CHEMICAL ENGINEERING TRANSACTIONS
VOL. 36, 2014

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Valerio Cozzani, Eddy de Rademaeker

ISBN 978-88-95608-27-3; **ISSN** 2283-9216

DOI: 10.3303/CET1436048

Development of Improved Strategies for the Lay-Out of Fire and Gas Detectors

Eugenio Mariotti[a], Annamaria Di Padova[b], Tiziana Barbaresi[b], Fabrizio Tallone[b], Alessandro Tugnoli*[a], Gigliola Spadoni[a], Valerio Cozzani[a]

[a]LISES - DICAM, Alma Mater Studiorum - Università di Bologna, Bologna, Italy
[b]LOSPEFA, Saipem S.p.A. Business Unit Engineering & Construction , Fano (PU), Italy
a.tugnoli@unibo.it

Fire and Gas (F&G) detection is an essential part of the mitigation system in facilities handling and storing flammable and toxic materials. While detector reliability might be very high, safety performance of a F&G system strongly depends on layout and coverage. Current reference standards for on-shore applications do not define the plant areas to be mapped, the coverage targets, and the reference hazardous scenarios to be considered. In the present study, a methodology aimed at the F&G coverage mapping was developed. The procedure is applicable in the Front End Engineering Design phase (FEED), where limited data is typically available. The development of the methodology considered the main aspects that define F&G system performance. Coverage targets for detection were set considering risk reduction goals and actual detector capabilities. Simple strategies were developed for the determination of the reference hazardous scenarios to be considered. A Matlab code for 3D F&G coverage mapping was developed. The proposed procedure was demonstrated by a simplified case study. The methodology proved itself a valid instrument to assist detector layout assessment.

1. Introduction

Safety concerns in oil and gas (O&G) plants are well known, as documented by several past accidents (Tugnoli et al., 2013). Besides the direct effects of the accident events, both fires and explosions may trigger cascading effects (Cozzani et al, 2009), which are deemed to have severe consequences on population and assets. Where inherent safety strategies are not applicable (see e.g. Tugnoli et al., 2011, 2012), passive and active protection measures should be implemented for consequence mitigation (Gomez et al., 2012; Landucci, 2009). Moreover, a proper layout design was identified to provide a synergic effect among different risk reduction strategies (Tugnoli et al., 2008). Fire and Gas (F&G) detection is an essential component of any active mitigation measure. While detector reliability might be very high, safety performance of a F&G system strongly depends on system layout and coverage. Despite detector design and selection being a well standardized topic, detector placement for O&G plant units does not fall under any current regulation. Standards for buildings (e.g. NFPA, 2013) are clearly not applicable to O&G plants. While detector placement traditionally relies on skilled expertise or internal company standards, the need for a consolidate methodology for F&G coverage mapping is widely recognized. In 1993 the HSE UK report (HSE, 1993) set a milestone for gas detection in the offshore field, using results from explosion studies in order to develop siting criteria for gas detectors. The CCPS book “Continuous Monitoring for Hazardous Material Releases” (CCPS, 2009), which provides a complete review of all aspects of gas detection, does not include F&G mapping. The ISA technical report 84 (ISA, 2010), which introduced the risk-based approach in the design of detection systems, does not provide complete criteria of mapping targets. Some companies developed internal standards, but they remain confidential documents. Other consultants have developed mapping software (e.g. Kenexis, Baker Eng., Micropack Detection, MES, Gexcon, Shell G.S.), but the methodologies used are frequently undisclosed or only cover partial aspects of the problem. Well known weak points of the current methodologies are the arbitrary definitions of the reference hazardous scenarios, the mapped volumes, and the coverage targets.

Please cite this article as: Mariotti E., Di Padova A., Barbaresi T., Tallone F., Tugnoli A., Spadoni G., Cozzani V., 2014, Development of improved strategies for the lay-out of fire and gas detectors, Chemical Engineering Transactions, 36, 283-288
DOI: 10.3303/CET1436048

2. Fire & Gas Detection Philosophy

F&G zoning is based on the identification of the hazardous event that may occur in a plant. For fire scenarios, hazardous areas are easily identified by the presence of flammable materials (Khakzad et al., 2014). In the case of hazardous gas clouds, the zoning process involves a much more complex modelling for predicting the behaviour of released gases: a gas cloud may migrate from the release point to areas of the plant where such hazard is not normally present, extending the number of plant areas to be monitored. Despite the possibility of different scenarios in case of flammable gas clouds (flash-fire, vapour cloud explosion (VCE), safe dispersion), the VCE is usually considered as the reference hazard due to the severe consequences and the potential for domino effect.

