The importance of testing in developing consequence and vulnerability models to support personnel risk calculations and to quantify potential risk mitigation

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Worldwide, industry standards and best practices require facility siting to be addressed for existing and new petrochemical facilities. Facility siting requirements vary by region and type of facility, but generally include the evaluation of fire, toxic, and explosion events; at a minimum, facility siting involves reviewing worst case credible events to establish maximum potential onsite impacts. However, in the past 10 years, the petrochemical industry has begun to transition from maximum consequence based facility siting to risk-based approaches that evaluate not only worst case credible hazards, but rather an extensive range of potential accidents from minor to worst case events, attaching the likelihood and predicted number of fatalities of each scenario assessed to produce results in terms of risk posed by facility operations.

To better understand consequences associated with potential hazards as well as the resulting vulnerability impacts, full-scale testing has become an integral part of process safety. As a response to incidents such as the 2005 BP Texas City explosion, testing has traditionally focused on understanding blast impacts on typical industry construction types such as wood trailers, blast resistant modules, pre-engineered structures, concrete buildings, etc. However more recently, risk assessments have resulted in testing the impacts of different types of hazards on both indoor and outdoor populations.

The goal of this paper is to present recent findings resulting from full-scale testing projects associated with not only advancements in explosion testing (blast resistant components, air/frame tents, etc.), but also current test findings linked with gas dispersions, thermal impact distances, heat rise in buildings, and toxic ingress. This paper will show how testing can refine modelling equations and methodologies as well as help the industry to better understand potential personnel vulnerability. Understanding associated hazard vulnerability is crucial to discerning both onsite and offsite risk, allowing for the quantification of risk associated with a range of impacts from high probability/low hazard to low probability/high accident scenarios.

With better understanding of occupant vulnerability associated with fire, toxic, and explosion events, the petrochemical industry now has additional resources at hand to quantify risk and risk reduction potential in order to assess “as low as reasonably practicable” (ALARP). This paper will also introduce an approach to address risk reduction potential for high risk buildings/outdoor areas, focusing on specific hazard types and calculated risks. This approach highlights the importance of understanding hazards and vulnerability as well as the impact investment has on overall risk values.

Keywords: Facility Siting, Quantitative Risk Assessment, Occupant Vulnerability, Risk Mitigation, Explosion, Thermal Radiation, Gas Dispersion

Introduction

Quantitative risk analysis (QRA) seems to first appear in the nuclear industry about 40 years ago, where it is commonly referred to as a probabilistic risk or safety assessment (PRA/PSA) (US NRC, 1975). Since then, the QRA approach has been expanded to applications in most large industrial systems, including the petrochemical industry. As with any new approach/technology, those impacted by the rollout tend to be sceptical when first exposed. This is typically compounded in situations where the data is reliant on simplified screening level models and probability data, especially if the results might have negative financial impacts or impose restrictive operational constraints. This poses a problem as for a QRA to be successfully applied to the decision-making process, those in charge must fully support the QRA process and have confidence in the analysis results and recommendations.

George E. Apostolakis states in his 2004 paper *How Useful Is Quantitative Risk Assessment?* that acceptance of QRAs in new industries follows a three phase pattern of progress (Apostolakis, 2004). Phase 1 begins the process with the safety community of that industry highly sceptical, which is followed by Phase 2 when engineers and decision makers become more familiar with the approach/technology and begin to pay attention to the knowledge available through QRA. Phase 3, which Apostolakis believes requires a culture change regarding safety management, is achieved when the safety community and decision makers begin to see the positives of QRA and successfully use it as a decision making tool. Apostolakis estimates the nuclear industry took approximately a quarter century to achieve Phase 3.

The petrochemical industry’s push for process safety initiatives first showed up in 1985 with The American Institute of Chemical Engineers (AIChE) creation of the Center for Chemical Process Safety (CCPS) following the chemical disasters in Mexico City, Mexico, and Bhopal, India (CCPS, 2007). Furthermore, in 2007 the CCPS published the *Guidelines for Risk-based Process Safety*, which builds upon the ideas published in AIChE’s 1989 book *Guidelines for Technical Management of Chemical Process Safety* and refined in AIChE’s 1992 book *Plant Guidelines for Technical Management of Chemical Process Safety* (CCPS, 2007). Assuming that the petrochemical industry follows a similar path as the nuclear industry and that Apostolakis’ conclusion that it took 25 years to transition from sceptics to believers, the petrochemical industry should now be transitioning into Phase 3 of the QRA acceptance process. This means that industry process safety personnel and decision makers should be approaching the point of comfort regarding the implementation of results from QRA studies.

