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Applications of Process Safety Concepts to the Hydrogen Economy

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Hydrogen is widely produced and used in the process industries with growing use in the public domain. While the former area of focus would obviously necessitate process safety considerations, the latter involves activities such as transportation in which occupational safety issues for individuals are paramount. The current research addresses this issue by identifying several areas of application in the hydrogen economy for three key process safety concepts: (i) inherently safer design, (ii) safety management systems, and (iii) the use of case studies. This paper thus illustrates, by means of referenced examples, the transferable nature of key process safety concepts to various features of the emerging hydrogen economy. The primary thesis of this work is the notion that inherently safety design principles, safety management systems, and lessons learned from case histories have broader implications for safety than would be apparent by restricting their use solely to the process industries.

1. Introduction

As noted by Guy (2000), hydrogen is largely produced as a synthesis gas for use in chemical production (e.g., ammonia and methanol) or recovered as a by-product for use in oil refineries. He further comments that while the safe handling of hydrogen by industry (especially industrial gas companies) is well-understood, use of hydrogen in the public realm can be problematic. The current paper demonstrates that the need for safer production, storage, distribution and use of hydrogen in all application sectors must be similarly well-understood and acted upon if the envisaged hydrogen economy is to materialize and endure.
Additional insight into the importance of safety for the hydrogen industry can be gained by looking at other areas of application. In addressing the issue of safety in the nanotechnology field, Amyotte (2011) made the following comments:

> *The nanotechnology world does not want, and neither should it need, a Bhopal, Buncefield or Gulf oil leak (all major and/or recent process/environmental incidents) to drive its safety culture. Simply put, nanotechnology industries cannot afford to ignore the hard safety lessons that have been learned and at times ignored by the chemical process industries.*

These comments apply equally well to industries involved in the production, distribution, storage and use of hydrogen. While there have been industrial accidents involving hydrogen (Rigas & Amyotte, 2013), the avoidance of further incidents will be accomplished by successful implementation of several factors – chief among which is knowledge transfer from the process industries. Added validity for this claim is given by the following quotes from a recent policy document produced by the Mary Kay O'Connor Process Safety Center (MKOPSC, 2012):

> *Other trends include the development of new processes. In part, this is due to a shift in fuel types as a result of the desired improvement in the sustainability and the reduction of carbon dioxide. The oil-based industry is expected to slowly change into a natural gas-based one, and the use of hydrogen as an energy carrier/fuel also can be expected. Certainly hydrogen – an element with properties that have been known for a long time despite its lack of large-scale use – requires a more stringent safety regime than do liquid hydrocarbons. (p. 23)*

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Due to sustainability requirements, a significant shift from conventional fuels (energy carriers) to biofuels, natural gas and hydrogen for power generation and automotive uses can be expected. These changes will create new hazards by enlargement of scale and widespread distribution, particularly in the case of hydrogen. (p. 38)

The current paper is therefore aimed at demonstrating, with illustrative examples, the applicability of three important process safety concepts to the broad field of hydrogen safety: (i) inherently safer design, (ii) safety management systems, and (iii) the use of case studies. It is based primarily (with relevant excerpts) on a more extensive treatment of the subject by Rigas and Amyotte (2012).

2. Inherently safer design

Inherent safety is a proactive approach in which hazards are eliminated or lessened so as to reduce risk without over-reliance on engineered (add-on devices) and procedural measures. The concepts of inherent safety (or inherently safer design, ISD) have been formulated in the process industries over the past 35 or so years, beginning with the pioneering work of Professor Trevor Kletz (largely in response to the 1974 cyclohexane explosion at Flixborough, UK). Many publications on ISD are now available (CCPS, 2009; Kletz and Amyotte, 2010).

Professor Kletz and others worldwide have formulated a number of principles or guidelines to facilitate inherent safety implementation in industry. Four basic principles have gained widespread acceptance. *Minimization* calls for the use of smaller quantities of hazardous materials when the use of such materials cannot be avoided, or keeping the treatment time of larger quantities to a minimum. It may also involve performing a hazardous procedure (e.g., with a batch system) as few times as possible when the procedure is unavoidable. *Substitution* calls for the replacement of a substance with a less hazardous material, or a process route with one that does not involve hazardous material. *Moderation* implies the use of hazardous materials in their least hazardous forms, or the identification of processing options that involve less severe conditions (e.g., a lower temperature, pressure or speed of rotation). *Simplification* requires the design of processes, processing equipment and procedures in a manner so as to eliminate opportunities for errors by eliminating excessive use of add-on safety features and protective devices.

