). Paul Anastas PhD, of the White House Office of Science and Technology Policy (Society, 2003), often labeled the "father of green chemistry" spoke at Cornell in March of 2004.

Universities generally cite a need for funding in order to establish GC programs, which legislation (discussed below) is attempting to provide. However, Dr. Woodhouse of RPI points out that universities can be pushed other ways - he sees an opportunity in the accreditation universities must renew. If accrediting organizations made the decision to require a phase in of new chemistry practices, universities could be helped to realize the importance of such a move.

Universities are a crucial place for the beginning of a green chemistry movement - over and over lack of training/education at this point is seen as perhaps the largest barrier to GC's implementation on a large scale. The role of universities is to train our future chemists with the skills and knowledge to create and work in a sustainable industry. Universities are a starting point, but they need a demand for the knowledge, and support (financial and otherwise) from government and industry in order to make the transition.

Non-Profit Organizations: Several not-for-profit organizations exist that are dedicated towards promoting green chemistry and enabling various entities to adopt it.

The American Chemical Society's Green Chemistry Institute (mentioned earlier) is a non profit dedicated to promoting collaboration between national and international governments and industries with universities and national laboratories.

The Zero Waste Alliance provides management support, as well as "assessments, strategy development, planning, assistance and guidance in implementing programs". The Alliance provides training and education on the tools, methods and concepts of "Zero Waste" and industrial ecology (such as life cycle assessments and full cost accounting), as well as serving as a resources clearinghouse, organizing conferences and workshops, and giving lectures.

The Green Chemistry Centre for Industrial Collaboration is a research and development service that improves chemical processes and products for industry through the use of GC principles. The Centre assigns researchers to industry products, lending their analytical equipment and expertise to address industrial needs.

It seems that at the moment, Non-profit organizations are attempting to bridge the education gap by directly providing services and training to industry that at the moment it may have trouble hiring itself. These organizations are serving a valuable role in promoting GC and waiting for the rest of society to catch up.

For-Profit Organizations: There do not seem to be many organizations that are attempting to make money on the promotion of green chemistry, but MVS Solutions appears to be doing so. MVS Solutions is a consulting company that offers GC development, support and consulting to both business and the government. The company claims "consumer sentiment is increasingly favoring eco-friendly and green alternatives over conventional products and processes. Consumers are becoming 'greener' in their purchases and lifestyles".

There is a healthy debate on consumer demand for green products, but at the moment, this company is functioning by at least claiming such a market exists. It remains to be seen whether companies such as MVS Solutions can convince industry of the dire need to aggressively market to the green consumer.

Government: There are several government departments that deal with matters relevant to GC. The EPA, DOE and NIST are the most prominent. Addressed later will be government's potential to function as a consumer.

The Environmental Protection Agency is very active in promoting green chemistry, proclaiming the importance of education to train chemists and educate students both already practicing and in the future. It runs two kinds of operations, the Office of Research and

Development conducting scientific inquiry, as well as doing outreach and promotion through the Office of Pollution Prevention and Toxics (OPPT). OPPT administers the Toxic Substances Control Act and Pollution Prevention Act 1990 (discussed later). Among several other programs, it also runs the Presidential Green Chemistry Challenge (also discussed later). The EPA also awards a relatively large amount of money through grants with the NSF to various GC programs.

The Department of Energy does not track its spending on Green Chemistry or identify any activities specifically focused on it, but it does conduct R&D that has many green chemistry applications (mostly with regard to energy-generating atomic and molecular processes).

The National Institute of Standards and Technology (mission: "To develop and promote measurements, standards, and technology to enhance productivity and improve the quality of life") also conducts R&D not specifically focused on GC but the research does come out with green chemistry applications.

The EPA is certainly active with GC, but when considered together with DOE and NIST, only a relatively small portion of their R&D budgets and effort go to green chemistry. In addition these efforts are not coordinated or strategic in nature.

Government has provided opportunity for the advancement of Green Chemistry, but more coordination and attention to the issue would help command and control to fully play its role.

