Chemistry Innovations in Sustainable Development

Sustainability Education for High Schools: Year 10-12 Subject Supplements

Lesson 9: Green Chemistry

An Introduction

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Disclaimer

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The Natural Edge Project

The Natural Edge Project (TNEP) is an independent non-profit Sustainability Think-Tank based in Australia. TNEP operates as a partnership for education, research and policy development on innovation for sustainable development. TNEP's mission is to contribute to, and succinctly communicate, leading research, case studies, tools, policies and strategies for achieving sustainable development across government, business and civil society. Driven by a team of early career Australians, the Project receives mentoring and support from a range of experts and leading organisations in Australia and internationally, through a generational exchange model. TNEP's initiatives are not-for-profit. Our main activities involve research, creating training and education material and producing publications. These projects are supported by grants, sponsorship (both in-kind and financial) and donations. Other activities involve delivering short courses, workshops, and working with our consulting associates as we seek to test and improve the material and to supplement the funds required to run the project. All support and revenue raised is invested directly into existing project work and the development of future initiatives.

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Lesson 9: Green Chemistry
An Introduction

The reason green chemistry is being adopted so rapidly around the world is because it is a pathway to ensuring economic and environmental prosperity. Green chemistry is powerful because it starts at the molecular level and ultimately delivers more environmentally benign products and processes.

Paul Anastas, Founder of Green Chemistry and Green Engineering[1]

Educational Aim

The aim of this lesson is to introduce the topic of 'Green Chemistry' and to set the context for the following three lessons. This lesson introduces a number of key Green Chemistry principles that scientists and engineers can use to move towards sustainable development.

Key Words for Searching Online

Green Chemistry Institute, Paul Anastas, Green Chemistry Principles, Green Engineering Principles, Atom Economy, Benign by Design, Green Solvents, Catalysis.

Key Learning Points

1. Chemical processes underpin most of our modern lifestyles - from manufacturing processed food to treating water, making textiles for furniture and clothing, and making the metals and fuel for the buses, trucks and cars we drive. The chemicals industry is one of the largest industry sectors of the global economy, and nearly every material or product made contains one or more of the thousands of chemicals used daily around the world.[2] Within this global context, the Australian plastics and chemicals industry plays a relatively small role, creating and selling AUD$24.6 billion of product each year (i.e. only 1.5 per cent of the global market). However, it still employs more than 81,000 people.

2. While the chemical industry has contributed significantly to human development over the last century, Rachel Carson's 1962 publication *Silent Spring*[3] demonstrated that at times this has occurred at the expense of human health and the environment. Carson showed that some chemicals like Mercury and Hexachlorobenzene (HCB) which don't break down (i.e. which are 'persistent'), can 'bio-accumulate' up the food chain, being stored in body fatty tissue as one animal eats another. Such chemicals can pose health risks to humans and other species. For example, some chemicals called 'endocrine' or 'hormone' disruptors can harm the

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1 Anastas, P. cited in Ritter, S. K. (2001) 'Cover Story: Green Chemistry', *CENEAR*, Vol. 79, No. 29, pp 27-34. Available at http://pubs.acs.org/cen/coverstory/7929/7929greenchemistry.html. Accessed 10 October 2008.

2 OECD (2008) *OECD Environmental Outlook to 2030*, OECD, Paris. Available at http://www.oecd.org/document/20/0,3343,en_2649_34305_39676628_1_1_1_37465,00.html. Accessed 3 December 2008.

3 Carson, R. (1962) *Silent Spring*, Houghton Mifflin, Boston.

reproductive systems of humans and wildlife, and other chemicals can be 'carcinogenic' (cancer-causing).

3. The design and development of safe and appropriate chemicals depends in part on the knowledge and capability of chemists and chemical engineers. For example, as scientists learn more about the theory and application of chemistry, and the relationships between chemicals and the environment, there are increasing opportunities to improve the design and production of chemicals for society. The Organisation for Economic Co-operation and Development (OECD) is currently assisting this process of improvement, by creating an online database to freely supply information about the risks and safety issues of different chemicals.[4] The Australian government has also created the *National Pollution Inventory*[5] to help industry and the community understand these risks.