The purpose of this paper is to discuss the role of full scale testing in reducing the scepticism toward QRA that is still prevalent within the petrochemical industry. Full scale testing provides validation points for industry safety personnel and decision makers while also providing necessary data points for improving predictive modelling codes. In addition, test data can be used to better predict occupant vulnerability values for predicted explosion, flash fire, jet/pool fire, and toxic gas impacts. With the improved understanding and visibility of occupant vulnerability for specified impacts achieved through testing, operating companies can more defensibly and accurately quantify safety benefits afforded by implementing risk mitigation strategies and justify expenditure of resources based on a fundamentally sound cost benefit basis.

Importance of Occupant Vulnerability in a QRA

When performing a QRA, one of the most important aspects of the risk assessment is the prediction of occupant vulnerability resulting from impacts of accident scenarios modelled. Occupant vulnerability is defined as the portion of an exposed population that could potentially suffer an injury or fatality if a postulated event were to occur, with the level of injury defined according to the technical basis of the vulnerability model being used (CCPS, 2007). Correctly predicting occupant vulnerability is essential to the accuracy of a QRA, but is a difficult factor to predict for different hazard types.

Occupant vulnerability predictions can be performed in several different ways. The first is correlations with actual data gathered during industry incident investigations; however, thankfully too few incidents happen in industry to have a good distribution of data for development of vulnerability models. Therefore, it is necessary to move to computer modelling and/or testing. Computer modelling, such as the MADYMO (MADYMO, 2014) code developed by TNO in the Netherlands, can predict human body response to a given impact. Figure 1 shows the human body kinematic response to impact by wood debris using MADYMO, which can then be correlated to standard injury levels using well-validated response criteria.

In addition to computer modelling, the problem of occupant vulnerability prediction can also be approached experimentally using sensory equipment and correlation models to determine human response to outside impacts (toxic gas, explosion, and fire). Figure 2 below shows how well-instrumented anthropomorphic test devices (ATDs) can be used to determine impact of debris produced by blast loads on typical structural systems. Tests such as that shown in Figure 2 can be run at various blast loads to develop data correlating injury level to blast load to determine the likelihood of fatality to a given event.

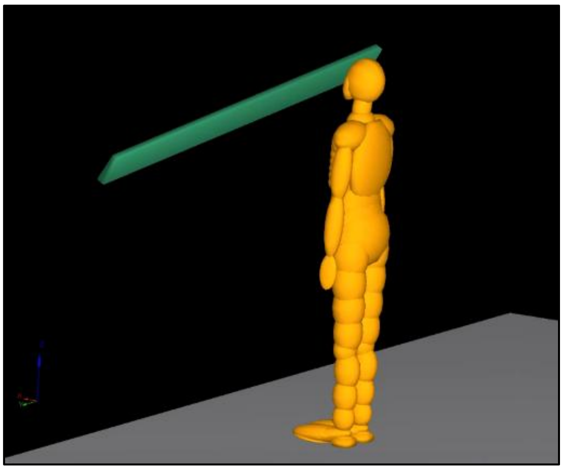

Figure 1: Human Body Impacted by Debris

Figure 2: Glass Breakage Vulnerability Analysis

Performing detailed computer modelling and experimental tests helps industry to better understand occupant vulnerability with regards to specific hazards and the benefit associated with potential mitigation strategies. However, vulnerability models should be ever evolving, becoming more accurate and representative of hazards as additional information is established. In a QRA, occupant vulnerability data should be applied in a consistent manner to allow comparison of risks across a facility or set of facilities. For scenarios where exposed populations are predicted to incur high risk, it may be necessary to do a detailed analysis (computational or experimental) to better understand occupant vulnerability.

Gas Dispersion (Flammable and Toxic) Hazards

Understanding gas dispersions is an essential step in performing an accurate QRA because flammable gas, toxic gas, and explosion impacts are dependent on the dispersion of gas and/or liquid. An accurate gas dispersion model that can reliably predict the geometry and concentration of a given release is essential in predicting hazardous impacts and subsequent occupant vulnerability for flammable gas, toxic gas, and explosion impacts. If gas dispersion is calculated inaccurately, the hazard impacts may be under or over predicted in the resulting risk assessment.

Gas Dispersion Modelling

There are many gas dispersion software models available that range in complexity from screening level integral models up to computational fluid dynamics (CFD) codes. The screening level software models such as ALOHOA, HGSYSTEMS, PHAST, SafeSite, etc. are relatively easy to use and are not time intensive; however, screening level models are less accurate than detailed CFD codes such as FLACS. Tests comparing integral models versus CFD show good agreement between the two approaches for open field releases, but geometrically complex systems such as offshore installations typically require CFD to obtain reasonable data (Fiorucci, 2008).

George E.P. Box, a British mathematician and professor of statistics at the University of Wisconsin, famously said, “All models are wrong, but some are useful” (Box, 2014). This is very true with regards to integral screening level dispersion models; they are easy and less time-consuming tools, but they are liable to some deficiencies and rely on a specific set of assumptions. However, with the transition into large scale testing capabilities, validation of existing models has become a viable way to benchmark the assumptions and simplifications utilised in existing screening level computer codes.

