CHEMICAL ENGINEERING TRANSACTIONS

VOL. 31, 2013

Guest Editors: Eddy De Rademaeker, Bruno Fabiano, Simberto Senni Buratti
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ISBN 978-88-95608-22-8; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1331129

Using Principles of Inherent Safety for Design of Hydrometallurgical Solvent Extraction Plants

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An Inherently Safe (IS) facility relies on the reduction or elimination of hazardous materials or processes through changes in the chemistry, physics and physical design of a process rather than by relying entirely on layers of add-on protection. The mainstream chemical processing industry (CPI) has adopted guidelines and Best Practices to better apply IS when designing or modifying facilities against fires and explosions. The mining and metallurgical refining industry – which is often chemical in nature - has not embraced IS nor are there published Best Practice Guidelines that promote IS in this industry. This paper addresses IS principles in general and explores specific IS opportunities for protection of hydrometallurgical solvent extraction (SX) plants using the concepts of intensification, substitution, attenuation, limitation of effects and simplification/error tolerance.

1. Introduction

Hydrometallurgical solvent extraction (SX) processes – featuring large quantities of open pool ignitable organic solvents - are common in the mining industry for concentrating and recovering non-ferrous metals such as copper, nickel, cobalt, uranium, tungsten, iodine and lithium. An Ignitable Liquid is any liquid or liquid mixture that will burn. A liquid will burn if it has a measurable fire point. Ignitable liquids include flammable liquids, combustible liquids, inflammable liquids, or any other term for a liquid that will burn.

Fire loss incidents and the widespread use of sub-grade tank farms and piping trenches, plastic piping, poor drainage, and closely spaced buildings demonstrate opportunities to improve the use of IS concepts for this industry

The metallurgical refining industry has designed and constructed facilities with an emphasis on personnel safety, production efficiency and cost effectiveness. The use of IS to eliminate or minimize property fire exposures has not seen widespread practice. Lessons learned from the mainstream CPI have not been communicated or applied.

As an example, SX plants have consistently used gravity flow as a cost and production-effective solution for transferring liquids and minerals through a process. In fact, Jergensen et al (1999) recommends utilizing gravity to the fullest extent possible in design of SX plants. This philosophy has been achieved by laying out SX plants with process equipment at different grade levels so that solutions can flow “downhill” without using pumps. Because of the use of large quantities of ignitable liquids and the potential for these liquids - if released - to flow unimpeded into other areas – gravity SX processes represent severe *inherent* fire consequences unless costly barriers, drainage and channelling are also provided.

It appears that little thought has been given to the fire protection consequences and challenges of this design feature during the historical evolution of SX plants and most hydro-metallurgical SX plants constructed today use some form of a sub-grade processing area (tank farm) and one-way gravity flow.

The use of sub-grade production units is an inherently unsafe layout where ignitable liquids are used and is a layout that would not be used by the mainstream chemical processing industry (CPI).

Gravity-assist layout is only one example where hydrometallurgical SX plants have been designed and constructed without IS in mind. The use of combustible and frangible corrosion-resistant materials – such as glass and plastic - for ignitable liquid storage, processing and piping systems has significantly increased the hazards of these facilities. These materials of construction are not rigorous and allow for rapid failure

Please cite this article as: Moore L., 2013, Using priciples of inherent safety for design of hydrometallurgical solvent extraction plants, Chemical Engineering Transactions, 31, 769-774 DOI: 10.3303/CET1331129

and release of ignitable contents during fire exposure. The use of combustible or frangible systems to handle or transport ignitable solvents is not a practice seen today in the CPI.

Another example of inherently unsafe layout is in the popular use of below grade trenches to carry solvent piping. Access to trenches for manual fire fighting is limited and the trenches often drain directly into lower grade tank farm areas of high production and monetary value. Trenches encircle solvent-filled cells, have open grated coverings, and represent severe fire exposure to production processes such as mixer-settlers (MS). Trenches also offer low spots for vapours or liquids to collect and may require mechanical ventilation systems to prevent vapour accumulation. The use of plastic piping in trenches further increases the hazard. The CPI long ago discontinued the use of sub-grade trenches for carrying ignitable materials and uses instead elevated, easily accessible and well ventilated piperacks.

The CPI – having experienced many fires and explosions of great impact to the industry and to the public – has embraced IS principles in the design phase of new facilities. Inherent safety is being promoted through corporate standards, public domain Best Practice publications, seminars, and at the chemical engineering university level. In many companies IS has become part of the design and chemical engineer's consciousness and has resulted in a safer industry.

This has not occurred in the mining industry.

This paper provides the reader with concepts and ideas on how to design SX facilities with IS principles in mind, hopefully without sacrificing cost effectiveness of operations.

