# Fire and Gas Detection and Mitigation Systems

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## ABSTRACT

Fire and Gas Detection systems are key components in the overall safety and operation of any production facility and its on-site personnel. These facilities have had serious safety problems over the years. Some recent statistics provided by the NFPA (National Fire Protection Association) reveals that between 1985 and 2004, there were 10 U.S. petroleum refinery fires with three or more deaths. In March of 2005, the BP Texas City Refinery explosion and fire killed 15 people and injured 200 others.

The Fire and Gas Detection system continuously monitors heat, smoke, temperature, and toxic or combustible gas levels with the use of dedicated field devices. If any combination of them (within a zone) exceeds a pre-determined level, the system will raise the alarm and take automatic action to close operating valves and damper doors, release extinguishants, cut off electrical power and vent dangerous gases.

Fire and Gas Detection Systems are included under the provisions of the OSHA 1910.119 (PSM) Regulation, Subpart L (Fire Protection) as they are intended to prevent or minimize the consequences of catastrophic releases of toxic, reactive, flammable or explosive chemicals. The NFPA 72 National Fire Alarm Code addresses the application, installation, location, performance and maintenance of fire alarm systems and their components. However, Gas Detection Systems are not included, in spite of the fact that detection of a release is the cornerstone upon which subsequent fire-fighting action depends.

Work is in progress by the ISA S84 WG 6 Committee to treat Fire & Gas Detection and Mitigation Systems as Safety Instrumented Systems in the process sector, and require that an appropriate SIL (Safety Integrity Level) rating, per IEC 61511 performance criteria, be achieved. Considering the importance of these systems to maintaining the operational integrity of the overall facility, this work is absolutely essential.

This paper discusses the application of Fire and Gas Detection and Mitigation Systems in process facilities, and the capabilities of these systems to meet the requirements of both NFPA 72, and a Safety Integrity Level of SIL 1 or 2, in compliance with IEC 61511.

# Introduction

Fire and Gas Detection and Mitigation Systems are key components in the overall safety and operation of any production facility and its on-site personnel. However, in many instances the overall importance of these systems has not been fully comprehended. In many cases they have been implemented using the DCS (Distributed Control System), or a COTS PLC (Commercial-Off-The-Shelf Programmable Logic Controller), with too few detectors and alarm devices, and without clearly defined performance goals. This is partly due to the fact that Process Safety Standards did not include F&G Detection and Mitigation Systems. However, it is to the credit of IEC 61511 that it includes both prevention and mitigation systems; F&G being considered under the mitigation aspects of this Standard.

Likewise, applicable national standards are typically prescriptive and do not address process areas. However, the latest edition (2007) of the NFPA 72 Standard, Annex B, provides a performance-based approach to designing and analyzing Fire Detection Systems. This approach utilizes two phases as follows:

1) Defining performance goals and objectives
2) System design and evaluation

This approach in many ways parallels the comparable safety lifecycle phases of the IEC 61511 Standard, and provides a consistent framework for design and implementation.

It should be noted that Gas Detection is not comprehended in these Standards, in spite of the fact that detection of a release is the cornerstone upon which subsequent fire-fighting action depends. As such, the detection of gas (combustible or toxic) is critical to either preventing a fire, or effectively mitigating its severity. The consequences that are reduced by installing a gas detection system are related to both fires and explosions.

In addition to the above, the ISA S84 WG 6 F&G committee is formulating guidelines for end users to apply the performance based concepts of the S84.00.01-2004/IEC 61511 Standard to Fire and Gas System implementation and verification. This work is the foundation upon which the actual performance of F&G Systems in the process sector will be evaluated. In addition to NFPA 72 and IEC 61511, the following Standards also apply:

DIN EN 54-2, 1997: Fire Detection and Fire Alarm Systems
BS EN 50402; Rev. 5, 2005. (Gas Detection)
IEC Draft 60079-29 (Gas Detection)
OLF Recommended Guidelines for the Application of IEC 61508 and IEC 61511 in the Norwegian Petroleum Industry; Rev. 2, 2004. (Appendix A.8 Fire Detection and Appendix A.9 Gas Detection)

It should be noted that BS EN 50402, IEC Draft 60079-29, and the OLF Guidelines address Safety Integrity Levels (SILs) for F&G systems.

## The Fire & Gas System As An SIS

The intended purpose of a Safety Instrumented System is to protect the personnel that operate dangerous process facilities, and prevent damage to the facility itself which results in substantial financial loss. The proximity of fuel, oil and gas to various sources of ignition, together with the possibility of human error demands Fire and Gas Detection and Mitigation Systems that are independent, and of the highest integrity. As such, the Fire and Gas System is essential in maintaining the operational integrity of the overall facility.