Depending on the features of the area and of the hazard scenario, different strategies are available to provide gas detection. The main options include 'release source monitoring', 'volumetric monitoring', 'path of travel/target receptor monitoring', and 'perimeter monitoring'. A complete review is provided by CCPS (CCPS, 2009). Volumetric monitoring has become the standard approach for detection in offshore O&G facilities and is considered in the following for method development: as a matter of fact it is the strategy of choice for detecting clouds that can lead to VCEs in highly obstructed and congested areas. The volumetric monitoring approach uses a three-dimensional array of detectors (point, beam, or a combination thereof) to ensure that a gas cloud cannot exist in the monitored space without contacting a sensor. Volumetric monitoring does not consider small releases, which typically result in flash fires or minor explosions with no relevant consequences. In applying the volumetric approach, it is irrelevant whether the releases originate within or outside of the volume being monitored.

Fire detection strategies typically rely on volumetric monitoring by flame detectors: these are directional devices which detect sufficiently intense flames only in their "field of view". Heat detectors (e.g. fusible plugs) may be also used as a secondary detection technology.

The effectiveness of a volumetric monitoring F&G system strongly depends on the detector coverage. Two definitions of coverage are adopted according to ISA Technical Report 84 (ISA, 2010):

- Geographic Coverage: this is the fraction of the area, at a given elevation of interest, or the fraction of the volume, where a detector array can detect a given target fire or gas cloud.
- Scenario Coverage: The fraction of all of the hazard scenarios (fires in the case of fire detection, and leaks in the case of gas detection) that a detector array can detect.

Geographic coverage is easier to calculate from limited data, and is only a function of the geometrical features. Scenario coverage, on the other hand, requires a complete identification and a detailed assessment of the potential hazard scenarios, which may be extremely resource intensive. While scenario coverage allows individual detector ranking and optimization, geographic coverage is the only approach applicable to early design phases of a plant. Hence, geographic coverage has been considered in the development of the following mapping procedure.

Fire & Gas systems are commonly designed to perform executive actions (e.g. emergency shut down) only upon voting of multiple detectors (usually 2ooN), whereas alarms are raised by the activation of only one detector (1ooN logic). Coverage targets are to be specified for each logic. Voting provides redundancy of the system and robustness against spurious events, thus enhancing system reliability.

3. Proposed Methodology

The present methodology provides guidelines for defining F&G coverage requirements and for assessing detector layouts. It applies to plant areas where the F&G system has been designed for volumetric monitoring (congested areas). The method provides a time-effective and robust way to achieve detector estimates in the FEED phase or sensor layout verification in the detail phase.

3.1 Coverage Assessment for Flammable Gas Detectors

The main steps of the assessment procedure for gas detectors are shown in Figure 1-(left).

In the first step, the plant is divided into areas with similar characteristics (e.g. materials present, operative conditions, degree of congestion). Each plant area is characterized for hazard potential by calculating the consequences of worst case VCE. An estimation of the maximum peak overpressure, P_0, of a VCE can be obtained by the GAME theory (Mercx et al., 1998), depending on the type of confinement of the area:

$$P_0 = 0.84\left[\frac{VBR \cdot L_p}{D}\right]^{2.75} D^{0.7} S_l^{\,2.7} \qquad \text{if flame front can expand in all 3 directions} \tag{1}$$

$$P_0 = 3.38\left[\frac{VBR \cdot L_p}{D}\right]^{2.25} D^{0.7} S_l^{\ 2.7} \qquad \text{if flame front has only 2 possible expansion directions} \qquad (2)$$

where *VBR* is the volume blockage ratio, *D* is the average obstacle diameter, S_l is the laminar burning velocity (material specific) and L_p is the flame path length, assumed equal to the greatest dimension of the area. Areas for which the calculated overpressure exceeds 150 mbar are considered hazardous and shall be assessed for volumetric detector coverage. The threshold of 150 mbar was assumed according to HSE (HSE, 1993) as the lower bound for structural damage from explosions.

For each hazardous plant area, the risk volume is the volume to be protected by gas detectors; it is also the volume considered to assess detector coverage. The risk volume for a plant area is identified by the smaller of the following: (i) the volume envelope containing the equipment in the area, with an allowance, taken from the outer edges of the equipment, equal to the average separation distance of the units, or (ii) the geometric boundary of the area. In any case the vertical extent of the risk volume is determined considering the average equipment and structure height in the area and in the immediately neighbouring ones: in fact releases above this height disperse harmlessly and jet fires have no structures to impinge on. Specific features of the area (e.g. large open spaces) should be also accounted in the definition.

