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The magnitude of damage due to a vapor cloud explosion can be estimated in many ways, ranging from look-up tables to quantitative risk analysis. An explosion overpressure analysis is a routine part of compliance with the American Petroleum Institute (API) Recommended Practice (RP) 752 when evaluating occupied buildings in a facility that processes flammable or reactive materials. In many cases, a risk-based approach is useful because consequence modeling studies often indicate major problems for buildings at existing facilities. One of the most common risk-based methods, overpressure exceedance, incorporates a wide range of potential explosion scenarios coupled with the probability of each event to develop the probability of exceeding a given overpressure at specific locations. But this and other methods that only use overpressure may not represent an accurate building response. By combining the risk-based methodology of the exceedance analysis with pressure and impulse data in the form of pressure-impulse (P-I) curves, a better measure of building damage can be generated. P-I curves for blast loading determination have been in use for decades, and allow the user to determine levels of damage based on a predicted overpressure and its corresponding impulse. Curves have been published for entire buildings, individual structural members, window breakage, and even consequences to humans. This paper will explore application of P-I curves for building damage, and will highlight some of the benefits, as well as some of the potential problems, of using P-I curves.

INTRODUCTION

Application of American Petroleum Institute (API) Recommended Practice (RP) 752 provides a means to locate occupied buildings at safe distances from potential fire, toxic release, and explosion overpressure events. The RP 752 method may indicate unacceptable consequences for many occupied buildings following some large (worst-case) events, even though they are unlikely. This is particularly true for potential vapor cloud explosion impacts in major petrochemical facilities. If a screening-level or simplified analysis shows unacceptable results for a building, API RP 752 does allow the analyst to perform a risk-based analysis to evaluate the acceptability of building impacts. One risk-based method is to apply overpressure exceedance curves. These measures of potential impact to a building incorporate a wide range of potential explosion scenarios, in addition to the probability of each of those events. This type of analysis has been discussed previously [1].

Because overpressure exceedance only takes into account peak side-on overpressure values, it does not fully describe the building response. The damage a building may sustain also depends on the impulse – a measure of the magnitude and duration of a blast wave. Impulse is expressed in units of overpressure and time, such as pounds per square inch times milliseconds, or psi-ms. For example, if a building experiences a 4 psi peak overpressure with a duration of 50 ms, the corresponding impulse may be on the order of 100 psi-ms. When both the overpressure and the impulse are accounted for in the analysis, a better estimate of the damage to a building, or the danger to the people working within that building, can be generated.

RISK-BASED EXPLOSION ANALYSIS

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. Blast curve models predict overpressure and impulse impacts as a function of distance from the center of the explosion. This data is used to define the peak side-on overpressure and the corresponding impulse that a building may experience for a given scenario. Results from these models are typically considered conservative, assuming that the correct modeling parameters were applied.

The explosion modeling methodology employed in the example presented in this paper is the Quest model for estimating flame speeds (QMEFS) [2]. 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.

In the case where a consequence analysis (with the models described above) shows the potential overpressure impacts to a particular building to be unacceptable, an analyst may employ 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 contours
    - Overpressure exceedance curves
    - Building damage curves

In a risk ranking, explosion events are evaluated based on their perceived likelihood, and combined with a limited number of consequence modeling results. A qualitative risk assessment typically defines a maximum "credible" event, such that the consequences and likelihood are directly linked to that event. Both methods can be made semi-quantitative but may not be helpful in producing results that are deemed reliable or acceptable.

To provide a more complete prediction of explosion impacts, the analysis can proceed to a fully quantitative approach. This process uses a much more expansive set of explosion scenarios, quantitative methods to describe the hazards (explosion impacts), and quantitative methods to describe the probability of each event. Event probabilities are developed using tools such as failure rate databases, ignition models, and local 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 full measure of risk, since they do not fully describe the total risk to building occupants(potential toxic and fire impacts are not included).

The output of a quantitative explosion analysis is typically in one of two forms: overpressure contours, which can only show the spatial location of the annual probability of being exposed to a specified overpressure value (similar to risk contours) or overpressure exceedance curves. These methods only demonstrate the overpressure of vapor cloud explosions, ignoring the impulse altogether. While overpressure-only methods may provide a useful prediction, the effect of impulse on building damage can be significant, and can be useful in understanding the effects of explosions.