4. Since the publication of *Silent Spring*, Australia and other nations around the world have signed a number of international conventions that legally require nations to safely manage and use chemicals. Some of these include:

   - *The Montreal Protocol on Substances that Deplete the Ozone Layer (1987):*[6] An international treaty ratified by over 180 nations, which aims to protect human health and the environment against adverse effects resulting from the production and use of ozone depleting chemicals. This treaty requires participating nations to phase-out producing a number of substances believed to be responsible for ozone depletion.

   - *The Basel Convention on Trans-boundary Movements of Hazardous Wastes (1992):*[7] An international Convention (or 'agreement') ratified by 170 nations, which aims to protect human health and the environment against adverse effects resulting from the generation, management, and trans-boundary movements and disposal of hazardous and other wastes.

   - *The Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade (2004):*[8] An international treaty which aims to reduce hazardous chemicals and pesticides in international trade among signatory countries ('parties'). It uses a legally binding *Prior Informed Consent* procedure, where exporters trading hazardous substances are required to obtain the prior informed consent of importers before proceeding with the trade.

   - *The Stockholm Convention on Persistent Organic Pollutants (2004):*[9] An international treaty to protect human health and the environment from Persistent Organic Pollutants (POPs), where member nations commit to take measures to eliminate or at least reduce the release of POPs into the environment.

4. With these increasing requirements, some chemical and related industries are recognising that it is becoming more cost effective to design toxic chemicals and waste out of the process in the first place, rather than dealing with hazardous products, and treating waste chemicals afterwards. In 2001, 20 national chemical engineering organisations gathered in Melbourne to

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4 See The Global Portal to Information on Chemical Substances at http://webnet3.oecd.org/echemportal/. Accessed 10 October 2008.
5 See National Pollutant Inventory at http://www.npi.gov.au/. Accessed 10 October 2008.
6 See United Nations Environment Programme - *Montreal Protocol on Substances that Deplete the Ozone Layer* at http://www.unep.ch/Ozone/Publications/MP_Handbook/index.shtml. Accessed 10 October 2008.
7 See Basel Convention on Transboundary Movements of Hazardous Wastes at http://www.basel.int/. Accessed 10 October 2008.
8 See Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade at http://www.pic.int/home.php?type=t&id=5&sid=16. Accessed 10 October 2008.
9 See the Stockholm Convention on Persistent Organic Pollutants (POPs) at http://www.pops.int/. Accessed 10 October 2008.

publicly commit to sustainable development, publishing the *Melbourne Communiqué*[10] which outlines their commitments (see Brief Background Information for the Communiqué text).

5. As the industry considers how to undertake chemistry for sustainable development, 'Green Chemistry' is an emerging philosophy that focuses on maximising the efficiency and effectiveness of a chemical reaction to achieve a certain goal, while minimising the use of energy, water and the production of waste.[11]

6. Paul Anastas is often referred to as the 'Father of Green Chemistry', as he coined and defined the term in 1991 when he was chief of the Industrial Chemistry Branch of the US Environmental Protection Agency. He continued to support green chemistry and green engineering while serving as assistant director for environment in the American White House Office of Science and Technology Policy, and is now the Director of the Green Chemistry Institute at the American Chemical Society.[12]

7. Anastas defines 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'.* He notes that, *'Green chemistry, environmentally benign chemical synthesis, alternative synthetic pathways for pollution prevention, benign by design: these phrases all essentially describe the same concept ... Green Chemistry principles can be applied to organic chemistry, inorganic chemistry, biochemistry, analytical chemistry, even physical chemistry.'*[13]

8. Anastas developed *12 Green Chemistry principles* to help scientists understand and implement the Green Chemistry philosophy. He has subsequently also co-authored a similar list of 'Green Engineering' principles for chemical engineers (see 'Brief Background Information').[14] The 12 Green Chemistry Principles are summarised as follows:

   1) *Prevention:* It is better to prevent waste at the outset than to treat or clean it up.

   2) *Atom Economy:* Chemical reactions should be designed so as many of the atoms as possible that are present in the starting materials, end up in the product rather than in the waste stream.

   3) *Less Hazardous Chemical Syntheses:* Synthetic production methods should be designed to contain little or no toxic materials hazardous to human health and the environment.

   4) *Designing Safer Chemicals:* Chemical products should be designed for safety as well as performing their intended function.