Consumers: Consumer demand is a significant shaper of industry practice, but there is disagreement on the pull of 'green products' for consumer choice, especially when higher prices are involved (not always the case in green chemistry). Woodhouse comments on the legislation regarding GC currently in Congress (discussed below), stating: "The green chemistry deliberations bring up the possibility of tackling the relationship between chemistry and society in a creative way by focusing on the social components explicitly".

MVS's solution has based its marketing on Paul Ray's "Cultural Creative", defining it as a "Relatively new term and market niche . . . a growing demography of about 45 million Americans that represent a new "world view". As a group, they are willing to take action on their values and represent socially responsible consumers. The Cultural Creatives now represent about 20% of the U.S. population and are making value-based choices in more and more product categories" (The Cultural Creative: 60% are women, median age is 42, median family income is $47,500, upper middle class information junkies, "purchases symbolize values").

Steven Bradfield of Shaw Industries cites consumer's call for green chemistry in shaping his textile company's path: "Customer demand and profitability are the most enduring drivers of green chemistry and sustainability. . . No regulations could have moved our industry so far and so fast in the direction of sustainable development [as market forces have]" (Bradfield testimony to Congress).

Larry Chalfan of Zero Waste Alliance also emphasized the government's role as a consumer. Formerly CEO of a semiconductor company, Chalfan explained that the government's choice to use his company's green products single-handedly established the company's market entry (Chalfan, pers. comm).

It is clear that market demand can make or break the rooting of green chemistry into general practice, but whether that market demand will issue a clear cry for environmentally friendly living has not been decided. It will determine the "culture and psychology of relevant disciplines and businesses" (Woodhouse 2004), however.

All of these major players occupy unique roles in determining the future of Green Chemistry. Consumers have the most freedom to shape this future, and government may need to supply the initial foundation upon which industry, non-profits and other organizations can build.

IV. Legislation

There is much legislation that impacts Green Chemistry. Some takes a remediation/end-of-pipe tack and some is focused on encouraging GC development.

General Laws: The U.S. has a legacy of general environmental laws aimed at limiting pollution. Among these that affect industry are the 1970 Clean Air Act, 1972 NEPA, 1972 Clean

Water Act, 1972 Federal Insecticide, Fungicide & Rodenticide Act, 1972 Ocean Dumping Act, 1974 Safe Drinking Water Act, 1976 Toxic Substances Control Act, 1976 Resource Conservation and Recovery Act, and 1980 creation of Superfund (Cann 2004).

This “command and control” legislation tends to deal with pollution after it is formed, and is concerned with treatment or abatement of dangerous waste. As end-of-pipe laws, they try to prevent exposure, which is not always effective. These laws could serve as motivation for industry to switch to green chemistry in order to avoid such heavy regulation as well as inevitable dangers for human health and the environment.

More Direct Regulation: Of the legislation from the past 30 years, two acts stand out as having more direct relevance to Green Chemistry: The 1990 Pollution Prevention Act and the Toxic Substances Control Act.

The Pollution Prevention Act established a change in thinking about pollution, requiring that pollution be prevented or reduced at the source whenever possible. It also gave EPA some flexibility to be creative with its strategies to fulfill its mandates, such as allowing for the Green Chemistry Challenge, discussed below.

The Toxic Substances Control Act requires that all chemicals produced or imported in the U.S. be tested, regulated and screened. This may provide a good forum for Green Chemistry products to be directly compared with conventional chemicals and hopefully highlight the advantages of the former.

Encouraging Green Chemistry: Since 1996, legislation has been created to encourage enterprise and development with GC, addressing issues of recognition, funding and advising. This consists of the Presidential Green Chemistry Challenge, EPA SMART Program, GREENSCOPE, and the Green Chemistry Research and Development Act of 2004 (currently up for decision).

The Presidential Green Chemistry Challenge is aimed at multiple sectors, and provides high level recognition and support for innovation in GC. The PGCC Awards program has given away over 40 awards since 1996, and provides the opportunity for competition among individuals and groups for “cleaner, cheaper and smarter chemistry” (EPA website). It also recognizes technologies incorporating GC principles that industry can use for pollution prevention.

