Applying Green Engineering Throughout the Curriculum

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Prepared for presentation at 2001 ASEE Annual Conference,
Environmental Engineering Division Session

Abstract

Green engineering embraces the concept that decisions to protect human health and the environment can have the greatest impact—and provide the most cost savings—when applied in the design and development of a process or product, before any waste is generated. Specifically, green engineering is the design, commercialization and use of processes and products that are feasible and economical while minimizing 1) generation of pollution at the source and 2) risk to human health and the environment. This paper presents tools and methods to incorporate green engineering throughout the curriculum.

Introduction

The need to introduce green engineering concepts to undergraduate students has become recognized to be increasingly important.[1] This need is being driven in part through the ABET engineering criteria 2000. Based on this criteria chemical engineering departments must incorporate "ethics, safety and the environment" into the curricula. An additional criterion that must be satisfied is to prepare students with a *broad education to understand the impact of engineering solutions in a global context*. The most common method to introduce green engineering has been through a senior/graduate level elective course on environmental engineering, with emphasis on *end of the process* treatment. Recently, courses have been developed that focus on methods to minimize or prevent waste streams from exiting chemical plants. These trends mirror those in industry, in which initial efforts were applied to waste treatment whereas current efforts are aimed at reducing the total volume of effluent treated as well as the nature of the chemicals treated. Efforts are now underway to incorporate aspects of green engineering throughout the curriculum.

In 1998 the Environmental Protection Agency initiated a program in green engineering to develop a text book on green engineering; disseminate these materials and assist university professors in using these materials through national and regional workshops. The textbook is titled, "Green Engineering: Environmentally Conscious Design of Chemical Processes," and the major authors are David Allen and David Shonnard. The textbook is a designed for both a senior and graduate chemical engineering course and a series of modules that can be employed throughout the chemical engineering curriculum. This paper reviews the current status and future plans of the green engineering program.

Green Engineering in Chemical Engineering Courses

Green Engineering is the design, commercialization, and use of processes and products, which are feasible and economical while minimizing 1) generation of pollution at the source and 2) risk to human health and the environment. The discipline embraces the concept that decisions to protect human health and the environment can have the greatest impact and cost effectiveness when applied early to the design and development phase of a process or product.

By providing risk assessment tools, EPA offers a unique approach to green engineering. The Green Engineering Program pioneers the use of risk assessment tools beyond just screening chemicals. The Green Engineering Program applies these tools to the design, retrofit, and optimization of feedstocks, waste streams, and unit operations in processes and products.

The concept of risk assessment takes into consideration the extent of harm a chemical and its use can pose to the environment. While traditional pollution prevention techniques focused on simply reducing as much waste as possible by treating all wastes as equal, risk assessment methods used in pollution prevention can help quantify the degree of environmental impact for individual chemicals. With this approach to pollution prevention, engineers can design intelligently by focusing on the most beneficial way to minimize risk.

By applying risk assessment concepts to processes and products, the engineer can:

- Quantify the environmental impacts of specific chemical on people and ecosystems.
- Prioritize chemicals that need to be minimized or eliminated.
- Optimize design to avoid or reduce environmental impacts.
- Design greener products and processes.

This presentation will highlight techniques to include green engineering in the chemical engineering curriculum. This may be through stand-alone courses, concepts in core courses such as thermodynamics or engineering economics, design projects, and as part of the assessment requirements for ABET Criteria 2000.

Environmental Courses

Most departments throughout the United States list at least one course in environmental training. Initially this course was in air pollution control and more recently has expanded to a survey course in environmental engineering. Courses in pollution prevention have existed for at least the past decade. The National Pollution Prevention Center web site lists 19 courses in the general area of pollution prevention on their web site.[2] This listing gives syllabi for courses added between 1988 and 1995; the majority of courses that have a significant pollution prevention component were added around 1993. Nearly all of the courses listed were designed as electives for graduate students or upper division undergraduates. Of the 19 courses listed, approximately one-half might be better classified as courses on waste treatment and minimization rather than pollution prevention.

In a recent survey on pollution prevention,[3] chemical engineering departments were asked for information on how they taught pollution prevention within their curriculum. The responses can be loosely classified into three categories:

1. Programs in which pollution prevention is taught as a separate elective class (30%).
2. Programs that offer a course in air pollution or waste treatment and include pollution prevention as a component within these elective courses (40%).
3. Programs that do not provide any specialized training in pollution prevention but may include some material within the regular course sequence, usually, the senior design course (30%).

