Safety Through Design in the Chemical Process Industry: Inherently Safer Process Design

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Abstract

In the last 50 years the chemical process industries have moved to large, world scale plants. Because of their size, these plants have an increased potential for major accidents. Recognizing this potential, the industry incorporated many engineered safety features into these plants to manage and control the hazards, and this effort has been successful in producing an excellent safety record. However, failures of these systems do occur on occasion, and these failures can result in major accidents. In recent years there has been an increased effort to develop *inherently safer* chemical processes, focusing on changing the process to *eliminate* the hazard, rather than on accepting the hazard and developing "add-on" design features to control it. Design approaches to inherently safer chemical process design will be discussed, including examples of inherently safer design. Some tools for measuring the inherent safety characteristics of chemical manufacturing processes will also be described.

Introduction

Since World War II, the chemical industry has seen a continuing trend toward the construction of larger and larger plants, to take advantage of the economies of scale in an increasingly competitive and global industry. This trend has increased the potential magnitude of accidents which could occur in these large plants, both in terms of risk to employees and surrounding communities and also in terms of the potential economic and business loss in case of an accident. Therefore, the industry has devoted significant resources to managing the risks associated with large plants and hazardous materials and processes. Much of this effort has focused on adding safety devices and features to reduce the likelihood and severity of potential accidents. In 1978, Kletz (1978) proposed a different approach - rather than adding on safety devices and controls to manage hazards, why not change the basic technology to eliminate the hazard from the process? The process would be "inherently safer", rather than relying on add-on safety features. Since 1978 the industry has increasingly recognized the importance of the inherently safer design approach, and has extended the concept to include safety, health, and environmental (SHE) characteristics of chemical manufacturing processes. Several excellent introductions to inherently safer chemical processes have been published (Kletz, 1991; CCPS, 1993a; IChemE and IPSG, 1995; Bollinger, et. al., 1996).

Inherent Safety

A chemical manufacturing process is described as **inherently safer** if it reduces or eliminates hazards associated with materials and operations used in the process, and this reduction or elimination is a permanent and inseparable part of the process technology. A hazard is defined as a physical or chemical characteristic that has the potential for causing harm to people, the environment, or property (adapted from CCPS, 1992). The key to this definition is that the hazard is intrinsic to the material, or to its conditions of storage or use. For example, chlorine is toxic by inhalation, gasoline is flammable, and steam at 600 psig contains significant potential energy. These hazards are basic properties of the materials and the conditions of usage, and cannot be changed. An inherently safer process reduces or eliminates the hazard by reducing the quantity of hazardous material or energy, or by completely eliminating the hazardous agent.

A traditional approach to managing the risk associated with a chemical process is by providing layers of protection between the hazardous agent and the people, environment, or property which is potentially impacted. This approach is illustrated in Figure 1 (CCPS, 1993b; Bollinger, et. al., 1996). The protective layers may include one or more of the following:

- The process design
- Basic controls, alarms, and operator control
- Critical alarms, operator control, and manual intervention
- Automatic actions — emergency shutdown systems and safety interlock systems
- Physical protection equipment such as pressure relief devices
- Physical mitigation systems such as spill containment dikes
- Emergency response systems — for example, fire fighting
- Community emergency response — for example, notification and evacuation

The layers of protection are intended to reduce risk by reducing either the likelihood of potential incidents resulting in an impact on people, the environment, or property, or by reducing the magnitude of the impact should an incident occur. The risk can be reduced to very low levels by providing a sufficient number of layers of protection, and by making each layer highly reliable (Figure 2). However, the basic process hazards remain, and there is always the potential — perhaps very small, but never zero — that all layers will fail simultaneously and the hazardous incident will occur. Furthermore, the layers of protection require significant expenditure of resources, both to design and build them initially, and to maintain their reliability throughout the life of the plant. Failure to adequately maintain the layers of protection may result in a significant increase in the process risk (Figure 3).

