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Risk-Based Approach – Mitigating Hazardous Scenarios

An Introduction to Fire and Gas Detectors Mapping Study

An ioMosaic White Paper

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Abstract

The main purpose of a Fire and Gas (FGS) mapping study is to identify and assess the placement and performance of gas flammable, toxic and fire detectors. The proposed approach links the robust risk-based quantitative assessment results with zone definition and categorization. It provides the exact location of FGS for ensuring detection coverage (i.e., detector coverage verification) and addresses which is the required reliability for ensuring the pursued risk reduction (i.e., functional safety availability verification). Even though the present manuscript focuses on detection coverage verification, both mapping and functional safety concepts are addressed. Functional safety requirements are fully addressed in a dedicated related reference covering Safety Instrumented Systems (SIS) [5].

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Introduction

Reference **[1]** provides an overview of layers of protection suitable to reduce the risk level of a process facility; i.e., measures intended to prevent and/or mitigate the identified hazardous scenarios. The cited paper **[1]** illustrates that based on the development and results of a risk-based quantitative assessment, the regions, zones or even more detailed locations (e.g., occupied buildings, critical process equipment) with an intolerable risk level can be identified and the associated hazardous scenarios that most contribute to the risk of these zones. It is confirmed that a sensitivity analysis and cost-benefit analysis can be performed with the aim to find which safeguards achieve the reduction of risk to an acceptable level at the most reasonable cost.

From all layers of protection considered in reference **[1]**, the Safety Instrumented Systems (SIS) and performance-based Fire and Gas Detectors Systems (FGS) were found to be the safeguards that should comply with very specific requirements stated in related standards; i.e., IEC 61508 **[2]**, IEC 61511 **[3]** and ISA 84.00.TR.07 **[4]**, respectively. While SIS selection and verification guidance can be found in reference **[5],** the main purpose of this manuscript is to address performance-based FGS intended to comply with standard **[4]** by introducing a risk-based Fire and Gas Mapping approach.

The proposed Fire and Gas Mapping Study is based on detailed results obtained during the development of a risk-based quantitative assessment. All introductory criteria for ensuring a complete and robust risk-based quantitative assessment are illustrated in references **[1]**, **[6]**, **[7]**, **[8]**, **[9]**, **[10]**, **[11]** and **[12].** Formally, the FGS mapping study is justified after comparing the actual risk levels in the process facility with worldwide recognized tolerability criteria and evidencing that risk reduction is required. Note that the magnitude of the risk reduction required (i.e., Risk Reduction Factor, RRF) is directly correlated to the Safety Integrity Level (SIL) and associated Probability of Failure of Demand (PFD) of the Safety Instrumented Function (SIF). While all these concepts are necessary to be introduced in the present manuscript, it is important to mention that "*Functional Safety*" requirements are fully develop in reference **[5]**, which allows the present paper to focus on how to link risk-based quantitative assessment results with zone definition, categorization and detector coverage verification.

Fire and Gas Mapping Study

The main purpose of a Fire and Gas (FGS) mapping study is to identify and assess the location and performance of detectors and covers both gas (flammable and toxic) and fire detection. The study is conducted ensuring the following tasks/phases:

- FGS Philosophy Considerations
- FGS Zone Definition and Categorization
- FGS Performance Targets
- FGS Detector Coverage Verification
- FGS Functional Safety Availability Verification

FGS Philosophy Considerations

The first step consists of ensuring the FGS philosophy considerations, which should be based on internal corporate guidelines and also related standards; i.e., ISA 84.00.TR.07 **[4].** Therefore, the configuration of flammable, toxic, hydrogen gas detectors, visual and audible alarms, both in process areas and buildings should comply with established criteria.

Automatic fire detection and alarm devices should be provided in process areas where there is a fire hazard and the following types of fire detectors (and also audible and visual alarms) could be considered as part of this study: combined UV/IR Flame Detector, Heat Detector (combined type), Linear Heat Detection Cable, Optical Smoke Detector, High Sensitivity Smoke Detector, Manual Alarm Call Points. Additionally, the fire detection and alarm actuation voting logic (i.e., functional safety, reliability), both automatic and manual (i.e., operation in both process areas and in non-process buildings) should ensure the given criteria.

