**SUSTAINABLE PROCESS DESIGN**

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**Introduction**

Design for sustainability as an independent field of study is both multidisciplinary and cross-cutting. It encompasses engineering, natural science, economics, finance, political science, social science and the humanities (Seay, 2014). It concerns governments, corporations and consumers (Seay, 2014). From a design perspective, professional competency in sustainability is critical concept that must be addressed in the development of new products and processes. This module will explore the issues involved with sustainable process design, particularly the issues of switching production from a fossil based feedstock to a renewable feedstock.

This educational module focuses on comparing and contrasting the chemical manufacture of acrolein from propylene with a green chemistry based process for manufacturing acrolein from glycerol. There are two contrasting characteristics from a manufacturing process that must be addresses. From a reaction engineering perspective, the partial oxidation of propylene to produce acrolein is an exothermic process and this excess heat can be used to generate steam. This is an inherent advantage that the glycerol based manufacturing process, which relies on an endothermic reaction must overcome. However, from a process safety perspective, propylene, which is stored as a liquid at high pressure, presents significant hazards which must also be addressed. Students will have to balance these two concerns as part of the inquiry activities included with the module. In addition, students will have the opportunity to incorporate environmental impact assessment, life cycle assessment and inherently safe design into process design.

This module utilizes process simulations created in an Aspen Plus environment to model the two competing Acrolein processes. Students are able to change feed stream input conditions as well as operating conditions in various unit operations and analyze the results. Additionally, the module will include a component instructing to students to analyze the potential environmental impacts of the processes under various operating conditions using the U.S. EPA’s Waste Reduction Algorithm (Young, et al, 2000). Finally, students will be guided to consider the life cycle impacts of the two manufacturing processes presented. Although a complete life cycle analysis will not be included as part of the scope, students will be instructed to use the principles of life cycle assessment to compare and contrast the potential impacts of the two processes.

Student learning will be achieved through the application of a set of four guided inquiry activities which are included with the module. The activities are designed to be customizable, based on the level of experience of the students. The active learning exercises can be conducted as group or individual learning activities.

**Rationale: Sustainable Process Design for Ensuring Sustainable Engineering**

Sustainable manufacturing processes based on the principles of green chemistry are important, not only from the perspective of waste minimization but also in terms of energy usage. In coming years, engineers will be required no design products and processes that are not only technically and economically viable but are also environmentally benign and socially responsible. This change will not be driven by governments, but by consumer demands for products they perceive as sustainable. That said, products in the future will still need to meet the same quality and functionality standards customers have come to expect. Companies who are unable to meet customer expectations in a sustainable way will have a difficult time competing in the modern marketplace. For these reasons, design for sustainability is a critical topic for process engineers. Incorporating tools for assessing environmental and life cycle impacts as well as for optimization will be critical for engineers in the future.

**Course Content: Sustainable Process Design, Theory and Applications**

**Introduction to Sustainable Process Design**

Ensuring that the natural resources required to manufacture the products and services needed by society are utilized in a way that preserves their availability for future generations is a key challenge for process and product design (Seay, 2014). The design choices that engineers make are more and more being influenced by social and environmental concerns, as much as technoeconomic factors (Seay, 2014).

The World Commission on Environment and Development, commonly called the Bruntland Commission, issued a report, published in 1987, in a book titled “Our Common Future” (Bruntland, 1987). In it, they drafted the following:

“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (Bruntland, 1987)

Although there is no single accepted definition of the term sustainability, the Bruntland Commission definition of sustainable development forms the basis of what sustainability means to the field of engineering. For design engineers in particular, sustainability has come to refer to the goal of designing, operating and maintaining products and processes in a manner that is economically viable, environmentally benign, and beneficial to society. In other words, a sustainable process or product is one that is designed, operated and maintained to meet the triple bottom line of economics, environment and society, both now and in the future.

In sustainability, we often talk about the “Triple Bottom Line” of Economics, Society and the Environment. Our goal in sustainable product and process design is therefore is to develop products and processes that are optimized to consider each of these goals. Even if we don’t achieve peak performance in any one single aspect, our designs are optimized to get the highest performance when considering all three. Although perhaps not immediately obvious, meeting the triple bottom line begins in the earliest phases of product and process development (Seay, 2014).

Sustainability is really all about optimizing. Instead of only focusing on one area (bottom line), we consider three. We know that products that aren’t profitable won’t get manufactured and processes that aren’t profitable won’t get built, but in addition to being profitable, we argue that products are processes must not do irreparable harm to the environment and must be beneficial to society.

