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A risk-based approach to flammable gas detector spacing

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Abstract

Flammable gas detectors allow an operating company to address leaks before they become serious, by automatically alarming and by initiating isolation and safe venting. Without effective gas detection, there is very limited defense against a flammable gas leak developing into a fire or explosion that could cause loss of life or escalate to cascading failures of nearby vessels, piping, and equipment. While it is commonly recognized that some gas detectors are needed in a process plant containing flammable gas or volatile liquids, there is usually a question of how many are needed. The areas that need protection can be determined by dispersion modeling from potential leak sites. Within the areas that must be protected, the spacing of detectors (or alternatively, number of detectors) should be based on risk. Detector design can be characterized by spacing criteria, which is convenient for design – or alternatively by number of detectors, which is convenient for cost reporting. The factors that influence the risk are site-specific, including process conditions, chemical composition, number of potential leak sites, piping design standards, arrangement of plant equipment and structures, design of isolation and depressurization systems, and frequency of detector testing. Site-specific factors such as those just mentioned affect the size of flammable gas cloud that must be detected (within a specified probability) by the gas detection system. A probability of detection must be specified that gives a design with a tolerable risk of fires and explosions. To determine the optimum spacing of detectors, it is important to consider the probability that a detector will fail at some time and be inoperative until replaced or repaired.

A cost-effective approach is based on the combined risk from a representative selection of leakage scenarios, rather than a worst-case evaluation. This means that probability and severity of leak consequences must be evaluated together. In marine and offshore facilities, it is conventional to use computational fluid dynamics (CFD) modeling to determine the size of a flammable cloud that would result from a specific leak scenario. Simpler modeling methods can be used, but the results are not very accurate in the region near the release, especially where flow obstructions are present. The results from CFD analyses on several leak scenarios can be plotted to determine the size of a flammable cloud that could result in an explosion that would generate overpressure exceeding the strength of the mechanical design of the plant. A cloud of this size has the potential to produce a blast pressure or flying debris capable of causing a fatality or subsequent damage to vessels or piping containing hazardous material. In cases where the leak results in a fire, rather than explosion, CFD or other modeling methods can estimate the size of a leak that would cause a fire resulting in subsequent damage to the facility, or would prevent the safe escape of personnel. The gas detector system must be capable of detecting a gas release or vapor cloud, and initiating action to prevent the leak from reaching a size that could cause injury or severe damage upon ignition.

Keywords: Flammable; Gas; Leak; Detection; Detector; Fire; Explosion; Dispersion; Modeling; Risk-based

1. Introduction

Risk is defined as the combination of likelihood and severity of the accident being considered, which in this case is a fire or explosion. The process of finding the size of gas cloud to be used in determining detector spacing (the design basis cloud) should be risk-based, rather than worst-case. This means that probability and severity must be evaluated together. Risk of environmental damage, injury, and financial loss can be held to a tolerable level by including design measures to ensure that risk criteria are satisfied. Detector spacing is an important measure, but not the only design measure for controlling risk. Appropriate design measures include minimizing the opportunity for leaks to occur, quickly and accurately detecting leaks, reliably

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taking appropriate action, and arranging piping and equipment to reduce the severity and chance of escalation for any fire or explosion that could happen.

The type of gas detector addressed in this article can detect flammable gas in the air at concentrations well below the lower flammable limit (LFL). For hydrocarbon gas or vapor, the current most sensitive and reliable technology uses infrared spectroscopy for either point or line-of-sight detection. Each detector has a circuit that continuously tests for detector failure, but some failures go unnoticed. The detection threshold is adjustable, and the individual detectors require calibration and full testing every year in typical service. The individual detectors are linked to a gas detection system, which interfaces with other systems: uninterruptible power system, fire detection, local and central control room alarms, leak isolation valves, fire fighting systems, building air intake controls, and usually, wind speed and direction monitoring.

Evaluating the fire and explosion risk for a process facility with many potential leak sources, ignition sources, weather conditions, and possible accident consequences is a challenge. As a result, it is unavoidable to include the complexities of process conditions under different operating modes, safeguard systems, facility layout, and ambient conditions into the risk assessment procedure. Evaluating the risk consists of identifying and assigning frequencies to the leak scenarios that could occur, categorizing the effectiveness of barriers or safeguard systems, identifying the various fire or explosion conditions that could result from each scenario, and estimating the degree of injury or damage that could occur to people, the environment, and business finances in each case. Obviously, the possible leak scenarios and outcomes are too many to count in all but the most trivial facilities. Accordingly, the leak scenarios and severity of effects must be grouped so that the risk evaluation process can be managed in a cost-effective way. The level of detail used in grouping the scenarios and effects determines the usefulness, cost, and duration of the risk analysis effort. For the purpose of estimating the spacing or number of detectors, it will be shown that is sufficient to group scenarios with enough detail to decide whether or not a fatality or escalating damage could occur at a certain frequency determined by project risk criteria. In a typical case for estimating detector spacing, satisfactory accuracy can be achieved by grouping leaks as small, medium, or large; grouping wind direction into four sectors; grouping release direction into six horizontal and vertical directions; and grouping process conditions into a few types of streams.

2. The importance of gas detectors

Once a large flammable gas leak occurs, if the leak is not detected, it can be expected to find an ignition source from a hot surface or spark, static electricity generated by the leak itself, by mobile equipment, or eventually from static electricity generated by a passing thunderstorm if the release is high in the air. Transient ignition sources can be created by dropped objects, periodic testing of diesel engines, maintenance activity, or passing transport equipment such as helicopters, ships, vehicles, or trains.