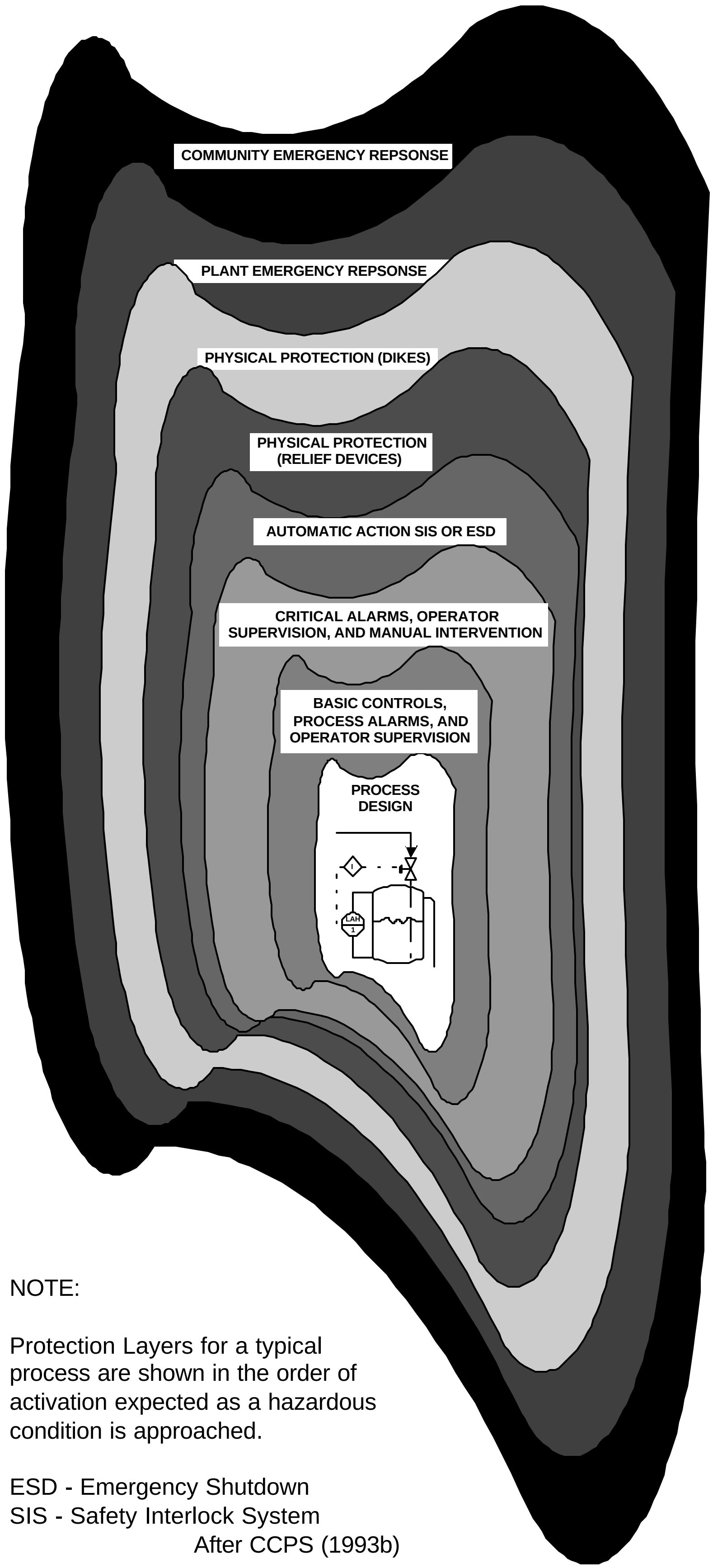

Figure 1: Typical Layers of Protection for a Chemical Manufacturing Process

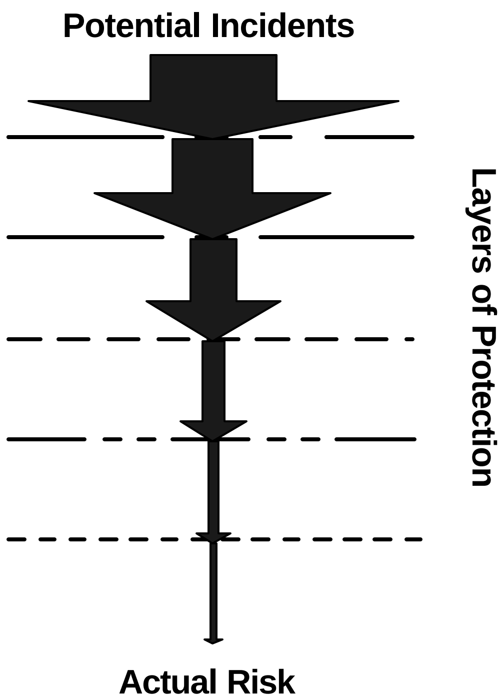

Figure 2: Risk Reduction Resulting from Safety Layers of Protection

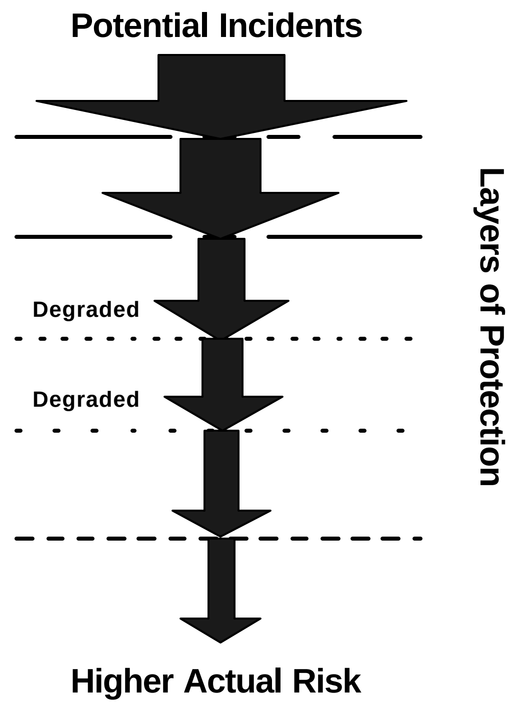

Figure 3: Reduced Effectiveness of Degraded Layers of Protection

The inherently safer design approach is to eliminate or reduce the hazard by changing the process itself, rather than by adding on additional safety devices and layers of protection. Ideally, hazards would be reduced to a level where no protective systems are required because the hazard is too small to be of concern (Figures 4 and 5). Even if this is not possible, an inherently safer process will allow the number of layers of protection to be reduced. The overall design is therefore more robust from a safety and environmental viewpoint, and is likely to be less expensive to build and operate because of the elimination of complex safety systems.

Relationship to Safety in Design

Safety in Design can be based on either of the approaches described. Add-on safety features and layers of protection can be identified and incorporated during design. In fact, they should be incorporated into the process design — we should anticipate potential accidents during design and provide the appropriate protective systems, procedures, and devices, rather than discovering the need for these layers of protection later on as a result of accidents and near misses.