FGS Philosophy considerations are complex and ioMosaic recommends developing an Assumptions Register document intended to establish the key criteria, assumptions and knowledge required to effectively develop all FGS mapping study tasks and phases.

FGS Zone Definition and Categorization

Basics and Definition

Zone definition is mainly intended to establish FGS performance targets for each selected zone. Accordingly, ioMosaic approach proposes to segregate the process areas into discrete zones to be independently analyzed for the determination of which hazardous/failure scenarios are present and which scenarios can be minimized or mitigated by using FGS; i.e., fire, flammable gas and toxic gas releases. These failure scenarios specifically address potential Loss of Containment scenarios (LOCs) with release of flammable and/or toxic mixtures. Note that LOCs to be addressed are characterized during the development of a risk-based quantitative assessment study.

When defining different zones (i.e., both process areas and non-process locations), the main purpose is to identify which areas have different hazards with varying risk levels; e.g., there may be areas with only toxic hazards that have to be separated from other areas that have only fire or combustible gas hazards. The basis of zone definition and categorization is that each selected area may require different types of FGS detection and different levels of performance. Additionally, the main purpose of zonification is to prevent the migration of combustible gas or toxic gas hazards from the process area to non-process areas where they can either impact humans or be ignited by electrical equipment.

Each zone will be segmented into smaller geographic divisions known as graded areas based on the risk-based quantitative assessment. This segmentation is used to establish the specific performance targets for all FGS to be placed in each zone. Each zone will be assigned a category to determine general requirements for FGS with the aim to ensure the FGS performance. Categories to be considered are defined as a direct function of the type of hazards identified in the zone (e.g., hydrocarbon fire, non-hydrocarbon fire) and is related to the nature of the zone (e.g., process areas, non-process areas with or without electrical equipment protection or occupied buildings, specific areas with turbine or engine enclosures, ventilation air intakes).

Therefore, each area receives a performance target for fire, flammable gas and toxic gas hazards which takes the form of Grades. Each of the grades serves to define a relative level of fire or gas risk with Grade A being the highest risk areas and Grade C being the lowest risk areas requiring detection **[4]** (see an illustrative example in **Table 01**).

Table 01: Example of Zones Categorization – Fire and Gas Performance Grades

Category / Grade Level	Description
A	Hydrocarbon processing with high exposure (high risk level area)
B	Hydrocarbon processing with moderate exposure (medium risk level area)
C	Hydrocarbon processing with low or very low exposure (low risk level area)
NA	Actual risk level is tolerable

The proposed approach is intended to analyze all process units covered in the risk-based quantitative assessment in order to determine and document the appropriate discrete zones. The zone selection is based on the definition of easily identifiable areas with respect to physical and/or process boundaries. After ensuring the most detailed and reliable list of zones and associated categories for FGS performance target definition (i.e., coverage and verification), the list of zones and categories are agreed with all interested parties and included in the proposed assumptions register document.

Risk-Based Approach for Zone and Category Definition

The zone definition and categorization will be based on the risk-based quantitative assessment results, which are considered the baseline and foundation for defining the boundaries of each area to be mapped for the analysis; i.e., the source of release and subsequent leak scenarios and its potential effects for gas (flammable and toxic) and fire (flame) detection optimization.

Once the risk-based quantitative assessment has been completed and the actual risk results have been compared with the applicable risk tolerability criteria, it is time to question if risk reduction is necessary; i.e., if there exists a gap between the actual and the tolerable risk levels. For example, based on individual risk contours, it is easy to identify if the actual results represent areas within the process facility analyzed that are considered intolerable.

In these cases, the installation of potential risk reduction measures (e.g., FGS) should be analyzed with the aim to reduce the risk of the hazardous scenarios that lead to high individual risk contours. **Figure 01** illustrates an example of individual risk contours estimated for a facility that handles hazardous substances. If an individual risk level greater than 1.00E-03 yr^{-1} (i.e., one fatality in 1000 years) is considered intolerable, it can be observed that the area within the red contour is an intolerable risk region.

