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Green Engineering Education through a U.S. EPA/Academia Collaboration

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The need to use resources efficiently and reduce environmental impacts of industrial products and processes is becoming increasingly important in engineering design; therefore, green engineering principles are gaining prominence within engineering education. This paper describes a general framework for incorporating green engineering design principles into engineering curricula, with specific examples for chemical engineering. The framework for teaching green engineering discussed in this paper mirrors the 12 Principles of Green Engineering proposed by Anastas and Zimmerman (*Environ. Sci. Technol.* **2003**, *37*, 94A−101A), especially in methods for estimating the hazardous nature of chemicals, strategies for pollution prevention, and approaches leading to efficient energy and material utilization. The key elements in green engineering education, which enlarge the "box" for engineering design, are environmental literacy, environmentally conscious design, and beyond-the-plant boundary considerations.

Motivation for Green Engineering Education

Engineering education at most institutions of higher education is based on a combination of scientific training and engineering problem solving and design. System boundaries for the problems used in typical curricula are narrowly focused and well-defined, such that students will achieve a solution using scientific principles and mathematical techniques. For example, in chemical engineering education, students are taught at an early stage to draw a "box" around the system to be analyzed in order to, for example, calculate mass and energy flows entering and leaving the system. This strategy for teaching chemical engineering continues into the upper division courses of reactor design, thermodynamics, transport phenomena, process control, unit operations laboratory, and even specialized courses in biotechnology and nanotechnology. The box approach to defining problems applies to other engineering disciplines as well, and it is a powerful concept for teaching engineering. Yet there is an increasing need to teach students to consider factors that are "out of the box". Although engineering education requires courses in business, social science, and humanities, there is little opportunity to integrate effectively these issues into the technological component of engineering education. Engineering education needs new methodologies and tools that enlarge the box so that solutions to engineering problems not only address the physical object or process under study but also important societal concerns, like the environment. Green engineering (GE) can be viewed as an attempt to integrate more completely environmental issues into a technological education. By illustrating techniques for incorporating broader issues into technological analyses, GE can be an important pedagogical tool.

In addition to their general value as pedagogical tools, the concepts of GE are gaining prominence within engineering education due to a number of other factors. As industrialized economies continue to grow, the increased output of goods and services creates mounting pressure to use efficiently resources and reduce environmental impacts of products and industrial processes. The traditional approaches of pollution control at the end-of-pipe are seen as less desirable in the face of more stringent environmental regulations and the escalating costs of waste management. One answer to the dual needs of sustained economic growth *and* a healthy environment is pollution prevention at the source of waste generation within the manufacturing processes. Designing manufacturing processes and products to have lower environmental impact requires an integration of traditional design and problem solving principles with nontraditional elements. Traditional approaches to teaching engineering design and problem solving focus on optimizing a single variable, for example, minimizing cost or maximizing revenues less costs. Incorporating environmental objectives into design and problem solving necessarily involves multi-objective optimizations since environmental impacts are notoriously difficult to translate into costs (see, for example, Total Cost Accounting Methodologies developed by the American Institute of Chemical Engineers' Center for Waste Reduction Technologies; *2*). The designs that achieve a balance between environmental impacts and traditional economic performance may be different than designs that optimize only traditional cost performance.

The changing nature of engineering education provides additional motivation for including environmentally conscious design in engineering curricula. The Accreditation Board for Engineering and Technology, Inc. (*3*) in the United States has stipulated in Criteria 3 (Program Outcomes and Assessment) that students must (i) demonstrate an understanding of the impacts of engineering solutions in a global and societal context, (ii) have a knowledge of contemporary issues, and (iii) understand professional and ethical responsibility. Furthermore, several professional engineering associations have made specific calls to include environmental aspects of engineering activities. For example, the American Institute of Chemical Engineers (AIChE), in their Program Criteria for chemical engineering education, states that graduates must demonstrate a "working knowledge, including safety and environmental aspects, of ..." chemical engineering practice. The key question therefore is "what is the nature of environmental effects that engineering students need to learn in order to perform their professional duties with minimum of environmental impacts"? Risk (hazard and exposure) assessment and GE concepts could be important answers to this question because these approaches require

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TABLE 1. Course (Module) Outline for "Green Engineering: Environmentally Conscious Design of Chemical Processes" (*13*)

	Principles[a]
Part I: A Chemical Engineer's Guide to Environmental Issues and Regulations. This section provides an overview of major environmental issues, and an introduction to environmental legislation, risk management and risk assessment.	
1. An Introduction to Environmental Issues	
2. Risk Concepts	
3. Environmental Law and Regulations: From End-of-Pipe to Pollution Prevention	1, 2
4. The Roles and Responsibilities of Chemical Engineers	
Part II: Environmental Risk Reduction for Chemical Processes. This section describes a variety of analysis tools for assessing and improving the environmental performance of chemical processes. The group of chapters begins at the molecular level, and then proceed to a detailed analysis of process flowsheets.	
5. Evaluating Environmental Fate: Approaches Based on Chemical Structure	1
6. Evaluating Exposures	
7. Green Chemistry	1, 2, 4
8. Evaluating Environmental Performance During Process Synthesis	1–4
9. Unit Operations and Pollution Prevention	2–4
10. Flowsheet Analysis for Pollution Prevention	10
11. Evaluating the Environmental Performance of a Flowsheet	1
12. Environmental Costs Accounting	2
Part III: Moving Beyond the Plant Boundary. This section describes tools for improving product stewardship and improving the level of integration between chemical processes and other material processing operations.	
13. Life Cycle Concepts, Product Stewardship and Green Engineering	1, 4, 12
14. Industrial Ecology	10
Additional Course Materials:	
Case Studies	
Glossary	

[a] By Anastas and Zimmerman (*1*).

the engineering student to incorporate environmental issues into all aspects of manufacturing processes.

