UNIQUE DESIGN EXPERIENCES
INTEGRATION OF INHERENT SAFETY INTO CAPSTONE DESIGN

Colin S. Howat[1]

Abstract *¾ Structuring a four-year, all-inclusive chemical engineering program is elusive. Effective integration of fundamentals prepares students for any chemical engineering topic. Capstone Design and Safety are effective integration courses. Knowledge integration in Design comes through synthesis and evaluation and engineering practice skills development. Problem solving methodology follows a six-step procedure. Synthesis and evaluation are based on a four-tier design evolution. The evolutionary development framework had six structures. Integration is re-enforced in Safety. The topics within the envelope of inherent safety are accident evaluation, hazard identification, probability and consequence estimation, and risk reduction. High-reliability and normal system accident theories are effective tools to allow students to identify sequences of events coupled with chemical engineering fundamentals beyond intended performance. Few curricula have the luxury of adding Capstone Safety. This paper presents a unique integration of Design and Safety. The focus is always on the integration of fundamentals and engineering practice skills. While the emphasis is chemical engineering, the intent and methods should be transferable to other fields.*

Index Terms ¾ Capstone Design, Conceptual Process Design, Curriculum Integration, Inherent Safety, Process Safety

INTRODUCTION

Rugarcia et al. (2000) state that structuring a four or five year program to fit all chemical engineering needs is, at best, elusive. The proliferation of areas into which chemical engineers practice and the advancement of chemical engineering knowledge make structuring a chemical engineering curriculum difficult. Nevertheless, a set of fundamental skills defines chemical engineers. These are material and energy balances (conservation of mass and energy), the transports, kinetics and thermodynamics. If these courses can be effectively integrated, students should be able to face any chemical engineering topic (Prausnitz, 1988). Further, if students are effectively taught to teach themselves, they can build on these fundamentals as they transform from generalists in school to specialists in industry (Longworth and Davies, 1996; Prausnitz, 1998). Felder (1998) underscores the focus on the development of skill sets for chemical engineers. Among others, he stresses 1) independent lifetime learning skills; 2) problem solving, critical thinking and creative thinking skills; and, 3) integrative thinking skills.

This author has developed three courses at the University of Kansas (USA) focusing on Capstone Design and Safety that address the goals of problem solving, synthesis (creativity skills), lifelong learning and integration.

Capstone Design

Capstone Design is the typical - and often, only - course in the chemical engineering curriculum that focuses on the above skills. In four of the nine “Thoughts of Teaching Design” papers, this author discusses how to integrate student knowledge through synthesis and evaluation, how to develop problem solving skills and how to integrate effectively modern computing tools (Howat, 1996, 1997a, 1997b, 1998a). Problem solving methodology as implemented follows a six-step procedure: engage, define, explore, plan, do and evaluate. While the method is based on Woods (1994), it emulates engineering practice espoused by Hoover and Fish (1941). The synthesis and evaluation focus is based on a four-part design evolution: Back-of-the-Envelope, Process Feasibility, Base Case and Optimized designs. Figure (1) is a representation of that evolution. All of the evolutionary steps historically incorporated these structures: Process, Input-Output, Recycle, Separation, and Heat Integration. The integration of the process simulation package follows the SOARED acronym: Sensitize, Oversee, Assess, Restrict, Experiment and Develop.

Safety

The Safety course is discussed in detail in the invited presentation Howat (1998b). The course has been modified to emphasize inherent safety centering on the concepts of minimize, substitute, simplify and moderate. The course structure is shown in (2).

The primary purpose of the course to provide the opportunity for students to broaden their synthesis and evaluation skills by providing the opportunity to examine chemical processes beyond the confines of intended performance.