An ignited gas leak can result in different consequences, depending on the situation (Ref. [1]). If ignition occurs immediately, the result will be a fire. In most cases of fire, the process pressure is high enough to cause the gas to exit at sonic velocity, causing a jet fire which acts like a torch. Liquid leaking from a high pressure source can behave in the same way. The high velocity creates enough turbulence for good mixing of the fuel, creating an intense flame temperature concentrated on one area. Flames of this type can cause steel objects in the path of the flame to lose strength in a matter of minutes. Impingement of a jet flame onto pressurized hydrocarbon piping or vessels can quickly lead to a so-called "domino-effect" escalation of the consequence. Typical fire water spray or deluge systems cannot protect metal surfaces exposed to a direct, high-velocity flame. Normal thermal insulation is torn loose by the high velocity. The only protection against a jet fire is a rigid fireproof barrier, such as a fire wall or a concrete layer sprayed onto the metal surface to be protected. However, sprayed-on barriers have several disadvantages. They can accelerate rust of the underlying metal, prevent proper inspection of critical structures, and prevent disassembly of piping or equipment that must be maintained. Fire walls impede operations and emergency egress. Fire walls also reduce the dispersion of flammable gas and amplify the pressures in an explosion. On an offshore facility, the added weight is a serious disadvantage. Clearly, it is critical to prevent jet fires wherever possible, rather than to try to protect equipment and personnel after a jet fire has started.

A flash fire or explosion will result if there is delayed ignition. The difference between a flash fire and explosion is that the increased combustion rate of an explosion generates higher pressure. The combustion velocity and expansion of the gas determine the blast pressure and destructiveness of an explosion. Combustion velocity, like any reaction rate, depends on the gas concentration, composition, temperature, and pressure, but will also be affected by congestion and confinement. The local gas concentration depends on dispersion factors such as leak velocity, wind speed, gas molecular weight, and degree of obstruction to gas flow. As the flame front moves through a cloud of flammable gas, the hot combustion gas expands and increases the velocity, turbulence, and temperature of the burning gas, which tends to increase the combustion rate. If the flammable cloud is in an area with many obstructions, the increase in turbulence will affect the flame speed, and the resulting blast pressure may reach destructive levels. If there is enough congestion for the combustion speed to increase beyond the sonic limit, the resulting detonation is especially destructive. In an explosion, there is a high potential for damage escalation due to flying debris. After a severe explosion, the fire protection systems are often too damaged to put out fires resulting from the original leak and blast-created leaks. There is not much opportunity to reduce the effects of an explosion. In some plants it is worthwhile to install a blast wall to protect a critical area of a plant, such as the control room. However, any blast wall will increase the blast effects on the unprotected side. For explosions, like jet fires, prevention is the most effective strategy for reducing risk.

In a typical process plant, the probability or frequency of leakage can be reduced, but not made negligible. From failure databases such as refs. [2,3], it is apparent that valves, flanges and equipment seals are the only credible sources of leakage. Theoretically, flanges or other piping connections could be eliminated by using only welded connections. But, the risk from having to cut and weld connections for maintenance may be worse than the risk from flange leaks. While it may be theoretically possible (but expensive) to eliminate all or almost all flanged connections, it is not possible to eliminate all valves. If a process has even a few valves or seals, then frequency of leakage is significant enough to look at the need for gas detection.

Gas detection and corrective action in response to flammable gas alarms can be very effective at preventing a serious fire or explosion. With proper attention to detector spacing and redundancy, a detector system can be designed to detect serious leaks to any desired level of reliability. If a leak is small, gas detection allows the leak to be isolated and repaired before the flammable cloud has the possibility to increase to a more serious size, ignite, or combine with any new cloud from another nearby leak. If there is a sudden large leak, it may be possible to limit serious consequences by actuating quick-closing isolation valves, depending on the gas capacity of the section of the process that is leaking.

The basic cost of a modern infrared single-point gas detector is roughly comparable to a 3-in. steel, 300-lb rated, gas shut-off valve with actuator. The installed cost of a gas detector system is a fraction of a percent of the cost of a typical process plant. In fact, the overall fire protection system in a process plant is generally less than 1% of the plant cost. In summary, gas detection systems are a relatively inexpensive part of a plant, considering the importance of their safety function and their effectiveness in preventing fires and explosions.

3. Risk-based approach

A safe design incorporating correct spacing for flammable gas detectors can be developed through a five-step process:

1. Start with a plant that uses good design practices to reduce the likelihood and severity of consequences due to leakage of flammable gas or liquid.
2. Establish the need for a detection system and estimate the frequency of leakage.
3. Establish the design-basis blast pressure that equipment in an explosion path will withstand. For fires, choose a radiant heat exposure criterion that will allow personnel in the area to escape safely.
4. Determine the size of a gas cloud that must be detected for the facility to have a tolerable risk.
5. Specify a system that will detect a cloud of the size of concern (design-basis cloud), adjusting the detector spacing (number of detectors) so there will be some overlap to compensate for detectors that need repair. The overall detection and response system must have a design integrity sufficient to achieve a tolerable risk.

The first step is to minimize the opportunity for leaks, as far a practical. Design development should begin with the application of the principles of inherently safer design, which may result in a process that uses less-hazardous materials, smaller quantities, or less severe operating conditions. Minimizing the number of valves and flanges step is already a normal part of design review, for the purpose of finding cost savings. Design standards should be chosen to reduce the likelihood of leakage at the locations where valves, flanges, and seals are required. Vent, drain and sampling valves should be connected to a vent or flare header where practical, rather than venting directly into the air. Otherwise, valves that can open to the air should have a flange or plug on the opening, and a normally-open back-up valve for maintenance. Careful attention to piping stress analysis is essential. It is especially important to absolutely minimize the potential for sudden failure, such as brittle fracture, stress-corrosion cracking, fatigue failure, and sudden impact. Leaks caused by impact can be minimized by including excess-flow valves on lines where impact damage is possible, such as fuel lines to gas-fired equipment. Where practical, the flanges on high-pressure gas lines should be located to direct leakage towards relatively open areas, rather than congested areas. In pipelines that contain a large quantity of flammable gas between isolation valves, there should be provisions for regular inspection of the lines, from the outside by surveys and from the inside by instrumented pigs.