The EPA SMART Program stands for Synthetic Methodology Assessment for Reduction Techniques. New chemicals submissions must describe manufacturing methods, and the program uses these to assess the methods and make recommendations of green chemistry applications to reduce their pollution. EPA will send any recommendations or concerns about the process to submitters intended for voluntary consideration.

GREENSCOPE addresses the need for a widely applicable system for determining the actual sustainability of intended “green” reactions or processes. The GREENSCOPE model provides the necessary sustainability indicators/metrics for Gauging Reaction Effectiveness for the Environmental Sustainability of Chemistries with a multi-Objective Process Evaluator. GREENSCOPE evaluates a reaction or process for its sustainability in terms of Environment, Energy, Efficiency, and Economics. GREENSCOPE is intended to provide for direct comparison between similar processes, having many implications for the large scale implementation of Green Chemistry.

The Green Chemistry Research and Development Act of 2004, at the moment making its way through Congress, is designed to stimulate undergraduate/graduate education in Green Chemistry in order to create a new generation of chemists familiar with green chemistry and its advantages and who can put it into practice. The Act would provide for R&D programs, demonstration projects at universities, industry and federal labs and make these results easily accessible in a database. Woodhouse has criticized the Act, saying that“ Social science and policy are not ruled out by proposed wording (of Act), but neither are they made as central as the situation may justify. . .much of what stands in the way of chemical greening is social and economic in nature”.

Current legislation runs over almost the complete spectrum, both regulating/attempting to minimize current pollution, as well as sowing several seeds to provide for encouragement of and assistance with green chemistry. At this point it does not address social barriers to GC's development, which in the opinion of some are the most critical, but the movement is still relatively new and there is room for progress in many areas. There is the beginning of the creation of the 'new generation of scientists' being called for widely, but this will take time to work into the industry and have the needed effect. In the mean time, the R&D money should help some to bridge the gap while new scientists are on the way. Legislation is only one part of the total forces needed, but at this point it is orienting itself in a helpful direction.

V. Market Incentives

Market incentives of green chemistry are internal, or within the chemical product development sector, and external, including incentives for other industrial sectors, social, and environmental conservation. Internal market incentives are economic incentives, competitive edge and positive reputation, efficiency in manufacturing, improved worker health and safety, reduction of risks and insurance costs, opportunities for selling licensed technologies and opportunities for companies to be capture first mover advantages in a new product development.

Green chemistry has survived market pressures because it is focused on efficiency and sustainability. Research shows that evolution in markets is based on the diversity in numbers and diversity in the productivity of the population of companies within a market selection and the rate of innovation effects. Using sustainability as a market approach increases the number of quality of behavioral determinants driving innovation. Therefore, economic incentives are increased profits due to the increases in productivity gained as a result of innovation based on sustainable practices (Moore, e-mail correspondence).

Companies in green chemistry are motivated by competitive and social pressures to 'green' products and processes (Moore, Bradfield 2004). Unlike other industrial sectors heavily regulated, or saturated with companies, green chemistry companies are not strictly regulated and are fairly new. Because green chemistry companies are at the forefront of innovation, competitive pressure is an encouraging incentive to keep striving for the competitive edge and avoid creative destruction. Companies can also gain a competitive edge by competing for distinction awards. Government and professional societies award companies with outstanding performance, raising the standards for performance while creating publicity for the companies.

The search for ways to lower capital spending has also proven a motivator of ‘green’ technologies (Earth’s, 2003). By conserving matter at the molecular level, efficiency in material use is improved, waste is reduced and product yield is improved. The following case studies provide insight on costs reductions in companies from different sectors but with the same methodology in mind.

Benign chemicals are not only safe for the environment but also for chemical handlers and applicators. Systems approaches in green chemistry include worker health and safety in analyzing best design processes of chemicals. Worker satisfaction and motivation is also increased in companies that promote safe product processes.

Approaches for the design of inherently safer chemicals can include using substances with lower vapor pressures in place of volatile substances that are associated with the majority of chemical accidents (Anastas, 1998). By using chemicals that eliminated the need for large inventory stockpiles of hazardous substances, accident risks can be reduced as well as insurance costs required to support the risks involved.

