

Inherently Safer Design (ISD) in Sour Gas Processing Facilities

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An estimated 40% of the world's remaining oil and gas reserves are sour; H₂S is highly toxic, flammable, explosive and corrosive. Engineering companies develop designs to separate oil/gas/water from well fluids. The oil is stabilized, de-sulfurized and desalted; and the sour gas may be treated or compressed and re-injected back into producing, depleted or non-producing reservoirs; to give improved well pressure and performance through miscible flood and as a means of sour gas disposal. With the development of tried, tested and proven process technology; compression and re-injection is taking place at increasingly higher pressures and H₂S concentrations. Given the relative cost effectiveness and importance of engineering in reducing the potential for major accident hazards associated with H₂S over the life-cycle of the facility; effective application of the principles of Inherently Safer Design (ISD) in sour service gas processing facilities is paramount. Successful application of the principles of ISD can improve Health, Safety and Environment (HSE) performance during construction, commissioning, operation and decommissioning phases. This paper discusses the application of ISD in sour service gas processing facilities including: safeguarding strategies, separation and segregation of layout, material selection and various Process, Pipeline and Piping design solutions. It also outlines tools and techniques that organizations can utilize to achieve inherent safety in design and uses examples drawn from projects in the sour gas arena.

Sour Gas, Inherent, Safer, Injection Compressor

INTRODUCTION

The practical application of Inherently Safer Design (ISD) in engineering can be a challenge. Engineering disciplines are often restrained in their work output by standards, codes, contract requirements and Clients wishing to reduce Capital Expenditure (CAPEX). The Process Safety Engineer may be seen as the one who champions, coordinates and secures ISD however in reality the entire team is working to the same constraints. Engineers should not view Health, Safety and Environment (HSE) as the domain of the Process Safety Engineer; all engineering decisions are HSE decisions. All Engineers require a sound theoretical knowledge and a structured approach to HSE in engineering and this should be integrated with an understanding of legal context, Project/Client philosophy, risk analysis and the broader Project/Engineering objectives; as well as constraints such as codes, standards, contract and CAPEX.

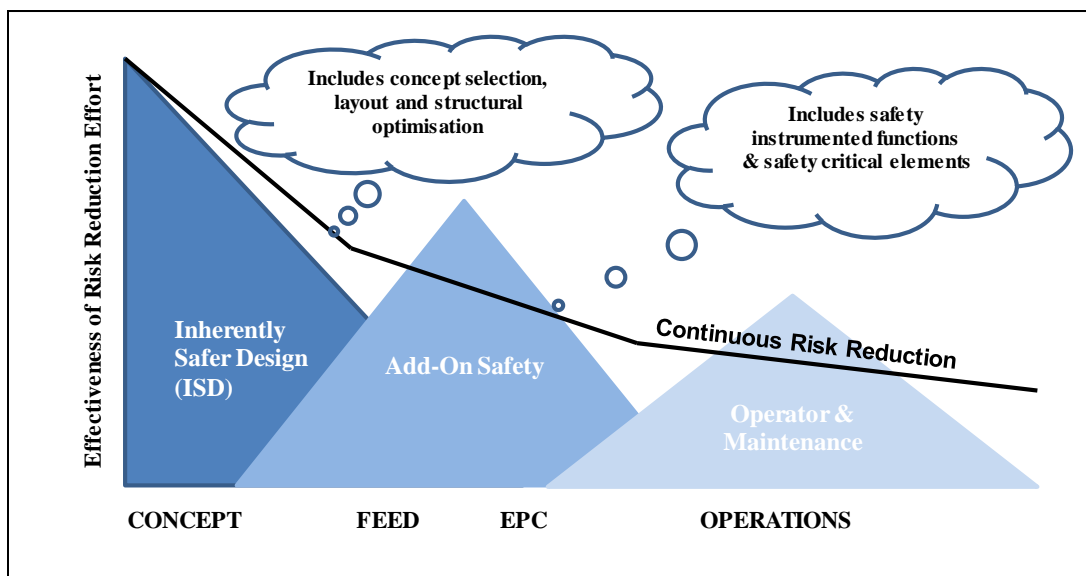


Figure 1. The Effectiveness of Risk Reduction Activities as the Design Progresses

The Principles of Inherently Safer Design (ISD)

Purists tend to regard inherent safety as eliminating/removing the hazard at source or “using materials or process conditions that are less hazardous” [CCPS, 2012]. However it is more helpful to think of ISD as a hierarchy of risk control where risk control measures are applied in an order of priority, though application throughout the range is required to secure As Low as Reasonably Practicable (ALARP) status. The table below outlines the classic definitions of ISD principles.

Table 1. Inherent Safety Principles [Khan, 2003]

Inherent Safety Principle	Definition
Intensification	Reduction in the quantity of hazardous materials
Substitution	Use of safer materials
Attenuation	Operation at comparably safer operating conditions such as room temperature and pressure and liquid phase
Limitation of Effects	Changing the design and operation for less severe effects (e.g. unit segregation)
Simplification	Avoidance of complexities such as multi-product or multi-unit operations, or congested pipe or unit settings
Error Tolerance	Making equipment robust, processes that can bear upsets, reactors able to withstand unwanted reactions, etc.
Avoiding Knock-on Effects	Ample layout spacing, fail safe shut down, open construction
Making Incorrect Assembly Impossible	Unique valve or piping systems to reduce human error
Making Status Clear	Avoidance of complicated equipment and information overloading
Ease of Control	Less hands-on control

This paper sets out how the principles of Inherent Safety which are widely applicable can be focussed for use in sour gas processing. After discussing the principles, the specifics of ISD as they impact safeguarding strategies, separation and segregation of layout, material selection and Process, Pipeline and Piping design are outlined; before closing with a review of the practicalities of achieving ISD.