CONSTRUCTION OF BUILDING DAMAGE CURVES

To incorporate impulse into an analysis, a QRA methodology is first applied. That methodology follows these steps:

- 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
    - Calculation of source strength (energy)
    - Overpressure and impulse calculation
- Probability analysis
    - Release event frequencies based on equipment failure rates
    - Ignition probabilities
    - Weather condition probabilities
- Combination of consequences and probabilities for use in risk measures

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. 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.

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 PES(s).

When each of the defined explosion events is modeled (using QMEFS), overpressure and impulse information are generated. Using the explosion location and a building location, the overpressure and impulse experienced by that building are determined. With this information, overpressure exceedance curves (OECs) can be generated. To incorporate impulse in building damage estimates, one extra step is required. Each overpressure and impulse data point is applied to a set of P-I curves appropriate for that building design to determine the probability of building damage. Once this value is calculated, a probability of building damage (PBD) curve can be created. A PBD curve is constructed in the same way as an OEC:

- Data are sorted based on the level of building damage (0%-100%).
- Beginning with the highest value of building damage, a cumulative sum of probability is generated, moving from high to low values of building damage.
- A plot is constructed which shows level of building damage versus cumulative probability.

Where an OEC represents a cumulative summary of the overpressure and probability of a full range of events that could affect a building, the PBD represents a cumulative summary of building damage for that range of events. Both methods can help to identify which buildings need further analysis or mitigation measures. If overpressures are relatively high for a particular building, the construction of a PBD might better describe how explosions may affect the building, due to the incorporation of impulse information.

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, dashed-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 characterized 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 and probability of building damage 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.

BUILDING DAMAGE ESTIMATES

When the set of potential explosion scenarios has been developed, the analysis then shifts to a determination of the damage done to the buildings for each explosion event. Both OEC and PBD curves were generated in the evaluation of blast wave damage to buildings in this example. Figure 2 shows the exceedance curve results for the example facility. This curve shows the cumulative probability of experiencing specific overpressures at each building. The maximum overpressures at the office and security buildings are quite low, and it is unlikely any of the release scenarios will cause significant damage to these buildings.

The overpressure-only method provides a simple means of evaluation, but does not fully represent the response of most buildings. The next step in blast wave evaluation is to also include the impulse corresponding to each incident overpressure. Using P-I curves that have been developed for specific building construction types (or specific buildings), a relationship between pressure and impulse pairs and a range of expected damage levels is established. For this work, P-I curves from a U.S. Department of Defense (DOD) report [5] were used. The DOD report describes the methodology and algorithms implemented in their SAFER software, which is used to perform risk-based explosion analyses.

The P-I curves presented in the DOD report are representative of several different types of structures including vehicles, trailers, and buildings constructed of wood, metal, masonry, and reinforced concrete. Each structure or type of structure has a unique set of P-I curves. When P-I curves for a specific building are not available, it is important to choose a set of P-I curves that best represents the target building, accounting for building codes and specific design features. The set of P-I curves chosen for this analysis were those for a small un-reinforced brick building. Of the P-I curves presented by the DOD report, these were selected as the most representative of the buildings in the example problem. For this example, all buildings were assumed to be of the same construction. A subset of the DOD P-I curves for this building type are shown in Figure 3.

