Addressing the unique challenges of hydrogen gas detection in 3D Fire & Gas Mapping

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Abstract

Fixed Fire and Gas Detection Systems are critical tools in a process plant/facility utilised to minimise risk to personnel, the environment and the facility. These systems are used to detect loss of containment leaks, and dangerous build-up of toxic and/or flammable gas or the presence of fires that may cause dangerous escalation. Fire and Gas Mapping software tools are increasingly used to understand the optimum quantity and layout of these detection systems. Fire and Gas Mapping software tools require the input of quantified physical performance targets, against which the fire and gas detector locations can be analysed and optimised.

A key performance target for flammable gas detection mapping is the size of the flammable accumulation or leak requiring detection. If the target gas cloud is too small, the resultant systems may not be realistic relative to the expected risks, overdesigned and a significant maintenance burden on the operator. Too large and the system may not achieve its primary function and detect critical loss of containment scenarios. Operator best practice documents and international guidance such as International Society of Automation (ISA) technical report (TR 84.00.07) help provide methods and criteria to set these physical performance targets. For flammable hydrocarbon gas risks (alkanes etc.), guidance on the size of target flammable gas cloud is well established. However, guidance on the size of target flammable gas clouds appropriate for hydrogen gas risks is lacking.

Considering the surging demand for cleaner fuel/zero carbon alternatives to hydrocarbons, the increased use of Hydrogen will present significant risks and challenges for those executing 3D fire and gas mapping studies (increase range of flammability, high ignition probability etc). These are presently not addressed adequately by existing standards and guidance, which are overwhelmingly focused on the detection of hydrocarbons. Using 3D computation fluid dynamics (CFD) explosion analysis, this paper aims to present an effective strategy for establishing appropriate flammable gas detection performance targets for hydrogen gas risks. In addition, an example of a scenario/risk-based approach will be presented using a case study to demonstrate how flammable hydrogen gas detection performance targets can be used to establish a realistic and effective hydrogen gas detection arrangement and reduce risks to ALARP.

Introduction

Flammable Gas Detectors (FGD) positioning plays a key role to detect the flammable gases in a timely condition. The ultimate function of the FGD is to detect this particular gas before it reaches a defined target gas cloud volume. The detection efficiency of this system majorly depends on the gas detectors' position and the layout density.

At present, there are two major approaches being practiced which utilise a performance-based gas detection mapping methodology for decision making regarding gas leak scenarios that can cause escalation. These approaches are as follows:

- Geographic approach; and,
- Risk-based mapping.

Currently, geographic approach is the most widely practiced approach in the process industries. This approach converts the coverage assessment to be performed by utilising representative volumes, termed the "target gas clouds", and spacing the gas detectors to have adequate detection coverage based on this defined target gas cloud. This target gas cloud is bigger and smaller depending on the congestion/confinement i.e. the more congestion/confinement the smaller the volume required to cause major escalation.

As per recent practice, there has been a shift towards utilising the risk-based fire and gas mapping which is becoming more common. This is being performed in line with ISA-TR84.00.07-2018, Guidance on the Evaluation of Fire, Combustible Gas, and Toxic Gas System Effectiveness standard. The risk-based approach uses historical leak frequencies and consequence analysis, and ignition probability models to quantify the risk from escalation scenarios.

Utilising the geographic and risk-based fire and gas mapping approach has resulted in significant progress in gas detectors layout design and optimization. However, the focus has majorly been on process installations with hydrocarbon services. This paper focuses on the newly emerging hydrogen industries, where currently, there is no existing definitive industrial standards to guide the design engineers on gas detectors layout for installations handling mostly hydrogen. The paper will detail a risk based approach that has been utilised using target gas cloud principles for a hydrogen facility, and a case study will be presented to demonstrate the proposed methodology.

Background Principles

Current Research

Over the years, many researchers have published risk-based methodologies for gas detection layout. (Defriend et al., 2008) proposed a risk-based volumetric monitoring methodology, based on company's risk tolerable criteria with the objective to estimate the required spacing between detectors. Recently, (Matiti et al., 2016) integrated the Computational Fluid Dynamics (CFD) modelling with risk-based approach combining consequence and frequency analyses with the aim to compare the results against company risk criteria.

In recent times, efforts have been made to automate the gas detector location optimisation by using mathematical models. Researchers have started to focus on using stochastic programming (SP) methods. This includes (Rahman et al., 2014) who focuses on ammonia plants using risk and economic analysis, however they did not utilize CFD to establish the target gas cloud that can cause escalation in a particular area.

(Legg et al., 2012) uses a mixed integer nonlinear programming (MINLP) model with a scenario-based approach, i.e. considering time for a gas cloud to reach the detectors. In subsequent studies, other optimization objectives such as minimizing the sum of distances between the nearby detectors and leak sources as well as maximizing the scenario coverage (Benavides-Serrano et al., 2015;) have been investigated. Most of the mentioned studies above have only considered a single value of probability for all scenarios (i.e., all scenarios are deemed to be equally probable). This still lacks in identifying the actual risk for each scenario and the decision will be biased towards the dispersion analysis and user judgement alone. The performance of methodologies which utilise user judgement to determine credible scenarios cannot fully establish the risk as this is a function of the number and type of leak scenarios modelled. The question that needs to be answered is whether the number of scenarios considered is adequate and representative of plant risk. Any inadequate representation of plant risk will bias the performance and the coverage achieved from such design.

(Rad and Rashtchian, 2016) proposed a risk-based methodology for the optimum placement of flammable gas detectors using an optimization formulation called Maximum Risk Reduction (MRR). (Rad and Rashtchian, 2016) do not screen out the small releases which are incapable of causing gas cloud large enough to cause escalation (note: frequency of these scenarios are typically high when compared to the larger detection critical releases which can cause escalation). The risk represented in (Rad and Rashtchian, 2016) would therefore be too conservative and may focus on detection in location where escalation is not likely. The analysis claims that detection will provide risk reduction i.e., reduce the likelihood of personnel fatality. However, the analysis does not re-model the consequences after detection (mitigated assessment) and therefore cannot establish the risk reduction from detection and potential isolation. The example in this paper also shows scenario-based detection and does not claim to highlight the reduction of risk from escalation. Once the target gas cloud has been reached after the release, detection with isolation will not remove the gas cloud from the environment but will only reduce the time that the gas cloud can be impacted by ignition sources before dispersion.