However, the greatest potential for realizing an inherently safer process design is early in development. At this time, the designer still has considerable freedom in technology selection. For a chemical process, perhaps the greatest opportunities lie in the selection of the chemical synthesis route to be used, including the raw materials, solvents, chemical intermediates, reaction steps, and other physical and chemical operations to be used.

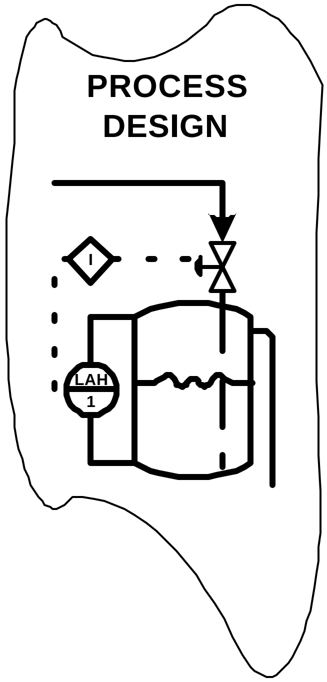

Figure 4: An Inherently Safer Process Requiring No Additional Layers of Protection

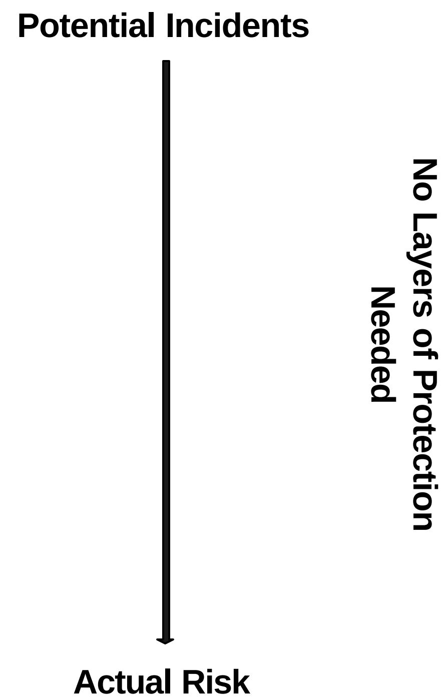

Figure 5: Incident Risk for the Inherently Safer Process

However, it is important to remember that it is never too late to consider inherently safer design options. In an existing plant, there will be different kinds of opportunities for modifications to improve inherent safety, but these opportunities can result in significant improvements. It may not be feasible to change the basic process chemistry and technology, but it may be possible to reduce inventory, simplify the plant, or otherwise make the plant more "user friendly." Significant improvements in the inherent safety of plants which have operated for many years have been reported (Wade, 1987; Carrithers, et. al., 1996; Gowland, 1996).