2. Fire Loss Experience in SX Plants

The need for improved fire prevention and protection is strongly supported by fire losses in global SX plants as shown in Table 1. Improper plant layout, spacing, drainage, protection, and use of combustible or frangible pipe and vessel construction materials were all major factors in the loss severity in these incidents

Table 1. Recent SX plant fire incidents. Damage estimates are indexed to 2013 US currency.

Location	Date	Process	Incident	Results	Ref.
Norway	1972	Cobalt-nickel SX using kerosene.	Solvent spill into pit	Three fatalities. Plant destroyed. US$75 M damage. Six months outage.	Hoy-Petersen et al (1974)
Australia	1999	Uranium-copper SX using kerosene.	Solvent release at plastic pipe.	Partial plant damage. Reported in excess US $40 M damage. Nine months outage.	Rizzuto, (2002)
Australia	2001	Uranium-copper SX using kerosene.	Solvent release at plastic pipe.	Widespread plant severe damage. Excess US $100 M damage. Two years outage.	Rizzuto, (2002)
US	2003	Copper SX using kerosene solvent.	Solvent fire involving M-S cells	Four M-S cells partially damaged. US $5 - 10 M reported by AP	Associated Press (2003
Mexico	2003	Copper SX using kerosene solvent.	Solvent fire	Total plant damage	Internet News services (2003)

3. General Principles of Inherent Safety

There are four tiers or layers-of-protection usually applied to loss prevention of a chemical processing facility:

- *Inherent safety* (IS) - A protection layer that relies on the reduction or elimination of hazardous materials or processes through changes in the chemistry, physics and physical design of a process. Examples of IS systems are described further in this paper.
- *Passive* - A protection layer that requires no mechanical device or system to actively function to limit or prevent the loss. The most favorable aspect of a passive system is its performance

reliability because it is not prone to failure upon demand. Examples of passive systems are non-combustible materials of construction, physical space separation, dikes, drainage systems, and fire walls.

- *Active* - A protection layer that requires a mechanical device or system to actively detect and respond to limit or prevent the loss. An active system must be:
    - reliably designed to work when intended
    - installed according to strict installation rules
    - maintained and tested over its entire life.
    - operate upon demand

  An active system is more prone to failure than a passive system and may cost more over the life of the plant. Examples of active systems are fire detectors, automatic sprinklers, automatic closing valves, pressure relief systems, and process safety interlocks.
- *Procedural* - A protection layer that requires human response to limit or prevent the loss. Because of the need for human reaction and response this form of protection is highly subject to failure or improper action. Examples are an operator pushing a control button to close a valve or a fire brigade hearing an alarm, responding and attacking a fire with hose streams.

These systems can be shown as representing rings or layers of protection that guard the facility from fire and other exposures. Failure of an inner layer can sometimes be overcome by outer layers, albeit often at higher cost and larger potential loss.

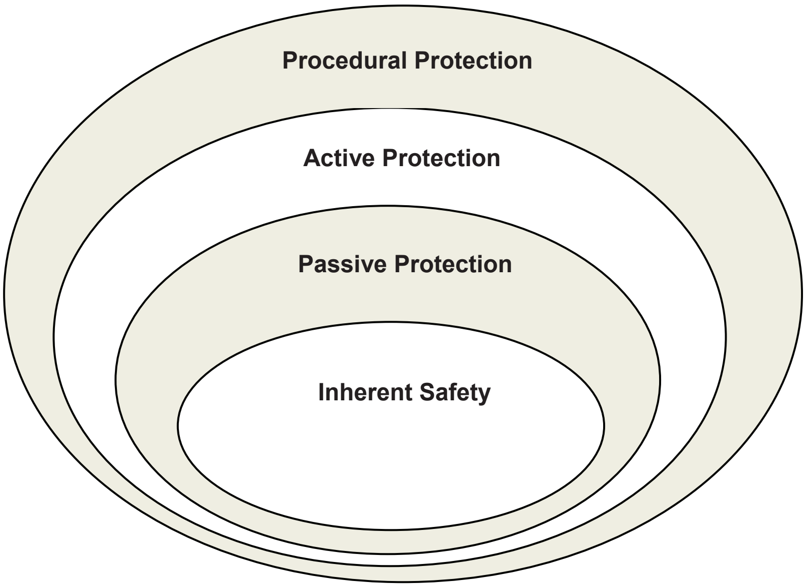

Figure 1. Layers of Protection (CCPS 2008)

There are five approaches to inherently safety (Kletz (1990, 1991)

