# CONSERVATION OF LIFE
## *as a Unifying Theme for Process Safety in Chemical Engineering Education*

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Conservation of energy (COE) and conservation of mass (COM)—both are fundamental principles that apply to all aspects of chemical engineering design, analysis, and education. In most cases, we cannot apply one without consideration of the other. Yet, a third fundamental principle exists that is too often not recognized as on the same level of importance as COE and COM: prevention of serious human injury, major property damage, and environmental harm, which is a primary focus of industrial chemical engineering practice. We choose to call this third principle "conservation of life" (COL), reflecting the need for fundamental awareness and application of process safety and product sustainability concepts in chemical engineering education. COL was first introduced to our knowledge by Lewis DeBlois,[1-3] who was DuPont's first corporate safety manager and later president of the National Safety Council, when he wrote in 1918:

> *… safety engineering, with its interests in design, equipment, organization, supervision, and education … bears as well a very definite and important relation to all other branches of engineering. This relation is so close, and its need so urgent, that I am convinced that some instruction in the fundamentals of safety engineering should be given a place in the training of every young engineer. He should be taught to think in terms of safety as he now thinks in terms of efficiency. Conservation of life should surely not be rated below the conservation of energy. Yet, few of our technical schools and universities offer instruction in this subject, and the graduates go out to their profession with only vague surmises on "what all this talk on safety is about."*[4]

Much of what DeBlois observed and recommended remains true today, over 90 years later, as identified by the U.S. Chemical Safety Board (CSB) in their report on the T2 Laboratories incident in 2009:

> *In 2006, the Mary Kay O'Connor Process Safety Center surveyed 180 chemical engineering departments at U.S. universities to determine whether process safety was part of their chemical engineering curricula. Of the universities surveyed, only 11 percent required process safety education in the core baccalaureate curriculum. An additional 13 percent offered an elective process safety course.*[5]

CSB recommended that the American Institute of Chemical Engineers and the Accreditation Board for Engineering and Technology (ABET) work together to improve requirements for chemical engineering education to include greater em-

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phasis on process safety, in particular awareness of chemical reactivity hazards. In response, the following additional program outcome has been proposed for the general ABET criterion for accrediting undergraduate chemical engineering programs:

> *Engineering programs must demonstrate that their students attain the following outcomes: (l) an awareness of the need to identify, analyze, and mitigate hazards in all aspects of engineering practice, for example design, operational procedures and use policies, hazards detection and response systems, fail-safe systems, life-cycle analyses, etc.*[6]

COL can be used by universities as a concept and unifying theme for increasing awareness, application, and integration of safety throughout the chemical engineering curriculum and for meeting the revised ABET accreditation criteria. Students need to think of COE, COM, and COL as equally important fundamental principles in engineering design, analysis, and practice. By providing students appropriate tools for evaluating and implementing COL principles, we can help them to better understand "what all this safety talk is about," and what their role is in contributing to safety in chemical engineering.

## COL PRINCIPLES

Five COL Principles have been developed and are shown in Figure 1. These principles are based on application of industry standard process safety and product sustainability practices and are intended to organize COL concepts and methodologies for application in various parts of the chemical engineering curriculum, as discussed further in the following section.

### *1. Assess material/process hazards*

A basic understanding of material and process hazards is required for safe engineering design and operations. A hazard can be defined as a physical or chemical condition that has the potential for causing harm to people, property, or the environment.[7] Examples of material hazards include flammability, toxicity, and reactivity. Examples of process hazards include high temperature, high pressure, and mechanical energy. Hazards assessment can be defined as the detailed evaluation and development of information about a chemical, material, mixing, or interaction of chemicals/materials and about any operating conditions that can create process hazards. Hazards assessment therefore provides the basic understanding and data for conducting further process hazards and risk analysis and management. The starting point for hazards assessment is often the Material Safety Data Sheet (MSDS), but the MSDS should be considered only for initial information, which should be verified and expanded on through additional literature and experimental data.

