Towards Bespoke 3D Fire & Gas Mapping: Integration of Risk-Based Approach and CFD Modelling

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Fire and Gas Detection Systems (FGDS) are critical tools in a plant utilised to minimise risk to personnel, the environment and the facility. Well-configured systems will facilitate the isolation of leaking inventories and expedite timely escape and evacuation of personnel. Typically, the systems are used to detect leaks and dangerous build-ups of toxic or flammable gas cloud or the presence of fires that may cause escalation. Systems should also be designed to minimise potential costly spurious alarms which interrupt production output at a minimum cost.

Historically, a prescriptive-based approach has been applied during the placement of these detectors, which in itself is typically founded on engineering judgement. Modern fire and gas mapping tools are becoming more widespread in order to understand the optimum number and layout of the detectors in question.

As outlined in International Society of Automation (ISA) technical report (TR 84.00.07) (International Society of Automation, 2010), two approaches can be utilised by the modern fire and gas detection mapping tools. A more traditional ‘geographic approach’ can be followed to estimate detector coverage and determine their required numbers and locations in a three-dimensional (3D) environment. However, this paper discusses the more sophisticated ‘3D risk-based approach’, which can be employed to combine consequence and frequency analyses with the aim to compare the results against company risk criteria. For risk-based fire and gas detection mapping, the As Low As Reasonably Practicable (ALARP) concept is used to judge the acceptability of detector configurations. Concepts from fire and gas detection mapping, Quantitative Risk Assessment (QRA), Reliability and SIL (IEC 61511) are incorporated to ensure an in-depth analysis, consistent with site asset integrity and safety studies.

Furthermore, advanced Computational Fluid Dynamics (CFD) modelling can be integrated into the mapping process: by performing detailed consequence analysis, the calibration and optimisation of the FGDS performance targets (such as dimensioning gas cloud size) can be achieved from more accurate prediction of explosion and dispersion hazards. This ensures a more realistic design, specific to the facility of interest.

This paper aims to highlight that, through the implementation of a ‘3D risk-based approach’ and the integration of detailed CFD modelling for the placement and coverage of detectors, the relative risk reduction effectiveness can be investigated and utilised in ensuring the risk is ALARP.

Keywords: 3D, Fire & Gas Mapping, Risk-Based, CFD

Introduction

Within the process industry in general, safety and efficiency are critical factors Fire and Gas Detection Systems ensure early action from process systems, thereby reducing the extent of harm from hazardous scenarios. These systems include early alarms for alerting personnel, and early control action, thus protecting personnel, assets and the environment. Fire and gas mapping ensures that the configuration of the detection system is able to deliver these critical needs comprehensively, efficiently and cost effectively. The current prevalent practice for fire and gas mapping is the geographic-based assessment. This is a semi-quantitative methodology which relies heavily on coarse assumptions and targets to deliver the design. This paper advocates the “Risk-Based Methodology” as outlined in ISA technical report (TR 84.00.07) (International Society of Automation, 2010) and highlights how the coarse assumptions can be minimised by utilising the outputs of typically available safety studies, and therefore enabling an integrated approach to facility risk reduction.

Background Principles of Fire and Gas Mapping

Fire and gas mapping is used to determine the optimum layout of fire and gas detectors within a facility. It ensures that the detector configuration gives minimum redundancy and maximises the area coverage, thereby reducing the effort required for ongoing maintenance. The technique can be applied to new sites or to existing installations. It improves safety and optimises systems by maintaining high safety levels while minimising the number of devices and therefore cost. To facilitate fire and gas mapping, software is used to allow for quick analysis of detector locations in relation to obstructions within a specific target zone.

Utilising fire and gas mapping software allows you to:

- Simulate fire and gas release scenarios;
- Perform area grading and determine zone extents in the case of fire detection;
- Use a 3D environment for detector calculations;
- Calculate gas detectors’ (both point and line of sight detectors) coverage;
- Calculate heat and flame detectors’ coverage with regards to the respective graded areas;
- Account for obstructions in a 3D environment;
- Allow multiple coverage targets to be specified within an area, and
- Produce outputs including area grading and detector coverage maps.

Protecting Facilities through Optimisation of Flammable Detection Locations

A flammable gas detection system is provided to monitor areas where flammable gases may potentially be released in hazardous concentration and accumulate. Gas detection is used to alert personnel to the presence and location of a hazardous build-up of flammable gas. This paper focuses on flammable gas detection, however the technique can also be utilised for flame detection.

