Gas Detector Coverage Calculation Using Scenario Coverage of Gaussian Dispersion Models

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Abstract

In the past few years, the use of quantitative risk analysis tools to determine the required number of location of gas detectors has gotten more attention in the literature and also in real world project execution. While there is great interest in these performance based methods, often referred to as fire and gas mapping, there is little information available on how these types of studies are performed. This paper will provide a discussion of how gas detector coverage, as defined in the ISA 84.00.07 technical report Guidance on the Evaluation of Fire and Gas System Effectiveness is calculated. Specifically, the paper will address the definition of scenario coverage and how it is more accurate and effective than more common, but less sophisticated geographic coverage, because it takes into consideration the actual leak sources and nature of the leak scenarios.

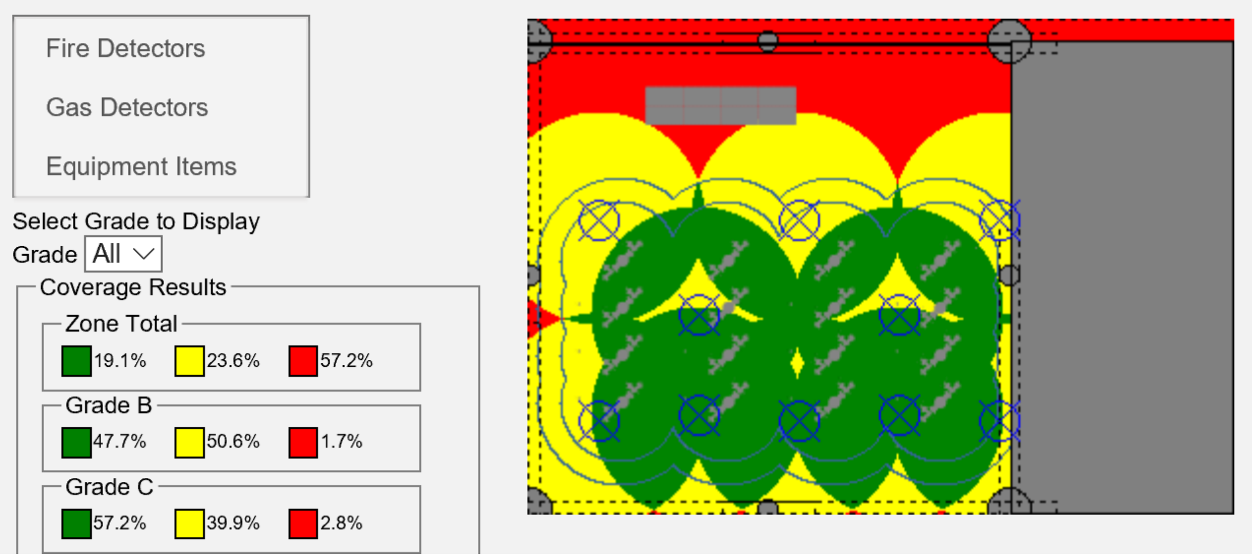
The paper will begin with a discussion of the creation of Gaussian dispersion models from a sufficient set of leak sources and leak conditions. These modeling results will then be manipulated to consider multiple release orientations and their relative frequency, along with consideration of wind directions by modifying the relative directional release frequency based on wind direction frequency. Next a discussion of integration of the risk is presented, discussing accumulation release frequency at all geographic positions based release scenarios present in those locations. Coverage calculation is then described as the determination of which scenarios are detectable given the detector locations relative to locations of released gas clouds. Resulting the calculation of coverage as a fraction of detected scenario frequency over total scenario frequency. The paper will then go on to provide an example of how results are typically presented both graphically and in a tabular format. The paper will give an overview of the entire process using a case study of a well bay in an offshore oil production platform.

Introduction

All safety instrumentation needs a basis of safety, or a set of rules or procedure that allows the designer to make systematic and repeatable decisions about the two key factors of safety instrumentation – where? and how much? For the problem of gas detector placement, the most basis of safety is "expert judgment". That means that a single person or a handful of people in a plant will basically use their gut-feel, supplemented with some rules of thumb to place detectors. Even worse, sometimes these experts are not even operating company stuff, but subcontractors from engineering companies and equipment vendors. This informal design process resulted in designs that were inconsistent and not repeatable.

In 2005, the International Society for Automation's SP 84 committee undertook the development of a technical report that would define the techniques and processes that could be used to convert the process of defining how many detectors are required and where to place them into a systematic and repeatable process based on quantitative risk analysis. Working group 7 was formed, and released the technical report ISA TR 84.00.07 technical report *Guidance on the Evaluation of Fire and Gas System Effectiveness*. This technical report defined a new quantitative concept that represents how well a fire or gas detection system functions called Coverage. The technical report defined two types coverage – geographic coverage and scenario coverage.

Geographic coverage was quickly adopted based on its ease of calculation. Geographic coverage is the fraction of a given area where if a gas cloud of design basis size or larger were to exist, the gas cloud would be detected by gas detector array. This process only requires the determination of a design basis or “critical” gas cloud size. For combustible gases, many operating companies used a 5m diameter spherical cloud based on work from the United Kingdom’s Health and Safety Executive. An example of the result of geographic mapping is shown in Figures 1 and 2.