The second step is to determine whether reduction of fire and explosion risk is needed, and whether a gas detection system would reduce the risk. API Recommended Practices (such as ref. [4]) require combustible gas detectors in some enclosed areas. In other areas, the need for detectors is determined by client requirements and standard practices. In the absence of specific design guidance, the need can be evaluated from the expected frequency of leakage and consequences of leakage in the event of ignition.

Sometimes, the client has standard practices covering the need for gas detectors. API recommended practices or other codes and standards for offshore, such as from DNV, ABS, and ISO are helpful in determining the need for these detectors. Other government requirements such as found in the US CFR's and requirements from other local governing bodies from other countries can also provide some limited guidelines. Unfortunately, the specific requirements on location of these devices are not always clear.

Where applicable standards are not specific, the probability of leakage should be estimated. If the probability of a serious leak is below the threshold of credibility, no detection is necessary. Any probability of 10^{-6} per year or less is considered non-credible by many companies and by the US Department of Energy. A design is tolerable if the probability of leakage is less than the threshold agreed upon for the project for a catastrophic fire or explosion. If there is a credible probability of leakage, then the consequences of leakage and cost of design improvement should be evaluated. The probability of leakage equals the average frequency of leakage, if the frequency is in the typical range. The total frequency for all leak sources is the sum of the individuals. For each leak source, the frequency of leakage depends on the type of equipment that could leak, conservatism of design rating compared to severity of process conditions, ambient conditions, and testing or inspection procedures. Table 1 shows mean values of leakage frequencies for generic conditions.

Table 1
Example frequencies of leakage

Leak source	Mean annual rate of occurrence
Reciprocating compressor	0.8
Aeroderivative gas turbine (3000 – 10,000 kW)	0.8
Crude oil pump	0.5
Electric-driven centrifugal compressor (various sizes)	0.03–0.5 (depending on size)
Ball valve in gas service	0.03
Emergency shutdown valve	0.006
Flanges (all sizes and ratings)	0.00009

The leakage frequency rates above include leaks large enough to eventually create a fire or explosion hazard, if the leak were allowed to continue and increase over an extended period of time. In other words this table applies to areas where there is no gas detection system, and can be used to evaluate whether a detection system should be added. In areas where there is an adequate leak detection system, only leaks of an immediately hazardous size need to be considered. The typical informal practice is to report a leak in a database as critical or hazardous if the detected concentration a few feet from the leak is greater than around 25% of the LFL. The data source for flanges is ref. [3]. The other data is from ref. [2].

After the probability and consequences of leakage are estimated, the question is "How much risk reduction can be achieved with a detection system?" The answer depends on whether prompt detection allows actions to be taken that will reduce the severity of the consequences.

If gas detection is needed, the third step is to establish the design blast pressure for explosions, and the radiant heat criteria for fire exposure to personnel.

Usually, the worst consequence from an ignited gas leak is metal fragmentation caused by the explosion blast pressure and impulse load imposed on vulnerable vessels, piping, structures, and equipment. The blast pressure that equipment can withstand can be estimated from calculations and experience with previous designs and company standards for the support of piping, vessels, and cable trays. An explosion can cause damage to the human body at pressures above 15 psig or 1.0 barg (Ref. [5]). However, severe injury from flying debris can occur at much lower blast pressures. Based on previous experience with explosions on offshore platforms, a pressure of 0.3 barg is chosen by some operating companies as the criterion for the estimated pressure that would cause damage to process vessels and piping. The design company piping stress engineers and vessel support engineers should validate this design pressure as being reasonable for their design standards. A higher design pressure such as 0.5 barg could be chosen, but would require stronger and/or more-closely spaced supports for vulnerable objects in the path of an explosion. It may turn out that higher design standards are needed for portions of the plant with a likely potential for high blast pressure. Some objects in the path of a potential explosion may not contain hydrocarbons, but still must be designed to withstand the design blast pressure in order to avoid injury to personnel or impact to hydrocarbon-containing piping and vessels.

Even when the risk from leaks is dominated by explosion damage and injury, the risk from fires must be evaluated, because the risk from leaks is the sum of explosion and fire risk. The degree of injury or probability of fatality from radiant heat depends on the radiant heat level and exposure time. Direct exposure to the flame of a jet fire is assumed to be fatal. Criteria for temporary exposures to radiant heat can be found in standards such as ref. [6].

The fourth step in determining detector spacing is to estimate the size of a gas cloud that is large enough to cause unacceptable risk, in other words, the design basis gas cloud. This requires that the expected financial damage and statistical number of injuries from leaks must be less than the corporate risk criteria. To achieve a tolerable level of risk, the percentage of clouds that are detected must be great enough to meet the risk criteria. The percentage detection goal for the system is derived from a project risk matrix. A risk matrix ranks the risk of a particular set of events such as fire or explosion into categories. The risk categories are useful for design only if they are related to quantitative criteria. The risk ranking is based on levels of frequency and severity, as shown in the hypothetical example in Fig. 1. Severity is usually measured in terms of injury to on-site personnel and the public, and dollar damage to the plant or corporation. For each risk category above the lowest, action must be taken to either absolutely reduce the risk, or to reduce the risk within cost-benefit guidelines. The definitions for risk level and resulting guidelines for risk reduction vary among companies. Whatever the guidelines are, the risk reduction matrix should provide quantitative guidance on the reliability required for protective systems such as gas detection.

The frequency of a particular consequence, such as "one or more fatalities" is calculated as the frequency of a fatality from jet fires plus the frequency of a fatality from explosions. The frequency of fatality from jet fires is the frequency of a leak large enough to cause a jet fire multiplied by the probability of immediate ignition, multiplied by the probability that one or more personnel will be present in the range of the fire. The frequency of fatality from explosion is the frequency of a leak large enough to exceed the design blast pressure (e.g., 0.3 barg), multiplied by the probability of delayed ignition, and multiplied by the probability that one or more personnel will be struck by blast fragments.