APPLICATION OF INHERENTLY SAFER DESIGN (ISD) IN SOUR SERVICE

Hydrogen sulphide H₂S is produced deep in oil and gas reservoirs by bacteria that oxidise organic compounds to obtain energy. An estimated 40% of the world's remaining oil and gas reserves are sour; H₂S is highly toxic, flammable, explosive and corrosive. Engineering companies develop designs to separate oil/gas/water from well fluids. The oil is stabilized, desulfurized and desalted. The sour gas may be treated or compressed and re-injected back into producing, depleted or non-producing reservoirs; to give improved well pressure and performance through miscible flood and as a means of sour gas disposal. With the development of tried, tested and proven process technology; compression and re-injection is taking place at increasingly higher pressures and H₂S concentrations. Given the relative cost effectiveness and importance of engineering in reducing the potential for major accident hazards associated with H₂S over the life-cycle of the facility; effective application of the principles of ISD in sour service gas processing facilities is paramount. Successful application of the principles of ISD can improve HSE performance during construction, commissioning, operation and decommissioning phases.

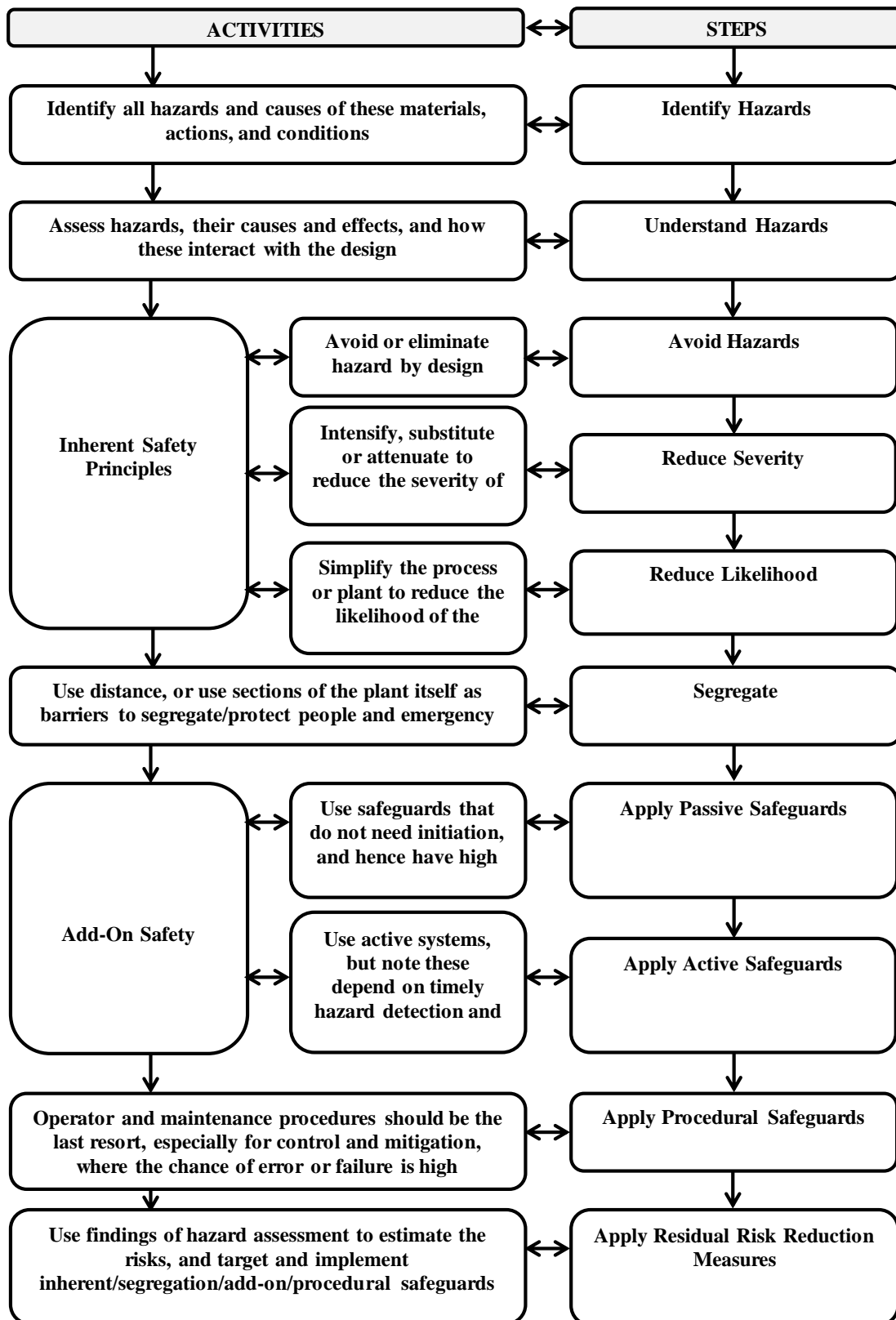


Figure 2. A Systematic Approach to Loss Prevention (Hierarchy of Controls) [Kletz, 2010]

SAFEGUARDING STRATEGIES

The process of concentrating sour material, and increasing the pressure and temperature is in direct opposition of the concept of inherent safety, that is to say “limiting the hazard by using materials and process conditions that are more benign” (CCPS, 2012). However this does not prohibit effective risk reduction and management through safeguarding strategies. The strategies for reducing risk whether directed towards reducing the likelihood or the severity can be classified into; Inherent, Passive, Active or Procedural (CCPS, 2012). Safeguarding Strategies, or engineered solutions, for sour service focus on the passive, active and procedural aspects of eliminating or reducing identified risk in a system. Passive solutions represent features that are present at all times and require little human intervention to ensure they work. Active solutions include for example safety instrumented functions and safety critical elements; they require an active system to operate and intervene, or an actively managed regime of integrity checks and maintenance to ensure they remain effective. Procedural solutions are those that are applied by the actions of operations and maintenance personnel and they may require some engineered features to facilitate procedure application. The passive, active and procedural safeguards highlighted in this paper are not exhaustive. The intention is to highlight unique or novel technologies that can be applied alongside conventional safeguarding techniques focussing on gaining improvement in ISD in sour gas facilities.

SEPARATION AND SEGREGATION OF LAYOUT (PASSIVE)

The Global Asset Protection Services (GAPS) standard [Global Asset Protection Services, 2015] used by insurers usually sets the minimum separation distances to be applied in facilities. The driver here is minimizing equipment damage, escalation of the incident (involving more equipment damage) and therefore insurer liability. GAPS sets out the minimum separation distance taking into account pool fire and heat radiation and specifies that the owner must undertake calculations for explosion. The GAPS standard is conducive to iterative design development. The initial plot layout and separation utilizes the inter-unit spacing table that enables the designer to set the overall plot plan showing unit blocks in early Front End Engineering Design (FEED). This is augmented by a coarse Quantified Risk Assessment (QRA) or consequence modelling for explosion or escalation events such as potential jet fire impingement on large hydrocarbon inventories. As the design progresses the intra-unit spacing table is used to place items within the unit plot plans. Towards the mid to late stage of FEED the QRA is developed that allows further plot optimization on the basis of risk.