Gas Dispersion Testing

There are several large scale test facilities across the world, which are utilised by a variety of companies, governments, and consultants. These test facilities, most of which were originally constructed to analyse blast energy and building response, have also been utilised to run flammable gas dispersion testing in terms of flammable extents and dispersion cloud shape/size. The results of these tests can be used as validation (how well does the model represent actual physical phenomena) and verification (how well the model does what it claims to do) for screening level integral models. As George E.P. Box also said, “Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful” (Box, 2014).

Figure 3 and Figure 4 below are included to show an example of a validation test for a ½-inch propane release at steady state conditions. A dispersion test was run, with the flammable gas cloud extents averaged at steady state to produce an overall cloud boundary (Figure 3). This cloud boundary was then compared to the test data (Figure 4) to determine the accuracy with which the integral model predicts cloud formation. Figure 5 and Figure 6 then show the corresponding integral model prediction for the overhead view versus the actual predicted dispersion loud. Results of validation studies such as this one can be used to refine integral models to close the gap between predicted and actual results, allowing screening level studies to become more accurate and useful.

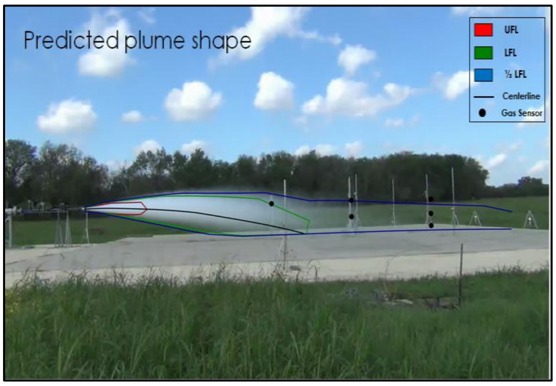

Figure 3: ½ inch Flammable Gas Dispersion, Actual Results

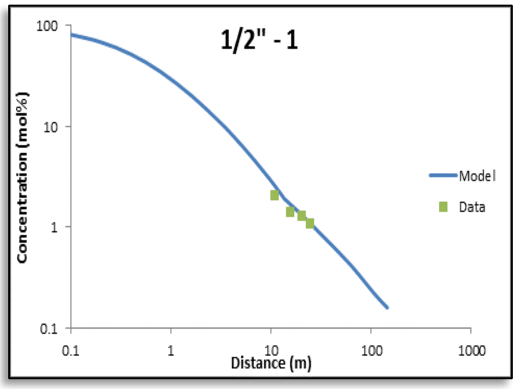

Figure 4: Comparison of Measured Values vs. Predicted Values

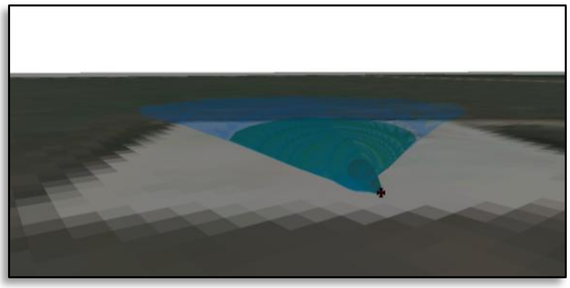

Figure 5: ½ inch Flammable Gas Dispersion. Model Predicted Dispersion

Figure 6: ½ inch Flammable Gas Dispersion. Actual Dispersion

Gas Dispersion Vulnerability

Depending on the material involved in the release, there are two types of potential human vulnerability impacts: flash fire exposure and toxic gas exposure. Flammable gas impacts (i.e. flash fire extents) in a QRA are well known; between upper flammable limit (UFL) and lower flammable limit (LFL), a cloud is expected to be at a flammable concentration where ignition is possible. However, what QRA studies sometimes fail to address is that personnel are still vulnerable in the range from LFL to ½ LFL. The 2nd edition of the CCPS book (Guidelines for VCE, Vessel Burst, BLEVEs and Flash Fires) states the following regarding this region of the flammable dispersion (CCPS, 2010):

> *The cloud border to the Lower Flammability Limit (LFL) defines a hazard zone for personnel safety; i.e. any person within the cloud LFL contour is likely to be in danger. Additionally, fuel-air clouds are often non-homogeneous in concentration and pockets of higher than average concentration can ignite outside the LFL border as estimated by a dispersion model using a prescribed averaging time. To account for such pockets and for uncertainties in modeling including plume averaging, a value of 0.5 LFL is typically considered as the border for an ignitable cloud. Lees (2005) attributes Feldbauer, et al. (1972) for first substituting 0.5 LFL for the LFL to account for the cloud area susceptible to ignition. Personnel outside these boundaries could also experience burns by radiation from a flash fire as the fire expands during combustion.*

Based on this description, vulnerability within the region of LFL to ½ LFL should be considered, although the chance of escape/survival is higher than within the flammable region. This argument is supported by experimental tests, which support the possibility of ignition outside of the LFL limits.