Therefore, the definition of zones needs to be focused on identifying which are the most contributing hazardous scenarios and associated outcomes that generate the red contour. However, it is important to mention that this is not an easy task when the total number of LOCs defined in a risk-based quantitative assessment for a whole site can entail hundreds or thousands of scenarios and even more when considering the multiple potential outcomes from a LOC. As a result, the key initial task to be performed for risk reduction is the identification of the specific hazardous scenarios that effectively contribute to the risk level in the area of concern.

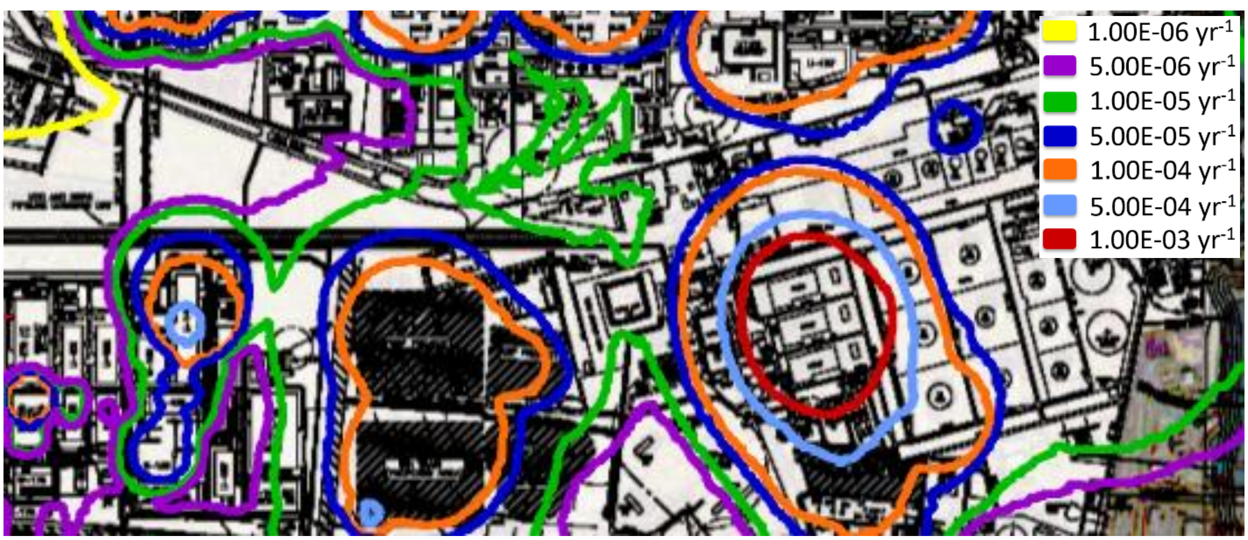

Figure 01: Example of Individual Risk Contours for a Given Facility

The challenge is to collect the specific LOCs with the greatest contribution to the zone or region identified with an intolerable risk level. However, there are advanced tools that allow analyzing the results from a risk-based quantitative assessment and extracting very specific information for risk reduction purposes. An example is the SuperChems™ **[13]** tool, which allows the user to identify individual hazardous scenarios contributing to target locations or zones. The development of risk contours, risk indices, exceedance curves and other useful parameters intended for quantitative risk ranking (see references **[1]** and **[11]** for detailed information) help on generating a list with the pursued LOCs.

Table 02 provides guidance on how useful and how to use these tools for LOCs identification and zone definition. Once the pursued key LOCs have been identified the safety engineers and managers can discuss how to address them.

The detailed information that can be extracted from each LOC identified can be very detailed:

- Piece of process equipment, which allows finding the specific location and definition of the LOC. It is possible to identify cause-consequence pairs (i.e., hazardous scenarios), including the value of the initiating event.
- Composition and phase of the hazardous material released, which allows identifying the typology of the hazard (i.e., toxicity, flammability) and also which type of risk reduction could be analyzed. For example, diking for vaporization reduction due to a liquid spill.
- Enabling conditions and conditional modifiers (e.g., location of ignition sources and associated probabilities of ignition, layers of protection in place) that contribute to the feasibility of the final outcomes. That includes knowledge on the final outcome frequency and probability of intermediate events.
- Impact distances of outcomes evaluated per each LOC.