The overall plot layout can lead to some interesting challenges and dichotomies. Minimum separation distance is required to satisfy the insurer, additional separation is required as per risk assessment to prevent escalation of Major Accident Hazards (MAH). Increased separation distance directly equals increased cost. The CAPEX motivation is always to shrink the plot. However the objective of the process safety group is to not only ensure sufficient spacing, to prevent escalation, but also to minimize the pipe runs because from the point of view of inherent safety we want to minimize the available inventory to leak between two isolatable points in the event of loss of containment.

H₂S Proximity (Toxic) Zoning Philosophy (Red/Yellow/Green)

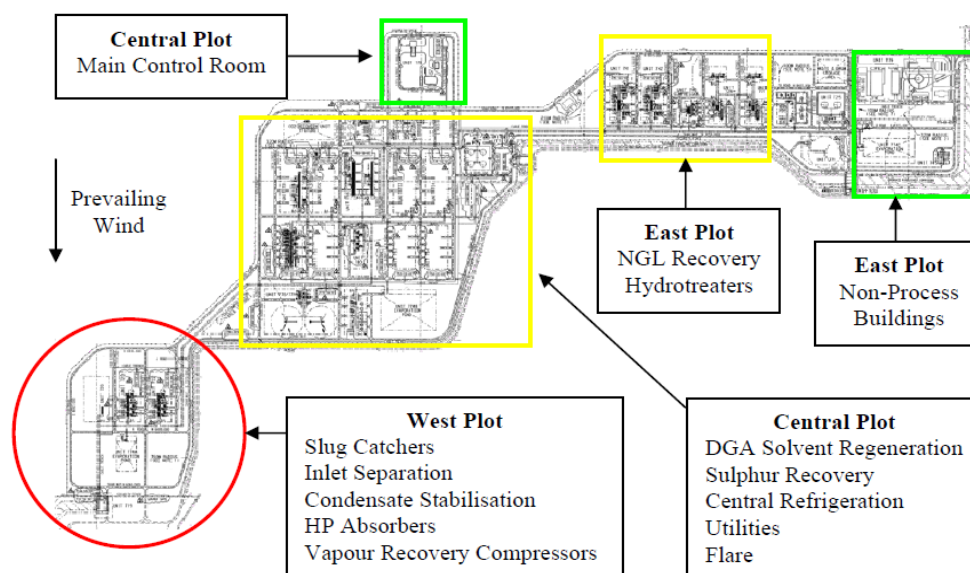


Figure 3. Red, Yellow and Green Zones on the Shah Gas Development [Schulte, 2013]

It is usual for Clients to develop a H₂S Proximity Zoning Philosophy whereby risk levels are determined for the units as being high, medium or low and they are assigned a zone red, yellow or green respectively. The zones are segregated so that high risk red zones are located as far away from occupied areas or buildings as possible. The red zone is minimized to the extent possible and the yellow zone is carefully delineated and restricted within the unit block. The assignment of a zone as red or yellow dictates operational requirements and working procedures to maintain a safe system of work and these requirements are addressed throughout engineering.

Red Zone

The Red Zone threshold is set at a level where serious acute toxic effects on the human body may result in a fatal injury within a short time frame (i.e. immediately). Red Zone work areas are strictly controlled. Non-intrusive work such as security or visual inspection may be conducted with mandatory requirement for personnel to carry functioning H₂S detector and emergency escape mini-filter breathing apparatus. Intrusive maintenance work may be conducted with mandatory requirement for personnel to wear Self-Contained Breathing Apparatus (SCBA) or equivalent. Personal H₂S detectors are worn at all times. Red zone shall make use of strict access control to monitor personnel location. A high level of H₂S training and competency attainment is required for red zone entry.

From a design perspective the primary objective is to apply the principles of ISD in removing and minimising red zones to the extent that is reasonably practicable. The design, where possible, shall avoid the requirement for foreseeable maintenance in red zone areas and facilitate escape when wearing SCBA e.g. stair access/egress and two means of egress. The design allows simple delineation of red zones for the purposes of operational site management. Red zones are segregated to the maximum extent possible from occupied buildings or areas where people may be present.

The FEED design assesses where prolonged work in red zones may be required. No major maintenance in Red Zone is allowed and so provisions are made to enable the Unit to shut-down and depressurise to perform major maintenance; particularly where SCBA may introduce other hazards such as heat stress. Wearing of SCBA sets can narrow the field of vision, increase body temperature (exacerbated by ambient climate conditions), reduce manoeuvrability/coordination and cause general discomfort. The overall impact is on productivity and coordination which can result in the potential to make errors or accidentally damage equipment e.g. valves/instrument connections. It is thus required to minimize the use of SCBA sets.

Simultaneous Operations (SIMOPs)

H₂S is highly toxic, flammable, and explosive so the operators concern for separation and segregation is the health, safety and lives of their personnel. SIMOPs are where you have large workforce numbers undertaking work, for example campaign maintenance or compressor repair, in close proximity to live plant. An operator may desire three gas compression and conditioning trains, to ensure the requisite availability and production output of the facility. Where it is known upfront that there is a requirement to be able to work on one positively isolated gas compression and conditioning train whilst the others are live, the owner will require a SIMOPs philosophy and increased separation distance in design to support the operational requirements for a safe working environment.

The SIMOPs Zone threshold is set at a level where serious acute toxic effects on the human body may result in fatal injury within a prolonged time frame (e.g. a few hours if untreated). The objective of the separation distance is that workers should not be exposed to immediately fatal concentrations of H₂S and that the separation distance gives them time to hear the alarm, recognize the emergency action required, don an emergency escape mini-filter breathing apparatus and escape the hazard to a temporary refuge. SIMOPs Zone work areas are strictly controlled. Within a SIMOPs H₂S Proximity Zone there is a requirement to eliminate and minimize large numbers of people undertaking maintenance work whilst adjacent plant is live.

