The Use of Overpressure Exceedance Curves in Building Siting

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Compliance with the American Petroleum Institute (API) Recommended Practice (RP) 752 has become an industry standard. Design and layout of new facilities can incorporate most of the principles and spacing requirements presented in API RP 752 with a basic consequence modeling study. Yet many existing facilities are finding that a basic consequence modeling study indicates major problems for onsite buildings when evaluating vapor cloud explosion impacts. The worst-case explosion scenarios, and often the “more likely” scenarios, typically show unacceptable overpressure impacts at buildings within or near hydrocarbon processing units. API RP 752 does allow the analyst to perform a risk-based analysis to evaluate the acceptability of building impacts. One of the most useful forms of a risk-based study is the generation of overpressure exceedance curves. These measures of potential impact to a building incorporate a wide range of potential explosion scenarios, and the probability of each of those events. This paper will explore the construction of overpressure exceedance curves for a typical hydrocarbon processing facility, and will highlight some of the benefits, as well as some of the potential problems, of their application.

INTRODUCTION

When performing the design and layout tasks for a new or proposed onshore hazardous materials facility, application of American Petroleum Institute (API) Recommended Practice (RP) 752 provides a means to locate occupied buildings at safe distances from potential fire, toxic, and explosion overpressure events. When coupled with the layout process, the use of RP 752 can provide valuable insight into providing either safe locations for personnel or protective structures for vulnerable work areas. This advantage available to facilities in the design stage is obviously not available to older, existing ones. When RP 752 is applied to older facilities, the results for many occupied buildings indicate unacceptable consequences. Oftentimes, the potential fire impacts on a building and the potential toxic vapor cloud impacts on building occupants are understood by the facility’s operator, and can be addressed through emergency response plans and personnel protective equipment. It is the potential vapor cloud explosion impacts that are of concern in petrochemical facilities, and those hazards may not be fully defined or understood. It is these potential explosion impacts that are the focus of this paper.

The standard method for evaluating vapor cloud explosions is to use a blast-curve correlation model. These are the “simple” models such as Baker-Strehlow-Tang (BST), congestion assessment method (CAM), and TNO multi-energy, among others. While these models are
relatively easy to use, they are not easy to use correctly. Modeling explosion scenarios with these models requires a proper description of the explosion source. Parameters such as the fuel reactivity, degrees of confinement or congestion, and volume occupied by the flammable vapor cloud are all important in evaluating each unique explosion scenario.

Results from blast curve models provide overpressure versus distance from the center of the explosion. This data is used to define the peak side-on overpressure that a building may experience. While impulse is also calculated (as a function of distance from the center of the explosion) by these models, overpressure is the primary measure of impact used to evaluate building damage. Results from these models are typically considered conservative, assuming that the correct modeling parameters were applied.

More advanced models such as computational fluid dynamics (CFD), can also be used to predict overpressure impacts. But because these models require considerably more resources to set up and run even one calculation, they are typically only used for evaluating specific scenarios. CFD approaches may be useful for offshore facilities where local geometries can cause significant variations in the near-field results. These models are also applied to locations where blast wave directionality, reflections, or channeling are important, or for very odd geometries in the explosion source area.

The explosion modeling methodology employed in the example in this paper is the Quest model for estimating flame speeds (QMEFS) [1]. This model is based on the BST model, but allows the user to specify the defining parameters in more detail. This avoids the step changes inherent in the typical low/medium/high categories defined by the BST model and gives the analyst more flexibility in describing an explosion scenario.

**RISK-BASED EXPLOSION ANALYSIS**

In the case where a consequence analysis shows the potential overpressure impacts to a particular building to be unacceptable, an analyst can turn to several different risk-based methods for a more complete assessment. This assumes that care has been taken to verify the applicability of the explosion modeling scenarios that are the root of the concern. The most common risk-based options include:

- Risk ranking (risk matrix approach)
- Qualitative risk assessment
- Quantitative analysis
  - Overpressure probability contours
  - Overpressure exceedance curves

In a risk ranking system, explosion events are evaluated based on their perceived likelihood. Assuming that this method is based upon previous explosion modeling, it represents a semi-quantitative approach. This method provides the analyst with a risk-based scale on which multiple accident (and impact) scenarios can be judged. Scenarios with moderate to high risk can be assigned risk reduction or mitigation measures. Low risk scenarios (those that have
minimal consequences or those that have very low likelihoods) can often be discounted and not considered in further evaluation.

A qualitative risk assessment is similar to a risk ranking system in that it involves a semi-quantitative assessment. The most common way to implement this approach is to select the maximum flammable material release magnitude on which to base the explosion calculations (e.g., a release from a 2-inch diameter hole). This serves to (potentially) limit the extent of the explosion impact, and creates a qualitative cut-off for the maximum “credible” event.