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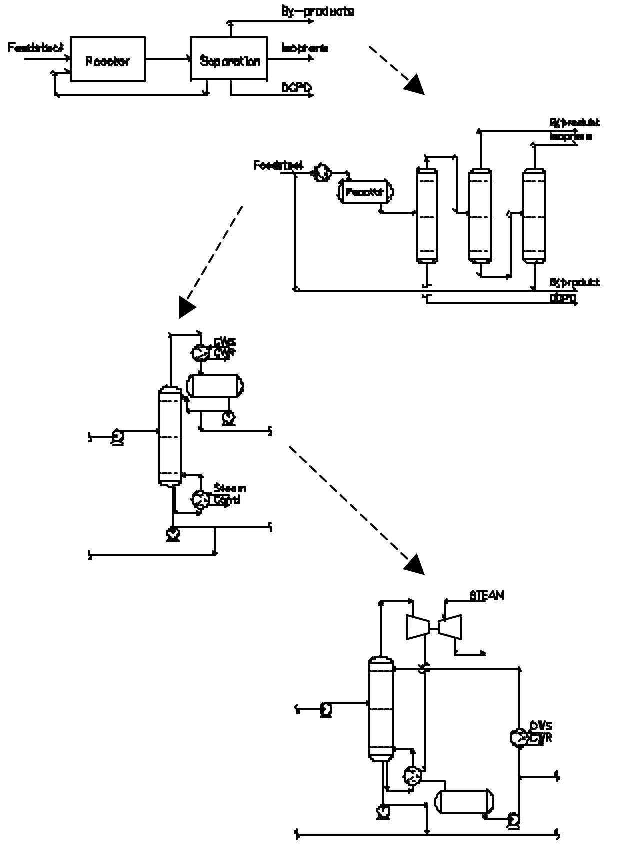

FIGURE 1
SCHEMATIC OF PROCESS SYNTHESIS AND EVALUATION INCLUDING BACK-OF-THE ENVELOPE, PROCESS FEASIBILITY, BASE CASE AND OPTIMIZED DESIGN STRUCTURES

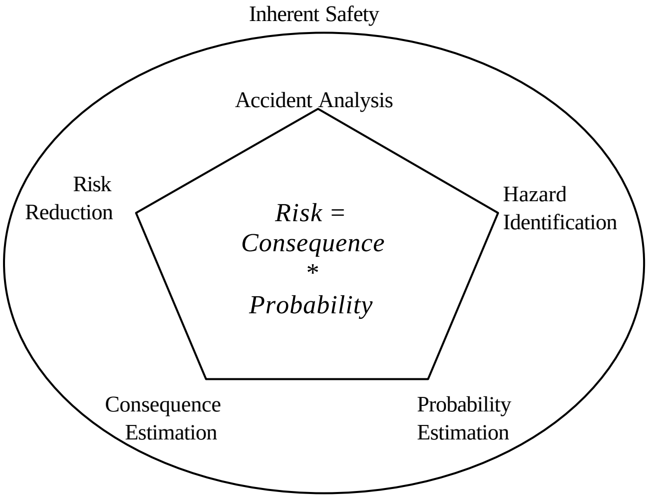

FIGURE 2
PLANT & ENVIRONMENTAL SAFETY: INHERENT SAFETY ENCOMPASSING TRADITIONAL PROCESS HAZARDS ANALYSIS

The Problem

Few curricula have the luxury of adding an additional required course in safety. Inherent Safety is a topic that can be incorporated into the synthesis and evaluation steps of Capstone Design. With the incorporation of unsteady-state simulation (Howat, 1998c) the principal important aspects of safety can be covered without an additional course. More importantly, the aspects of analyzing beyond intended performance, often neglected in traditional design, are incorporated into the Capstone Design course, enhancing the likelihood of meeting course outcomes.

The effectiveness of any integrated course relies on more than content. It also requires appropriate teaching methods. The traditional approach to teaching has the professor lecturing, assigning reading and assigning closed-ended problems. The students listen, take notes and solve problems using easily found procedures/equations. Not only does this not emulate practice and, therefore, not prepare students for graduation, this does not address the learning styles of students (Wankat and Oreovicz, 1993; Felder and Silverman, 1988). Much more effective are: cooperative learning, open-ended problem solution, open-ended problem formulation, brainstorming, open-ended discussion and trouble shooting. The effectiveness also requires extensive experience (Felder et al., 2000).

There are two principal obstacles to adopting the teaching methods suggested above and incorporating them into an integrated course in design and safety.