The characteristic target cloud to be detected is evaluated for each area as the smallest spherical cloud, at uniform stoichiometric concentration, that could result in a VCE exceeding 150 mbar. The size of the target cloud is predominantly a function of the geometry of the area, since levels of obstruction and blockage ratios is well known to govern overpressure from VCEs. While specific studies (e.g. CFD simulations) may be required for some applications, the following general recommendations are suggested: (a) for highly congested or confined areas (VBR>0.3) consider a spherical cloud of 5m diameter (HSE, 1993); (b) for other areas, calculate cloud size by GAME relations (Eq(1) and (2)), assuming a 150 mbar maximum overpressure. Hence, a trial gas detector layout is defined considering a detector grid with spacing equal to the characteristic dimension of the target gas cloud.

Risk reduction obtained through a F&G system strongly depends on the volume coverage provided by detectors (ISA, 2010), so that specifying a coverage target actually means setting a risk reduction objective (DeFriend et al., 2008). While from a theoretical standpoint targets can be specified to achieve any desired degree of risk reduction, in practice obtaining a reduction beyond one order of magnitude is limited by economic considerations, as evidenced by several authors (see e.g. Gruhn, 2007; Huser et al., 2004; Wright, 2011). Target coverage can be calculated for a one order of magnitude risk reduction by event tree analysis (ISA, 2010). Mariotti (2013) carried out a detailed analysis for a typical O&G plant, accounting for factors such as differentiated voting logics for alarm and executive actions, probability of failure on demand of the equipment, and human error for manual activation upon alarm.

Mapping can be practically defined as the calculation of the coverage achieved and the verification of the target coverage. For point-type gas detectors, the coverage of each detector is equivalent to a sphere of the size of the target cloud to be identified; thus the overall coverage is calculated by considering the combined effect of spheres positioned at the detector locations throughout the risk volume. The 1ooN co-

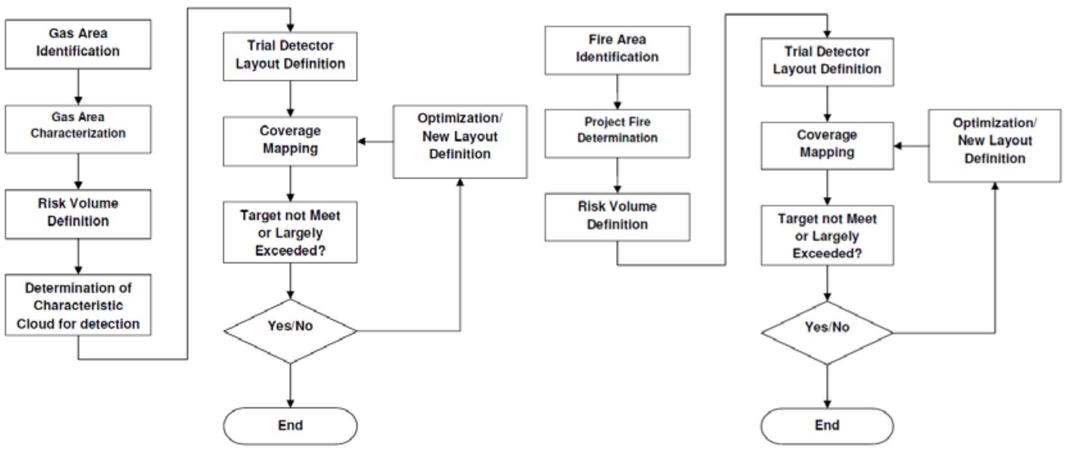

Figure. 1. Flow Diagram of the Flammable Gas Coverage assessment (left panel) and of the Flammable Gas Coverage assessment (right panel)

average is calculated as the ratio of the volume included in the spheres to the total risk volume. MooN coverage is calculated as the ratio of the overlap between the volumes of M spheres to the total risk volume. Coverage delivered by open-path type detectors can be assessed in a similar way.

3.2 Coverage Assessment for Fire Detectors

The main steps of the assessment procedure for flame detectors are shown in figure 1-(right). There are several similarities with the procedure for gas detection.