   5) *Safer Solvents and Auxiliaries:* Benign solvent systems, solvent-free methods, or biphasic systems should be used for reactions that integrate preparation and product recovery.

   6) *Design for Energy Efficiency:* Energy requirements for chemical processes should be minimised, using ambient pressure and temperature where possible.

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10 See UK Institution of Chemical Engineers - *Melbourne Communiqué, agreed in Melbourne at the 6th World Congress of Chemical Engineering* at http://www.icheme.org/sustainability/Melbourne_communique.pdf. Accessed 3 December 2008

11 See The Green Chemistry Institute website at http://www.chemistry.org/greenchemistry/institute. Accessed 24 August 2008.

12 American Chemical Society (2006) 'Weblog Interview: Paul Anastas, Father of Green Chemistry', *ACS News Service*. Available at http://acsnewsservice.typepad.com/acs_news_service_weblog/2006/06/weblog_intervie.html. Accessed 24 August 2008.

13 Anastas, P. and Williamson, T.C. (1998) *Green Chemistry, Frontiers in Design Chemical Synthesis and Processes*, Oxford University Press; Anastas, P. and Warner, J. C. (1998) *Green Chemistry: Theory and Practice*, Oxford University Press, New York.

14 Anastas, P. and Warner, J. C. (1998) *Green Chemistry: Theory and Practice*, Oxford University Press, New York, p 30.

7) *Use of Renewable Feedstocks:* Raw materials should be sourced from renewable feedstocks wherever technically and economically practicable.

8) *Reduce Derivatives:* Unnecessary derivisation (i.e. temporarily modifying the physical/ chemical process) should be avoided, to reduce waste products.

9) *Catalysis:* Catalysts should be used to lower the activation energy barrier of a reaction, and thereby use less energy.

10) *Design for Degradation:* Chemical products should be designed to decompose into benign substances at the end of their functional life, to prevent persistence in the environment.

11) *Real-time analysis for Pollution Prevention:* Real-time, in-process monitoring and control should be allowed (i.e. budgeted) for in a chemical process, to avoid the formation of hazardous substances.

12) *Inherently Safer Chemistry for Accident Prevention:* The type and form of a substance used in a chemical process should be chosen to minimise the potential for chemical accidents, including releases, explosions, and fires.

9. Using Green Chemistry and Green Engineering principles, chemists and chemical engineers have the potential to make a significant contribution to sustainable development. In this Green Chemistry module, the following three lessons provide an overview of where Green Chemistry and Green Engineering principles are being applied. Each lesson addresses a key topic as follows:

    1) Lesson 10 considers the opportunity for chemistry to help *mitigate climate change* through addressing the issues of reducing greenhouse gas emissions, and capturing greenhouse gases from the atmosphere.

    2) Lesson 11 introduces the role of chemistry in *reducing toxicity* of products and services, and the concept of 'benign by design', where products and services are designed so that they don't use or produce toxins in the first place.

    3) Lesson 12 looks at the role of chemistry in providing better ways to power our lifestyles, through the design and manufacture of *better batteries*. This includes reducing the amount of hazardous substances used in batteries, and also designing the batteries to support renewable energy production (for example solar and wind energy).

10. Globally there are now significant networks, research institutions, companies, and government agencies working on Green Chemistry and Green Chemical Engineering, which are highlighted in this module. Major players within the chemicals industry - such as 3M, Dupont, Dow, Herman Miller and Interface - are now seeking solutions that avoid the environmental and economic costs associated with hazardous waste treatment and disposal (examples in Lesson 10, 11 and 12). Students who would like more information than the four lessons in this module may be interested in the American Chemical Society website, which provides an extensive selection of green chemistry education materials for high schools.[15]

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[15] See American Chemical Society - *Green Chemistry Educational Resources* at http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_SUPERARTICLE&node_id=1444&use_sec=false&sec_url_var=region1. Accessed 10 September 2008.