The Fire and Gas System functions to mitigate the effects of a hazard. A small gas release that already presents a fire hazard is prevented from becoming a larger hazard; a small fire is prevented from becoming a larger fire, etc. Mitigation efforts address three specific areas as follows:

a) Life Safety
b) Property/Asset Protection
c) Environmental Impact

In this scenario, the detection of fire or gas is critical, and the performance of the system heavily depends on the coverage factor of these detectors. The probability of failure (or fail to function) of these detecting devices is composed of two failure modes as follows:

a) Detector Failure
b) Detection Failure

A Detector Failure is a failure of the sensing device to detect gas or flame in its presence and respond properly. This is a failure of the device itself.

A Detection Failure is a failure to detect the presence of gas or flame in a zone or area, given it is present. This is essentially a design problem that can be caused by poor placement of the detectors, too few detectors, etc.

The Detection Coverage factor is related to detection effectiveness and is determined by the number of detectors, the placement of detectors, and in the case of gas, the elevation of the detectors depending upon the type of gas and its density relative to ambient air. A delay in activation of the system due to a failure to detect the incipient hazard in a timely manner would result in a situation beyond the mitigation capabilities of the F&G System. This implies that to be effective, time is critical as the F&G System must operate within its mitigation limits.

## Determining The Risk

Risk is calculated as the product of Frequency and Consequences. The consequences that can be reduced by installing a gas detection system are related to both fires and explosions.

Fires from small or medium leaks are quite dangerous and can have fatal consequences. The purpose of the gas detection system is to detect small and medium leaks. Larger leaks are most likely detected by pressure sensors on the process equipment. In addition, when leaks are detected, mitigation is essential and typically both the ESD (Emergency Shut Down) System, and usually Blowdown are activated. As such, the quantity of gas released is minimized and the ignition probability is reduced. It stands to reason that when more detectors are installed one is able to detect smaller leaks, and consequently reduce the number of undetected leaks. However, there is a point of diminishing returns, where installing more detectors does not further reduce the risk, due to a reduction in the size of the leak detected, and the amount of gas released.

Explosions most often result from medium and large leaks. These leaks are easier to detect due to the size of the gas cloud, or by pressure sensors on the process equipment. In order to mitigate the situation, it is imperative to detect and stop the leak quickly.

The best place to detect a leak is to find where it is most likely to occur; i.e., high leak frequency. Some of the variables that impact the detection of a leak are as follows: Gas type, location, direction, wind direction, wind speed, and leak rate. As such, the determination of the number and location of gas detectors is not a simple task, and must be given serious consideration. Factors for consideration are cost, coverage, leak detection time, and mitigation of the incipient hazard.

In most cases, it is easier to detect fire than gas. However, the same basic rules apply to both:

1) Define the Hazard
2) Identify the Hazard (and its frequency)
3) Instrument the Hazard
4) Calculate the Risk Reduction
5) Assess the Residual Risk
6) Modify Design as required to satisfy risk criterion.

## Risk Reduction

The design objective of the Fire and Gas System is to reduce the risk associated with the occurrence of the incipient hazard. As is the case, Prevention Systems (ESD) reduce the frequency of the hazard; and Mitigation Systems (F&G) reduce the consequences.

A conservative approach to evaluating risk reduction is to use a base case where the Fire and Gas System does not respond in the event of a release. In this situation there is no mitigation and the full effect of the release is realized. Comparison against the company's risk guidelines will quickly confirm if this scenario is acceptable. This can be done via a risk matrix given the frequency and severity of the hazard. It is also possible to use a semi-quantitive approach to risk assessment such as LOPA (Layer of Protection Analysis), where risk is determined by estimating the average weighted consequence based on an event tree model of the Fire and Gas System, including Detection Coverage and Mitigation Effectiveness.

It should be noted that the F&G System model assumes that Mitigation Effectiveness is high because the system is able to detect the incipient hazard and take action prior to escalation. As such, mitigation would be successful. A delay in activation of the system due to a failure to detect the hazard in a timely manner would result in a situation beyond the mitigation capabilities of the F&G System. This implies that to be effective the F&G System must operate within its mitigation limits.

Given that the base case (no mitigation) exceeds the company's risk guidelines, additional risk reduction is required, and a Fire and Gas System should be considered to reduce the residual risk. The process is identical to that used for assessing ESD Systems.

For a given design (i.e., Detection Coverage, F&G System Safety Availability, and Mitigation Effectiveness), one can compute the Average Weighted Consequences, and given the frequency of the hazard, the mitigated risk. If the mitigated risk satisfies the company's risk criteria, the design for this hazard is complete. If not, the design should be improved by increasing detector coverage, or improving Fire and Gas System Safety Availability.