First, most entering faculty have very little experience outside academe. Second, there is resistance on the part of the faculty and students to adopt these methods. Many universities rely on research overhead for much of the budget. Consequently, faculties are hired for their research potential. They rightly conclude that academic advancement will be based primarily upon research. Any commitment beyond the minimum to non-research activities is a distraction from advancement (Rugarcia et al., 2000). Further, the types of teaching methods recommended require flexibility in approach. Without sufficient experience and with a need to stay on syllabus, adopting those methods implies a loss of control and a degree of discomfort resulting in professorial reluctance. Students also object because their self-evaluation is clouded, they must use skills not generally required for their success to date and the level of learning is higher. Some aspects of these observations are discussed in The Chronicle of Higher Education (1999). Any integrated course must provide the necessary flexibility so that faculty can use the material without undo effort, without undo discomfort and with sufficient breadth to allow free-ranging discussions. It must also provide a learning environment so that student reluctance is lessened.

PRINCIPLE OF THE APPROACH

The opportunities provided by Capstone Design and Safety allow students to reach their fullest potential as chemical engineering aspirants. Time and outside demand require an efficient integration of the two courses. To be effective, the students determine the direction, synthesize ideas, make specifications, evaluate them and modify the process. This is effectively done if the problem statement is vague and the professor allows the students sufficient reins to explore their path. Including safety in the synthesis structure provides greater opportunity for integration of the chemical engineering fundamentals. The effect of this approach is that the professor will contribute significant time, must exercise restraint, must be flexible in solution and should have sufficient experience to be comfortable with results substantially different from his or her own.

This latter point is particularly important when teaching Capstone Design, generally, and this integrated course, specifically. Professors must recognize that a properly taught design class requires that there is no correct solution. This results in a loss of security by the professor who is comfortable with typical text-based courses wherein the there is one correct answer and very few correct approaches. In this integrated class where synthesis leads to a myriad of solutions and safety analysis increases this number exponentially, the professor must be extremely flexible in evaluating students and their progress.

Further, since students dictate the direction by the progress of their synthesis and evaluation, a set, rigid calendar is inappropriate and less than optimal. Therefore, the professor must keep in background where he or she wants the class to progress while allowing students nearly free-rein in direction.

SYNTHESIS STRUCTURE

The synthesis structure used in the integrated course includes the following:

- Process Information
- Process Operations Structure
- Feed, Product, Byproduct and Waste Structure
- Inherent Safety Structure
- Recycle Structure
- Separations Structure
- Heat Integration Structure
- Process Control Structure

This is a modification of the conceptual flowsheet steps given in Douglas (1988). The principal modifications used in this integrated course are the inclusion of the Inherent Safety Structure and the Process Control Structure. This paper focuses primarily on the integration of safety of which these two synthesis aspects are particularly important. They are the topic of the next two sections.

INHERENT SAFETY STRUCTURE

A hazard is defined as a physical or chemical characteristic of the process which, if released, could cause harm. It is relatively straightforward to identify toxicity, flammability, reactivity, corrosives, high temperature and high pressure, among other hazards. It is more difficult to evaluate whether these present substantial risk which may require changes to their evolving process design. In this synthesis step, students must evaluate the hazards of their process, examine alternative configurations and focus their synthesis efforts on reducing the hazards. This requires that the course include hazard identification, hazard evaluation and synthesis solutions. This integrated course uses Hazard and Operability Studies (HazOp) for the hazard identification, Layer of Protection Analysis for the hazard evaluation and Inherent Safety Concepts for synthesis.

HazOp's provide a structured approach for students to examine their processes. It forces them to look beyond intended performance by applying Guide Words (Deviations) to the Process Intent (flow), e.g. More Flow. Students then must determine whether this deviation impacts the process operation. While the focus is on a small aspect of the process, e.g. a tank, students begin to recognize that this deviation may impact processing steps up and down stream from that under study. Students then determine whether the deviation poses a safety concern and whether there are any safeguards present to protect against this deviation and subsequent consequence. The student result is that they begin to evaluate beyond intended performance requiring greater integration than that required for steady-state (or, intended batch) operation. However, it does not provide an evaluation tool for modifying the process.

That modification tool is the relatively new concept of Layer of Protection Analysis (2001). LOPA is a simplified quantitative risk assessment tool the steps of which are:

- Identification of the scenario
- Identification of the initiating event
- Identification of the Independent Protection Layers
- Determination of Scenario Frequency (Probability)
- Determination of Scenario Consequence
- Evaluation of Scenario Risk

This methodology is easily implemented and provides an evaluation tool to compare alternatives. Reducing probability or consequence to a more tolerable risk level gives the students comfort that they are implementing safer designs.