Even more motivation is provided by the availability, through the Internet and other sources, of environmental data and also of environmentally conscious design methodologies and computer-aided design tools. Many of these new methods and tools have been or are being developed by the U.S. Environmental Protection Agency (EPA) (*4*, *5*). For example, the EPA's New Chemicals Program, located in the Office of Pollution Prevention and Toxics (OPPT), was established to help manage the potential risk from chemicals introduced into the marketplace. A series of systematic assessments are performed on a manufacturer's or an importer's premanufacture notification (PMN). Using computer-aided estimation tools, environmental physical–chemical and fate properties of new chemicals are predicted as well as toxicity to aquatic organisms and potential carcinogenic effects. With these properties the designer can estimate environmental impacts using a structured approach, as discussed in the following sections. As all engineering disciplines use chemicals in their designs to various degrees, these tools have general applicability.

Thus, GE education is motivated by the need to include environmental factors in engineering design, the requirements of accreditation boards and professional societies, and the emergence of new design tools. This paper describes the elements of a GE curriculum. The key elements include the following:

(i) environmental literacy,

(ii) a hierarchical design approach for incorporating environmental impacts in engineering design, and

(iii) beyond-the-plant-boundary (supply chain and product stewardship) considerations.

Specific examples of these curriculum elements for chemical engineering are provided.

Elements of Green Engineering Education

Although there has been a growing technical literature describing "green" approaches to chemical product and engineering design (*6*–*12*) and a growing number of university courses, these attempts at GE education tended to focus on pollution prevention or control, mostly without significant emphasis on risk concepts (environmental impacts) or systematic design approaches. Therefore, in early 1998, the Office of Pollution Prevention and Toxics of the U.S. EPA initiated the Green Engineering Project with the initial goal of producing curricula describing green design methods for chemical engineering.

After preliminary discussions among the EPA and academia participants, three major curricular areas were identified. The first of these areas is environmental literacy. Few engineering students, with the exception of environmental engineers, received a systematic, coherent introduction to environmental issues, risk assessment, environmental regulations, and professional responsibilities. Understanding these concepts is a prerequisite to understanding the analytical tools (although not the general concepts) of GE. The second area in which educational materials are needed is in the methods used for integrating the tools of GE into current design practices—the methods used for expanding the box of engineering analysis and design. Finally, educational materials are needed that give students a broader perspective on how the environmental attributes of their designs affect and are affected by larger systems—thinking beyond the process boundary.

Table 1 shows an outline of a GE course designed for the chemical engineering curriculum (*13*); these general topics are also applicable to other engineering disciplines. One can also view the components of this outline as a set of modules for incorporation into the core curriculum within traditional courses or as a single course on GE. It begins in Part I with an introduction to environmental issues, risk assessment, and environmental legislation. Part II describes systematic design tools for assessing the environmental performance of chemical processes and tools for improving that performance. The sequence of these topics follows a hierarchy of design activities, from early design activities at the molecular level to detailed design steps at the process level, an approach

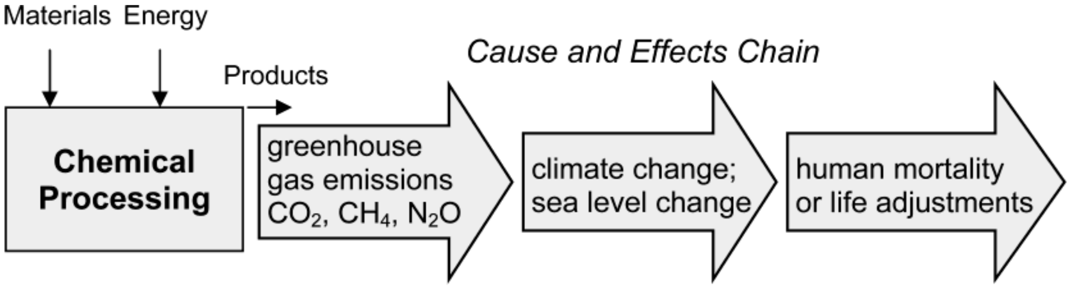
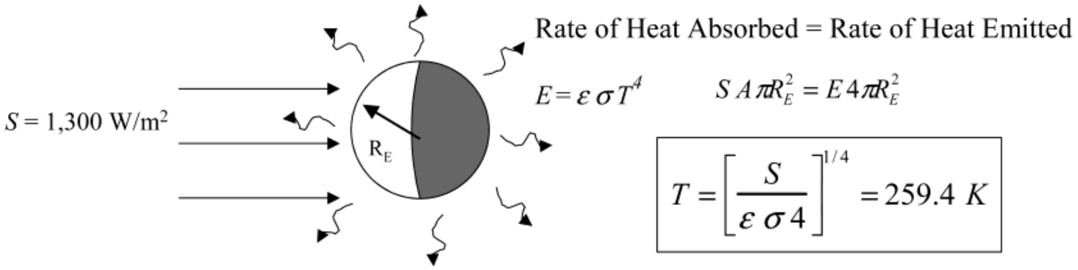
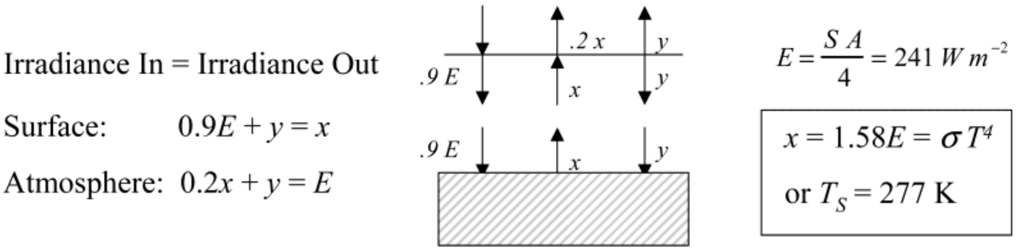