Brief Background Information

Industry Take Up and Interest

Rachel Carson's classic 1962 publication *Silent Spring* demonstrated significant and disturbing links between 'everyday' chemicals that society took for granted, and serious environmental and human health concerns. In the publication, Carson showed how the concentrations of some chemicals did not break down in the environment (i.e. were persistent), but increased (or 'bio-accumulated') in animals' fatty tissue as predators ate their prey, ultimately becoming toxic to both humans and the environment. Since *Silent Spring*, there have been growing calls for safer chemical processes and products that can eliminate persistence and toxicity risks. In 1991 an American scientist called Paul Anastas coined and defined the term 'Green Chemistry' as a philosophy that could address concerns raised by Carson and others. He defined the philosophy 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'.*[16]

In Australia and globally, chemical industry associations and their members have made strong commitments to achieving sustainable development and 'Green Chemistry' (also referred to as 'sustainable chemistry'). For example, In their 1996 report *Sustainable Development and the Chemical Industry* the International Council of Chemical Associations' (ICCA) stated, *'The global chemical industry believes that the key to improving the performance of the industry is both its commitment to achieving environmentally sound sustainable development and improved performance and transparency.'*[17] In 2001, 20 national chemical engineering organisations from around the world gathered in Melbourne to publicly commit to sustainable development, publishing the *Melbourne Communiqué*[18] which outlines their commitments, as follows:

We, the representatives of twenty organizations representing chemical engineers world-wide, subscribe to the following statement:

- *Entering the Twenty-First Century, we in the chemical engineering profession renew our commitment to using our skills to strive to improve the quality of life, foster employment, advance economic and social development, and protect the environment through sustainable development.*
- *Chemical engineering uses the principles of science to develop and provide technologies that improve the lives of people everywhere. From chemical engineering come materials: minerals, metals, ceramics, polymers, paper and composites. Food production and processing and water purification rely on chemical engineering. To enhance the health of the world's peoples, chemical engineering makes possible vaccines, pharmaceuticals and biotechnology. Shelter, clothing, transport and information technology all rely on chemical engineering. We develop and deliver the energy resources on which communities depend.*
- *In meeting society's needs we are committed to designing processes and products that are innovative, energy-efficient and cost-effective, and that make the best use of scarce resources. We are committed to the highest standards of personal and product safety. We*

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16 Anastas, P.T. and Warner, J.C. (2000) *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford.
17 International Council of Chemical Associations (1996) *Sustainable Development and the Chemical Industry*, ICCA. Available at http://www.cefic.be/position/icca/pp_ic010.htm. Accessed 9 September 2008)
18 See UK Institution of Chemical Engineers - *Melbourne Communiqué, agreed in Melbourne at the 6th World Congress of Chemical Engineering* at http://www.icheme.org/sustainability/Melbourne_communique.pdf accessed 3 December 2008

seek to eliminate waste and adverse environmental effects in the development, manufacture, use and eventual disposal of the products of society.

- *In an increasingly global society, we are committed to meeting the collective needs of the world's growing population while working to avoid and eliminate practices that are unsustainable. We recognize the profound concern relating to climate change. We must promote a better understanding of the complex science surrounding climate change, while also striving to develop and implement sound technologies to mitigate its effects.*
- *We commit to developing public understanding of the challenges and choices facing our world and the role chemical engineering can play. We will use our talents, knowledge, and organizational skills for the continued betterment of humanity to protect the public welfare. We will practice our profession according to its high ethical standards. We will promote lifelong professional development and will enthuse the brightest young people so that they enter our profession.*

We will take this Communiqué to our members, reinforcing their awareness of their obligations to serve society. We also commit to working with industries, governments, universities and other organizations that shape the future of the world.

We acknowledge both our professional responsibilities and the need to work with others as we strive to meet the challenges facing the world in the Twenty-First Century.

In 2003, the UK Chemical Industries Association (CIA) adopted a new vision for the sector which was based on an economically sustainable industry, stating that '*By putting sustainable development at the heart of everything the industry does ... CIA members are committed to the development of a safer, greener, ethically sound and prosperous UK chemical industry.*'[19] The peak chemical industry body for Europe (CEFIC), which represents 25 national chemical industry associations, has also made such commitments to sustainable development, as well as running a wide range of programs.[20] In Australia, the Plastics and Chemicals Industries Association (PACIA) is the national body representing Australia's plastics and chemicals manufacturing sector. PACIA is currently developing a 'Sustainability Leadership Framework'[21] in consultation with its members and stakeholders.[22]