Students do need direction during synthesis of reduced-risk processes. The concepts of Inherent Safety provide that direction. Normal system theory which is the basis of inherent safety was chosen as the directional tool over traditional High Reliability System Theory because it is more easily implemented in this integrated course and because it is the direction in which industry is moving. With relatively low effort, students are able to grasp the concepts of minimization, substitution, moderation and simplification.

PROCESS CONTROL STRUCTURE

Process dynamics and process control are typically taught as a separate course from Capstone Design. However, this must be included when evaluating layers of protection. The important material discussed as part of the integrated course is the development of the basic process control system, the safety instrumented system and safety integrity levels. The basic process control system requires identification of the controlled, measured and manipulated variables. The purpose is to give intended performance. The safety instrumented system and the safety integrity levels result from the LOPA analysis and the acceptable risk criteria. This integrated course does not cover process dynamics as traditionally taught. It does, however, cover unsteady-state process simulation to analyze the effect of deviations that are identified in the HazOp. Any steady-state process simulator can do an Euler integration of a process response. The error caused by the solution method is more than offset by the insight provided from viewing the process response. Since the modules used are the same used during the process synthesis, there is no learning curve and there are no approximations necessary for phase equilibria, reaction kinetics and physical properties.

This discussion of process control is not a substitute for the traditional class. It may not be necessary if control is taught well before design. But, the inclusion of these topics and the impact of the control system on the robustness of the process are necessary when incorporating the inherent safety structure into the synthesis steps.

CLASS CONTROL

Students will rapidly and inappropriately embrace the eight synthesis steps as a step-wise procedure for synthesizing a chemical process. Instead, it is intended as a framework over which the students move adding detail as they learn more about their process. The professor who uses this integrated course should require students to iterate with the perpetual goal of racing to the solution, returning to add detail and racing to the solution again. This is not the model that students have studied under and are comfortable in embracing. Professors should impose the tiered structure of (1) or a modification thereof. This has four benefits.

First, students are forced to practice as done in industry where designs truly evolve from the vague to specific over a number of iterations, thus better preparing them for practice.

Second, students are forced to estimate the chemical behavior of the system with little information. This helps them to begin the solution process when the path is unknown and to identify what they need to know and how well they need to know it.

Third, students are forced to move through the design and not dwell on aspects that may, with additional insight, be insignificant to the process design development and evaluation criteria.

Fourth, students are forced to use the eight synthesis steps as a framework adding only the necessary detail to accomplish the solution at hand. The ultimate goal of an efficient, elegant, economic and safe design can cause student paralysis because the step from the present to that state is far too large.

OBJECTIVES

The Accreditation Board for Engineering and Technology (ABET) requires 'Outcomes' to be assessed by faculty and students, the results of the assessment of which leads to improvements in the course. More importantly, these outcomes should be characterized as objectives that the students and faculty are expected to meet by the end of course. These objectives should range in achievability from easy to difficult. The following bullets are the principal objectives for this course with example sub-objectives given in italics. To be effective, the objectives should be detailed and faculty assessment of students should be based on these detailed objectives.

- Students must experience the creation process of design and be able to apply it to synthesize and evaluate solutions to significant integrated problems.
  Examples:
  Students will be given a brief memo identifying a potential need and develop a process that meets that need.
  Students will identify the information that they need to complete the process synthesis and evaluate the impact of that information on their process design.
  Students will develop an understanding of the hazards associated with their process and evaluate those hazards using risk evaluation.
- Students must recognize the need for, select values for and evaluate the impact of the specifications inherent in a process subject to process and project constraints.
  Examples:
  Students will select a feed temperature for the reactor and evaluate the impact of that temperature on conversion and volume requirements for the reactor and

on the separation requirements for subsequent processing.
Students will select a feed temperature for the reactor and evaluate the risk associated with that specification.

