

A Program to Help in Designing Courses to Integrate Green Engineering Subjects*

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The need to introduce green engineering concepts to undergraduate students has become recognized to be increasingly important by industry and the general populace. Green engineering can be considered as the way engineering should be done, in that it results in products and processes that have a reduced risk of harm to both the environment and to humans. The use of green engineering practices is a method to reach sustainable development. In many engineering disciplines, aspects of environmental engineering are only taught in an optional senior year course. By placing this subject at the end of their university preparation, this tends to leave an impression with students that environmental concepts are added on after the engineering work is completed. Since one of the precepts of green engineering is that it should be conducted at all levels of engineering practice and design, we believe that it should be taught at all levels. Instead of having only an optional course in environmental or green engineering, we believe that it is more appropriate to integrate green engineering concepts in a range of courses within an engineering discipline. In 1998 the US Environmental Protection Agency initiated a program in green engineering to develop a text book on green engineering, to disseminate these materials and assist university faculties in using these materials through national and regional workshops. This program has developed teaching aides that include: presentation graphics, lecture notes, example problems, homework problems, case studies and experiments. These tools have been tailored to fit specific engineering classes, such as freshmen and sophomore engineering, mass and energy balances, separations, reaction engineering, process design. Using green engineering principles at the start of the design process can lead to processes and products of a sustainable future.

INTRODUCTION

GREEN ENGINEERING was originally defined by the US Environmental Protection Agency (EPA) as the design, commercialization and use of processes and products that are feasible and economical while minimizing the generation of pollution at source and risk to human health and the environment [1]. At a recent conference, this definition of green engineering was more broadly defined as transforming 'existing engineering disciplines and practices to those that promote sustainability. Green Engineering incorporates development and implementation of technologically and economically viable products, processes, and systems that promote human welfare while protecting human health and elevating the protection of the biosphere as a criterion in engineering solutions' [2]. The San Destin Declaration of Green Engineering Principles lists nine principles for engineers to follow in order to fully implement green engineering solutions:

1. Engineer processes and products holistically, use systems analysis, and integrate environmental impact assessment tools.

2. Conserve and improve natural ecosystems while protecting human health and well-being.
3. Use life cycle thinking in all engineering activities.
4. Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible.
5. Minimize depletion of natural resources.
6. Strive to prevent waste.
7. Develop and apply engineering solutions, while being cognizant of local geography, aspirations and cultures.
8. Create engineering solutions beyond current or dominant technologies; improve, innovate and invent (technologies) to achieve sustainability.
9. Actively engage communities and stakeholders in development of engineering solutions.

In addition to these principles, the conference participants felt strongly that there is a duty to inform society of the practice of green engineering. These principles were based in part on a previous paper giving 12 green engineering principles and examples of their use [3].

The need to introduce green engineering concepts to undergraduate students has become recognized as increasingly important [4]. This need is being driven in part through the US Engineering Accreditation Commission's Accreditation Board for Engineering and Technology (ABET). ABET's

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chemical engineering program criteria require the incorporation of 'safety and environment aspects' into the curriculum. Additionally, all engineering students must have an 'understanding of professional and ethical responsibility. Students must demonstrate the broad education necessary to understand the impact of engineering solutions in a global and societal context'. Programs must have a 'major design experience that incorporates engineering standards and realistic constraints that include most of the following considerations: economic; environmental; sustainability; manufacturability; ethical; health and safety; social; and political' [5].

Major chemical companies [6] such as DuPont [7], BP [8], Dow [9], Merck [10], and Rohm & Haas [11] have adopted a green approach, to move toward a sustainable future. In addition, professional organizations have taken up issues in sustainable development, such as the American Institute of Chemical Engineers' Institute for Sustainability [12], the Center for Waste Reduction Technologies [13], the American Chemical Society [14] and the Chemical Industry Council's Responsible Care Program [15]. A secondary factor in this drive is the news coverage given to governmental solutions to world environmental issues.