Select Grade to Display

Grade All

Coverage Results

	🟩	🟨	🟥
Zone Total	19.1%	23.6%	57.2%
Grade B	47.7%	50.6%	1.7%
Grade C	57.2%	39.9%	2.8%

Figure 1 – Typical Geographic Coverage Map with Results Table

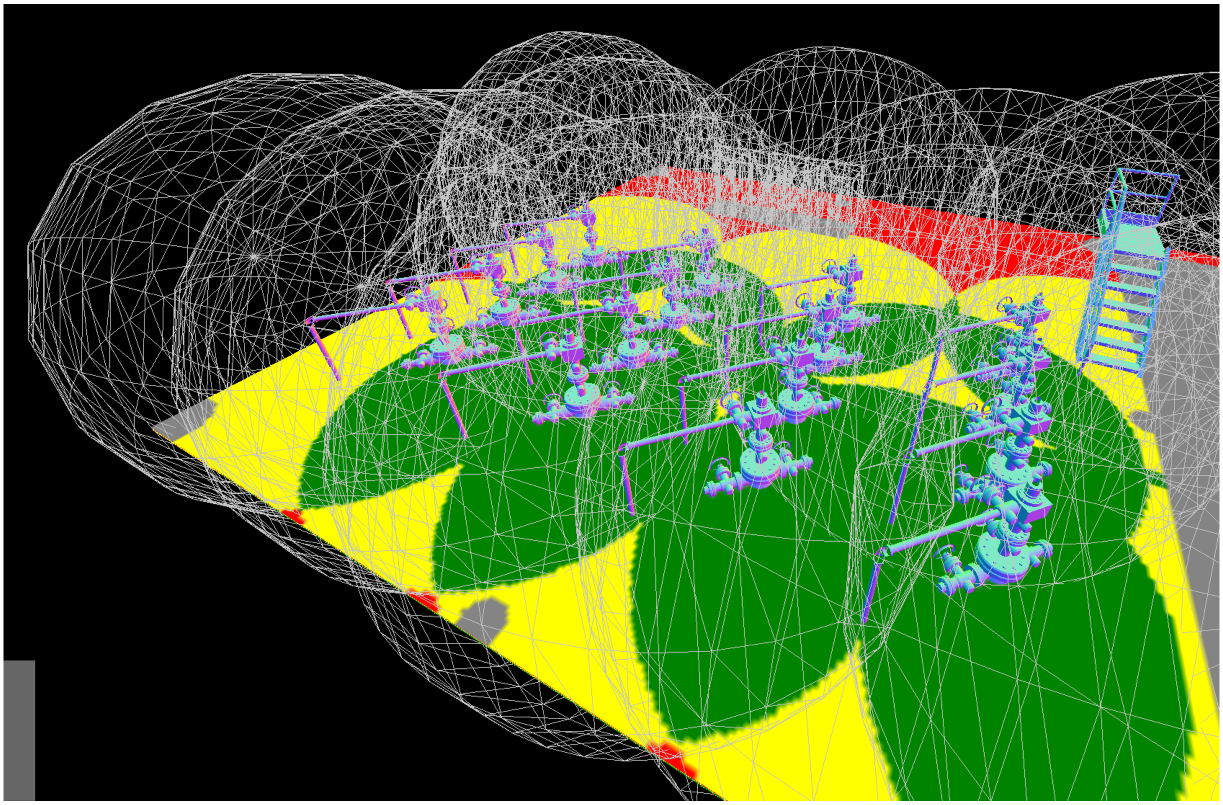


Figure 2 – Geographic Coverage Map Superimposed into 3D Model with Gas Detector Coverage Bubbles Shown in Wire Frame

While geographic coverage was quickly adopted, it was not long before risk practitioners began to question its accuracy and effectiveness. The same attributes that made geographic coverage calculations easy to perform were also viewed as limits on the processes accuracy. Specifically, geographic coverage suffers from the following limitations.

- Only performs geometric analysis that is based on geometry of Design Basis gas cloud
- Does not consider origin of the leaks
- Does not consider how wind direction and speed affect gas cloud locations
- Does not consider the relative frequencies of leaks from different sources

In order to address the limitations of geographic coverage, many risk practitioners moved to scenario coverage in order to improve the quality of their analysis over the "geometry only" results generated by scenario coverage.

Scenario Coverage

Unlike geographic coverage, which focuses on the geometry of a "volume of detection" (called a "cone of vision" for fire detectors) that represents the what the detector "see", scenario coverage delves much deeper into the analysis by considering the size and location of all the potential gas clouds that could occur as the result of a leak in a piece of equipment in the covered area – intersecting the location of the hazard with the location of the detection equipment. It can easily be seen that this type of approach is significantly more powerful the geographic coverage approaches, but it is also very apparent that the level of effort to perform the analysis has increased by orders of magnitude, not only in the engineering effort required to developed all of the new scenarios, but also in terms of sheer computing power as the quantitative analysis that must be performed for this type of analysis must be repeated thousands of times in different directions and weather conditions.

