GENERAL MONITORS

SIL 104: Impact of gas detection coverage on SIF SIL rating

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Selecting the technology and knowing where to place gas detectors for maximum coverage effectiveness are probably the two most critical decisions for any fire and gas system (FGS) designer. A wrong choice of technology coupled with an inappropriate positioning of the gas detector may render the gas detection loop completely 'blind' to nearby gas leaks. In recent times, the need to estimate the probability of failure upon demand of gas detection related safety instrumented functions, have brought into sharper focus the importance of appropriate detection technology selection and detector positioning, as these are the fundamental factors that significantly determine the level of detection coverage.

Many FGS experts have long realized the difficulty of achieving a high SIL rating for gas detection related *safety instrument functions* (SIF) unless a very high level of *detection coverage* (i.e. probability of the gas sensor detecting gas) is achievable. The approach used by many to calculate the *average probability of failure upon demand* (PFD_{avg}) of a gas detection related SIF simply assumes that the gas sensor has a 100% probability of detecting the passing gas cloud. In reality, a 100% probability of detection is quite likely to be overly optimistic especially when the gas sensor is not located in close proximity to the actual leakage point or if one or more environmental influences such as wind, terrain, stationery objects and area mechanical congestion exists to make gas cloud movement unpredictable or erratic.

To demonstrate how detection coverage could affect the SIL rating of a gas detection related SIF, this article will use a modified event tree called the *FGS Risk Model*. The FGS risk model was developed by safety systems experts to take into consideration two other factors besides FGS availability. These two factors are detection coverage and mitigation effectiveness. These two factors together with FGS availability (see definition below) are collectively called FGS Effectiveness. An understanding of the FGS risk model is needed to appreciate the following mathematical illustration.

FGS RISK MODEL

The simplified FGS risk model shown in Figure 1 has three conditional branches and four consequence outcomes. The definition of each conditional branch is as follows:

- Detection coverage = probability that a gas leak will be detected
- FGS availability = $1 - (PFD_{sensor} + PFD_{logic\_solver} + PFD_{final\_element})$
- Mitigation effectiveness = probability that the consequence of the gas leak will be mitigated

  [Note: Mitigation effectiveness is not covered in this article. It is assumed to be perfect (=1) in all calculations.]

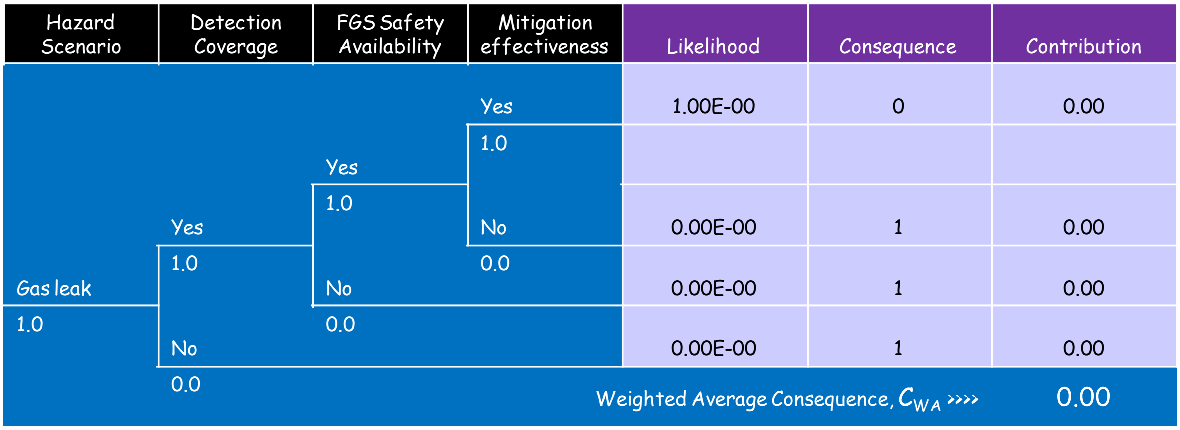

Figure 1: FGS risk model

The combinational probabilities of all 3 conditional branches will produce 4 likelihood outcomes and the product of each likelihood outcome with its corresponding *Consequence* will in turn produce a consequence contribution factor. The subsequent summation of all contribution factors will result in a *Weighted Average Consequence* (C_{WA}) factor.

[Note: The consequence of an event is typically determined separately by a quantitative consequence analysis which is outside the scope of this article. For simplicity, the consequence factor in Figure 1 is shown as either 1 or 0].

The *Residual Risk* (R_R) of the allocated process risk (after the inclusion of a FGS) is then calculated by;

$R_R = C_{WA} \times F_U$ (where F_U = unmitigated frequency of gas leak per year)

In the example shown as Figure 1, it is assumed that:

⇒ the gas sensor will definitely detect the gas leak (i.e. detection coverage = 1);

⇒ the FGS hardware is constantly available (i.e. FGS availability = 1);

⇒ the risk introduced by the gas leak can be mitigated perfectly (i.e. mitigation effectiveness = 1).