Intensification (also called Minimization) - reducing the presence or amounts of a hazardous material. In one CPI intensification example, a process required large quantities of flammable feedstock. In the past it had a large day tank within the process unit. This tank was fed from bulk storage tanks located many hundreds (meters) of feet away. The day tank was found to severely expose the production unit to fire, and in fact was originally installed only as a production convenience if supplies were temporarily cut off from the larger tanks (due to a pump failure, for example). The day tank was eliminated and spare pumps installed for reliability. The plant was able to operate as efficiently without the large volume hazardous inventory within the production unit.
Substitution - Replacing a hazardous material with a non-hazardous or less-hazardous material. The classic example of substitution is the use of water as a coolant instead of combustible and highly corrosive thermal oil. Using non-combustible materials instead of low flash point hydrocarbons is another example

such as the substitution of supercritical carbon dioxide instead of hexane solvent in the extraction of caffeine from coffee beans. The hazards of fire and explosion from the solvent are eliminated.

Attenuation - Using less hazardous process conditions or a less hazardous form of material. Attenuation is commonly achieved by using lower temperatures and pressures. It may be achieved through process chemistry (i.e., a new process with less potentially energetic effects). It might also be achieved by using less flammable or corrosive materials.

Limitation-of-Effects - Designing a facility to minimize the impact of a release of material or energy. The most common example of Limitation-of-Effects is proper siting and location of facilities. Space separation can reduce the impact of an energetic release at one location from impacting another by minimizing radiant heat and explosion-generated pressure effects and projectiles. Other examples are providing drainage (which channel flowing liquids to a safe location) and considering prevailing winds and meteorological conditions in design

Simplification and Error Tolerance - Designing a facility so that operating errors are less likely or the process is more forgiving if errors are made. An example is ergonomic design of control systems and control panels. The easier it is for an operator to respond and find the correct shutoff button (for example) the better chance of an orderly safe shutdown.

4. Applying Inherent Safety in Hydro-Metallurgical Solvent Extraction Plants

Many modern hydro-metallurgical solvent extraction plants have a layout shown by Figure 2. While there are many variations, typically multiple side-by-side mixer-settler (MS) cells with high volumes of kerosene are located above a sub grade pit filled with processing equipment, pumps and tanks known as the tank farm. Encircling the MS cells are plastic solvent pipes in trenches, which feed the tank farm by gravity. Use of gravity to flow liquids downwards saves on cost.

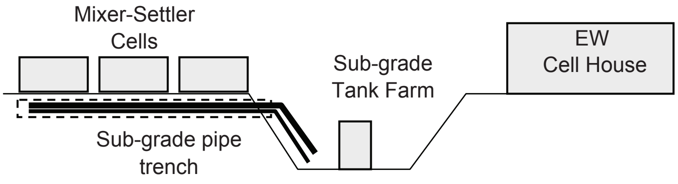

Figure 2. Cross sectional view of “typical” SX plant layout (drawing by author)

Piping systems and vessels in SX plants require corrosion resistance due to acids in solution. Piping in newer SX plants are often high density polyethylene (HDPE) due to low cost, ease of construction, and high corrosion resistance. Some older plants use glass piping which is easily broken.

The use of plastic – especially a thermoplastic like HDPE - creates conditions for failure and release of additional solvent during fire exposure. Plastic pipes are non-conductive and cannot eliminate static charges nor be grounded. Black plastic pipes in hot climates also can cause solvents to heat – by solar radiation – above flash points and ignition of vapours or mists has occurred inside pipes.

Common solvent extractants are mid weight petroleum products, usually a high purity kerosene with flash points in the 38 to 60^{o} C range. Although ignition sensitivity of kerosene is less than lower flash point materials, once ignited it will burn similar to lighter hydrocarbons, producing about 46.4 kJ/g of energy (Collins et al 1978).

The traditional response to fire protection of an SX plant is to add on multiple layers of passive, active and operational protection systems once process and layout design has been determined. Fire protection design may be done months after layout design and impact on design may not be possible. To compensate for poor layout costly, high volume water or foam-water deluge systems are needed in MS cells, pipe trenches, along elevated pipe ways, solvent tanks, and over pumps. Protection may also involve provision of sophisticated fire detection systems, large fire water systems, and barriers or drainage systems.

Properly designed and reliably installed protection systems supplemented by passive barriers and emergency response can protect SX facilities against severe fire damage and should be provided where and when needed based on a hazard risk assessment. However, because kerosene presents a severe and fast developing fire, protection systems must act together rapidly with very high reliability or the fire will gain control and overtax protection systems. If high volume kerosene storage, piping or processing systems fail under fire exposure and release additional fuel the protection system design-basis may well be exceeded. Once a kerosene liquid fire has grown beyond a controllable size, fixed protection systems may not be able to limit the damage.