Vulnerability to toxic gas exposure is less understood than flammable gas (flash fire) exposure. Because of the obvious environmental impacts of releasing toxic gas to the atmosphere, large scale toxic dispersion experimental testing is more difficult. Therefore, toxic gas endpoints of interest can be obtained using published probit equations that are appropriate for each hazard. The endpoints of interest for a particular material can vary widely depending on the source used, which can cause confusion and a lack of understanding in which probit equation to use. Without the ability to do experimental testing, data to validate toxic probit equations will be hard to come by and may only be known in the unfortunate instances where an industry event occurs, an example of which is the Bhopal, India gas tragedy in 1984.

Explosion Hazards

Once the gas dispersion component of a QRA has been completed, the next essential part of a QRA is to review the explosion characteristic; i.e. what happens if a flammable cloud is ignited after dispersing over zones of congestion and confinement. Explosion hazards are probably the most widely studied hazards within industry, with the highest experimental focus. The reason for this is that most of the high consequence events that have happened in industry are a result of explosion events. These include the 1974 explosion at Flixborough that resulted in 28 deaths and 89 injuries, the 1984 San Juanico disaster in Mexico that resulted in 500-600 deaths and another 7,000 injuries due to burns, the 1989 Phillips Pasadena explosion that resulted in 23 deaths and 314 people injured, and notably the BP Texas City explosion in 2005 that resulted in 15 deaths and 170 injuries.

Explosion Modelling

A gas explosion is characterised by rapid combustion in which high temperature combustion products expand and affect their surrounds, potentially causing structural damage and direct human injury. In the petrochemical industry, the main focus is on vapour cloud explosions (VCEs). VCE energy and flame speed are a function of three factors: congestion level of the volume filled by the flammable cloud, confinement level of the volume filled by the flammable cloud, and the material fuel reactivity. As with gas dispersions, the models associated with modelling explosions range from simplified screening level models to detailed CFD codes. Screening level explosion models include the TNT Equivalency model, the TNO model, the Multi Energy model, the Baker-Strehlow-Tang (BST) model. The most popular CFD code for explosions is FLACS, which uses an empirical correlation model to do detailed calculations.

One of the most notable screening level models is the BST model, which was developed specifically to address estimations of blast effects from VCEs. The model was developed in 1994 by Baker, Tang, Scheier, and Silver (Baker, 1994), and later improved upon by Baker, Doolittle, Fitzgerald, and Tang (Baker, 1998). This methodology requires development of a model to represent potential explosion sites and a calculation of burning velocity for fuel mixtures (Lea, 2002). The strengths of this methodology are that it is easy to use, fast to perform an analysis, takes into account geometrical details, and can handle multi-ignition points. This model, as with other models widely used in industry screening level explosion calculations today, typically results in conservative results.

Explosion Testing

The BP Texas City event was a turning point for the petrochemical industry in terms of explosion safety. Following that event, API RP 752, *Management of Hazards Associated with Location of Process Plant Buildings*, and API RP 753, *Management of Hazards Associated with Location of Process Plant Portable Buildings*, were introduced by the American Petroleum Institute as recommended practices for siting occupied buildings onsite. These two recommended practices are some of the first that explicitly refer to using a risk-based approach to siting buildings.

One result of the implementation of API RP 752 and API RP 753 is that facility operators started using blast resistant modules (BRMs) within process units to house personnel instead of using modular buildings and wood trailers. This opened a whole new market within the petrochemical industry, which consisted of the design (see Figure 7), construction, and testing of BRMs (see Figure 8). However, BRMs are a relatively expensive way to house large numbers of people during construction or turnaround; as a result, owners/operators started using temporary tents to house large number of transient personnel. This move towards the use of tents in place of temporary buildings could be viewed as a sceptical response by industry to the introduction of practices that were deemed to be restricting operational flexibility. As industry trended towards tents to house large populations, concerns regarding their use led to the development of API RP 756 to address the siting for tents, which was developed based on experimental test data correlated to the BST model (Baker, 1998).

Figure 7: Example BRM - Hunter

Figure 8: BRM Explosion Test

To assist in the development of API RP 756, the API committee contracted full scale experimental testing on a range of tent arrangements from typical pole and frame tents to blast resistant airbeam shelters. Although API RP 756 addresses fire and toxic hazards, the primary focus is on explosion vulnerability calculations. Results of the testing show that because of the motion/velocity of fabric walls, there is a reduction in reflected pressures, the back surface pressure is reduced for net loading, and reduced load transfer is present to support structural elements (see Figure 9 for test image and Figure 10 for LS-DYNA CFD model run). Additionally, due to the soft sided nature, fabric tents are expected to have lower vulnerability than similar full construction buildings with similar building damage.

