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Guest Editor's Note:

Green Chemical Engineering

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Green Chemical Engineering will lead us to a bright, sustainable future. Designers must strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible. Use your chemical knowledge of properties like boiling point, melting point, freezing point, vapor pressure, and water solubility. In addition chemical engineers must note flammability, explosivity, compressibility, viscosity, and properties that affect heat and mass transfer. These are the starting points when we are designing a new chemical process. We have to do more. Most of us are less familiar with properties related to toxicity to environmental organisms and humans. The engineer must have a systems perspective: i.e., the ability to do mass and energy balances. Don't just look at your laboratory bench or pilot plant process. Look at your systems-factory scale-whole industrial park scale. Designers need to select chemicals or materials whose properties will not cause harm to the environment or to people. With the right choice of chemicals and materials, a designer can control how much energy is required and the form of that energy; e.g., heating, cooling, light, microwave, pressure, etc. In terms of putting toxics into the environment energy matters as much as the choice of chemicals.

It is better to prevent waste than to treat or clean up waste after it is formed. A central tenets of green technologies is to make only the amount that is needed for a process. From a business perspective, this makes absolute sense. Think out the new process or procedure that you want to try. How much of everything goes into making your product? Do you need all of these things? If you have to heat the reaction, a large pot of solvent is going to need a lot of heat. Less solvent would need less heat. The engineer might design a process in which the reaction is run to low conversion, a separation is achieved to recover the product, and the unused reactant is recycled back to the reactor, allowing higher overall conversion.

Separation and purification operations should be designed to minimize energy consumption and materials use. Industrial separation processes are very energy intensive. Historically, for liquid and condensable gases, multistage distillation has been the workhorse process. Many bulk organic chemicals involve distillation, which adds significantly to their production CO_2 footprints. Thus, avoiding distillation, making distillation more efficient, and searching for alternatives to distillation are very important. One technology that has broken the hold of distillation in a large scale application is reverse osmosis membrane separation for water desalination. Reverse osmosis uses mechanical pressure to overcome the osmotic pressure exerted by the salt solution and thereby push the water through a selective skin. As calculated by the change of free energy of mixing, the theoretical energy to de-mix water and salt is approximately 1 kWh/m^3 of water, the current best membrane technologies have a real energy cost of 4.0 kWh/m^3 and thermal "distillation" type technologies use on the order of 50 kWh/m^3. When you see caparisons like this, you know the old, familiar technologies may need updating.

Products, processes and systems should be designed to maximize mass, energy, space, and time efficiency. It is simplicity that will allow us, as a society, to become more sustainable. In the past, there was no consideration regarding the complexity of the reaction, and material, energy and production requirements that will be needed to take this chemical reaction from the bench to the pilot plant to production. As

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chemical engineers, we can utilize our knowledge to influence and accelerate the development of sustainable chemical design, synthesis and production. Maximizing efficiency is achieved by having scientists and engineers create designs that maximize efficiency in mass, energy, space (i.e. real estate) and time. In the area of energy efficiency, it is best to stay close to room temperature and pressure. The need to heat and cool over large ranges requires substantial quantities of energy and can also be quite inefficient. Chemists need to pay attention to subsequent steps in a synthesis and design the route to use heating (or cooling) that has already been done in a preceding step. Additionally, if you can minimize the mass of materials being moved you are saving energy. In the area of space, or in this context real estate, it is prudent to design reactions (and their subsequent processes) to be as small as possible. By having smaller reaction volumes, the heating and cooling load demands are less. The increased need for expensive materials to construct larger reaction vessels is reduced. The longer a chemical reaction takes, the more money that was being consumed on materials, energy and operations. In addition, the longer the reaction runs, it is consuming valuable reactor real estate preventing other reactions from being performed.

Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials. Remove a product from the reaction equilibrium. That shifts the equilibrium to the right. More product forms. You are pulling the reaction to the right. The importance of inexpensive raw materials is important. Material availability, combined with the economies of large-scale facilities, have brought enormous value to the quality of life. Most electric power today is produced in centralized, large-scale plants. Why not small generators at the place we need them? Distributed generation is the use of small-scale converters to produce power as needed for a localized facility, such as a home or a single building. The generator is chosen to suit the availability of local resources, such as a solar cell array in sunny areas, or small wind turbines in windy areas. The future will bring a great variety of solutions to our energy needs. Keep an open mind. Technologies we have not yet imagined will find a place in our future plans.

Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition. The complexity in a beginning state depends on factors such as the number of atoms and/or functional groups present in a molecule, the type, quality and quantity of energy within a system, and the economic value in a starting material. A lot of chemical manufacturing involves taking simple compounds and making complicated ones. Decreasing entropy costs money and energy. Once these compounds are made, we should try to keep their complex nature. We are starting to look at designing products with characteristics that are favorable for recycle, reuse and repurposing. Products made for fast and safe disassembly, that use materials that are not complex and are abundant. Use the fewest number and least different types of materials.

Targeted durability, not immortality, should be a design goal. When a Chemical Engineer and a Chemist discuss how to formulate a product, they should focus on what exactly is the job that product is supposed to do. As a chemist designs a polymer for a fabric. How long does this need to last? A chemical product should do a job and do it well. It may not need to last forever. Be sure to tell the customer about your plan. Many people care enough about pollution and overfilled landfills that they will understand. Tell the truth to your customers. They will understand.

Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw. Design your product to do a specific job, but it does not need to cure everything.

Material diversity in multicomponent products should be minimized to promote disassembly and value retention. Keep it simple. The plastic housing for a computer could use one type of plastic--and tell us what that is. That way it may be disassembled and recycled. Keep the number metal elements in a computer hard drive to a minimum. Food containers can be made of one type of plastic (clearly label what type of plastic it is) and not layers of different ones.

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Design of products, processes, and systems must include integration with available energy and materials flows. When we spend years working on a new synthesis to produce the next big reaction or molecule, it is very easy to keep our focus in our little world of lab reactors. However, when transferred into a larger scale, a chemical process is a system of interrelated units-inputs & outputs. Chemical process is not a set of separated parts, but a complete unit. Use the inter-relationships of the parts to our advantage. Chemical Engineers would recognize this as the application of Process Integration-a systematic framework to optimize the mass and energy required for a given process.

Products, processes, and systems should be designed for performance in a commercial "afterlife". This summarizes the whole concept of reuse and recycle. Applying this principle to electronics design can help engineers create features that enable the recovery of materials for reuse into products of same or higher value. Disassembly features allow for the quick sorting and removal of components and materials for servicing. Components can be refurbished and sold as re-marketed equipment, or can be disassembled to separate valuable components for reuse elsewhere. Embedded ISO 11469 identification codes for plastic type on plastic parts increase the chances of reuse and make it easier to sort materials that are in demand.

Material and energy inputs should be renewable rather than depleting. The Earth contains finite resources to support sustainable development into the future. Standards of living will rise for many countries, increasing pressure on finite resources. As increased demand meets an ever shrinking resource supply, prices for commodity materials and energy will rise. There are environmental costs as well to continued reliance on non-renewable raw materials. Innovations in Green Chemistry and Engineering will happen. The world is depending on Chemical Engineers to convert the laboratory bench discoveries to production of things that make our lives better. Engineers can work wonders with efficient methods and new materials. Talk to everyone. For your ideas as an engineer to advance, you must communicate to business people and laypeople in non-technical terms.

Green Engineering was developed by Anastas and Zimmerman (2003), "Design through the Twelve Principles of Green Engineering". Much of the information in this editorial is based on work by David Constable, Director, ACS Green Chemistry Institute®. It is also based on the significant contributions of the following: Martin Abraham, Matthew J. Realff, David Wang, Mchael A. Gonzalez, Michael A. Matthews, Concepcíon Jiménez-González, and David Shonnard.

Reference:

Anastas, P. T., & Zimmerman. J. B. (2003). "Design through the Twelve Principles of Green Engineering" - Sustainability requires objectives at the molecular, product, process, and system levels. Environmental Science & Technolology, 2003, 37(5), 94A-101A. DOI: 10.1021/es032373g