All this information is valuable for defining the risk reduction strategy and it allows defining the zones and categories to be addressed during the FGS mapping study development.

Table 02: Tools and Results for Zone Definition and Categorization

Tool	Description
Individual Risk Contours	Identification of zones with intolerable risk levels (i.e., probability of fatality) impacted for all outcomes that contribute to hazardous effects; i.e., toxicity, thermal radiation and overpressure. Note that also is relevant to evaluate more specific individual risk contours per type of hazard; i.e., only considering toxic effects, or thermal radiation effects, or overpressure effects.
Toxic Rik Contours	Identification of zones with risk levels evaluated at a given toxic concentration or dose of interest; i.e., certain level of human vulnerability. Reference **[9]** reviews the state-of-the-art of damage criteria due to toxic dispersions.
Thermal Risk Contours	Identification of zones with risk levels evaluated at a thermal flux or doses of interest; i.e., certain level of human and/or structural damage. Reference **[9]** reviews the state-of-the-art of damage criteria due to fires.
Overpressure Risk Contours	Identification of zones with risk levels evaluated at an overpressure or impulse of interest; i.e., certain level of human and/or structural damage. Reference **[9]** reviews the state-of-the-art of damage criteria due to explosions.
Exceedance Curves	Exceedance curves for addressing toxicity, or thermal radiation, or overpressure can be developed for dedicated target locations; e.g., occupied buildings, critical process equipment. SuperChems™ **[13]** generates a list of LOCs that impact the location under analysis.
Risk Indices	Used to quantitatively compare the contribution of a given number of selected LOCs identified to contribute to a specific zone with an intolerable risk level by using risk contours or exceedance curves. IR_{TOT} (Total Individual Risk) and PLL (Potential Loss of Life) are valuable indices used when addressing risk contribution.

Note: Risk-based tools based on SuperChems™ capabilities **[13]** and technical knowledge **[14]**.

FGS Performance Targets

The purpose of this task is to define how well the system should perform. Performance refers to the ability of the system to reliably detect the hazard of concern and take the proper safety actions to mitigate that hazardous condition. It is important to specify how much performance is required. Based on ISA's Technical Report **[4]**, the two primary modes of FGS failure are the following:

- **Coverage:** insufficient number, type or location of fire or gas detectors resulting in a hazard that is not detected by the FGS.
- **Safety Availability:** component failures of FGS hardware that result in the FGS being in an unavailable state when a demand condition arises.

The results of the risk-based quantitative assessment (i.e., technical basis of the proposed FGS mapping study) verifies that quantitative risk tolerances have been achieved using detailed quantification of the hazard and risk. The determination of FGS performance targets will be defined via detection coverage and safety availability.

FGS Detection Coverage

ISA Technical Report TR 84.00.07 **[4]** defines two types of coverage that may be evaluated:

- **Scenario Coverage:** specifically takes into account the relative likelihood of a fire or gas release in any specific location within a monitored area. The location, magnitude and likelihood of specific hazard scenarios are evaluated and it is fully developed when performing a complete and robust risk-based quantitative assessment.
- **Geographic Coverage:** (i.e., "what can the detector see") is defined as a type of coverage which essentially asks what fraction of a geographic area is being monitored by a fire or gas detector array. This type of coverage determines whether or not the detector array would be able to detect a specific size or magnitude of hazard if a fire or gas release were to occur in a specific location. The geographic coverage is presented in terms of a color-coded map in addition to tabular results.

Based on the knowledge developed during the execution of the risk-based quantitative assessment and after ensuring the definition and categorization (Grades) of the zones to be analyzed for detector coverage, the FGS performance targets can be defined. **Table 03** provides an example of targets **[4]**:

- Fire detection performance targets are evaluated in locations where fires could occur with sufficient intensity to result in life-safety and/or business impact.

- Combustible gas detection performance targets are evaluated in locations where ignited gas clouds could cause damage from explosion overpressure. In these locations the smallest gas cloud that has the potential to cause such damage or the smallest gas cloud that can reasonably be developed, is used to define requirements for placing combustible gas detectors.

