Develop and Design Inherently Safer Process Plants

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Biographical Sketch - Victor H. (Vic) Edwards, PhD, PE

- Director of Process Safety for Aker Solutions US, Inc.
- AIChE Fellow
- 1998 Employee of the Year
- 2007 Process and Construction Division Award for HSE excellence in design
- Three DuPont awards for engineering excellence in Health, Safety, and Environment; two DuPont awards excellence in HSE during 26 years as an alliance engineering contractor
- 2003 Service Award from the Mary Kay O'Connor Process Safety Center at Texas A & M University
- Chairman of the Technical Advisory Committee of the Process Safety Center
- More than 60 technical publications
- Chaired the first Process Plant Safety Symposium
- Chaired the second Plant Operations and Design Conference
- B. A. from Rice University; Ph. D. from University of California, Berkeley in chemical engineering
Acknowledgments

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Safe Design and Operation of Process Plants is Challenging

- Manufacture of fuels uses and produces products that burn with significant energy release.

- Certain basic chemicals such as mineral acids and halogens are toxic and/or corrosive.

- Chemical transformations may either require or release energy.

- Many manufacturing processes produce benign products but require hazardous chemical intermediates in their manufacture.
Develop and Design Inherently Safer Process Plants

“What you don’t have can’t leak”
- Trevor Kletz, 1977

Emphasis on the *Inherent Nature of the Process*
Numerous Contributions to Inherently Safer Design Since 1977

For example, see


Four Basic Process Risk Management Strategies

- Inherent
- Passive
- Active
- Procedural or Administrative

Preferred ranking of methods to control process risks

*Inherent > Passive > Active > Procedural*
Layers of Protection in a Process Plant
Inherently Safer Process Concepts (Kletz, 1998)

- Substitution
- Minimization or Intensification
- Moderation or Attenuation
- Simplification
- Limitation of (Hazardous) Effects
- Avoiding Knock-On Effects
- Making Incorrect Assembly Impossible
- Make Status Clear
- Tolerance
- Ease of Control
- Administrative Controls/Procedures
Four *Principles* of Inherently Safer Processes

AIChE Center for Chemical Process Safety (CCPS, 2009) reduced these *eleven concepts* of inherently safer processes to the following *four principles*:

- Minimize
- Substitute
- Moderate
- Moderate and Simplify
First Order and Second Order Inherent Safety

- 1st Order Inherent Safety Changes the *Chemistry of the Process*

- 2nd Order Inherent Safety Changes the *Process Variables*

- CCPS (2009)
Three New or Neglected Inherently Safer Concepts

- Hybridize or Transform

- Stabilize or Ensure Dynamic Stability

- Limit Hazardous Effects
Case Study – Flixborough

- Flixborough process for partial oxidation of cyclohexane with air:
  - Produced Nylon intermediates
  - Large inventories of hot cyclohexane liquid with air injection
  - Low conversion rates (typically 3% to 5%)
  - Very large release (50 tons) of cyclohexane vapor found an ignition source
  - 28 people died
  - Many more injured
  - Plant destroyed
The Aftermath of Flixborough
**Hybridize or Transform – A New IS Concept**

- Chen (2004) discovered an inherently safer process for partial oxidation of cyclohexane
  - Addition of water inerts the vapor phase
  - Safe to use pure oxygen for partial oxidation
  - Higher conversions and smaller inventories now practical
  - This is an example of *Hybridize or Transform – A New IS Concept*
Hybridize or Transform – A New IS Concept

- Chen (2004) discovered that because cyclohexane and water form an azeotrope, the vapor phase is inerted and non-flammable.

- Although Chen did not claim that his discovery illustrated a novel Inherently Safer Concept, it is different from the classical definition of Substitute because the same reactants, the same reactions, and the same products are involved.

- If the name Substitute were broadened to Change in Chemistry or Hybridize, then it could be lumped in with the many successful applications of Substitute.

- Chen’s inherently safer process results in Moderate as a byproduct because higher oxygen concentrations permit higher reaction rates at lower temperatures and pressures, but his hybrid process is inherently different because of the addition of a new component, water, with its transforming effect on the flammability limits.
Future Opportunities for *Hybridize* or *Transform*

- **Definition:** *Hybridize* or *transform* is the addition of one or more chemicals to a reaction mixture to make the desired reaction(s) inherently safer.

- Although not proposed by Chen (2004), there may be many other opportunities to *transform* or *hybridize* other potentially hazardous reactions to make them inherently safer.
  
  - There are many chemicals that could form azeotropes with one or more reactants or products that would inert the vapor phase of a two-phase reacting mixture.
  
  - For example, certain halocarbons may form azeotropes and may also be inert to further oxidation by air or halogens.
  