Green chemical companies have the opportunity to license new products while capturing the first mover advantage. Green chemistry companies are able to ride the wave of chemical product failure and redesign processes to discover more efficient methods. These discoveries are fair play as new licensed products and can gain economic benefits. The discovery can create niche markets while giving companies the opportunity to establish itself and gain a first mover advantage.

External incentives of green chemistry are market, consumer, conservation and legislative incentives. New markets can be created to supply demand of softer chemicals. Through the innovation of new chemicals and licensing, chemicals can be outsourced from smaller companies, creating higher productivity, job opportunities and a focus on natural capital.

The perception that chemicals should be feared can be avoided by informing consumers through educational programs, proper labeling, and building a positive public image of companies through marketing tactics and recognition awards. Trust will promote further innovation since companies recognize that social pressures for "greener" products will move companies further to practice green chemistry. The shift will be worthwhile when the market sees consumer interests that outweigh the challenges in shifting over.

Green chemistry is created on the need to conserve our natural resources. These initiatives will protect resources in all scales from local communities downwind of chemical plants to a reduction in global warming trends.

Legislation of the command-and-control sort provides the incentive for companies to move ahead on their own to avoid further regulation. Money appropriated to help the fledgling industry provides the incentive for further research and development, education of scientists, and awards may satisfy some egos.

Green Chemistry has the strength of a variety of incentives working for it- it makes sense in many different ways, and one can be hopeful that these will naturally exert their power to help green chemistry grow and perhaps replace 'conventional' chemistry.

VI. Green Chemistry – Comparison with Natural Capitalism by HLL

At present, the costs of a synthetic process for a chemical must include not only those costs for feedstocks and equipment, but also the full cost of regulatory compliance, the costs of waste disposal, liability costs and treatment costs, including plant modification for end of pipe treatment. Through "full costs accounting," authors Anastas and Warner state that this accounting strategy gives new standards for the economics of manufacturing. The power lies in the chemists, to reduce these costs by redesigning chemicals and their processes. This desire to include all costs in the chemical product development industry supports Hawkins, Lovins, and Lovins (HLL), position in their book Natural Capitalism. By setting prices that properly value the impact incurred on the natural environment, natural capitalism will likely increase present prices of chemicals. Green chemistry can be an incentive to reducing the prices back to present day prices by avoiding the environmental impact. However, because we do live in a complex market, it is a challenging notion to fully understand how full costs accountants can factor in what green chemistry hopes to save in costs, while correctly pricing the impact already incurred on natural resources and more to come.

Green chemistry supports HLL's position on resource productivity. By implementing system approaches and using sustainable recyclable chemical syntheses, chemical yield will be more efficient, creating higher productivity. Green chemistry will also create a demand for green chemists and created new opportunities for outsourcing of soft chemicals as raw material from distributing companies, creating more jobs. Green chemistry as a pollution prevention method is rooted on the concept of biomimicry. In designing new syntheses through a non-linear approach, green chemistry mimics nature by incorporating natural process and eliminating wastes.

Interface Corporation's shift into a service economy was quickly accepted by their clients for their innovative effort in saving time, material, and providing them the service they required. Taking the business one step forward, in using selenium as its main material for its carpets, Interface embarked on a greening method that incorporates the conveniently reusable properties of materials while still focusing on a service strategy. This is clearly a form of green chemistry in that it focuses on a recyclable, material reduction approach viable due to the use of a material that is environmentally benign. Green chemistry is a smart and safe investment in natural capital.

VII. Case Studies

A. Rohm and Haas Co.

Rohm and Haas Co. is a $7 billion (annual sales revenue) specialty chemical company that has more than 100 manufacturing, technical research and customer service sites in over 27 countries. Rohm and Haas technology is found in paints and coatings, adhesives and sealants, household products, pharmaceuticals, personal computers and electronic components, construction materials. They serve the specialty crop market by designing biochemicals, and they offer a wide range of turf and ornamental products as well.

Rohm and Haas is committed to principles of responsible care and sustainable development, realizing that they must go beyond compliance with existing regulations and embrace the concepts of green chemistry, life-cycle thinking, and risk assessment in the general management framework, new product development and corporate decision-making. They feel that "companies can no longer be compliant with environmental regulations, believing that they will be economically secure" (Reinert, 2001). They proclaim that operating sustainably creates long-term value and achieves a greater competitive edge.