In nearly all cases, the courses are targeted at upper division undergraduate or graduate students and are elective courses. Only a small number of departments require all seniors to take a course in pollution prevention. Although the number of survey responses represents a minority of chemical engineering departments, these results would appear to be consistent with anecdotal information that many chemical engineering programs are now looking into ways in which pollution prevention can be incorporated into the graduate and undergraduate curriculum.

There are several recent articles on pollution prevention courses given in the senior and graduate years. The most recent by Abraham describes possibly the only pollution prevention course that is required for all seniors. [4] For example, Grant et al.[5] describes a senior/graduate elective taught at North Carolina State University that focuses on environmental management, while Simpson and Budd[6] describe a similar course developed at Washington State University. These courses are designed to provide a select set of students that are interested in the environment, an excellent set of tools to tackle problems in pollution prevention. When pollution prevention is taught as an elective course, the majority of students will pass through the curriculum without the knowledge regarding the impact of chemical technology on the environment. To reach all students in the engineering curriculum and satisfy EC2000, aspects of green engineering should be introduced in courses throughout the curriculum.

Pollution Prevention Texts and References

Based on the chemical engineering pollution prevention survey, the most popular textbook used in an advanced elective course is the text by Allen and Rosselot[7] titled, "Pollution Prevention for Chemical Processes." The text is divided into three sections that describe macro, meso and micro-scale pollution prevention. This text has a small section on ranking of pollution prevention modifications.

The recent text by Mulholland and Dyer[8] gives many examples in which pollution prevention not only allows the company to comply with regulations, but it is also financially responsible.[9] Both of these authors are from DuPont's waste reduction team and provide a practical guide for practicing pollution prevention in the chemical process industries. The authors use the classic unit operations approach and show how chemical engineering principles can be used to implement pollution prevention strategies. These authors utilize a problem solving strategy similar to that given by Fogler and LeBlanc[10]. The authors start by defining the process variables and constraints, brainstorm to develop numerous options, search the literature and examine case studies from other industries, and finally decide on a economically viable solution, implement it into the facility, and evaluate the effectiveness. Again this text does not utilize risk assessment strategies of green engineering.

Pollution prevention educators also mention other books that can be used in a course. For example, Freeman[11] has produced a handbook referenced by many pollution prevention educators. Other general texts include those by Rossiter[12] and Theodore[13], and a new text that is being completed by Paul Bishop at University of Cincinnati. For those courses with an emphasis on mass integration, the text by El-Halwagi[14] is available. For case studies and pollution prevention problems, one can consider the compilation of problems by Allen[15] titled, "Pollution Prevention: Homework and Design Problems for Engineering Curricula." This 155 page problem set can be ordered from the AIChE for $35 and contains examples involving fugitive and process emissions during cleaning operations, and examples of life cycle assessment are contained within a smaller volume. Other resource texts can be found on National Pollution Prevention Center for Higher Education web site.[2]

Recent advances toward the approach of spreading Green Engineering concepts in the curriculum were recently presented to engineering faculty at an EPA/ASEE workshop titled, "Green Engineering Educators Workshop," that was held at the 1999 ASEE conference in Charlotte, North Carolina. This session introduced the green engineering textbook that is being collaboratively written through the principal authors of David Shonnard and David Allen and additional collaborators of Paul T. Anastas, Scott Prothero, and Kirsten Sinclair. The major new contribution of this text is several sections on environmental risk assessment.

The book is divided into 3 major sections: 1) A chemical Engineer's Guide to Environmental Issues and Regulations 2) Environmental Risk Reduction for Chemical Processes 3) Moving Beyond the Plant Boundary. . The first section provides an overview of major environmental issues, and an introduction to environmental legislation, risk management and risk assessment. The second section contains tools for assessing the environmental profile of chemical processes and the design tools that can be used to improve environmental performance. These tools include release estimation approaches and pollution prevention strategies, total cost accounting, and green process design. This group of chapters begins at the molecular level, examines unit operations, and then proceeds to an analysis of process flowsheets. The final section contains the tools for improving product stewardship and improving the level of integration between chemical processes and other material processing operations. Additional information on this text can be found on the green engineering EPA website.[16]

This textbook includes software tools that have been developed for green engineering. The adjacent table gives a brief summary of the software that is referenced in the text. The EPA green engineering website provides details on the software's availability and the sources for purchasing and or downloading.