The safe systems of work and design requirements are very much the same as for Red zone working. Following the provision of adequate separation distance, SIMOPs work activities are managed through the facility specific H₂S HSE Management System, which incorporates the requisite Permit to Work and other requirements as needed to manage the residual risk to ALARP on an ongoing basis through the life of the facility. Incorporation of SIMOPs requirements into design is a relatively new concept; with increasing H₂S concentrations and higher injection pressures it is a welcome development.

Escalation of Events

Quantified Risk Assessment (QRA) and Fire and Explosion Risk Assessment (FERA) enables the designer to determine the credible escalation events e.g. sustained jet fire impingement on large inventory of volatile liquid hydrocarbons; which can escalate to a Boiling Liquid, Expanding Vapour Cloud Explosion (BLEVE) with associated fireball and missiles/projectiles. The studies also enable the determination of the extent of the hazard. This information is used to increase plot separation distances as an inherently safer approach in the first instance. It is important to remember the escalation events must be credible.

Where a credible risk of BLEVE exists, bullet tanks are oriented so that the end caps are not directed towards occupied buildings/or areas. It is very difficult to predict with any confidence the trajectory of missiles though there have been studies showing the end caps generally travel in the direction of orientation, so plot layout accounts for the line of sight of the end caps.

Plot Layout

H₂S is toxic and acutely hazardous to health therefore the overall Plot layout must take into consideration a number of key HSE issues relating to the prevailing wind condition:

- It is important that any temporary or permanently occupied buildings, e.g. construction compounds or administration buildings are placed upwind of any large credible loss of containment events. This is inherently safer.

- When a flare is operating as per design the combustion products from a sour flare contain CO₂, CO, NO, NO₂ and SO₂ which are hazardous to human health. Under abnormal conditions a flare may fail to ignite causing 'flame out' whereby sour material is dispersed into the atmosphere from the flare stack. It is important that flares are placed downwind of any permanent occupied buildings and with due consideration to any pre-existing or planned permanent occupied buildings whether industrial or public. This is inherently safer.
- With regards to emergency escape to a temporary refuge; emergency escape mini filter breathing apparatus generally has a 15 minute usage limit. Whilst theoretically the industrial filter medium can withstand 15 minutes exposure it is not good practice to push the limits. These constraints, coupled with a sound HSE philosophy, enable systematic development of plot layout. For example, you must be able to reach a temporary refuge within 15 minutes from any location on the plot. Sensible assumptions about walking speed wearing breathing apparatus, where breathing is laboured, allow the calculation of how many temporary refuges are required and optimization of location; taking into consideration physical access barriers e.g. security fencing, pipe track or sleeper way. The plot should be orientated to allow the escapee to travel crosswind and upwind, so that they are not continually travelling through a toxic plume.

Ultimately the prevailing wind direction can dictate the orientation of the overall plot plan; particularly when considering the existing infrastructure.

MATERIAL SELECTION (PASSIVE)

In sour gas injection facilities, there are areas where careful material selection is required due to the presence of high H₂S content and extreme operating pressures and temperature conditions. Establishing an integrated material selection and testing programme ensures the safe operation of equipment when installed in high sour and extreme process services, to prevent against the dangers of possible corrosion, fatigue, leaks or ruptures etc.

Where sour gas plants are located in regions with extreme cold weather conditions, there is the challenge of contending with low ambient temperatures when the injection pipelines are being depressurised. For instance, at sub-zero design temperatures in cold winter periods, it has been established from similar sour gas plants that injection lines subjected to ultra-high pressures are susceptible to brittle failures. Whilst the risk is greatest in extreme cold environments, rigorous assessment is required for all ambient conditions, even in arid desert locations.

An integrated material selection process for different materials to be used in the construction of the above ground gas injection lines and plant equipment can be studied for non-heat traced operating conditions at the respective minimum and maximum design conditions. The study should also establish for each material the ease of welding, availability, economics and attainability of the required properties. This paper does not cover details of different material selection and their respective testing, since there are many references already available.

- Where injection pipelines are above ground, pipelines constructed from carbon steel based material are susceptible to embrittlement as carbon steel is known to have a low temperature coefficient for heat conduction. An alloy rich material such as F-22 low-alloy steel could be considered ideal for above ground injection pipelines since it is able to retain good toughness when subjected to varying temperatures.
- Selecting materials with an excellent resistance to reducing and oxidizing fluids, such as sour gas, is important for equipment as the injection compressor suction drums or gas injectors which are in constant operation with sour gas fluids. Alloy materials like Alloy 825, a nickel-iron-chromium alloy can be selected for cladding the internal walls of the drums to meet design conditions and prevent localised corrosion in the drums. Also, material such as Inconel 625 can be used for certain components.
- Where air coolers are employed in continuous mode, there is a possibility of overcooling of stagnant process sour gas which can eventually lead to liquid formation in the air coolers especially in cold climates. The cooling tubes may be subjected to condensation which can gradually lead to corrosion; hence, employing an alloy based material such as Alloy 825 as the construction material can help reduce the risk of possible corrosion in the cooling tubes [Block, 2005].

PROCESS, PIPELINE AND PIPING DESIGN (PASSIVE, ACTIVE AND PROCEDURAL)

There are many difficulties and dangers associated with working in sour fields, such as toxicity of the sour gases, hydrate blockage formation, and corrosion of equipment, that have prevented these resources from being used in the past. The main aim of process design is to create a process that is cost-effective, safe, and environmentally friendly throughout the whole lifetime of the plant.

Compressor System (Passive)

The sour gas compressor plant is the core of the sour gas injection process. In some cases compression can operate at pressures above 600 barg and with H₂S levels exceeding 25 mol%. The need to select the right manufacturers with proven compressor design experience in high pressure and sour gas application is important, as working closely with a carefully selected compressor manufacturer will offer the opportunity to enhance the design to meet the project requirements. The

sour gas leaves the oil and gas separation and treatment section typically at low pressure and high temperature. The sour gas is then cooled and compressed in three or four stages to a pressure in excess of the sub surface storage formation for injection. After each stage, sour gas is cooled, without entering dense phase region. The condensed sour water and any hydrocarbon condensate are removed after each compression stage. The compressed sour gas from the last stage is re-injected into the reservoir to provide partial reservoir pressure maintenance, and reduce the need for gas processing and sulphur production. Figure 4 shows a typical injection compressor system which consist of three compression stages.