If semi-quantitative methods are not helpful or produce results deemed unacceptable, the analysis can proceed to a fully quantitative approach. This process uses quantitative methods to describe the hazards (explosion impacts) and quantitative methods to describe the probability of each event. Probabilities are developed using tools such as failure rate databases, ignition models, and probabilistic weather data. Quantitative approaches for determining occupied building explosion impacts follow the methodology of a quantitative risk analysis (QRA), but cannot be referred to as a measure of risk, since they do not fully describe the total risk to a building. The output of a quantitative explosion overpressure analysis is typically in the form of one of two approaches: overpressure probability contours (similar to risk contours) or overpressure exceedance curves. Probability contours typically can only show the spatial location of the probability of being exposed to a specified overpressure value. While this has some value, especially if there is a target threshold value for one particular building, the analyst often needs more information.

The generation of overpressure exceedance curves (OECs) provides a substantial amount of information for specific locations that may be affected by explosion events. OECs represent a cumulative summary of the overpressure and probability of a full range of events that could affect a building. The OEC technique has been applied in facility or building siting studies worldwide [2], and is accepted as a viable means of making decisions concerning the suitability of buildings in and near flammable materials facilities, for compliance with API RP 752.

CONSTRUCTION OF OVERPRESSURE EXCEEDANCE CURVES

To generate OECs, a quantitative analysis is required. Adhering to the methodology used in a QRA, the following steps are completed:

- Accident scenario selection
  - Multiple release locations
  - Multiple release sizes
  - Defined set of potential explosion sites (PESs)
- Dispersion analysis
  - Multiple atmospheric stabilities
  - Multiple wind speeds
  - Multiple wind directions
- Explosion modeling
  - Comparison of flammable cloud volume to PES volume
o Calculation of source strength (energy)
o Overpressure calculation
• Probability analysis
  o Release event frequencies based on equipment failure rates
  o Ignition probabilities
  o Weather condition probabilities
• Combination of consequences and probabilities to generate OECs

This methodology is consistent with that published by CCPS [3] for chemical process QRAs. It begins with accident scenario selection, and in the context of vapor cloud explosions, must consider all potential release sources and each potential explosion site (PES). Because most flammable materials do not produce damaging overpressures when ignited in open areas [4], PESs must be defined in regions of confinement or congestion. Each PES is assigned several parameters that are used in the explosion model when calculating the strength of a potential explosion event.

Release events are selected to include a wide range of potential flammable vapor clouds, from all possible release locations. It is important to remember that a PES can be filled with flammable gas from many different sources, including those evolving in adjacent process units. Multiple releases (i.e., hole sizes) are evaluated for each release location. This provides a probabilistic distribution for the release magnitudes, where large events (e.g., pipe ruptures) have low probabilities, and small events (leaks) have higher ones.

Release and dispersion modeling is conducted for each potential flammable fluid release selected. The dispersion behavior of flammable vapors is calculated using the lower flammable limit (LFL) as the endpoint. For each release scenario, modeling is carried out for multiple weather conditions (atmospheric stability, wind speed, and wind direction). This allows a determination of which PESs a particular flammable cloud may reach. This can include the PES in which a release originates, and those that are some distance away. A flammable cloud may have sufficient mass to be involved in multiple PESs simultaneously. Provided that the PESs are separated by approximately 3-5 meters of open space, ignition of the flammable cloud will result in independent explosions from each PES [5].

The end product of these first two tasks is the creation of a list of all potential explosion events. Each event will be characterized by the fuel reactivity (specific to the released material), the volume involved (all or part of a PES), and the confinement/congestion parameters that describe the PES. In a typical petrochemical process plant, the list of explosion events will number in the tens (or sometimes hundreds) of thousands due to the many combinations of release events, hole sizes, weather conditions, and available PESs.

To construct an OEC, the list of potential explosion events is evaluated in reference to one specific location. The explosion model is run for each event, and the resulting overpressure at that point is calculated. For any one building, multiple points may need to be evaluated in order to account for shorter distances between the different sides of the building and the various PESs that exist around it.
The construction of an OEC involves creating a data set of predicted overpressure (for the specified location of concern) and probability pairs for the entire range of explosion events considered in the analysis. Each data point represents a unique explosion event and its specific probability of occurrence. The data set is then sorted by peak overpressure from high to low. An exceedance curve is generated by creating a cumulative sum of the probability values, beginning with the highest overpressure value. Thus, for any overpressure value represented by the exceedance curve the probability is the summation of the probability of that particular overpressure plus the probabilities of all events resulting in higher overpressures at the specified location. The exceedance curve then represents the probability of experiencing or exceeding a particular overpressure value, for the location specified.

EXAMPLE ANALYSIS

As an example, consider a small hydrocarbon processing facility with eight small equipment groups. The layout of this fictional facility is shown in Figure 1. In the figure, the facility’s four occupied buildings are labeled, and the PESs (regions of congestion due to process equipment) are shown as bold-outlined polygons. The PESs have various properties of confinement and congestion due to the obstacle density and restriction of flame expansion that is present in each particular area. All the flammable materials evaluated in this example can be classified as medium reactivity.