An example calculation of the frequencies of occurrence of a fatality is shown on the consequence-probability diagram in Fig. 2. This example applies to a hypothetical case of a high-pressure gas line in vertical position with a flanged valve and piping flange for maintenance that could direct a leak toward other lines on the north and south sides, a walkway on the east, or open space on the west. In this example, CFD results indicated that a leak of 10 mm diameter, or equivalent area, is sufficient in some wind conditions to cause an explosion exceeding 0.3 barg, and a 0.3 barg blast wave has enough force to send dangerous debris flying into any nearby personnel or vessels. A separate consequence diagram would be done for leaks of greater diameter which are less likely to occur, but if they do occur are more likely to cause an explosion exceeding 0.3 barg. Fig. 2 represents only part of a hypothetical analysis on several lines and vessels. Leak frequencies were taken from ref. [3]; the direction of the leak is affected by the orientation of the valve stem; wind direction probabilities from local weather history; probability

Consequence	Frequency				
	A	B	C	D	E
I	3	3	3	2	2
II	3	3	2	2	2
III	3	2	2	1	1
IV	2	1	1	1	1

Risk Ranking

High risk	3	Unacceptable - design must be altered
Medium risk	2	Risk reduction measures must be adopted, if practical
Low risk	1	Tolerable - reduce risk if life-cycle cost improves

Frequency Definitions

Category	Definition	Working Definition
A	Possibility of repeated incidents	100 or more times per facility life
B	Possibility of isolated incidents	10 times in facility life
C	Possibility of occurring sometime	Once in facility life cycle
D	Not likely to occur	Once in 10 facility lives
E	Practically impossible	Once in 100 or more facility lives

Health and Safety Consequence Considerations

Category	Considerations
I	*Fatalities/serious impact on public.* One or more fatality
II	*Serious injury to personnel/limited impact on public.* Severe but non-fatal
III	*Medical treatment for personnel/ no impact on public.* Lost Time Incident (LTI)
IV	*Minor impact on personnel.* First aid only.

Fig. 1. Example of a risk matrix.

of immediate ignition from calculated duration and frequency of ignition sources (mobile equipment, nearby boats, testing of engine-driven firewater pumps, and thunderstorms); probability of delayed ignition from generic data in ref. [7]. In the example, the estimated fatality rate for this one line is 8.8×10^{-10} per year.

In some cases, detection does not reduce risk. A leak with a large initial flow will have a low potential for damage, if automatic isolation valves are located near both sides of the leak and they close quickly enough to limit the flammable cloud size. But a large flammable cloud that appears suddenly may ignite before the leak rate can be diminished by detector-activated isolation valves; this tends to occur in large pipelines, because large valves take more time to close, valves that close too quickly can cause hydraulic forces on the pipe and valves, and the expense of large, tight shutoff valves discourages their use. As noted earlier, each valve is a potential leak source. Fortunately, large leaks are rare. Reference [3] shows the relationship between leak size and likelihood. Fig. 3 gives a graphical image of a cumulative leak rate distribution for multiple leak sources, showing that the majority of leaks will be initially small. The probability of a large leak depends somewhat on the site. Reference [9], a comprehensive current assessment of damage mechanisms in all industries, lists all of the known causes of leakage in metals. Most of the mechanisms for corrosion, erosion, and cracking are gradual, and therefore detectable by inspection. There are mechanisms, such as hydrogen embrittlement, that appear suddenly – but these mechanisms can be prevented by correct choice of metallurgy. With correct metallurgy and an inspection program, the only conditions that lead to catastrophic failure are physical impact, thermal shock, and flame impingement, which occur from accidents. The probability of accident conditions depends on the site-specific opportunities for accidents. Data sources such as ref. [7] may be used to estimate such probabilities. Usually, it is necessary to perform a site-specific assessment to determine the probability of accidents such as mobile equipment collision and dropped objects from cranes.

Leaks that ignite immediately to produce a jet fire may be detected by the fire detection system soon enough to reduce financial loss and injury caused by heat damage to nearby metal structures and process containment, but not in time to avoid injury to someone unlucky enough to be directly in the path of the flame. The probability of loss and injury caused by the escalation effects from heat damage can be roughly estimated from the response time of the fire detection and leak isolation system, compared to the duration of protection provided by metal wall