As discussed above, gas detection and coverage assessment of facilities is typically assessed through the use of fire and gas mapping software, ensuring that the set performance targets for coverage are met. The type, location and quantity of gas detectors monitoring process areas are selected to detect a gas release as soon as practicable before a flammable cloud capable of causing damaging overpressures can develop.

Additionally, engineering judgement is used to consider factors such as detector accessibility for calibration and maintenance without the use of scaffolding and detector placing that ensures protection from environmental effects which may influence their operation.

The following section describes the traditional geographic approach in determining detector placement. This procedure is retained in the "Risk-Based Approach" (discussed later in the paper); however, it utilises a more integrated approach (using company risk criteria which is typically already defined for studies such as QRA, SIL and LOPA) and the main assumptions, such as the target size and determination of the gas cloud, are refined to enable a more accurate assessment (from CFD and failure rate data).

Area Zone Categorisation

Performance requirements are specified for each area identified as necessitating gas detection. They are based on the nature of the hazard, the consequence of ignition and considers factors such as gas composition, confinement and congestion in the area, potential for ignition and required response time.

The methodology applied in gas detection assessments utilises a representative nominal gas sphere. This assumption permits a reasonably accurate assessment of detector coverage.

The smallest flammable gas cloud that has the potential to cause damaging blast overpressures following ignition is used as the target gas cloud. The size of this gas cloud usually varies depending on the level of congestion, degree of confinement, ratio of gas in air and the gas uniformity.

Experiments reported in HSE OTO Report 93 002 (Health and Safety Executive, 1993) show that, for low order alkanes (C1 – C4), the size of the smallest gas cloud that can cause damaging overpressures (i.e. generally taken to be blast loads in excess of 150 mbarg) is about 5 metres for partially confined vented volumes with blockage ratios of up to 0.3 or 0.4 (high blockage). This is used as the basis for conventional geographic fire and gas mapping studies.

Based on similar reasoning, other typical values of target gas cloud sizes are given in Table 1.

Table 1: Typical Performance Targets for Geographic Gas Detector Mapping

Area Category	Target Flammable Gas Cloud Size (m)
Confined Space	4
Partially Confined Space	5
Open	10

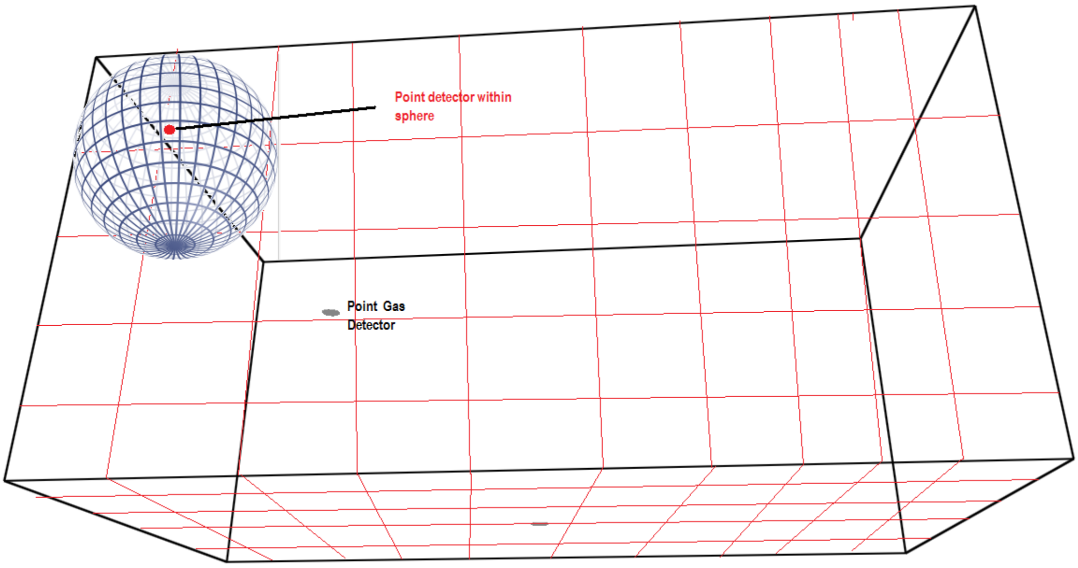
This paper discusses the use of CFD to more accurately determine the smallest gas cloud that should be detected based on the specific characteristics of the facility of interest and therefore removes the semi-quantitative nature of gas area zoning.