Rohm and Haas is the only two-time recipient of the Presidential Green Chemistry Award. The Presidential Green Chemistry Awards Challenge was initiated by an alliance of the chemical industry, the EPA, and the Clinton Administration in 1995, to identify and promote fundamental breakthroughs in chemistry that prevent pollution through source reduction and process redesign and are useful to industry. The company won the award first in 1996 for the development of a much safer and more effective anti-fouling agent called Sea-Nine 211. The fouling of ships by marine organisms such as barnacles, algae and seaweed, is a major problem which can be extremely costly to ship operators if not prevented. Increased fuel consumption is needed to overcome the drag (also contributing to negative environmental effects like global warming and acid rain). To combat fouling, harmful marine antifouling paints containing tributyltin (TBT) have traditionally been used. However, Rohm and Haas responded to the call from the IMO for an alternative to tin-based marine paints for large commercial vessels. Rohm and Haas effectively sought out a niche market. The company came up with alternative green chemistries, and the adoption date for the international ban on TBT was moved up from 2006 to 2003. In countries with stringent environmental regulations, such as in the U.S., Sea-Nine 211 has been a breakthrough for commercial vessels. In many countries where TBT discharge limits have been set for maintenance and repair yards, limits are extremely difficult and expensive to meet, and so the Rohm and Haas' green chemistry alternative has been desirable. Major paint manufacturers have already greatly invested in alternative products based on Rohm and Haas' green technology, which demonstrates their environmental commitment and faith in Sea-Nine 211 as a cost-effective anti-fouling agent.

The award Rohm and Haas received fell under the category for Designing Safer Chemical Products; Sea-Nine 211 degrades rapidly in sea water and sediment, does not bioaccumulate in marine organisms and is not a chronic/reproductive toxin. Rohm and Haas report that its metabolites are 100,000 times less toxic than the parent compound;" and that it has a half-life of less than one hour (Rohm and Haas, CIS General News). In developing Sea-Nine 211, Rohm and Haas incorporated the concept of biomimicry – and they clearly state this (Rohm and Haas, Sea-Nine 211). They explain that the recognition and avoidance of substances that interfere with essential life processes are a natural characteristic of organisms. Sea-Nine 211 harnesses this characteristic of nature to prevent fouling. It reacts with the proteins of organisms that come into contact with the paint surface. Metabolic processes requiring these proteins are interrupted as a result. Such interference then stimulates the organism to identify and avoid further obstructions to its life processes by moving to a more suitable environment that can support it. The marine organism will naturally seek out surfaces that foster a biologically active environment.

Sea-Nine 211 is just one highly effective and versatile member of the isothiazolone family of biocides produced by Rohm and Haas. In 1998 the company was honored a *second* *time* with the Presidential Green Chemistry Award, for the development of a new, more environmentally and user-friendly family of pesticides. Several members of the diacylhydrazine family, which controls insects in turf and variety of agronomic crops, have already been commercialized. One member of the family is Confirm, a breakthrough in caterpillar control, which effectively aims at "target" species and is safer for applicators and consumers. The value of crops destroyed worldwide by insects is tens of billions of dollars, and only a few insecticides have been able to combat this destruction over the past years. Confirm has been able to successfully control caterpillars and replace many older, less effective and more toxic pesticides.

Once again, Rohm and Haas looked to nature in designing a safer product. Confirm strongly mimics a natural substance found within the insect's body (20-hydroxy ecdysone) that triggers molting and regulates development in insects. As a result, Confirm greatly disrupts the molting process in target insects and induces them to stop feeding and die soon after exposure. Since 20-hydroxy ecdysone neither occurs nor serves any biological purpose in most non-arthropods, Confirm is much safer than other pesticides to a wide range of non-target species like mammals, birds, earthworms, plants and aquatic life. Its selectivity makes it safe to a large number of key beneficial, predatory, and parasitic insect species, as well as predatory arthropods and mites. Unlike traditional pesticides, Rohm and Haas' new family of pesticides will not create outbreaks of target or secondary pests due to destruction of key natural predators and parasites in the ecosystem. Thus, the need for repeated applications of even more insecticides and the overall chemical load on both the target crop and the local environment is reduced.