One of the notable impacts from their study is that the marginal utility vs. iteration number that allows to examine the effectiveness of adding more detectors to the recommended layout. This would allow the design engineers to identify which detector has provided significant amount of risk reduction. However, Rad and Rashtchian, 2016 proposes a new way of representing risk reduction which is not typically used in industry while the proposed study provides a visual risk contour to allow engineers to easily distinguish the high-risk areas in line with current industries' practice regarding the representation of risk.

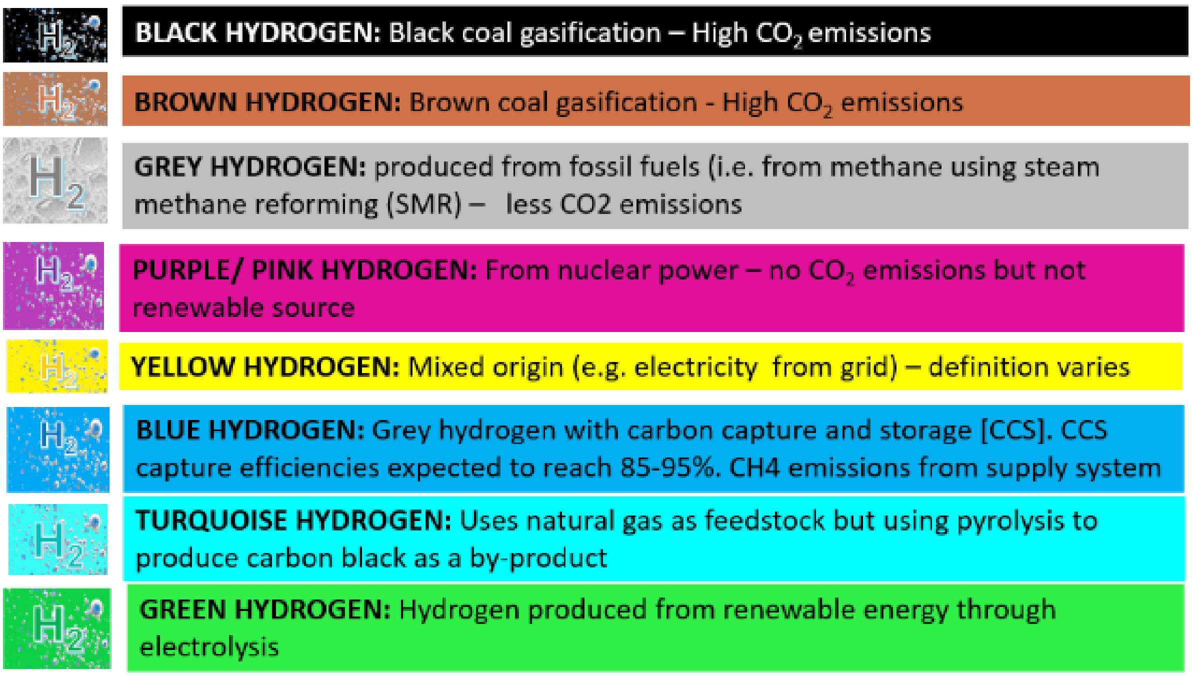
Ferrara et al., (2016) compared the performance of geographic approach with scenario-based methodology using two different case studies. However, only one release rate has been modelled in the study as "design leak rate" and a detailed split of the frequency of release based on different hole sizes (i.e., small, medium, and large) had not been performed. The impact on the risk mitigation from isolation may differ depending on hole size, however Ferrara et al., (2016) study does not consider this. It should be noted that the effect of isolation is more pronounced for fire detection than the gas detection. Although the fire detection was also considered part of the project used for the case study, this is not part of scope of this paper.

Although the research and joint initiative with process industries has resulted in a significant progress in gas detectors layout design and optimization, the focus has majorly been on process installations with hydrocarbon services. Currently little guidance for the design engineers on gas detectors layout for installations handling hydrogen. Hence, this study will propose the required detection requirement criteria for facilities handling hydrogen gases using risk-based methodology. Important factors differentiating hydrocarbon releases and hydrogen releases such as ignition probability, frequency analysis, target gas cloud, and flammable gas dispersion properties will be detailed within this paper.

Hydrogen vs hydrocarbon

Currently there is a huge demand to decarbonise heavy industries including the oil and gas sectors (Mah et al., 2018). A large number of countries has developed strategies which include ambitious targets for increasing hydrogen production, as well as optimizing the system for efficient production (Idris et al., 2018). Hydrogen technology already exists and is ready for deployment in a variety of ways as shown in Figure 1.

Figure 1 Types of Hydrogen



BLACK HYDROGEN: Black coal gasification – High CO_2 emissions

BROWN HYDROGEN: Brown coal gasification - High CO_2 emissions

GREY HYDROGEN: produced from fossil fuels (i.e. from methane using steam methane reforming (SMR) – less CO2 emissions

PURPLE/ PINK HYDROGEN: From nuclear power – no CO_2 emissions but not renewable source

YELLOW HYDROGEN: Mixed origin (e.g. electricity from grid) – definition varies

BLUE HYDROGEN: Grey hydrogen with carbon capture and storage [CCS]. CCS capture efficiencies expected to reach 85-95%. CH4 emissions from supply system

TURQUOISE HYDROGEN: Uses natural gas as feedstock but using pyrolysis to produce carbon black as a by-product