The most common method of introducing green engineering has been through a senior/graduate level elective course on environmental engineering, with emphasis on *end of the process* treatment. Courses have been developed that focus on methods to minimize or prevent waste streams from exiting chemical plants. These trends mirror those in industry, whereby initial efforts were applied to waste treatment after the design work had been completed. Using green engineering principles, not only are waste stream flows minimized, but the types of chemicals used in the process are examined to reduce their harm to humans and the environment. 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, to disseminate these materials and assist university faculties in using these materials through national and regional workshops in coordination with the Chemical Engineering Division of the American Society for Engineering Education (ASEE). The textbook, *Green Engineering: Environmentally Conscious Design of Chemical Processes* [16], by Allen and Shonnard, is designed for both a senior and graduate chemical engineering course and has a series of accompanying modules that can be employed throughout the curriculum. Efforts are currently underway to integrate green engineering concepts throughout the curriculum through the development of instructor guides, case studies, homework problems and in-class examples.

GREEN ENGINEERING IN CHEMICAL ENGINEERING

Green engineering is the design, commercialization, and use of processes and products which are feasible and economical while minimizing (1) the generation of pollution at source and (2) the 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, the EPA offers a unique approach to green engineering. The Green Engineering Program pioneers the use of risk assessment tools beyond just screening chemicals. It 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 and human health. While traditional pollution prevention techniques focused on simply reducing waste as much as possible by treating all wastes as equal, risk assessment methods used in green engineering can help quantify the degree of environmental impact for individual chemicals. With this approach, 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 a specific chemical on people and ecosystems;
- prioritize chemicals that need to be minimized or eliminated;
- optimize design to avoid or reduce environmental impacts; and
- design greener products and processes.

This paper highlights techniques for including green engineering in the chemical engineering curriculum. This may be through standalone courses, concepts in required courses such as reactor design, separation processes, design projects, and as part of the assessment requirements for ABET accreditation.

ENVIRONMENTAL COURSES

Most departments throughout the United States list at least one course in environmental training. Initially this course was in air and water pollution control and in many cases has expanded to a survey course in environmental engineering. Over the last 10 years, courses in pollution prevention have been added to engineering programs. An example of courses in pollution prevention can be found at the National Pollution Prevention Center website [17]. This listing gives syllabi for

courses added between 1988 and 1995; nearly all of the courses listed were designed as electives for graduate students or upper division undergraduates. Of the 19 courses listed in chemical engineering, 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 [18], 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:

- programs in which pollution prevention is taught as a separate elective class (30%);
- programs that offer a course in air pollution or waste treatment and include pollution prevention as a component within these elective courses (40%); and
- 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 have been several articles recently 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 [19]. Grant *et al.* [20] describe a senior/graduate elective taught at North Carolina State University that focuses on environmental management, while Simpson and Budd [21] 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 with 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 knowledge regarding the impact of chemical technology on the environment. In addition, by placing this subject at the end of their university preparation, this tends to leave an impression with students that environmental concepts are only considered after the engineering work is completed. Since one of the precepts of green engineering is that it should be conducted at all levels of engineering practice and design, we believe that it should be taught at all levels. Instead of having only an optional course in

environmental or green engineering, we believe that it is more appropriate to integrate green engineering concepts into a range of courses within an engineering discipline.

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 [22], which is divided into three sections that describe macro-, meso- and micro-scale pollution prevention. A recent text by Mulholland and Dyer [23] provides a practical guide for practicing pollution prevention in the chemical process industries. Freeman [24] has produced a comprehensive handbook referenced by many pollution prevention educators. Other general texts include those by Rossiter [25], Theodore [26], and Bishop [27]. For those courses with an emphasis on mass integration, the text by El-Halwagi [28] is available. For case studies and pollution prevention problems, one can consider the compilation of problems by Allen [29]. Other resource texts can be found on the National Pollution Prevention Center for Higher Education website [17].

Recent advances toward the approach of spreading green engineering concepts through the curriculum were presented to engineering faculty at several EPA/ASEE workshops from 1999 to the present. These workshops introduced the new green engineering text, *Green Engineering: Environmentally Conscious Design of Chemical Processes*, by Allen and Shonnard [16]. The book is divided into three main sections: (1) The Chemical Engineer's Guide to Environmental Issues and Regulations, (2) Environmental Risk Reduction for Chemical Processes, and (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 the level of integration between chemical processes and other material processing operations. This textbook includes software tools that have been developed for green engineering (Table 1). Additional information on this text can be found on the green engineering EPA website [30].