FIGURE 1. Greenhouse gas emission from chemical processes and the major cause and environmental effects chain. (□) Current curricula focus only on process and products, not emissions. (⟹) Added causes and effects.



a) Earth radiation balance, no atmosphere



b) Earth radiation balance, with atmosphere

FIGURE 2. Steady-state radiation energy balance for the earth without (a) and with (b) the effects of an infrared absorbing atmosphere (adapted from ref *14*). S = flux of solar energy, A = 1 planetary albedo, E = flux of infrared energy, ϵ = emissivity (= 1 for no atmosphere), σ = Stephan−Boltzmann constant, T = temperature (K), x = flux of infrared energy leaving the earth's surface, y = flux of infrared energy leaving the atmosphere. The steady-state surface temperature (T_S) of the earth, which for this problem is assumed to have an atmosphere with a solar radiation absorptivity of 0.1, an infrared absorptivity of 0.8, and a surface absorptivity of 1.0 is approximately 17 K higher than the case of no atmosphere containing greenhouse gases.

frequently used in chemical process design. In Part III, concepts from life cycle assessment (LCA) and industrial ecology are introduced, integrating chemical process design with the entire chemical product supply chain, and introducing concepts and tools for assessing the environmental performance of products from cradle to grave.

Also shown in Table 1 is a mapping of the course modules into the 12 Principles of Green Engineering by Anastas and Zimmermann (*1*). Clearly, there exists a strong overlap in content, particularly in methods to estimate the hazardous nature of chemicals, methods for pollution prevention, and approaches leading to efficient energy and material utilization. More detailed descriptions of each of the major conceptual elements of GE education are provided next.

Part I. Environmental Literacy. Developing a basic understanding of environmental issues, regulations, and professional responsibilities is an important part of GE education. Students must be made aware of the environmental consequences of engineering practice. Examples of key environmental issues include global climate change, stratospheric ozone depletion, acidification, smog formation, human and ecosystem toxicity, hazardous/nonhazardous waste generation, and natural resource consumption. An effective way to teach this material is to use a simple cause and effect chain discussion, as illustrated in Figure 1 for global climate change. Another effective approach for introducing environmental issues to engineers is to present trends in environmental data, identifying industrial sectors that contribute to those issues. Students then have the information to begin making connections between engineering practice and the various environmental problems.

To reinforce environmental concepts and to better link the material with traditional engineering courses, problems can be used that require the student to apply core engineering concepts and methods. Figure 2 shows a problem intended to reinforce the concepts of global warming and the greenhouse effect employing radiation heat transfer as the core concept. This kind of problem could be integrated into an introductory chemical or mechanical engineering heat transfer course. In addition to providing these quantitative results, the instructor might expect students to discuss the possible negative effects of global warming (hotter climate, sea level rise, increased incidence of disease, altered weather patterns, disruption of land use, migration of human populations, reduced life expectancy) and solutions to reduce or delay it (increased efficiency of chemical production and electricity generation, reduce fossil fuel consumption, use renewable energy sources, sequester CO_2, create chemicals with a lower global warming potential).

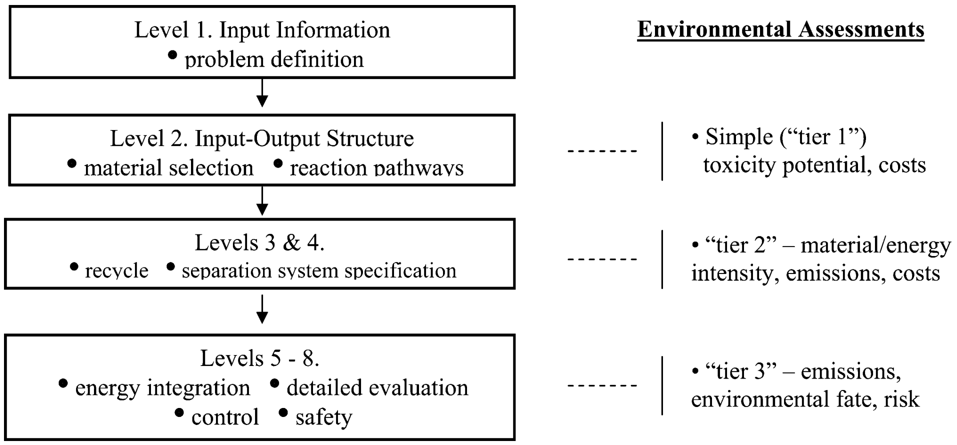


FIGURE 3. Hierarchical design and environmental/cost assessments of process designs. Tiered environmental assessments are added to the traditional design methods.

Engineering students should be introduced to other GE concepts, like risk, environmental regulations, and professional responsibility. Risk is the product of the probability that an event will occur and the severity of that occurrence. Educational materials covering these topics are available in ref *13*.