Approaches to Inherently Safer Design in the Chemical Industry

Chemical process risk management approaches can be classified into four categories:

- ***Inherent*** — Eliminating the hazard by using materials and process conditions which are non-hazardous.
- ***Passive*** — Minimizing the hazard by process and equipment design features which reduce either the frequency or consequence of the hazard without the active functioning of any device.
- ***Active*** — Using controls, safety interlocks, and emergency shutdown systems to detect and correct process deviations. These systems are commonly referred to as engineering controls.

- ***Procedural*** — Using operating procedures, administrative checks, emergency response, and other management approaches to prevent incidents, or to minimize the effects of an incident.

Marshall (1990) categorizes risk management strategies as strategic and tactical. Strategic approaches include measures which have "wide significance, and which represent a 'once and for all' policy decision." Inherent and passive approaches tend to fall into the "strategic" category. Tactical approaches include measures "which are added on at a late state or those which entail frequent repetition." Active controls and procedural approaches tend to be "tactical." Safety in Design can entail both strategic and tactical risk management approaches, but the greatest benefits are realized from the early consideration of strategic risk management measures.

There are four basic strategies for implementing inherently safer chemical processes:

- ***Minimize*** — Use smaller quantities of hazardous substances
  - ♦ Continuous reactors (stirred tanks, loop reactors, tubular reactors) in place of batch reactors
  - ♦ Reduced inventory of raw materials and in-process intermediates
  - ♦ High efficiency heat exchangers

  Example: A 50-liter loop polymerization reactor has a capacity equal to that of a 5000-liter batch reactor (Wilkinson and Geddes, 1993).

- ***Substitute*** — Replace a material with a less hazardous substance
  - ♦ Water based paints and coatings
  - ♦ Alternative chemistry using less hazardous materials
  - ♦ Less flammable or toxic solvents

  Example: Acrylic esters were formerly manufactured using the Reppe process, using acetylene, carbon monoxide, and a nickel carbonyl catalyst. The newer propylene oxidation process uses significantly less hazardous materials (Hochheiser, 1986).

- ***Moderate*** — Use less hazardous conditions, a less hazardous form of a material, or facilities which minimize the impact of a release of hazardous material or energy
  - ♦ Dilution
  - ♦ Refrigeration of volatile hazardous materials
  - ♦ Granular agricultural product formulations in place of powders

  Example: The distance to an atmospheric concentration of 500 ppm of mono-methylamine in the event of the failure of a 2-inch pipe is reduced from 1.9 miles to 0.6 miles by reducing the temperature of the monomethylamine from 10ºC to -6ºC (Carrithers, et. al., 1996).

- ***Simplify*** — Design facilities which eliminate unnecessary complexity and make operating errors less likely, and which are forgiving of errors which are made
  - ♦ Develop fundamentally simpler technology with fewer reactions and processing operations

- ♦ Eliminate unnecessary equipment (question need for each device or feature)
- ♦ Remove unused or abandoned equipment
- ♦ Human factors considerations in design

Example: Design vessels to withstand the maximum pressure which can be generated, rather than providing complex emergency relief systems, including devices such as scrubbers, catch tanks, or flares to contain the relief system effluent.

Kletz (1991), CCPS (1993a), and Bollinger, et. al. (1996) give a number of specific examples of the implementation of each of these strategies in the chemical industry.