Table 1. Green engineering software

Software	Description
<i>Air CHIEF</i>	Emission factors for criteria pollutants and hazardous air pollutants, biogenic emissions, wastewater treatment emissions model
<i>ChemSTEER</i>	Screening tool for exposure and environmental releases; includes vapor generation and occupational dermal models
<i>ECOSAR</i>	Estimates ecotoxicity in surface water using structural activity relationships
<i>E-FAST</i>	Exposure, Fate Assessment Screening Tool: software for use in screening-level assessment of chemicals released to surface water, landfills, and from consumer products
<i>E-FRAT</i>	Environmental Fate and Risk Assessment Tool: integrated emission estimation software
<i>EPIWIN</i>	Estimates p-chem and fate properties associated with environmental risks
<i>GCES</i>	Green Chemistry Expert System
<i>OncoLogic</i>	Cancer Expert System, or OncoLogic [®] , analyzes a chemical structure to determine the likelihood that it may cause cancer
<i>SMILES</i>	Converts chemicals with CAS numbers into SMILES notation for use in EPIWIN database
<i>Tanks 4.0</i>	Storage tank emission software
<i>UCSS</i>	Use Cluster Scoring System: computerized screening tool designed to systematically identify and screen concerns related to chemicals in commerce
<i>WAR</i>	Chemical Process Simulation for WAste Reduction: WAR algorithm
<i>PARIS II</i>	Computer Aided Solvent Design for Pollution Prevention
<i>ChemFate</i>	Environmental Properties database on the Internet
<i>SCENE</i>	Simultaneous Comparison of Environmental and Non-Environmental Process Criteria

GREEN ENGINEERING THROUGHOUT THE CURRICULUM

As a result of the increasing importance of environmental issues, 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 aim to make students more aware of their actions in a global environment. A recent paper by Wiedenhoft [31] shows how to introduce basic concepts of pollution prevention to freshman students. Another example in the material balance course by Rochefort [32] introduces pollution prevention using a material balances module developed by the Multimedia Engineering Laboratory at the University of Michigan [33]. The extent of green engineering concepts covered in the aforementioned courses depends on the student audience.

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 [34]. 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. The engineering college at the Virginia Polytechnic and State University has developed green engineering concentrations within their B.Sc. programs [35]. This requires two green engineering core courses, six credit hours of interdisciplinary electives and six credit hours of

disciplinary engineering electives (which are required to have at least 25% green engineering content).

It is natural to weave the tools of green engineering throughout the chemical engineering curriculum. A good starting-point is an introduction to environmental regulations followed by the tools for risk assessment. Green engineering can be coupled with whatever is currently being taught in a chemical engineering curriculum. Table 2 is a summary of green engineering activities that can be incorporated into a chemical engineering curriculum followed by a discussion of initiatives that are underway at Rowan University. The goals of the ASEE/EPA-supported project are to develop instructor guides to assist in mapping green engineering topics into various chemical engineering courses and provide homework problems, in-class examples and case studies for faculty to use.

FRESHMAN ENGINEERING

Many engineering colleges have now instituted a freshman engineering course. These courses provide excellent opportunities to introduce freshmen to the basic concepts of green engineering. Instead of employing a lecture-style format, freshmen could be introduced to green engineering through case studies and hands-on projects. For example, at Rowan University, students in our Freshman Engineering Clinic investigate commercial household products through reverse engineering. The students are very familiar with products such as coffee machines, computers, hair dryers, and common household toys, because they have been exposed to these items since birth. Hesketh *et al.* [36] have students dissect coffee machines to find out how they work. They discover a large number of individual components

Table 2. Integration of green engineering in the chemical engineering curriculum

Chemical Engineering Course	Green Engineering Topic
Freshman Engineering Clinic	Green engineering project drip coffee maker Introduction to environmental regulations
Sophomore Engineering Clinic	Introduction to life-cycle assessment Life-cycle assessment of a product Environmental regulations
Material & Energy Balances	Emissions terminology/calculations 'Green' material and energy balances
Mass Transfer/Equilibrium Stage Separations	Mass separating agent Risk assessment
Material Science	Estimation of properties EPA PMN case studies: polymers or electronic materials
Heat Transfer	Introduction to heat integration
Chemical Thermodynamics	Estimation of chemical properties
Separation Processes	Pollution prevention strategies Novel 'green' separation process integration
Chemical Reaction Engineering	Pollution prevention strategies Green chemistry
Process/Plant Design	Heat integration and mass integration Flowsheet analysis Life-cycle assessment
Process Dynamics & Control	Pollution prevention modeling and control
Unit Operations Laboratory	Green engineering experiments
Design for Pollution Prevention	Heat and mass integration Process analysis
Senior Engineering Clinic/Senior Project	Real industrial projects in green engineering

and are asked to conduct a life-cycle assessment of these materials. Other freshman engineering programs, such as the one at the New Jersey Institute of Technology [37], 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.