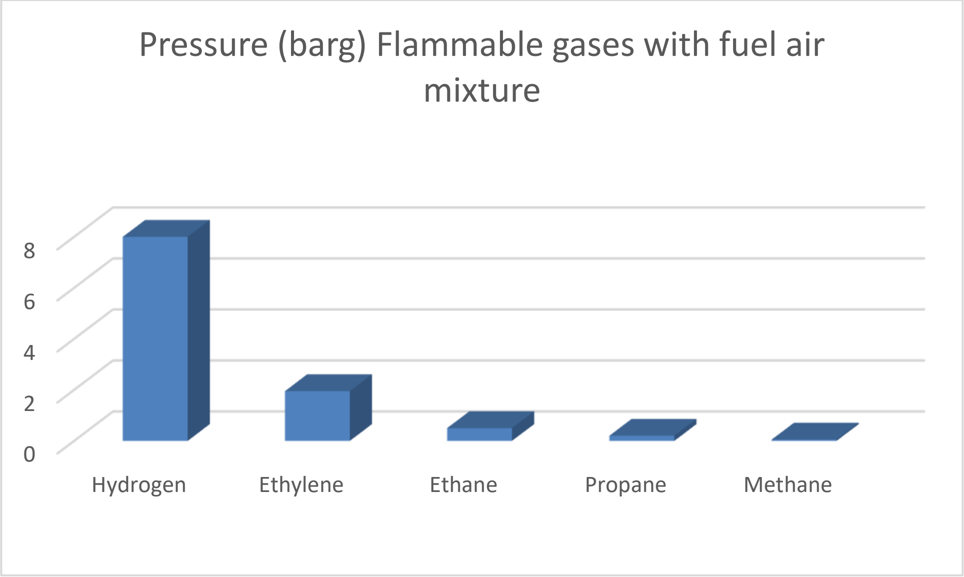
GREEN HYDROGEN: Hydrogen produced from renewable energy through electrolysis

Safety concerns on hydrogen fuel have been one of the major limiting factors for hydrogen commercialization (Mah et al., 2018). Hydrogen is flammable and explosive over a very wide range of concentrations in air (4%–75%) and it is explosive over a wide range of concentrations (15%–59%) at a standard atmospheric temperature (Keçebaş and Kayfeci, 2019), and it behaves as an ideal gas over a wide temperature range and even at high pressures. It is odourless, colourless, very buoyant and very diffusive and can potentially accumulate at high points. Although it is buoyant, initial nearfield dispersion of gaseous H_2 releases is typically driven by momentum with no significant buoyancy effect until at low velocities (e.g. interaction with objects or ground).

When compared with hydrocarbon releases, hydrogen is more easily ignited and therefore has a higher ignition probability in the event if there is a release. The minimum ignition energy is 0.02mJ, when compared to 0.3mJ for methane. A weak spark, electrostatic discharge due to the release or a person can therefore cause ignition.

In the presence of congestion, a higher overpressure is expected from a hydrogen cloud, when compared to an equivalent volume of hydrocarbon. This is due to the higher laminar burning velocity. Note: Hydrogen releases are also more likely to cause detonations, however this paper focuses only on the smallest cloud that can cause escalating overpressures. Therefore, detonations are not discussed further in this paper. Figure 2 shows the comparison of explosion pressure for various stoichiometric fuel-air mixtures in a 10 m wedge-shaped vessel.

Figure 2 Comparison of explosion pressure for various stoichiometric fuel-air mixtures (Bjerketvedt et al., 1997).



The frequency of leaks can also be impacted by a hydrogen inventory, with particular concern on material selection, and the impact of hydrogen embrittlement and high temperature hydrogen attack on the likelihood of a leak. Due to the above differences between hydrocarbons and hydrogen, detection requirement for hydrogen gas should be identified uniquely and different from hydrocarbon detection requirements.

Methodology

Overview

Using methods detailed in ISA technical report TR 84.00.07 [Ref. **Error! Reference source not found.**] a scenario-based approach was utilized to incorporate consequence analysis and risk criteria. The study performed scenario-based mapping assessments as part of an overall risk-based F&G detection optimization process. The assessment covered both the practical locations of detectors but also the effectiveness of the fire and gas system in terms of risk reduction.

Detailed below is the study approach used to review the effectiveness of the F&G system and provide a basis for recommendations. This including developing an initial design and then subjecting the initial design to a rigorous risk-based assessment. The size of scenarios requiring detection were first determined by CFD calculation as detailed the following sections. The optimal detector locations were then assessed in MES 3D F&G Mapping software 'AMNIS' and Risk Integration tool 'MERIT', and then subsequently verified utilising CFD as a final check.

Initial Design

In this step, the need for a gas detection system was based on a qualitative assessment of the risk in a particular area of the facility. An initial detector configuration was proposed for the areas of the facility under consideration based on expert judgement and good engineering practices i.e. flammable gas detectors we positioned in areas where flammable gases may potentially be released in hazardous concentrations causing escalation due to exceeding an overpressure of 150 mbar.