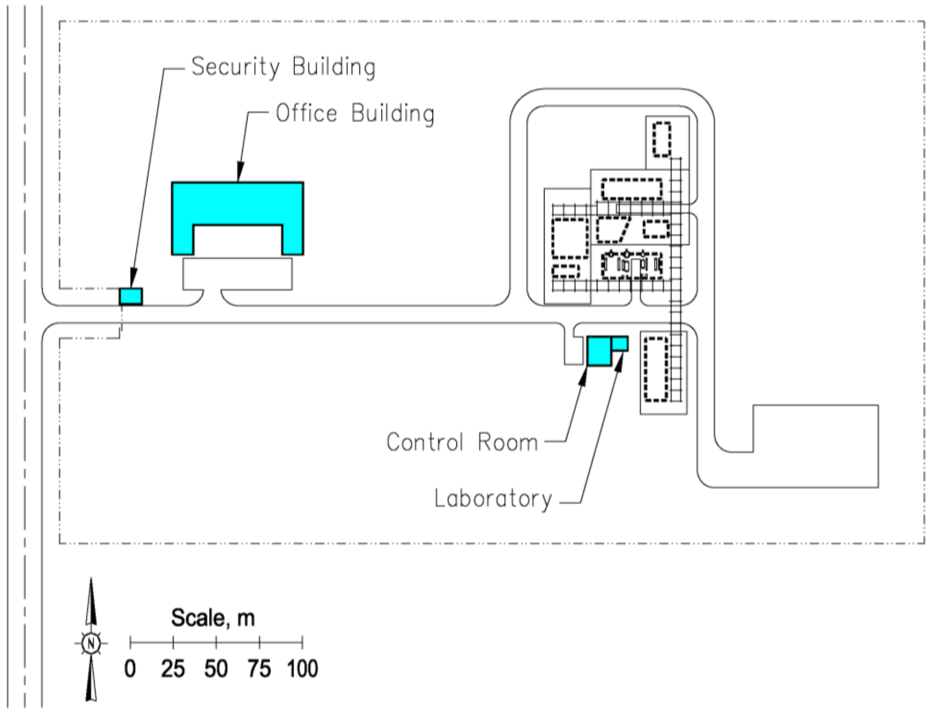

Figure 1
Example Facility Layout

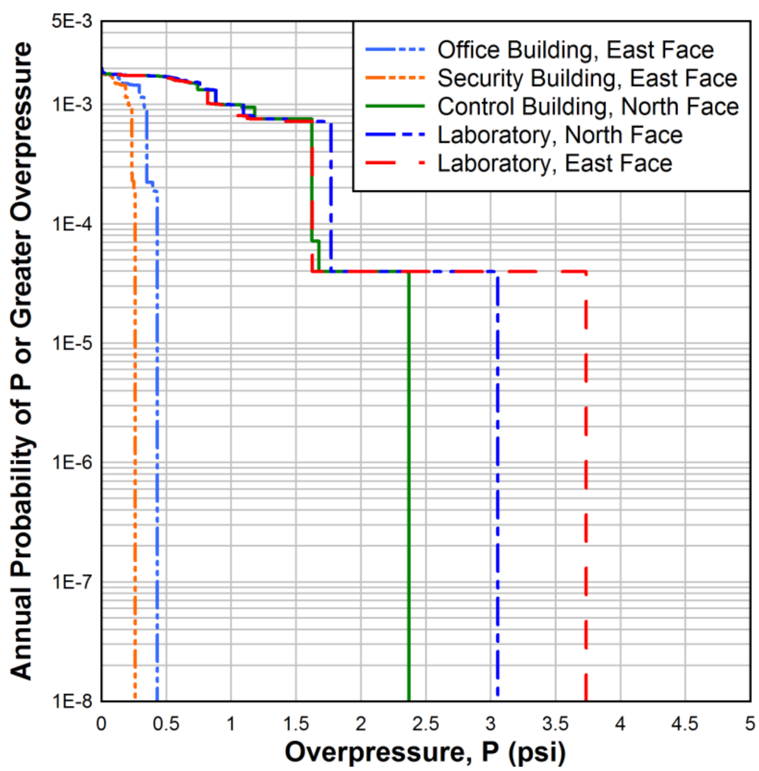

Figure 2
Overpressure Exceedance Curves for the Buildings in the Example Facility

The P-I curves represent percent damage levels (0.1% to 100%) that a building may sustain in an explosion. It is important to note that building damage is not a measure of building collapse, but rather, the level of damage that necessitates repair or replacement of the building. 100% damage is the point where the building is no longer inhabitable, is considered a 100% financial loss, or a functional loss. This does not mean that the building has completely collapsed or is grossly displaced (partial collapse is possible). 100% damage simply represents the point where the building is economically irreparable.

Also shown in Figure 3 are the P-I pairs predicted in this analysis. Each data point on the plot represents the potential impacts of one explosion event on a wall of one building; the entire data set contains approximately 25 thousand pressure-impulse pairs per building. Based on the selected P-I curves in the figure, the impacts from most of the explosion events are well below the 0.1% damage level (no/negligible damage). As suggested in the OECs in Figure 2, the P-I pairs for the office and security buildings are entirely under the 0.1% P-I curve and thus, the release scenarios will not have a measurable impact on the office and security buildings. These buildings are removed from further analysis.