### *2. Evaluate hazardous events*

Multiple hazardous events, such as loss of containment, fires, explosions, runaway reactions, etc., can be described for most chemical processes, based on the material and process hazards and intended or accidental processing steps. Consequence analysis and modeling consist of identifying and evaluating the direct, undesirable impacts of potentially hazardous events, resulting from failure of engineering and/or administrative controls for the process. The purpose of consequence analysis is to help estimate the type, severity, and number of potential injuries, property damage, and environmental harm that could result from different event scenarios.[8] In conducting consequence analysis, the impacts of possible hazardous events are evaluated for a range of small to catastrophic failure events. A small event could be caused by a small-diameter hole in a vessel or pipe or possibly a procedural error such as leaving a valve open or in the wrong position. Catastrophic failure events are those where there is a complete and sudden failure of any equipment, structure, or system resulting in major loss of containment of chemicals or energy. Even though catastrophic failure events are rare, the consequences of such an event could be significant and should be carefully evaluated.[9]

### *3. Manage process risks*

Process hazards/risk analysis consists of the detailed, methodical evaluation of process equipment, materials, conditions, and operating steps in order to control and reduce process risks. Specific

1. Assess material/process hazards
   - Develop basic data on reactivity, flammability, toxicity, etc.
2. Evaluate hazardous events
   - Apply methodologies to estimate potential hazardous impacts
3. Manage process risks
   - Evaluate risk vs. acceptable risk criteria
   - Apply inherently safer approaches
   - Design and evaluate multiple layers of protection
4. Consider real-world operations
   - Implement comprehensive PSM systems
   - Recognize importance of human factors
   - Learn from experience – Case Histories
5. Ensure product sustainability
   - Implement product safety / stewardship practices
   - Apply life cycle management

***Figure 1.*** *COL Principles.*

failures of process equipment, operating procedures, or related systems that can lead to potentially hazardous events must be identified and evaluated to ensure that appropriate and reliable safeguards (layers of protection) are provided to achieve acceptable risk levels. Typical hazards evaluation methods include hazard and operability analysis (HAZOP), what-if/checklist analysis, failure modes and effects analysis (FMEA), and fault tree analysis (FTA).[7] Risk analysis can range from qualitative to semi-quantitative (*e.g.*, Layer of Protection Analysis)[10] to quantitative,[11] depending on the potential risks associated with the process. The initial process design and risk analysis activities also provide the greatest opportunities for consideration and implementation of inherently safer process concepts[12,13] to significantly reduce process risks.

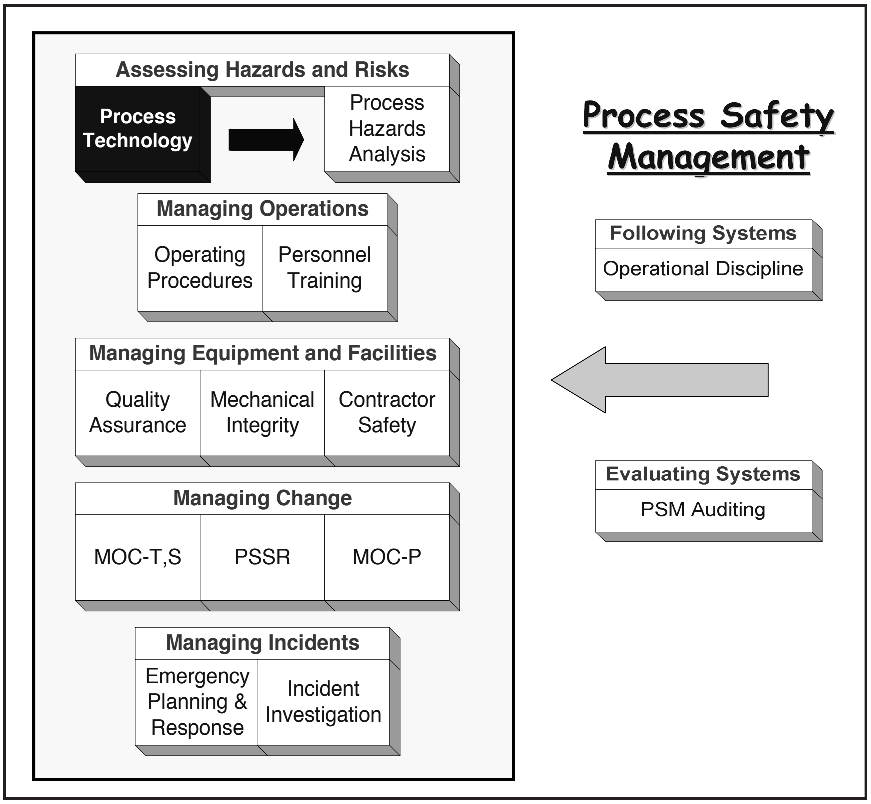


***Figure 2.** Elements of a process safety management program.*

### *4. Consider real-world operations*

Process hazard identification, evaluation, and management is essential to chemical engineering design, but consists of only the initial elements of a sound industrial process safety management program, as shown in Figure 2. Real-world chemical operations must develop and implement systems for operating procedures, training, management of change, equipment maintenance and reliability, etc.,[14,15] in order to obtain desired results. In addition, humans make mistakes, so human factors[16-18] must be considered during the initial risk analysis, management of day-to-day operations, and emergency response. Incidents and case studies[19,20] also provide opportunities for learning from previous problems to help prevent their re-occurrence.