- Toxic detection performance targets are evaluated in locations where toxic gas clouds could cause serious injury and this is based on the likelihood and severity of the toxic gas hazards present.

FGS Safety Availability

In addition to setting performance targets for coverage, performance targets have to be established for the Probability of Failure on Demand (PFD) of the equipment that comprises the instrumented fire and gas function. It is important to comply with FGS performance targets calculated based on tolerability criteria and as defined criteria established in standards **[2]**, **[3]**, **[4]**.

Some gas detectors will actuate on the process as indicated in Process Cause and Effect Matrix, as they belong to Instrumented Protective Functions (IPFs) loops. These critical loops (including gas detectors, logic solver and final element) must comply with the estimated Safety Instrumented Level (SIL), identified when evaluating the Risk Reduction Factor (RRF) when comparing the actual risk and tolerable risk levels. However, normally the authorization from the operator is considered.

Therefore, functional safety criteria has to be established for addressing IPFs related to gas and fire detectors systems.

Table 03: Fire and Gas Detection Performance Based on Zone Categorization / Grades

Grade	Coverage	Hazard Type	Comments and Clarifications
A	0.9	Fire	A minimum of 90% detector coverage is achieved for detection of a 10 kW incipient stage fire.
		Combustible	A minimum of 90% detector coverage is achieved for detection of a spherical gas cloud 5 meter in diameter anywhere in the zone.
		Toxic	A minimum of 90% detector coverage is achieved for detection of zones where a toxic life-threatening hazard could occur from relatively small gas release a t a distance well outside the localized area of the release.
B	0.8	Fire	A minimum of 80% detector coverage is achieved for detection of a 50 kW incipient stage fire.
		Combustible	A minimum of 80% detector coverage is achieved for detection of a spherical gas cloud 5 meter in diameter anywhere in the zone.
		Toxic	A minimum of 80% detector coverage is achieved for detection when there is a moderate degree when an injury-level toxic hazard could occur from a small release at a distance well outside the localized area of the release.
C	0.6	Fire	A minimum of 60% detector coverage is achieved for detection of a 100 kW incipient stage fire.
		Combustible	A minimum of 60% detector coverage is achieved for detection of a spherical gas cloud 10 meter in diameter anywhere in the zone.
		Toxic	A minimum of 60% detector coverage is achieved for detection when an injury-level toxic hazard could occur only from a large release at a distance beyond the localized area of the release.

FGS Detector Coverage Verification

The detector coverage verification phase of the proposed risk-based FGS mapping approach ensures the following key characteristics:

- Geographic coverage for both fire and gas detection arrays. The geographic coverage is intended to determine the fraction of the area of a monitored process zone in which, if a fire or gas release were to occur, would be detected.
- Generation of a colorized map of the coverage provided in a zone, along with tabulated and calculated results. The fire and gas mapping tool performs modeling in three dimensions and calculates the analysis results for any user-selected elevation of interest.
- Modeling of the effects of changes in detector elevation away from the elevation of interest, the effects of changing angle of declination with respect to the elevation of interest and modeling of multiple different detector sensitivity settings for each detector, the impact of obstructions to fire detector view in full three dimensions, including multiple obstruction geometries.
- Illustration of tabular results of the area where no detectors, a single detector, or two or more detectors are sighted and a color-coded map of the elevation of interest showing where no detectors, a single detector, or two or more detectors are sighted.
- Illustration of the coverage verification as one fire coverage map and one gas coverage map for each zone, with tabulated results of the mapping analysis.

With the aim to comply with all coverage verification execution characteristics illustrated above, a 3D software developed by insight numerics, i.e., Detect 3D **[15]** can be used, which is a model, windows-based software that includes an optimization feature using genetic algorithms allowing the minimization of detector counts while achieving the coverage target criteria.

Flame Detection and Fire Mapping

Detect3D **[15]** uses powerful ray-casting algorithms to accurately determine the obstructed Field Of View (FOV) of flame detectors. Using the data from thousands of rays cast from each detector. A full 3D representation of coverage areas is built, which can be visualized using contours or isovolumes. Any manufacturer and model of flame detector can be used with Detect3D **[15]**. Insight Numerics has partnered with several manufacturers to provide a live database of FOV information (maximum range, cone of vision etc.) that can be used directly during the analysis. In addition to the manufacturer data, custom FOVs can be created.