Detector Coverage Assessment for Flammable Gas

The coverage assessment for flammable gases follows the following summarised steps:

- A flammable gas sphere with specified target size is moved to every sampling point within the fire zone (see Figure 1);
- Sampling is taken for every grid point within the fire zone. This is as release sources and directions cannot be predicted with certainty and that plumes can be dispersed by prevailing wind or ventilation. For each location, the ability of the deployed sensors to detect the target gas cloud is measured and quantified in terms of percentage of the overall volume of interest; and
- Results are then collated for every sampling point, i.e. whether the combination of detected flammable gas levels and number of detectors indicating detection on the specific sampling point will (depending on the voting system) result in an alarm or a control action.

Figure 1: Representative Flammable Gas Cloud within Fire Zone



The gas detector coverage assessments are conducted to ensure that the specified performance targets in terms of coverage factors are met. Typical coverage targets range from 70 - 90 % depending on operator requirements.

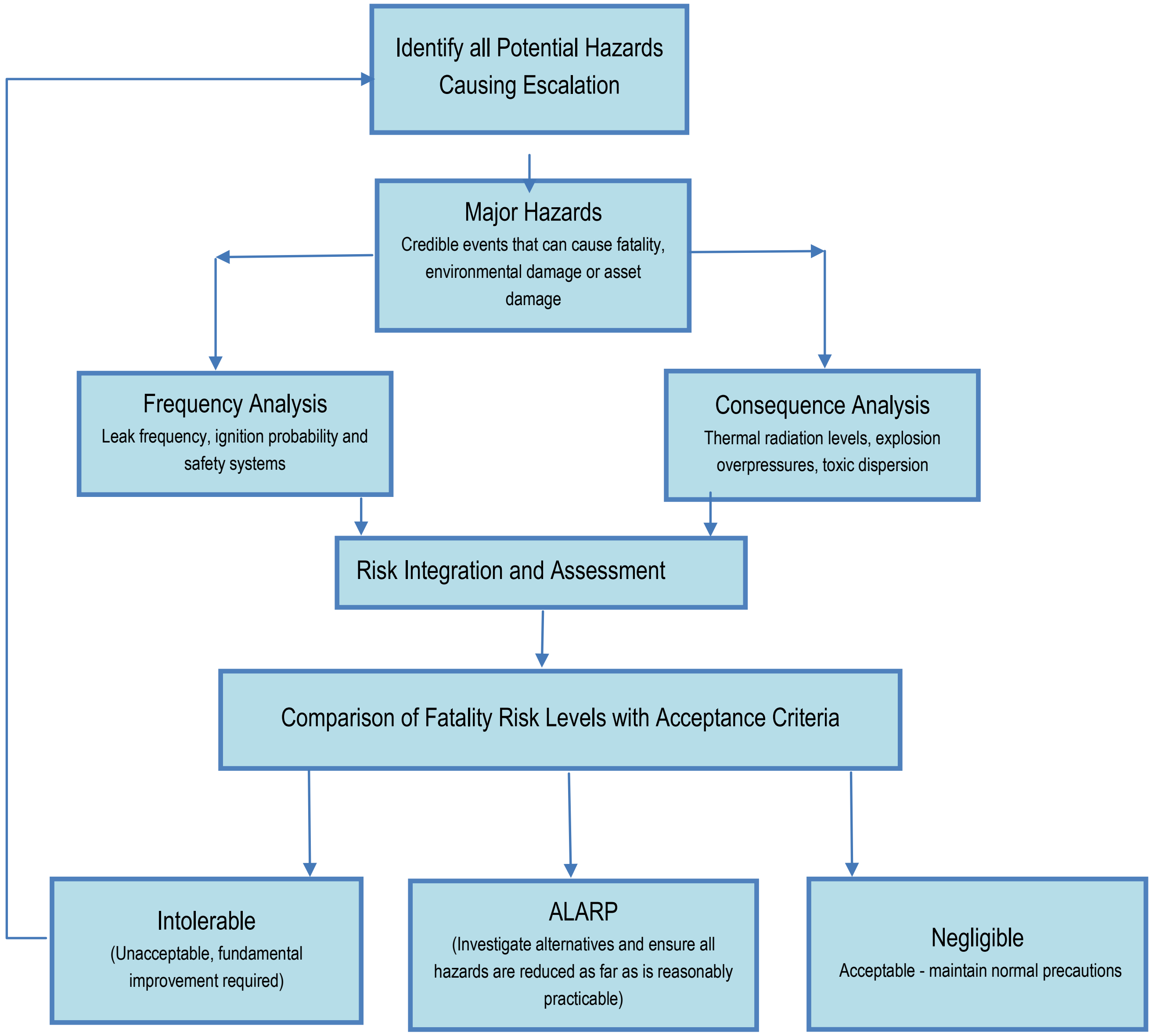
This paper discusses the use of a risk-based approach to set detection performance standards: this enables the gas detectors to be designed to take into account facility layout, release sources and operating parameters. It allows the operator to design the facility with consideration of facility specific parameters, such as reduced operating pressures, overpressure protection and operator occupancy.