2.1 Minimization

In their review of infrastructure options for hydrogen refueling stations, Markert et al. (2007) comment that current scenarios are still in the very early stages of development and therefore offer cost-saving opportunities as would be brought about by the ISD approach. This advice acknowledges the fact that inherent safety is typically most effective when considered early in the design sequence. While it is possible to retrofit ISD principles to existing plant to some extent, incorporation of inherent safety thinking in preliminary hazard and risk assessments can be highly beneficial. This is particularly important with respect to minimization – i.e., storing as little hydrogen as possible (Markert et al., 2007).

Markert et al. (2007) present a comparison of three hydrogen refueling alternatives with the current system for gasoline (petrol) production, storage, distribution and dispensing as shown in Figure 1. The process chain for centralized production and either truck or pipeline distribution (i.e., the first two non-petroleum options in Figure 1) is shown schematically in Figure 2. Here one sees the need for careful consideration of the inventories to be stored both centrally and at medium-scale. The on-site option, on the other hand, eliminates the need for medium-scale storage – a case of 100 % minimization. There are, of course, a myriad of safety, environmental and cost factors that must be considered in selecting from the full range of such alternatives. The point being made here is that ISD should be one of these factors.

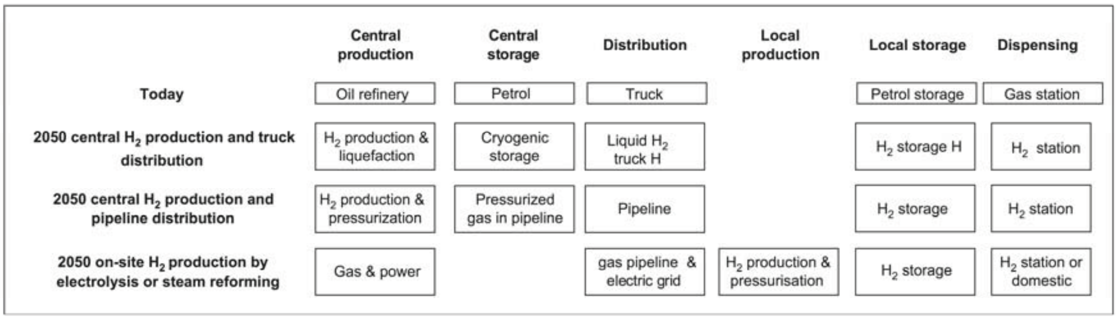

Figure 1: Comparison of gasoline and hydrogen production, storage, distribution and dispensing schemes (from Markert et al., 2007, with permission)

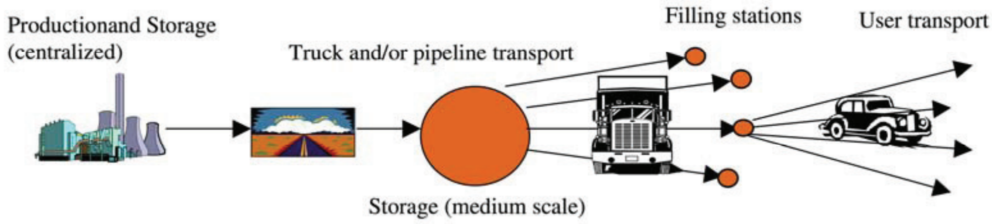

Figure 2: Process chain for centralized production of hydrogen and distribution by truck/pipeline (from Markert et al., 2007, with permission)

2.2 Substitution

As previously described, one interpretation of the substitution principle is the replacement of a substance with a less hazardous material. This clearly demonstrates the fact that inherent safety must be viewed as hazard-specific. If one were to consider substituting some other material for hydrogen in a given application, the hazard being avoided must be specified (as in the familiar substitution of non-flammable helium for flammable hydrogen when a lighter-than-air gas is desired). An extension of this point is the use of other substances not as a substitute for hydrogen, but as a means of avoiding hydrogen generation. Pebble-bed nuclear reactors utilizing helium rather than water as a coolant offer the inherently safer advantage of eliminating water from the reactor core. The release of hydrogen gas in the event of an upset is therefore also eliminated (Bradsher, 2011).

It is, however, the features of hydrogen associated with it being an abundant, cleaner-burning fuel that make it attractive as a substitute for other fuels such as hydrocarbons. It is necessary, therefore, to also invoke the second interpretation of substitution – that of replacing a processing route with one that does not involve hazardous material. The example in the previous section of minimization of hydrogen inventories in storage also applies here. Although shown earlier that hydrogen can be transported by pipeline or truck from centralized plants (Markert et al., 2007), a more practical, cost-effective production method is on-site catalytic reforming from natural gas (Sherman, 2007). While this latter approach does address the issue of large inventories of hydrogen, it also has a significant environmental impact because of the carbon dioxide generated during the process (Guy, 2000). To ease this and other problems, Guy (2000) comments on the importance of indirect and direct production of hydrogen by other renewable energy sources and by sunlight, respectively. These are also examples of synthesis route substitution.