The world's chemistry and chemical engineering communities have responded to help industry achieve this vision, with over 25 major research institutions focused on the development of Green Chemistry. The 'Father of Green Chemistry' Paul Anastas is the Director of the Green Chemistry Institute at the American Chemical Society, which now involves chapters in over 20 nations. Its goal is to, *'promote green chemistry research, education and outreach'*.[23] The UK Green Chemistry Network,[24] the Japanese Green and Sustainable Chemistry Network,[25] and

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19 Chemical Industries Association (2005) *Holding up the mirror: reflections one year on*, CIA sustainable development report 2005, CIA, UK, p4. Available at www.cia.org.uk/newsite/sustainability/CIASDReport05.pdf. Accessed 12 April 2008.
20 CEFIC (2002) *Programmes and initiatives of the Chemical Industry*, CEFIC. Available at http://www.cefic.be/Templates/shwStory.asp?NID=478&HID=628&PHID=55 Accessed 12 April 2008.
21 See Plastics and Chemicals Industries Association (PACIA) – *Sustainability Leadership Framework* at http://www.pacia.org.au/index.cfm?menuaction=mem&mmid=021&mid=021.026.001. Accessed 12 April 2008.
22 Plastics and Chemicals Industries Association (2007) 'Sustainability Leadership Framework: Plastics and Chemicals Industry Discussion Paper', PACIA, Richmond, Victoria. Available at http://www.pacia.org.au/_uploaditems/docs/4.sustdiscpaper.pdf. Accessed 12 April 2008.
23 See Green Chemistry Institute at www.chemistry.org/greenchemistryinstitute. Accessed 12 April 2008.
24 See UK Green Chemistry Network at www.chemsoc.org/networks/gcn/. Accessed 12 April 2008.
25 See Sustainable Chemistry Network of Japan at www.gscn.net/indexE.html. Accessed 12 April 2008.

Italy's Interuniversity National Consortium 'Chemistry for the Environment' (INCA)[26] have similar goals. There is also significant financial support by government institutions such as the US EPA and chemical societies including the American Chemical Society.

The set of 12 Green Chemistry Principles developed by Paul Anastas is helping to guide chemists and chemical engineers in progressing towards sustainability, in major chemical and manufacturing companies such as 3M, Dupont, Dow, Herman Miller and Interface.[27] Three of the more complex principles are explained here:

Principle 2) Atom Economy:[28] *Green Chemistry and Green Chemical Engineering seeks to achieve waste reduction through improved atom economy,[29] reacting as few reagent atoms as possible in order to reduce waste*.

The Green Chemistry principle of optimising the atom economy introduces a new goal into reaction chemistry: designing reactions so that as many of the atoms as possible that are present in the starting materials end up in the product rather than in the waste stream - essentially pollution prevention at the molecular level. Synthetic approaches have been created in both industry and academia that produce far less waste (i.e. are atom efficient) while being significantly more environmentally benign.[30] Better 'atom economy' could be achieved, for example, in making a chemical by putting together smaller 'building block' chemicals, rather than by breaking down a much larger starting material and discarding most of it as waste.

Principle 5) Safer Solvents and Auxiliaries:[31] *Green Chemistry and Green Chemical Engineering seeks to utilise benign solvents to develop more efficient synthetic routes.*

In chemical manufacturing and processes there are solvents used every step of the way. All of these must then be treated before disposal. Although solvents do not participate in liquid phase chemistry, they provide the medium within which the chemical reactions take place. Through the properties of this liquid medium a chemist can manipulate the reactants, heat transfer and separation. Many traditional solvents are volatile petroleum-based substances otherwise known as volatile organic solvents (VOCs). Other types include chlorinated solvents, which, along with the VOCs, pose risks to the environment and are flammable, toxic or carcinogens.

These organic solvents are of concern to industry because of the volume used, their toxicity, and the costs of purchase and disposal. While such solvents can be recycled, they often require costly and energy-inefficient purification procedures such as distillation, and use of the recycled products is limited to non-pharmaceutical processes such as the petrochemical and plastics industries.

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26 See INCA Italy at http://www.incaweb.org/. Accessed 10 August 2008.

27 Greiner, T., Rossi, M., Thorpe, B. and Kerr, B. (2006) *Healthy Business Strategies for Transforming: The Toxic Chemical Economy*, Clean Production Action Report. Available at http://www.cleanproduction.org/library/CPA-HealthyBusiness-1.pdf Accessed 12 February 2008.