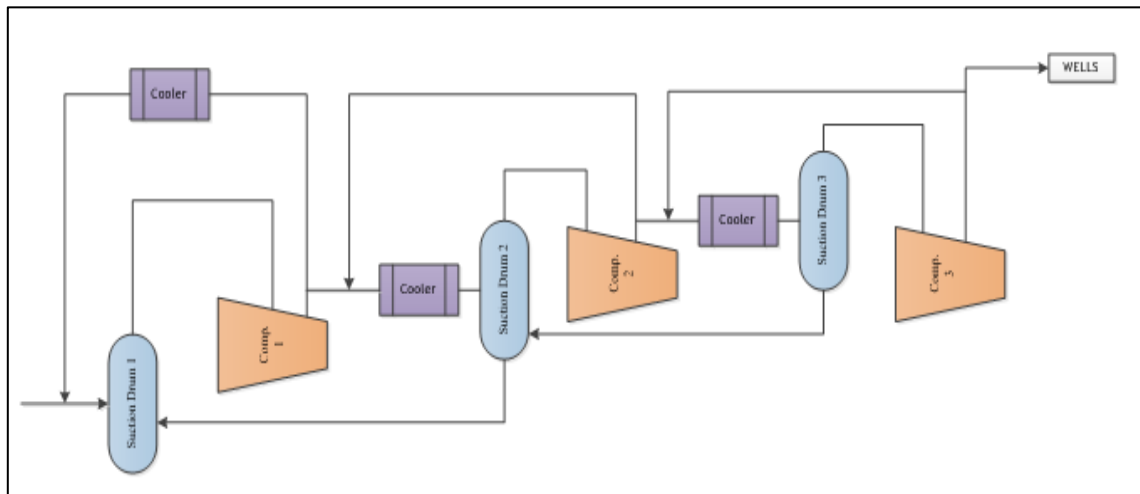


Figure 4. Schematic for a Typical Injection Compressor System

Leak Path Minimization (Passive)

With high pressure operation the potential for leak or catastrophic failure of process equipment and piping becomes more likely, hence an inherent safer approach is to design your system for total containment. This means all process piping/equipment shall be fully pressure rated to withstand the highest pressure that can be expected at all operating conditions. A very simple example is designing injection compressor discharge piping and joints capable of withstanding the maximum possible pressure, if outlets are closed. If total process containment is not possible or practicable, an alternative solution is leak path reduction.

The main aim of leak path reduction is to minimize the risk of exposure of people to sour gas release during the high pressure sour gas compression process. The potential for sour gas leak from compressor rotating and stationary seal rings is a significant concern. Suitable sealing in a compressor will reduce leak paths and potential loss of containment leading to less risk to people, asset and environment. Oil seals were very common in old compression designs but their use today is restricted to lower risk applications due to lower reliability and operational problems. Modern re-injection compressors are designed to utilize tandem dry gas seals. These operate on the principle of creating gas barriers between rotating and stationary seal rings, which act against the flow of leaking process gas eliminating potential sources of sour gas leaks. The sealing function is achieved without liquid injection as the sour gas injection process is normally designed to operate as a dry plant. The tandem dry gas seal design has three layers of protection against the release of sour gas. The primary and secondary seal gas systems are designed for high pressures such that they can withstand the process gas design pressures to eliminate sour gas discharge into the atmosphere. The secondary seal gas which is mainly nitrogen has the capability to actively prevent hydrocarbon release in the event of the primary seal failure. The secondary vent is routed to atmosphere while the vent for the primary seal gas is routed to a flare system, thereby preventing any hydrocarbon gas leakage to the atmosphere. The tertiary seal forms a third and final barrier against sour gas release into the atmosphere. A typical tandem dry seal gas is shown Figure 5.

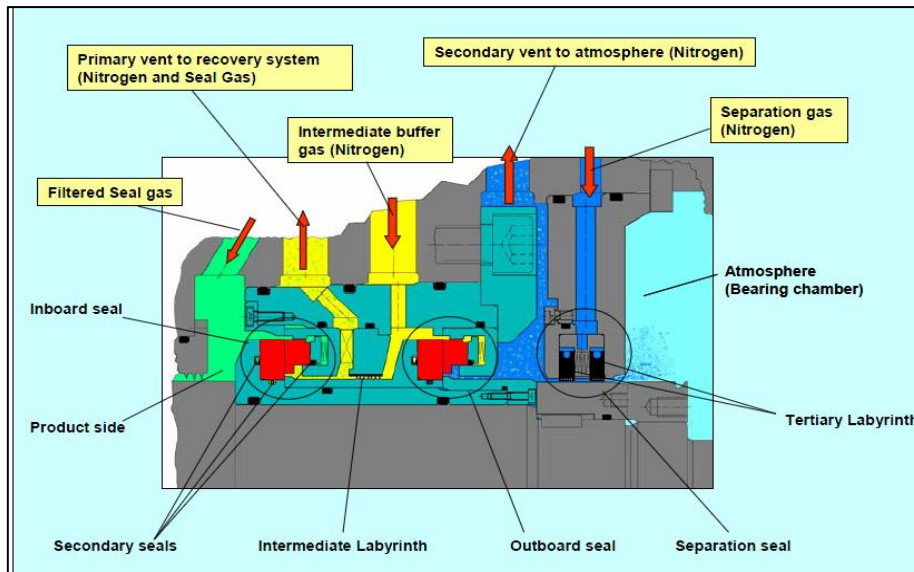


Figure 5. Typical Tandem Dry Seal Arrangement (Block, 2005)

Flange joints are another vulnerable point of pressurized systems. A bolted flange joint leaks when the material contained in the system escapes through the gasket pores or around the gasket and the flange face. This occurs when the load on the gasket has fallen below its minimum seal pressure. The main factors which cause a bolted flange to leak are gasket creep, bolt creep, vibration, elastic interaction and differential thermal expansion (George, 2010). Use of fit for purpose gasket and bolt selection followed by correct placement of gasket and proper tightening of bolts can reduce likelihood of failure of flanged joints. An inherent safer approach will be use of welded pipe and butt welded valves with special stem sealing wherever possible, minimise the use of flanges and eliminate threaded connections. By eliminating the likelihood of sour gas leaking to atmosphere this leads to lower risk of fire, explosion and toxic gas release to people, asset and environment.