Gas Detection and Gas Mapping

Point and open-path gas detectors can be added in Detect3D **[15]** for the assessment of gas detector layouts. The coverage of the gas detector layout is calculated using the "Design Gas Cloud" method popularized by BP and Shell. In this method, a spherical gas cloud is chosen to be used as a design basis for the detector layouts. Although gas clouds are never spherical, the complexities involved in characterizing gas clouds more accurately are so great that a sensible approach is to represent the statistical average of the gas clouds as a sphere. The advantage of this approach is that it is clear, easy to understand and can be justified by considering maximum overpressures. It is also widely accepted in industry and guidance on cloud diameters is readily available in most cases.

Coverage Visualization

Coverage is especially important for evaluating the effectiveness of detector layouts. In Detect3D **[15]**, all coverage data is three dimensional and can be visualized using contours on horizontal or vertical planes or using isovolumes (simply "3D contours").

The most useful combination of isovolumes and contours is often the zero-coverage (0ooN) isovolume combined with multiple contours at different heights. The zero coverage isovolume is exactly the same as a 3D "shadow" created in areas which are not covered by detectors, either due to these areas being beyond the limits of a detector's influence, or being obstructed (in the case of flame detectors).

The contours provide easily digestible results at many different coverage levels (0ooN, 1ooN, 2ooN etc.). A common method that engineers use to design the initial layout is simply to add or aim detectors at large blind spots and supplement those decisions with the data provided by the contours. **Figure 02** illustrates an example of a coverage calculation.

In complex projects where the geometry may obstruct the clear view of the results a "clip plane" is available. The clip plane removes geometry above or below it from view, allowing a clearer picture of the coverage that may otherwise be obscured to the user.

It is important to mention that two additional and valuable features can be analyzed when developing the proposed FGS mapping study: (1) FGS mapping optimization, optimizing detector layouts so that the minimum number of detectors are specified for a target coverage criterion; and (2) Equipment Coverage, when the coverage is required at a certain distance from key equipment items.

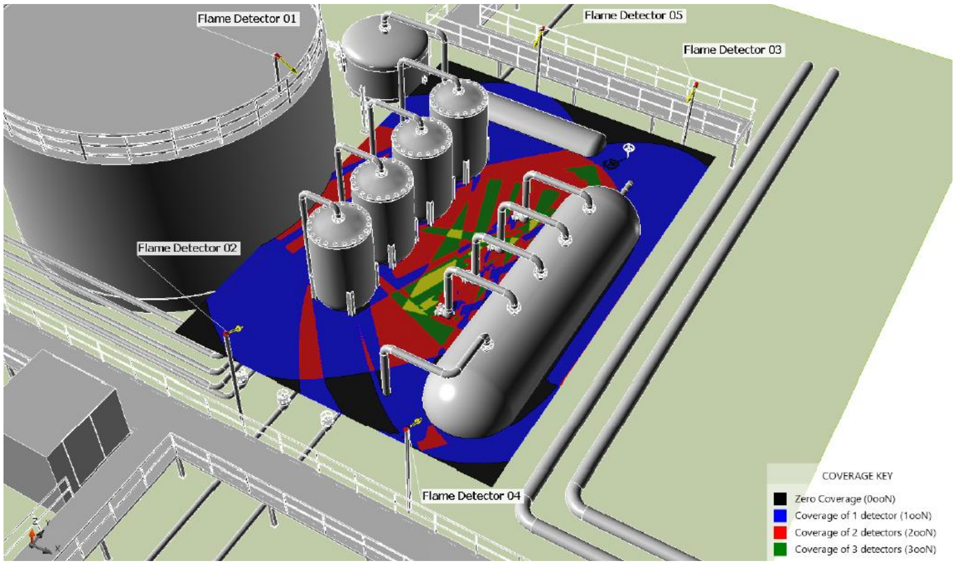

Figure 02: Example of Coverage Contour at 2 Meters Above Ground Level

Note: Illustration extracted from www.insighnumerics.com **[15]**.