28 See Cleaning Up with the Atom Economy at http://portal.acs.org/portal/fileFetch/C/CTP_005634/pdf/CTP_005634.pdf. Accessed 10 August 2008.

29 Trost, B. (1995) 'Atom economy - A challenge for organic synthesis: Homogeneous catalysis leads the way', *Angewandte Chemie International Edition,* Vol. 34, p259.

30 See USA EPA - *1996 Greener Synthetic Pathways Award: Mosanto Company* at http://www.epa.gov/gcc/pubs/pgcc/winners/gspa96.html. Accessed 3 December 2008; Emsley, J. (1994) 'A cleaner way to make Nylon', *New Scientist*, March 12, p15; Borman, S. (1992) 'Aromaic amine route is environmentally safer', *Chemical Engingeering News*, USA, November 30, pp26-7; Stinson, S. (1993) 'Cleaner Routes Found to Rubber Antioaonants', *Chemical Engineering News*, September 6, p 30-31; Hendrickson, J. B (1996) 'Teaching alternative synthesis: The Syngen program', in Anastas, P.T. and Williamson, T. C. (eds)*Green Chemistry: Designing chemistry for the environment*, American Chemical Society Symposium Series, No. 626, ACS Washington, DC.

31 Breslow, R. (1998) 'Water as a solvent for chemical reactions', in Anastas, P. and Williamson, T. (2000) *Green Chemistry, Frontiers in Design Chemical Synthesis and Processes*, Oxford University Press, Chapter 13; Li, C. (2000) 'Water as Solvent for Organic and Material Synthesis', in Anastas, P., Heine, L., Williamson, T. and Bartlett, L. (2000) *Green Engineering,* American Chemical Society, November, Chapter 6.

Research into environmentally benign solvents and solvent-less systems has been one of the most active and successful areas of green chemistry research in the last ten years. Work is underway to replace VOCs with non-toxic, non-volatile, recyclable and renewable solvents in a wide variety of chemical processes.[32] Renewable biomass feed-stocks are now being used for solvents for common reactions. There has also been significant research into solvent options such as using high-temperature water and microwave heating, sono-chemistry (chemical reactions activated by sonic waves) and combinations of these and other enabling technologies like liquids that separate easily and which are easier to recover as they don't need an additional extractive processing step.[33]

Principle 9) Catalysis:[34] *Green Chemistry and Green Chemical Engineering seeks to utilise catalysts to reduce waste by avoiding processing steps.*

Another very important area of Green Chemistry is the science of catalysis, where catalysts are used to trigger reactions, often using less energy in the process. Estimates are that 90 per cent of all commercially produced chemical products involve catalysts at some stage in the process of their manufacture.[35] However, as for solvents, many catalysts are toxic, derived from non-renewable resources, and are difficult or impossible to reuse or recycle. Significant research is underway to find catalysts that are non-toxic and that are sourced from renewable resources. Research is also underway to find catalysts that allow the use of less toxic reagents, such as using hydrogen peroxide in place of traditional heavy metal catalysts.

Chemical Engineering and the 12 Principles of Green Engineering

> *Chemical engineering has a history of embracing new disciplines and has a special role to play in the change process to achieve sustainability. An understanding at the micro and molecular levels and the integration of this knowledge into macro systems will be integral to the shift towards process engineering addressing the sustainability framework. Breakthroughs in greenhouse gas reduction, climate change prevention and process redesign will require a strong base of chemical engineering science. I see opportunities for chemical engineers to play a leadership role by collaborating with other industries in building critical mass and contributing to step change beyond best practice, by broadening the scope of the discipline and by restructuring chemical engineering education at an individual level*

Dr Robin Batterham, President
International Council of Chemical Engineering, 2005[36]

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[32] US EPA (2001) *The Presidential Green Chemistry Challenge Awards Program: Summary of 2000 Award Entries and Recipients*, US Environmental Protection Agency, Washington, CD, see The Micare Liquid CO_2 Dry Cleaning Process, p25. Available at http://www.epa.gov/gcc/pubs/docs/award_entries_and_recipients2000.pdf. Accessed 3 December 2008; US EPA (1998) *The Presidential Green Chemistry Awards Program: Summary of 1997 Award Entries and Recipients*, US EPA, Washington, DC, see DryWash™: Carbon Dioxide Dry Cleaning Technology, p23. Available at http://www.epa.gov/gcc/pubs/docs/award_entries_and_recipients1997.pdf. Accessed 3 December 2008

[33] Strauss, C. (1999) 'Invited Review. A Combinatorial Approach to the Development of Environmentally Benign Organic Chemical Preparations', *Australian Journal of Chemistry*, Vol. 52, p 83.