Part II. A Hierarchical Environmentally Conscious Design Approach. At the core of GE is environmentally conscious design of engineered products and processes. If GE design tools are to be effective, they must complement the design tools currently in use. A hierarchical approach is an effective way to incorporate environmental aspects into the design activity. At early design stages, engineers are concerned with the environmental implications of major input and output materials, with issues of product use and recycle, and of waste treatment alternatives. As the design becomes more defined and detailed, issues of pollution prevention at the process level become important (in-process recovery and recycle, heat integration, and mass integration). In the final design stage, the engineered process is evaluated and perhaps optimized using not only economic objectives but also a comprehensive set of environmental objectives. We will focus the remaining discussion in this section on chemical process design, but note that the general concepts are applicable to other engineering disciplines.

Hierarchical approaches are described in textbooks for creating chemical process designs (*15*, *16*). Design strategies are applied in sequence, starting with the input−output structure of the process and then proceeding to more detailed aspects of the design, for example, the separation and byproduct recovery systems. Douglas (*16*) and others added waste minimization to the hierarchical design framework by inserting guiding questions regarding the environmental implications at each level.

GE adds more quantitative elements of risk and environmental impact assessment to this hierarchy, as shown in Figure 3. This approach for environmentally conscious design, which relies on three tiers of impact analysis, incorporates GE concepts in a systematic way into the design process. The tier 1 environmental assessment is applied at the earliest stage of design when a large number of design alternatives, for example, raw materials and reaction pathways, are present and where only the most basic input and output information is available for raw materials, products, and byproducts. This assessment is based on toxicological (or other impact categories) properties of each raw material, product, and byproduct. The goal is to screen out chemicals having very high impact potentials. Following this, a preliminary process flowsheet with reactors, separation units, storage vessels and streamflow rates would be evaluated using a tier 2 environmental assessment. Direct emissions from major process units and fugitive releases from numerous minor sources are estimated using emission factors (*17*). Targeted pollutants can then be identified from the process emissions (Toxic Release Inventory chemicals, greenhouse gases, ozone-depleting substances, criteria pollutants, etc.) and listed per mass of product. In addition, energy consumption, total mass of materials, and water usage is also compiled (*2*, *18*). Material and energy flow profiles of chemical processes are sometimes available (*19*, *20*) for use in these assessments.

Later, at the point of detailed process design, normally only two or three alternative flowsheets remain to be evaluated. A tier 3 environmental assessment would add multimedia environmental fate and transport calculations (*21*) to the emissions from the tier 2 assessment. In addition, a number of impact indicators would be used to characterize the various environmental effects of each emitted chemical. More details on tiers 1−3 of this assessment are described below.

Once the basic input−output structure of the process has been established, it is wise to perform a preliminary environmental impact assessment. Often at this stage, only limited, conceptual information on the process is available. As a simple example of the tier 1 impact assessment method, consider two alternative processes for the manufacture of methyl methacrylate (MM); the acetone−cyanohydrin process and the isobutylene route. What would be an appropriate method for evaluating these alternatives? Traditional methods for process evaluation use cost as the screening criteria. For example, the value of the product would be compared to the costs of the raw materials. Approximate stoichiometric and cost data for MM and for other processes are available (*20*). A simple environmental screening method should indicate the potential of the process materials to cause environmental and/or health damage, and it should rely only on input and output data. One set of environmental criteria that could be used at this early design stage is the persistence, bioaccumulation, and toxicity of the chemicals. While persistence and biocaccumulation can generally be estimated using software tools (*4*) or measured values may be used (appendix F in ref *13*), toxicity is more problematic. The ideal toxicity parameter would recognize a variety of potential human and ecosystem health end points and would be readily accessible. However, no such parameter exists. A variety of simple toxicity surrogates have been employed, including Threshold Limit Values (TLV), Permissible Exposure Limits (PEL), and Recommended Exposure Limits (REL).

TABLE 2. Stoichiometric, Cost, Persistence, Bioaccumulation, and Toxicity (TLV) Data for Two Methyl Methacrylate (MM) Synthesis Routes

compound	stoichiometry (mass per mass of MM[a])	cost ($/lb)	persistence[b] (atmos. half-life/ aquatic half-life)	bioaccumulation[c] (concn in lipid/ concn in water)	toxicity[d] 1/TLV (ppm)
Acetone−Cyanohydrin					
acetone	−0.68	$0.43	52 d/weeks	3.2	1/750
hydrogen cyanide	−0.32	$0.67	1 yr/weeks	3.2	1/10
methanol	−0.37	$0.064	17 d/days	3.2	1/200
sulfuric acid[e]	−1.63	$0.04			1/2 (estd)
methyl methacrylate	1.00	$0.78	7 h/weeks	2.3	1/100 (PEL)
Isobutylene Process					
isobutylene	−1.12	$0.31	2.5 h/weeks	12.6	1/200 (estd)
methanol	−0.38	$0.064	17 d/days	3.2	1/200
pentane	−0.03	$0.11	2.6 d/days	81	1/600
sulfuric acid[e]	−0.01	$0.04			1/2 (estd)
methyl methacrylate	1.00	$0.78	7 h/weeks	2.3	1/100 (PEL)

[a] A negative stoichiometric index indicates that a material is consumed; a positive index indicates that it is produced in the reaction. [b] Atmospheric half-life estimated based on reaction with hydroxyl radical, aqueous half-life estimated based on biodegration (EPI Suite software, see ref *4*). [c] Bioaccumulation is an indication of the chemical's potential to accumulate through the food chain. [d] TLV is threshold limit value, and the inverse is a relative indicator of inhalation toxicity. [e] Sulfuric acid half-life short due to reaction with ammonia.