### *5. Ensure product sustainability*

Chemical products must be designed and managed for human health and safety throughout the product life cycle from manufacture to intended use to ultimate disposal without the potential for significant environmental impact. Comprehensive product stewardship programs should include environmental risk assessment and management, regulatory compliance, life cycle analysis, and stakeholder engagement.[21] Student awareness and understanding of the social, environmental, and economic impact of chemical engineering design and analysis is essential for ensuring optimal product sustainability practices.

| | Typical Core Courses in a ChE Curriculum | | | | | | | | | | | | Electives | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Introduction to ChE | Material & Energy Balances | Thermodynamics | Fluid Mechanics | Heat Transfer | Mass Transfer/Separations | Engineering Materials | Process Control | Reaction Engineering | Statistical Design of Experiments | Unit Operations Laboratory | Process Design | Particle Technology | Pollution Control Technology | Biochemical Engineering | Green Engineering |
| **Assess material/process hazards** | | | | | | | | | | | | | | | | |
| Develop basic data on reactivity, flammability, toxicity, etc. | | x | x | | | | x | | x | | x | | x | | x | x |
| **Evaluate hazardous events** | | | | | | | | | | | | | | | | |
| Apply methodologies to estimate potential hazardous impacts | | x | x | x | x | x | | | x | x | x | x | x | x | x | x |
| **Manage process risks** | | | | | | | | | | | | | | | | |
| Evaluate risk vs acceptable risk criteria | | | | | | | | | | x | | x | | x | | x |
| Apply inherently safer approaches | x | | | x | x | x | | x | x | | x | x | | | | x |
| Design and evaluate multiple layers of protection | x | | | x | x | x | | x | x | | | x | | | | |
| **Consider real-world operations** | | | | | | | | | | | | | | | | |
| Implement comprehensive PSM systems | | | | | | | | | | | | x | | | | |
| Recognize importance of human factors | x | | | | | | | x | | x | x | x | | x | | x |
| Learn from experience -Case Histories | x | | | x | x | x | | x | x | | | x | x | x | | x |
| **Ensure product sustainability** | | | | | | | | | | | | | | | | |
| Implement product safety/stewardship practices | x | | | | | x | x | | | x | | | | | x | x |
| Apply life cycle management | x | x | x | | | x | x | | x | | | | x | x | x | x |

***Figure 3.** Application of COL in undergraduate chemical engineering curriculum.*

Application of COL principles is intended to help achieve "the

**SACHE Modules by COL Principle**

**1. Assess material/process hazards**

- Chemical reactivity hazards (2005)
- Dust explosion prevention / control (2006)
- Explosions (2009)
- Properties of materials (2007)
- Reactive and explosive materials (2009)
- Runaway reactions (2003)
- Seminar on fire (2009)
- Etc.

**SACHE Modules by ChemE Course**

**Reaction Engineering Course**

- Chemical reactivity hazards (2005)
- Hydroxylamine explosion case (2003)
- Reactive and explosive materials (2009)
- Runaway reactions (2003)
- Runaway reactions: Experimental characterization and vent sizing (2005)
- Rupture of a nitroaniline reactor (2007)
- Etc.

***Figure 4.*** *SACHE Modules for COL Principles (examples).*

goal is zero" with respect to injuries, incidents, and environmental/social impact associated with chemical engineering practices and products. Awareness and use of these principles by students should help them understand their important roles as engineers in helping make achievement of this goal a reality. Students may simply wish to think of these concepts as "people in = people out."

A practical method for measuring the impact of COL in either process or product safety is to consider risk reduction, such as shown in Eq. (1):

$$\Delta R = \log\left(R_o / R_p\right) \tag{1}$$

$\Delta R$ is the order of magnitude improvement in risk for the event being evaluated, where $R_p$ is the risk level (*e.g.*, fatalities per year) when COL principles have been applied, and $R_o$ is the inherent risk associated with the handling, processing, or use of potentially hazardous materials or products. Cost-effective risk reduction improvements should be identified and considered for implementation, based on application of COL principles. $\Delta R$ measures the collective risk improvement, and risk criteria[22] are typically used to determine if an overall acceptable level of risk has been achieved.

