"The effects of sulphide stress corrosion cracking can have a devastating effect on a natural gas transmission pipeline.

The challenge of how to provide effective protective systems to solve this problem can now be achieved using modern analyser technology and IEC 61508 risk based design."

WHITE PAPER

Introduction

Processing natural gas before shipment in transportation pipelines is a necessity to meet the stringent entry requirements of pipeline operators.

In addition to removing water and other hydrocarbon components, high levels of sulphur can be a barrier to entry into a pipeline transportation system.

Sulphur exists in natural gas as Hydrogen Sulphide (H_2S). If natural gas contains more than 5.7 milligrams of H_2S per cubic meter, it is termed 'sour gas'[1].

H_2S, or sour gas has highly corrosive properties that can cause embrittlement of steel pipelines through a process of sulphide stress corrosion cracking (SSCC). For this phenomenon to occur, free water (H_2O) must be present in the pipeline together with high levels of H_2S over a period of time.

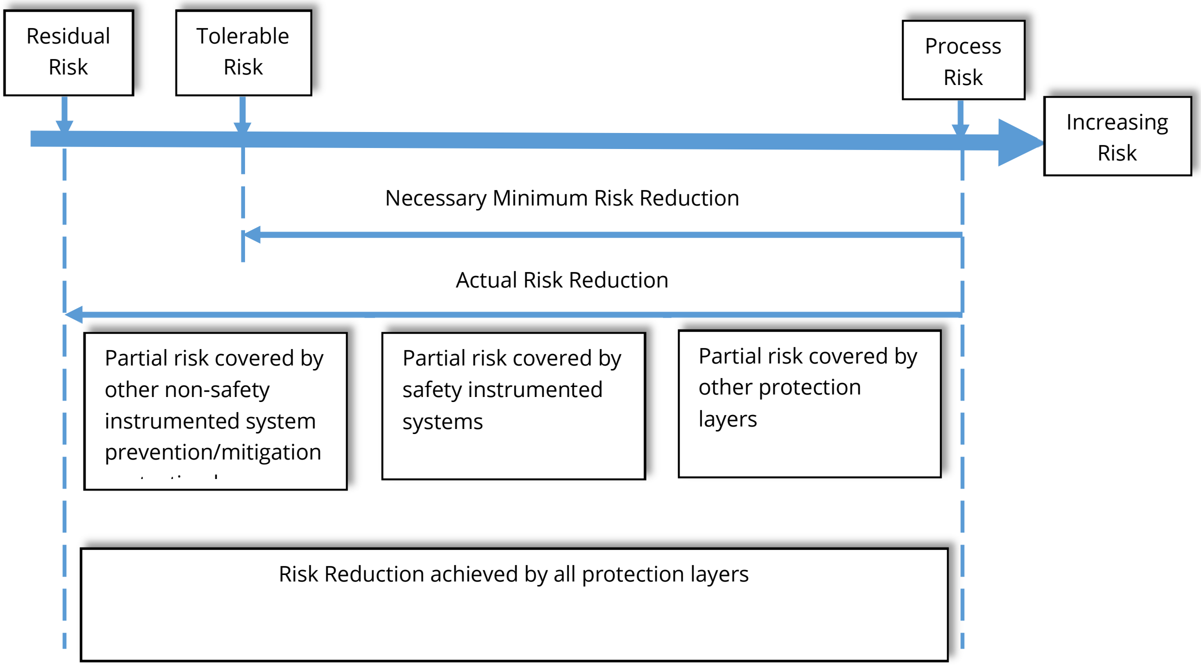
SSCC is a significant risk that can lead to catastrophic failure of a natural gas transportation pipeline resulting in loss of containment of an extremely hazardous material. Obviously, this can give rise to significant safety, environment and commercial consequences.

The severity of the consequences, or process risk, may exceed the tolerable risk limits set out in an organisation's health, safety and environment policy. They may also exceed what is deemed acceptable to the Regulator (the Health and Safety Executive - HSE, in the United Kingdom) in terms of the risk to workers and members of the public[2]. From a commercial point of view, the loss of a pipeline system due to SSCC would likely result in significant financial impact as well as reputational damage for the organisation concerned.

[1] Sour gas definition, naturalgas.org website.
[2] Reducing Risks Protecting People, UK Health & Safety Executive.

