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What Do Gas Blows, Iron Dust Accumulations and Sulfidation Corrosion Have in Common?

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This paper presents an analysis of three process incidents recently investigated by the US Chemical Safety Board (CSB): (i) Kleen Energy natural gas explosion (Middletown, CT), (ii) Hoeganaes Corporation iron dust flash fires and hydrogen explosion (Gallatin, TN), and (iii) Chevron Richmond refinery pipe rupture and fire (Richmond, CA). The starting point for the analysis is identification of the main hazardous materials, activities or conditions underlying the specific incident losses. These are, respectively: (i) Kleen Energy – purging of process pipelines with natural gas, (ii) Hoeganaes Corporation – accumulations of combustible iron dust in work areas, and (iii) Chevron Richmond refinery – a pipeline damage mechanism known as sulfidation corrosion. While the three incidents have many aspects in common, chief among the similarities are the key process safety concepts of inherently safer design (ISD), recognition of warning signs (precursor events), and safety culture. Each incident is analyzed for evidence of these concepts.
The analysis is drawn from the relevant CSB investigation reports with the primary objective of illustrating the strong experiential learning that case histories of actual incidents can provide. While the lessons learned from these incidents are useful in and of themselves, capturing these lessons by incorporation in a safety management framework extends their usefulness to the prevention and mitigation of other potential process incidents. A typical process safety management system is employed in the current work to accomplish this secondary objective. Overall conclusions are made concerning the effectiveness of ISD, precursor recognition, and safety culture with respect to risk reduction in the process industries. It is anticipated that this work will help in communication of lessons learned to both the research and practice communities.

1. Incident descriptions and hazards involved

The US Chemical Safety and Hazard Investigation Board (Chemical Safety Board or CSB) is an independent, non-regulatory federal agency that conducts root cause investigations of chemical accidents at fixed industrial facilities (CSB, 2015a). The current paper examines three different – yet, fundamentally similar – incidents or series of incidents investigated by the CSB over the past five years. The objective in doing so is to identify these common features and relate them to typical process safety management system elements, hence drawing attention to the lessons learned and opportunities for safety improvements.

1.1 Kleen Energy

Figure 1 shows a *gas blow* (used to remove pipeline debris) at the Kleen Energy power plant in Middletown, CT one week before repeated application of this procedure lead to an explosion that killed six workers. The fuel for the explosion was natural gas being forced through a pipe at a pressure of 4.5 MPa and eventually exiting into a congested, outdoor work area where a number of potential ignition sources existed (CSB, 2010).

1.2 Hoeganaes Corporation

Figure 2 shows overhead *iron dust accumulations* at the Hoeganaes facility in Gallatin, TN, which manufactured iron powder for the production of metal parts in the automotive and other industries. Combustible iron dust deposits in this workplace helped fuel three separate incidents: (i) an iron dust flash fire that killed two workers, (ii) another iron dust flash fire that injured one employee, and (iii) a hydrogen explosion resulting in multiple iron dust flash fires killing three workers and injuring two others (CSB, 2011).

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Figure 1: Cleaning of fuel gas piping by gas blow at Kleen Energy site one week before incident (CSB, 2010).

Figure 2: Iron dust deposits on elevated surfaces at Hoeganaes Corporation facility (CSB, 2011).

1.3 Chevron Richmond Refinery

Figure 3 shows the result of *sulfidation corrosion* of a pipeline at the Chevron refinery in Richmond, CA. The pipe ruptured and a hydrocarbon vapour cloud was formed; nineteen employees in the vicinity narrowly escaped injury when the cloud ignited. The general public were less fortunate, with 15,000 nearby residents eventually seeking medical treatment due to emissions from the process fire (CSB, 2013, 2014, 2015b).

Figure 3: Pipeline degradation due to sulfidation corrosion at Chevron Richmond refinery (CSB, 2013).