In this case, all areas where flammable materials are handled or stored are considered for volumetric protection by flame detectors. The project fire, or characteristic fire, to be considered for mapping is the smallest fire that can lead to escalation in the area. The following guidelines were identified for characteristic fire definition: for pool fires, consider the smaller fire which (a) causes a 37.5 kW/m^2 radiative flux at a distance from the pool centre equal to half the average spacing between equipment in the area, or which (b) has a diameter equal to the average unit spacing; for jet-fires consider the smaller fire which (a) has a flame length equal to the average equipment spacing, or which (b) causes a 37.5 kW/m^2 radiative flux at a distance from the release point equal to the average equipment spacing. The 37.5 kW/m^2 value for radiation is deemed to be the threshold for escalation due to severe structural damage and failure; other referenced values can be used as well (Cozzani et al., 2013).

Once the project fire has been determined and the most appropriate type of detector has been selected, the maximum distance between the fire and the detector can be calculated by the inverse square law, according to the method described in NFPA 72 standard (NFPA, 2013):

$$S = \frac{kPe^{-\zeta d}}{d^2} \qquad (3)$$

where *S* is the radiant power reaching the detector (W), *k* is the proportionality constant for the detector, *ζ* is the extinction coefficient of air (0.001–0.1m^{-1}), *d* is the distance between the fire and the detector and *P* is the radiant power emitted by the fire (W) (product of surface emissive power and radiant area of the flame). The minimum S for commercial detectors is usually known for fires burning a reference substance (e.g. n-heptane); caution should be exerted for generalization to other substances.

The risk volume is defined for flame detection following the same method defined for gas detection. A trial detector layout is created into the volume, by making a hypothesis on the sensor number and position and by trying to maximize the floor coverage of the area.

Target detector coverage is defined by risk-based approaches, as previously discussed for gas detection. Typical targets also in this case are equivalent to a one order of magnitude reduction of the risk.

Coverage at any given point depends on whether there is a line-of-sight from flame surface to the detector and whether the fire is within the range of distance and the angle (cone of vision) of the detector itself. 3D mapping software performs the required geometric calculations. The desired coverage is achieved by iterative layout trial. The causes of poor coverage shall be investigated by analyzing view-cones (e.g. incorrect orientation, blockage due to piping and equipment, etc.) and different position of the detectors shall be considered. It is not practically possible to account for all possible obstructions in the 3D mapping study and detectors might need slight repositioning during the installation phase, though experience has shown that moderate repositioning does not invalidate mapping results.

4. Case Study

A case study is presented in order to better illustrate the developed procedure and to show its applicability. A section of a gas compression facility is considered. Processed streams contain simple hydrocarbons from C1 to C10. The plant can be divided into four areas with homogenous characteristics. However in the following, only the compressor K.O. drum area is discussed for sake of brevity.

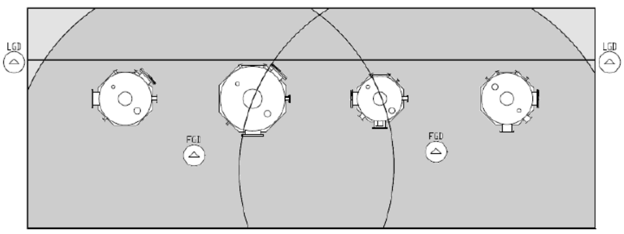

Figure 2: Coverage contour plot at 6m elevation: light grey, 1oo3 coverage; dark grey, 2oo3 coverage

4.1 Coverage Assessment for Flammable Gas Detectors

The K.O. drum area has been first analyzed in order to identify a potential VCE hazard. Considering the composition of the reference stream and a VBR of 10 %, the GAME Eq.(1) yields a maximum peak overpressure of 227 mbar. Therefore the area is a possible location of VCEs having the potential to cause accident escalation and should be assessed for volume monitoring.

Next, the risk volume for the area is defined drawing a box from the pipe-rack edge to the outermost points of the drums for a length of 3 meters, which is the average separation distance between the drum units (see Figure 2). The height of the box is equal to the highest of the drums (12 m).

According to the defined procedure, the target gas cloud to be detected was determined using the GAME equation: Eq.(1) for P_0 = 150 mbar yields a characteristic cloud diameter, L_p, of 18 m. Common practice for detector placement uses a regular grid with constant spacing. Given the characteristic cloud dimension, a first trial layout with horizontal spacing of 9 meters was proposed; only one layer of detectors is placed at 6 m elevation, half the height of the volume. Eight point-source detectors were necessary.

