# Principles and Practices in Sustainable Development for the Engineering and Built Environment Professions

## Unit 3 - Biomimicry/Green Chemistry

### *Lecture 11: Definitions and Principles of Green Chemistry and Green Chemical Engineering*

*The chemicals industry is central to the pursuit of a sustainable society; without it, the prospects of sustainably meeting the needs of nine billion people by the second half of this century are zero.*

**Vision for a Sustainable UK Chemical Industry, 2005**[1]

**Educational Aim**

To provide and outline of what 'Green Engineering' is as defined by Paul Anastas *et al*.[2] To introduce the concept of 'Green Chemistry' and state the 12 Principles developed for this field of science. The purpose of covering this material is to show an example of a field where engineers can take the inspiration from nature and apply it.

**Required Reading**

Hargroves, K., Smith, M. and Paten, C. (2007) *Engineering Sustainable Solutions Program, Critical Literacies Portfolio – Role of Engineers in Sustainable Development A*, The Natural Edge Project, Australia, Unit 2 Lecture 7.

**Learning Points**

1. What exactly is Green Chemistry? Anastas and Warner define Green Chemistry as,[3]

*Green chemistry, environmentally benign chemical synthesis, alter¬native synthetic pathways for pollution prevention, benign by design: these phrases all essentially describe the same concept. Green chemistry is 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. Green chemistry is not complicated although it is often elegant. It holds as its goal nothing less then perfection, while recognizing that all of the advances and innovations towards this goal will contain some discrete risk.*

2. Green Chemistry is an overarching philosophy of chemistry defined by a set of principles. Green Chemistry principles (see Brief Background Reading) can be applied to organic chemistry, inorganic chemistry, biochemistry, analytical chemistry, even physical chemistry. The focus is on minimising the risks and maximising the efficiency of any

chemical reaction. Green Chemistry seeks to reduce and ideally eliminate pollution at its source.

3. Paul Anastas et al in the book *Green Engineering: Introduction*[4] refers to Green Engineering as being all about 'pollution prevention' - the design of systems and unit processes that reduce the need for the use of hazardous substances while minimising energy usage and the generation of unwanted by-products. The 12 Principles of Green Engineering is a modification of the Green Chemistry principles to engineering.[5] The 12 Principles of Green Engineering can be used to re-engineer entire systems. The Principles are integrated and hence must be applied in whole, rather than in isolation, to achieve significant outcomes.

4. These principles of Green Chemistry and of Green Engineering, which are featured here in this module, provide a checklist for scientists and chemical engineers to use when designing new materials, products, processes and systems. The principle's focus one's thinking in terms of sustainable design criteria and have been proven time and again to provide a thorough guide to help develop innovative solutions to a wide range of problems. Systematic integration of these principles is key to achieving genuine sustainability for the simultaneous benefit of the environment, economy, and society.

5. Green Chemistry and Green Engineering are fields that provide a sophisticated tool kit to help enable Biomimicry efforts, open up exciting new Whole System re-Design options and help achieve radical resource productivity.

6. The 12 principles of Green Engineering is, if you like, an operational checklist based on the 12 Principles of Green Chemistry to help engineers apply green chemistry principles to engineering challenges. The 12 Principles of Green Engineering, are as follows:[6]

1. Engineers must ensure that all energy transfers and materials are as inherently non-hazardous as possible.
2. Waste prevention is preferred over waste clean-up.
3. Separation and purification processes must exercise the highest amount of energy and materials productivity as possible.
4. Products, processes and systems must be designed to exercise the highest efficiency of time, space, energy and mass.
5. Products, processes and systems must use available energy and materials on the basis of output required, rather than input supplied.
6. Making decisions on the nature, reuse or recyclability of products must consider the embedded entropy and complexity as an investment.
7. Product, process and system design should aim for durability, not 'immortality'.
8. Products, processes and systems should, where possible, avoid being designed with unnecessary excess capacity or capability.
9. Multi-component products should require minimal material diversity to maximize design for disassembly and value retention.

10. Products, processes and systems must exercise characteristics of Industrial Ecology, by including integration with available energy and materials flows.

11. Products, processes and systems must be designed for performance beyond their commercial life.

12. Material and energy inputs should be sourced from renewable, rather than depleting, feedstocks.

**Brief Background Information**

The 12 principles of Green Chemistry are:[7]

1. ***Prevention***: It is better to prevent waste than to treat or clean up waste after it has been created.

2. ***Atom Economy***:[8] Synthetic methods should be designed to maximise the incorporation of all materials used in the process into the final product.

3. ***Less Hazardous Chemical Syntheses***: Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

4. ***Designing Safer Chemicals***: Chemical products should be designed to achieve their desired function while minimising their toxicity.

5. ***Safer Solvents and Auxiliaries***: The use of auxiliary substances (e.g. solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.

6. ***Design for Energy Efficiency***: Energy requirements of chemical processes should be recognised for their environmental and economic impacts and should be minimised. If possible, synthetic methods should be conducted at ambient temperature and pressure.

7. ***Use of Renewable Feedstocks***: A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.

8. ***Reduce Derivatives***: Unnecessary derivatisation (use of blocking groups, protection/deprotection, temporary modification of physical/chemical processes) should be minimised or avoided if possible, because such steps require additional reagents and can generate waste.

9. ***Catalysis***: Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

10. ***Design for Degradation***: Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.