Risk Based Assessment Methodology

This section summarises the methodology utilised to perform the risk-based fire and gas detector layout optimisation. Figure 2 shows a typical flow chart applied for the risk assessment in this study. Only flammable gas hazards, i.e. explosions, which can escalate to secondary events have been considered for the purpose of this paper. However, the technique has also been utilised for flame detection and toxic gas detection.

The paper advocates the utilisation of the 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.

Figure 2: Risk Assessment Methodology



Risk Acceptance Criteria - Safety

Typical risk criteria are scenario dependent, and are represented by a sliding scale reflecting less risk tolerance for events with greater consequences than those with lesser consequences. Table 2 (typical table from industry) describes the consequence and frequency criteria typically used for risk-based layer of protection assessments for Safety Hazards. Criterion can also be set for environmental hazards and damage to asset.

Table 2: Target Frequency for Health and Safety Hazards

Severity level	Health and Safety Consequences	Target frequency
A	Potential for 500 or more fatalities	- -
B	Potential for 50-499 fatalities	- -
C	Potential for 10 - 49 fatalities	1E-06/yr
D	Potential for 5-9 fatalities	1E-05/yr
E	Potential for 1 or 4 fatalities	1E-04/yr
F	Potential for Major Health Effects: Permanent partial disability	1E-03/yr
G	Potential for Medium impact health/ safety incident: Recordable injury	1E-02/yr
H	Potential for Low impact health/ safety incident: First aid or exposures causing noticeable irritation but no actual health effects	1E-01/yr

Assumptions

To reduce risk to people, the environment and the business within acceptable bounds, Fire and Gas Detection Systems provide three main functions:

- Detect – Monitor the surroundings for hazardous releases and fires or accumulation of explosive gases;
- Alarm – Enable appropriate action to be taken by initiating alerts to response personnel; and
- Protect – Reduce escalation and/or minimise loss by performing appropriate and effective actions.

Fault Trees are developed to account for the Probability of Failure on Demand (PFD) and therefore the probability that the system will not respond in a fire or gas scenario. Vendor data or equipment failure rates from industry databases are used to determine the PFD for the elements within the fire and gas loops, i.e. detectors, logic solvers and final elements to build the fault tree. The PFD are calculated and applied in the fire and gas model to investigate the risk reduction level in each fire zone.

Detection Assumptions

In the event of successful gas detection, its effectiveness in preventing ignition is approximated using time dependent ignition models. This is as gas detection would not stop the existence of a flammable gas cloud, but it would reduce the size of the gas cloud and the likelihood of ignition.

Alarm and Response Assumptions

The following assumptions are based on an actual facility, however, assumptions that are facility specific should be used.

Key F&G alarm actions are initiated manually by an operator from the F&G control panel and/or from other safe locations.

Using Table 3 as a basis, operator response time can be at least 6 minutes. The six-minute response time can only be credited if the “never exceed, never deviate” approach is utilised. This includes the time it takes to recognize the alarm, to diagnose the problem and to fully initiate action.

Credit is taken for an operator limiting the release of flammable gas inventory but not for stopping ignition of the flammable gas cloud if it meets an ignition source. Note: When using typical time to escalation values used in industry Quantitative Risk Analysis studies, for flame detection, the operator response time would be sufficient to prevent escalation from a pool fire (10 minutes) in the facility. However, escalation is deemed to have occurred from a jet fire (5 minutes) before the operator can fully respond to an alarm. Table 3 presents the typical operator time restrictions with their associated risk reduction factors and descriptions.

Note: The voting philosophy dictated that on confirmed flammable gas detection with 2 leaks, automatic shutdown would be initiated.