Examples of Inherently Safer Design from Outside the Chemical Industry

The concepts of inherently safer design apply outside the chemical industry as well. In fact, these examples are sometimes very useful in explaining the idea to engineers and others in the chemical industry, because they often relate to everyday life experiences and are easily understood. Some examples include:

- Railroad crossings
  - ♦ Procedural — Warning signs with operator training
  - ♦ Active/Procedural — Warning lights and audible alarms, with operator training
  - ♦ Active — Automatically activated crossing gates
  - ♦ Inherent — Grade separation
- Architecture — Falling down the steps is a common injury in the home. Single story houses eliminate the danger.
- Soda cans — When the "pop top" soda cans were first developed, the opening tab was separated from the can upon opening. The tabs were thrown on the ground or sometimes placed in the can, with obvious injury potential. In a modern pop top can, the tab remains attached when the can is opened.
- Lawn mowers — The string trimmer is an inherently safer device than the steel bladed rotary lawn mower (limitation of effects).
- Control of a transport vehicle — Consider the difference in difficulty of directional control of various types of transportation vehicle, and relate that to the complexity of the systems required:
  - ♦ Train — control in one dimension (forward–backward)
  - ♦ Bus — control in two dimensions (forward–backward and left–right)
  - ♦ Helicopter — control in three dimensions (forward–backward, left–right, and up–down)
  - ♦ Now consider the difficulties in controlling a time machine!
- Writing utensils — This is not a safety example, but it does illustrate the concept of simplification. The standard ball point pen does not work well in a zero-gravity environment. Therefore, in the course of the United States space program, the high tech "space pen" was

developed. It worked very well, and is commonly available today. The space program of the Soviet Union was more cost conscious, and could not afford to devote scarce resources to such a development. The cosmonauts used pencils. We should always be asking if a simpler tool will do the job.

Design Conflicts and Trade-Offs

Engineering design is the art of compromise. Design objectives are often in conflict, and may be mutually exclusive. The designer must choose which of the alternative solutions has the best overall balance of characteristics with respect to all of the design objectives. This is also true in considering inherently safer processes.

In general, chemical processes have a number of different hazards. Ideally, we would like to identify inherently safer process alternatives which simultaneously reduce or eliminate all of the potential hazards. Unfortunately, in the real world this seldom, if ever, occurs. A process alternative which is safer with respect to one hazard may increase other hazards. For example, one process solvent may be non-flammable and toxic. An alternative solvent is flammable and non-toxic. Which is inherently safer? There is no general answer. The designer must identify and consider all of the hazards and apply appropriate decision making tools to identify the best overall solution.

Understanding safety trade-offs can be difficult, but not nearly so difficult as understanding trade-offs among less closely related design criteria. For example, how do you compare a process which reduces waste generation and potential environmental contamination, but uses a very toxic chemical intermediate, to an alternative process which uses less hazardous materials but generates more waste? There is no "correct" answer to this type of question — ultimately it is a question of values. Decision analysis tools are appropriate for consideration of this type of question (CCPS, 1995). Measurement of inherent safety characteristics, which will be discussed in the next section, is a key element in good decision making.

Metrics for Inherent Safety

How do you measure inherent safety? The chemical industry is just beginning to develop tools for measuring inherent safety. Some of these tools have been used for risk management and loss prevention for some time, but we are just beginning to recognize their value in understanding the inherent safety of processes.

Accident Consequence Analysis

The analysis of the potential consequences of an accident is a useful way of understanding the relative inherent safety of process alternatives. These consequences might consider, for example, the distance to a benchmark level of damage resulting from a fire, explosion, or toxic material release. The Rohm and Haas Major Accident Prevention Program (MAPP) (Renshaw, 1990) encourages inherently safer process development by requiring accident consequence analysis for a standard list of potential chemical process accidents for a specified list of high hazard chemicals. Accident consequence analysis is of particular value in understanding the benefits of minimization, moderation, and limitation of effects. Table 1 illustrates the use of consequence analysis as a metric for understanding the benefits of a number of inherently safer process options.

Table 1: Examples of Potential Accident Consequence Analysis as a Measure of Inherent Safety

Inherent Safety Strategy	Description	Consequence
Minimize	Chlorine transfer line rupture — distance to 20 ppm atmospheric concentration, D atmospheric stability, 3.4 mph wind speed	2-inch line - 3.4 miles 1-inch line - 1.2 miles
	Explosion overpressure 100 feet from a reactor	3000 gallon batch reactor - 1.1 psig 50 gallon continuous reactor - 0.3 psig
Substitute	Concentration in the atmosphere 500 feet downwind from a large spill from a storage tank, D atmospheric stability, 3.4 mph wind speed	Methanol - 1000 ppm Butanol - 130 ppm
Moderate	Distance to 500 ppm atmospheric concentration for a large spill of monomethylamine, D atmospheric stability, 3.4 mph wind speed	Stored at 10ºC — 1.2 miles Stored at 3ºC — 0.7 miles Stored at –6ºC — 0.4 miles
	Concentration in the atmosphere 500 feet downwind from a large spill from a storage tank containing methyl acrylate, D atmospheric stability, 3.4 mph wind speed	2500 sq. ft. concrete containment dike — 1100 ppm 100 sq. ft. concrete containment pit — 830 ppm