Scenario coverage can be summarized in the following steps:

- Identify and define streams and associated equipment items
- Perform dispersion modeling to establish the dimensions of the gas clouds from each stream
- Determine the leak rates of all equipment items associated with each stream
- Plot release scenario gas clouds on coverage map, considering release direction and wind directions, and individual scenario frequencies
- Accumulate frequency of gas clouds at each point to draw geographic risk profile
- For each scenario, determine if detected by comparing detector locations to gas cloud locations
- Calculate scenario coverage from detected scenario frequency and total scenario frequency
- Accumulate frequency of undetected gas clouds at each point to draw residual risk profile

For the balance of this paper, the steps will be discussed in more detail and implemented in an example problem. The example problem is combustible gas detection of for well bay of an offshore gas production platform, but the concepts can be directly applied to virtually any facility in the process industries. A simplified plot plan of the facility is shown in Figure 3.

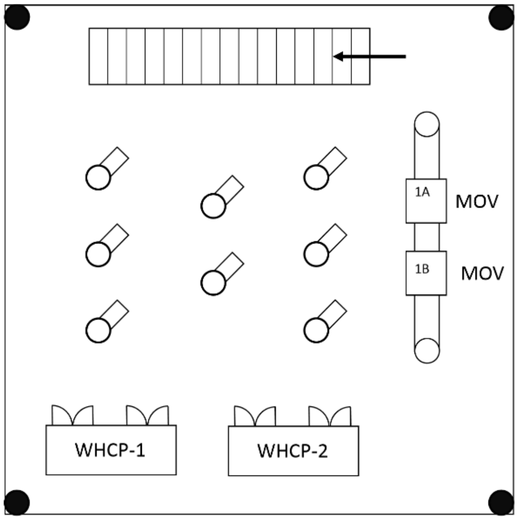


Figure 3 - Plot Plan of Sample Facility – Well Bay

The sample facility contains seven well heads, a transport pipeline with two motor operated valve (MOV) stations, two well head control panels, and a stair well connecting to the upper and lower decks of the platform.

Stream Definition

A stream is the basic unit of analysis for consequence modeling. One set of consequence models is developed per stream. A stream, like a HAZOP node, is a means of collecting a group of equipment items and piping into a single entity for the purpose of simplifying and reducing the number of calculations that must be performed. A stream is established by grouping equipment whose operating conditions are close enough together that a single modeling run will be representative for all of the selected equipment. A stream is a set of process conditions that includes the following parameters:

- Temperature
- Pressure
- Composition (Fractions of each component chemical)

Development of a stream list is typically a fairly straightforward exercise. Many process flow diagrams from chemical process industry plants already contain this information. Not only is the stream defining information included in heat and weight balance tables, the equipment items where those conditions apply are also generally clearly shown on the process flow diagram itself with flag that relate a heat and weight balance table to the related equipment section.

For the sample facility, all of equipment shown in the module, whether well head or piping, would be included in a single stream because the temperature, pressure, and composition contained in the process equipment is very similar.

Dispersion Modeling

Once the streams have been defined, dispersion modeling is performed. While this paper specifically, and the state-of-the-art in industry in general, is to use Gaussian dispersion models, the same concepts apply to computational fluid dynamics models, which the author expects to replace Gaussian dispersion modeling for this task in the future. A series of dispersion models will be run for each stream. The number and types of models will generally follow the customs of quantitative risk analysis studies with a few modifications to suit the problem of gas detection mapping.

While a discussion of dispersion modelling is out of the scope of this discussion, a few points that make dispersion modeling for gas detector mapping are important. When performing dispersion models for gas detection modeling, the number of hole sizes selected for releases is smaller, and focuses on the smallest – traditionally 5mm diameter. While large hole sizes may contribute to higher risk levels because of the consequences they can generate, due to their large size, they are also very easy to detect with a small number of detectors. As a result, including these scenarios into the risk profile generally does not assist in the task of detector placement. Generally, only one wind direction and release orientation are considered in the dispersion modeling, the full range of these variables are accounted for later in the analysis through probabilistic methods. While traditional dispersion modeling calculates distances out to end points that represent various levels of consequence to humans or equipment, the dispersion modeling for gas detection mapping is only concerned with the alarm set point of the gas detection equipment.

The final consideration for dispersion modeling for gas detector mapping is elevation. When modeling is done in three dimension, the only elevation of interest with respect to results are the two detection elevation planes. Most processes have one or two gas detection elevation planes depending on the gas hazards that are present. For dense gases, a detection plane is typically set at 0.5 meters, low enough to detect dense gases but high enough to prevent kicking, splashing, and minor flooding from causing damage to the detectors. For buoyant gases, a detection plane is typically set at 2.5 meters, high enough so that personnel at grade cannot reach up and interfere with them, but low enough that they can be maintained from a step ladder.

For the sample problem, the gas released is primarily methane, so the detection plane – and associated dispersion modeling results were calculated at 2.5 meters for the 10,000 PMM endpoint (shown in blue) that corresponds to the set point of the combustible gas detectors (i.e., 20% of the lower flammability limit [LFL]). Figure 4 presents the dispersion modeling results for the single scenario analyzed in this example.