Table 3: Typical Operator Time Restrictions with Associated Risk Reduction Factors (Mannan, 2005)

Time (min)	Where?	How Many?	Restrictions	RRF
<10	Any	Any	Operator must troubleshoot the alarm and determine appropriate response	1
2 – 10	Control room	Single operator	Drilled response, also known as a "never exceed, never deviate" response. It the alarm is received, the operator should execute a specific action every time without delay. Staffing should also be adequate so that there is an operator present at all times to respond to the alarm. If the operator response is to troubleshoot the alarm, less than 10 minutes is not an adequate amount of time and no RRF is allowed	10
>10	Control room	Single operator	Operator action is complicated, that is, large number of alarms generated by initiating cause and the response is not clear or documented	1
>10	Control room	Single operator	The operator is trained on alarm response, has procedures available to examine and practices that action periodically	10
>10	Control room	Two operators	All operators listed must receive the same information. Both operators can make independent responses, which completely mitigate the event. Alarm must not be operator re-settable. The operators are trained on alarm response, have procedures available to examine and practice the action periodically	100
>20	Field	Single operator	The operator is trained on alarm response, has procedures available to examine and practices the action periodically	10
>20	Field	Two operators	All operators listed must receive the same information. Both operators can make independent responses, which must completely mitigate the event. Alarm must not be operator re-settable. The operator is trained on alarm response, has procedures available to examine and practices the action periodically	100

Protection Assumptions

It is assumed that protection systems such as Emergency Shutdown Valves (ESDVs) are sufficient to isolate and/or prevent the release of further hazardous materials to the surrounding environment, thereby mitigating escalation. The effect of mitigation can vary and assumptions on mitigation effectiveness must be selected carefully in separate studies.

Common Cause Failure Assumptions

The common cause failure is the result of one or more events, causing concurrent failures of two or more separate components supposedly independent. This will lead to the failure of the system. The PFD for common cause failures between detectors is assumed to be 10% of the PFD of the individual detectors for the purpose of this Risk Based F&G study.

Overall Risk Reduction Assumptions

The PFD for the Fire and Gas System is calculated using the fault tree analysis methodology as shown Figure 3, Figure 4 and summarised in Table 4 for four different number of detectors.

It can be seen from the fault tree analysis that the main limiting factor for alarm action is the human error from the operator with PFD of 1E-01 as discussed in Section 3.2.3 while the main limiting factor for control action is the final element (ESDVs) with PFD of 1E-02.

This analysis can determine clearly the main factors affecting the fire and gas detection system. It enables the operator to perform targeted improvements in terms of voting philosophy, training to operators or hardware improvements.

Figure 3: Fault Tree Analysis – PFDs for Detectors (1ooN Architecture for Alarm)

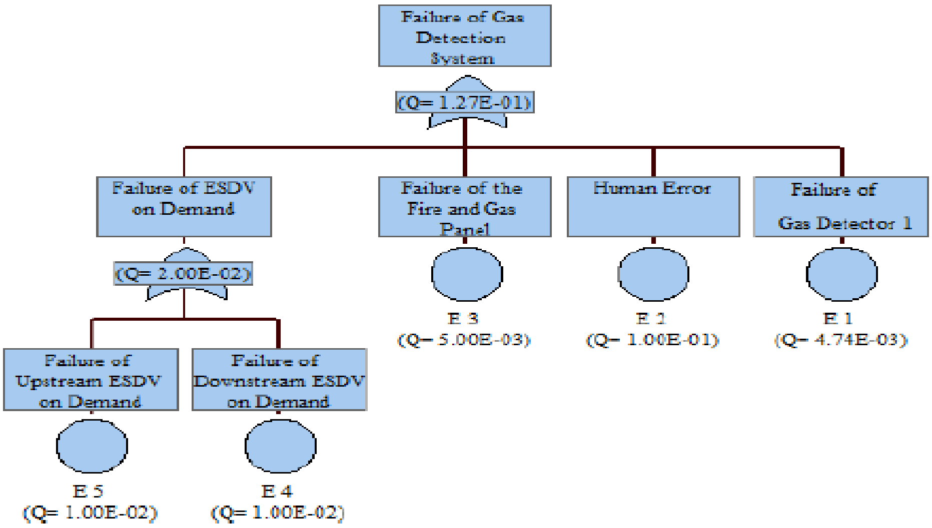


Figure 4: Fault Tree Analysis – Control Action (2ooN Architecture) for Flame Detection (Location Visible to 2 Detectors)