Although techniques for measuring profitability and environmental exist and are widely used, societal sustainability is harder to quantify. Clearly people need jobs and the income they provide, but should our health or safety be compromised in the process? These are the types of questions we have to answer in order to achieve sustainability. Another aspect of sustainability is that of intergenerational equity. This concept requires determining what, if anything, is our debt to future generations. Intergenerational Equity can be a tricky concept. It doesn’t necessarily mean that we must leave specific resources (like oil) to future generations, but we must leave the capacity for future generations to meet their own needs.

**Sustainability and Green Chemistry**

The fields of Sustainability and Green Engineering are closely related. Green Engineering is an important part of sustainability, however, the goal of sustainable design is find the optimum process and product designs that benefit society and are economically viable, in addition to being environmentally friendly. A sustainable design is one that provides benefit to all three sectors.

Clearly, the engineer’s ability to reduce cost is greatest in the earliest stages of process design. This idea is fairly obvious. An analogy can be made to environmentally conscious design as well. The engineer’s greatest opportunity the influence the environmental performance of the process is at the beginning as well. Although “end of the pipe” strategies can always be employed later, the inherent environmental performance is often decided in the early stages of design.

**12 Principles of Green Chemistry**

These principles were developed by Anastas and Warner for the US EPA. The 12 Principles of Green Chemistry provide a framework for making design decisions during the discovery phase of a capital project. In general, the 12 Principles address: Alternative Feedstocks, Green Solvents, Synthesis Pathways and Inherently Safer Chemistry. The 12 Principles of Green Chemistry as proposed by Anastas and Warner are as follows (Anastas and Warner, 1998):

* **Prevention**

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

* **Atom Economy**

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

* **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.

* **Designing Safer Chemicals**

Chemical products should be designed to effect their desired function while minimizing their toxicity.

* **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.

* **Design for Energy Efficiency**

Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.

* **Use of Renewable Feedstocks**

A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.

* **Reduce Derivatives**

Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.

* **Catalysis**

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

* **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.

* **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.

* **Inherently Safer Chemistry for Accident Prevention**

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

These principles generally only address the chemistry of a process (note that they are not called the 12 Principles of Green Engineering). Therefore, these heuristics must be put into the context of conceptual process design. Processes that appear green may not be when we consider the entire lifecycle. We also find that environmental performance begins to waiver when we consider the entire process design, beyond just the reactor. For example, sometimes a greener solvent may lead to a more difficult separation, which would require additional energy. In other words, as engineers, we are uniquely qualified to take a systems view, realizing that the object of our optimization changes based on our unique situation.

In order to ensure that processes based on the 12 Principles of Green Chemistry truly represent improvements over traditionally designed processes, methods for quantitative assessment are needed. Design tools like heat and power integration, mass integration and process optimization must be combined with assessment tools such as life cycle assessment and potential environmental impact assessment to quantify the sustainability performance for a process. Additionally, validated metrics for sustainability assessment are also required. Understanding how to apply these tools is a critical area of competency for process design.

**Case Study**

Acrolein is an important specialty chemical intermediate. It is used as a feedstock in the production of the essential amino acid methionine or can be further oxidized to produce acrylic acid. Most acrolein is produced via the partial oxidation of crude oil derived propylene. However, acrolein can also be produced using a green chemistry based process via the catalytic dehydration of glycerol. Glycerol has been produced recently as a side product from the manufacture of biodiesel from vegetable oils or animal fats. In fact for every 9 kg of biodiesel produced, 1 kg of glycerol is produced as a side product. Finding additional markets for this glycerol is important to improving the economic viability of the biodiesel process. This case study will focus on comparing and contrasting the chemical manufacture of acrolein from propylene with a green chemistry based process for manufacturing acrolein from glycerol from the perspective of a material and energy balance, potential environmental impacts and inherently safe process design.

**Connections to Existing Core Curriculum**

The National Academy of Engineers has expressed the need for sustainability in engineering education in its report titled *The Engineer of 2020: Visions of Engineering in the New Century* as follows:

“It is our aspiration that engineers will continue to be leaders in the movement toward the use of wise, informed, and economical sustainable development. This should begin in our educational institutions and be founded in the basic tenets of the engineering profession and its actions.” (NAE, 2004)

Although sustainability can begin to be incorporated early in the curriculum, it is in the capstone design course that students really get the chance to put what they have learned into practice. Since the elements of sustainable process design include economics as a key pillar, students must be able to determine profitability for multiple design cases. In many chemical engineering curricula Engineering Economics is a senior level course, often included in a senior design sequence. Therefore, this material is best suited for incorporation in the capstone design course.

**References for Further Reading**

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