Table 1: Green Engineering Software[16]

SOFTWARE	DESCRIPTION
Air CHIEF	Emission factors for criteria pollutants and hazardous air pollutants, biogenic emissions, wastewater treatment emissions model
ChemSTEER	Screening tool for exposure and environmental releases; includes vapor generation and occupational dermal models
ECOSAR	Estimates ecotoxicity in surface water using structural activity relationships

E-FAST	Exposure, Fate Assessment ScreeningTool: software for use in screening-level assessment of chemicals released to a surface water, landfills, and from consumer products
E-FRAT	Environmental Fate and Risk Assessment Tool: integrated emission estimation software
EPIWIN	Estimates p-chem and fate properties associated with environmental risks
GCES	Green Chemistry Expert System
OncoLogic	Cancer Expert System or OncoLogic ® analyzes a chemical structure to determine the likelihood that it may cause cancer
SMILES	Converts chemicals with CAS numbers into SMILES notation for use in EPIWIN database
Tanks 4.0	Storage tank emission software
UCSS	Use Cluster Scoring System: computerized screening tool designed to systematically identify and screen concerns related to chemicals in commerce
WAR	Chemical Process Simulation for WAste Reduction: WAR Algorithm
Paris II	Computer Aided Solvent Design for Pollution Prevention
ChemFate	Environmental Properties Data base on the Internet
SCENE	Simultaneous Comparison of Environmental and Non-Environmental Process Criteria[17]

A goal of the Green Engineering Program is to develop a Green Process Design software package that integrates selected models and tools with process design software.

Green Engineering throughout the Curriculum

As a result of the environmental movement, most universities have instituted environmental courses that can be taken by all university students to fulfill their humanities requirements. These courses typically have titles such as Man and the Environment or Environmental Ethics and have a goal of making students more aware of their actions in a global environment. A recent paper from the Colorado School of Mines by Wiedenhoeft[18], shows how they introduce basic concepts of pollution prevention to freshman students. These courses are valuable and are useful to show students the environmental impact of our lifestyle and give students a technological background for their future courses. The following is a listing of activities at Rowan University in our attempt to integrate green engineering throughout the curriculum.

Freshman Engineering

Many engineering colleges have now instituted a freshman engineering program. These courses provide excellent opportunities to introduce freshman to the basic concepts of green engineering. Instead of employing a lecture style format, freshman should be introduced to green engineering through case studies and hands-on projects. For example at Rowan University, freshman students investigate commercial household products through reverse engineering. The students are very familiar with products such as coffee machines, computers, and hair dryers, and common household toys, because they have been exposed to these items since birth. Hesketh *et al.* [19] has students dissect coffee machines to find out how they work. They discover a large number of individual components that are inside coffee machines including electrical circuit boards, thermal switches, one-way valves, tubular heaters, silicone tubing. The housing of most coffee machines, and other appliances, is molded polypropylene. Students are then asked to conduct a life cycle assessment of these materials. Extensive use is made of the Kirk-Othmer and McKetta references volumes.

Other freshman engineering programs, such as the one at New Jersey Institute of Technology presented by Golub *et al.*[20], use a case study approach in which students have to site and design a manufacturing facility that either uses or generates hazardous materials. In this example, students are asked to consider pollution prevention strategies in their process plant design. The philosophy is to make a typical senior level design problem accessible to freshman students. In this simple design problem the students are guided into the concepts of pollution prevention in chemical process design. NJIT also uses an aspirin plant siting in the freshman engineering course.

Sophomore Engineering

At Rowan University, our sophomore engineering clinic is a multidisciplinary sophomore design course. In this course we have communication faculty working with engineering faculty to have engineers learn communication skills through working on an engineering design project. In this years project we are analyzing the solid waste stream of the university. Chemical and civil engineering students work in teams to assess and improve solid waste management strategies for the campus. The teams research recycling technologies, perform a life cycle analysis for each major component of the waste stream, investigate fluctuations in the markets for various recyclable materials, and weigh economic, environmental, and social factors that impact recycling programs. One of the driving philosophies behind the project is to increase awareness of the lifetime and fate of common products and introduce the concept of product stewardship to engineers. This goal can easily be accomplished within the context of a traditional chemical engineering course by applying life cycle analysis to any disposable item (e.g. food packaging, paper, beverage containers). If this activity is extended to include a persuasive argument or debate, it can also strengthen students' oral or written communication skills.