2. Inherently safer design

One of the underlying similarities with respect to causation of the Kleen Energy, Hoeganaes and Chevron incidents is inadequate consideration of the principles of *inherently safer design, ISD* (or simply, *inherent safety*). Inherent safety is a proactive approach in which hazards are eliminated or lessened so as to reduce risk with decreased reliance on add-on safety devices and safe-work procedures (Kletz and Amyotte, 2010). The four basic principles of ISD are minimization, substitution, moderation and simplification. Within a framework known as the hierarchy of controls, ISD is the most effective risk reduction technique – followed in order of decreasing effectiveness by passive engineered safety devices, active engineered safety devices, and finally procedural safety measures.

The CSB recommendations (CSB, 2010) arising from the Kleen Energy explosion well-address these basic features of inherent safety. There is clear evidence of use of the hierarchy of controls in these recommendations which incorporate first, elimination of the fire and explosion hazard by prohibiting the release of flammable gas to the atmosphere for the purpose of cleaning fuel gas piping, through to the use of combustible gas monitoring, and the development of flammable gas safety procedures and training. One specific recommendation invokes the inherent safety principle of substitution in the case of replacing natural gas with a less hazardous gas, such as air, in the cleaning of fuel gas piping. The principle of simplification is also relevant here in helping to ease the complex requirements for discharge design when using natural gas for pipeline cleaning. CSB (2010) also addresses the issue of whether alternative cleaning methods are technically feasible by commenting that safer alternatives, such as air, are just as effective as natural gas for cleaning fuel gas piping.

In the case of the three Hoeganaes incidents, the explosion pentagon provides insight into the role of ISD in explosion prevention and mitigation. The pentagon consists of the familiar fire triangle elements of fuel, oxidant and ignition source, augmented by the need for fuel/oxidant mixing and some degree of confinement of the resulting combustible mixture. In general, confinement can be addressed by explosion relief venting (a passive engineered safety measure), oxidant by inert gas blanketing (an active engineered safety measure), and ignition sources in part by hot-work permitting (a procedural safety measure). Much more effectively, the fuel component of the explosion pentagon (i.e., iron dust accumulations) can be eliminated or minimized by ISD considerations – e.g., through the design of equipment to contain dust so that it does not escape and does not have to be cleaned up, and by facility design for easy and effective cleaning (Frank and Holcomb, 2009). A good procedural program of adequate housekeeping can also be thought of as having strong ISD overtones (Amyotte, 2013).

CSB (2013) and CSB (2015b) dealing with the Chevron Richmond refinery incident each contain several pages of informative text on various aspects of inherently safer design. These interim and final investigation reports describe the role of inherent safety within the hierarchy of controls, as well as the facts that ISD is hazard-specific and is most easily and effectively introduced early in the process life cycle (e.g., at the design/build stage). Substitution of a higher chromium-content steel alloy (e.g., “9-Chrome”) – which is less susceptible to sulfidation corrosion than the low-silicon carbon steel in place – is arguably the most significant missed ISD opportunity in this case.

3. Recognition of Warning Signs

A second common causation factor in the Kleen Energy, Hoeganaes and Chevron incidents is failure to *recognize and heed warning signs* of potential process safety issues. (The general discussion in this section follows Amyotte et al., 2014). With respect to ease of recognition, process incident warning signs can be weak or strong in addition to their physical (e.g., asset integrity) or conceptual (e.g., safety culture) nature. Numerous resources are available for guidance on potential warning signs. For example, Gerstein (2008) – published in the popular literature – is essentially a book about early warnings. The publications of sociologist Andrew Hopkins, such as Hopkins (2009), are especially helpful in understanding the relationship between warning signs and the elements of an effective safety culture and safety management system (as illustrated in the next two sections).

From a technical engineering perspective, work on leading and lagging indicators by organizations such as the AIChE Center for Chemical Process Safety is also beneficial in identification of warning signs. CCPS (2012) provides additional advice on examination of the following areas for warning signs: (i) leadership and safety culture, (ii) training and competency, (iii) process safety information, (iv) procedures (operating and maintenance), (v) asset (mechanical) integrity, (vi) risk analysis and management of change, (vii) audits, (viii) learning from experience, and (ix) near-miss and incident reporting/investigation. While publications such as Khakzad et al. (2015) are available for a quantitative overview of the use of precursor data in assessing the likelihood of major process incidents, our focus here is on the last two qualitative measures in the listing from

CCPS (2012). Our reasoning for this approach is that it is imperative for an industrial site to act on lessons learned from its own operations, from those within its company operations, and more broadly from what is happening within the industry itself.