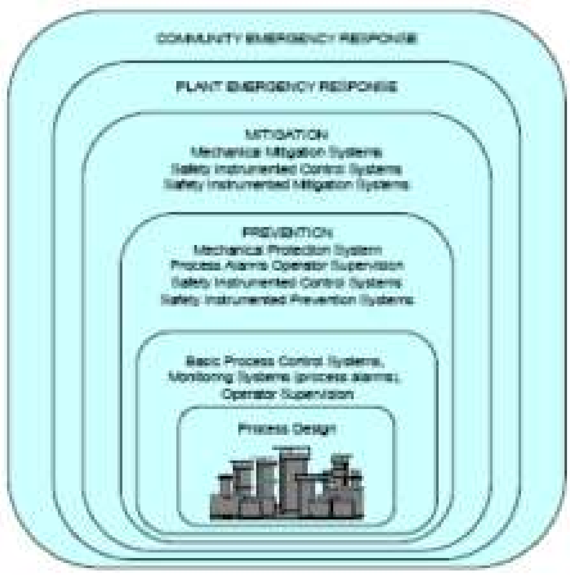
Assessing the Risk

When there is a gap between the perceived process risk and the tolerable risk set by an organisation, protective layers are needed to reduce the process risk to an acceptable level commonly termed the 'residual risk', which is the risk remaining after the protective layers have been put in place. This is illustrated in the following diagram.



As shown in the above diagram, there are a number of protective layers that can be put in place to reduce the risk to below an organisation's tolerable limit. These multiple layers of protection are often collectively referred to in the industry as 'Defence in Depth' and one particular layer of protection is that provided by a safety instrumented system (SIS). The diagram on the right is frequently used to compare the multiple layers of protection to the 'layers of skin of an onion'.

This **White Paper** is concerned with the design of the risk reduction provided by a SIS in the protection of a natural gas pipeline from the effects of SSCC. The design of this layer of protection uses a risk based approach to deliver a known amount of risk reduction using an International Standard, IEC 61508[3] for the design of such systems.



[3] IEC 61508 Functional Safety of Electrical/Electronic/Programmable Electronic Safety Related Systems.

Market Drivers

During the lifetime of an oil & gas facility, the physical characteristics of the process can change due to variations in the composition of feedstock, the introduction of different raw materials or a change in the 'operating envelope'.

In today's highly competitive environment, organisations are constantly seeking to maximise the return on investment in plant assets. This is reflected in the drive to reduce operating costs and to extend the working life of an asset wherever it is safe and practical to do so. Modifying the plant to meet a change in operating conditions is always an option should the need arise.

With this in mind, an increase in the H_2S component of natural gas feedstock presents an immediate problem for legacy equipment in that it may not be rated for sour gas service. In some cases it may be feasible to modify the design of the process to accommodate the change in feedstock by installing new suitably rated equipment. But often this is impractical or too costly, as would likely be the case for a natural gas pipeline not rated for sour gas service.

When an inherently safe solution to this problem cannot be found, an alternative course of action is to install protective measures which are both proportionate to the risk of the hazard and reasonably achievable in terms of practicality and cost.

Historical Approach

The original design of a process facility will have taken account of the physical properties of the raw materials processed and specified equipment accordingly. Where equipment is 'wetted' by sour gas, materials are usually specified to NACE requirements[4].

A number of processes are available to remove H_2S from natural gas, however, some produce water as a by-product. When this is the case, additional processes, such as molecular sieves may be needed to produce export quality gas that is sufficiently low in H_2S and water content.

To ensure that the quality of the export gas remains within contractual quality limits, on-line instrumentation (analysers) is usually installed to provide independent high level water dew point and H_2S alarms. In the event of a high level alarm, an Operator is required to take some form of corrective action to restore the quality of the export gas in a timely manner. This has been a standard approach for many years because on-line analysers have been considered to be insufficiently reliable to use in a system providing automatic shutdown. The problem with this approach is that the Operator is not a very reliable layer of protection and only warrants a limited amount of credit in any risk analysis.

The solution is then to provide a layer of automated protection using a SIS that has predictable reliability performance characteristics and hence provides a known amount of risk reduction.

The Solution

The design of the SIS layer of protection is based on a combination of modern on-line analyser technology and a risk based design process using the IEC 61508 standard.

In this section we look at what is required to achieve a risk based solution. Secondly, we look at what technologies are available, with which to build a suitable analyser based SIS.

[4] NACE International (formerly the National Association of Corrosion Engineers), MR0175 / ISO 15156.

IEC 61508 advocates the use of a lifecycle approach from initial concept to final decommissioning of the SIS to produce a credible design solution that satisfies the expectations of an organisation and the Regulator. This is an important factor because the guidance given in IEC 61508 is seen as 'current best practice' by Regulators in many countries throughout the world.