One method of using TLV and PEL values to define a toxicity index is to use the inverse of the TLV (see, for example, ref *22*):

$$\text{environmental index} = 1/(\text{TLV}) \qquad (1)$$

The concept is simple. Higher TLVs imply that higher exposures can be tolerated with no observable health effect, implying a lower health impact. A simple way to express this relationship mathematically is with an inverse relationship, as shown above. Using the TLV (or PEL or REL) as a surrogate for all toxicity impacts is a gross simplification since it only accounts for direct human health effects via inhalation. However, there is value in using these simple indicators in rough, qualitative evaluations of potential environmental impacts.

Table 2 shows the stoichiometry, costs, persistence, bioaccumulation, and toxicity indicator (i.e., 1/TLV) of the main raw materials, products, and byproducts for these alternative processes for MM production. The raw material costs per pound of MM are simply the stoichiometric coefficients multiplied by the cost per pound. For the acetone−cyanohydrin pathway, these costs are $0.60/lb of MM, while for the isobutylene route, these costs are $0.38/lb of MM. From this simple analysis, it is clear that the isobutylene route has lower costs for raw materials.

A simple stoichiometry weighted toxicity assessment can also be performed (eq 2):

$$\text{overall environmental index} = \sum_i |\nu_i| \times (\text{TLV}_i)^{-1} \qquad (2)$$

where $|\nu_i|$ is the absolute value of the stoichiometric coefficient of reactant or product i, and the summation is taken over all reactants and products. Substituting values from Table 2 for each route results in a value of 0.86 for the acetone−cyanohydrin route and 0.01 for the isobutylene route. A similar calculation could be performed using the other environmental criteria in Table 2 or using alternative criteria (global warming potential, etc.). In the present case, isobutylene is superior from both cost and environmental perspectives. In principle, this simple method could be used to screen a large number of synthesis alternatives.

The next stage in the design of chemical processes is the synthesis of an initial process flowsheet, with the selection of process units (reactors, separation technologies, storage tanks, etc.), additional raw materials, fuels, and catalysts. A wide variety of rule-based approaches are available for improving flow sheet performance at this level (*9*, *23*−*26*), and it is beyond the scope of this paper to describe them all; however, a comprehensive compilation has been developed (*13*). In parallel with refining the unit operation design, a second tier of environmental assessment based on preliminary emission inventories should be performed. This second tier of GE is also described at length by Allen and Shonnard (*13*).

Costs and the environmental performance of a chemical process depend on both the performance of the individual unit operations and on the level to which the process streams have been networked and integrated. Detailed design analysis considers, among other activities, process integration, which attempts to increase the efficiency of process energy and mass utilization by exchanging energy and mass between source and sink streams in the process. An energy source stream is one with a high energy content that requires cooling and a sink is a stream that requires heating. Rather than satisfying these process stream energy exchange demands with utilities that are external to the process, such as steam derived from fossil fuel combustion and cooling water from the environment, heat integration methods target the maximum possible energy exchange between streams to design a minimum-cost heat exchange network (HEN). Tools for heat integration include a temperature interval table and heat load diagram (pinch diagram).

Just as heat integration is the use of energy that would otherwise be wasted, mass integration is the use of materials within the process that would otherwise exit as waste streams. Mass integration involves the use of mass exchangers and streams internal to the process to satisfy raw material requirements, maximize production, and minimize waste generation. Engineering approaches for mass integration include segregation, recycle, interception, and sink/generator manipulation (*27*). Segregation is the avoidance of mixing waste streams so that subsequent use or recovery is possible. Interception is the selective removal of pollutants from process waste streams in order to avoid the discharge of a valuable or highly toxic component. Interception is also used to prepare waste streams for recycle. Sink/generator manipulation is the adjustment in conditions of unit operations (temperature, pressure, etc.) in order to reduce waste generation to acceptable levels.

There are many analogies between heat and mass integration and the tools for mass integration are similar to those for heat integration. One of these analogous tools for mass integration is the combined load line graph (*27*), which

TABLE 3. Streamflows and Compositions for Mass Integration

rich stream				lean stream			
stream	flow rate (kg/s)	y_{in}	y_{out}	stream	flow rate (kg/s)	x_{in}	x_{out}
R_1	5	0.10	0.03	L	15	0.0	0.14
R_2	10	0.07	0.03				
R_3	5	0.08	0.01				

is used in the design of a mass exchange network (MEN). From this diagram, one can determine the maximum mass exchange possible using mass exchange agents (MSAs) that are *internal* to the process and the minimum mass exchange using MSAs *external* to the process (additional material consumption and expense). To do this, the composition of the component of interest and streamflow rates must be known, as shown for a simple example in Table 3. The rich streams contain the component that must be removed from the source (in) to target (out) composition using mass exchange with the single lean stream. In this problem it is assumed that a single equilibrium relationship is applicable for the component of interest from all three rich streams ($y = 0.67x$). To present the total mass transfer load from the rich streams to the lean stream on a single mass load diagram, the mass fractions in Table 3 for the rich streams (y) are converted to equivalent mass fractions expressed as lean stream (x) using the equilibrium relationship. The mass transfer loads in each composition interval (calculated using the in and out compositions for the various streams) are determined, summed, and then plotted on the mass load diagram, shown for this example in Figure 4.

The lean stream curve in Figure 4 is shown with an arrow pointing upward indicating that the concentration in this stream will increase as a result of mass exchange. The composite rich stream curve is shown with an arrow pointing downward. The rich or lean curves may then be moved vertically, in Figure 4 the rich composite curve, until a minimum composition difference is achieved. From the diagram, the maximum mass exchange load to be accomplished using internal MSAs is then identified. The minimum mass exchange load to be achieved using external MSAs is also shown in Figure 4. The mass exchange targets shown in the combined mass load diagrams can be approached in the design of the MEN.