Confirm "has low toxicity to mammals by ingestion, inhalation and topical application, and has been shown to be non-oncogenic, non-mutagenic, and without adverse reproductive effects" (EPA, 1998 Designing Safer Chemicals). It can be used at relatively low doses and poses no significant spill hazard. This "reduced risk pesticide" (classified by the EPA) has been called "chemically, biologically and mechanistically novel" (EPA, 1998 Designing Safer Chemicals Award).

In addition to their award-winning green chemistries, Rohm and Haas had demonstrated their commitment to other principles of green chemistry through the use of renewable, resource-based materials instead of nonrenewable raw materials; through replacement of solvent-based systems with water-based, solvent-free or powder systems; and through reducing the level and/or number of inert, nonessential ingredients in production (Reinert, 2001). As an example, from 1997 through 2002, Rohm and Haas engineers cut energy use by nearly 25% at their Houston monomers production facility. Production was simultaneously increased by 17%. The site now saves about 4.2 trillion BTUs annually. Sustainability efforts in engineering at the Houston facility have eliminated 440 tons of on-site NO_x emissions and 67,000 tons of CO_2. "Economic benefits are equally clear, with over $18 million in avoided energy costs" says Fitzpatrick (Rohm and Haas, 2004 Keynote Address).

Rohm and Haas believe that working closely with government, academic groups, and NGO's on sustainable technologies is essential and accelerates the pace of innovation. They clearly emphasize collaboration and relationship building, even between firms. However, it is not easy. J. M. Fitzpatrick, President and CEO of Rohm and Haas, who spoke at the 2003 international conference in Tokyo, explained that there is a conflict between collaboration and competition: "Companies that develop new and successful technologies will be inclined to use it as competitive advantage rather than share it with competitors. That's a risk/benefit equation we all have to calculate at some point." (Rohm and Haas, 2003 Tokyo International Conference speech). Rohm and Haas knows for certain that the speed at which today's market demands new chemistries, better processes, and greener products is accelerating – and translates into higher profits for everyone. They currently endorse the green chemistry bill, recognizing the need for "additional collaboration, knowledge transfer, and crucial research" in the field of green chemistry (House Committee on Science, March 2004).

Rohm and Haas also believe that marketing is "the most powerful tool in our arsenal to promote and encourage the use of green chemistries" (Rohm and Haas, 2003 Tokyo International

Conference speech). Collaboration between researchers and marketing is key to their business and helps scientists hear first-hand the expectations of customers. They make sure their marketing department knows about the regulatory drivers impacting customers and gear their research to help customers meet new regulations. They speak to actual customers – "the customer of our customers" – to understand the features consumers want, as well as understand buying trends and "green" purchasing. As Fitzpatrick says, "when it comes to the business case for sustainability, I think one doesn't have to look far beyond our very own customers. Directly or indirectly, they are beginning to call for more sustainable products, or at the very least, are willing to change their purchasing decisions to new technologies so long as the pricing is right and it's marketed in a way that resonates with them" (Rohm and Haas, 2004 Keynote Address).

B. Green Synthesis of Ibuprofen: "Chemists must not only strive to develop reactions that produce high yields, but these same reactions must also aim for incorporation of all the atoms of the reactants into the desired products, thus eliminating the production of unwanted byproducts" (Cann and Connelly, 2000). One example of this is the green synthesis of ibuprofen. Ibuprofen is a common over-the-counter drug that falls in the category of a nonsteroidal anti-inflammatory, along with aspirin and acetaminophen. It is commonly used to reduce pain, swelling, and fever, and is found in any of the following brand name drugs: Advil; Genpril; Haltran; Medipren; Midol 200; Motrin; Nuprin; or PediaProfen (Medline Plus, 2004).

The Boots Company of England developed the old method of producing ibuprofen, now known as "brown" synthesis, during the 1960's. This method involved six stoichiometric steps with various waste byproducts produced in the course of the reactions. The reactions involved in this process presented less than 40% efficiency, because less than 40% of the molecules by weight are incorporated into the desired product. This type of reaction is characterized by "poor atom economy." Since about 30 million pounds of ibuprofen are produced annually, the waste from this chemical process alone added up to 35 million pounds of waste each year, the majority of which remained "unwanted, unutilized, and unrecycled" (Cann and Connelly, 2000).