[34] Ibid.

[35] See R&D Magazine - *Recognizing the Best in Innovation: Breakthrough Catalyst* at http://www.rdmag.com/ShowPR~PUBCODE~014~ACCT~1400000100~ISSUE~0509~RELTYPE~R100~PRODCODE~00000000~PRODLETT~AO.html. Accessed 3 December 2008.

[36] Batterham, R. (2006) 'Sustainability: The Next Chapter', *Chemical Engineering Science,* Vol. 61, pp4188-4193

Green engineering principles are based on the green chemistry principles, developed to help guide chemical engineers. As for the Green Chemistry principles, the 12 Green Engineering principles provide a checklist for scientists and chemical engineers to use when designing new materials, products, processes and systems. Making products, processes and systems more inherently benign can come about by either changing the inherent nature of the system, or changing the circumstances/conditions of the system to reduce the release of toxins and associated exposure to harmful effects, or both.[37] As for green chemistry, it is therefore important to apply these Green Engineering principles systematically, and together rather than in isolation, to achieve significant improvements. The 12 principles are summarised as follows:

The 12 Principles of Green Engineering[38]

1) *Inherent rather than circumstantial:* The inherent nature of the selected material should be taken into consideration to ensure that it is as benign as possible (i.e. non-toxic, and/or minimal energy and materials inputs required to complete the process).
2) *Prevention instead of treatment:* Materials and processes that generate minimal waste should be used, which can avoid costs and risks associated with substances that would otherwise have to be handled, treated and disposed of.
3) *Design for separation:* Products should be designed with physical and chemical properties that permit self-separation processes, to reduce waste and save in disassembly and reassembly time and costs.
4) *Maximise mass, energy, space and time efficiency:* Products should be designed for maximum efficiency, using real-time monitoring to ensure the actual process is performing in accordance with the required design conditions.
5) *Output-pulled versus input-pushed:* The amount of materials or energy used should be minimised, by applying Le Châtelier's Principle[39] to continually remove products or 'outputs' so that the output is then 'pulled' through the system.
6) *Conserve Complexity:* Complexity in products should be minimised to create more favourable properties for reuse and recycling.
7) *Durability rather than immortality:* Products should be designed to have a targeted lifetime, to avoid environmental problems such as waste to landfill, persistence and bioaccumulation.
8) *Meet need, minimise excess:* Technologies should be innovated that target specific demands of the user to minimise waste and cost.
9) *Minimise material diversity:* Products should be designed with less material diversity to create more options for recyclability and reuse.
10) *Integrate local material and energy flows:* Products, processes and systems should be designed to use local materials and energy resources to minimise inefficiencies and consumption associated with transportation.

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[37] Anastas, P.T. and Zimmerman, J.B. (2003) 'Design Through the 12 Principles of Green Engineering', *Environmental Science and Technology*, March 1, 2003, ACS Publishing.

[38] Anastas, P., Heine, L., Williamson, T. and Bartlett, L. (2000) *Green Engineering*, American Chemical Society; Anastas, P.T. and Zimmerman, J.B. (2003) 'Design Through the 12 Principles of Green Engineering', *Environmental Science and Technology*, March 1, 2003, ACS Publishing.

[39] Le Châtelier's Principle states that when a stress (such as temperature or pressure) is applied to a system at equilibrium, the system readjusts to relieve or offset the applied stress. This principle can be applied in an 'input-pushed' process, where the addition of more inputs (stresses) leads to the generation of more outputs.

11) *Design for commercial 'afterlife':* Products, processes and systems should be designed so their components can be reused or reconfigured to maintain their value and useability for new products (sometimes referred to as 'design for modularity').

12) *Renewable rather than depleting:* Renewable materials should be used so that the source can be replenished and provide virtually infinite service with minimal, if any, waste.

Key References (Alphabetical Order)

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