INHERENTLY SAFER DESIGN ACTIVITIES OVER THE PAST DECADE

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This paper identifies significant developments in the field of inherently safer design over the previous decade (roughly from the late 1990s to the present). The paper is therefore a review of the literature on inherent safety over this time period, and is organized into eight major topics: (i) the positioning of inherent safety within the hierarchy of controls, (ii) major reviews of the subject area, (iii) process intensification, with an emphasis on reactors and unit operations, (iv) examples of the application of inherent safety principles other than intensification (e.g., substitution), (v) measurement of the level or degree of inherent safety, (vi) the relationship between inherent safety and process safety management, including safety culture, (vii) the role of inherent safety in dust explosion prevention and mitigation, and (viii) case studies of incidents where a lack of inherent safety considerations played a role in causation.

KEYWORDS: Inherent safety, inherently safer design, intensification, substitution, attenuation, simplification

"The time has come," the Walrus said.

–Lewis Carroll, *The Walrus and the Carpenter*

INTRODUCTION

The purpose of this paper is to review various developments that have occurred in the field of inherently safer design during the past ten-year period. This timeframe corresponds roughly to the interval between publication of *Process Plants: A Handbook for Inherently Safer Design* by Kletz (1998) and the present, at which time the book is being revised for a second edition. The revised material forms the basis of the current paper.

The work reported here does not represent the only significant activities in the field of inherent safety over the past decade. Further, space limitations preclude referencing all archival papers and conference presentations that have been identified. Nevertheless, it is hoped that readers will gain an appreciation of how far the concept of inherent safety has moved from being common sense (which it has always been), to common knowledge (which it likely is now), to common application (which it is approaching).

HIERARCHY OF CONTROLS

Inherently safer plants are those which are designed and operated according to the systematic approach to loss prevention illustrated in Fig. 1. With this approach, the preferred order of consideration for risk reduction measures is – from most to least effective – inherent safety (with its various principles), passive engineered safety, active engineered safety, and procedural safety. Andrew Hopkins uses the phrase *hierarchy of controls* to describe essentially the same idea; i.e., there is a hierarchical ordering of controls to deal with hazards and the ensuing risk (Hopkins, 2005). This hierarchy covers the spectrum from elimination (at the top of the hierarchy) through engineering and administrative (procedural) controls, to PPE (personal protective equipment) at the bottom of the hierarchy. Manuele (2005) calls this sequence the *safety decision hierarchy*.

The ranking of safety measures is not a new idea. However, increasing use of the term *hierarchy of controls* does at least two things, both of which help to advance the use of inherent safety principles in process design. First, the hierarchy clearly indicates that inherent safety is not a stand-alone concept. Inherent safety works through a hierarchical arrangement in concert with engineered (passive and active) and procedural safety to reduce risk. Second, the hierarchy of controls does not invalidate the usefulness of engineered and procedural safety measures. Quite the opposite – the hierarchy of controls recognizes the importance of engineered and procedural safety by highlighting the need for careful examination of the reliability of both mechanical devices and human actions. These considerations must therefore be incorporated into the overall process of risk assessment.

SUBJECT AREA REVIEWS

There has been an increasing recognition over the past decade that the principles of inherent safety have a key role to play in the field of environmental process engineering. More broadly, the integration of environmental (E) with health (H) and safety (S) concepts is clearly a topical issue in process engineering research and practice. It is important to adopt a life-cycle approach when dealing