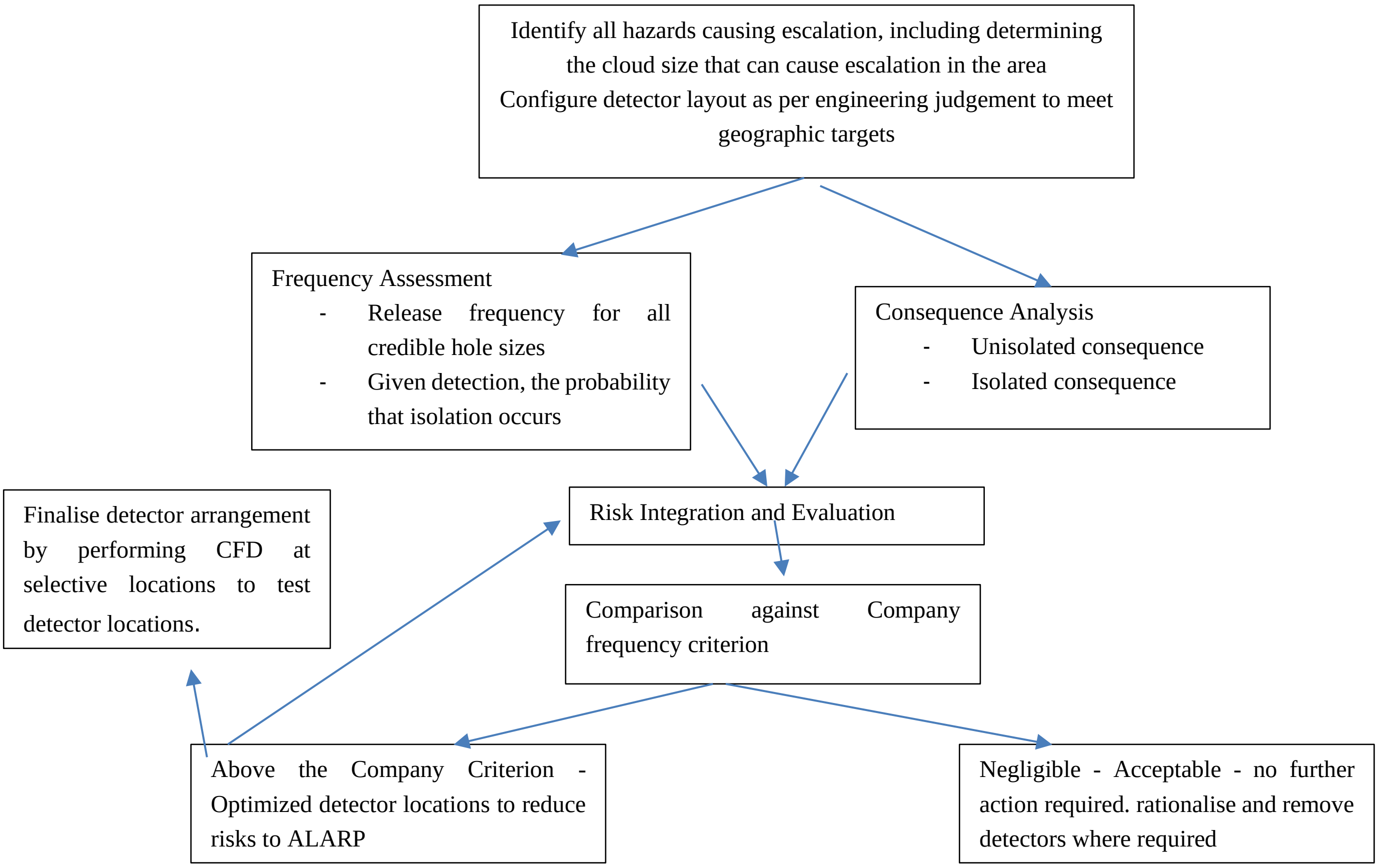
Risk Based Assessment

The study utilised the As Low As Reasonably Practicable (ALARP) concept to judge the acceptability of fire and gas detector configurations. The ALARP principle is used by many companies and regulatory bodies to ensure efforts have been made to reduce the risk to as low as reasonably practicable. The principle is generally that the risk is reduced to levels below a specified intolerable level and risk reduction measures are implemented unless the costs are grossly disproportionate to the benefit derived. The following sections detail the risk-based fire and gas detection optimisation methodology.

Risk Based Assessment Methodology

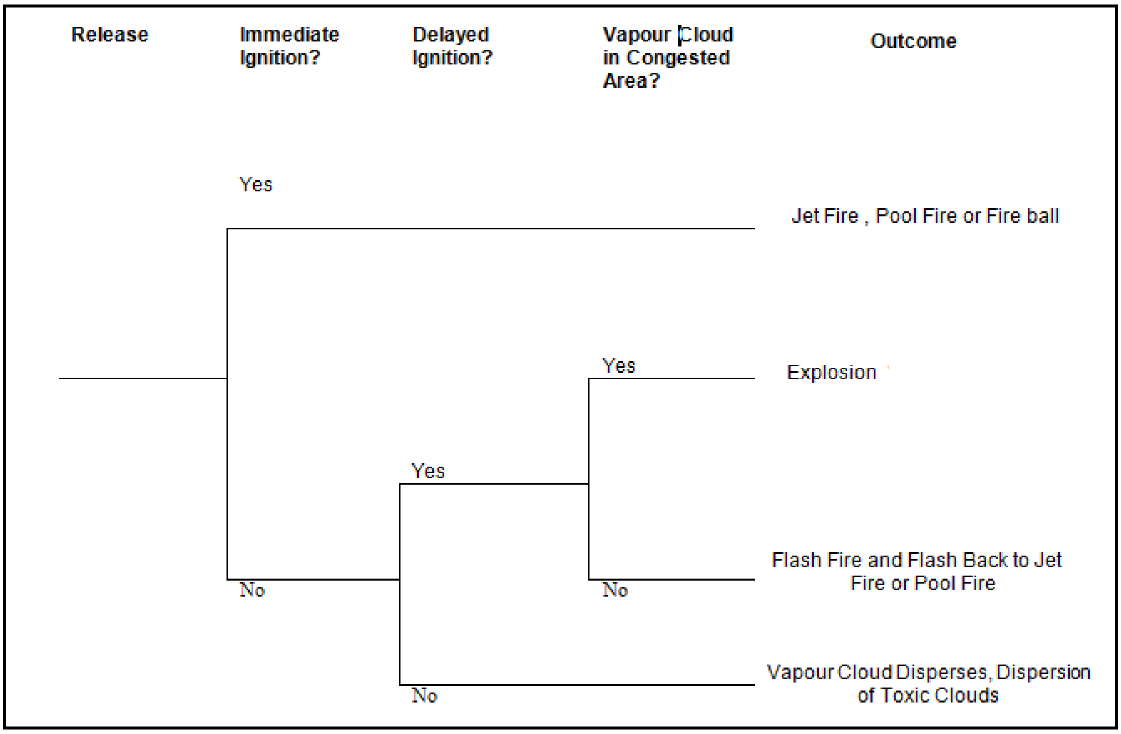
This section details methodology utilised to perform this risk-based F&G assessment. Figure 3 shows the flow chart applied for the risk assessment in this study. Only flammable gas hazards which can escalate to secondary events are considered as part of this paper, although the same principles can be applied to toxic and fire detection.

Figure 3 Risk Based Gas detector Mapping Methodology



A sample event tree highlighting the potential consequences of hydrocarbon and toxic releases is illustrated in Figure 4Figure 4. Event trees provide a logical representation of the development of a hazardous event to give a range of end event outcomes. For example, a gas release may ignite to give a jet fire (on immediate ignition) or an explosion/flash fire (in the event of delayed ignition) or it may pose a hazard by remaining as an unignited toxic gas cloud. Probabilities are assigned to each branch in the event tree. The frequency of each outcome event is then determined by multiplying the initiating event frequency by the probabilities along that branch of the event tree as shown in Figure 4. Instead of presenting simple event trees, which do not provide a good picture of the risks relative to the locations of equipment and fire and gas detection, results are provided over the facility plot plans.