The lifecycle begins with a detailed hazard and risk assessment of the problem scenario and uses this to define a target specification for the safety instrumented function (SIF) under consideration. The target specification is given in two parts; the safety function and safety integrity. The former is a description of what the SIF is required to do in practical terms to mitigate the hazard. The latter is a performance target that indicates the required reliability of the SIF. This is defined as the safety integrity level (SIL). The mode of operation of the SIS depends on how often it is called upon to act. IEC 61508 defines the mode of operation in the following ways.

Low demand mode*: where the safety function is only performed on demand, in order to transfer the equipment under control into a specified safe state, and where the frequency of demands is no greater than one per year.*

High demand mode*: where the safety function is only performed on demand, in order to transfer the equipment under control into a specified safe state, and where the frequency of demands is greater than one per year.*

Continuous mode*: where the safety function retains the equipment under control in a safe state as part of normal operation.*

The remainder of the lifecycle is concerned with the design, operation, maintenance, modification and final decommissioning of the SIS.

The Lifecycle Approach

The main advantage of using a lifecycle approach is the opportunity to minimise 'systematic error' in the design process, but this is not the only benefit. The SIL targeting part of the lifecycle process defines a protection system performance level that will provide a known amount of risk reduction in relation to the perceived process risk and an organisation's corporate risk guidelines.

A further benefit of the lifecycle approach is that it can be used to make use of existing plant infrastructure, e.g. the on-site emergency shutdown system (ESD) to realise a cost effective modification. It also serves as a reference point in future SIS modification projects.

Applying Risk Based Design

The IEC 61508 standard offers guidance on acceptable criteria for the selection of equipment hardware (and software if required). The standard states that the following aspects must be taken into account during the selection process.

- Quantification of the effects of random hardware failures.
- Assessment of architectural constraints on hardware safety integrity.
- Measures in place for the avoidance and control of systematic faults.

Quantification of random hardware failures is performed using standard reliability engineering techniques. Two methods are available to comply with architectural requirements and these are described as Route 1_H and Route 2_H in IEC 61508. There are similar methods for complying with systematic safety integrity requirements and these are referred to as Route 1_S, Route 2_S and Route 3_S in IEC 61508.

Quantification of the effects of random hardware failures is relatively straight forward using the guidance given in part 6 of the standard. Complying with the requirements for architectural constraints and systematic safety integrity is less clear and is dependent on the information available.

If an 'End User' has a significant amount of field operational failure data on the performance of the analysers under consideration, then Routes 2_H and 2_S might be the preferred route to compliance. Route 2_S is referred to as 'Proven in Use' and this describes an assessment of the performance of the equipment on the 'End Users' site.

If field operational failure data is not available, then an alternative might be to use Routes 1_H and 1_S. This is a possible course of action because a number of analysers on the market have their software element certified to a specific SIL category, in accordance with IEC 61508 part 3 and so achieve compliance with Route 1_S. Route 1_H is a hardware analysis and the favoured approach is to perform this using failure mode effect analysis (FMEA). This is an analysis of random hardware failures to quantify safe and dangerous failures. This information is then used to compute a failure rate for reliability calculations, determine safe failure fraction (SFF) and diagnostic coverage (DC).

Safe failure fraction is a parameter used in conjunction with the target SIL to determine the degree of redundancy, or hardware fault tolerance required in the SIS design. IEC 61508 provides reference tables to enable the designer to determine the required redundancy depending on how complex the equipment is.

Diagnostic coverage is a parameter that is used in performing the reliability calculations for the SIS.

Definitions of both Safe Failure Fraction and Diagnostic Coverage are given in IEC 61508.

Available Technology

There are a number of technologies on the market that would be suitable for natural gas pipeline monitoring. The most popular of these are;

Lead acetate tape – this technology has been available for several decades. It has evolved over this period of time and benefited from advancements in micro-electronics to become one of the standard methods for detecting H_2S in natural gas pipeline transmission systems. Key advantages of this type of analyser are its relatively low purchase cost and low operational complexity. On the downside, this category of analysers tend to be more maintenance intensive than it's modern counterparts. It reportedly has problems accommodating H_2S excursions during process or pipeline upsets.