When the FDA approved ibuprofen for over-the-counter use in the mid 1980's, the Boots Company and the Hoeschst Celanese Corporation (now the Celanese Corporation) agreed to work together as the BHC Company to develop a new method of synthesis for ibuprofen ("green synthesis") in order to develop a higher yield process to be able to compete more effectively in the now open market (Cann and Connelly, 2000). The product of the research was a 3-step catalytic process that was over 77% efficient. The single waste product, acetic acid, can be recovered and reused, bringing the efficiency to approximately 99%. In addition, the process avoids the problem that many pharmaceuticals manufacturing processes have, which is using large quantities of solvents to drive the reactions, thus creating large volumes of aqueous waste contaminated by salts (U.S. EPA, 2004).

This remarkable redesign was the recipient of the 1997 EPA Alternative Synthetic Pathways Award. The EPA cites it as "a model of source reduction, the method of waste minimization that tops EPA's waste management hierarchy" (U.S. EPA, 2004). The BHC Company also won the prestigious Kirkpatrick Chemical engineering Achievement Award in 1993 for their revolutionary tactic (BASF ExAct, 1999).

This particular case study is one of the poster children of green chemistry because it is an example of a win-win situation. There is a large reduction in waste, improved competition in the market, and much publicity for the companies involved in this new green synthesis of ibuprofen.

C. Green Chemistry and Water Conservation: The chemical industry is the largest manufacturing consumer of water. Although chemical products are diverse, water is used for multiple roles making it essential to chemistry. It could be used for feedstock, waste control, cooling thermal electric power plants and other heat sources. A 2001 report by the Organization for Economic Cooperation and Development indicates that within the industrialized (OECD) countries the chemical industry was the largest consumer of water (43%) followed by metals processing (26%), pulp and paper (11%), with other uses accounting for 20% (OECD, 2001).

The chemical industry impacts the environment not only by the amount of water it consumes but also by how it affects the environment. The discharge of wastewater from chemical industries is a major contributor to the degradation of aquatic ecosystems. Through processes such as production, delivery, utilization and product disposal, chemical industries discharge large quantities of chemicals to water bodies. Critical sources of water pollution include wastewater from water treatment, pulp and paper bleaching, metals processing, pharmaceutical manufacturing, textile dying and cleaning, corrosion control, and processes as varied as photography and photolithography (OECD, 2001). Some of them are toxic chemicals and bio-accumulative metals which are hard to treat by current technologies or non-degradable. In the UK, there are 27 restricted substances (including mercury and its compounds, and carbon tetrachloride) which are particularly hazardous when discharged to water bodies or sewers (OECD, 2001). Other more dangerous substances may exist that we do not yet know about. For example, the U.S. Emergency Planning and Community Right to Know Act (EPCRA) covers only 650 of the 75,000 chemicals in use in the U.S. today (OECD, 2001). Even regular chemical products like fertilizers influence water quality dramatically, increasing the nutrient loading to waterways from farm chemical run off.

As a system science (Thomas, 2001), green chemistry can provide scientifically based solutions to protect water quality and relieve the increasing global pressures on water quantity (Dennis, 2001). It could increase efficient use of resources and make significant reductions in water pollution from chemical production. It is a useful tool compared to approaches like “end of pipe” mediation, which lack effectiveness due to poor operation and maintenance. The following case study highlights green chemistry as an environmental strategy in reducing water pollution.

Industrial case: Süd-Chemie Inc. is a specialty chemical and industrial minerals company. Catalysts are one of its main products for industrial and consumer markets. However, the synthesis of catalysts is often accompanied by the discharge of large amounts of wastewater and other pollutants, such as NOx, SOx, and halogens (Süd-Chemie). In response to this concern, Süd-Chemie developed and demonstrated a new synthetic pathway to make catalysts that is able to achieve virtually zero wastewater discharge, and zero nitrate discharge. It substantially reduces both the consumption of water and discharge of wastewater. The redesign of the reaction has been estimated to eliminate 378,900 tons of wastewater discharges, about 14,300 tons of nitrate discharges, and about 3,800 tons of NOx emissions for every 5,000 tons of oxide catalyst produced (Süd-Chemie).