Figure 4
Event tree analysis



Perform Unmitigated Risk Assessment

The frequencies and consequences results were combined using the in-house risk integration software, MES MERIT to generate the unmitigated risk contours. The frequencies of overpressure scenarios capable of causing escalation were calculated for every grid point within the plot plan. The average frequency of overpressure scenario within the escalation sensitive area was used to establish the overall unmitigated escalation risk within each zone. Areas where the risk exceeds 1e-4 require that the gas detection is optimised.

Perform Mitigated Risk Assessment

The first mitigated risk assessment was performed using the detector coverage from the initial detection design as described earlier. The frequency of the hazard scenario with consideration of the benefit of a gas detection system (detector coverage and gas system safety availability) was calculated for every grid location (1m grid) within the relevant area. For this analysis, the main requirement was to determine the frequency and risk of undetected releases, however, the methodology can also incorporate the probability of failure on demand to isolate, based on detecting a particular release. In this case the frequency of the escalation scenario while considering isolation would also be included in plotting the risk contour.

Perform Optimised Mitigated Risk Assessment

Following review of the unmitigated and mitigated risk assessment detector locations were optimised to the provided coverage and help mitigate those risks to acceptable levels.

General Data and Assumptions

Weather Data

Meteorological data for the facility was sourced, with typical weather conditions selected for use in the consequence and risk modelling. The weather data was grouped into 16 different directions and the probability of wind direction was entered into MERIT.

Hole Sizes and Leak Frequency Data

The leak frequencies were derived from UK HSE's Hydrocarbon Release Database (HCRD) (HSEUK) which is widely used throughout the industry for risk assessment work onshore and offshore. The following representative hole sizes were used in this study for leaks from equipment containing hydrocarbon/flammable/toxic inventories:

- 7 mm equivalent hole, equivalent to small release;
- 22 mm equivalent hole, equivalent to medium release;
- 70 mm equivalent hole, equivalent to large release; and
- 150 mm corresponding to major release or full-bore rupture (FBR).

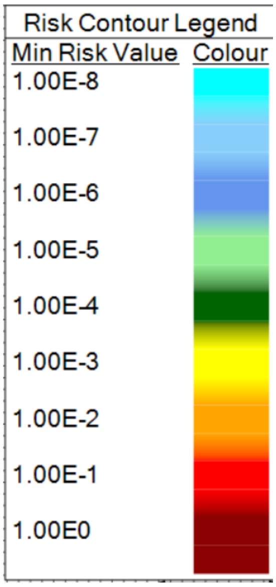
Ignition Probabilities

Ignition probability data used for this study was sourced from the Energy Institute IP Research Report (Ignition Probability Review, 2006) suggests that a split of 40/60 (immediate/delayed) for ignition is reasonable. For hydrogen releases, the ignition probability was multiplied by 2 as per guidance from (International Association of Oil and Gas Producers, 2019).

Risk Acceptance Criteria

The following risk contour legend shown in Figure 5 describes the escalation frequency/risk associated with the risk contours shown on the plot plans. Areas that have dark green risks or higher are typically prioritised to reduce risks to ALARP (using 1.0E-04 as the benchmark). Risks below 1E-4 is typically considered ALARP for escalation in industry.

Figure 5 Risk Contour - Legend



Risk Contour Legend

Min Risk Value	Colour
1.00E-8	🟦
1.00E-7	🟦
1.00E-6	🟦
1.00E-5	🟩
1.00E-4	🟩
1.00E-3	🟨
1.00E-2	🟧
1.00E-1	🟥
1.00E0	🟥

Impact Criteria

The analysis performed in this F&G mapping study was used to assess the impact of F&G detection on the layout based on risk assessment and asset damage risk criteria. Note: This paper acknowledges that this analysis technique cannot be used as the only decision-making tool when defining the plant's equipment layout.

Flammable Cloud

Gas detection was considered required in areas where flammable gas can accumulate and explode causing escalation, this was based on the different levels of congestion/confinement as assessed in CFD. As per OTO (1993) report, and typical industry practice, overpressures above 150mbar were considered to be capable of causing escalation. The aim was to detect only clouds that are capable of causing escalation i.e. smaller gas clouds were not targeted.

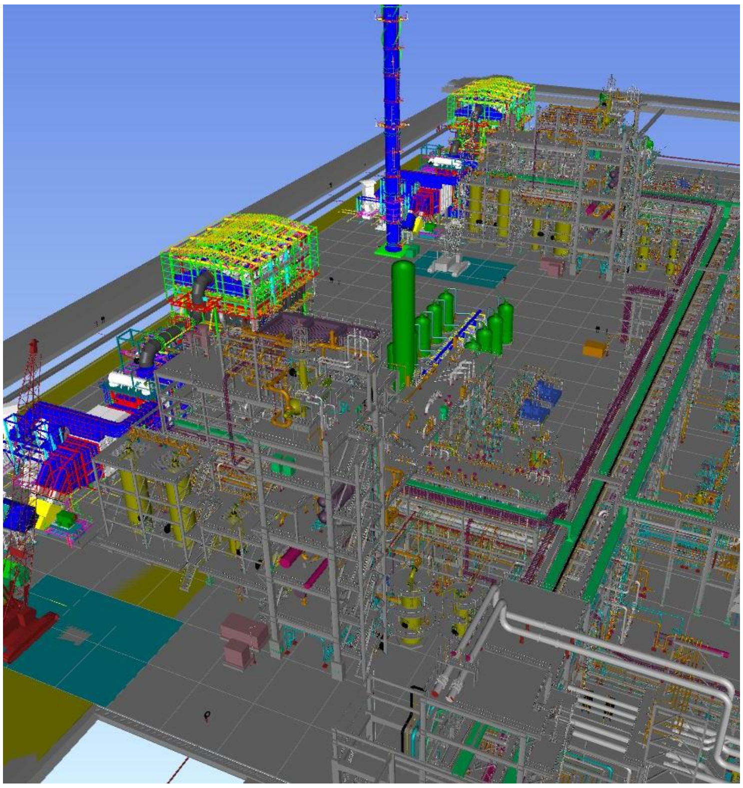
A detailed three-dimensional CFD model was imported/generated in the FLACS software package. A set of representative streams was selected to determine the minimum size of gas cloud that can cause escalation.). FLACS has been well validated through small, medium and full-scale experiments and is regarded as one of the most accurate tools for vapour gas cloud and dust explosions and blasts in complex process areas.