The energy integration and mass integration tools described above, used at the detailed stage of process design, can have a significant impact on the environmental performance of a process. However, understanding the details of these impacts and complex tradeoffs that might occur requires a third tier of environmental assessment (Figure 3). Environmental assessments at the third tier of analysis go beyond simple input−output (tier 1) and emission-based (tier 2) assessments by linking the release of each compound to a number of impact categories. This more detailed impact assessment is relatively computer and data intensive; however, a number of methodologies and software tools are under development, as discussed next.

A number of these tools are available from the U.S. EPA and academia. When used with process emission estimation, the TRACI software tool (*28*) predicts environmental concentrations using a “level III” multimedia model and exposure via multiple pathways to yield cancer and noncancer indices as well as several media-specific environmental impacts (global warming, ozone depletion, eutrophication, etc.). Indicators for approximately 500 compounds are compiled in these databases. The Waste Reduction (WAR) Algorithm software tool (*29*) and the Environmental Fate and Risk Assessment Tool (EFRAT; *30*) use similar, though perhaps less rigorous, environmental fate and relative risk assessment models as compared to the TRACI tool. However, these latter tools have been incorporated into or linked with commercial chemical process simulators, thus automating the simulation and impact assessment tasks.

To illustrate a tier 3 impact assessment, consider the volatile organic compound (VOC) recovery process design shown in Figure 5. In this process a VOC mixture is separated from a gaseous waste stream by absorption into oil and then recovered from the oil using a distillation column. Figure 6 is a plot of global warming (GW), acidification (AR), and smog formation (SF) indices as a function of absorber oil flow rate. Increasing the absorber oil flow rate increases the recovery of the VOCs and reduces the impacts of VOC emissions to the environment (I_{GW} and I_{SF}) but will require additional energy inputs to the distillation column reboiler and their associated impacts (I_{AR}). The results from this simple design illustrate the tradeoffs in impacts that are often observed when processes are evaluated on environmental issues. The environmental information provided by a tier 3 assessment allows for more sound process design decisions and will aid in process improvement.

The results shown in Figure 6 were generated using a commercial process simulator (HYSYS) to predict mass and energy balances for the process and a linked impact assessment software tool (EFRAT). Although the presentation of the equations to calculate process impacts is beyond the scope of this paper, details of each impact indicator are presented elsewhere (*13*, *30*).

In this section a hierarchical environmentally conscious design approach was described using chemical engineering examples. The general framework is applicable to other disciplines, with some modifications. In chemical processes, the feed materials are often of petroleum origin, are processed in a similar fashion, and therefore carry with them similar environmental burdens. Significant impacts on the environment from a chemical product often reside in the manufacturing process itself. In this case, the hierarchical approach described above can reduce these impacts. In contrast for other disciplines, the input materials often carry very different environmental burdens (metal vs plastic auto body parts, for example) and the majority of the impacts to the environment occur during product use and disposal; therefore, an assessment method that captures total life cycle impacts may be more appropriate. LCA and industrial ecology are an additional set of tools for GE, and these will be discussed next, again using chemical engineering examples.

Part III. Moving Beyond the Plant Boundary: Integrating Engineering Design with Larger Scale Industrial Systems. While it is appropriate to focus on evaluating and improving the environmental performance of chemical processes, it is also important to recognize that chemical manufacturing processes are a part of a larger system of material and energy flows. Analyzing the relationships between chemical processes and products and these larger systems is frequently accomplished using the tools of LCA and industrial ecology (IE).

The tools of LCA recognize that products, services, and processes all have a life cycle. For products, the life cycle begins when raw materials are extracted or harvested. Raw materials then go through a number of manufacturing steps until the product is delivered to a customer. The product is used and then disposed of or recycled. Traditionally, chemical process designers have been concerned with process life cycles up to and including the manufacturing step. That focus is changing. Increasingly, chemical product designers must consider how their products will be recycled. They must consider how their customers will use their products and what environmental hazards might arise. Simply stated, engineers must become stewards for their products and processes throughout their life cycles. An introduction to

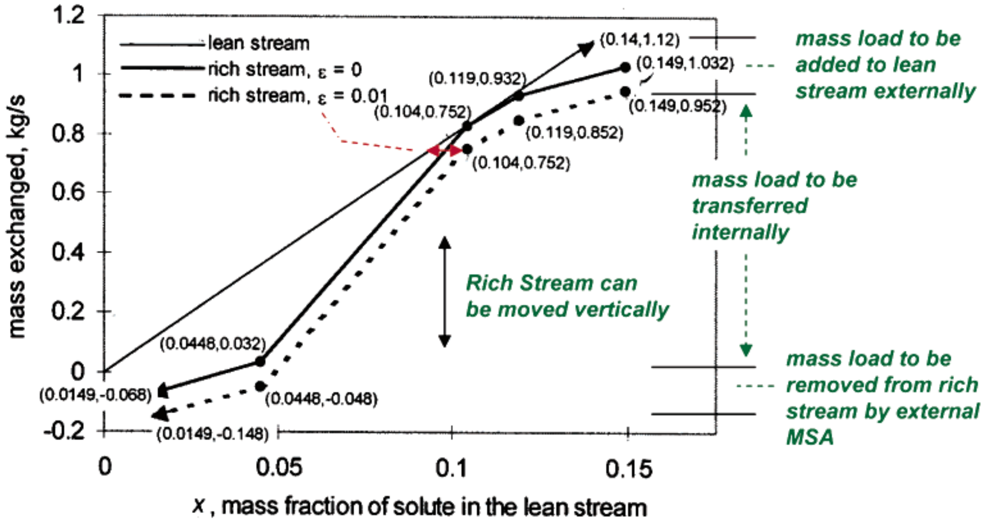


FIGURE 4. Combined mass load diagram for the example shown in Table 3. ϵ = a minimum acceptable composition difference for the mass exchanger network.