Figure 9: Experimental Tent Response to a Given Load

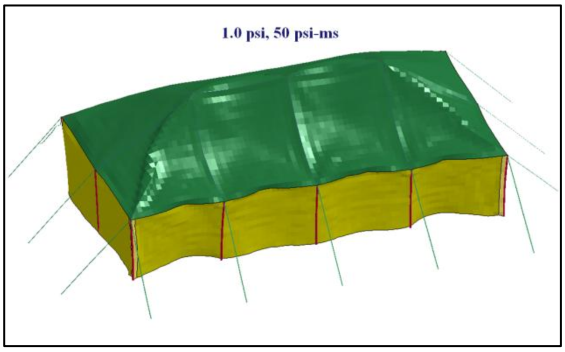

Figure 10: LS-DYNA Model for Tent Response to a Given Load

Explosion Vulnerability

Having been the focus of much research since the 1940s, the vulnerability of outdoor personnel to explosions is well established, with pressure limits for ear drum rupture, haemorrhage, and probability of death for overpressure impact. Review of previous accidents has shown that at pressure waves around 1 bar (15 psig), outdoor vulnerability approaches 100%. However, even at lower loads such as 0.2-0.35 bar (3-5 psig), a significant level of vulnerability is likely due to debris injuries to personnel in the immediate vicinity and potential injuries to personnel working in elevated positions. Therefore, it is important to look at a range of blast thresholds and corresponding vulnerability values associated with explosion impacts.

For building occupants, vulnerability is directly associated with a) the applied blast load (pressure and impulse), b) the building construction type, and c) the location of personnel within the building structure. Depending on the building type, a differing level of damage is expected as a result to a given blast load. Additionally, vulnerability is different depending on the structure type; i.e. if a building with a heavy concrete roof collapses, nearly 100% vulnerability is expected whereas if a light-construction building fails, a lower vulnerability is expected. Conversely, a building that sees virtually no building damage but has weak windows or doors may see high occupant vulnerability in the event of an incident.

Thermal Radiation Hazards

Typically, thermal radiation hazards are the least recognised hazard type in both consequence and risk assessments. The main reason for this is that industry focus has largely been placed on gas dispersion and explosion hazards, with money and research applied to these hazard types rather than thermal radiation. Typically, deaths are attributed to the main event – i.e. the initial flash fire or the vapour cloud explosion. However, industry experience indicates that most secondary escalation and injury impacts are related to thermal radiation, so understanding the mechanism and vulnerability behind thermal radiation is key to improving risk assessment predictions.

Thermal Radiation Modelling

Traditionally, thermal radiation modelling has been conducted using the Shell-Chamberlain model. The Chamberlain model is based on the effective diameter of the source as well as a range of other factors, but was correlated to vertical flare releases only and does not accurately represent horizontal jet fire modelling with buoyancy effects (Chamberlain, 1987). Therefore, industry is trending towards using the Johnson Model to analyse the effects of horizontal jet fire releases (Johnson, 2004). The Johnson model, which takes into account the influences of the jet momentum flux, buoyancy forces, and wind momentum flux allows a more realistic representation of thermal radiation impacts. Figure 11 below shows the horizontal lift-off expected from horizontal jet buoyancy effects, which are also highlighted in Figure 12 for a Fire Dynamic Simulator (FDS) CFD analysis of thermal impacts on a building structure. Note that by recognising the effects of lift-off, credit can be taken for personnel being able to safely evacuate from the rear side of the building.

Figure 11: 1-inch Propane Jet Fire Test

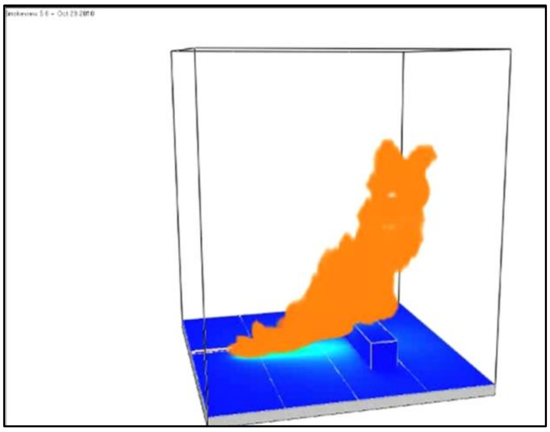

Figure 12: FDS Thermal Radiation for Jet Fire Impact on a Building

The correlations utilised in the Johnson model are based on full-scale experimental testing conducted by Shell, which were used to improve the existing Shell-Chamberlain model to account for the balance between the initial jet momentum flux and the buoyancy and wind momentum forces applied to the flame. Within industry, many QRAs still contain results developed using the Shell-Chamberlain flare model; it is therefore likely that thermal radiation impacts are over-predicted in these QRAs. Significant benefit could be obtained by revisiting these analyses to improve the accuracy of predicted jet/pool fire impacts.