Vapour cloud explosion simulations were carried as representative locations within the unit, and the flammable gas cloud to calculate the minimum cloud that could generate 150 mbar overpressure. Various representative ignition sources were also modelled to incorporate the impact of ignition location on the potential overpressure.

Case Study: Process Description

The case study presented in this paper consist of a hydrogen plant (Figure 6) with a start-up system, which consisted of a start-up interchanger and an electrical heater. The equipment was used for catalyst reduction of the pre-reformer and was used with nitrogen and hydrogen. Various feedstocks such as natural gas, heavy naphtha, propane, hydrogen facility saturated gas and mild hydrocracker off-gas and in various combination are typically used as the design feedstock.

Figure 6 3D Model Overview of the Hydrogen process



The flammable gas detection requirements for the plant are described in Table 1 below.

Table 1 Flammable Gas Detection Performance Targets

Hazard	Type of Detector	Detection Target / Spacing Criteria	Geographic Detection Coverage Target	Voting	Set Points	Assessments
Flammable Gas	Point IR (Hydrocarbon) Point Catalytic (Hydrogen)	Flammable Gas Scenarios Leading to Explosions Hazards as per CFD Analysis	80% 1ooN	1ooN	20% and 50% LFL	Flammable Gas Assessment

Risk Reduction Assumptions

The objective of the gas detection system was to provide early warning to personnel of potentially loss of containment events that could cause escalation in terms of flammable gas and enable initiation of remedial actions to avoid /minimize escalation of events and risk reduction measures to be taken.

Gas detection systems were provided to perform three main functions:

- Detect – monitor for potentially hazardous releases / accumulation of explosive gases and fires;
- Alarm – initiate alerts to response personnel allowing appropriate action to be taken; and
- Protect – drive actions that effectively reduce escalation and/or minimise loss.

Gas detection systems in this study was configured to ensure that detection probability was within acceptable bounds.

Alarm and Response Assumptions

It was assumed for this study that key gas alarm actions were initiated manually by an operator from the gas control panel and/or from other safe locations. Operator time has been taken to be at least 10 minutes. This included the time it takes to recognize the alarm, to diagnose the problem, and to fully initiate action.

Results and Discussions

As per the modelling, based on the congestion of the area and three representative locations (Figure 7), a hydrogen gas cloud with a radius of 6.3 m could cause escalation (see Table 2). Any scenarios that are unlikely to cause a cloud size of less than 6.3 meters were therefore screened out of the risk analysis i.e. very small leaks not capable of accumulating significantly were removed from the modelling in the MERIT model. This ensured that very small gas clouds that are not capable of causing escalation, but which are likely to have a higher frequency of release are discounted from the risk assessment. The smaller clouds would likely skew the findings, and mislead the engineer into placing detectors where the risk of escalations is not great. Table 3 also highlights the equivalent gas size volume for hydrocarbon releases in the same area as larger than 20 meters. Therefore, gas detection requirements for hydrogen streams are shown to be typically more onerous when considering equivalent congestion.

It should be noted that the target cloud size is highly dependent on the congestion in the area, and therefore these clod sizes are only applicable for this facility. Other facilities with differing congestion would require dedicated CFD modelling to determine the target cloud.

Figure 7 Representative Cloud Position to Determine Overpressure

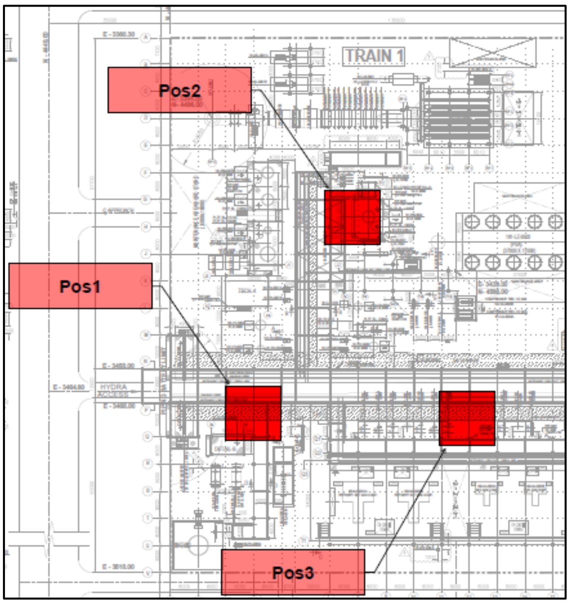
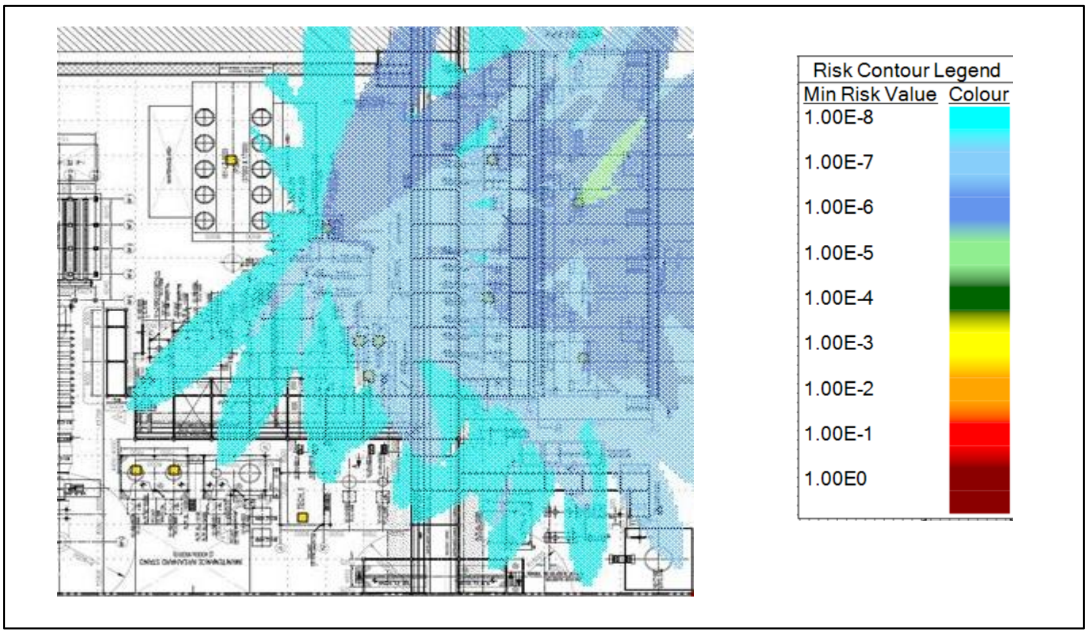