2.3 Moderation

While it is not always possible to eliminate a given hazard, moderating the form of a material or the conditions under which it is processed can be beneficial in terms of risk reduction. Storing hydrogen as a liquid is attractive because of the high energy density per unit volume (Motavalli, 2007). Potential downsides include the need for heavy, bulky cryogenic tanks – particularly in the case of hydrogen as a transportation fuel – as well as the intrinsic hazards of very low temperatures given that the normal boiling point of hydrogen is -252.9 °C.

Metal hydrides provide a means to store hydrogen in solid form (Motavalli, 2007), and offer an inherently safer approach in some regards to liquid and gaseous storage (Pasman and Rogers, 2010). Pasman and Rogers (2010) further comment, however, that while the hydride itself can be viewed as inherently safer, production of hydrides with acceptable risk and retrieval of the hydrogen at moderate temperatures remain challenging and hence the subjects of intensive research.

2.4 Simplification

The simplification principle was considered by Xu et al. (2009) in their study of multi-layered stationary high-pressure hydrogen storage vessels (SHHSVs) having the following characteristics:

- As uniform a stress distribution as possible,
- As few welds as possible,
- High fatigue resistance to avoid failure from pressure swings caused by repeated vessel filling and discharging,
- A convenient arrangement for on-line leak monitoring, and
- Hydrogen-compatible materials of construction.

The stipulation of as few welds as possible is also related to the concept of minimizing potential leak and failure locations (welds, flanges, etc.).

3. Safety management systems

A key engineering tool for industrial practice is a management system designed to address the pertinent risks. Management of process hazards leading to fire, explosion and release of toxic materials is accomplished by means of safety management systems typically having 12 - 20 separate elements. One example of such a process safety management (or PSM) system is given in Table 1.

Table 1: Elements of process safety management (CSChE, 2012)

No.	Element
1	Accountability: Objectives and Goals
2	Process Knowledge and Documentation
3	Capital Project Review and Design Procedures
4	Process Risk Management
5	Management of Change
6	Process and Equipment Integrity
7	Human Factors
8	Training and Performance
9	Incident Investigation
10	Company Standards, Codes and Regulations
11	Audits and Corrective Actions
12	Enhancement of Process Safety Knowledge

Safety management systems are also relevant to addressing the hazards of hydrogen and the ensuing risks involved in various activities. For example, the US Department of Energy (DOE) has recommended a six-element safety plan (with 16 separate items) for DOE-funded hydrogen and fuel cell projects (Table 2). An analysis of this plan conducted by the present authors (Rigas & Amyotte, 2012) shows a strong correlation with the model process safety management system displayed in Table 1. Clearly, issues of safety management are as important in the safer handling of hydrogen as they are for other hazardous materials such as hydrocarbons and petrochemicals.

Table 2: Safety plan elements for US DOE-funded hydrogen and fuel cell projects (DOE, 2010)

No.	Element
1	Scope of Work
2	Organizational Safety Information: Organizational policies and procedures, Hydrogen and fuel cell experience
3	Project Safety: Identification of safety vulnerabilities, Risk reduction plan, Operating procedures, Equipment and mechanical integrity, Management of change procedures, Project safety documentation
4	Communication Plan: Employee training, Safety reviews, Safety events and lessons learned, Emergency response, Self-audits
5	Safety Plan Approval
6	Other Comments or Concerns

As a general example of the correlation between Tables 1 and 2, Rigas and Amyotte (2012) comment that essentially all of the typical process safety hazard identification techniques have been successfully applied to various sectors of the hydrogen industry. These include techniques referenced under both *process risk management* (Table 1) and *identification of safety vulnerabilities* (Table 2): checklist (CL), what-if (WI) analysis, failure modes and effects analysis (FMEA), fault tree analysis (FTA), and hazard and operability (HAZOP) study.

A specific example arises in the work of Kikukawa et al. (2009) who used HAZOP and FMEA to identify hazards and assess risks for liquid hydrocarbon fueling stations. Their risk assessment process shown in Figure 3 is similar to that for general process risk assessment, with the understanding that any risk reduction measures recommended through use of Figure 3 should be thoroughly examined for the introduction of new hazards. Further, Kikukawa et al. (2009) employed a risk matrix to discern whether a given risk was tolerable; this is a common approach in the process industries.