Separation Processes

This course inherently applies green engineering technology based the topics covered which include primarily membrane processes, e.g., reverse osmosis and adsorption processes. This course presents the principles, design and application of rate-controlled separations (see course notebook). The reverse osmosis applications are drawn from the instructor's own background in using reverse osmosis for pollution prevention in a variety of industries. Numerous examples are also provided for using reverse osmosis for water purification and desalination. A second technology area is adsorption topics which is applied to both liquid and gas phase separations. The liquid phase adsorption is taught almost exclusively using the application of activated carbon adsorption for removing organic contaminants from a process stream. Finally a significant portion of the class is devoted to novel separations in emerging areas and several of the innovative techniques are in the area of green engineering.

Chemical Reaction Engineering

The synthesis of a process design represents a hierarchical decision process, in which the choice of a particular component impacts all other process decisions. The central feature of most chemical processes is the conversion of raw materials into useful products. As a result, the reactor design is one of the central tasks in the synthesis of a chemical process. The selection of design characteristics, *i.e.*, conversion, reaction temperature, use of solvent, etc. dictate many of the remaining process considerations associated with separations and recycle, heat exchange, and use of utilities. Thus, it is appropriate to consider the environmental impacts of a reactor design problem in the context of green engineering.[21]

Numerous traditional topics of reaction engineering can be applied to green engineering. For example, in a parallel reaction scheme wherein one reaction leads to the desired product, the reaction temperature, the concentration of the reactant, or the reactor type can often be used to control the selectivity. Similarly, the incorporation of a heterogeneous catalyst can accelerate the rate of reaction or effect the reaction selectivity. Multiphase reactions, and in particular gas-liquid reactions, and the impact of mass transfer on the rate and selectivity also have a significant role in controlling the reactor design.[4]

Bourne and Gablinger[22] have shown how process chemistry developed in the laboratory can go awry when scaled to industrial reactors. An excellent example of the classic series-parallel reaction using an azo dye chemistry is presented by Bourne and Gholap.[23] The chemist will optimize the reaction to obtain very high reaction rates for the desired reaction. However, in the industrial reactor, micromixing occurs, negatively impacting the process chemistry.[24] However, as explained by Etchells[25] (1998), a typical undergraduate reactor design course focuses on ideal reactors and would overlook the impacts of mixing on the reaction chemistry and the formation of trace byproducts. Rowan is currently being funded by NSF to adapt this experiment for the undergraduate curriculum.

The Green Engineering Educators workshop developed a case based on the production of acrylonitrile. In this example, Shonnard[26] illustrates a risk-based approach for reactor optimization based on reactor type, temperature, residence time, mixing, and selectivity. He shows that the mass-based approach gives avenues that minimize HCN generation whereas the risk based approach indicates that the formation of acetonitrile should be minimized. Acetonitrile is about three times more toxic than HCN and the downstream removal rate of acetonitrile is very low. This is an excellent example of optimizing reactor operating conditions to reduce the production rate of a toxic chemical instead of the classic maximum yield of a desired product.

An additional element of pollution prevention in reaction engineering is the development of new reactor separator configurations. Combined reactor separators may be used in driving a reaction beyond the chemical equilibrium, such that higher conversion can be obtained in a single vessel. An excellent industrial example of this technique has been employed by Eastman Chemical[27], in which they utilize a single reactive distillation unit for the production of methyl acetate. An essentially pure product stream is obtained from acetic acid and methanol feeds, with only water produced as the by-product. In related experimental work we are developing a membrane reactor for the production of ethylene from ethane. This combined separator/reactor configuration will result in lower energy consumption requirements as well as higher conversions of ethane. This engineering clinic project is being funded by the NSF to develop innovative membrane technology experiments.

