USE OF CFD IN ONSHORE FACILITY EXPLOSION SITING STUDIES

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Significant releases (on the order of 50–100 kg/s) of hydrocarbons, whether as flashing liquid or dense gas, combined with moderate winds can, in less than one minute, generate very large flammable vapour clouds in an onshore facility. This potential has been realized in several accidents, both in the past (e.g., Flixborough, 1974), as well as more recently (e.g., Jaipur and San Juan). In onshore siting studies for facilities, whether driven by the API RP-752 or the Seveso-II/III directive, the typical approach is to use blast curve methods like the Multi-Energy method (MEM), the Congestion Assessment Method (CAM2) or the Baker-Strehlow-Tang (BST). When applying such methods, the typical approach is to only consider blast energy for the flammables inside one unit of the plant at a time (one congested area). This assumption may be acceptable if the spacing between units is sufficient and if there is no risk for deflagration-to-detonation-transition (DDT). However, recent accidents like the Buncefield explosion tell us that DDT cannot be easily ruled out and that, if that assumption is made, the typical blast-curve approach may be far from conservative. Another significant limitation of the blast-curve approach is that only few mitigation solutions can be evaluated. In this paper a CFD-based approach is presented which can be used to evaluate: i) the minimum (critical) gas cloud sizes to achieve DDT for different areas of an onshore facility; ii) the potential for generation of large gas cloud sizes from the dispersion of gaseous or liquid releases; and iii) if required, the effectiveness of various mitigation methods (e.g., soft barriers, confinement, deluge) to limit DDT-potential.

INTRODUCTION

Recently there have been several severe vapour cloud explosion accidents in onshore facilities around the world. At the end of 2009, two massive explosions occurred at tank farms in San Juan, Puerto Rico and Jaipur, India, with significant damage off-site. Both of these accidents had similarities to the Buncefield explosion of 2005 (BMIIB, 2009): in fact, in San Juan windows were reported broken 2–3 km away from the site, while 12 people lost their lives in the Jaipur explosion. Significant explosions have already occurred in 2010 as well, with multiple fatalities both at a petrochemical plant in Lanzhou, China, and the Tesoro Refinery, Anacortes, USA.

According to international standards ISO 13702 (1999) and ISO 19901-3 (2010) explosion risk studies on offshore oil and gas installations are required to be performed using validated consequence models that are able to take into account the effect of geometry confinement and congestion, and to evaluate mitigation options. As such, CFD tools are typically required by both of these standards. Safety requirements are generally functional (i.e., performance-based) rather than prescriptive. A risk study will therefore have to evaluate how the consequences of vapour cloud explosions may be kept below a certain threshold through both design and mitigation, to minimize the likelihood of collapse of structures or the failure of barriers.

Risk assessment studies for onshore facilities – at least in countries adopting API-RP 752 or national regulations based on the Seveso-II directive – instead tend to be simpler and driven by the “credible worst-case” approach. For a given plant, the largest units (congested areas) are identified, and are assumed to be filled with a stoichiometric flammable air/gas mixture. The explosion strength of the flammable cloud is assumed, based on subjective congestion/confinement considerations, and thereafter blast strength isopleths are calculated using a set of energy curves. Blast loads are then estimated for buildings intended for occupancy, and if these structures meet the explosion criteria, it satisfies the regulatory requirements. The blast loads, however, are growing with the flammable gas cloud volume assumed as “maximum-credible” (e.g., smaller gas clouds give smaller blast loads).

One implicit assumption in the worst-case approach is that only the flammable cloud inside a congested region of the plant will contribute to the blast energy. This assumption is based on the fact that deflagration flames, which are driven by turbulence, will decelerate once the flames leave the turbulence-generating congested region. Under these conditions, the use of “safe” separation distances between different congested units may thus limit the energy from each independent congested region contributing to the blast waves instead of grouping the regions and flammable clouds together.

There is however one major condition to the validity of this assumption: it is only valid in the deflagration regime. If the flames accelerate to high enough flame speeds (on the order of 1000 m/s), there is a potential risk for deflagration-to-detonation transition (DDT). Detonation flames propagate by shock-ignition, i.e., shock-waves ahead of the flame auto-ignite to generate new shock-waves. Detonation flames therefore need no turbulence to sustain, and will continue to propagate at high velocity as long as the gas concentration stays within the detonation limits and the gas cloud thickness is above ~13 detonation cell sizes (Desbordes, 1995). For gases like propane, this means that a 1.5 m thick flammable cloud may propagate a detonation, for methane the cloud needs to be more than 4 m thick. If a detonation occurs, it can often have a dramatic effect on the far field blast pressures. Not only can the blast energy contributing to the shockwaves be one or two orders of magnitude higher, but the blast "epicenter" may also get closer to the buildings of concern as flammable gas outside the "congested" areas may also contribute to the explosion severity. As such, the efficacy of safety gaps or regions outside the congested area may be nullified if DDT occurs.