Risk Indices

A number of risk indices have been developed over the years as chemical process loss prevention and risk management tools. Many of these are based on the inherent characteristics of the processes, and they can be used as measures of process inherent safety. In general, these indices measure a single aspect of inherent safety, and it is necessary to use several indices to obtain a full understanding of the overall process characteristics.

The Dow Fire and Explosion Index (FEI) (Dow, 1994a) and the Dow Chemical Exposure Index (CEI) (Dow, 1994b) are two commonly used tools which measure process inherent safety characteristics. Gowland (1996) reports on the use of the FEI and CEI in the development of safety improvements for a urethane plant. Table 2 shows the results of the FEI calculation for several processes where alternative designs were feasible. Table 3 (from Dow, 1994b) shows the difference in the CEI for the failure of a 2-inch pipe for a number of different chemicals.

Table 2: Fire and Explosion Index for Process Options

Operation	Options	Fire and Explosion Index
Ethyl Acrylate Storage	2 million lb. inventory	151
	200,000 lb. inventory	130
	50,000 lb. inventory	120
Ethylene oxide storage	Location A	230
	Location B	190
Agricultural Product Reaction	Batch Process A	185
	Batch Process B	180
	Continuous Process	145
Acrylic Acid Warehouse Storage	Location A	87
	Location B	90

Table 3: Chemical Exposure Index for a 2-Inch Pipe Failure (from Dow, 1994b)

Chemical	State	Chemical Exposure Index
Hydrogen Chloride	Liquid	1000
	Gas	610
Chlorine	Liquid	1000
	Gas	490
Ammonia	Liquid	380
	Gas	100
Butadiene	Liquid	290
	Gas	100
Vinyl Acetate	Liquid	40
	Gas	10

These indices measure the inherent safety characteristics of processes in only two specific areas — fire and explosion hazards and acute chemical inhalation toxicity hazards. Other indices are required to evaluate other types of hazards. Rohm and Haas is beginning to use five different indices to measure various inherent process risks at an early stage in design (Hendershot, 1997). These include:

- Dow Fire and Explosion Index (Dow, 1994a) — Fire and explosion hazards
- Dow Chemical Exposure Index (Dow, 1994b) — Acute chemical exposure hazards
- In-house Chronic Exposure Index — Long term chemical exposure hazards

- Environmental Risk Management Screening Tool (ERMST®) from Four Elements, Inc. (ERMST, 1996) — Environmental hazards, including air, ground water, surface water (human), surface water (ecological), and waste water
- Transportation Risk Screening Model (ADLTRS®) from Arthur D. Little, Inc. (ADLTRS, 1994) — risk to people and the environment from chemical transportation operations

These indices can be calculated fairly quickly for each of a number of process options and design variations. Each gives a unitless risk index value, which only has meaning relative to other indices calculated using the same tool. The indices can then be used for ranking the various options relative to the various safety and environmental characteristics. The index values are then used along with a decision analysis tool (we are currently using a weighted scoring method [CCPS, 1995]) to determine which of the process options best meets the overall needs and priorities of the process designer.

The INSIDE Project Toolkit

The INSIDE (INherent SHE In DEsign) Project is a European government/industry project sponsored by the Commission of the European Community to encourage and promote inherently safer chemical processes and plants (INSIDE Project, 1997). The INSIDE Project expands the inherent safety concept to include inherent approaches to Safety, Health, and Environmental (SHE) aspects of chemical processes. The project has developed a set of tools, the INSET Toolkit, to identify inherently safer design options throughout the life of a process, and to evaluate the options. Table 4 summarizes these tools, and they are described in more detail by the INSIDE Project (1997).