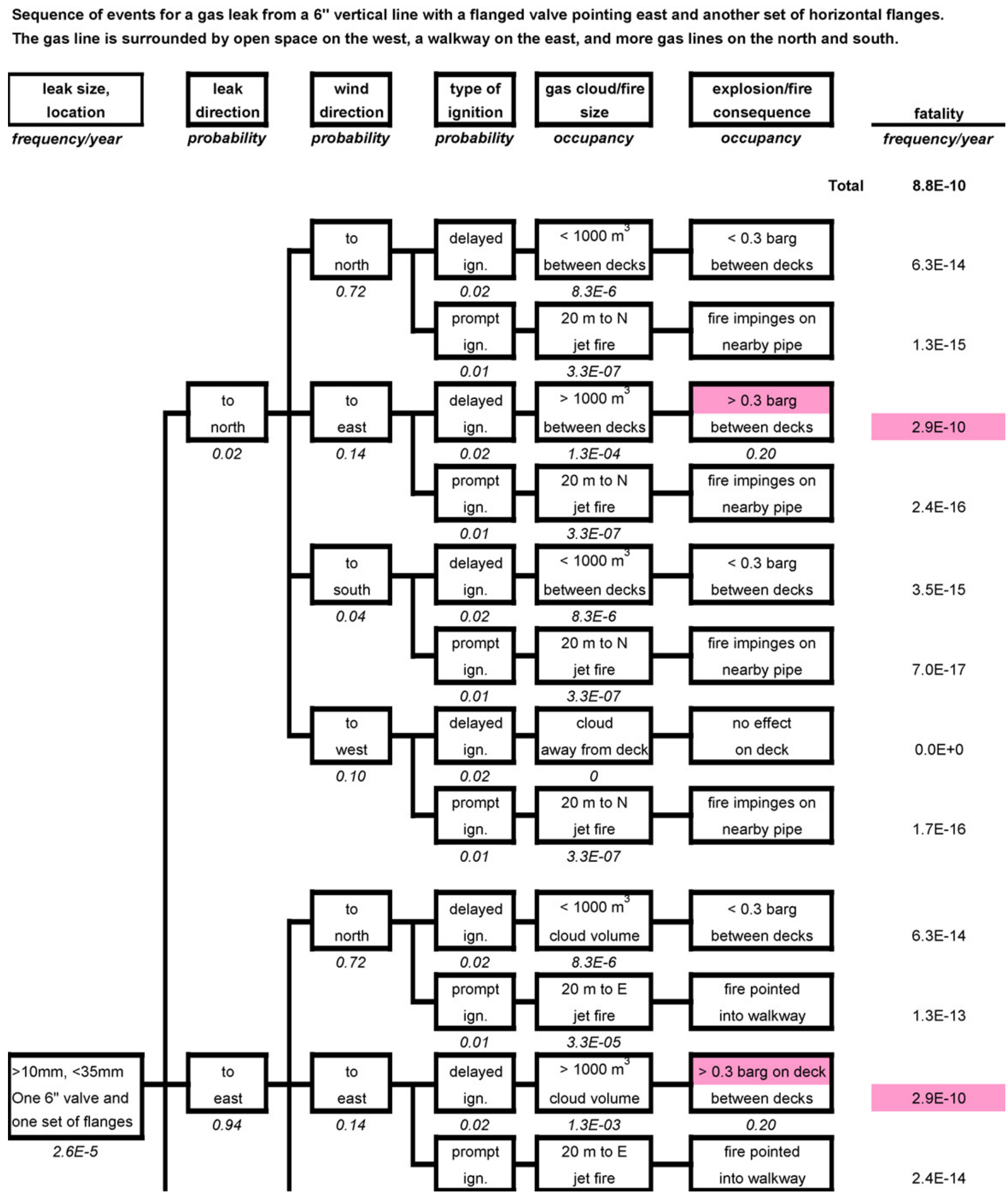

Fig. 2. Example of a consequence–probability diagram.

thickness and passive fire protection. The probability of immediate injury to personnel can be estimated from the staffing plan. Although it is possible to only roughly estimate the level of risk that cannot be reduced by gas detection, this risk is usually small even when calculated conservatively. If the irreducible risk exceeds or approaches the tolerable level, the entire design concept must be reconsidered. However, with a typical design, the gas detection system will make the risk acceptable by detecting a high percentage of gas clouds prior to ignition.

For explosions, the severity of damage and injury makes a dramatic increase when the blast exceeds the pressure at which fragmentation and flying debris occur. This situation occurs when the gas cloud size is large enough to exceed the design-basis blast pressure established in the previous step. The cloud size sufficient to cause fragmentation varies, depending on local conditions such as the shape and concentration profile of the cloud, location of obstructions in and around the cloud, and the type of material subject to fragmentation. For the facility, or even an area of the facility, there will be a range in cloud sizes that result in the same design-basis pressure. Gas dispersion modeling gives gas cloud properties related to size, location, concentration, and residence time of flammable gas in an area. Combining this cloud information with the leak frequency and the distribution of leak sources is key to under-

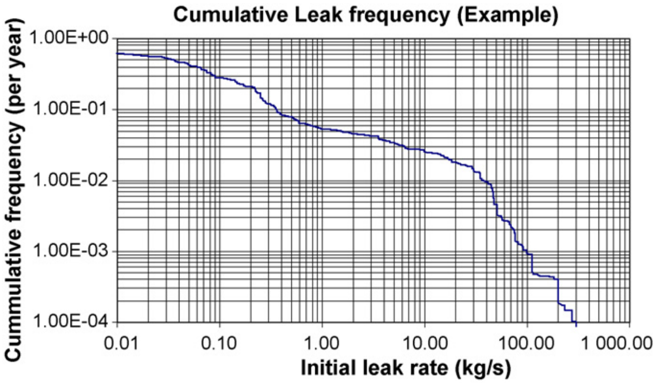

Fig. 3. Example of a leak rate distribution.

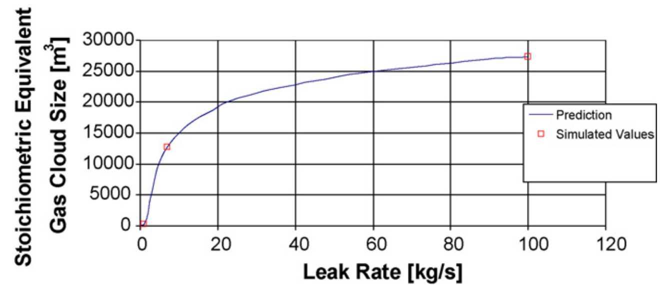

Fig. 5. Gas cloud size prediction.

standing probability and gas cloud probability at the time of ignition.

For a modern offshore production platform, CFD (computational fluid dynamics) analysis is the standard method for determining the cloud size and blast pressure for representative release scenarios. The CFD method solves the differential equations for gas flow across a computational grid created within a three-dimensional model of the plant. This method duplicates the flow of gas from a leak, as affected by wind and natural convection during the dispersion of a flammable gas cloud through the plant. Running a CFD simulation of a gas cloud dispersion can give results similar to those presented in Fig. 4. The figure shows a gas cloud dispersion from upper flammable limit to lower flammable limit at steady state. Running several simulations with varying leak rates and wind conditions provides an understanding of the gas cloud size distribution. For example, Fig. 5 shows the gas cloud sizes resulting from a simulation with leak rates of 1, 7, and 100 kg/s leak rates. Other runs were made at different wind conditions to gain an understanding of the ventilation in the area, in order to produce representative results. A cloud size prediction curve can be made from a few simulations, but should be validated by further simulations to obtain the correct shape.