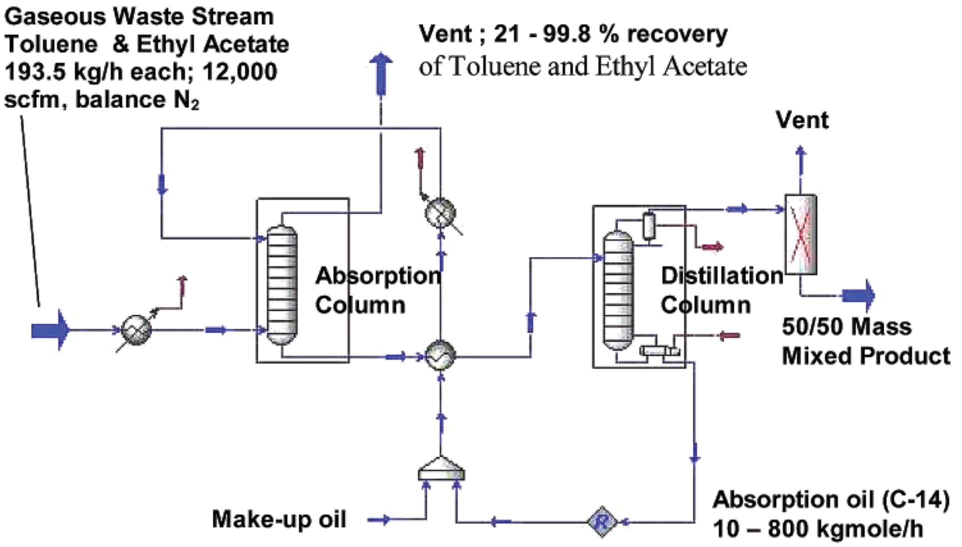


FIGURE 5. Process flowsheet for VOC recovery and recycle from a gaseous waste stream.

this emerging area and the systems tools that are involved in the analysis of product life cycles is provided by Allen and Shonnard (*13, 31*) and other sources (*32*−*34*).

Engineers must also increasingly understand the networks of industrial systems that produce the raw materials for processes, use the products of processes, or are markets for the byproducts of processes. Finding productive uses for materials and byproducts is a principle that has been used for decades in manufacturing. What is relatively new, however, is the search for chemical byproduct uses in industries that extend far beyond chemical manufacturing. Chemical engineers will take on design tasks such as managing the heat integration between a power plant and an oil refinery or integrating water use between semiconductor and commodity chemical manufacturing. Such design tasks are currently at the brink of our design abilities. To make these design tasks more common, engineers must begin to integrate process design tools from fields ranging from chemical manufacturing to semiconductor manufacturing and from pulp and paper processing to polymer recycling. The emerging set of tools for examining material and energy flows across industrial sectors are often described as the tools of industrial ecology since the webs of material flows have some analogies in biological systems. Some emerging tools in this area are well described by Allen and Butner (*35*).

University Courses and Curriculum Using Green Engineering

GE material can be incorporated into engineering education at the undergraduate or graduate levels in a number of ways; as a required course, as an elective, and as modules in core courses. The following examples illustrate some of these approaches for incorporating GE material into the chemical engineering curriculum and even into the curriculum for nonengineering majors.

Required Course. At Michigan Technological University, GE is taught within a combined senior-level semester-long course titled "CM4310 Chemical Process Safety/Environment". Goals of the course are to

(i) teach fundamental concepts of safety and environmental issues related to chemical processing,

(ii) present methods and software tools for assessing safety and environmental performance of process designs, and

(iii) provide methods to improve safety and environmental performance.

Ten weeks of the course are for process safety and five weeks are for GE. Course format for the GE portion uses lectures, weekly homework assignments, a writing assignment on an environmental issue, and a graduate student-run workshop to demonstrate the tier 3 impact assessment

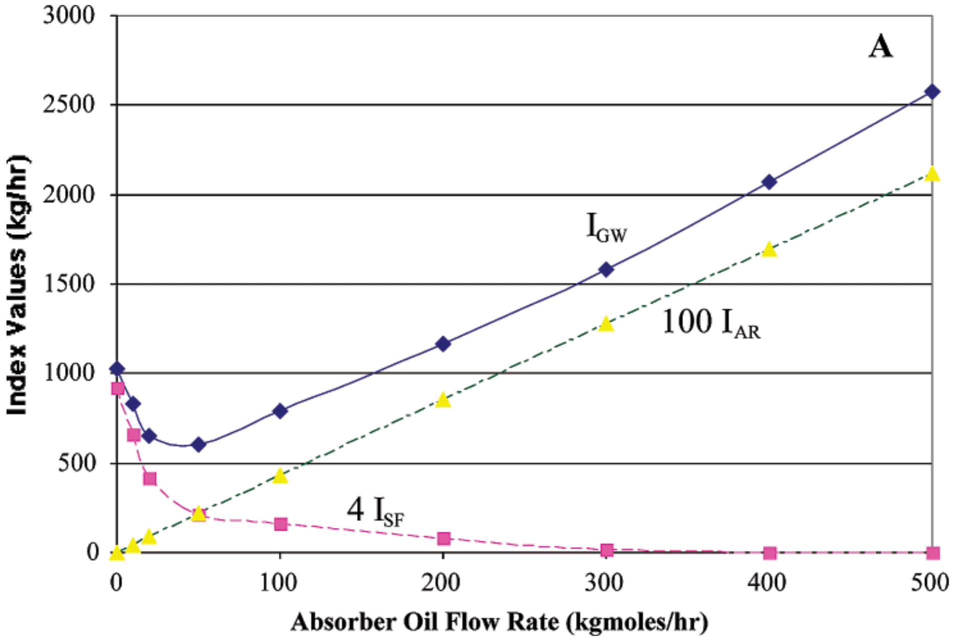


FIGURE 6. Environmental indices for the flowsheet in Figure 5 vs flow rate.