  - *Hybridize* is not limited to partial oxidation by oxygen or halogens; hydrogenations are another example of potential applications.
  
  - Reactive distillation may offer opportunities for novel *hybrid* processes.
Stabilize or Ensure Dynamic Stability

- Not all process designs are inherently stable.
- The process engineer must ensure dynamic stability as well as ensuring that the steady-state mass and energy balances are achieved.
- Some existing processes have narrow safe operating limits, and are made stable by the addition of control systems.
- Dynamic stability and control of chemical processes has been studied extensively (Edgar, *et al.*, 2008).
- Designing the process to be more inherently stable to process upsets with and without control systems is clearly inherently safer, although this concept is not addressed in most discussions of IS.
- The IS concept “Ease of Control” has usually been interpreted to mean a process with a control system that the operator can understand clearly and manage effectively.
Stabilize or Ensure Dynamic Stability

- CCPS (2009) briefly mentions the advantages of designing processes that are inherently more stable or robust:
  
  “It is inherently safer to develop processes with wide operating limits that are less sensitive to variations in operating parameters…Sometimes this type of process is referred to as a ‘forgiving’ or ‘robust’ process.”

- Ensure Dynamic Stability or Stabilize should be added to the list of IS concepts to be sure that it is not overlooked.
Stabilize or Ensure Dynamic Stability

- Application of other IS concepts may adversely impact dynamic stability.

- For example, reduced liquid inventories (Minimize) in a distillation train makes the process inherently safer by decreasing the consequences of loss of containment.

- However, smaller inventories in the base of a column or in an overhead reflux tank may make level control difficult in those vessels, decreasing process stability.
Reactor Stability – Another Example of Stabilize
Limitation of Effects - Often Neglected IS Concept

- David Clark (2008) reminds us of the too often neglected IS concept of *Limitation of Hazardous Effects*
- There is a strong non-linear decrease of fire, explosion, and toxic effects with separation distance.
- Initially, comparatively small increases in separation distance lead to a large decrease in hazardous effects.
- Subsequent increases in separation distance provide little additional benefit.
- Consequence modeling offers a means to quantify the potential benefits of hazard reduction by limitation of effects.
Example – An Application to One Plant Site

- A 10% increase in separation distance between all units increased the total plant investment cost by only 3%.
- Doubling the separation distance for a hazardous unit representing 10% of the investment cost of the plant would again cost only 3% more.
- Because of the non-linear effect of separation distance, doubling the separation distance for the hazardous unit will reduce explosion overpressures on the adjacent units by a factor of four.
Limitation of Effects - Often Neglected IS Concept

- The initially strong decrease in hazardous effects with modest increases in separation distance will often justify increased capital cost.

- Generous spacing also offers important benefits in crane and other maintenance access, ergonomic advantages, and decreased risk of incident escalation.

- Future plant expansions or process improvements are also facilitated by increased spacing, although expansions that decrease spacing may increase hazardous effects.
Different IS Concepts are Best Applied at Different Stages of a Process Plant Development

- Although inherently safer checklists are often used at the screening Process Hazards Analysis (PHA) level, much more is needed throughout the development and design of a process plant.
- Substitute is best done during the product and process research phases before significant investment in a particular product and process to produce it.
- Hybridize or Transform is also best done during process research and development, as is Moderate.
- Minimize, Simplify, and Error Tolerance are all optimum during the process development, conceptual design, and detail design phases.
- Stabilize or Ensure Dynamic Stability is also best done during design development.
- Limitation of effects, which is closely related to passive protection, has its greatest impact during development of the plot plan and equipment arrangement.
Tools for Inherently Safer Process Plant Design

- Process hazards reviews
- Chemical interaction matrices
- Dow Fire & Explosion Index and Chemical Exposure Index
- Fire, explosion, and toxic release consequence modeling and risk assessments
- Layer of protection analysis
- Spacing tables for units and for process equipment
- Dynamic process simulation
- Inherent safety analysis
- Periodic design reviews during product and process research, development, and design
More Tools for Inherently Safer Process Plant Design

- Reviews of plant siting, plot plan, equipment arrangement, and 3-D computer models
- Occupied building evaluation and design
- Area electrical classification
- Safety integrity level assessments and safety instrumented systems
- Human factors reviews
- Ergonomics reviews
- Safety case development
- The design process itself
Summary and Conclusions

- Methods for inherently safer design of process plants have been advanced by many able contributors since it was proposed by Trevor Kletz in 1977.
- Inherently safer design has proven very valuable previously in risk reduction in the process industries.
- Three new or neglected inherently safer design concepts have been presented here:
  - Hybridize or Transform
  - Stabilize or Ensure Dynamic Stability
  - Limit Hazardous Effects
- Inherently safer process concepts should be applied throughout the process plant life cycle.
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