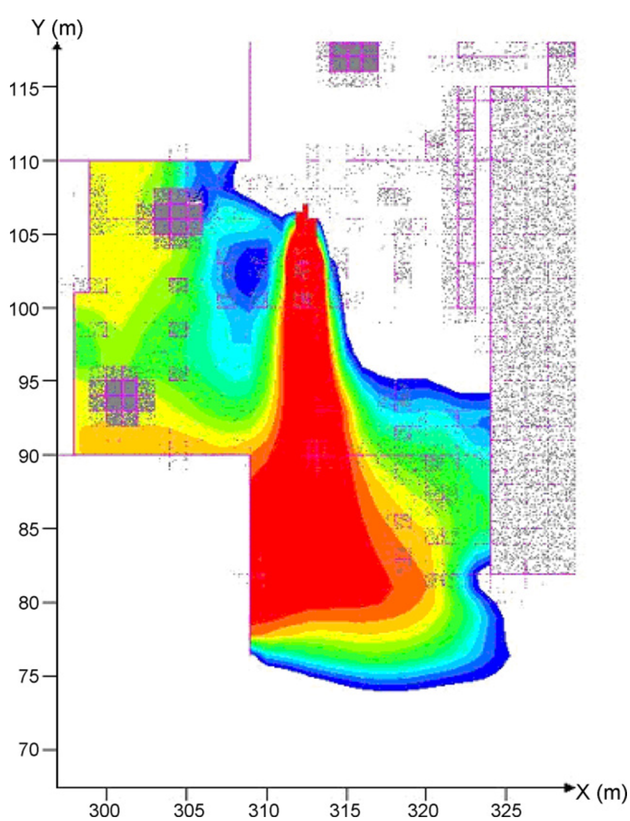

Fig. 4. Example gas dispersion simulation.

Note that the cloud volume is reported in cubic meters of equivalent stoichiometric mixture, because this parameter correlates well with explosion energy and pressure. The equivalent stoichiometric volume of the cloud is calculated from the volumes of different ranges of concentration in the cloud, out to the LFL. For detector placement, the potential explosion pressure is needed, along with the extent of the cloud concentration that will initiate a system response. The detector network will initiate action when the flammable gas concentration is below the LFL, typically at 25%. However, dispersion modeling is usually somewhat conservative in expressing the size of a cloud. In consideration of the uncertainty in dispersion methods and resulting conservatism in modeling, the cloud size should be measured out to the LFL for the purpose of detector spacing.

After ignition, CFD simulation includes the effects of heat of combustion, degree of reaction completion, rate of combustion, and heat transfer with surrounding objects or firewater spray. The method accounts for explosion pressure amplification or dissipation caused by barriers and obstructions within the plant. The size of cloud that can exceed the design blast pressure in the event of an explosion is somewhat different for each gas release and wind scenario within the plant. Furthermore, the blast pressure from a particular cloud depends on the timing and location of the ignition source. Fig. 6 shows an example of the variability in the relationship between gas cloud size and calculated blast pressure for different wind and ignition scenarios with the same natural gas release scenario on the same offshore platform. There is a range of cloud sizes in the area under investigation that can yield the design blast pressure. An example of the range in cloud sizes for an area with many leak sources is shown in Fig. 7. The leak scenarios included in Fig. 7 were chosen to represent the relative probabilities of leak sizes, locations and weather conditions. After determining the size of a particular cloud in terms of equivalent stoichiometric volume, dispersion results can be used to relate that to the volume of the cloud that is above the LFL. The relationship between equivalent stoichio-

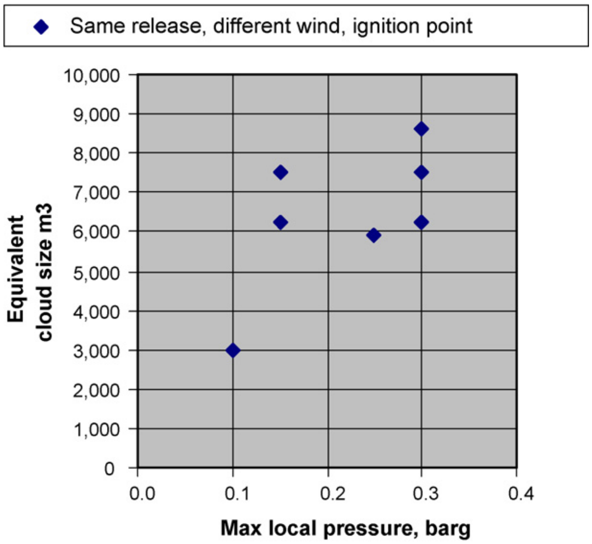

Fig. 6. Gas cloud size and blast pressure for a single leak scenario.

metric volume and volume above the LFL will not be linear, because large clouds tend to have a higher proportion of gas above the UFL.

The results of the CFD analysis will depend on how the release scenarios are chosen. The analysis should include the scenarios that are most likely to occur, as well as those expected to cause the most damage. Leaks from areas with the greatest number of potential leak sources should be included, as well as leaks from the highest-pressure sources directed towards the most vulnerable areas or towards areas where blast wave amplification can be expected due to confinement barriers or a high density of obstructions.