SOPHOMORE ENGINEERING

Further integration of green engineering can be applied across the disciplines at the sophomore year. At Rowan University, our Sophomore Engineering Clinic is a multidisciplinary sophomore design course with a major focus on communication skills. A recent project was to analyze the solid waste stream of the university. Chemical and civil engineering students worked in teams to assess and improve solid waste management strategies for the campus. The teams researched recycling technologies, performed a life-cycle analysis for each major component of the waste stream, investigated fluctuations in the market for various recyclable materials, and weighed economic, environmental, and social factors that impact recycling programs. One of the driving philosophies behind the project was to increase awareness of the lifetime and fate of common products and introduce the concept of product stewardship to engineers. This goal was easily 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). This type of problem assignment

could also be placed in a mass and energy balance course.

MATERIAL AND ENERGY BALANCES

The introductory material and energy balance course is a logical place for the basic terminology and concepts of green engineering. Unit conversions typically used in green engineering process calculations, methods of representing pollutant/emission concentrations, and various defining equations used in green engineering can easily be included. Overall, 'closing the balance' of a chemical manufacturing process, balances on recovery and reuse operations in green engineered processes, green chemistry in stoichiometry, combustion processes and environmental impact fit nicely into the core fundamentals of material balances. Single and multiphase systems should include calculation of pollutant volatility using vapor pressure and condensation calculations (gas-liquid equilibrium) for vapor recovery processes. Representation of various forms of energy in a green engineering process can also be incorporated into the course, such as recovery of energy in a process, energy use in green chemistry reactions, and energy of combustion processes.

SEPARATION PROCESSES

Separation topics covered can be applied in a green engineering way as an overall role in pollution prevention, such as in the reduction of byproducts, waste minimization, emissions reduction, etc. The choice of the proper mass-separating

agent from a green engineering standpoint for the particular industrial separation is a key criterion to be presented. Ultimately a separation course should present a sound rationale for the 'green' integration of separation technologies in a reuse/recovery mode where valuable material(s) may be recovered and reused in the overall process. These approaches should be applied in the discussion of design and application of the various separation methods to the system being purified, fractionated or concentrated. Separation processes courses also need to encompass a broad range of both traditional and novel unit operations such that a student can see the pros and cons of their application from a green engineering standpoint.

At Rowan, a two-semester sequence of separations courses is taught, with the first being equilibrium-staged (distillation, extraction, absorption, etc.) and the second rate-controlled (reverse osmosis, ultra/microfiltration, adsorption, crystallization, etc.). When each of these processes is discussed, a specific problem or case study can be employed showing an application for material recovery/reuse or related pollution prevention. For example, reverse osmosis applications in pollution prevention, reuse/recovery and mass integration in a variety of manufacturing processes can be described. Reverse osmosis use in the electroplating industry to recover and reuse purified water and recover and reuse concentrated plating metals is an excellent example, from an environmental and economic standpoint, since both separated streams can be reused. For a more advanced topic, students can investigate the integration of a novel technology, membrane pervaporation, with a traditional separation, distillation, in azeotropic separation. A good design case here is replacing the entrainer benzene in ethanol-water separation with the pervaporation technique, since the potential release of benzene in the environment is removed. In the above cases, students can perform calculations to quantify the environmental improvements.

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. reactor type, conversion, temperature, use of solvent, etc.) dictate many of the remaining process considerations associated with separations and recycling, heat exchange, and use of utilities. Thus, it is appropriate to consider the environmental impact of a reactor design problem in the context of green engineering [38].

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 affect the reaction selectivity. An additional element of pollution prevention in reaction engineering is the development of new reactor separator configurations. We have developed a student project using a membrane reactor for the production of ethylene from ethane, which has resulted in lower energy consumption requirements as well as higher conversion [39].

A final area in which pollution prevention can be emphasized in the reactor design class 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, the question could be asked: 'Can one of the products be used as a raw material for another feed stream?' A mapping of green engineering topics (from the Allen and Shonnard *Green Engineering* text) into a reaction engineering course using the Fogler text [40] is shown in Table 3. This can serve as a guide to incorporate green engineering into other chemical engineering courses.