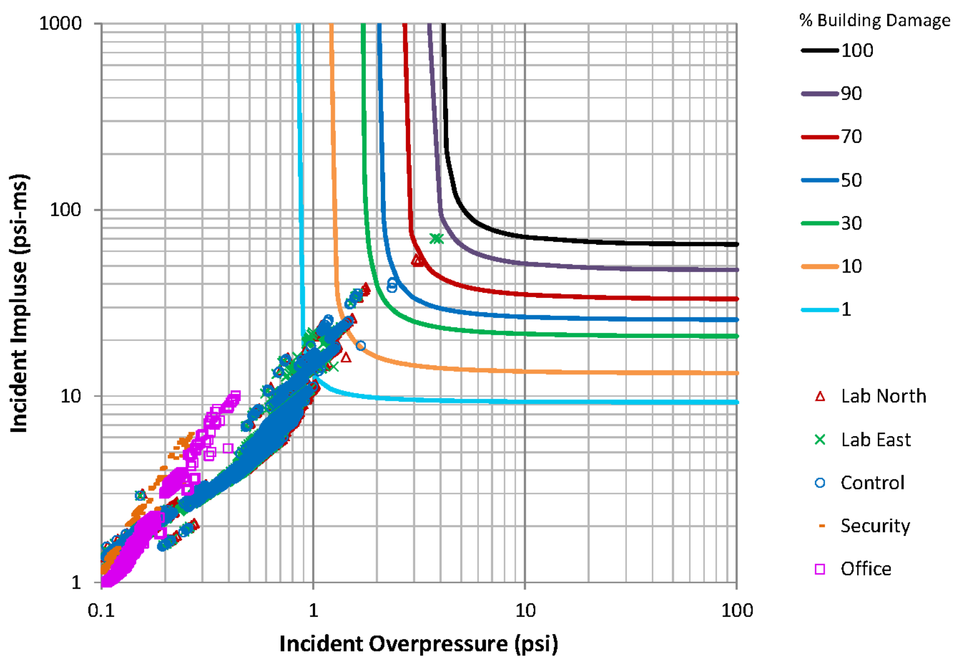

Figure 3
Pressure-Impulse Curves for a Small Un-Reinforced Brick Building with Overpressure-Impulse Impacts for Each Building

The predicted damage for the remaining two buildings extends to slightly more than 80% building damage at the upper end. The P-I data was applied to the P-I curves to qualitatively determine the percent building damage for each explosion event. Because each P-I pair has a corresponding probability, a new data set of event probability versus building damage, or the PBD curve can be made. The result of performing a cumulative sum on this data is shown in Figure 4, for the lab and control buildings.