The possibility of DDT or detonation is not cited in the API-RP 752 (2009) standard and it is rarely considered even when risk studies are performed according to the Seveso-II directive. But are detonations that unlikely?

The Buncefield Major Incident Investigation Board (BMIIB, 2009) concluded in their final report that a transition to detonation likely occurred during the Buncefield petroleum vapour explosion in 2005. The Buncefield site consisted mainly of large tanks and limited piping, and it was initially unclear how the flames may have accelerated to the point of a DDT. It was ultimately determined that the dense vegetation along the roads surrounding the site provided the congestion necessary to accelerate the flames into a likely detonation. Vegetation within and around the plant is also suspected to have provided the necessary congestion for flame accelerations in the San Juan and Jaipur explosions, although DDT may not have occurred in those accidents.

In recent years, accidental detonations are likely not unique to the Buncefield incident. In August 2008, the Sunrise Propane explosion occurred at an LPG facility in Toronto (Ontario Fire Marshal 2010 report, see Figure 1).

Figure 1. Three frames from a CCTV camera observing Sunrise Propane explosion from a distance. The very fast flame acceleration into the third picture (>1000 m/s), a very intense light, as well as videos captured from other angles seeing flames accelerate through vegetation were among the reasons for concluding a DDT was seen (Ontario Fire Marshal, 2010). Courtesy of Ontatio Fire Marshals Office.

The report indicated that during an LPG transfer from one truck to another, a flashing release of LPG at 10 kg/s took place for possibly up to 15–20 minutes, creating a large flammable propane cloud at the facility. FLACS CFD simulations used in the investigation demonstrated that the facility could be covered by propane gas in around 3 minutes. CCTV cameras located a distance from the facility recorded the explosion event, where one or two frames showed a very bright flame and unconfined (open area) flame speeds exceeding 1000 m/s. This event was concluded to likely be a DDT. Two possible explanations for the DDT were considered: it was caused by flames burning through thousands of stacked propane bottles, or the more likely explanation: video footage indicated that the flames accelerated through trees near the site.

With this in mind, we should consider the following questions:

1. Are DDTs such unlikely events in onshore petrochemical facilities that they should not be considered in risk studies?
2. If DDTs cannot be ruled out, can the current API-RP 752 and similar Seveso-II approaches be considered acceptable?

LIMITATIONS WITH THE CURRENT SIMPLIFIED APPROACH FOR ONSHORE RISK STUDIES?

API-RP 752 mentions two typical approaches for choosing the flammable gas cloud size to be used with blast curves: either to assume *a filled congested volume or a* ***smaller*** *dispersion calculated congested volume*.

The integral dispersion models, typically applied to predict the smaller dispersion calculated volume, are not capable of resolving geometry effects. For instance: wind speeds inside a process unit will be much lower than that measured outside the unit due to object congestion; and recirculation zones/wakes due to partial confinement may actually trap gas instead of allowing it to dissipate in the wind. These integral models often have limited capability for low wind scenarios, where gravity and structures can prevent dissipation of a flammable cloud, as was seen at Buncefield, or for release scenarios involving high momentum jet releases upwind, which are later blown back into the facility in a very uniform concentration, possibly near stoichiometric concentrations.

Detailed CFD simulation studies showed that the potential to generate very large vapour clouds is significant, when evaluating sizeable releases of pressurized dense flammable gases, and in particular, flashing releases. For similar hole-sizes and operating pressures, a flashing release of a liquid may typically give release rates 3–4 times higher (material dependent) than the equivalent release of a gas. The flashing release also has a different mixing mechanism than the gaseous release, resulting in lower velocities and velocity gradients. A consequence of the phase transition and energy balance, homogeneous vapour concentrations (at a low temperature) can occur at the distance where all the particles have evaporated. For large flashing releases, the reactive cloud size can easily be 100 times larger than the congested volumes considered for the blast study (see example in Figure 2). As the density is typically high for the flashing releases, there will be limited vertical mixing outside the jet region. Wind speeds above 2 m/s may however lift some of the dense cloud. One should also keep in mind that inventory sizes may be very large for tanks containing superheated liquids (e.g., LPG), and it may be much more difficult to design shut-down systems or pressure relief systems compared to a pressurized gas system. A flashing release may thus empty a significant part of a tank content without any significant reduction in release rate (other than that caused by reduced hydrostatic pressure as the tank empties).