Table 2 Results – Comparison of equivalent sphere radius for Hydrogen and hydrocarbon

Cloud Position	Hydrogen Cloud		Hydrocarbon Cloud (Methane)	
	Stoichiometric Cloud Volume (m3) for 150 mbarg	Equivalent Sphere Radius (m) for 150 mbarg	Stoichiometric Cloud Volume (m3) for 150 mbarg	Equivalent Sphere Radius (m) for 150 mbarg
01	130	6	>4000	>20
02	180	7	>4000	>20
03	880	12	>4000	>20

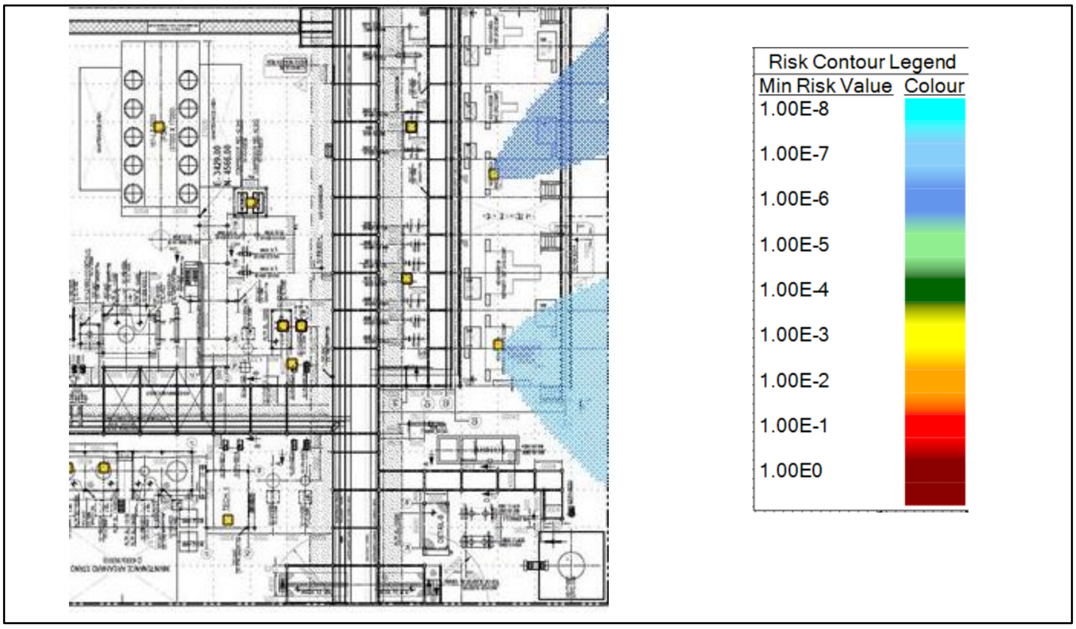
Unmitigated Risk: The unmitigated escalation risk due to explosion can be seen in Figure 8. The unmitigated escalation risk contour represents the predicted frequency of explosions from clouds capable of causing escalation to the surrounding equipment in the facility. The unmitigated explosion frequency is equivalent to the escalation risk. CFD results were used to determine the size of flammable gas accumulations capable of causing escalation within this unit (Figure 6 and Table 2). Using the quantitative risk assessment methodology, leak frequencies and consequences were integrated to generate the risk contours (Figure 7). For this case, the escalation risk did not exceed 1.0E-04/yr in the majority of the unit. Therefore it was concluded that escalation sensitive equipment is unlikely to be impacted at above the target risk.

Figure 8 Flammable Gas Detection Assessment: Unmitigated Risk



Initial Design: An initial design for the gas detection system was developed, and the mitigated escalation risk contour can be seen in Figure 9. The contour represents risk from undetected scenarios that are capable to cause escalation due to explosion. The risk from these scenarios was significantly less than the unmitigated contours and highlights the effectiveness of the detector locations in terms of providing early detection of potential escalation events. The are no areas above the 1E-04/yr target. However, additional risk reduction was required to ensure detection within the compressor shelter.

Figure 9 Flammable Gas Detection Assessment: Mitigated Risk



Optimised Design: The design was optimised based on the mitigated risk contours i.e. considering detection. Iterative steps were taken in placing the detectors to fully optimise the locations and minimise the risk as indicated in Figure 10. It can be seen that risks from undetected scenarios are significantly reduced below 1E-04/yr and are therefore considered ALARP. The detection coverage achieved was 99% (as shown in Table 3) which is higher than the detection target of 90% with 1ooN voting (See Table 1). It should be noted that the below is not representative of a reduction in risk of escalation. In the event that a flammable gas cloud is released, isolation will only limit the time that the gas cloud can be impacted by ignition sources before the flammable cloud can dissipate.