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 advanced 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 source by process modification and pollutant interception. 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 developing 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 commonly available software like Excel (Microsoft Corp, Redmond, WA) and specialized commercial packages like GAMS (General Algebraic Modeling System, GAMS Development Corp, Washington DC). The rationale 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

Table 3. Mapping of green engineering concepts to a reaction engineering course

Topic	Reaction Engineering Text Source (Fogler 1999)	Green Engineering Text Source
In a reactor design project, two pathways are examined to produce cumene using Tier 1 Environmental Performance Tools	Chapter 1: Mole Balances Chapter 2: Conversion and Sizing Chapter 3: Rate Laws and Stoichiometry	8.2 Tier 1 Performance Tools (pp. 200–215) 9.3 Pollution Prevention for Chemical Reactors 9.3.1 Material Use and Selection for Reactors
4.6.2 Membrane reactors	Chapter 4: Isothermal Reactor Design	9.5 Pollution Prevention Applications for Separative Reactors (pp. 283–286)
5.3 Method of half-lives—the use of the half-lives method (example is the attack by OH radicals on hydrocarbons)	Chapter 5: Analysis of Rate Data	5.3 Estimating Environmental Persistence— 5.3.1 Estimating Atmospheric Lifetimes
Maximizing desired products and minimizing undesired products by: choice of reactor types, reaction temperature and pressure	Chapter 6: Multiple Reactions	9.3.2 Reaction Type and Reactor Choice 9.3.3 Reactor Operation (pp. 261–274)
Pseudo-steady-state approximation for the attack by OH radicals on hydrocarbons	Chapter 7: Nonelementary Reaction Kinetics	5.3 Estimating Environmental Persistence— 5.3.1 Estimating Atmospheric Lifetimes
Heat integration—minimizing energy inputs (only an introductory comment for reactor design)	Chapter 8: Energy Balances Chapter 9: Unsteady-State Nonisothermal Reactors	10.1 & 10.2 Process Energy Integration
Green chemistry: alternative pathways	Chapter 10: Catalysis Chapter 11: External Mass Transfer Chapter 12: Internal Diffusion Chapter 13: Residence Times Distributions Chapter 14: Models for Nonideal	7.2.3 Synthesis Pathways Reactors

graduate students and researchers may benefit from a more comprehensive optimization tool such as GAMS that can be applied to many fields. 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 IN THE JUNIOR AND SENIOR YEARS

In the last two years of the Rowan Engineering curriculum, students have taken a project-based course for all four semesters called Junior and Senior Engineering Clinic. In this clinic, student teams work on multidisciplinary research and design projects supported by industry, or state or federal agencies [41]. Many of these projects investigate the use of new and innovative technologies to replace traditional unit operations [42]. 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, examine reductions in the generation of pollutants at source and assess reductions in risk to human health and the environment. In many of the industrially funded projects there is a large reduction in risk and pollutant generation. Many of these projects have continued in the summer by

involving students through a Research Experience for Undergraduates Program in Pollution Prevention funded by the National Science Foundation.

ASSESSMENT AND FUTURE PLANS

The above-mentioned Rowan initiatives have been assessed in several ways. We have used course evaluations with specific questions, student focus groups (drawn across the four years), senior exit interviews, alumni surveys, employer/internship surveys and student portfolio reviews. Our broad goals are program assessment (for ABET) and assessment for specific curriculum initiatives and projects like this one. We have had very positive responses from students related to green engineering curriculum initiatives. For example, a student focus group indicated that environmental issues were being covered very well in our engineering clinics but that they would like to see more in other courses. This helped confirm our more thorough course integration plans, as mentioned above. Assessment of student portfolios in our 'capstone' senior plant design course indicated that students were quite capable of designing a process by incorporating engineering standards and realistic constraints that include economic, environmental, sustainability,

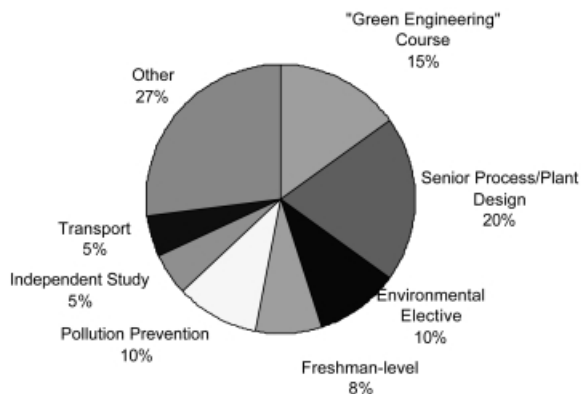


Fig. 1. A faculty survey on the use of green engineering text and workshop materials in chemical engineering courses.

manufacturability, ethical, health and safety, social, and political considerations.