Flashing liquid substances with high boiling points released at elevated temperatures (30–50°C above the boiling point) may evaporate more gradually and not fully evaporate, often resulting in a very homogeneous gas mixture with some additional liquid particles. If this homogeneous gas concentration is between LFL and stoichiometry, this may give a large, very uniform, highly explosive vapour cloud in the event of an ignition, as the passing flames may evaporate just enough flammable fog

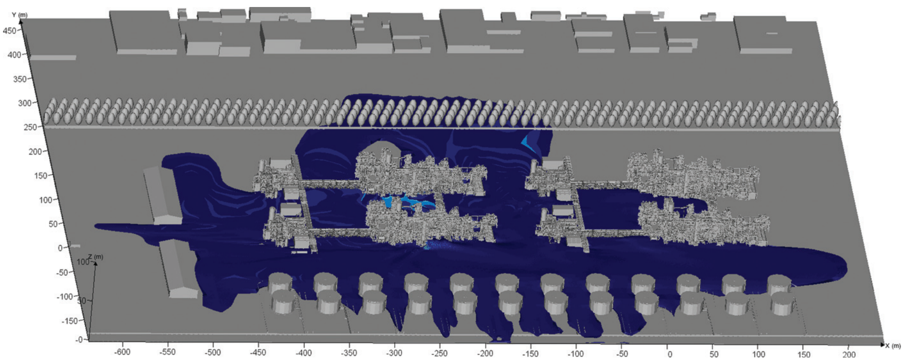

Figure 2. Flashing releases 50–100 kg/s can within minutes fill large facilities with highly reactive flammable mixtures. The illustration shows flammable cloud predicted with FLACS from a 4″ LPG release (200 kg/s) during low wind conditions (2 m/s), the leak direction is against the wind. Traditional consequence studies will tend to strongly underestimate the flammable gas plume, as the integral dispersion models ignore geometry and can not handle low wind scenarios.

for optimal (stoichiometric) combustion (Hansen, 2004). The Flixborough accident seems to have been such a scenario (HSE, 1975).

As a conclusion to this part, the typical approaches used in onshore facilities for determining flammable gas cloud sizes can underestimate the hazardous gas clouds by orders of magnitude. Also the use of integral models for dispersion studies in onshore facilities will be very inaccurate, one should be particularly concerned about flashing liquid releases when evaluating potential for the generation of large highly reactive gas clouds, due to potentially higher release rates and differences in the mixing mechanism.

The blast-curve approaches typically also have several weaknesses, including limited ability to predict the actual explosion source strength or dynamics. Some models (Pierazio, 2005; Puttock, 1995) have developed relations for source strength based on experimental data, mostly at scales much smaller than plant-scale, and using subjective, averaged assumptions of congestion and confinement. In particular, relations for congestion level (volume blockage is a poor measure for flame acceleration potential) may be questionable when scaled-up to real plant scale. If used with conservative assumptions regarding energy/cloud size and source pressure, however, the blast curve methods may efficiently provide reasonable and valuable far-field pressures. CFD tools can be used in combination with blast-curves like TNO-Multi-Energy Method (van den Berg, 1985), to predict both the source energy and general pressure level.

"Conservative" assumptions should include the possibility for DDT and detonation of the entire vapour cloud outside a congested unit, like discussed in the introduction. This is seldom done in API-RP 752 or Seveso-II studies, but can change the scenario from a tolerable accident to some completely unacceptable.

One of the main problems with using too simplified consequence tools and approaches for onshore explosion siting studies is that the effect of geometry and most mitigation methods cannot be predicted. This prevents innovative development of gradually safer design and improved mitigation concepts. On the other hand, for offshore oil and gas installations, the more functional requirements and risk criteria in standards like ISO 13702 (1999) and ISO 19901-3 (2010), stimulate (and actually require) the evaluation of layout options and mitigation, forcing the industry to be innovative with regard to safety. Since the simple consequence tools are unable to accurately evaluate the effect of mitigation methods like change of layout and wall/deck configurations or water deluge, the plant operator cannot know if a given mitigation measure has a net positive or negative effect on the total risk, making it difficult to justify investments in mitigation measures.

PROPOSED IMPROVEMENTS FOR ONSHORE SITING STUDIES

To improve certain limitations with typical onshore explosion studies, an alternative CFD-based approach is proposed next. The details of the method have similarities to approaches used on oil and gas offshore installations, and would provide recommendations to the recent additions to API-RP 752, where advanced blast tools such as CFD are now a recognized tool for risk-base approaches. There will be significant focus on establishing accurate explosion pressures inside the plant, and how to mitigate explosion consequences to prevent intolerable pressure levels and particularly DDTs.