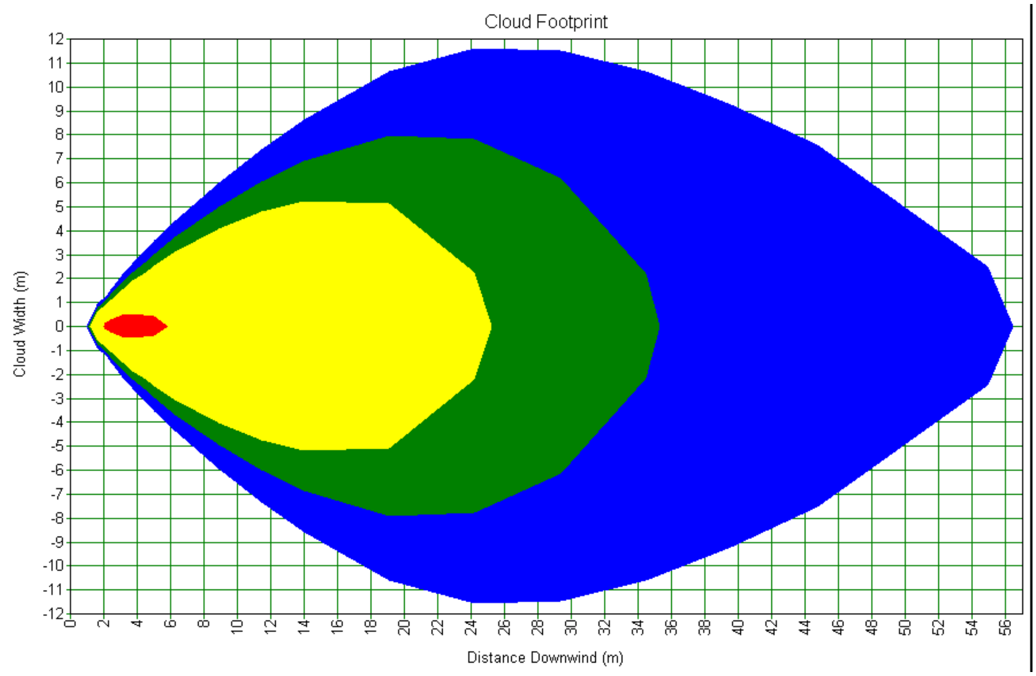


Figure 4 – Dispersion Modeling Results – Buoyant Gas Detection Elevation Plane

The results shown in Figure 4 will result in a scenario entry into the gas detection mapping software of 56 meters in length and 23 meters in width.

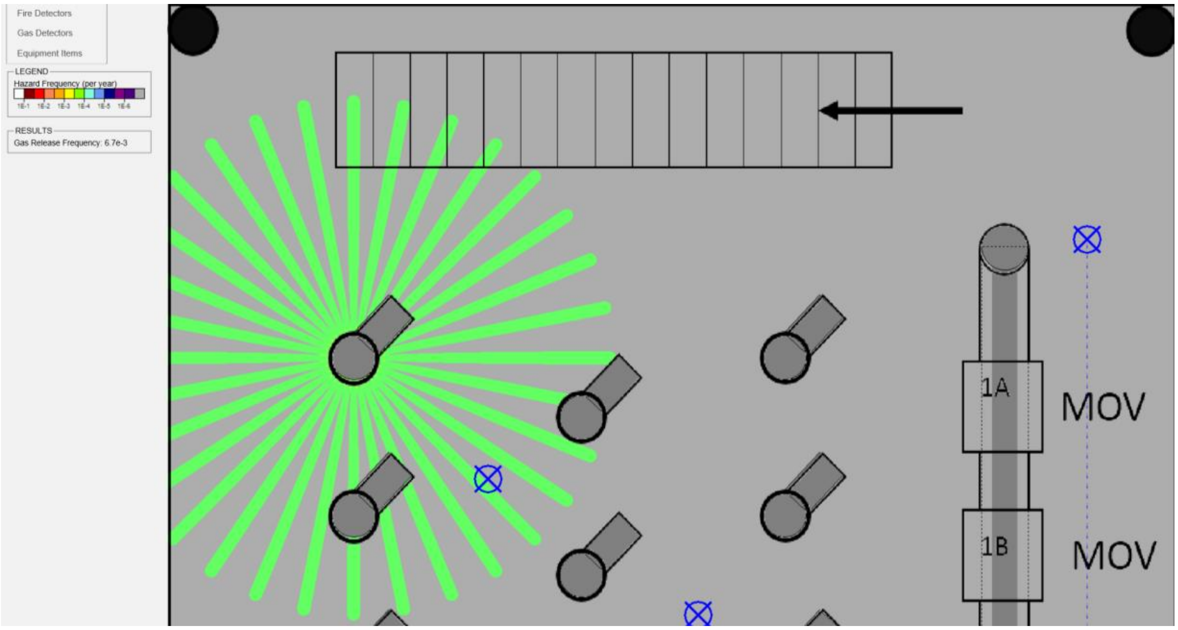
Determine Leak Rates

The leak rates are estimated in the same way as traditional QRA. Instead of trying to predict leak rates based on initiating events and protection, as would be done in Layer of Protection Analysis (LOPA) or fault tree analysis. Leak rate determination for this problem is performed utilizing historical leak rate data. These data are widely available on line from sources like the United Kingdom's Health and Safety Executive. Unlike the stream data which is combined, the leak rates are assigned to each individual piece of equipment that is expected to be a leak location.