Each leak scenario should be investigated over a range of wind conditions. Wind rose data is necessary for ensuring that the analyzed wind speeds are appropriate for the site. A range of wind speeds should be analyzed because it is difficult to predict the worst speed prior to analysis. Low wind speeds result in less dilution of a flammable gas cloud, which increases the volume of cloud above the LFL. On the other hand, high wind speeds cause more mixing within the cloud, especially for large clouds. Mixing within the cloud can cause more of the cloud to be near stoichiometric concentration, which increases the blast pressure. Combustion speed and hence blast pressure is much higher for

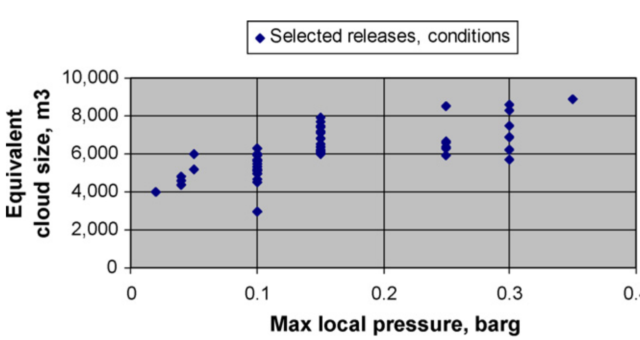

Fig. 7. Gas cloud size and blast pressure for a representative sampling of leak scenarios.

a gas mixture near the stoichiometric point. The chosen scenarios should constitute a representative sampling of possible conditions across the distribution of high and low-probability scenarios.

Likewise, the worst-case ignition point is difficult to predict. However, the explosion pressure is not very dependent on the location of the ignition point. Therefore, choosing at least one ignition location near the center of the cloud and one near the edge will give realistic explosion loads.

With scenarios chosen as described above, a plot similar to Fig. 6 is generated. At the design-basis pressure, the range of cloud sizes can be expressed as a probability distribution function. The cloud size that must be detected (design basis cloud) corresponds to the percentile that is tolerable according to the risk criteria after irreducible risk is considered. For example, suppose 80% of the leak risk must be eliminated to reduce the risk to a tolerable level, suppose that 10% of the leaks result in risk that cannot be prevented by detection, and suppose that 1% of the time the detection and response system will be nonfunctional (unavailable). Then, 91% of the reducible risk must be eliminated by detection. In this example, the detector spacing must be close enough (number of detectors must be great enough) to detect no less than the largest 91% of the gas clouds that could create the design-basis blast pressure, for all possible wind directions. Consequently, this step gives the basic probability requirement for the detection and response system, but the spacing must be determined for the particular system logic, detector type, and maintenance plan.

The fifth step is to determine the detector spacing (or number of detectors) needed to provide a detection and response system of the appropriate integrity to achieve tolerable risk. The actual value of required integrity must take into account the integrity of all system components: control logic, wiring, and response system, not just the individual detectors.

System failures included in the unavailability are: detector fails to detect the specified concentration of flammable gas around the detector, and failure of alarm logic or signal transmission system to alert operators or activate emergency mitigation systems. In addition, the detection system must minimize false alarms, because of the hazards introduced by a sudden shutdown and restart, and because operators will ignore alarms if they are perceived to be false.

Plant operating companies have had to adjust two factors to balance the trade-off between false alarms and inadequate detection. One factor is the sensitivity of the detectors, which depends on the location of the detectors, and the adjustable alarm threshold of each detector. Recommended practices have been developed by API for the location and installation of detectors, discussed in the next paragraph. The common practice among operating companies is to set the initial detection threshold at 10–20% of the LFL, with a more urgent alarm at 25–50% of the LFL. Most operating companies have found that a setting below 10–20% of the LFL results in too many nuisance alarms, without much improvement in the speed of responding to those leaks that require immediate action.

Another factor in the trade-off between false alarms and inadequate detection is detector redundancy. A single infrared flammable gas detector has an average false alarm frequency of once every 30 years. For a well-maintained facility with an average time of 2.8 h to restore a detector to service, there is a probability of 3.3×10^{-5} of a detector being in a dangerously failed condition, or an integrity of 99.9967% (Ref. [2], p. 530). This integrity, while high for a field instrument, can give inadequate system integrity when there are many detectors in the network. The integrity represents the percentage of time that the network is ready to perform the safety function. Using standard reliability methods (see ref. [8], for example), the integrity of a detection and response system can be calculated from the logical relationship and integrities of the individual detectors and control system components. The integrity of the overall detection and response system is the product of the integrity of the detection network and the integrity of the control system including logic, wiring, and response devices. Common-cause failures (failures of two or more detectors due to a factor external to the detector network) must be considered, although this involves greater uncertainties because many common-cause failures are due to human error or unknown causes. Using the method and common-cause judgment factors in ref. [10], the detector network integrity is 99.99967%, in a typical facility without a rigorous program of common-cause failure prevention. At first glance, it would seem that a detector network with 100% redundant detectors with 1-out-of-2 logic would be more than adequate. In a system that only has an alarm function, 1-out-of-2 logic is often sufficient. The main problem is that the 1-out-of-2 logic will have twice as many false alarms. To combat false alarms, some operating companies use 2-out-of-2 logic, where both detectors must alarm before action is taken. But 2-out-of-2 logic doubles the probability that detector failure will prevent necessary response. Consequently, most operating companies have concluded that when the system has a shutdown function, essential detection networks should be designed with 2-out-of-3 voting logic. Reliability calculations demonstrate that a 2-out-of-3 voting system generally provides acceptable probability of detection and a negligible probability of false alarm. In a 2-out-of-3 arrangement, three separate detectors are located in the area around a potential leak. When one detector reaches the initial threshold (typically 10% of the LFL), a warning alarm is given; when two detectors reach the high threshold (typically 25% of the LFL), definitive action is taken, such as leak isolation.

There are standards for designing detector systems. Where combustible gas detectors are required, the API standards RP 14C, RP 14F, and RP 14G provide guidance on location, installation, and redundancy. The normal practice for the past several years has been to locate the detectors near the main leak sources for flammable gas, such as at pump and compressor seals, areas with numerous flanges, well bay areas, etc., downwind of the leak source or on either side and at a certain elevation. Confined spaces where flammable gas can accumulate will certainly require gas detection. The height for gases heavier than air would normally be mounted 2 ft above grade, whereas for gases lighter than air approximately 7 ft 6 in. above grade or at least 2 ft above the leak source. Light gases can accumulate in pockets at higher elevations, such as seen on offshore platforms, but maintenance and testing of the device may warrant a lower elevation. A building air handling system supply inlet located within a potential vapor cloud release is normally protected (at the inlet or in the ductwork) with gas detectors to ensure the shutdown of the air supply. Closing of the main dampers and placing the air handling system in recirculation mode is commonly initiated upon detection.