When the potential release scenarios are identified and evaluated with the PESs chosen for this facility, a set of potential explosion scenarios is developed. Using the methodology described above, overpressure exceedance curves can be generated for each of the four occupied buildings identified in Figure 1. The locations chosen for evaluation on the buildings were the closest faces to the process area. For the office building and security building, the eastern faces were evaluated; the northern faces of the control room and laboratory building were evaluated. In addition, the eastern face of the laboratory building was evaluated due to its proximity to one PES.

Figure 2 shows the exceedance curve results for the example facility. To use these curves, either the overpressure or probability axis may be used as a basis. For example, using the laboratory east face curve in Figure 2, an overpressure of 1.5 psi or greater is expected to occur with a probability of about $7 \times 10^{-4}$ per year. Likewise, the overpressure associated with a $1 \times 10^{-4}$ per year exposure is about 1.6 psi. As can be seen in Figure 2, for lower probabilities (less than about $4 \times 10^{-5}$ per year) the east face of the laboratory building is vulnerable to overpressures about 0.7 psi higher than the north face.
Figure 1
Example Facility Layout

Figure 2
Overpressure Exceedance Curves for the Buildings in the Example Facility
Once one or more overpressure exceedance curves have been developed for a specific location (typically an occupied building), the building’s risk must be assessed. This usually involves application of risk acceptability or risk tolerance criterion for the occupied building, and an evaluation of the building’s ability to withstand the calculated overpressure. A common approach to this portion of the analysis is to evaluate the overpressure at a building corresponding for a specific probability of exposure. For example, if a company sets $1.0 \times 10^{-4}$ probability of building occupants being injured as their tolerable risk criterion, then the overpressure corresponding to that probability is compared against the structural response of the building and its ability to withstand that loading. If that level of overpressure is sufficient to cause damage to the building which results in injuries to its occupants, then the probability of explosion impacts becomes intolerable and some form of risk mitigation is required. If the overpressure corresponding to the $1.0 \times 10^{-4}$ probability is lower than the damage threshold (i.e., a level of damage that is incapable of injuring building occupants), the risk is viewed as tolerable.

If a $1.0 \times 10^{-4}$ criterion is applied to the example presented above, then an overpressure less than 0.5 psi must meet the damage threshold for the office and security buildings in order for an intolerable condition to exist. For most buildings of “ordinary” construction, this magnitude of overpressure is incapable of causing significant building damage or injuring building occupants. Some windows may be broken and other minor damage may result, but it is unlikely that the building will suffer structural failure.

If a $1.0 \times 10^{-4}$ criterion is applied to the control and laboratory buildings, overpressures of about 1.6 to 1.7 psi are used for a tolerability analysis. If we assume that the buildings are steel-framed with metal siding, 1.7 psi is capable of causing significant damage, to the extent that building occupants may be injured. The buildings are not expected to collapse, but could experience significant deformation, and will likely experience loss of much of the exterior metal sheathing. This type of result indicates that the control and laboratory buildings either need to be moved to a more remote location or upgraded to withstand overpressures up to 1.7 psi in order to protect occupants from injury.

Because an OEC analysis provides a quantitative approach to determining potential explosion impacts, it is a significant improvement over a consequence-only approach. The coupling of probability to consequence (thus a risk-based approach) allows the large consequence events to be viewed in light of their low probability, and shows that the most probable events are the ones with small overpressure impacts. In many cases, it shows that the “worst-case” events (those producing the largest overpressures) that are traditionally used for siting purposes have a frequency low enough to fall below typical acceptability guidelines even when considered in a cumulative sense in the OEC.

One potential problem with the OEC approach is that it does not take into account the impulse on the building. Explosion modeling (e.g., the QMEFS model) does predict both overpressure and impulse for any given explosion. Yet the OEC methodology effectively de-couples the overpressure and impulse when it creates the cumulative probability curve in terms of
overpressure only. A similar curve can be generated for impulse (an impulse exceedance curve), but it cannot be used with or compared to the OEC in any meaningful way.

CONCLUDING REMARKS

The application of overpressure exceedance curves represents a significant improvement to basing building siting solely on consequence analysis results. An OEC analysis brings probability into the analysis in a quantitative fashion, accounting for weather conditions, differing release sizes, and the specific layout of the facility. Once a probability threshold is selected, use of the OEC information can be applied much like in a consequence-only evaluation. This type of analysis satisfies the requirements of API RP 752 for the explosion overpressure impact portion of an assessment. If there are no significant toxic or fire hazards for the building, this type of analysis can form the basis for building siting decisions. In addition, the construction of OECs can be used to site temporary or portable buildings. In this case, the generation of OECs constitutes a “detailed analysis” – one of the options for the evaluation required by API RP 753. Care must be taken to evaluate temporary or portable buildings with regard to their lighter construction, applying the guidance presented in RP 753.

REFERENCES