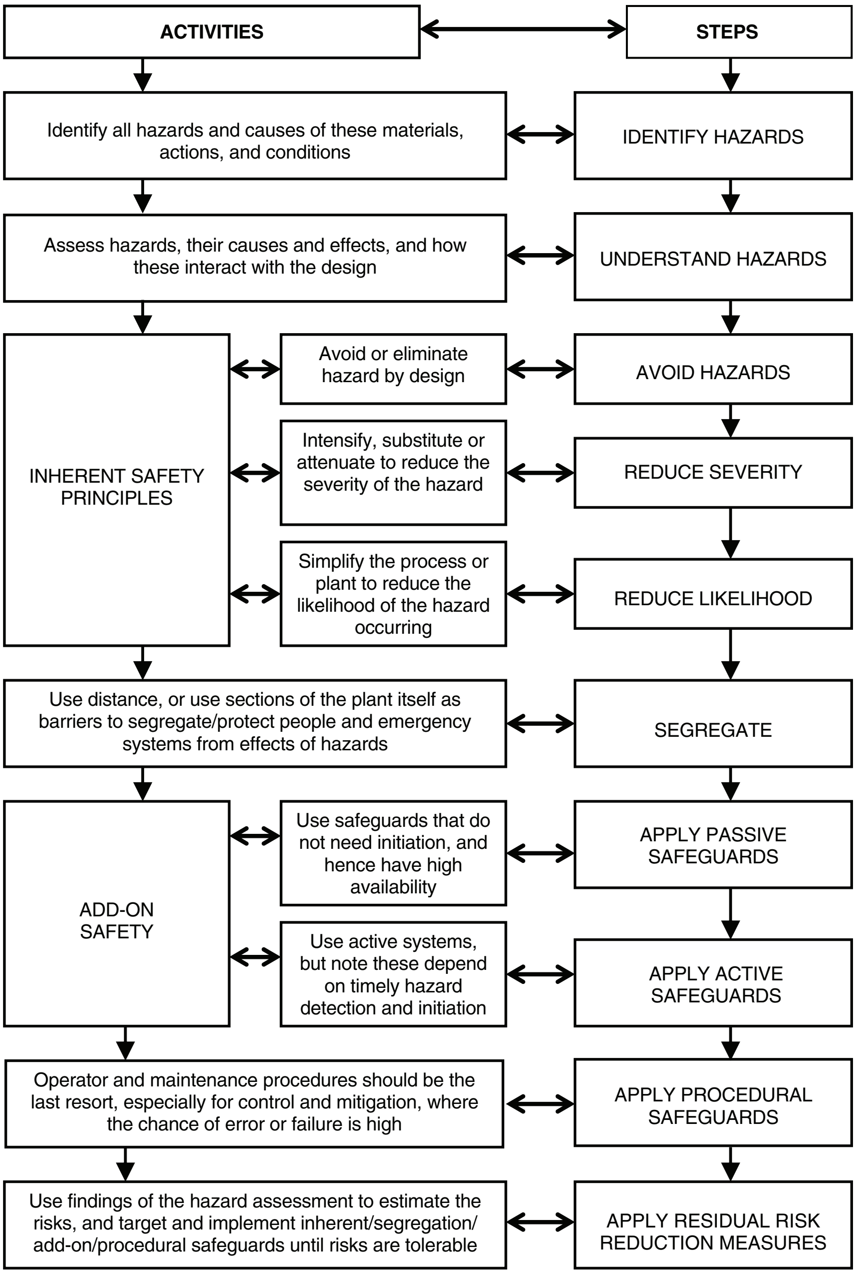

Figure 1. A systematic approach to loss prevention (hierarchy of controls)

with EHS integration throughout all phases of plant design, construction, operation and shutdown. A publication of the American Institute of Chemical Engineers (CWRT/CCPS, 2001) highlights the benefits to be gained by integrating the concepts afforded by various paradigms within the EHS field. See Table 1 from CWRT/CCPS (2001).

The scope of inherently safer design is thus seen to extend throughout the process design life cycle. This is a recurrent theme in the numerous inherently safer design resource publications that have appeared in the literature over the past ten years or so (Hendershot, 1997, 2006; Gupta and Edwards, 2002; Khan and Amyotte, 2003; Kletz, 2003; Edwards, 2005; Moore et al., 2006, 2008; Green and Perry, 2008; CCPS, 2009). These various review articles and texts contain a wealth of examples of inherent safety application.