In the case of the Kleen Energy incident, CSB (2010) provides ample evidence of previous gas blow and natural gas purging events at other facilities that could have served as precursor warnings: (i) Calpine's Wolfskill Energy Center natural gas plant in Fairfield, CA (2003), (ii) FirstEnergy power generation station in Lorain, OH (2001), (iii) ConAgra Foods production facility in Garner, NC (2009 – less than eight months before the Kleen Energy explosion), (iv) Ford Rouge power plant explosion in Dearborn, MI (1999), (v) Hilton Hotel explosion in San Diego, CA (2008), and (vi) a hotel construction explosion in Cheyenne, WY (2007).

The Hoeganaes facility in Gallatin, TN experienced three iron dust flash fires (and one hydrogen explosion) in which a total of five workers were killed and three injured over a four-month period during 2011. These events were in addition to numerous other flash fires that did not result in serious injury, test results confirming the explosibility of the iron dust accumulating in the plant, and audit reports indicating the need for improved housekeeping (CSB, 2011). Learning from experience and acting on the lessons available from incident investigations were clearly inadequate.

With respect to the Chevron Richmond refinery hydrocarbon release and fire, CSB (2013) identifies the following range of hazard warnings: (i) results from previous corrosion inspections at the Richmond refinery, (ii) sulfidation corrosion incidents at other Chevron refineries including the El Segundo refinery, and (iii) a sulfidation corrosion incident and ensuing fire at BP's Cherry Point refinery. Additionally, a 2006 CSB Safety Bulletin published in response to the BP Texas City refinery explosion and fire (CSB, 2006) provides further information on the specific matter of corrosion of carbon steel (in this case by high temperature hydrogen attack).

4. Safety culture

The final common similarity considered here in terms of causation of the Kleen Energy, Hoeganaes and Chevron incidents is *safety culture* shortcomings. Hopkins (2005) describes three concepts that address a company's cultural approach to safety, and makes the argument that the three are essentially alternative ways of talking about the same phenomena: (i) safety culture, (ii) collective mindfulness, and (iii) risk-awareness. He further defines a safety culture as embodying the following subcultures: (i) reporting, (ii) just, (iii) learning, and (iv) flexible.

Based on the discussion in the previous section on well-publicized gas blow/purging incidents (especially the ConAgra Foods explosion), it is reasonable to raise questions as to the efficacy of Kleen Energy's learning subculture (which should not be restricted to events occurring only within a given facility's fence line). CSB (2010) comments in the following manner on the underlying common theme of the Kleen Energy and ConAgra explosions: *…companies should use safer methods and not release flammable gases in close proximity to ignition sources and workers.* It is impossible to mount a credible argument against this notion; yet it is equally difficult to envisage its implementation without a company's belief in the collective mindfulness principle of preoccupation with failure (Hopkins, 2005). Another principle of collective mindfulness – sensitivity to operations – describes the importance of front-line operators maintaining situational awareness by virtue of them being well-informed about ongoing operations and the potential for operational failure (Hopkins, 2005). Deficiencies in this regard help explain the lack of both a safety meeting and review of the gas blow procedure prior to pipe cleaning work on the day of the fatal incident (CSB, 2010).

The safety culture gaps at the Hoeganaes plant are now self-evident in light of the discussion to this point – especially the comment in the previous section with respect to three significant loss-producing events over a four-month period. These repeated incidents call into question the commitment to a learning subculture and possibly other subcultures identified in the first paragraph of this section. Additionally, CSB (2011) gives details of acceptance of the combustible dust hazard to the extent that operators had little choice but to tolerate facility conditions. Iron dust flash fires occurred but did not result in serious injuries until the first fatal incident, creating a situation where evidence (i.e., warning signs) was normalized. Evidence normalization, also known as normalization of deviance, is a key indicator of a culture of risk denial – or alternatively, a lack of risk-awareness (Hopkins, 2005).