A properly designed F&G System should be able to provide safety performance in the SIL 1 range (RRF = 10 to 100), given sufficient detector coverage. Based on past experience, additional detectors will probably be needed to meet these performance-based design requirements.

## Performance-Based Requirements

The performance-based requirements for F&G Systems are not unlike those employed in the design of ESD Systems. Performance-based Standards typically require diagnostic coverage, redundancy, etc. and verification to ensure that the actual performance of the Safety Instrumented Functions (SIFs) meet their specified SILs. However, this is a departure from past experience, where prescriptive design was used and system performance was usually assumed to be sufficient. While these techniques have proven adequate for buildings, living accommodations, etc., they do not address the F&G Detection and Mitigation requirement of process facilities, the safety of which are comprehended in the IEC 61511 Standard for the process sector.

The shift to performance-based design utilizes the familiar SIL criteria of this standard. For example, to meet SIL 1 the system must be able to detect the presence of gas or flame and respond with appropriate mitigation at least 90% of the time. For SIL 2 at least 99% of the time, and for SIL 3 at least a formidable 99.9% of the time. Given today's technological limitations, SIL 2 and SIL 3 are simply not achievable in process facilities. However, SIL 1 performance is possible, given an optimized design with sufficient detector coverage. As detector coverage is a result of sensor placement, this aspect of the F&G system's design is most critical. A comprehensive assessment of detector coverage involves analysis of the potential sources of fire and gas within a defined process area (zone), and the placement of detectors accordingly. There are several possible methods that can be used. One is geographic detector coverage; another is scenario detector coverage. However, data on the type, size and shape of the gas release to be detected are required to perform a basic analysis of gas detector coverage.

Geographic detector coverage is basically populating a selected geographic area with detectors based on a specified detection criteria (i.e., gas cloud of less than 5 meters at 30% LEL), and voting logic for the detectors; i.e., 1ooX (1-out-of-X) or 2ooX (2-out-of-X). Based on the total area, the fraction that is covered by 1ooX, 2ooX, etc. determines the overall geographic coverage. It should be noted that geographic coverage is homogeneous, and is not sensitive to the frequency of fires in any specific area. Likewise, if your objective is to detect a 5 meter gas cloud using 2oo2 voting, then do not space the detectors on a 10 meter grid.

Scenario detector coverage comprehends specific hazards within a monitored area, and populates the area in the vicinity of these hazards with detectors. This grouping of detectors is voted (i.e., 1ooX or 2ooX) to detect the hazard. Each identified hazard is addressed in this manner, and the overall coverage is determined by the ratio of detectable release frequency to total release frequency (for all hazards).

In many cases, geographic detector coverage is best applied to flame and open path IR; while scenario detector coverage is best applied to gas and smoke.

## The Fire & Gas Model

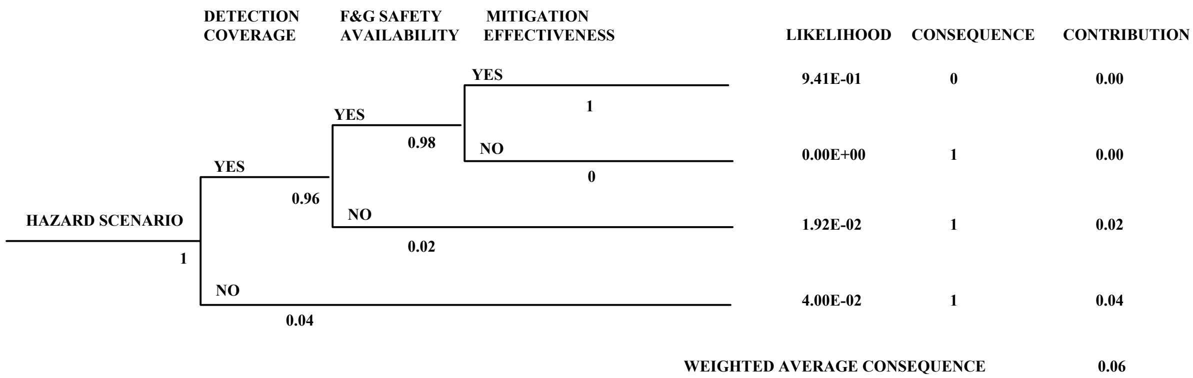
The basic model consists of an event tree with three basic components: Detection Coverage, F&G System Safety Availability, and Mitigation Effectiveness.