PROCESS INTENSIFICATION

The term *Process Intensification (PI)* has become firmly established in the vocabulary of chemical process engineering researchers and practitioners. Process intensification

Table 1. Paradigms available for integration within an EHS framework

Paradigm	Safety	Health	Environment
Inherent safety	✓✓✓	✓✓	✓
Pollution prevention		✓	✓✓✓
Green chemistry	✓✓	✓	✓✓✓
Green technology	✓		✓✓✓
Design for the environment		✓	✓✓✓

✓✓✓ = Primary focus; ✓✓ = Secondary focus; ✓ = Directly linked benefit

results in substantial improvements in the scale, cleanliness, energy efficiency, cost effectiveness, and safety of units designed to effect physical changes or molecular transformations in materials. Size reduction of unit operations and chemical plants is a key goal of process intensification.

Quoting from the publisher's description of the latest book in this area, "PI . . . is now reaching a maturity that is seeing (these) concepts applied to a wide range of processes and technologies." (Reay et al., 2008). Evidence of the maturity of process intensification can be found in the existence of a journal devoted to advances in the field (*Chemical Engineering and Processing: Process Intensification*), as well as a *Process Intensification Network* (2009), organized by the authors of Reay et al. (2008) and hosted by Newcastle University, UK.

The motivation for process intensification often comes from the economic side of the business equation. In today's world, the economic need for PI is being increasingly framed within the context of global competitiveness and sustainable development (Charpentier, 2007, 2009). Sometimes, however, the driving force behind PI is the attendant safety benefits, as seems the case with the recent IMPULSE project (Integrated Process Units with Locally Structured Elements) described by Khoshabi and Sharratt (2007). In this work, smaller and more efficient devices such as microreactors and compact heat exchangers are expected to present a lower risk of fire and explosion, as well as fewer harmful emissions, than traditional plant equipment.

Khoshabi and Sharratt (2007) concludes with the statement that while major releases and hazards are less likely for IMPULSE plants, the potential for operator exposure and minor problems (e.g. pump leakage) may be greater. This remark is a helpful reminder that inherent safety involves both change, which must be managed, and tradeoffs, which must be assessed. No single approach can be expected to cover all issues that arise during process design and operation. In this regard, Etchells (2005) has provided a useful listing of the potential problem areas, as well as the benefits, of process intensification.

Potential safety benefits of process intensification include the following (Etchells, 2005):

- Reduction of inventories of hazardous materials and the consequences of process failures.
- Reduction in the number of process operations, leading to fewer transfer operations and less pipework (thus reducing leakage).
- Containment of explosion overpressures in smaller vessels, so that passive and active devices (e.g. rupture disks and automatic suppression systems, respectively) may not be needed.
- Reduction in the number of process incidents during transient conditions because of fewer startups and shutdowns with continuous, intensified plant.
- Less variable (and easier-to-control) heat evolution than in batch reactors when dealing with exothermic reactions.
- Easier-to-achieve heat transfer because of the enhanced specific surface area of continuous, intensified plant, thus reducing the potential for runaway reactions.

Potential safety issues related to process intensification include the following (Etchells, 2005):

- Requirement for high temperatures and pressures, and high-energy inputs. For example, the use of microwaves has been reported in intensified desorption processes for the regeneration of adsorbents used in the control of organic vapour emissions (Cherbanski and Molga, 2009).
- Increase in process complexity and an accompanying increase in the complexity of control systems.
- Heightened concerns with respect to control and monitoring due to shorter residence times for many intensified processes.
- Higher potential for equipment failure or operator error if the process pipework becomes more complex.
- Increased rate of energy release due to enhanced reaction rates as a result of improved mixing.
- Introduction of a new ignition source with the combination of rotating equipment and friction sensitive materials.
- Overheating of thermally unstable materials on complex heated surfaces subject to fouling.
- High throughput leading to the possibility of rapid accumulation downstream of off-spec products.
- Closer proximity of people to smaller plant.