## APPLICATION OF COL TO CHEMICAL ENGINEERING CURRICULA

There are three main reasons for use of COL as a unifying concept and •theme in undergraduate chemical engineering education:

- *Emphasize importance of safety to students as a fundamental principle that must be considered and evaluated in all aspects of engineering practice equivalent to COE and COM*
- *Consistent application and reinforcement of safety integrated throughout the curriculum*
- *Meet ABET accreditation changes related to safety.*

Use of COL will help develop a process safety culture in the curriculum, where students see connections and applications related to COL in most courses. Students will not be able to easily compartmentalize COL as a separate, unrelated activity, but will see it as an activity that is inherent to all courses and engineering activities. Using a spiral learning model, COL will build up awareness, understanding, and capability related to safety as students gain experience by revisiting the COL principles at increasing levels of depth and breadth. Ultimately, students will demonstrate knowledge and application of COL principles in the capstone design course reports and presentations[22-24] by addressing subjects such as:

- *Process hazards*
- *Hazardous events*
- *Hazard/risk analysis*
- *Layers of protection*
- *Human factors issues*
- *Product safety and life-cycle considerations.*

An example of where COL principles could be applied in the undergraduate chemical engineering curriculum is shown in Figure 3.

Additional resource materials for both engineering instructors and students for use in applying COL in undergraduate chemical engineering education are planned. Excellent training materials currently exist that can be used to get started with COL immediately, including:

- *SACHE modules*[26,27]
- *Engineering texts*[28-31]
- *Incident compilations*[19,20]
- *US Chemical Safety Board investigations*[32]
- *Process Safety Beacon*[33,34]
- *Process safety literature* (e.g., *Process Safety Progress*).

A SACHE module introducing COL has been prepared, and materials have been tested in presentations at several universities. Many SACHE modules are currently available,[27] which can be sorted for application of the COL principles. An example is shown in Figure 4.

## EXAMPLE

A simple example of a classroom active-learning exercise that reinforces the principles of COL in a separations course was adapted from the April 2003 *Process Safety Beacon*.[33,34] The article describes an incident involving a fire and explosion originating in an activated carbon drum used to control hydrocarbon emissions from a flammable liquids storage terminal. Starting with COL principle four—consider real-world operations—the class is presented with a basic description of the incident, and then asked to work through the first three COL principles of assessment, evaluation, and management of process hazards applied to this case study. The class is divided into small teams of two or three students and allowed a short time to work on the problem. Students typically reference the table of Failure Scenarios for Mass Transfer Equipment.[7] An instructor-led classroom discussion solicits student input and may include the following observations and recommendations:

1. *Assess Hazards: Flammable materials exist in the carbon bed and hydrocarbon vapor, and low thermal conductivity in the carbon bed reduces heat transfer rates with a potential for exceeding the auto-ignition temperature.*
2. *Evaluate Hazards: Reference the fire triangle, as shown in Figure 5, and identify sources for fuel (organic materials), oxygen (air in the tank space) and heat (exothermic heat of adsorption reaction).*

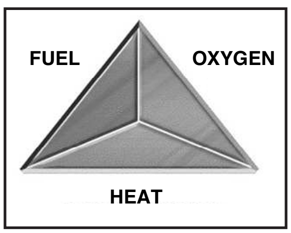


***Figure 5.** Fire triangle.*

3. *Manage Risk: Apply LOPA[10] to recommend passive and active design solutions that include: proper flow distribution in the bed, minimizing the bed cross sectional area, continuous monitoring of bed temperature, flooding/inerting, flame arresters, foam fire protection, interlock to isolate feed on detection of high temperature, etc.*

## SUMMARY

COL is a fundamental principle equivalent to COE and COM in terms of application to all aspects of chemical engineering design, analysis, and practice. COL can be used as a concept and unifying theme integrated into the undergraduate chemical engineering curriculum to emphasize and reinforce consistent application of COL principles, increase student awareness and capabilities, and help meet revised ABET accreditation requirements. One author's university—University of Minnesota, Duluth—has officially adopted COL for use in its undergraduate chemical engineering program. Other universities may benefit from a similar approach.

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