The interim and final reports on the Chevron Richmond refinery fire both contain brief safety culture analyses. CSB (2013) describes the use of more than 100 clamps throughout the refinery to mitigate leaks from process piping. This establishes at least a tentative link between the frequent use of leak repair clamps and possible normalization of deviance with regard to a weak mechanical integrity management system (CSB, 2013). CSB (2015b) provides a practical definition of normalization of deviance: *the acceptance of events that are not supposed to happen*. With this description in mind, the actions of firefighters on the day of the 2012 incident under review here become somewhat more understandable. Their decision to remove insulation from the onstream pipe was consistent with a previous incident in 2010 in which a leaking unit was kept in operation until there was no choice but to shut down and effect repairs. Hazardous leaks were normalized to the extent that operations continued (CSB, 2015b). In reality, these leaks were warning signs of a much more severe event.

5. Safety management system elements

Table 1 lists the twelve elements of the process safety management (PSM) system recommended by the Canadian Society for Chemical Engineering (CSChE, 2012). This system is based on an earlier counterpart developed by the AIChE Center for Chemical Process Safety (CCPS, 1989).

Table 1: Twelve-element process safety management system (CSChE, 2012).

Elements
1. Accountability: Objectives & Goals 2. Process Knowledge & Documentation 3. Capital Project Review & Design Procedures 4. Process Risk Management 5. Management of Change 6. Process & Equipment Integrity 7. Human Factors 8. Training & Performance 9. Incident Investigation 10. Company Standards, Codes & Regulations 11. Audits & Corrective Actions 12. Enhancement of Process Safety Knowledge

The exercise of assigning each hazard and common causation factor to a particular element in Table 1 illustrates the essential features and usefulness of a robust system for managing process safety.

Table 2: Assignment of hazards and common causation factors to PSM elements and components.

Hazard Causation Factor	PSM Element	PSM Component
Gas blow	8. Training & Performance	8.2 Operating/maintenance procedures
Iron dust accumulation	2. Process Knowledge & Documentation	2.1 Chemical/occupational health hazards
Sulfidation corrosion	6. Process & Equipment Integrity	6.5 Preventative maintenance
Inherently safer design	4. Process Risk Management	4.3 Reduction of risk
Warning signs	9. Incident Investigation	9.5 Incident recording/reporting/analysis
Safety culture	1. Accountability: Objectives & Goals	1.9 Company expectations

The results of our analysis in this regard are given in Table 2 (with inclusion of a relevant component for each element, as per CSChE, 2012). While other researchers or practitioners might make different assignments, this would have no impact on the central thesis that PSM is a system approach driven by technical requirements rooted in the natural, engineering, management and social sciences. We also acknowledge that correlation of a given hazard or causation factor could be made with virtually all PSM elements (as we have previously done with the inherently safer design concept in Amyotte et al., 2007).

Figure 4: Two sides of poster handed out by public interest group during CSB public meeting April 19, 2013.

6. Concluding remarks

The present work has described three distinct incidents (or series of incidents in the case of Hoeganaes) that occurred in a diverse range of industry sectors. Incident-specific hazards, similar causation features (key process safety concepts), and relevant process safety management elements and components have been discussed. The lessons learned from these incidents and the analysis herein presented can be categorized as: (i) engineering lessons, (ii) management lessons, and (iii) legacy lessons.

Engineering lessons relate to the hierarchy of safety controls, with the need for thoughtful consideration of inherently safer design principles being a prime example. Management lessons are those relevant to company personnel in management positions as well as the safety management system itself. Examples in this category include the need for a strong process safety culture and a means to ensure incident precursor recognition. Legacy lessons describe the long-lasting impacts arising from a major process incident. Figure 4 graphically illustrates the negative legacy of one of the incidents reviewed in the current paper.

Overall, the legacy lessons of the Kleen Energy, Hoeganaes and Chevron incidents can best be described by the following quote from Fung (2013): *The future success of the chemical industry will depend more on social license to operate than technological advancement*.

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