A notable benefit of this type of analyser is that it can be purchased with SIL 2 software certification[5]. This feature enables it to comply with route 1_S of IEC 61508 requirements for SIS equipment selection. Full compliance can then be achieved by following route 1_H and conducting an FMEA on the analyser and sample system hardware. Alternatively, route 2_H may be followed if the 'End User' has sufficient quality field operational failure data.

Ultraviolet (UV) H_2S Analyser[6] – this proprietary technology uses frontal elution chromatography to separate and eliminate the H_2S from other contaminates prior to gas analysis using (UV) absorption

[5] NovaSulf™ HG400 Series H_2S Analyser.

[6] 933RM UV H_2S analyser, Amtek Process Instruments.

spectroscopy. This analyser has multi-component capability but this does not include H_2O. Market research suggests that this analyser is not available with SIL certification (hardware or software).

More recent technological developments include the use of Tunable Diode Laser Spectroscopy (TDLS). This has been used in many applications, two of which are described below for the detection of H_2S and other components.

Tunable Diode Laser Absorption Spectroscopy (TDLAS)[7] – this is a relatively new technology compared to lead acetate tape and is considered more versatile because a single TDLAS platform can be used detect water vapour and H_2S by selection of appropriate diode lasers. This class of analyser has the benefit of very low measurement ranges and low maintenance overhead. Again, it has multi-component capability, including H_2O but market research suggests that this analyser is not available with SIL certification.

Tunable Diode Laser Photo Acoustic Spectroscopy (TDLPAS)[8] – this is also a proprietary technology that is based on the absorption of modulated laser light in a photoacoustic cell. It has similar characteristics to the TDLAS analyser in that it has multi-component capability but again, it is not available with SIL certification.

Analysers incorporating Tunable Diode Laser Spectroscopy share a number of common benefits, including.

- Minimal maintenance
- Infrequent calibration requirements
- Fast response time
- No moving parts
- Self diagnostics
- Simultaneous measurement of multiple components
- High spectral resolution and accuracy

It should be noted that regardless of which technology is ultimately selected, the key to successful analyser operation is in the design of the sampling system and the quality of the maintenance regime. Properly trained personnel are essential to ensure the analyser system is accurately calibrated and maintained for optimal performance.

Key Features

- Following IEC 61508 produces a coherent and auditable design that provides a known amount of risk reduction to mitigate process risk.
- The standard provides clear guidance on selection of equipment, which ultimately leads to more predictable performance and reliability.
- The lifecycle approach ensures that the SIS is maintained at optimum performance level for its entire lifetime.
- Building redundancy into the design facilitates maintenance.
- Regular proof testing ensures the SIS continues to perform at an optimum level.
- An option worth considering is to employ different analyser technologies to increase diversity and to provide an opportunity to gather field operation data for future performance comparison. This option also enables the configuration of 'discrepancy alarms' between analysers to not only give an indication of performance but to also give an early warning of a potential process upset or equipment malfunction.

[7] 5100 Series Gas Analyser, Amtek Process Industries.

[8] HLT Hilase H_2S, CO_2 and H_2O Analyser, Hobre Analyser solutions.

Conclusion

Sulphide stress corrosion cracking is a significant risk that can result in catastrophic consequences. However, if the risk can be quantified, then protection layers can be put in place to reduce the risk to an acceptable level.

The IEC 61508 standard provides a structured approach to quantifying the risk and designing the safety instrumented system protection layer to provide a known amount of risk reduction. The lifecycle approach advocated by the standard can be used to design a credible protection system and by doing so, demonstrate that the risk of the hazard has been reduced to as low as reasonably practicable.

Modern laser technology has improved the performance of process on-line analysers to the point where they can now provide a credible protection layer in a risk reduction program.

Modern technology makes use of advanced microelectronics to give greater functionality and more accurate and repeatable measurement. Whilst the introduction of more embedded software increases the risk of systematic failure, IEC 61508 provides the means to ensure this is minimised through a controlled design process.

Although SIL certification is not supplied with some analyser systems on the market, this does not prevent an organisation from seeking ‘self – certification’ for hardware and software. There is a cost involved in doing this and one approach may be to partner with a manufacturer to share the cost. In any event, SIL certification in accordance with IEC 61508 would likely be a considerable benefit to both parties.

There are now a number analyser technologies on the market today, which offer an alternative to the traditional lead acetate tape device. Although the lead acetate tape device is still a consideration in a natural gas pipeline protection system, the availability of other technologies allows diversity to be built into the SIS design which offers additional integrity benefits. The use of diversity in the design of a SIS also enables comparisons to me made and field performance data to be gathered to improve the design of future systems.