For the sample problem, a review of the literature yielded that oil and gas production well heads leak at a rate of about 7.0E-3, and that about 96% of these leaks are "small" (i.e., about 5mm in diameter).

Plot Release Scenarios

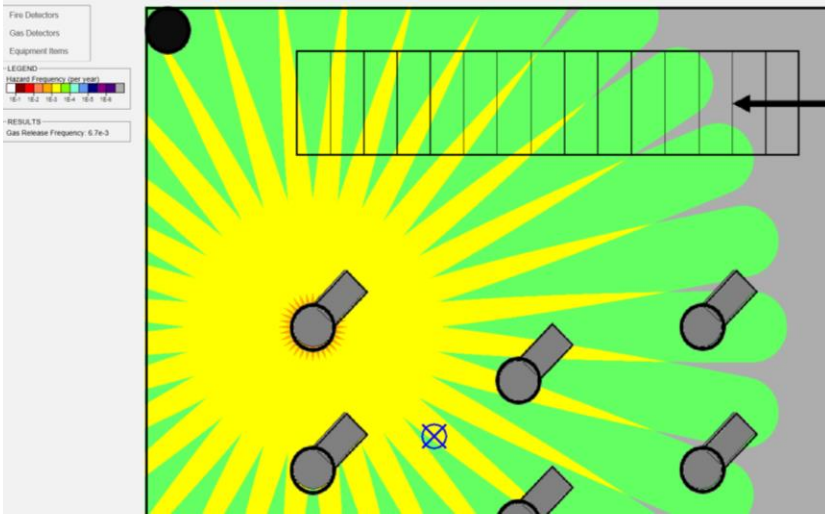
Once the dimensions of a release scenario are known, they can be plotted on a plan view drawing of the facility. In Figure 5, gas releases are plotted from the first wellhead. In order to more clearly demonstrate the concepts, the size of the cloud was modified to 10 meters in length and 0.5 meters in diameter so that each individual release direction (in this case 32 directions were modeled) can be viewed with no overlaps. It should also be noted that the color represents the frequency of that release, in accordance with the legend shown in the drawing. The frequency of each individual cloud is equal to the overall release frequency divided by the number of release directions, assuming that a release is equally likely in any direction.



Gas Release Frequency: 6.7e-3

Figure 5 – Gas Release Scenarios (Modified) Plotted on Plan Drawing – 32 Release Directions

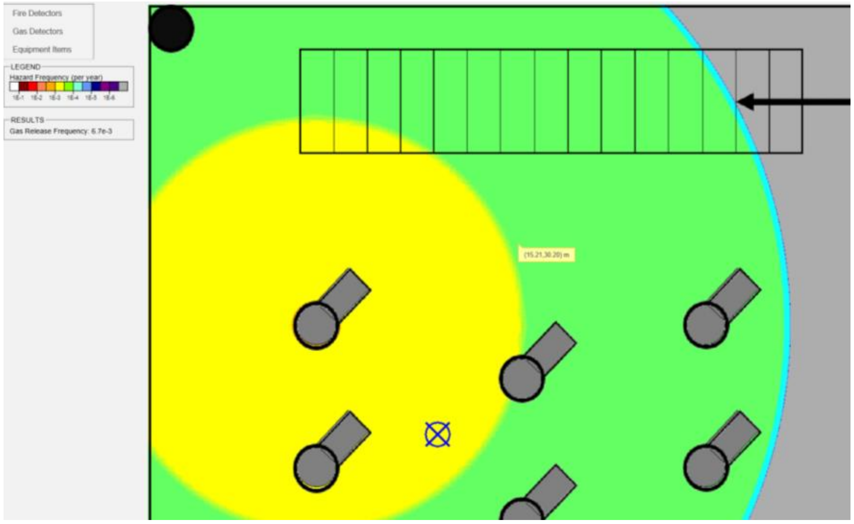
Figure 6 is the same concept as Figure 5, but in this case the size of the gas cloud is increased to 20 m in length and 3 meters in width (which is still smaller than the calculated dimensions. It is quickly apparent that the frequency of existence of a gas cloud in the "overlap" areas of the clouds is higher than in the main part of the cloud. The reason for this increase in frequency is that all of the frequencies of all of the clouds are summed for each location to develop a composite frequency of existence of a gas cloud in a given location.



Gas Release Frequency: 6.7e-3

Figure 6 – Gas Release Scenarios (Modified, Larger) Plotted on Plan Drawing – 32 Release Directions

In order to make the assessment even more accurate, the number of direction of the release is then increased from 32 to 720. As shown in Figure 7, this removes the jaggedness from the geographic risk profile, and also clearly demonstrates that the frequency of the existence of a gas cloud is higher nearer to the release source.