Future plans are to have modules developed for various chemical engineering courses and disseminate them through the website (<http://www.rowan.edu/greenengineering>). This website is developed for both student and faculty use to provide news and updates on EPA and green engineering activities and software, and provide information on the student paper competition.

OTHER ACTIVITIES OF THE ASEE/EPA GREEN ENGINEERING PROGRAM

Seven modules have been developed, to be used in conjunction with the *Green Engineering* text, that can be used in a number of chemical engineering courses. These are summarized in Table 4 and can be obtained in PowerPoint (Microsoft) format directly from the green engineering website [30]. They include handouts, additional instructor information, case studies and supplemental material from the textbook that can be used with each chapter. The initial results of several faculty workshops show that chemical engineering faculty are using the *Green Engineering* textbook in a variety of courses. Fig. 1, which shows the results of the faculty surveyed, illustrates the wide possibilities for integrating this information into both traditional and new courses [30]. Efforts are currently underway to develop green engineering homework problems and illustrative examples to be integrated into all the courses in a chemical engineering program.

The Green Engineering Program has been successful in initiating green engineering courses and modules within the chemical engineering program. Regional workshops have been conducted

Table 4. Green engineering modules to accompany Allen and Shonnard text

Module	Appropriate Courses
Module 1: Environmental literacy: environmental issues, risk, exposure, and regulations	Process/Plant Design: Introduce environmental literacy and regulations before assigning projects Freshman Engineering: Introduction to issues regarding environment/society/industries
Module 2: Estimating emissions and exposures: case studies from the EPA PreManufacture Notice process	Process/Plant Design: Use with plant environmental review for impact study Material Science: Producing polymers, electronic materials
Module 2a: Evaluating environmental partitioning and fate: based on chemical structure	Process/Plant Design: Use as a preliminary screen of chemical products and raw materials Materials Science, Thermodynamics: Module on estimating properties Material and Energy Balances: Module on estimating mass partitioning in closed systems
Module 3: Evaluation of alternative reaction pathways	Process/Plant Design: Green chemistry concepts and a screening of chemical products and raw materials on the basis of economics and environmental impacts Reactor Design: Waste and risk minimization approaches
Module 4: Environmental evaluation and improvement during process synthesis	Material and Energy Balances: Criteria pollutant emissions from energy consumption, emission of global change gases, calculate emission factors from combustion stoichiometry Continuous/Stagewise Separations: Evaluate environmental aspects of mass separating agents Process/Plant Design: Pollution prevention strategies for unit operations Reactor Design: Environmental aspects of chemical reactions and reactors, pollution prevention strategies for chemical reactors
Module 5: Process integration of heat and mass	Material and Energy Balances: Introduce concept into recycle and recovery processes Continuous/Stagewise Separations: Separation process streams for mass integration Process/Plant Design: Perform audit on plant and optimize/integrate mass and energy flows
Module 6: Flowsheet environmental impact assessment	Process Design: Develop and use environmental objective functions to rank process, design alternatives, rank process designs quantitatively based on environmental criteria Transport Phenomena: Module on interphase mass transfer in the environment
Module 7: Life-cycle assessment	Freshman Engineering: Introduction to evaluating the environmental impacts associated with the production, use, and disposal of products Process/Plant Design: Examine chemical product from life-cycle assessment viewpoint

throughout the United States, at the American Society for Engineering Education annual conferences [30], and the national ASEE Summer School for Chemical Engineering Faculty [43]. A national student contest in green engineering has been conducted at the American Institute of Chemical Engineers' annual meeting to involve faculty and students even further.

CONCLUSIONS

The engineer, as the designer of products and 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 engineering curriculum. Within this paper, several examples of green engineering modules, case studies and experiments that may be used in courses from the freshman through graduate level have been provided. Our student assessment results have been very positive and show that integrating green engineering concepts early and often in the chemical engineering curriculum leads to enhanced student preparation in this important area.

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