Allen and Rosselot[7] give an example based on the production of MTBE using two routes. The first is the traditional reaction scheme followed by a separation process. The second uses a catalytic distillation tower that drives the equilibrium-limited reaction by separating MTBE from the reactants. Additionally several units are eliminated reducing fugitive emissions and using fewer heat exchangers and process water. A second reactor-separator technology is the membrane reactor, which can be used to selectively remove one of the products from the reactive environment, minimizing the possibility of sequential conversion to undesirable products, or driving the reaction beyond the single-phase equilibrium point. Oyama[28] shows for the reforming of methane using CO_2, that higher yields of CO and H_2 can be achieved in a membrane reactor than possible in a fixed bed, because the H_2 product passes through the membrane. Thus, the reverse reaction cannot occur. The use of the membrane catalyst also provides a feasible route to the production of a pure hydrogen stream, an important element in the future development of fuel cell technology.

A final area in which pollution prevention can be emphasized in the chemical engineering curriculum is the area of green chemistry. Here, one investigates whether a new reaction route can be identified that minimizes the possibility of worker or surrounding environmental exposure? Alternatively, can one of the products be used as a raw material for another feed stream?

As an example, consider the production of phthalic anhydride, used as an additive to PVC to impart flexibility.[29] Phthalic anhydride can be produced from the partial oxidation of either o-xylene or naphthalene. Considering only sources of raw materials, we note that naphthalene is recovered from coal tar, which is a by-product of coking operations used in the steel industry. Napththalene has a lower price than o-xylene but the raw material (obtained from steel-making operations) contains sulfur compounds.[30] Wiedemann and Gierer[31] describe an alternative low energy process for phthalic anhydride production from naphthalene run by Veba Chemie AG. In this process one of the byproducts, maleic acid, is recovered through a scrubbing operation and used to produce maleic anhydride. For each metric ton of phthalic anhydride produced 40 to 50 kg of maleic anhydride can be reclaimed. This example shows how a byproduct can be recovered and sold as high value chemical.

The production of maleic anhydride is a second example in pollution prevention. The predominate feedstock for commercial production is benzene, which is a recognized toxic compound. Unfortunately benzene is still the predominant feedstock outside the US.[32] In addition to the reduced health risks the n-butane route has several economic advantages including, cheaper feedstock and a higher theoretical yield than benzene.[33]

The Combined Research and Curriculum Development program supported by the National Science Foundation provides three examples of alternate process chemistry, summarized in Table 2. In each case, a potentially hazardous starting material or intermediate is eliminated

Table 2
Reaction Engineering Case Studies from the Combined Research and Curriculum Development Program[37]

Project	Comments	Contact
New route for production of p-nitroaniline	Eliminates need for chlorine and chlorinated organics	Brennecke
Production of dimethyl carbonate	DMC is a potential oxygenated fuel additive, it can also replace phosgene as raw material. Phosgene is not used as a raw material in this process.	Shaeiwitz
Production of polyurethanes from dimethyl carbonate	Phosgene replaced as raw material	Shaeiwitz

from the reaction process. For example, in the production of p-nitroaniline, the formation of a chlorobenzene intermediate is replaced by a reaction step involving nucleophilic aromatic substitution for hydrogen (NASH). This novel chemistry is now being incorporated into the development plans of Monsanto's Rubber Chemicals Division (now Flexsys America, Inc), and has been cited by the Environmental Protection Agency as a Presidential Green Chemistry Challenge Award recipient in 1998. Several additional examples of green chemistry that have been cited as Award recipients, including

- The development of surfactants to be used in conjunction with supercritical CO_2 as an alternative reaction solvent
- Conversion of glucose into chemical feedstocks using microbial pathways
- Production of lactate esters from carbohydrate feedstocks using selective membrane reactors
- The use of novel non-biological catalysts in the manufacture of pharmaceuticals.

Information about each of these processes can also be found on the EPA web-site (http://www.epa.gov/greenchemistry/presgcc.htm).