Not all of the above benefits, nor all of the concerns, will occur in a given application of process intensification. They remind us, however, that assessment and management of process risks are comprehensive undertakings that are crucial to any commercial endeavour, and that tradeoffs are often presented by inherent safety application. These points are evident in the many process intensification efforts described in the literature for various unit operations such as heat exchange and distillation, as well as for chemical reactors (often combined with heat exchange). Some reactor examples from the recent process development and process safety literature will serve as illustrations.

Benaissa et al. (2008) describe a type of continuous heat exchanger-reactor known as an open plate reactor (OPR). The reaction system studied was the esterification of propionic anhydride by 2-butanol to yield butyl propionate and propionic acid. They used a combination of kinetic modelling and experimentation to determine temperature and concentration profiles during the synthesis reaction and to decide on optimal operating conditions that could be adequately controlled. By changing from a batch to a continuous processing mode, this heat exchanger-reactor design leads to smaller inventories and therefore minimization of the consequences of a hazardous release. A HAZOP study was also used to investigate accident scenarios leading to runaway reaction. The study revealed that in the case of simultaneous stoppage of both process and utility flows, the stainless steel sandwich and reaction plates helped to dissipate some of the energy released by the reaction (thereby offering additional thermal mass as an inherent characteristic of the apparatus).

A similar improvement in inherent safety can be accomplished by a switch from batch to continuous processing in a spinning disk reactor (SDR), as described by Boodhoo and Jachuck (2000). In this particular type of thin-film reactor, styrene was polymerized using centrifugal acceleration to create highly sheared films of thickness 100 μm–200 μm on a rotating surface. From the perspective of the simplification principle, there is additional complexity because of the introduction of moving parts. While this may on the one hand be viewed as a disadvantage (Reay et al., 2008), Boodhoo and Jachuck (2000) comment that the rotational speed can also be seen as an additional parameter for control of reaction rate and product quality.

The safety aspects of membrane reactors have recently been reviewed by Chiappetta et al. (2006), who describe these devices as being capable of taking advantage of the synergistic effects of separation and reaction in a chemical process. In some applications the membrane serves to provide a controlled feed of a given reactant, thus improving reagent distribution, maintaining a low concentration level and avoiding side reactions.

This is the case for gas-phase oxidation of hydrocarbons, in which the gradual feeding of oxygen through a membrane avoids the formation of hot spots and limits the likelihood of reaction runaway (Coronas et al., 1995). In the porous-wall ceramic membrane reactor (PWCMR) described by Coronas et al. (1995), oxygen is supplied as it is consumed and thus the reactor can be operated outside the flammability range of the oxygen/hydrocarbon mixture while maintaining a sufficiently high conversion. Attenuation of reaction conditions is therefore achieved in addition to intensification of hazardous inventories.

Another reactor classification discussed by Reay et al. (2008) is the microreactor. Microreactor technology dates from the 1970s (DeWitt, 1999), but it has been over the last decade that these devices have made the transition from laboratory tools to production reactors in the chemical process industries (Fischer et al., 2009). Burns and Ramshaw (1999) describe a benzene nitration reactor in which rapid mass transfer can be accomplished by stable parallel flow in capillaries of bore size between 127 μm and 254 μm. The integration of heat exchange with chemical reaction has also been achieved with a micro-structure combination used for fuel processing (Kolb et al., 2007).

Inherently safer operation of microreactors is of course brought about by reduction of the inventory of the reacting mixture. This advantage can manifest itself in different ways. For example, microreactors are generally characterized by a high surface-area to volume ratio, which if large enough can significantly increase the time to reaction runaway (de Graaf and Tikku, 2007). Additionally, the narrow diameter of flow channels facilitates use of the quenching distance concept for determination of maximum safe capillary diameters in gas-phase oxidation reactors, as evidenced by the work of Fischer et al. (2009) with stoichiometric ethane/oxygen mixtures.