In this 'perfect response scenario', C_{WA}= 0, and R_R = 0, which means that the process risk allocated to the FGS is completely mitigated by the FGS with no residual risk.

With this understanding, we can now look at some scenario based illustrations to observe the impact of detection coverage on the SIL rating of gas detection related SIF.

SCENARIO BASED ILLUSTRATIONS

Three different scenarios are illustrated.
1) 100% (perfect) detection coverage
2) 99% detection coverage
3) 95% detection coverage

For each scenario, 5 sets of calculations are presented.
1) No FGS present
2) SIL1 rated FGS present
3) SIL2 rated FGS present
4) SIL3 rated FGS present
5) Summary of risk reduction achieved

Mitigation effectiveness is assumed to be always perfect when a FGS is present (i.e. mitigation effectiveness factor = 1). The frequency of gas leaks is assumed to be not more than once per year (i.e. $F_{unmitigated} = 1$).

Scenario 1: 100% (perfect) detection coverage

Calculation 1: No FGS present (i.e. detection failure = 1, FGS failure = 1, mitigation failure = 1):

No FGS	
FGS SIL =	0
PFD_{FGS} =	0
FGS availability =	0
Detection coverage =	0
Mitigation effectiveness =	0

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	0.000	0.000	0.000	0.000	0.000	0.000
Mitigation failure	1.000	0.000	0.000	1.000	0.000	1.000	0.000
FGS failure	1.000	0.000	1.000		0.000	1.000	0.000
Detection failure	1.000	1.000			1.000	1.000	1.000
						C_{WA}	1.000
						$F_{unmitigated}$	1.00E+00
						Unmitigated risk	1.00E+00

Calculation 2: SIL 1 FGS is used:

SIL 1 FGS	
FGS SIL =	1
PFD_{FGS} =	0.099
FGS availability =	0.901
Detection coverage =	1
Mitigation effectiveness =	1

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	1.000	0.901	1.000	0.901	0.000	0.000
Mitigation failure	1.000	1.000	0.901	0.000	0.000	1.000	0.000
FGS failure	1.000	1.000	0.099		0.099	1.000	0.099
Detection failure	1.000	0.000			0.000	1.000	0.000
						C_{WA}	0.099
						$F_{unmitigated}$	1.00E+00
						R_R with SIL1 FGS	9.90E-02

Calculation 3: SIL 2 FGS is used:

SIL 2 FGS	
FGS SIL =	2
PFD_{FGS} =	0.0099
FGS availability =	0.9901
Detection coverage =	1
Mitigation effectiveness =	1

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	1.000	0.9901	1.000	0.990	0.000	0.000
Mitigation failure	1.000	1.000	0.9901	0.000	0.000	1.000	0.000
FGS failure	1.000	1.000	0.0099		0.010	1.000	0.010
Detection failure	1.000	0.000			0.000	1.000	0.000
						C_{WA}	0.010
						$F_{unmitigated}$	1.00E+00
						R_R with SIL2 FGS	9.90E-03

Calculation 4: SIL 3 FGS is used:

SIL 3 FGS	
FGS SIL =	3
PFD_{FGS} =	0.00099
FGS availability =	0.99901
Detection coverage =	1
Mitigation effectiveness =	1

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	1.000	0.99901	1.000	0.999	0.000	0.000
Mitigation failure	1.000	1.000	0.99901	0.000	0.000	1.000	0.000
FGS failure	1.000	1.000	0.00099		0.001	1.000	0.001
Detection failure	1.000	0.000			0.000	1.000	0.000
						C_{WA}	0.001
						$F_{unmitigated}$	1.00E+00
						R_R with SIL3 FGS	9.90E-04

Calculation 5: Summary of risk reduction achieved:

	Type of FGS			
	SIL3 FGS	SIL2 FGS	SIL1 FGS	NO FGS
Mitigated risk =	9.90E-04	9.90E-03	9.90E-02	1.00E+00
Unmitigated risk =	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Risk reduction =	1010	101	10	1

The calculations show that when detection coverage is perfect (i.e. detection coverage = 1), the risk reduction that can be achieved by each FGS is closely in line with the respective SIL rating.