TABLE 4. Integration of Green Engineering in the Chemical Engineering Curriculum

freshman engineering clinic	green engineering project drip coffee maker introduction to environmental regulations
sophomore engineering clinic	life cycle assessment of a product environmental regulations
mass & energy balances	emissions estimation life cycle assessment project II tier 1 assessment: cost, persistence, bioaccumulation and ecotoxicity
chemistry & organic chemistry	environmental risk assessment green chemistry
equilibrium stage separations	mass separating agent risk assessment
material science	estimation of properties, EPA PMN case studies: polymers or electronic materials
heat transfer	heat integration (simple)
chemical thermodynamics	estimation of chemical properties
separations	green solvents or replacements through innovative membrane and adsorption technologies
chemical reaction engineering	pollution prevention strategies green chemistry
design	heat integration & mass integration flowsheet analysis life cycle assessment
process dynamics & control	pollution prevention
unit operations laboratory	green engineering experiments
design for pollution prevention	heat and mass integration process analysis
engineering clinic	real industrial projects in green engineering

software tool, EFRAT. During the workshop, using a simple process flowsheet as a case study, students link a process simulation output file with the environmental impact assessment software, estimate emissions from process units, and generate output tables of environmental impact indices for process units and chemicals. Grading for this course is based on end-of-chapter homework assignments, the writing assignment, and an examination.

Green Engineering throughout the Chemical Engineering Curriculum. At Rowan University, the Green Engineering program in Chemical Engineering has started with strong backing from the dean of the college and the department chair, enabling material to be incorporated throughout the entire curriculum. GE linkages to individual course activities are given in Table 4. A web site at Rowan University makes the GE curriculum materials shown in Table 4 available to students and faculty (www.rowan.edu/greenengineering).

Green Engineering Course for Nonengineers. This paper has focused on the challenges and opportunities associated with incorporating GE into the engineering education. There are, however, other significant opportunities for introducing GE concepts to university students. Many universities are beginning to recognize that developing technological literacy should be a part of the general education of all university students. One possible approach to developing technological literacy would be to teach students the general concepts of mass and energy balances, applying these concepts in the analysis of coupled engineered and natural systems at local, regional, and global scales. One such course is offered at the University of Texas by the Chemical Engineering Department.

The course begins with a brief description of biogeochemical flows (grand cycles) of the six elements (carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur) that are the major constituents of living tissue and that account for 95% of the biosphere. Understanding these "grand cycles", which describe how the earth's systems process materials, is critical to developing an understanding of global environmental changes. The course then focuses on engineered systems, noting that in many of the grand cycles are now significantly affected by flows generated by human activities. So, the grand cycles of material flows must include a description of material and energy flows in both natural and engineered environments.

This leads to analyses of anthropogenic material flows at the national level, in industrial sectors, and for consumer products. Students in the course gain a quantitative appreciation of the interactions between engineered systems and the natural environment, they are introduced to problem-solving techniques, and they become familiar with some of the most widely applied engineering principles—mass and energy balances.

Outreach Activities of the Green Engineering Program at U.S. EPA

The goals of the Green Engineering Program at the U.S. EPA are (i) to incorporate green or environmentally conscious thinking and approaches in the academic and industrial communities regarding the design, commercialization, and use of processes and products and (ii) to promote and foster development and commercialization of green approaches and technologies. Thus, the two most important targets for GE outreach activities are academia and industry.

Over the past several years, the GE Program has worked with universities and the ASEE's Chemical Engineering Division to develop GE education materials, to provide GE training for professors, and to incorporate GE into engineering curricula. For example, a number of "Green Engineering Educator" workshops were conducted between 1999 and 2002 in association with ASEE. These workshops provided participants with lecture modules, problem sets and solutions, and software tools to aid in teaching environmentally conscious process design and course materials. To date approximately 200 professors from 90 schools across the country have attended these workshops. These GE education materials can be downloaded from the Green Engineering web site (www.epa.gov/oppt/greenengineering).

In addition to these workshops, other education outreach programs have been initiated. At the AIChE Annual Meeting, a GE poster contest for undergraduate and graduate students has been established to encourage projects that demonstrate innovative applications of GE concepts or novel uses of GE in education. In addition, at these AIChE meetings awards are given to students for the best papers describing original research in GE, such as process optimization using environmental objectives, process integration to achieve waste minimization, environmental reaction engineering, green chemistry, and many other topics. The Green Engineering Program at the U.S. EPA, over the next few years, will work with AIChE and other professional engineering societies to incorporate GE into continuing education for practicing engineers. The green engineering website at www.epa.gov/oppt/greenengineering provides further information on these outreach activities.

Conclusions

This paper describes the key elements in GE education with specific examples of these elements for chemical engineering. The key elements are (i) environmental literacy, (ii) environmentally conscious design, and (iii) beyond-the-plant boundary considerations. The ultimate goal for introducing GE to engineering education is to provide the next generation of engineers with the knowledge necessary to create greener and safer products and processes. GE enlarges the scope of engineering design to encompass critical environmental issues; therefore, GE is an important framework for achieving goals of sustainable development.

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