EXAMPLES OF OTHER INHERENT SAFETY PRINCIPLES

Intensification remains the inherent safety principle most often applied in industry and appearing in the archival and conference literature. Examples of the usage of other inherent safety principles are also evident, such as:

- *Substitution* of materials of construction – use of electro-conductive, corrosion resistant plastics to reduce risk of electrostatic ignition (Astbury and Harper, 2001).
- *Substitution* of process route – comparison of thermal characteristics of two different nitration systems to determine inherently safer route from a thermal process safety perspective (Venugopal and Kohn, 2005).
- *Attenuation* of material hazard – growing carbon nanotubes on aluminum oxide carriers (Horng, 2007).
- *Limitation of Effects* by equipment design – mitigating offsite impacts of release of a toxic and flammable liquid by installation of a revised dike around the storage tank, thus reducing the surface area available for evaporation by 60 % (Ferguson, 2004).
- *Simplification* by using stronger equipment – burst-resistant design of pressure vessels for wide range of service at varying pressure, temperature and corrosivity (Zhu and Shah, 2004).
- *Avoiding Knock-On Effects* – comprehensive facility siting and plant layout considerations for avoidance of domino effects. This topic has received considerable attention since the BP Texas City incident in 2005 (e.g., Tugnoli et al., 2008a, 2008b).

MEASUREMENT OF INHERENT SAFETY

The measurement and evaluation of inherent safety – i.e., the development of inherently safer design metrics – has been the subject of considerable interest and activity over the past decade. Approximately thirty different research contributions have been identified in this area. At the time of writing the current paper, the various indices and methodologies are being reviewed and so only general comments can be made here. Further, the references cited in this section are intended only as examples of some of the efforts undertaken worldwide; the reference listing here is most definitely not exhaustive.

The INSIDE (*IN*herent *S*he *I*n *DE*sign) project was one of the earliest and most comprehensive efforts in this regard, resulting in a number of tools for consideration of inherent safety, health and environment aspects in the early stages of a project. The Dow Fire & Explosion Index, an existing hazard identification/risk assessment tool, has been the subject of inherent safety exploration by Etowa et al. (2002) and Suardin et al. (2007). Various groups have developed new indices or methods of assessment (e.g., Gupta and Edwards, 2003; Khan and Amyotte, 2005; Leong and Shariff, 2009), and others have made comparisons among available indices and methods (e.g., Rahman et al., 2005; Adu et al., 2008). This important area will be the subject of further correspondence from the current authors.

PROCESS SAFETY MANAGEMENT

Safety management systems are recognized and accepted worldwide as best-practice methods for managing risk. They typically consist of 10–20 program elements that must be effectively carried out to manage the risks in an acceptable way. Having an effective management system for process-related hazards (fire, explosion, toxic releases, etc.) is therefore a critical corporate objective in the chemical process industries. Although there are examples in the literature of inherent safety applications within industry (e.g., Ashford and Zwetsloot, 2000; Zwetsloot and Ashford, 2003; Overton and King, 2006), the explicit incorporation of the principles of inherent safety within process safety management systems has not been comprehensively addressed. A step in this direction has recently been taken by Amyotte et al. (2007a).

Interest in the topic of safety culture has increased dramatically in recent years, again largely because of incidents such as the BP Texas City explosion in 2005. Two key points have emerged: (i) typical occupational

Table 2. A hierarchical view of various means of preventing and mitigating dust explosions