Other leak sources relate to piping systems and the majority of these are vibration induced failures of small bore piping. The vibration issue is not properly address via piping design code, and the negative effect of vibration might be incorrectly ignored in design stage. In injection compressor plant this vibration can be noticed on small branch connection which includes relief lines, instrumentation ports, nozzles, drains and valves etc. Figure 6 shows the different factors which contribute to vibration in the compressor and associated piping systems. The piping vibration can be mitigated if a proper design philosophy is applied and vibration assessment is performed during design stage. The inherent safety approach is to avoid small bore piping where possible. Unfortunately, avoidance is not always practical and the best solution is to design them such that they are less subjected to vibration i.e. by reducing the level of vibration to which piping system is exposed or provide adequate support so that it can withstand any vibration. In addition appropriate vibration detection and trip systems can also be installed for a compressor which can trip the system and thereby avoid any vibration induced failure.

Last but not least care should be taken to ensure the compressor safeguarding system has a fail-safe design. This means that failure of the controls or associated systems will result in the system going to the operational mode that has been pre-determined as safest (DNV, 2010). Examples related to the injection compressor include anti-surge valve will ‘fail to open’ position, shutdown valves will ‘fail to close’ position and depressurisation valves ‘fail to open’ position.

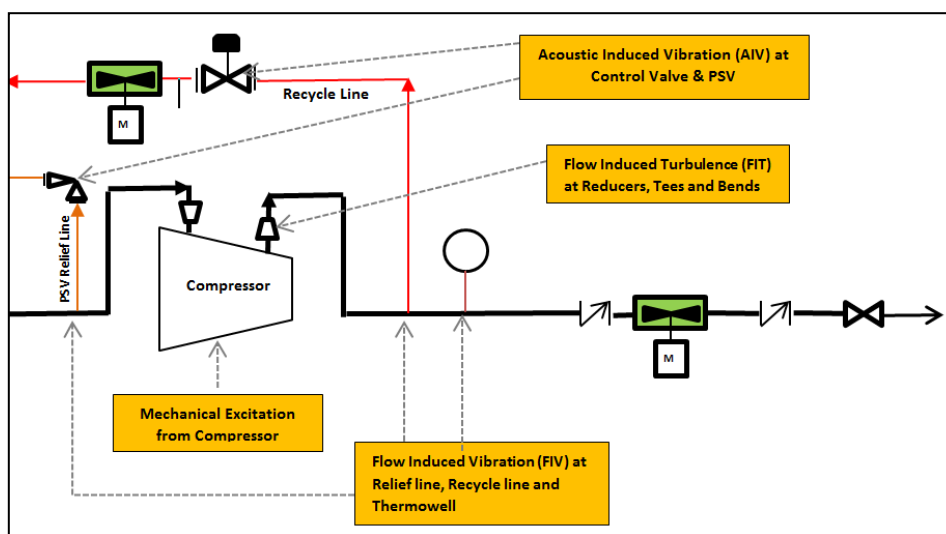


Figure 6. Vibration Risk Zones for Compressor and Associated Piping System

Unrestrained Pipeline (Passive)

The expansive or mechanical behaviour of buried pipelines under pressure and temperature depends primarily on the interaction between the pipes and surrounding soil, and even more so with sour gas injection pipelines subjected to high pressures and high temperature (HPHT) conditions. Tests have shown that designing gas injection pipelines as conventional restrained pipelines at high design temperatures may introduce expansion stress and possible rupture. To reduce such risk, HPHT pipelines may be designed as unrestrained heavy wall pipelines, with expansion loops buried in engineered backfill/padding to achieve the required fatigue life. With such design, the HPHT pipelines will expand and relieve any force without damage. Further control of such forces is achieved with the use of relatively small anchor blocks on the pipeline. A typical representation of pipeline expansion loops and anchor block arrangement is shown in Figure 7.

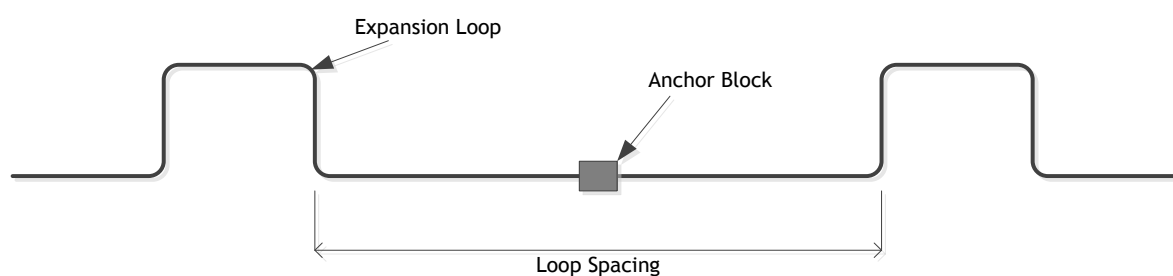


Figure 7. Typical Pipeline Expansion Loop Schematic

This strategy to safeguard the pipeline from the risk of rupture and sour gas release is considered a “walk away” design solution, robust enough to last the plant’s life cycle without the need for high levels of maintenance. However, this should not stop designers utilising some form of monitoring to ensure the HPHT pipelines are behaving as designed.

Isolation (Passive)

Injection lines and equipment in sour gas service should be designed to have double block and bleed to maintain positive isolation regardless of pressure rating. This approach for sour service lines establishes a double barrier of isolation between the injection lines and wells. In the event of an upset this will help limit inventories to be flared, or in the event of a leak it will limit the size of a loss of containment event, and allow for the removal and/or reinstatement of piping connecting a well head in a safe manner without having to shut-down or flare a much larger volume.

Hard-Pipe Venting (Passive)

The application of hard-piping to closed hydrocarbon drains or flare in sour gas service is an ISD compared to using flexible hose connections for draining through a bleed. Having all low point drains including low point pockets from injection lines hard-piped to a closed drain header with the drain lines design to slope, will ensure fluids are freely drained. This can help eliminate the venting of sour fluids to the atmosphere when bleeds are opened, thus reducing the risk of having operators use temporary flexible hoses to connect bleed valves to a safe location or drain.