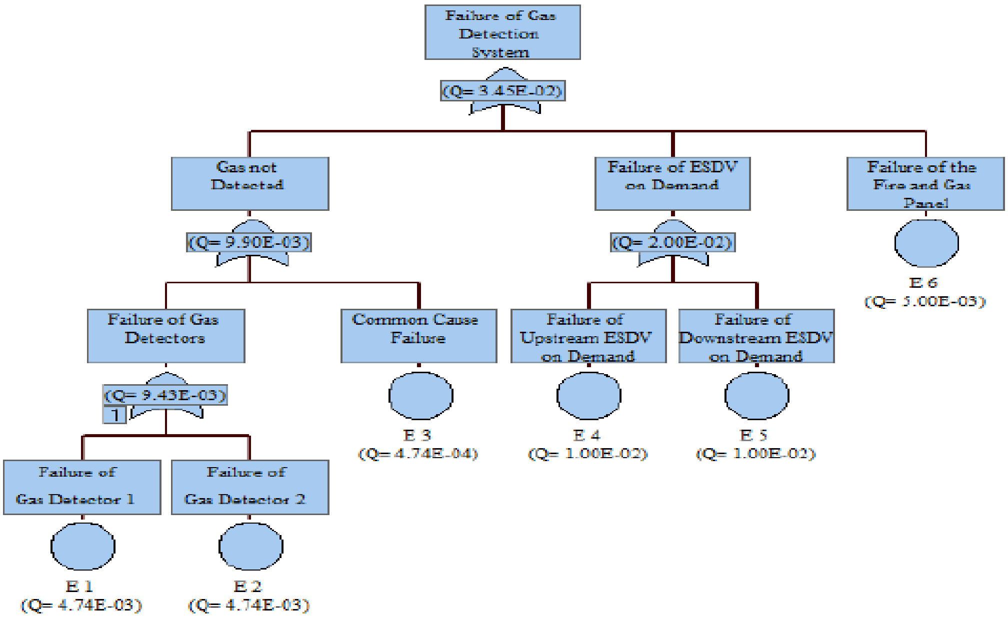


Table 4: PFDs for Detectors (2ooN Architecture for Control)

Number of Gas Detectors able to detect at a Location	Probability of failure to Alarm when Required (PFD Alarm)	Probability of failure to perform control Action when Required (PFD Control)	Failure probability of detection system when required PFD Utilised in AMNIS
1	1.27E-01	-	1.27E-01
2	1.23E-01	3.45E-02	3.45E-02
3	1.23E-01	2.54E-02	2.54E-02
4	1.23E-01	2.53E-02	2.53E-02

Methodology Overview

The methodology utilises the findings of the more traditional geographic approach and uses it as an input to the "risk based approach" for optimisation. The risk based fire and gas detection optimisation study methodology assesses the effectiveness of the fire and gas detection system in terms of risk reduction to an acceptable level according to the operators' risk criteria.

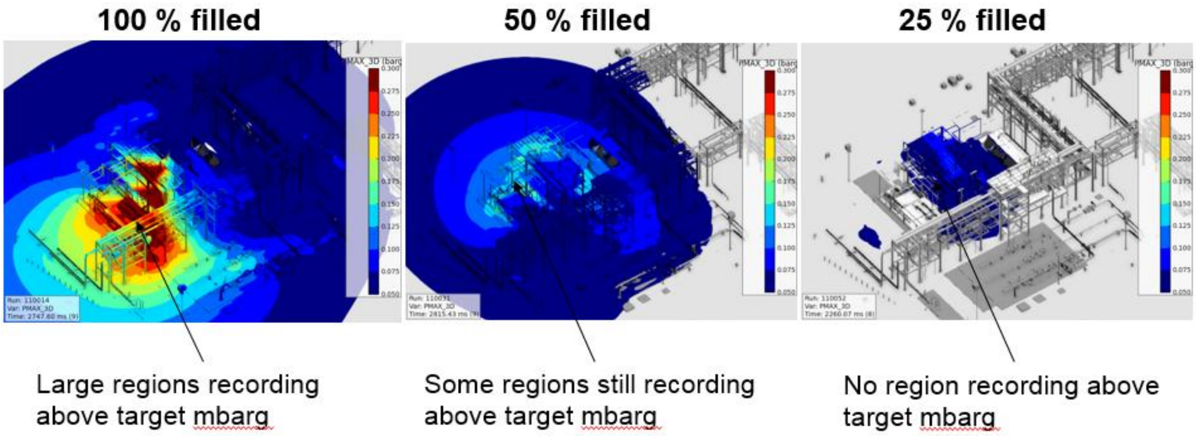
The method adopts a two-staged approach and progresses through the following stages to provide appropriate assessment:

- Develop Initial Design utilising CFD for Fire Zone Categorisation; and
- Risk Based Assessment.

Area Zoning (Fire Zone Category) using CFD Modelling

Using CFD modelling, an assessment of the congested / confined areas is made to determine the potential level of overpressures that could be generated (See Figure 5). Highly confined or congested regions of the plant may suffer damage from small flammable gas accumulations, while 'open' spaces may not be able to develop significant explosion overpressures (but where detection of a large release is still desirable). The smallest cloud size that could lead to the minimum overpressure causing escalation due to equipment damage is then used as a basis for the study. This is in this case greatly influenced by the equipment strength.