For a single leak source, or a single air inlet to be monitored, the detectors are typically arranged so that at least two detectors will initiate a response to the design basis leak. If the detectors and connected response system were perfect, there would have to be just enough detectors so that one detector is in the path of the LFL envelope, regardless of wind direction. In other words, the number of detectors depends on the angle of dispersion from the source.

For a single leak source, the number and spacing of detectors in a 1-out-of-N network is chosen so that theoretically there will always be at least one detector in the path of the LFL envelope of the design basis flammable cloud, and that the integrity of the network (including common-cause failures) equals or exceeds the integrity that was assumed when the overall system reliability goal was chosen. Applying combinational logic, the probability of failure of the detector network, not counting control system logic and connections is $(1\text{-I})^N$, where I is the integrity of a single detector. The integrity of this detector network is $1\text{-}\{(1\text{-I})^N\}$. For a 2-out-of-N network, there must be at least two detectors in the path of the design basis flammable cloud. The equation for a 2-out-of-N network is given two paragraphs down. For the example given at the end of step 4, the goal was to detect 91% of the gas clouds that could produce the design basis blast pressure, based on a goal of no more than 1% system failure (an integrity of 99%). In this case, the integrity of the detection and response system must be at least 99%. Until the analyst develops some experience-based judgment, it will be necessary to investigate both 1-out-of-N and 2-out-of-N networks to determine which is more cost-effective for an application.

For a single leak source, the prevailing wind direction should be considered. If there is a strong likelihood that the wind will be from one direction, the upwind detectors can be spaced farther apart. For example, if a hazard with an annual probability of less than 10^{-6} is tolerable, when the wind is from a direction that occurs less than 10% of the time, a leak that occurs with a probability of 10^{-5} has to be considered. The other 90% of the time, a leak with a probability of about 10^{-6} has to be considered, which means considering a smaller cloud that could result in the same blast pressure, as shown in Fig. 7.

In a typical processing area, there are multiple potential leak sources, and N detectors must be placed above and/or below the potential leaks (depending on gas density). The area that must be monitored has to be large enough so that a leak from any potential source will be detected, regardless of wind direction. In an area with multiple potential leaks, the prevailing wind direction is unimportant, because in general a detector will be upwind of some sources, but downwind from others. In a 2-out-of-N network, at least two detectors must initiate a response. As in the case where there is only one leak source, the number and spacing of detectors in a 2-out-of-N network is chosen so that theoretically there will always be at least two detectors in the path of the LFL envelope of the design basis flammable cloud from any leak source, and that the integrity of the network (including common-cause failures) equals or exceeds the integrity that was assumed when the overall system reliability goal was chosen. The detector network will fail if all N or $N-1$ detectors fail, but any fewer failures will result in at least 2 functional detectors. From the binomial distribution (Ref. [8]), there is only one combination where all N detectors fail, and N combinations where 1 detector alone does not fail. The probability that all N detectors fail is $(1\text{-I})^N$ and the probability that $N-1$ detectors fail (and 1 does not) is $N\,I\,(1\text{-I})^{N-1}$. The integrity of a 2-out-of-N network, I_N, is:

$$I_N = 1 - \{N\ I\ (1-I)^{N-1} + (1-I)N\},$$

where I is the integrity of a single detector. A value of N can be determined for any desired value of I_N, in order to meet the risk criteria. In an area with many potential leak sources, there may be many groups of N detectors, each with separate logic. In any group, if N is too great, there will be too many false alarms.

As an example of how maintenance can affect the integrity of a detector network, we can look at an unmanned facility. For facilities that are normally unmanned, it is necessary to plan all detector repairs and testing for the same scheduled date, typically at 3-month intervals. For example, with a repair interval of 3 months, the required number of detectors is 1.74 times that of a manned facility where detectors are repaired twice a week.

Although 2-out-of-3 detector networks are typical, risk analysis may show that different detector logic or arrangement may be required to provide acceptable risk at minimal cost. The number of single-point gas detectors in certain areas can be minimized by utilizing optical infrared beam or open path gas detection. This type of detection will lower the cost of multiple gas detectors while providing much better protection. The transmitter/receivers can be located around metering areas, down pipe racks or around the perimeter of a unit that has the numerous flanges or other leak sources. With this type of technology, the exact location of the leak source is unknown, but the coverage will be much better, with the main concern met by knowing there is a leak in the system, and providing for specific action to be taken.

Engineering companies and vendors are accustomed to working with company and industry standards, so not much more needs to be mentioned about system design once the detector spacing is established.

4. Summary

Determining the appropriate spacing (or number of detectors per space) for flammable gas or vapor detectors requires the engineering expertise to calculate the resistance to blast pressure for piping, structures, vessels, and supports. To determine detector spacing requires a method for evaluating the fire and explosion consequences of specific leak scenarios, taking into account leak parameters, gas properties, weather, and a three-dimensional outline of the plant. From a review of the consequence analyses for a representative sample of releases, the design-basis flammable cloud can be determined, which is the cloud size sufficient to cause an unacceptable risk to the facility due to flammable gas leaks. There will be some residual risk, including risk that cannot be reduced by detection, and the small risk that the detection system itself will fail when needed. Detector spacing should be close enough to detect the design-basis flammable cloud within the probability required to meet risk criteria. System probability must be calculated for the chosen type of detector, system redundancy, and maintenance program. Detector system design can proceed using conventional design methods, once the spacing is determined.

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