Detection Coverage and Mitigation Effectiveness have already been discussed. F&G System Safety Availability is defined as (1-$PFD_{avg}$), where $PFD_{avg}$ is the average value of the Probability of Dangerous Failure over the Proof Test Interval. For the F&G System, the $PFD_{avg}$ for each safety function is the summation of the Sensor $PFD_{avg}$, the Logic Solver $PFD_{avg}$, and the $PFD_{avg}$ of the Mitigation Devices. Each of these contributions will be determined using its respective dangerous undetected failure rate, voting architecture, and Proof Test Interval. This is consistent with the handling of these components in accordance with the methodology presented in the IEC 61511 Standard.

In performing these calculations, it should be noted that failure rate data is required for the detection and mitigation devices. In many cases, this data may be difficult to obtain from the manufacturers, or of questionable value. While it is not required to use SIL approved devices in F&G Systems (likewise for ESD Systems), it makes the task of safety performance verification considerably easier and much more credible; because the required failure data is more reliable. As such, using SIL certified devices (in accordance with the requirements of IEC 61508) has some definite advantages.

Another point of note is the fact that the F&G logic solver is operating in the de-energized state (as opposed to energized for ESD applications) and is required to energize its outputs to implement the safety function. As such, diagnostics used to test a “stuck-on” condition are no longer of value, as outputs are usually “off”, and in the “safe” state. In this case, failure to energize outputs would be classed as a dangerous undetected failure, if additional diagnostics were not included in the logic solver design; (i.e., “stuck off” condition).

As an example, given an unmitigated hazard frequency of 1.5 E-3 per year, a 96% Detection Coverage target, and a Mitigation Effectiveness of 100%; the basic F&G Model is as follows:




The equation for risk as used in LOPA is calculated as follows:

$$\begin{aligned} \text{Risk} &= C_{WA} * f_{unmitigated} \\ &= 0.06 * 1.5\text{ E-3 per year} \\ &= 9.0\text{ E-05 per year} \end{aligned}$$

where $C_{WA}$ is the Weighted Average Consequence.

If this result is less than the target risk tolerance criterion, then no additional mitigation is required.

The consequences associated with the mitigated hazard are minor and are not a safety hazard (= 0). The likelihood of the mitigated hazard is 94%, and its frequency is 1.41 E-3 per year (0.94 * 1.5 E-3 per year).
The PFDavg is 0.06 (1 - 0.94), and the RRF (Risk Reduction Factor) is 16 (1/0.06) – a low-range SIL 1.

The target detection coverage in the example was set at 96%. Using two flame detectors, results show approximately 97% of the geographic area to be covered by 1 or more detectors. However, only 55% is covered by both detectors. By adding a third detector (at minimal cost) we can improve the detection coverage to 97% for two detectors, allowing for 3% blind spots in the corners of the area. This improvement in coverage allows for 1oo2 or 2oo2 voting, in lieu of 1oo1, with further reduction of the risk.

This example was based on flame detection. Gas detection coverage is more difficult to achieve but by applying the Scenario Detector Coverage method, thereby optimizing the placement of gas detectors, similar results can be achieved. However, it should be apparent that to meet SIL 1 performance levels, additional detectors will be needed to provide the required detection coverage.

## Conclusions

Fire and Gas Detection and Mitigation Systems are essential in maintaining the operational integrity of process facilities which utilize toxic, reactive, flammable or explosive chemicals. Their intended purpose is to protect the personnel that operate these facilities, protect the facility itself, and limit the effects of possible acts of sabotage. As such, they more than qualify as Safety Instrumented Systems (SIS).

Unlike past experience, it is realistic to apply performance-based criteria to Fire and Gas System design and implementation in accordance with the ISA S84.00.01/IEC 61511 Standard. Because of the limitations of current technology, it is unlikely that Fire and Gas Detection Systems in process facilities will achieve a level of performance greater than SIL 1 (RRF between 10 and 100), due to the fact that achievable risk reduction is limited by detection coverage, rather than Safety Availability. However, it is quite possible to achieve a SIL 2 level of performance in enclosed areas using current technology. In any case, employing a performance-based framework is a major milestone in establishing safety performance requirements for these critical systems.

The work in progress by the S84 WG6 F&G Committee and others worldwide will provide essential guidelines and a consistent framework for the implementation of Fire and Gas Systems in process areas, utilizing a risk based approach as per the ISA S84.00.01/IEC 61511 Standard. This effort is absolutely essential and long overdue. These guidelines will encourage manufacturers to develop better detection technologies to satisfy market demand, thereby improving the safety performance of Fire and Gas Detection and Mitigation Systems in process facilities.

## Acknowledgements

The Fire and Gas model presented herein was originally developed by the ISA S84 WG6 F&G Committee, and the author gratefully recognizes their work.

## References

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