Thermal Radiation Testing

Most of the large-scale testing facilities mentioned in the Gas Dispersion section are also utilised for thermal radiation testing. Test results, as expected, support the Johnson model's prediction that horizontal jet fires experience lift-off (see Figure 11), thus decreasing their hazardous impact distances. However, experimental results indicate that the Johnson model may also be conservative for most petrochemical materials. As a result, experimental testing is critical to understanding thermal effects for personnel both indoors and outdoors. Until a more accurate screening level model has been developed, QRA studies should use a conservative approach to thermal impacts.

Above in the explosion section, this paper has mentioned the use of BRMs within process units as a way to reduce overall explosion risk. Although this is a good idea to prevent explosion impacts, BRMs have an increased thermal radiation exposure risk when placed in process units; this becomes especially true for any modules that that have windows facing process units. Experimental testing has shown that for a ½-inch (12mm) propane release at 31 lb/min (14 kg/min), a typical window under jet fire impingement could catastrophically fail within a few seconds due to thermal stresses, exposing internal populations to full thermal impacts. Figure 13 and Figure 14 are images from one of these tests, with Figure 13 showing the impingement external to the BRM and Figure 14 showing the resulting effects inside the BRM a few seconds later. Once the window failed, experimental results indicate that escape would be unlikely.

Figure 13: External View of Jet Fire Impingement on BRM with Window

Figure 14: Internal View of Jet Fire Impingement on BRM with Window

Thermal Radiation Vulnerability

As with toxic gas vulnerability, thermal radiation occupant vulnerability is difficult to predict within the petrochemical industry. An article published for the Health and Safety Laboratory by S. Jagger suggests a thermal dose unit (TDU) of 2,000 $(kW/m2)^{4/3}$*s be used within the petrochemical industry as a threshold of lethality. This is equivalent to approximately 55 kW/m^2 for 10 seconds (Jagger, 2004). However, this is correlated to a 50% vulnerability; 100% vulnerability is listed at 3,500 $(kW/m2)^{4/3}$*s, or 100 kW/m^2 for 7-8 seconds. The 100% vulnerability value of 3,500 TDUs corresponds to the un-piloted ignition of clothing, although this does not account for flame resistant clothing.

These values appear to be reasonable for use within industry QRAs, especially considering items such as shielding, escape, etc. are often not explicitly accounted for, which adds safety margin to the analysis. Additionally, incident history indicates that for thermal radiation fatalities, incidents tend to be either an immediate incapacitation/fatality or survival with severe burns. Therefore, when conducting a QRA that produces results in terms of the likelihood of fatality, the argument can be made for using short duration, high thresholds for thermal radiation as high lethality endpoints.

Risk Mitigation

If a QRA has been adequately performed using experimentally verified models and justifiable occupancy vulnerability data, QRA results can be used to identify potential risk mitigation strategies and quantify their potential safety benefits. These risk mitigation strategies can involve a variety of options from reducing scenario impacts by limiting scenario inventory, installing sophisticated shutdown systems, installing specialised equipment less likely to fail, etc. to reducing building/outdoor area risks by upgrading building structures, relocating personnel, improving designs of shelter-in-place locations, etc. Each of these risk mitigation measures can be quantified and compared on a risk reduction versus cost benefit basis to be used as input on decisions regarding what changes, if any, should be implemented.

Gas Dispersion

A 2013 study by Anthony Sarrack outlines a methodology and approach to develop optimal risk-based toxic design. This analysis involved a case study on risk versus cost benefit design of a shelter-in-place (SIP) location (Sarrack, 2013). This study allows a range of factors such as supplied breathing air, air infiltration through HVAC systems, HVAC shutdown reliability, air ingress, and duration of release to be investigated to aid in determining ALARP. This type of analysis allows for a reasonable investment decision to be made based on risk reduction benefit. For example, if a consequence analysis shows 5,000 ppm of hydrogen sulphide at a building location, it may be deemed unfeasible to protect indoor personnel from that concentration. However, if a risk assessment reveals that there is only a single identified scenario that results in a hazard impact of that level but the rest of the hazards impact at around 200 ppm at the building location, it may be a cost effective risk reduction measure to design a building upgrade to withstand all but the highest level of impacts.

To determine the level of protection for building occupants within a SIP location, there are several tests that can aid in determining the SIP's effectiveness. Air tightness testing (Figure 15) can be utilised to determine effective air leakage rate from the outside (toxic environment) to the inside of the building. Once identified, these leak points (shown in Figure 16) can be reduced, thus resulting in a lower vulnerability level for personnel inside the building. By quantifying risk reduction afforded by the mitigation strategies, associated costs can be compared to determine if the actions are practical (if implementing the changes represent practical methods of reducing risk).