Figure 5: CFD Modelling to Determine Target Gas Clouds



Develop Initial Design

The gas detection coverage assessment for the facility is assessed with the 3D Fire and Gas Mapping software, AMNIS, an in-house program developed by MES and used by major oil and gas operators and engineering companies.

It determines a fraction of the geometric area that is covered if there is a release. Target flammable gas sizes determined by CFD modelling are used to determine the initial positions of the fire and gas detectors. Best industry practice and MES experience is utilised on factors such as ease of accessibility for calibration and maintenance without the use of scaffolding and also locating the detectors in areas that ensure protection from environmental effects.

The fire and gas assessment is then used to optimise the locations of detectors through the coverage assessment while ensuring that the set performance targets for the coverage are met. The gas detection system is assessed for its adequacy in providing sufficient protection for areas where flammable gases may potentially be released in hazardous concentration.

Risk-Based Assessment

Initially, the area is assessed to understand the expected severity level expected from an escalation event. This assessment defines the target frequency discussed in Table 2. Below is an example assessment.

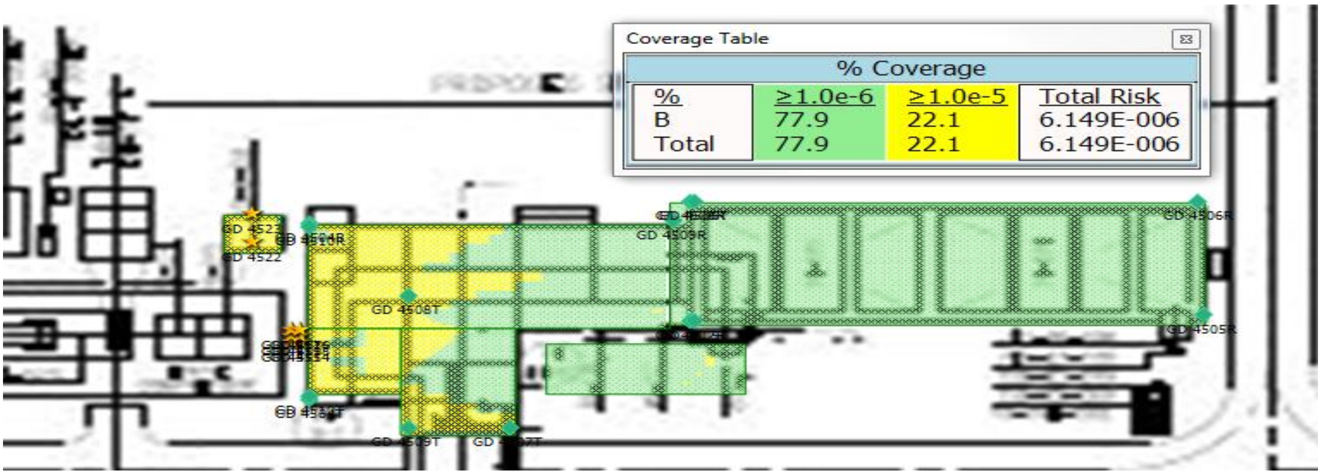
> *"The major accident hazards impacting the compressor area are potential explosion from a flammable cloud accumulation in the compressor housing and potential jet fire from the pipeline running from the reception facility to the compressor area.*
>
> *The compressor area is manned by one operations personnel for 20 minutes per day and 2 maintenance personnel for 20 minutes twice daily. A major accident hazard impacting the compressor area could result in escalation and potential fatality. The occupancy of the workers in the compressor area will be considered for the assessment of escalation impact on safety of personnel. An occupancy of approximately 0.04 has been conservatively assumed (i.e. 60 minutes daily for the three (3) workers per year) and applied in the AMNIS model for this area."*
>
> *Based on the risk criteria, a severity level E with target frequency of 1E-04 per year has been taken as the escalation risk criteria for safety for the compressor area. This is because there is a possibility of 1 or 2 fatalities and several injuries or health effects resulting from an escalation from a major accident hazard in the compressor area."*

The frequencies and consequence results from Project QRA study reports are combined within the software to generate the unmitigated risk contours. The frequencies of overpressure scenarios capable of causing escalation are calculated for every grid point within the sensitive area.

The average frequency of an overpressure scenario within the escalation sensitive area is used to establish the overall unmitigated escalation frequency within each zone. This is then compared to target values set in Table 2. This will determine the residual risk and target areas that require risk reduction.