FGS Functional Safety Availability Verification

Once the total number of FGS has been established based on the detection coverage phase, a FGS requirements specifications document set is developed. The purpose of this document set is to provide a comprehensive conceptual design that can subsequently be used as the basis for fire and gas equipment supply and detailed design activities such as equipment selection and logic development and programming. The specifications contain both functional requirements (SIL ratings identified per each FGS to be installed based on risk reduction factors characterized during the risk-based quantitative assessment) and integrity requirements, which should be in general accordance with Clause 10 of the IEC 61511 standard **[3]**.

Note that reference **[5]** provides specific guidance and criteria for addressing the SIL selection and verification calculations of a SIS. The following contents are only intended to highlight the key tasks and actions to be performed during the analysis of a SIS performance and authors encourage the reader to refer to **[5]** for a more detailed explanation.

The document set will be composed of multiple parts. The first section describes the general requirements of the entire FGS system. This section contains all general information that pertains to the entire FGS system, along with specific notes that detail any special situations or exclusions to the general requirements. In addition to the general requirements the following documents are generated and incorporated: (1) FGS Logic Cause and Effect Diagrams; (2) FGS Detector List with detector types, locations, orientations and set points; and (3) FGS Detector Layout Diagrams.

The main purpose of the FGS safety availability verification is to reduce the probability that a FGS component will fail to function as intended, which would inhibit the FGS from activation. This safety availability calculation is very similar to the SIL calculations performed for a typical Safety Instrumented System (SIS) intended to prevent the hazardous scenario. The specific objectives of FGS verification is to select equipment that is appropriate for the FGS performance target by ensuring that the proposed design and associated testing and maintenance philosophy achieve the selected FGS safety availability (SIL) targets.

Reliability models that allow calculation of the relevant design parameters of SIL, safety availability and achieved fault tolerance are developed and the calculations are performed using databases of equipment failure rates and associated failure attributes with the aim to characterize the component selection, the fault tolerance, the functional test interval, common cause failures and diagnostic coverage. The calculation of the Probability of Failure on Demand (PFD) takes into account two considerations:

- The target PFD of the detection is established according to the SIL of the overall function.
- The probability of occurrence of each of the failure scenarios is calculated taking into account the following parameters:
  - The dangerous failure rate of each detector
  - The diagnostic coverage for dangerous failures of each detector
  - The same failure rate of each detector
  - The routine maintenance and calibration interval of each detector
  - The repair time of each detector.
  - The time each detector is off-line when it is routinely maintained or calibrated
  - The proof test interval of each detector
  - The proof test duration of each detector
  - Common cause failure rate of identical and for diverse instruments (common cause failures can be treated as a special failure scenario)
  - The PFD of each failure scenario results from the PFD of each of the detectors that need to fail as part of the failure scenario
- The safe failure rate of the FGS is calculated to ensure that the spurious alarm rate or trip is acceptably low. The diagnostic coverage for safe failures is addressed if diagnosed architectures are used.

Conclusions

Once the risk-based quantitative assessment has been completed and the actual risk results have been compared with the applicable risk tolerability criteria, it is time to question if risk reduction is necessary; (i.e., if there exists a gap between the actual and the tolerable risk levels). In these cases, the installation of potential risk reduction measures (e.g., Fire and Gas Detectors, FGS) should be analyzed with the aim to reduce the risk of the hazardous scenarios that lead to high risk levels.

This manuscript addresses a specific layer of protection that requires specific knowledge and criteria for a proper installation; i.e., Fire and Gas Detectors. The main purpose of a Fire and Gas (FGS) mapping study is to identify and assess the placement and performance of gas (flammable and toxic) and fire detectors. The proposed approach links the robust risk-based quantitative assessment results with zone definition and categorization. It provides the exact location of FGS for ensuring detection coverage (i.e., detector coverage verification) and addresses which is the required reliability for ensuring the pursued risk reduction (i.e., functional safety availability verification). Even though the present manuscript focuses on detection coverage verification, both mapping and functional safety concepts are addressed. Finally, functional safety requirements are fully addressed in a dedicated related reference covering Safety Instrumented Systems (SIS) **[5]**.

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