According to the study by Mariotti (2013) a 90 % target coverage is required for alarm, based on a 1ooN voting logic. Executive actions are instead activated on a 2ooN voting logic: the target coverage in order to achieve a risk reduction of one order of magnitude has been calculated as 85% for gas detectors.

Gas Detector 3D mapping was performed by a specifically developed Matlab® code; the proposed layout provided a coverage of 100 % for 1oo8 logic and 92.1 % for 2oo8 logic. The trial layout is clearly oversized. Moreover spacing detectors on a grid pattern resulted in detectors inefficiently covering space outside the risk volume. Therefore a more efficient layout was considered: it relies on the combined use of open-path and point detectors (Figure 2). The new layout meets the coverage targets, by achieving a 99 % coverage for the 1oo3 logic and 85 % for the 2oo3 logic, while requiring a much lower number of detectors. It should be noted that this result was possible because of the relatively simple and small geometry of the area and the need to detect a relatively big cloud; meeting coverage targets is more complex and demanding in terms of detector number and layout optimization process for more complex process areas.

4.2 Coverage Assessment for Flame Detectors

The K.O. drum area handles flammable gases and liquids and should be considered for fire detection. Two target scenarios were identified according to the proposed procedure: (i) a three meter long horizontal jet-fire, and (ii) a 1.4 m diameter pool fire, which causes a 37.5 kW/m^2 radiative flux in a 3m circle. The flames were modelled by the Phast® code (DNV, 2013) obtaining the following radiant powers: 7.34 kW for the jet-fire and 838 kW for the poolfire. Type and model of the detector selected for the application influence detection distances and, consequently coverage mapping results. Considering a typical IR flame detector, the inverse square law yields characteristic fire view distances of 29 m for the target jet-fire and 39 m for the target pool fire. The cone of view of the considered detector has an angle of ±45°.

Having performed gas mapping, the same reference risk volume previously isolated shall be kept for fire mapping as well. The definition of a trial layout for flame detectors is less direct than for gas detectors, since line of sight is an issue. The first trial layout was proposed by heuristically trying to maximize floor coverage (Figure 3-Left): it consists of 3 flame detectors placed at the upper vertices of the risk volume.

According to the study by Mariotti (2013) a 90 % target coverage is required for alarm (1ooN voting logic), while a 75 % target coverage is set for fire detection on a 2ooN voting logic. For the trial layout, the 3D mapping by the developed Matlab® code yields a 93 % coverage for 1oo3 and a 73 % coverage for 2oo3. Proposed layout falls short on the 2oo3 requirement and layout optimization is needed.

An alternative layout was defined relocating one of the detectors in order to obtain a better coverage of the area between the drums Figure 3-(right). This new layout resulted in an insufficient 2oo3 coverage (65 %), while the 1oo3 coverage was unnecessarily high (97 %). Several other layouts were tested for different arrangements of three detectors in the area; unfortunately no layout was able to meet the 2oo3 target. Therefore a four-device layout was considered, easily meeting the targets.

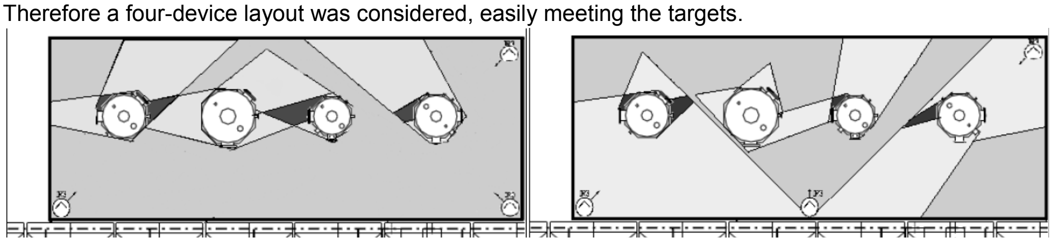

Figure 3: Trial (left panel) and alternative (right panel) layout analyzed for fire detector layout (plot at 12m elevation). Black, 0ooN coverage; light grey area, 1ooN coverage; dark grey, 2ooN coverage

5. Conclusions

The present study introduces a methodology developed for supporting F&G coverage mapping. The methodology is simple enough to be applicable in the Front End Engineering Design phase (FEED), where limited data is typically available. The step-by-step methodology considers all of the main aspects which define F&G system requirements and which have an impact on detector layout definition. It sets coverage targets for detection considering risk reduction goals. It guides the identification of the reference hazardous scenarios to be used in gas and flame detection. It provides heuristic criteria for risk volume definition. Integration with 3D mapping codes allows for swift coverage calculation, accounting for the voting logic considered for the activation of alarms and the mitigation of actions.
A simplified case study provided a demonstration of the methodology: it was found to be easy and fast to apply, and proved itself a valid instrument to assist detector placement and layout assessment.