Selective additional CFD runs were then conducted to verify the detector locations against simulated cases (Figure 11)

Figure 10 Flammable Gas Detection Assessment: Optimised Mitigated

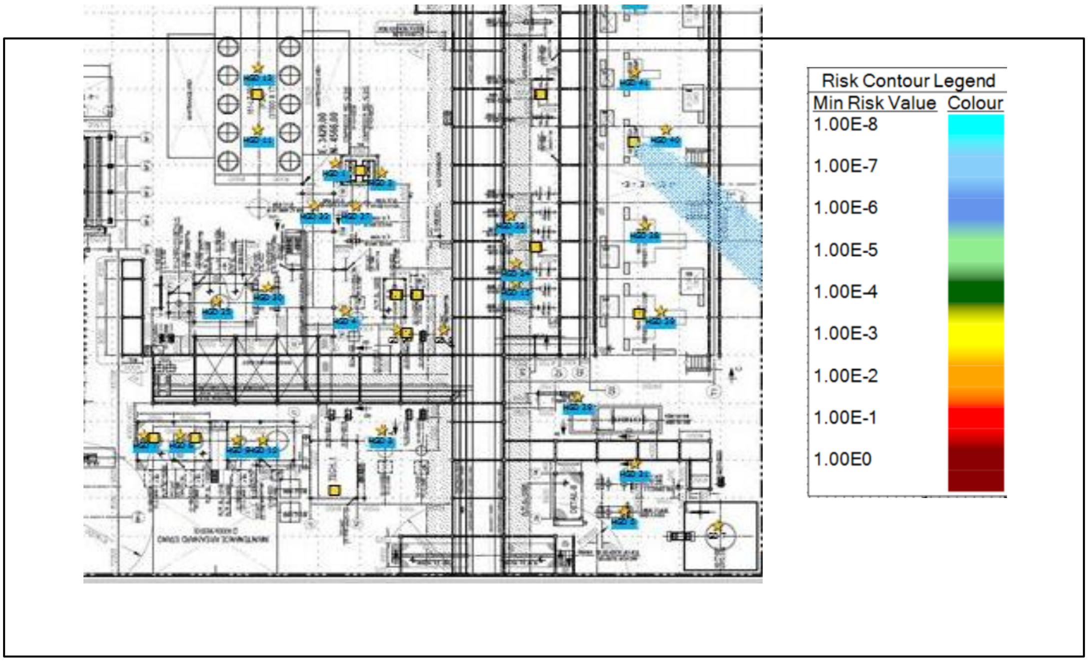
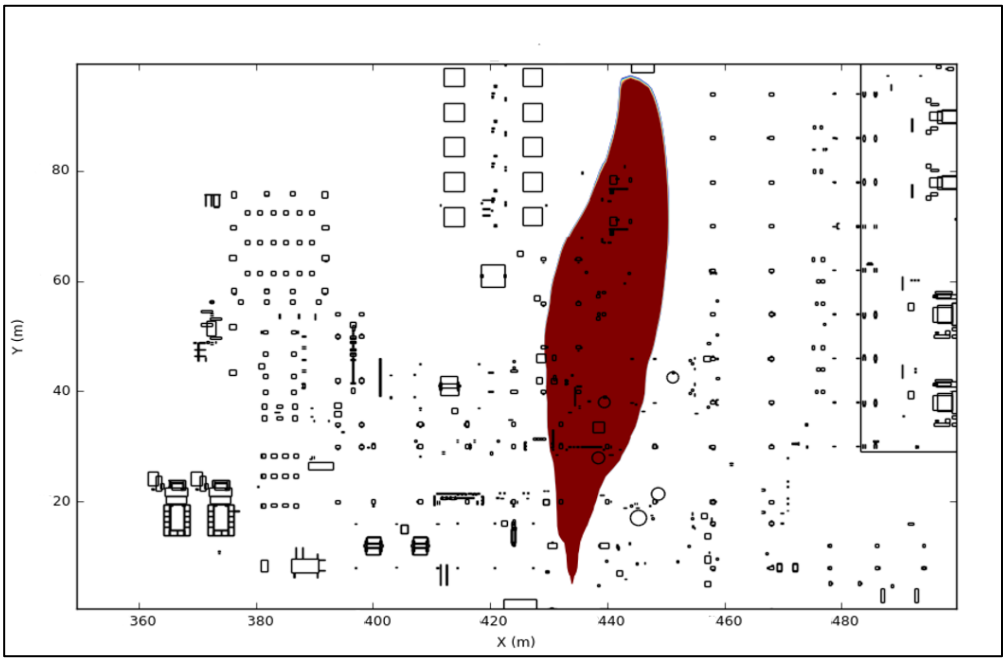


Table 3 Results – Detection Performance

Hazard Type	Number of No Detection	Number Of Overall Detection	Number Of Scenarios	No Detection Percentage	Detection Percentage
Flash Fire	1	111	112	1%	99%

Figure 11 0.5LFL Cloud footprint at 1.5m elevation



Conclusion and Recommendations

Performance-based gas detection mapping has become the main practice in oil and gas industries. However, the focus has majorly been on process installations with hydrocarbon services. Currently little guidance is available for the design engineers on gas detectors layout for installations handling hydrogen provided that hydrogen needs a different criteria or detection requirement. Hence, this study has proposed the required detection requirement criteria for facilities handling hydrogen gases using risk-based methodology. From the case study, considering the congestion in this particular facility, a gas cloud with a radius of 6.3 m was reported as able to cause the escalation due to explosion. Comparing to hydrocarbon, equivalent gas size volume for hydrocarbon releases in the same area would be as large as 20 meters. The flammable gas detection mapping has been conducted and the analysis for unmitigated risk, mitigated risk and the optimised detection layout was also discussed. The optimised design able to achieve a 99% of coverage with only one scenario not detected.

There are a few recommendations can be drawn from this study. First, the dispersion analysis used to generate the risk contour was conducted using a simplistic model (2D model), and this must be further reviewed. This is as such models are not be able to cater for obstructions. Risk modelling using only the CFD methodology however for the thousands of consequence runs required to generate the risk contour is likely to take a long time. On the other hand, using CFD for a limited number of cases is open to error as it solely based on the judgement of the engineer to pick selected cases. Therefore considering currently existing computing capabilities, a risk contour based on the 2D modelling where thousands of runs can be performed in a relatively short amount of time is considered the best current solution, this is also inline with current risk analysis practice when calculating individual risk to personnel.

Therefore, in future, when capabilities are available, a full risk analysis can be applied using CFD. This analysis, should be linked to potential impact on personnel risk and also highlight sensitive vessels which could cause significant escalation risk.

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