As a result a facility that has to rely only on fixed fire protection has a higher inherent risk than one which has designed in IS.

While add-on protection is often the only economic solution for existing plants, there are opportunities to lower the overall hazard of new SX plants through inherent safety.

The ideal IS approach is to completely change the technology or process chemistry of SX plants. Some ideas are:

- Develop and use a non-ignitable organic solvent (Intensification)
- Develop and use a less ignitable organic solvent (Substitution)
- Use an additive that lowers the resistivity of the solvent to eliminate the potential for static electricity generation (Attenuation)
- Develop a process to extract minerals by significant reduction in quantities and flow of solvent and eliminate large open pools of kerosene (Intensification)

Until such time as technology changes are made potential IS opportunities should focus on changes to design and layout concepts. Some ideas are:

- Stop the practice of gravity flow in SX process (Simplification and Error Tolerance)
- Install equipment at the same grade level rather than using lower grade areas (Figure 3) (Limitation-of-Effects)

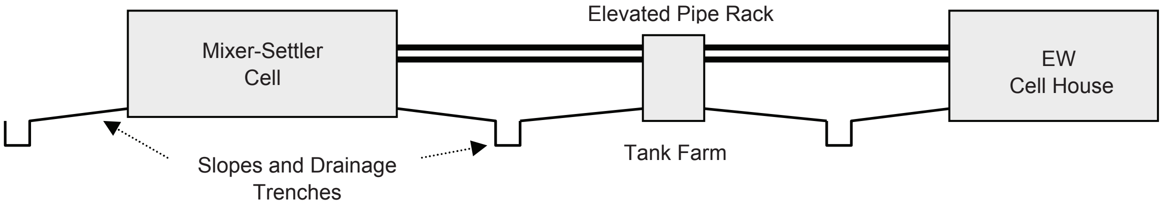

Figure 3. In this IS design sub-grade trenches and tank farms are eliminated, processes are at the same grade with high volume channelled drainage systems, buildings are well separated and pipes (all steel) are on elevated piperacks for easier response and inspection. (Drawing by author)

- Eliminate the use of sub-grade trenches for piping; place piping on elevated piperacks located away from solvent storage or drainage discharge areas (Limitation-of-Effects)
- Separate buildings, vessels and process areas by physical distance based on a risk assessment that includes the impact of radiant heat, wind effects and drainage patterns (Limitation-of-Effects)
- Lower mixer-settler roofs to rest on or near the top of the liquid layer to minimize or eliminate space for flammable vapour accumulation (Intensification)
- Provide liquid and fire barriers such as walls, curbs and dikes between buildings, vessels and process areas (Limitation-of-Effects)
- Provide high capacity drainage systems for spilled solvents with discharge to a safe, remote area. (Limitation-of-Effects)
- Provide high capacity emergency dump (scuttling) systems for mixer-settler cells and other vessels with large quantities of solvents with discharge to a safe, remote area. (Limitation-of-Effects)
- Locate solvent pumps outside of dikes or sub-grade areas enclosing solvent tanks and other equipment (Simplification/error tolerance)
- Use robust, fire resistant conductive materials (like stainless steel) for piping and vessels rather than combustible, frangible, or non-conductive materials like thermoplastics or glass. (Substitution)
- Eliminate materials like rubber for flexible connections on piping (Substitution)
- Find methods to reduce static or mist generation in solvent systems such as submerging in-feed nozzles, minimizing bends and restrictions in piping, reducing solvent flow velocities, and using low turbulence pumps (Intensification).

5. Conclusions

This paper has explored the use of inherent safety concepts for design of hydro-metallurgical solvent extraction plants in the mining industry.

As long as ignitable solvents are used in SX plants reliance on traditional passive, active, and procedural protection systems will be needed to detect, react to and suppress fires in addition to IS.

With creative thinking, motivation and a willingness to effect change the IS principles of intensification, substitution, attenuation, limitation of effects and simplification/error tolerance can be applied to eliminate or reduce the hazard and minimize the need for costly and less reliable add-on fire protection.

The degree to which this can be done is in the hands of the process designer, the mining engineer and the accountant. The use of IS should never limit or impede technology, design or operation and cannot always be economically achieved. However, without the knowledge that IS can be designed in – if carefully considered in the earliest conceptual stages – it will never become part of the mining industry's culture and best practices.

It is recommended that this hydrometallurgical processing industry:

- Study new SX technologies that reduce or minimize the fire hazard
- Form global working groups to study improvements to SX plant design and inherent safety
- Publish Best Practice guidelines on SX plant loss prevention including use of inherent safety
- Support seminars and symposiums on SX plants with focus on loss prevention

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