Flaring and Emission (Passive)

Flare systems are designed to safely dispose any unwanted gas generated in sour gas processing facility during both normal operation and emergency scenarios (e.g. during an external fire impinging on a process vessel or due a compressor failure etc.). In an emergency situation, a large inventory of high velocity sour gas must be flared and this creates significant safety (thermal radiation, noise) and environment impact (NO_x, SO_x, CO and CO₂ emissions). These challenges can be overcome by use of flare gas reduction and recovery process. An example related to sour gas compressor plant is recycling inventory to a second train and thereby reducing any sour gas flaring inventory.

In cases where planned maintenance shut-down activities are scheduled in a sour gas facility, sweet gas can be employed to purge the sour gas injection plant and pipelines to avoid non-emergency sour gas flaring thereby reducing any Sulphur Dioxide (SO₂) emissions and environmental impact. Consideration can be given to designing the process of sweet gas purging in an automatic mode, as this will minimise human intervention during sweet gas purging operation. Technology exists for graphical displays and software programming that can be built specifically for sweet gas purging automation.

Overpressure Protection (Active)

System overpressure conditions are very likely scenarios to occur in sour gas injection plants if not adequately controlled through safer and reliable overpressure protection design. Since these facilities are characterised by HPHT conditions requiring high capacity injection compressors to operate within these process parameters, safeguarding and controlling against overpressure scenarios is important. The use of High Integrity Pressure Protection Systems (HIPPS), often as the last line of defence for protecting downstream operation from over pressurisation is becoming increasingly popular. HIPPS are independently instrumented protective devices, a type of Safety Instrumented Systems (SIS) designed with higher integrity to take a process to a safe state when predetermined conditions are met. Each Safety Instrumented Function (SIF) within a SIS is designed to have a Safety Integrity Level (SIL) rating which may vary from one system to the other depending on the process to be controlled. Due to their high-integrity performance, HIPPS can sometimes be considered a better design

alternative to traditional mechanical relief devices for overpressure protection of production wells and injection flowlines, rather than relying upon numerous Pressure Safety Valves which can present hazards such as leaks or are simply not feasible, particularly in some gathering systems.

Hydrate and/or Corrosion (Active)

Water condensation and/or hydrate formation are serious design/operation issue within sour gas injection facilities; and represent a significant risk to process safety as it can result in the plugging of both pipes and safety critical instrumentations. Hydrates typically form in a process where light hydrocarbon, H₂S, water vapour and low temperatures or high pressures are present. A better solution to ensure safety and efficiency of plant is preventing the hydrate formation (Neutrium, 2015).

Even if hydrate formation is avoided by maintaining the compression temperature above the hydrate formation temperature or by use of a specific dew point monitoring or moisture analysing device, any excess water accelerates corrosion of equipment and piping in contact with sour gas, this is the main reason why dehydration of sour gas is required ideally before being fed to sour gas compression. The dehydration facilities help in reducing the quantity of water vapour in a sour gas and this will lower the dew point and therefore lower the likelihood of hydrate formation. There are several dehydration technologies available; Molecular sieves and Glycol dehydration are commonly used.

Enhanced Smart-Pig for Pipeline Inspection (Procedural)

The use of full inspection on pipeline is a technology that is readily available with varying capabilities. Smart pigs can be used to inspect pipelines for defects but current technology is limited to inspecting up to 40mm pipe wall thickness. Working with recognised pigging specialists can prove to be valuable, as this limitation can be improved for gas injection pipeline thickness ranging up to say 55mm. The enhanced smart-pig tool gives engineers the flexibility of designing HPHT injection pipelines beyond the typical thickness of 40mm.

Moisture Analysers for Wet Upset Conditions (Procedural)

Sour gas injection plant designed to operate in a water dry environment may be subjected to wet sour service under upset conditions. A wet sour service environment introduces the potential for wet H₂S cracking, corrosion and accelerated fatigue of associated piping and pipelines. The impact of wet upset condition is long term considering this phenomenon can go undetected before they manifest in the form of corrosion which can lead to leak, rupture and/or possible loss of containment. The provision of moisture analyser alarms on inlet lines to the injection compressor systems helps gives clarity for operations personnel required to intervene upon wet upset conditions. The analysers can be programmed to trip at variable thresholds (minimum concentration of moisture) depending on the ambient temperature.

Breathing Air System (Procedural)

A well designed and robust breathing air system can be implemented at sour gas facilities especially in areas where personnel are expected to be under air at all times. Such design may include a series of multiple outlet manifolds that can be installed at risk areas to supply breathing air to personnel via personal airline hoses. The portable retractable airline hose reels can be used over longer distances, and they make for good housekeeping when not in use, as they keep work areas tidy and safe. They are a much safer replacement for SCBA packs which can create hazard particularly when working at heights. It is important for engineers to design the air line connections to be incompatible with all other fittings for non-breathable air or gases. Careful consideration should also be given to the valve connection on the “person side” to prevent ingress of gases/dirt when not connected to the breathing air supply mains.

PRACTICALITIES OF ACHIEVING INHERENTLY SAFER DESIGN (ISD)

ISD is a relative concept and does not provide absolute yes/no answers. You can never guarantee a 100% safe design. One option may be inherently safer than another; one option may be safer than another taking into consideration the planned mode of operation; two options may present the same risk level but one risk may be easier to manage. Applying the principles of ISD only means something when you are comparing one option against another.

A sound strategy for effective application will make use of a range of tools and techniques owing to the associated advantages and disadvantages of each, which could include: Procedures, Checklists, Workshops, Hazard Indices e.g. Dow FEI and CEI, Engagement Surveys, ISD Training, Competence or Traditional Risk Studies. The selection of tools and techniques will depend on the organizations policy or attitude towards ISD, existing HSE management system framework, available resources, baseline competence and any constraints given by legal, contractual or standard requirements.

The below table outlines a range of tools and techniques for implementing ISD; used by organizations in the oil and gas industry. The table highlights advantages and disadvantages of each.