References

CCPS (Center for Chemical Process Safety), 2009, Continuous Monitoring for Hazardous Material Releases. John Wiley & Sons, Inc., Hoboken, NJ, USA.

Cozzani V., Tugnoli A., Bonvicini S., Salzano E., 2013, 9 -Threshold-Based Approach, 189-207, 2013, Domino Effects in the Process Industries, Eds. Reniers G., Cozzani V., Elsevier, Waltham, MA, USA.

Cozzani V., Tugnoli A., Salzano E., 2009, The Development of an Inherent Safety Approach to the Prevention of Domino Accidents, Accident Analysis & Prevention, 41, 1216-1227.

DeFriend S., Dejmek M., Porter L., Deshotels B., Natvig B., 2008, A risk-based approach to flammable gas detector spacing, J Hazard Mater. 159(1), 142-151.

DNV (Det Norske Veritas), 2013, Phast® code, <www.dnvgl.com/software> accessed 12.12.2013

Gomez-Mares M., Tugnoli A., Landucci G., Cozzani V., 2012, Performance Assessment of Passive Fire Protection Materials, Industrial & Engineering Chemistry Research, 51 (22), 7679–7689.

Gruhn P., 2007, SIL ratings for fire & gas system hardware are we barking up the wrong tree?, Proceedings of the 62nd Annual Symposium on Instrumentation for the Process Industries, College Station, TX, USA, 31-38.

HSE (Health & Safety Executive), 1993, Offshore gas detector siting criterion - Investigation of detector spacing, OTO 93/002. <www.hse.gov.uk> accessed 12.12.2013

Huser A., Oliveira L.F., Dalheim J., 2004, Cost optimizations of gas detector systems, art. no. 51567, Proceedings of the 23rd International Conference on Offshore Mechanics and Arctic Engineering – OMAE, June 20-24, Vancouver, BC, Canada, 2, 545-551.

ISA (International Society for Automation), 2010, ISA-TR84.00.07-2010, Guidance on the evaluation of fire, combustible gas and toxic gas system effectiveness. ISA, Research Triangle Park, NC, USA.

Khakzad N., Khan F., Paltrinieri N., 2014, On the application of near accident data to risk analysis of major accidents, Reliability Engineering & System Safety, 126, 116–125.

Landucci G., Molag M., Reinders J., Cozzani V., 2009, Experimental and analytical investigation of thermal coating effectiveness for 3 m^3 LPG tanks engulfed by fire, J. Hazard. Mater. 161, 1182-1192.

Mariotti E., 2013, Development of improved strategies for lay-out of fire and gas detectors, Master’s Thesis in Chemical Engineering at University of Bologna, A.A. 2011/12, Bologna, Italy.

Mercx W.P.M., Van den Berg A.C., van Leeuwen D., 1998, Application of correlations to quantify the source strength of vapour cloud explosions in realistic situations. Final report for the project: ‘GAMES’, TNO Report PML 1998-C53, TNO, Rijswijk, The Netherlands.

NFPA (National Fire Protection Agency), 2013, NFPA 72: National fire alarm and signaling code. NFPA, Quincy, MA, USA.

Tugnoli A., Gyenes Z., Van Wijk L., Christou M., Spadoni G., Cozzani V., 2013, Reference criteria for the identification of accident scenarios in the framework of land use planning, Journal of Loss Prevention in the Process Industries, 26(4), 614-627.

Tugnoli A., Khan F., Amyotte P., Cozzani V., 2008, Safety Assessment in Plant Layout Design using Indexing Approach: Implementing Inherent Safety Perspective; Part 1 – Guideword applicability and method description, Journal of Hazardous Materials, 160 (1), 100–109.

Tugnoli A., Landucci G., Salzano E., Cozzani V., 2012, Supporting the selection of process and plant design options by Inherent Safety KPIs, J. Loss Prevention in the Process Industries, 25, 830-842.

Tugnoli A., Santarelli F., Cozzani V., 2011, Implementation of Sustainability Drivers in the Design of Industrial Chemical Processes, AIChE Journal, 57, 3063–3084.

Wright R., 2011, SIL-Rated Fire (& Gas) Safety FunctionsFact or Fiction?, Proceedings of the Safety Control & Instrumentation Systems Conference, Perth, WA, Australia.