Gas Release Frequency: 6.7e-3

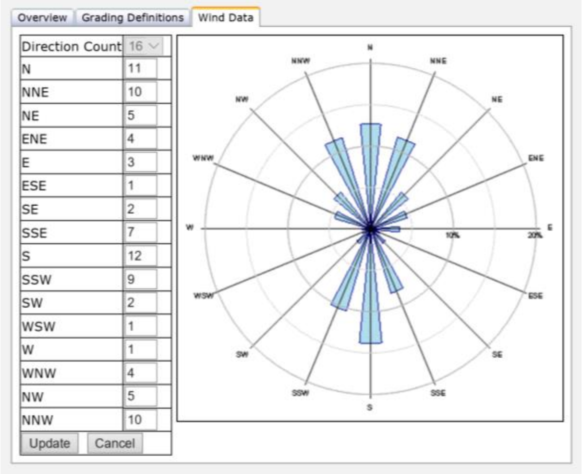
Figure 7 – Gas Release Scenarios (Modified, Larger) Plotted on Plan Drawing – 720 Release Directions

Considering Wind Directions

The geographic risk profile that is represented in Figure 8 did not directly take into consideration wind directions. In order to address this issue, an analyst could run a separate dispersion model for each combination of release direction and wind direction, but even if only 16 wind direction and 32 release direction are considered, this would require 512 dispersion models to be run for each wind speed / atmospheric stability combination, all of which would need to be separately entered into the mapping tool. At this time, this degree of effort is not feasible for a typical industrial project. Instead, wind directions are accounted for through probabilistic methods.

Current best practices utilize probabilistic approaches to address different wind directions by weighting the probability of different release directions based on wind direction probability. Reconsider Figure 5. All of the gas clouds are the same frequency (thus their colors are all the same). Addressing the wind direction effect of gas cloud location can be estimated by modifying the condition probability of a release direction by the conditional probability that the wind is blowing in the direction of the release.

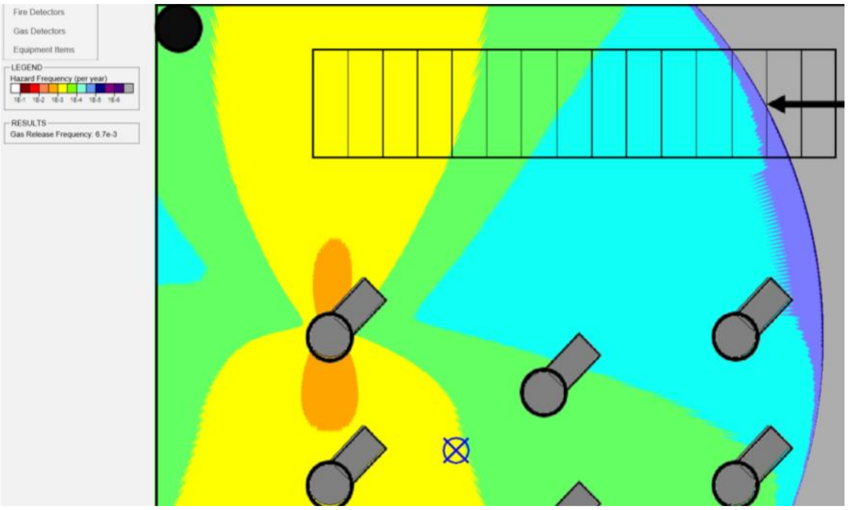
For the sample problem, the probability of wind direction is entered based on location weather station data as shown in Figure 8.



Direction Count	16
N	11
NNE	10
NE	5
ENE	4
E	3
ESE	1
SE	2
SSE	7
S	12
SSW	9
SW	2
WSW	1
W	1
WNW	4
NW	5
NNW	10

Figure 8 – Wind Direction Relative Probabilities

The effect of entering in the wind data, is that all 720 directions of the release now have their frequencies weighted based on the relative probability that the wind is coming from the direction upwind of the release. Once wind directions are considered, the geographic risk profile that was shown in Figure 7 changes as shown in Figure 9.



RESULTS

Gas Release Frequency: 6.7e-3

Figure 9 – Gas Release Scenarios (Modified, Larger) Plotted on Plan Drawing – 720 Release Directions – Directional Frequency Weighted by Wind Direction

After demonstration of the effect of weather conditions on the reduced gas cloud size, the dimensions of the gas cloud are returned to the actual calculated gas cloud dimensions of 56 meters in length and 23 meters in width. The resultant geographic risk profile is shown in Figure 10.