- Students must develop the confidence to begin the creation of a solution to a problem even though the solution path is unknown and to use the discoveries along the path to continue the development.
  Example:
  Students will develop the first tier process design using extensive estimations and use the results from that analysis to develop the next synthesis tier.
- Students must be able to develop solutions without extensive computational support.
  Example:
  Students will estimate the impact of a process operating change on the material and energy balances and then confirm that estimation using process simulation.
- Students must develop the confidence to work with the ambiguity of chemical engineering information and the uncertainty in chemical engineering solutions.
  Examples:
  Students will examine the uncertainty in the kinetic data and translate that uncertainty into process operation.
  Students will develop equipment and controls with sufficient robust behavior to accommodate this uncertainty.
- Students must review the content of the chemical engineering curriculum reinforcing the foundation of your knowledge.
  Examples:
  Students must evaluate the suitability of literature phase equilibria data for the process design application.
  Students must be able to develop a phase equilibria database suitable for the process design application.
  Students must be able to extract kinetic data from the literature.
  Students must be able to develop a description of the kinetic data, understand the limitations and the process implications.
- Students must recognize the need for, develop and practice problem-solution strategies that are appropriate for the practice of synthesis and evaluation in the context of chemical engineering design.
  Examples:
  Students will read a problem statement and be able to define what is actually asked and anticipate the solution form.
  Students will explore the problem based on the definition and identify the information required to solve the problem.
  Students will repeatedly evaluate their evolving solutions to determine whether the problem is properly defined and whether the plan for solution will lead to solving the defined problem.

The full object list is too long for this media. The sub-objectives are modified based on the assigned problem. The criteria for problem selection must be invoked to insure that the principal bulleted objectives are addressed during the course.

IMPLEMENTATION

Design problem criteria for effective integration of safety into Capstone Design must be established to allow students to effectively address the outcomes and sufficiently narrow to allow students a reasonable chance to succeed in synthesizing an efficient, elegant, economic and safe design within the time frame allowed. Specifically, the problem should include:

- Sufficient breadth in chemical engineering content to provide the opportunity for students to review the fundamentals of chemical engineering
- Sufficient depth of chemical engineering content to provide the opportunity for students to synthesize diverse processes addressing the design constraints
- Sufficient complexity to ensure that students develop a multi-operation process such that design specifications of one operation impact another
- Sufficient simplicity to allow students to mentally encompass their evolving process such that they can develop a mental model of the process and are able to project the impact of modifications in one area on another
- Sufficient economic breadth to provide an economic criteria in evaluation
- Sufficient hazard content to provide a risk criteria in evaluation
- Sufficient industrial importance to given students confidence that they can address 'real-world' problems

The constraints of one semester course with significant demands placed on students by others limits the type of problem that can be selected for this integrated course. An example problem that has proved effective is to have students synthesize a concentration unit for recovering isoprene from a naphtha cracker C_5-cut. The problem is presented as a memo documenting a telephone conversation with a client. The object is to produce an economic concentrate which reduces shipping costs and reduces the cyclopentadiene content, thus providing a substantial economic aspect. Cyclopentadiene is a catalyst poison in subsequent isoprene polymerization, but, more importantly here, it spontaneously dimerizes, trimerizes and polymerizes exothermically. It also reacts with isoprene resulting in an economic loss of product. This series of reactions has the potential to runaway thus providing the risk aspect. Dicyclopentadiene can be recovered as an economic product reducing waste and improving economics. The kinetics and phase equilibria are complex requiring significant data base, separation, reaction, heat transfer, sensitivity and control considerations during synthesis. Multiple processing steps are required each of which impacts the others in the process. Multiple configurations are possible. Inherent safety evaluation using layer of protection analysis provides significant opportunity for decision evaluation during synthesis.

OBSERVATIONS

The inclusion of Hazard Identification, Layer of Protection Analysis and Inherent Safety does result in students better prepared to practice. However, without removal of material from the conventional process design class, the amount of material is far too great for a single semester course. Consequently, traditional topics such as the mathematical methods for optimization have been eliminated from the integrated course. Topics related to start-up are melded into the LOPA and process control discussion. Sensitivity analysis to the data base is now covered indirectly in the LOPA analysis, unsteady-state simulation and process control development.

Student performance as measured by the seven major objectives discussed above increased when safety was integrated into design. This is largely due to the forced examination of the process performance outside of the intended operating constraints. Consequently, students were forced to anticipate what might go wrong and develop engineering fundamental descriptions of the sequence of events.

This author has taught Capstone Design since 1983 and Safety since 1987. He enjoys the luxury of having two separate classes. Nevertheless, the introduction of the safety into the design synthesis evaluation improved performance in both classes. Even with the luxury of two separate classes, inherent safety should be integrated into Capstone Design.

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