11. ***Real-time analysis for Pollution Prevention***: Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

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

From the Green Chemistry principles the Green Engineering principles that follow were developed. The principles focus one's thinking in terms of sustainable design criteria and have proven time and again to be the source of innovative solutions to a wide range of problems. Systematic integration of these principles is key to achieving genuine sustainability for the simultaneous benefit of the environment, economy, and society. The 12 Principles of Green Engineering can be used to re-engineer entire systems. The Principles are integrated and hence must be applied in whole, rather than in isolation, to achieve significant outcomes. Green Chemistry and Green Engineering are fields that provide a sophisticated tool kit to help enable Biomimicry efforts, open up exciting new Whole System re-Design options and help achieve radical resource productivity.

The 12 principles of Green Engineering is, if you like, an operational checklist based on the 12 Principles of Green Chemistry to help engineers apply green chemistry principles to engineering challenges. The 12 Principles of Green Engineering, are as follows.

***The Principles of Green Engineering***[9]

*Principle 1: Inherent rather than circumstantial*. Though the negative impacts of hazardous substances can be minimised, this is often at the expense of a significant amount of time and resources (human, materials and energy), which further impose environmental and social impacts. Designers should take into consideration the inherent nature of the selected material 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).

*Principle 2: Prevention instead of treatment*. The concept of waste can be assigned to material or energy that existing processes cannot turn into useful products. The generation and handling of physical waste further creates other 'wastes' – waste of time, money and effort. Using materials and processes that generate minimal waste removes the costs and risks associated with substances that would otherwise have to be handled, treated and disposed of.

*Principle 3: Design for Separation*. Separation of products typically expends much of the energy and resources of most manufacturing processes. Designing products with physical and chemical properties that permit self-separation processes rather than induced conditions (such as high energy, temperature processes or the use of solvents) decreases waste, saves costs and reduces processing times.

*Principle 4: Maximise mass, energy, space and time efficiency*. If a system is designed and applied at less than maximum efficiency, resources are being wasted throughout the process. Space and time issues can be considered to eliminate waste and maximise efficiency (in addition to consideration of material and energy used). In optimised processes real-time monitoring systems can be used to ensure the process is following accurate behaviour based on required design conditions.

*Principle 5: Output-pulled vs. Input-pushed*. Le Châtelier's Principle[10]essentially 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. But the same principle can be applied the other way – 'output-pulled' – where the outputs are continually minimised or removed from the system and the output is then 'pulled' through the system to minimise the amount of materials or energy used.

*Principle 6: Conserve Complexity*. Products that require more materials, energy and time are generally more complex, high-entropy substances. Recycling complex materials in many cases comes at sacrificed value (down-cycling) – such materials should be designed for reuse, where as materials of minimal complexity have more favourable properties for recycling.

*Principle7: Durability rather than immortality*. Products that last beyond their useful life often are the cause of environmental problems such as waste to landfill, persistence and bioaccumulation. By designing products that in addition to withstanding anticipated operating conditions (supported by maintenance and repair) possess a targeted lifetime, such issues can be avoided.

*Principle 8: Meet need, minimise excess*. 'Over-designing' products to embed flexibility and 'worst case scenarios' can often result in high manufacturing and operating costs. Technologies that target specific demands of the user not only minimises waste and cost, but further provides an alternative to 'off the shelf' technologies.

*Principle 9: Minimise material diversity*. Products such as computers, due to their diversity of materials used in electronic and packaging components, are difficult to recycle with existing methods while upfront designs that satisfy the same need with less material diversity have more options for recyclability and reuse.

*Principle 10: Integrate local material and energy flows*. Products, processes and systems should be designed to use local materials and energy resources – that is, resources that are as close as possible to the source of operation – to minimise inefficiencies and consumption associated with transportation.

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

*Principle 12: Renewable rather than depleting*. The use of materials from a finite source – a source in which its rate of replenishment is negligible with respect to its depletion – has significant environmental effects due to their inability to be 'cycled' back to the source for reuse. Renewable materials by their very nature can be re-cycled to replenish the source (primarily ecological systems) and provide virtually infinite service with minimal, if any, waste.

Note: 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.[11]

**Key References**

- Hargroves, K. and Smith, M.H. (2005) T*he Natural Advantage of Nations: Business Opportunities, Innovation and Governance in the 21st Century*, Earthscan, London, Chap

1: Natural Advantage of Nations. Available online at http://www.naturaledgeproject.net/NAON_ch1.aspx. Accessed 5 January 2007.

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

- Green Chemistry Institute (n.d.) *Overview of the field of Green Chemistry*. Accessed 5 January 2007.

- Wikipedia (2007) *Green Chemistry*. Available athttp://en.wikipedia.org/wiki/Green_chemistry. Accessed 5 January 2007.

- Royal Society of Green Chemistry (n.d.) *Green Chemistry*, RSC Publishing, London. Available athttp://www.rsc.org/Publishing/Journals/gc/index.asp. Accessed 5January 2007. Green Chemistry is a peer reviewed scientific journal devoted to green chemistry published by the Royal Society of Chemistry since 1999. It publishes research papers and reviews articles on any aspect of Green Chemistry that have to be conceptually accessible to a wide audience of chemists and technologists, including final year undergraduate students and postgraduate students. Sarah Ruthven is the editor of Green Chemistry and the current chair of the Editorial Board is Professor Martyn Poliakoff, University of Nottingham, UK.

- Royal Society of Green Chemistry (n.d.) *Green Chemistry News Archive*. Available atwww.rsc.org/Publishing/Journals/gc/greenchemistrynewsarchive.asp. Accessed 5 Jan 2007.