Scenario 2: 99% detection coverage

Calculation 1: No FGS present (i.e. detection failure = 1, FGS failure = 1, mitigation failure = 1):

No FGS	
FGS SIL =	0
PFD_{FGS} =	0
FGS availability =	0
Detection coverage =	0
Mitigation effectiveness =	0

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	0.000	0.000	0.000	0.000	0.000	0.000
Mitigation failure	1.000	0.000	0.000	1.000	0.000	1.000	0.000
FGS failure	1.000	0.000	1.000		0.000	1.000	0.000
Detection failure	1.000	1.000			1.000	1.000	1.000
						C_{WA}	1.000
						$F_{unmitigated}$	1.00E+00
						Unmitigated risk	1.00E+00

Calculation 2: SIL 1 FGS is used:

SIL 1 FGS	
FGS SIL =	1
PFD_{FGS} =	0.099
FGS availability =	0.901
Detection coverage =	0.99
Mitigation effectiveness =	1

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	0.990	0.901	1.000	0.892	0.000	0.000
Mitigation failure	1.000	0.990	0.901	0.000	0.000	1.000	0.000
FGS failure	1.000	0.990	0.099		0.098	1.000	0.098
Detection failure	1.000	0.010			0.010	1.000	0.010
						C_{WA}	0.108
						$F_{unmitigated}$	1.00E+00
						R_R with SIL1 FGS	1.08E-01

Calculation 3: SIL 2 FGS is used:

SIL 2 FGS	
FGS SIL =	2
PFD_{FGS} =	0.0099
FGS availability =	0.9901
Detection coverage =	0.99
Mitigation effectiveness =	1

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	0.990	0.9901	1.000	0.980	0.000	0.000
Mitigation failure	1.000	0.990	0.9901	0.000	0.000	1.000	0.000
FGS failure	1.000	0.990	0.0099		0.010	1.000	0.010
Detection failure	1.000	0.010			0.010	1.000	0.010
						C_{WA}	0.020
						$F_{unmitigated}$	1.00E+00
						R_R with SIL2 FGS	1.98E-02

Calculation 4: SIL 3 FGS is used:

SIL 3 FGS	
FGS SIL =	3
PFD_{FGS} =	0.00099
FGS availability =	0.99901
Detection coverage =	0.99
Mitigation effectiveness =	1

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	0.990	0.99901	1.000	0.989	0.000	0.000
Mitigation failure	1.000	0.990	0.99901	0.000	0.000	1.000	0.000
FGS failure	1.000	0.990	0.00099		0.001	1.000	0.001
Detection failure	1.000	0.010			0.010	1.000	0.010
						C_{WA}	0.011
						$F_{unmitigated}$	1.00E+00
						R_R with SIL3 FGS	1.10E-02

Calculation 5: Summary of risk reduction achieved:

	Type of FGS			
	SIL3 FGS	SIL2 FGS	SIL1 FGS	NO FGS
Mitigated risk =	1.10E-02	1.98E-02	1.08E-01	1.00E+00
Unmitigated risk =	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Risk reduction =	91	51	9	1

The calculations show that when detection coverage is less than perfect (i.e. detection coverage = 0.99), the risk reduction that can be achieved by each FGS is significantly impacted. Calculation 5 shows that the risk reduction that is achievable by a SIL3 FGS is lowered to SIL1 (risk reduction < 100), the risk reduction that is achievable by a SIL2 FGS is also lowered to SIL1 (risk reduction < 100) and a SIL1 FGS will fall below the minimum SIL level.

Scenario 3: 95% detection coverage

Calculation 1: No FGS present (i.e. detection failure = 1, FGS failure = 1, mitigation failure = 1)

No FGS	
FGS SIL =	0
PFD_{FGS} =	0
FGS availability =	0
Detection coverage =	0
Mitigation effectiveness =	0

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	0.000	0.000	0.000	0.000	0.000	0.000
Mitigation failure	1.000	0.000	0.000	1.000	0.000	1.000	0.000
FGS failure	1.000	0.000	1.000		0.000	1.000	0.000
Detection failure	1.000	1.000			1.000	1.000	1.000
						C_{WA}	1.000
						$F_{unmitigated}$	1.00E+00
						Unmitigated risk	1.00E+00

Calculation 2: SIL1 FGS is used

SIL1 FGS	
FGS SIL =	1
PFD_{FGS} =	0.099
FGS availability =	0.901
Detection coverage =	0.95
Mitigation effectiveness =	1

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	0.950	0.901	1.000	0.856	0.000	0.000
Mitigation failure	1.000	0.950	0.901	0.000	0.000	1.000	0.000
FGS failure	1.000	0.950	0.099		0.094	1.000	0.094
Detection failure	1.000	0.050			0.050	1.000	0.050
						C_{WA}	0.144
						$F_{unmitigated}$	1.00E+00
						R_R with SIL1 FGS	1.44E-01

Calculation 3: SIL2 FGS is used

SIL2 FGS	
FGS SIL =	2
PFD_{FGS} =	0.0099
FGS availability =	0.9901
Detection coverage =	0.95
Mitigation effectiveness =	1