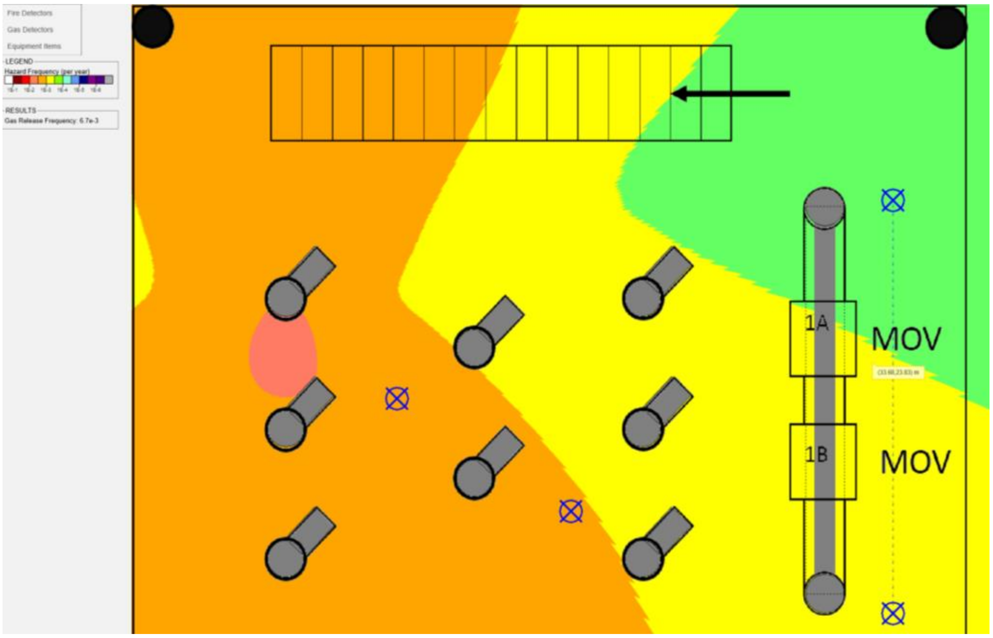
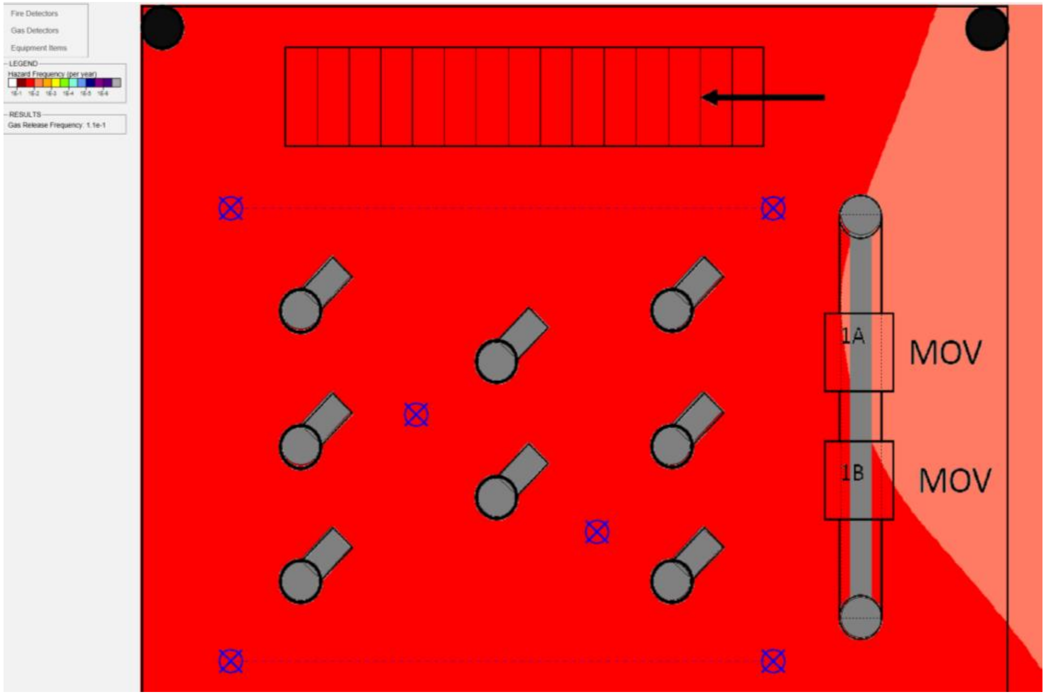


Figure 10 – Gas Release Scenarios (Actual Dimensions) Plotted on Plan Drawing 720 Release Directions – Wind Direction Weighted

Finally, before presenting the overall geographic risk profile, the release needs to be associated with all equipment items in the zone that can leak. The results in Figure 10 only represent the first well head. The same scenarios need to be added for the other well heads and pipeline and valve stations. When the scenarios for these devices are added, the result is updated as shown in Figure 11. In addition to the graphic results, it should also be noted that the overall release frequency for all of the release scenarios in the zone has been calculated as 1.1E-1 per year.