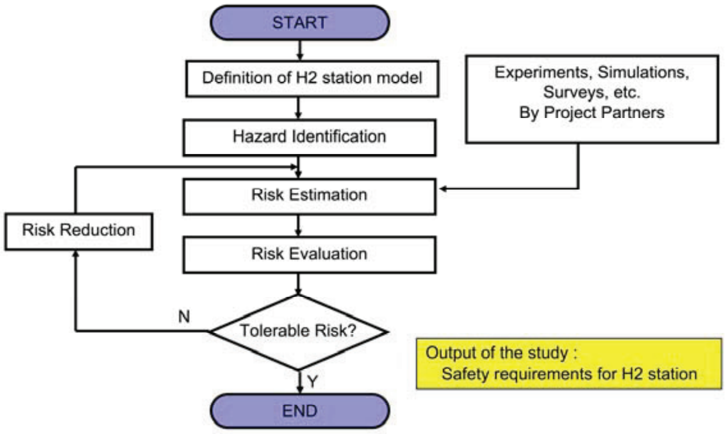

Figure 3: Risk assessment process for liquid hydrogen fueling station (from Kikukawa et al., 2009, with permission)

4. Case studies

Case histories, or studies of previous incidents, are widely used in the field of process safety so that lessons can be learned and future incidents prevented. All industry sectors would benefit from consideration of how case studies can be used to reinforce valuable lessons related to the legacy (or long-lasting impact) of an incident, engineering-related issues, and management system deficiencies.

Case studies (hydrogen-related or otherwise) can be developed from a variety of sources including: (i) everyday life experiences, (ii) newspapers and magazines, (iii) topical conferences, (iv) technical papers, (v) books related to safety or case studies and also from other industries and applications, (vi) training packages, (vii) trade literature, (viii) Loss Prevention Bulletin, and (ix) US Chemical Safety Board reports.

Representative case studies for each of these avenues are given in Rigas & Amyotte (2012). For example, the Loss Prevention Bulletin (LPB) published by the Institution of Chemical Engineers (IChemE) in the UK is a good source of case studies arising from process accident and near-miss reports. An online search with the keyword *hydrogen* identified a number of LPB issues describing several incidents and elucidating the accompanying lessons learned, as shown in Table 3.

Table 3: Hydrogen case study examples found in the Loss Prevention Bulletin (Rigas and Amyotte, 2012)

Issue	Year	Case Study
015	1977	Fires involving hydrogen in a naptha cracker and in a hydrogenation reaction
068	1986	Vapour cloud explosions involving hydrogen-rich gases
083	1988	Failure of a woven-steel braided flexible hose on a hydrogen installation area
156	2000	Explosion of hydrogen in a pipeline intended for transfer of CO_2 gas from an ammonia plant
207	2009	Hydrogen explosions from charging batteries
		Unexpected generation of hydrogen in a new process for production of aluminium chloride
		Hydrogen generation inside sealed components at a refinery storage terminal
215	2010	Hydrogen explosion in an electrolyter plant

It is to be expected that the primary focus in the Table 3 case studies is on process safety. Nevertheless, lessons related to root causes such as safety device failures and management system inadequacies are transferable to a broad range of hydrogen applications involving connection fittings (Issue 083), pipeline transfer (Issue 156), batteries (Issue 207), and unknown generation sources (Issue 207).

In a similar vein, the US Chemical Safety Board is another organization relevant to the issue of case study usage. As noted on its web site (www.csb.gov), the CSB is a non-regulatory agency that conducts root cause investigations of chemical accidents at fixed industrial facilities. The reports of its investigations are available on the CSB web site for downloading and are often accompanied by video footage and animation of the incident sequence and root causes/lessons learned. The safety bulletin (CSB, 2006) on the ISD practice of *making incorrect assembly impossible* (a sub-principle of *simplification)* is an excellent hydrogen-specific, and widely applicable, example of the significant case study value of CSB reports.

5. Conclusion

Hydrogen releases in the process industries can readily lead to fires and explosions given the abundance of ignition sources to be found in a process plant. To prevent the occurrence and mitigate the consequences of releases of hydrogen and other hazardous materials, the process industries have relied for decades on a number of safety measures. Key among these are inherently safer design principles, use of an effective safety management system, and examination of previous incidents for lessons learned.

The wide use of hydrogen as an energy carrier will require safety assurances throughout the entire production, distribution and end-use chain. Major issues affecting the acceptance of hydrogen for public use are the safety of hydrogen installations (production and storage units) and in its applications (e.g., vehicle or home use) (Rigas and Amyotte, 2012). The current paper has demonstrated by means of illustrative examples how the tools and experience of the process industries can be used to good effect in meeting these safety requirements.

Process safety, occupational safety, and the broad field of industrial safety all have the same goal – the avoidance of incidents leading to injury or fatality, loss of property and other assets, business interruption and delays in production, and degradation of the natural environment. While the specific hazards and vulnerable targets may be different in each area of safety focus, there exist basic risk reduction measures having transferable features that cross the boundaries of safety regimes. It is our contention that inherent safety, safety management systems and the use of case studies are three such measures.

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