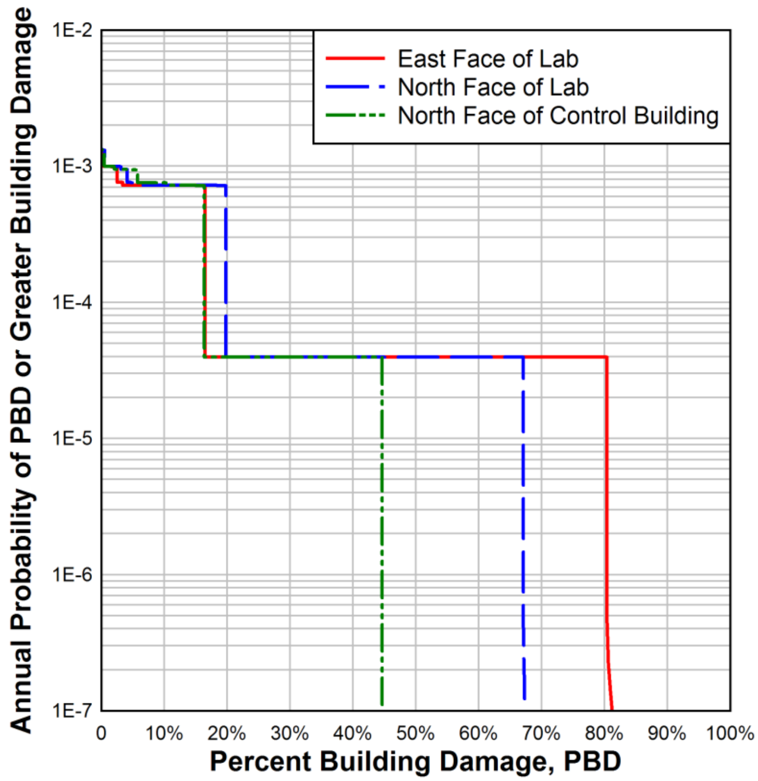

Figure 4
Probability of Building Damage for Lab and Control Buildings

APPLICATION OF BUILDING DAMAGE CURVES

Once a PBD curve has been developed for an occupied building, that building's risk can be assessed. This often involves application of a risk acceptability or risk tolerance criterion for the occupied building. Risk acceptability or tolerance criteria are usually determined by the facility owner. A common approach to this portion of the analysis is to evaluate the potential damage to a building in light of the predicted probability of occurrence. For example, if a company sets a 1.0×10^{-4} probability of building occupants being fatally affected as their tolerable risk criterion, then the building damage corresponding to that probability is compared against a selected building damage threshold. This requires an understanding of what levels of damage are capable of fatally affecting building occupants. If the probability of damaging a building and subsequently killing occupants is below the criterion, the risk due to explosions is viewed as tolerable.

For the example presented in this paper, if the assumption is made (or an evaluation determines) that the control and lab buildings can sustain 30% damage and occupants will not be killed, the application of a 1.0 x 10^{-4} criterion shows an acceptable explosion risk. If, however, a 10% building damage threshold is shown (or assumed) to result in occupant fatalities, then the 1.0 x 10^{-4} criterion may result in an unacceptable risk. In this case, either the building's method of construction or its location relative to the process area may require review. Placing the building further away from potential explosion sites, or strengthening the building's construction would decrease the risk to personnel inside the building. For most existing buildings, relocation is not feasible so methods of strengthening the building should be considered in the case of unacceptable occupant risk.

Because a PBD analysis provides a quantitative approach to determining potential explosion impacts on facility buildings, it is a significant improvement over a consequence-only approach. In addition, because it incorporates impulse as well as overpressure into this analysis, it provides a more extensive representation of potential building impacts. The coupling of probability to predicted 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 those with small impacts. In many cases, it shows that the "worst-case" events (those producing the greatest overpressures, impulses, and building damage) that are traditionally used for siting purposes have a frequency low enough to fall below typical acceptability guidelines.

One potential problem with the PBD approach is the need to relate building damage to personnel fatality. This is important when determining risk to personnel who work in these buildings. The DOD report contains a relationship between building damage and probability of fatality, but shows that 100% building damage level results in a maximum probability of fatality of 0.175 for a small brick building. This appears to be low compared to other sources which relate peak incident side-on overpressure only to probability of fatality for different building types [6]. In addition, as with the selection of P-I curves for a building, the relationship between building damage and occupant fatality is potentially different for each building or building type. For example, an unreinforced masonry building which sustains 50% damage may have a higher probability of affecting occupants than does a steel-framed, steel siding building that sustains 50% damage. These issues warrant further analysis.

CONCLUDING REMARKS

The use of probability of building damage curves (PBD) can make building siting studies more useful. Using both impulse and overpressure in the analysis of building damage can present a more realistic assessment of the effects of accidental releases on occupied buildings. Adopting a quantitative analysis methodology allows the analyst to account for weather conditions, multiple release scenarios, differing release sizes, and the specific layout of the facility. 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. A quantitative approach can also demonstrate the low likelihood of the worst-case scenarios due to the incorporation of event frequencies, while the probability of building damage provides a better estimate of the vapor cloud explosion risk to a building than simple consequence-only methods.

It is important to note that the selection of P-I curves for use in this type of analysis should be based on the actual building being evaluated, or a set of curves that is sufficiently representative of the building in question. If uncertainties exist, the analysis should select curves for a weaker building (a conservative approach) consistent with the recommendations of API RP 752 [7].

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