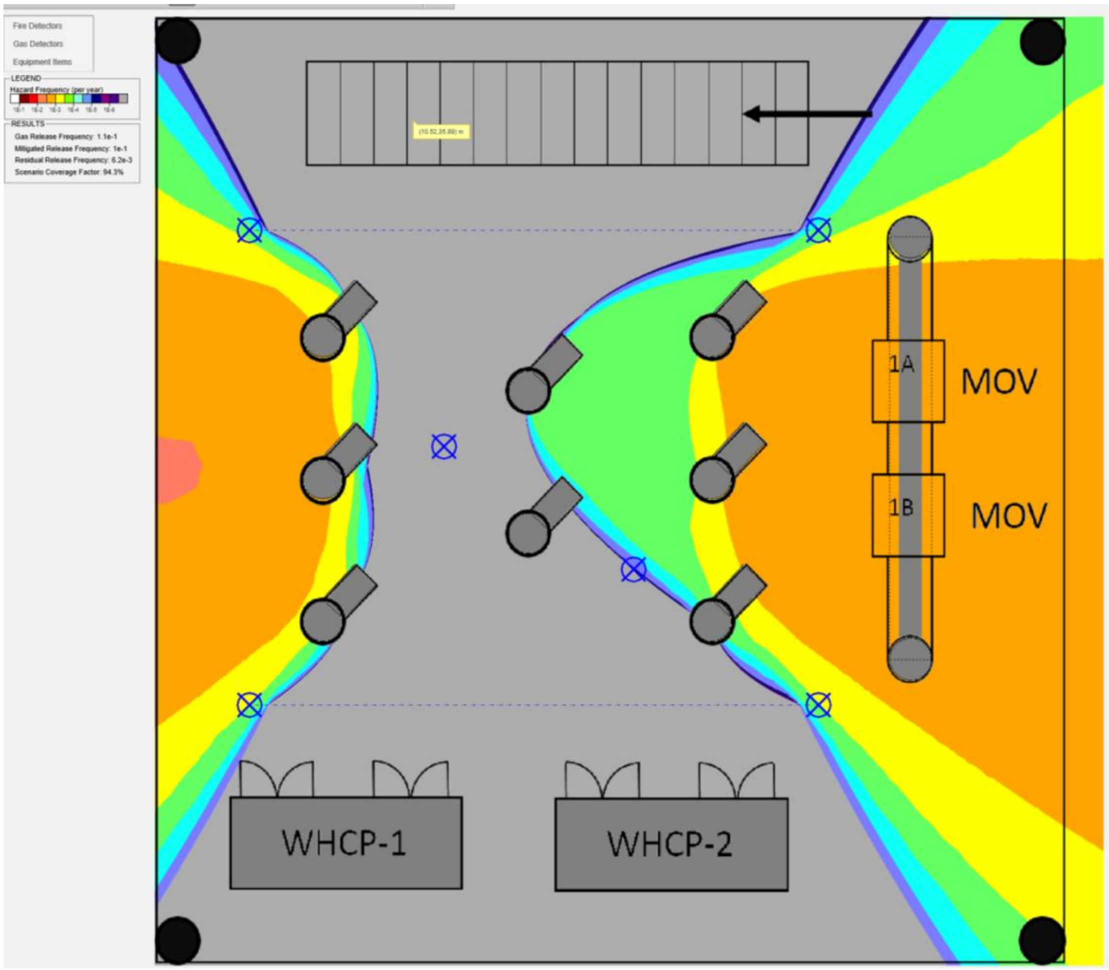
Gas Release Frequency: 1.1e-1

Figure 11 – Complete Geographic Risk Profile

Modeling Detection Equipment Effectiveness

Figure 11 is the overall geographic risk profile of the zone under study, but it does not take into consideration the effectiveness of the gas detection array, either in graphical representation or through numerical calculation. Addressing the effectiveness of gas detection for this zone is a matter of going analyzing the gas cloud generated by each of the scenarios (720 per equipment item), and determine if a detector is located within the gas cloud – for point source detectors, or if a sufficient amount of the gas cloud crosses the beam of an open path detector. As each gas cloud is analyzed, if it is determined that the gas cloud will be detected, its frequency is accumulated in the summation of all detected scenarios, and its presence is not drawn into the residual risk profile.

Figure 12 is the final geographic risk profile that represents the frequency of gas cloud presence only of those gas clouds that will not be detected by the modeled gas detection array. This type of figure is referred to as a Residual Risk Profile. In addition to the graphical representation of the residual risk, numerical figures are presented for overall release frequency, detected release frequency, residual (undetected) release frequency and coverage. In this case, the coverage achieved was 94.3% which exceeded the selected coverage target of 90%, demonstrating that the existing gas detection array of the facility is sufficient.



Gas Release Frequency: 1.1e-1
Mitigated Release Frequency: 1e-1
Residual Release Frequency: 6.2e-3
Scenario Coverage Factor: 94.3%

Figure 12 – Complete Residual Risk Profile After Consideration of Detector Coverage

Conclusion

At the same time that the use of quantitative risk analysis tools for the placement of gas detectors, a process referred to as gas detection mapping, is growing in acceptance and use, the tools and techniques used to perform these tasks are also rapidly advancing. The earliest methods for gas detection mapping that rely only the geometry are rapidly being obsoleted by techniques that consider the source location, size, and frequency of the gas leaks that are to be detected. Geographic coverage (i.e., the geometry only technique) is being replaced with scenario coverage. Luckily, the ISA 84 committee envisaged and defined this more advanced technique even before it came into widespread use.

Scenario coverage begins with dispersion modeling to determine the extents of a gas cloud that can be detected. Currently, the state of the art is use of Gaussian dispersion models, but the technique can employ computational fluid dynamics, which will become more prevalent as algorithms become more efficient and computing power increases. After modelling the extents of the gas clouds at the elevation of detection are plotted on a plan view of the area under study, summing up the frequencies of the overlapping clouds, resulting in a graphical representation of risk. Finally, the effectiveness of the gas detector array is assessed by determining, for each gas cloud, which ones intersect with gas detection equipment. Then a graphical coverage map of residual risk can be created, along with a calculation of the frequencies of the detected gas clouds divided by the total frequency of all releases, the scenario coverage. This coverage is then compared against the target to determine whether or not the gas detection array is sufficient.