Explosion prevention		
Preventing explosible dust clouds	Preventing ignition sources	Explosion mitigation
Process design to prevent undesired generation of dust clouds and particle size reduction and segregation *Inherent Safety – All Principles*	Smouldering combustion in dust, dust fires *Procedural Safety – may also involve aspects of Inherent Safety or Engineered Safety*	Good housekeeping (dust removal/cleaning) (Mitigation with respect to secondary dust explosions; prevention with respect to primary dust explosions) *Inherent Safety – Intensification*
Keeping dust concentration outside explosible range *Inherent Safety – Intensification*	Other types of open flames (e.g. hot work) *Procedural Safety – may also involve aspects of Inherent Safety or Engineered Safety*	Explosion-pressure resistant construction *Inherent Safety – Simplification*
Inerting of dust cloud by adding inert dust *Inherent Safety – Attenuation*	Hot surfaces (electrically or mechanically heated) *Procedural Safety – may also involve aspects of Inherent Safety or Engineered Safety*	Explosion isolation (sectioning) *Inherent Safety – Limitation of effects (product choke)* *Inherent Safety – Avoiding Knock-On Effects (unit segregation)* *Engineered Safety – Passive (physical barrier)* *Engineered Safety – Active (isolation valve)*
Intrinsic inerting of dust cloud by combustion gases *Engineered Safety – Active*	Heat from mechanical impact (metal sparks and hot-spots) *Procedural Safety – may also involve aspects of Inherent Safety or Engineered Safety*	Explosion venting *Engineered Safety – Passive*
Inerting of dust cloud by N_2, CO_2 and rare gases *Engineered Safety – Active*	Electric sparks, arcs and electrostatic discharges *Procedural Safety – may also involve aspects of Inherent Safety or Engineered Safety*	Automatic explosion suppression *Engineered Safety – Active* Partial inerting of dust cloud by inert gas *Engineered Safety – Active*

safety indicators such as lost-time injuries (LTIs) are inappropriate as the primary indicator with respect to process safety, and (ii) leading indicators are generally viewed as being more useful than lagging indicators. Hopkins (2007) has recently commented that the most important consideration for process safety indicators is that they measure the effectiveness of the various controls comprising the risk control system. This affords an opportunity to link back to the elements making up the process safety management system and assess the level of commitment to the principles of inherent safety within that system. Little work appears to have been done in this area which has been identified by Glendon (2008) as a major challenge for industry (i.e., the linking of safety culture methodologies with process safety approaches and broader systems safety and risk management concepts).

DUST EXPLOSION PREVENTION AND MITIGATION

In their comprehensive review of explosion prevention and protection systems, Pekalski et al. (2005) comment that when designing or modifying a process, the concept of safety should already be present at the earliest stages of the design. In other words, one should not simply jump in and begin applying commercially available preventive and protective systems. Pekalski et al. (2005) recommend the adoption of various modern design and safety management approaches, the first of which they list as inherently safer design.

This same line of thought has been the theme of a series of publications attempting to make explicit the use of inherent safety principles in the prevention and mitigation of dust explosions (Amyotte et al., 2003a, 2003b, 2007b, 2009). A recent contribution from Amyotte and Eckhoff (2009) has reviewed dust explosion causation, prevention and mitigation, and has again emphasized the key role of inherent safety within the hierarchy of controls. See Table 2, adapted from Amyotte and Eckhoff (2009).

CASE STUDIES

Case studies highlighting a lack of application of inherent safety principles have appeared in the literature. For example, Sanders (2002) describes several incidents in which inherent safety considerations were poor, including examples of incompatible chemicals and deceptive piping designs. The Westray coal mine explosion (May 9, 1992 in Plymouth, Nova Scotia, Canada) has been the subject of a comprehensive inherent safety analysis by Goraya et al. (2004) from an incident investigation perspective. Additional resources include texts such as Kletz (2009) and process incident reports such as those found on the web site of the US Chemical Safety Board (www.csb.gov).

CONCLUSION

The field of inherent safety has not been stagnant over the past decade. It has grown both in recognition and application. Key contributors to this growth have been the adoption of the hierarchy of controls by some practitioners, the maturation of the complementary field of process intensification, and the development of inherently safer design metrics. There remains much to be done, and there will undoubtedly emerge new driving forces for change. (Although not within the scope of the current paper, regulatory issues and matters of site security will likely play a role in further usage of inherent safety.) Areas such as process safety management systems, process safety culture, and explosion prevention and mitigation represent fertile ground for explicit incorporation of inherent safety principles.

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