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	0.950	0.9901	1.000	0.941	0.000	0.000
Mitigation failure	1.000	0.950	0.9901	0.000	0.000	1.000	0.000
FGS failure	1.000	0.950	0.0099		0.009	1.000	0.009
Detection failure	1.000	0.050			0.050	1.000	0.050
						C_{WA}	0.059
						$F_{unmitigated}$	1.00E+00
						R_R with SIL2 FGS	5.94E-02

Calculation 4: SIL3 FGS is used

SIL3 FGS	
FGS SIL =	3
PFD_{FGS} =	0.00099
FGS availability =	0.99901
Detection coverage =	0.95
Mitigation effectiveness =	1

Scenario	Hazardous event	Detection coverage	FGS availability	Mitigation effectiveness	Likelihood	Consequence	Contribution
FGS success	1.000	0.950	0.99901	1.000	0.949	0.000	0.000
Mitigation failure	1.000	0.950	0.99901	0.000	0.000	1.000	0.000
FGS failure	1.000	0.950	0.00099		0.001	1.000	0.001
Detection failure	1.000	0.050			0.050	1.000	0.050
						C_{WA}	0.051
						$F_{unmitigated}$	1.00E+00
						R_R with SIL3 FGS	5.09E-02

Calculation 5: Summary of risk reduction achieved:

	Type of FGS			
	SIL3 FGS	SIL2 FGS	SIL1 FGS	NO FGS
Mitigated risk =	5.09E-02	5.94E-02	1.44E-01	1.00E+00
Unmitigated risk =	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Risk reduction =	20	17	7	1

The calculations show that when detection coverage is reduced to 95% (i.e. detection coverage = 0.95), the risk reduction achievable by a SIL3 or SIL2 FGS will both be reduced to SIL1 (risk reduction < 100), and the difference in achievable risk reduction between SIL3 and SIL2 FGS is insignificant.

CONCLUSION

It is obvious from this simple illustration that the percentage of detection coverage has a significant impact on the eventual SIL rating of a gas detection related SIF.

A field study report released by the Offshore Safety Division of HSE UK (OTO 2000 112, Dec 2000), suggests that only about 60% of hydrocarbon gas releases (out of 1801 reported gas releases cases between October 1992 and March 2000) on offshore facilities were detected by the equipment that were put in place for gas detection purpose. Reasons for the 40% non-detection were not detailed in the report, so arguably these failures could have been caused or influenced by other factors besides poor detection coverage. Nevertheless, the statistical evidence presented is enough to implicitly suggest that the likelihood of a lower than 95-99% detection coverage is a highly probable scenario (due to various causes), certainly in the case for offshore applications and likely to be similar for onshore applications.

If, as the HSE study suggests, a greater than 99% detection coverage is improbable, and if there are no other considerations that warrants its implementation, then it may not make a lot of sense to implement a costlier SIL3 or SIL2 SIF hardware solution for most gas detection systems, since the effective risk reduction is at best no greater than SIL1.

SIL level	Risk reduction
3	> 1,000 to ≤ 10,000
2	> 100 to ≤ 1,000
1	> 10 to ≤ 100

Figure 2: Relationship between SIL levels and risk reduction

Finally, regardless of what SIF hardware is selected, good detection coverage remains an important design element for gas detection systems, as this determines whether or not the system would be effective in providing protection against dangerous gas leaks.

Some methods to improve detection coverage that can be considered are:

- Usage of computational fluid dynamics (CFD) modelling techniques to approximate gas cloud dispersion scenarios under different environmental conditions. Knowing where the probable gas dispersion path would be will greatly increase the ability of the engineer to place gas detectors more precisely.

- Where possible, apply detection technology that is more impervious to wind direction/speed and other environmental influences. An example of this technology would be the ultrasonic gas leak detector, which detects ultrasonic frequencies created by escaping pressurized gas at the leakage point, and is therefore not affected by onsite wind conditions or other common environmental factors

- Where possible, apply detection technology that supports post installation detection coverage verification. A technology that features this is the ultrasonic gas leak detector, where the effective detection coverage can be verified through N_2 leak tests after the detector is installed with all surrounding process equipment, piping, vessels etc. fully constructed. If necessary, the gas leak detector could be re-positioned to improve detection coverage.

- For large area monitoring of outdoor uncongested locations that are exposed to wind, apply a detection technology that is able to detect low concentration hydrocarbon gas clouds to account for dilution effects caused by the wind. An example of this technology would be the optical open path IR beam hydrocarbon gas detector that is sensitive to parts-per-million (ppm) levels of hydrocarbon gases.

- Understand the process equipment construction and mechanical layout so that point type gas detectors can be placed as close as possible to potential gas leak points to increase the likelihood of detection.

- Understand the process well so that the type of gas release (e.g. low/high fraction release, condensate release, liquid spills, gas jet release, flashing liquid release etc.) can be anticipated and the gas detector better placed to increase the likelihood of gas detection.