Design for Pollution Prevention

At Rowan University, a senior elective/graduate course in design for pollution prevention is offered every fall semester. In this class, students are exposed to advance engineering design computing tools. The course is intended to provide the students with an understanding of current technology in the design field specifically molded for energy conservation, waste minimization and pollution prevention at the source by process modification and pollutant interception. The course does not follow a particular text since it covers a wide variety of topics. The students are first introduced to environmental regulatory law and the relation between the industrial activity and the environment. The rest of the semester is then devoted to develop the necessary skills to design and retrofit processes so the environmental impact is minimized. To accomplish this, students learn basic optimization theory, from unconstrained optimization to linear and non-linear programming modeling. The course is computer-intensive as students are required to pose and solve optimization problems using EXCEL and GAMS[34] with different solvers. The rational behind the choice of these programs lies in the fact that practicing engineers are more likely to find EXCEL in the workplace than GAMS while graduate students and researcher may benefit from a more comprehensive tool such as GAMS. The course then covers topics in heat integration, heat exchanger network design, heat integration in distillation columns and finally mass exchangers network systems.

Engineering Clinic Jr./Sr.

In the last 2 years of the Rowan Engineering clinic sequence students work on multidisciplinary research and design projects. Industry, State or Federal government funds these projects. Many of these projects are investigating the use of new and innovative technologies to replace traditional unit operations. All of these projects start with an assessment of the current process and predict the impact of the new technology on the economics of the process and examine reductions in generation of pollutants at the source and assess reductions of risk to human health and the environment. In many of our industrially funded projects there is a large reduction in risk and pollutant generation.

We have many examples of the application of green engineering throughout our curriculum at Rowan University. Below is a table summarizing the use of green engineering modules, homework problems, and special projects that we are striving to implement at Rowan University.

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
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

Examples of Green Engineering Courses from Other Universities

Pollution prevention examples can also be incorporated within the more traditional chemical engineering courses. For example, Rochefort[35] introduces pollution prevention in his material balances course using the Ford Wixom material balances module developed by the Multimedia Engineering Laboratory at the University of Michigan[36] and adds a pollution prevention component in which the "bad actors" are identified.

The chemical engineering departments at the University of Notre Dame, West Virginia University and the University of Nevada at Reno, are implementing through courseware, research and design projects a program on pollution prevention.[37] The overall program includes the development of three new courses: 1) Environmentally Conscious Chemical Process Design, 2) Ecology and the Environment and 3) Environmental, Flows. In addition, they are incorporating research results into instructional modules that are integrated throughout the chemical engineering curriculum, with a special emphasis on the design sequence. Information on the entire project can be found at http://www.nd.edu/~enviro.

College of Engineering Integration of Green Engineering

The engineering college at Virginia Polytechnic and State University has developed a green engineering program that was recently highlighted in Prism.[38] At Virginia Tech a steering committee initially identified 70 courses throughout Virginia Tech's curriculum that had an environmental component in which 56 of those courses were in engineering. As a result all of Virginia Tech's engineering departments offer courses devoted to or containing significant green engineering content. In this program a student can obtain a concentration in green engineering within their B.S. program. This requires 2 green engineering core courses, 6 hours of interdisciplinary electives and 6 hours of disciplinary engineering electives. A disciplinary engineering elective is required to contain at least 25% green engineering content. In chemical engineering at Virginia Tech these courses are the core chemical engineering courses of Mass & Energy Balances, Separation Processes, Chemical Reactors, Chemical Engineering Laboratory and Process and Plant Design. This incorporation on a college basis is an excellent example of integrating green engineering concepts throughout the curriculum.

Green Engineering Modules and Case Studies

In the Green Engineering Program, 7 modules have been developed that can be used in a number of chemical engineering courses. These are summarized in Table 2 and can be obtained directly from the green engineering website.[39] In addition there are a number of case studies included at the end of each chapter in the text. The initial results of several workshops show that chemical engineering professors are using the green engineering textbook in a variety of courses. The figure below illustrates the wide possibilities for integrating this information into traditional and new courses.