Table 4: Summary of INSET Tools (INSIDE Project, 1997)

Tool	Description
A	Detailed Constraints and Objectives Analysis
B	Process Option Generation
C	Preliminary Chemistry Route Options Record
D	Preliminary Chemistry Route Rapid ISHE Evaluation Method
E	Preliminary Chemistry Route Detailed ISHE Evaluation Method
F	Chemistry Route Block Diagram Record
G	Chemical Hazards Classification Method
H	Record of Foreseeable Hazards
I	ISHE Performance Indices
J	Multi-Attribute ISHE Comparative Evaluation
K	Rapid ISHE Screening Method
L	Chemical Reaction Reactivity - Stability Evaluation
M	Process SHE Analysis - Process Hazards Analysis, Ranking Method
N	Equipment Inventory Functional Analysis Method
O	Equipment Simplification Guide
P	Hazards Range Assessment for Gaseous Releases
Q	Sting and Plant Layout Assessment
R	Designing for Operation

Table 5: INSET Toolkit Inherent SHE Performance Indices (INSIDE Project, 1997)

Index	Description
I.1	Fire and Explosion Hazard Index
I.2	Acute Toxic Hazard Index
I.3	Inherent Health Hazard Index
I.4	Acute Environmental Hazard Index
I.5	Transport Hazards Index
I.6	Gaseous / Atmospheric Emissions Environmental Index
I.7	Aqueous Emissions Environmental Index
I.8	Solids Emissions Environmental Index
I.9	Energy Consumption Index
I.10	Reaction Hazards Index
I.11	Process Complexity Index

The tools of particular interest with regard to metrics for measuring the inherent safety of chemical processes are the ISHE Performance Indices listed in Table 5 (Tools I.1 through I.11). The ISHE Performance Indices are relatively simple, intended for hand or simple calculator computation, so that a large number of process options can be rapidly evaluated. The various inherent safety, health, and environmental aspects of a process are evaluated using separate indices, and no attempt is made to combine the indices into a single overall measure. The INSET Toolkit instead recommends a multiattribute decision analysis technique to evaluate the overall inherent SHE aspects of the various process options. The INSET Toolkit is in the final stages of development, and will be available for evaluation and use in the summer of 1997 from INSIDE Project sponsors. The INSET Toolkit is particularly interesting as an Inherent SHE measurement tool because it represents the consensus combined expertise of a number of companies and organizations, and because it is intended to consider safety, health, and environmental factors in one set of tools.

Overall Inherent Safety Index

Some initial work on the development of an overall inherent safety index has been done at Loughborough University in the United Kingdom (Edwards and Lawrence, 1993; Edwards, et. al., 1996). A number of factors related to inherent safety are evaluated, including:

- Inventory
- Flammability
- Explosiveness
- Toxicity
- Temperature
- Pressure
- Process yield

A single number overall index characterizing the inherent safety of the overall process is generated. The relative contributions of the various components of the index to the total value may also be useful in understanding the process characteristics. This index is considered a prototype by the developers, and more work will be needed. Table 6 summarizes the application of this proposed inherent safety index to a number of alternative routes for the manufacture of methyl methacrylate.

Table 6: Evaluation of Six Alternate Manufacturing Processes for Methyl Methacrylate Using a Proposed Inherent Safety Index (from Edwards and Lawrence, 1993)

Process Route	Inherent Safety Index
Acetone cyanohydrin	~120
Ethylene based/propionaldehyde	~75
Propylene based	~70
Ethylene based/methyl propionate	~50
Isobutylene based	~50
Tertiary butyl alcohol based	~50

Summary

Inherent SHE represents a fundamentally different approach to Safety in Design. The objective becomes to eliminate or reduce hazards by changing the basic technology, rather than by adding safety devices and other layers of protection to a control hazards. While it is possible to reach a desired degree of safety using either approach, safety devices and layers of protection add significant cost to a chemical plant over its life cycle. Furthermore, the hazard is still present, and there is always the potential for an accident due to simultaneous failure of several layers of protection, or degradation of the layers of protection in the future. For many chemical processes, the inherent SHE approach to Safety in Design represents the most cost effective and robust approach.

The chemical industry is beginning to develop tools to measure inherent SHE characteristics of processes. Measurement tools which can be quickly and easily used early in the life cycle of the process design are particularly important, because that is the time at which the designer has the greatest opportunity to change the basic process technology. A number of measurement tools have been developed in the past few years, and the applicability of several existing tools (for example, the Dow Indices) to the understanding of inherent SHE has been recognized. There is still a more work to do in this area, in calibrating tools which have been developed, improving them, and better understanding how they can be applied in the real world.

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