The detector locations and any variables of the complete fire and gas system are then optimised to ensure that maximum risk reduction is obtained and areas of high escalation risk are targeted (see Figure 6).

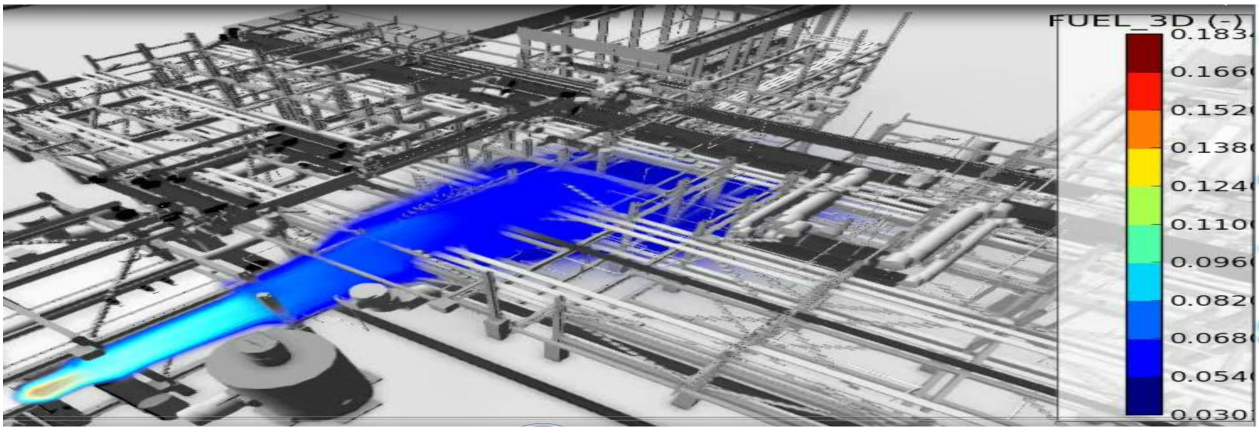
Figure 6: Escalation Frequency using Risk Based Approach



CFD Optimisation Analysis

The proposed flammable gas detection layout determined after AMNIS 3D coverage risk based assessments can be finally analysed for effectiveness in the CFD package by conducting dispersion analysis (see Figure 7). The main objective of the CFD dispersion analysis is to simulate selected scenarios of concern (considering environmental conditions as well as the gas concentration profiles with time at the suggested detector locations) and confirm adequacy of the gas detection system.

Figure 7: CFD Dispersion Test Analysis



Facility	Fire Zone	Run No	Goegraphic Coverage Met	Dispersion Leak Detected	Detector ID	Set Point Reached	Time To Reach Set Point
#	3	311101	Yes	Yes	GD 3	High High	2.8s
		311102	Yes	Yes	GD 2	High High	4.6s

Conclusion

Risk-based fire and gas mapping assessment should be used for the majority of hydrocarbon facilities. The principles are more effective and facility specific than the traditional geographic approach.

The principles enable the Operator to better integrate Fire and gas Mapping with other Safety/Asset Integrity studies such as Quantitative Risk Analysis, Hazard and Identification Studies, Hazard and Operability Studies, Safety Integrity Level studies and Alarm Prioritisation Studies.

MES has also demonstrated how advanced CFD modelling can now be fully integrated into the mapping process. Notably, by performing detailed CFD explosion, the mapping ofvthe target gas cloud size was based on more accurate explosion hazards.

The methodology illustrated in this paper enables the Operator to apply and document the specific reasons for choosing the most cost effective and robust system possible, and has pushed the boundaries in what designers, engineers and asset owners can expect from safety studies. This results in a robust ALARP argument to both the stakeholders and the regulators.

References

International Society of Automation, 2010. Technical Report - “Guidance on the Evaluation of Fire, Combustible Gas and Toxic Gas System Effectiveness” - ISA-TR84.00.07, 2010.

Health and Safety Executive, 1993. Offshore Technology Report – “Offshore Gas Detector Siting Criterion Investigation of Detector Spacing” – OTO 93 002. Stationery Office publications, Norwich

American Institute of Chemical Engineers, 2000, “Guidelines for Chemical Process Quantitative Risk Analysis”, John Wiley & Sons Inc. Publication, United States of America

Vinnem, 2007. “Offshore Risk Assessment”, Centre for Marine and Petroleum Technology, London

Mannan, 2005, “Lees Loss Prevention in the Process Industries”, Elsevier Butterworth – Heinemann, Oxford