The surplus of NOx in water bodies is a major cause of eutrophication, a widespread environment problem, posing many negative effects on aquatic ecosystems. High concentrations of the nutrients N and P provide food for algae and aquatic weeds to grow very fast and cover the whole surface of the water bodies while reducing the concentration of oxygen dramatically. The loss of oxygen will kill fish and aquatic biodiversity and reduce water quality. Hence, it will render water unusable for drinking, fisheries and agriculture.

By applying this novel technology, Süd-Chemie not only improved their impact on the environment, but also gained economic benefit. It is estimated that the market value for their solid oxide catalysts is approximately $100 million (Süd-Chemie). As the first company to use the green process for making a catalyst for the synthesis of "green" fuels and chemicals, Süd-Chemie is seeking patent protection for the development. It offers the company a potential market for technology transfer. Because of its contribution to water environmental protection, Süd-Chemie earned the Alternative Synthetic Pathways Award in 2003 by the US EPA (Presidential, 2004). By developing and applying this wastewater-free Process for catalysts synthesis, Süd-Chemie realized both the environmental and economical benefits. There is no obvious barrier for this firm to adopt the approach of green chemistry.

VIII. Barriers

Fully adopting green chemistry comes with numerous challenges for implementation. As a fairly new method it is challenged with limitations of lack of infrastructure, such as equipment and material availability that follow green chemistry principles. The lag time for researching methods, gathering results and publishing outcomes is a problem since there is a limiting amount of existing research on green chemistry. Knowledge transfer of patents becomes a conflict between collaboration and competition to share information and further research and development (Rohm and Haas, 2003 Tokyo International Conference speech). Competitive pressures make companies skeptical of sharing information in order to keep first mover advantages. There is a need for green chemistry in universities as part of curriculum to train future green chemists. In addition, switching costs are high and risky, and as a new and widely unproven technology, firms are reluctant to gamble with high stakes. The EPA's Tracy Williamson points out however, that this is a barrier for new technologies of any kind, and does not necessarily indicate that green chemistry should have more trouble than others (Warshall 1999). In order to reduce risks with innovation, there needs to be more economic incentives in place. The Green Chemistry Research and Development Act of 2004 provides some funds for this purpose, but perhaps not enough. Edward Woodhouse criticizes that there are no funds in the bill appropriated for effecting change in societal attitudes that must occur for green chemistry to succeed (Woodhouse 2004). There is also a need for more programs and policies to promote research and provide appropriate awards (Reinert, 2001); this includes resolving the social and economical built-in challenges of introducing a new technological approach into the market. Consumers are a limitation to green chemistry in that they take no compromises in quality. Greener products walk a fine line; consumers do not buy a product unless it offers the same or better performance as the original. Many players in green chemistry emphasize the power of the consumer, so green chemistry must either market itself incredibly well or be able to emphasize advantages outside of environmental benefits in order to get the consumer dollar vote.

Tax incentives are not in place for companies to pursue green chemistry either. Sam Moore, CEO of Burlington Chemical Co. described the most significant limitation to his green chemistry company was that he would prefer a change of current tax laws to less complicated tax consumption laws for reducing production costs (Moore, 2004). An overlying challenge is the institutional failure currently seen in the chemical sector, efficiency, and conservation efforts compromised in today's highly bureaucratic industry.

IX. Conclusions

In spite of some barriers, green chemistry does seem to represent the logical next step in chemical production development. It is necessary to adopt new safer more efficient manufacturing process that not only will create revenue for companies but will conserve natural resources. This win-win opportunity must be pursued as a new direction for the chemical industries. Green chemistry is a result of scientific innovation as the chemical industry evolves into a smarter, environmentally conscience approach.

Although barriers do exist, they are only the growing pains of this new industry. With the cooperation of major players and legislation, green chemistry can flourish into a useful strategy for improvement in market practices and global environmental conservation.

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