Table 2 Range of Tools and Techniques for Implementing ISD

Description	Advantages	Disadvantages
<p>Procedure</p> <p>A Company document that details what is required, by whom and when; with regards to ISD.</p>	<p>Makes it clear what is required, by whom and when.</p> <p>Consistent application across multiple Projects.</p> <p>Procedure usually has supporting documents and attachments e.g. guidance, checklists, forms that support implementation.</p> <p>Procedure is usually accompanied by a company HSE management system framework that enables the procedure to be implemented e.g. training, competency verification, quality checking on deliverables.</p>	<p>Dependent upon the quality of content.</p> <p>The requirements may not be flowed down contractually to the Designer.</p> <p>The procedure may not be clear as to what the Designer's responsibilities are.</p> <p>The selected Designer may not possess the same level of ISD awareness and competency as the Company baseline expectation.</p>
<p>Checklist</p> <p>A checklist that asks pre-defined questions regarding the opportunity to apply specific ISD strategies or requirements; and requires a record of ISD implemented or actions required.</p>	<p>Takes a large amount of 'leg-work' out of the task and makes it easier for Projects to undertake.</p> <p>Consistent areas of verification and application across multiple Projects.</p>	<p>Dependent upon the checklist relevancy and quality of content.</p> <p>Dependent upon the competency and diligence of individuals(s) populating the checklist.</p> <p>Can take lower priority on Projects with an aggressive schedule.</p> <p>Can become a tick box exercise.</p>
<p>Workshops</p> <p>A facilitated workshop where a multi-discipline team are aligned on the principles of ISD, Project philosophies and strategies, are given the opportunity to review Project specific design options, make group decisions and generate actions for the Project to execute.</p>	<p>Great for generating alignment of purpose, securing group engagement and generating enthusiasm, motivation and meaningful ISD actions.</p>	<p>The alignment, enthusiasm and motivation to undertake the actions agreed can meet inertia once the Project work gets underway.</p> <p>People within the organization change over time and the knowledge or ownership of actions can get forgotten.</p>
<p>Engagement Survey</p> <p>A survey that asks employees questions regarding ISD and leadership, organizational culture, competency, activities/application, decision making and perceived barriers</p>	<p>A useful tool to understand the baseline competency within an organization, engagement in ISD and organizational barriers to implementation.</p>	<p>The survey in itself does not yield any improvement or action regarding ISD.</p> <p>Employees may answer as they think management want to hear.</p> <p>The results are open to interpretation.</p> <p>The Designers perspective may be different to the Company.</p>
<p>ISD Training</p> <p>Either academic university led, industry courses or in house giving awareness of the principles of ISD and exercises in practical application.</p>	<p>An essential starting point and baseline for engineering knowledge to grow.</p>	<p>Training in itself does not give competence.</p> <p>Competence in an engineering discipline is required to maximize training impact.</p>
<p>Competence</p> <p>Competence is defined as theoretical knowledge supported by experience and practical application.</p>	<p>Effective at securing ISD in engineering.</p>	<p>By definition it takes time and experience to acquire competence.</p> <p>Competence needs to be supported by an environment that enables or allows ISD application.</p>

Description	Advantages	Disadvantages
<p>Traditional Risk Studies</p> <p>Process Hazards Analysis (PHA) (Hazard Identification (HAZID) and Hazards and Operability (HAZOP) with risk ranking),</p> <p>Layers of Protection Analysis (LOPA) and Quantified Risk Assessment (QRA) facilitate the proactive identification of hazards, assessment of frequency and consequence and the development of proportionate risk control measures.</p>	<p>Commonly understood and applied methodologies in industry.</p> <p>Better reflects the application of a hierarchy of risk controls through the range of available risk control strategies to achieve ALARP.</p> <p>The studies are effective if used at the right stage of design and in an iterative manner to influence design decisions to achieve risk reduction.</p>	<p>Potential to miss opportunities for impactful ISD early design decisions if not applied coherently.</p> <p>Potential to highlight required design changes late and cause schedule delay and increased design cost.</p>

In practice the approach used in engineering depends upon the Client philosophy and requirements, the scale and complexity of the Project, and schedule/budget constraints. As a minimum the traditional safety studies are always applied. These must be supported by competent application of methodology and engineering input; cost conscious Projects with tight schedules can diminish the effectiveness of the traditional safety studies approach to securing ISD upfront. Larger, high risk and high complexity Projects, tend to be executed by Clients with forward thinking attitudes to process safety and risk management. These Projects tend to incorporate procedures, checklists, workshops, engagement surveys, ISD training as well as the traditional safety studies. Arguably larger, high risk, Projects have more to lose and can therefore reap more rewards from the upfront investment in applying ISD.

CONCLUSIONS

The process of concentrating sour material, and increasing the pressure and temperature, is in opposition to the purist's interpretation of ISD whereby the risk is reduced through modification to the materials and process conditions. To effectively achieve ISD in sour service within the engineering process, it is necessary to adopt a hierarchy of risk controls, safeguarding strategies and engineering solutions to secure ALARP status. The risk controls are broadly categorised as Inherent, Passive, Active or Procedural. This paper explored unique or novel aspects, specific to sour service, which included the following safeguarding strategies: separation and segregation of layout, material selection and various Process, Pipeline and Piping design solutions.

- Plot layout, separation and segregation are key components of the application of ISD in sour service, which is addressed very early on in the design process.
- An integrated material selection process is essential to ensure the facility meets the rigours of high H₂S concentration, pressure and temperature conditions in operational use.
- Process, Pipeline and Piping solutions specific to sour service and that represent Passive, Active or Procedural safeguarding strategies were outlined. These included:

Table 3 Passive, Active or Procedural Safeguarding Strategies Outlined

Passive	Active	Procedural
Compressor System, Leak Path Minimization, Unrestrained Pipeline, Isolation, Hard-Pipe Venting and Flaring and Emission.	Overpressure Protection and Hydrate and/or Corrosion mitigation.	Enhanced Smart-Pig for Pipeline Inspection, Moisture Analysers for Wet Upset Conditions and Breathing Air System.
Definition: Passive solutions i.e. features that are present at all times and do not require activation or action.	Definition: Active solutions e.g. safety instrumented functions and safety critical elements.	Definition: Procedural solutions applied by operations and maintenance personnel.

Finally there are a number of tools and techniques that could be used to support the ISD process; due to the advantages and associated disadvantages of each, a range of approaches is required to achieve effective application of ISD. The selection of tools and techniques will depend on the organizations policy or attitude towards ISD, existing HSE management system framework, available resources, baseline competence and any constraints given by legal, contractual or standard requirements.

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