Figure 15: A Blower Door Test for Gas Ingression

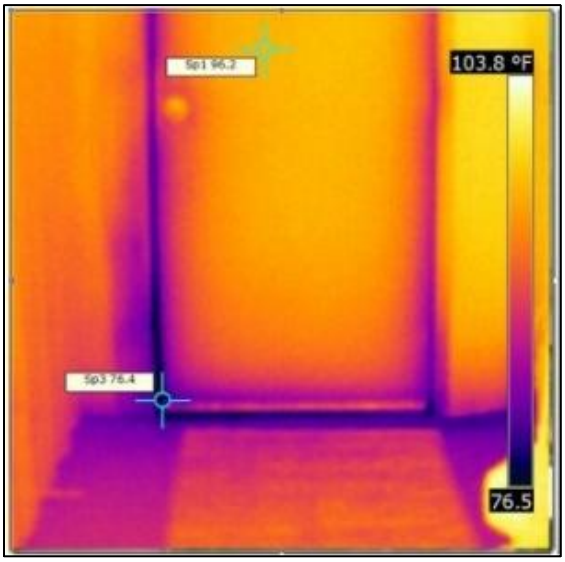

Figure 16: Infrared Imaging to Determine Leak Points in Building Structures

Explosion

In addition to building toxic risk mitigation, building explosion risk mitigation can be assessed in a risk reduction versus cost benefit analysis. This type of analysis involves evaluation of risk reduction that is achieved by implementing upgrades ranging from minor changes to an upgrade that allows the building to withstand maximum predicted blast loads and comparing those results to associated costs of each option (Dyer, 2013). With the change in industry expectations of "maximum credible event" moving from small hole sizes to full bore ruptures, it is often cost prohibitive to design all of the occupied buildings to be strong enough to protect occupants for the maximum predicted blast loads. However, if the vulnerability of scenarios is combined with frequency and likelihood to determine a risk-based building design, it is possible to design an upgrade to protect personnel in a manner that minimises risk to the extent reasonably practicable.

Figure 17 shows the beginnings of this approach, with blast loads predicted to cause significant vulnerability plotted on a P-i building response curve (Concept 1). The goal of the risk-based building upgrade is to design an upgrade that shifts the damage curves up, effectively eliminating additional scenarios as shown in Figure 18 (Concept 2) and Figure 19 (Concept 3). Finally, a risk reduction versus cost of upgrade analysis can be completed for multiple options, allowing the facility decision makers to determine the optimum design option (Figure 20). As this example shows, with an effectively completed detailed QRA, decision making for investing money to reduce risk can be a quantitative approach to determine potential building upgrades.