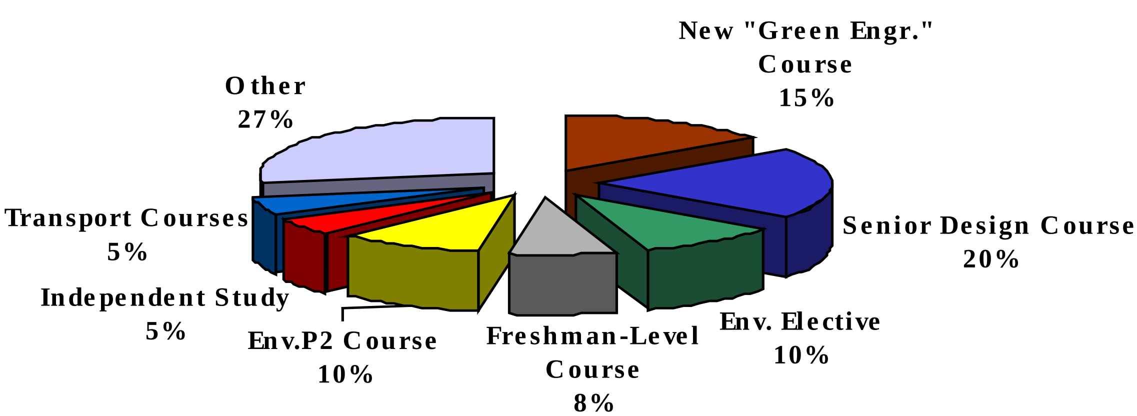

Table 2 Green Engineering Modules in Chemical Engineering Courses

Module	Appropriate Courses
Module 1: Environmental Literacy: Environmental Issues, Risk, Exposure, and Regulations	**Design course**: Introduce environmental literacy and regulations before assigning projects **Freshman Engineering**: Introduction to issues regarding environment / society / industry
Module 2: Estimating emissions and exposures: Case studies from the EPA PreManufacture Notice (PMN) process	**Plant Design** **Industrial chemistry** **Polymers** **Electronic materials**
Module 2a: Evaluating Environmental Partitioning and Fate: Approaches based on chemical structure	**Design course**: Use as a preliminary screen of chemical products and raw materials **Materials course/thermodynamics course**: Module on estimating properties **Mass and energy balances course**: module on estimating mass partitioning in closed systems
Module 3: Evaluation of Alternative Reaction Pathways	**Design course**: Green Chemistry concepts and a screening of chemical products and raw materials on the basis of economics and environmental impacts **Reactor design course**: Waste and risk minimization approaches
Module 4: Environmental Evaluation and Improvement During Process Synthesis	**Mass/energy balance course**: criteria pollutant emissions from energy consumption, emission of global change gases from energy consumption, calculate emission factors from combustion stoichiometry **Continuous/stagewise separations course**: evaluate environmental aspects of mass separating agents **Design course**: pollution prevention strategies for unit operations **Reactor design course**: environmental aspects of chemical reactions and reactors, pollution prevention strategies for chemical reactors
Module 5: Process Integration of Heat and Mass	**Mass/energy balance course** **Continuous/stagewise separations course** **Design course**
Module 6: Flowsheet Environmental Impact Assessment	**Process Design course**: develop and use environmental objective functions to rank process, design alternatives, rank process designs quantitatively based on environmental criteria **Transport phenomena course**: Module on interphase mass transfer in the environment
Module 7: Life Cycle Assessment	**Freshman Engineering** **Mass/energy balance course** **Design Course**
Environmental Cost Accounting	**Plant Design**

Future Activities of the ASEE/EPA Green Engineering Program

At the 2002 chemical engineering summer school in Boulder Colorado, there will be several sessions devoted to green engineering. The first session will relate the use of Green Engineering materials in a stand-alone technical elective - which, in essence, will be a broad overview of the textbook and supporting materials. The environmental material will be presented in the context of both assessment and design, starting from molecular level and progressing through unit operations, flowsheet analyses, and life cycle assessment. Specific topics will include an environmental literacy section (environmental issues and regulations), an introduction to risk, evaluating environmental partitioning and fate, evaluation of alternative reaction pathways, exposure and releases of processes, and the environmental evaluation of process flowsheets and unit operations. The second session will deal with incorporating portions of the textbook in current chemical engineering courses, including process design, transport, unit operations, and thermodynamics. The final session will provide hands-on activities for participants, where applicable software will be utilized in a case study format to illustrate green engineering methodologies. In 2001 there is a plan for 2 workshops. One of these will be in Texas and the other will be associated with a national meeting.

Summary

The chemical engineer, as the designer of chemical processes, also has a central role in designing chemical processes that have a minimal impact on the environment. We as educators can prepare our students to use the risk assessment tools of green engineering to design new processes and modify existing processes. As a result, green engineering could become a central component of the chemical engineering curriculum. Within this paper, we have provided several examples of green engineering modules, case studies and experiments that may be used in courses from the freshman through graduate level.

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