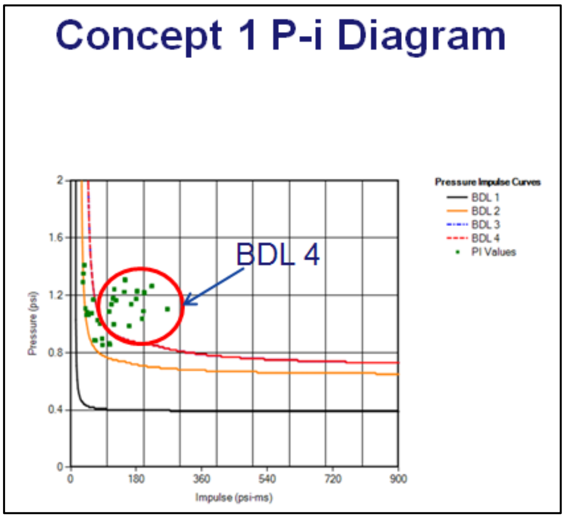

Figure 17: Concept 1 P-i Diagram (Base Case) with Blast Loads

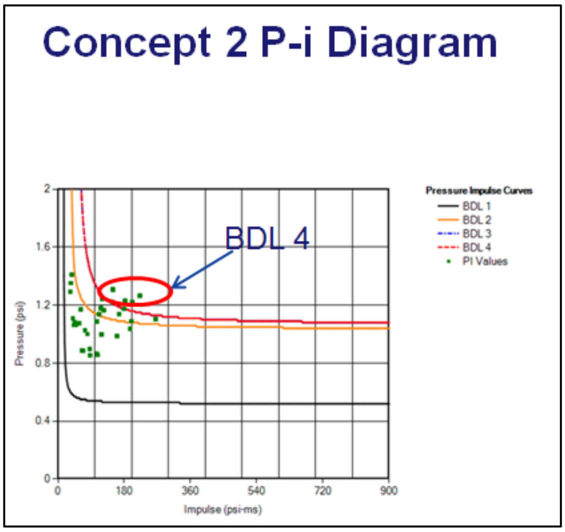

Figure 18: Concept 2 P-i Diagram (Upgrade Option) with Blast Loads

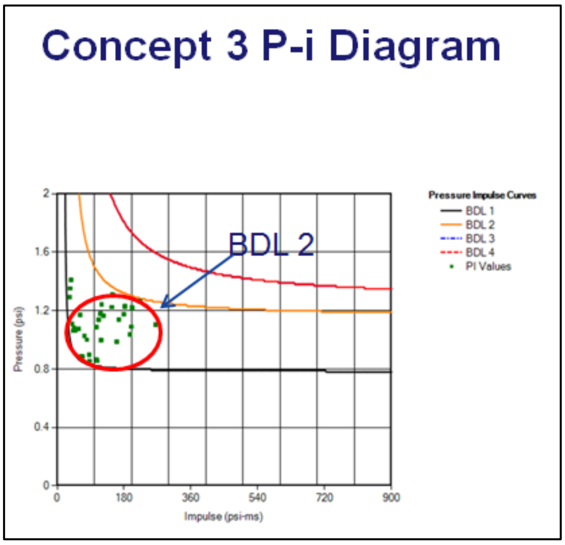

Figure 19: Concept 3 P-i Diagram (Upgrade Option) with Blast Loads

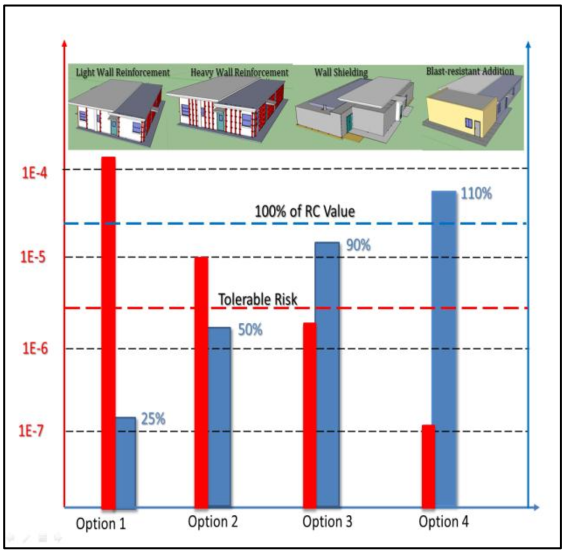

Figure 20: Relative Risk versus Cost for Different Design Concepts

Thermal Radiation

The most effective way to mitigate thermal risk is to either provide a barrier between thermal radiation resulting from jet/pool fires and high population areas or to designate fire shelter-in-place, which could further benefit from fire duration reduction and/or cooling provisionAs with toxic and explosion risk, thermal radiation risk can be assessed for practical mitigation on a cost/benefit basis. One common way to provide thermal mitigation is to retrofit the inside of walls with Rockwall, which creates a thermal insulation barrier that provides additional time for building occupants to either escape or shelter-in-place. Figure 21 shows an example of Rockwall installed inside walls.

Another effective example of a quantitative risk evaluation of thermal radiation exposure risk mitigation is to create an interconnecting corridor between high occupancy buildings to allow a building occupant to effectively move away from thermal hazards in a protected environment (see Figure 22). An effectively completed QRA can aid in decision making about risk reduction by quantifying potential risk reduction for thermal radiation mitigation items such as thermal barriers and effective insulation.

Figure 21: Rockwall Thermal Barrier on Wall Inside

Figure 22: Interconnecting Corridor Escape Route

Conclusion

In conclusion, testing via detailed CFD computer models and physical experiments have, and will continue to aid the petrochemical industry in improving the level of understanding of occupant vulnerability levels associated with a given impact. With a better understanding of occupant vulnerability associated with fire, toxic, and explosion events, industry process safety engineers and decision-makers may become more familiar and confident in results of a risk assessment. With improved confidence, the petrochemical industry will inevitably use QRA results to achieve the fundamentally sound objective of minimizing risk to the extent practical.

Additionally, having a better understanding of vulnerability from specific hazard types on particular buildings/populations can aid significantly in focusing resources on risk reduction efforts that are shown to quantifiably reduce risk. For example, if a QRA indicates that a building has high risk, the knee-jerk reaction may be to reduce or eliminate the population within that building which may then be dismissed as overly restrictive or expensive, resulting in nil risk reduction being achieved. However, if a detailed QRA has been completed with robust vulnerability models, it may indicate that, for example, the building is high risk due to toxic hydrogen sulphide exposure and cost effective risk reduction can be achieved by providing escape masks at £100 per person, to dramatically reduce the risk, and such cost effective risk mitigation would certainly be approved for implementation.

In summary, as stated previously, “All models are wrong, but some are useful”. It is important for decision makers to view QRA as a useful tool, a tool which can be utilised in decision making but should not be solely relied on. And as with all services and products, you get what you pay for; a good quality risk assessment may cost more than an off the shelf study, but the ability to aid in decision making is worth the price of the analysis.

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