The study can either be carried out as a worst-case approach, identifying the worst possible consequences and how to mitigate, or as a probabilistic risk assessment with the goal to limit the probability of intolerable, escalating scenarios to one every ten thousand years (10^{-4}) or some other tolerable limit.

Since this approach will be using CFD, there is a need for a detailed description of the geometry layout. Different options exist:

- For some of the modern facilities, reasonably accurate CAD-models may be available and can be directly imported into the CFD consequence software.
- If no CAD-model exists, one option is to perform a laser-scan of the facility and generate a 3D model. This approach may be expensive, and can often have a prohibitive cost for a project.
- A third option is a manual implementation of a geometry model of the facility.

Manually modeling a complex facility in detail may require several man-months and have a high associated cost. As such, there are more efficient approaches such as the representative congestion screening method, RCM, (Hansen et al., 2010, see Figure 3). RCM requires that the main structures, confining walls/decks and largest vessels are manually implemented, and all the remaining congestion will be represented by repeated idealized obstructions. With this approach, a geometry model can be established within a few days, with the accuracy of the model increasing as the effort level increases. For all of the above approaches, there may be a need to evaluate that the congestion level in different parts of the plant is representative of what is expected for this type of facility. Optimally, the congestion level would be checked by a site visit or review of photos or videos of the site. If analysis of the geometry model (pipe lengths for different pipe diameters or object surface area) indicate that the congestion is too low, it is common to use anticipated congestion methods to increase the congestion level.

The consequence study will consist of an explosion study and in most cases a dispersion study. Depending on the approach chosen, the study can be performed in many different ways. The three approaches include: (1) the worst-case approach; (2) the realistic worst-case approach; and (3) probabilistic risk analysis.

The worst-case approach will require performing numerous explosion simulations for a range of large vapour clouds that are located in different parts of the plant. Different ignition locations are used to ensure that a DDT cannot occur even with very large, near stoichiometric

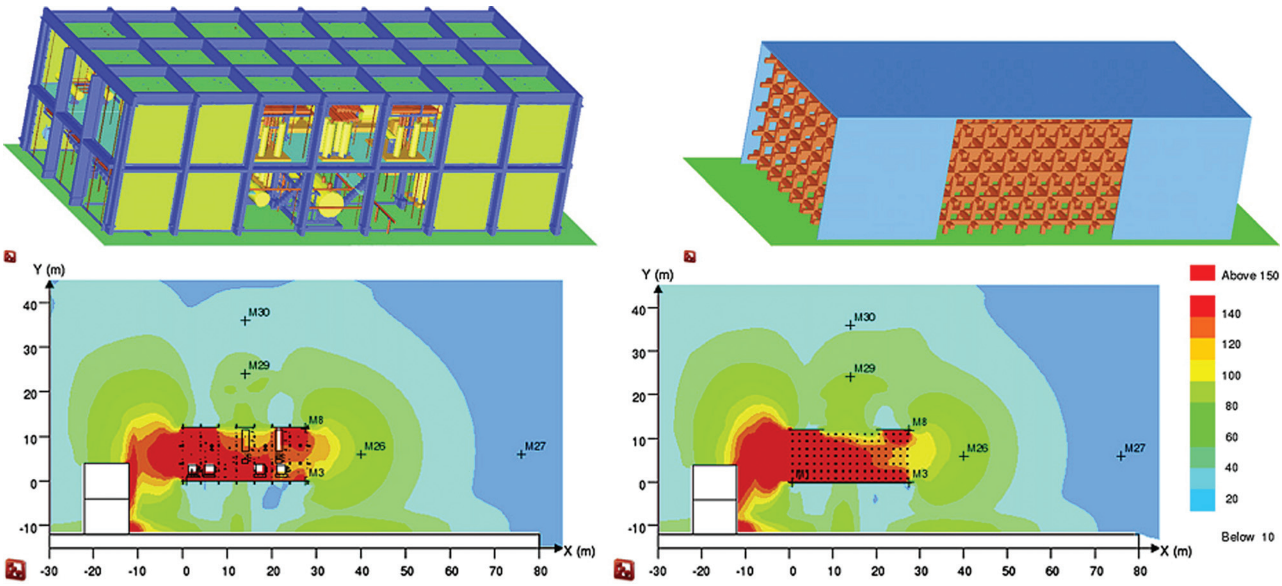

Figure 3. Accurate geometry model (left) and representative congestion model (RCM, right) are shown with the same area/volume congestion (Hansen et al., 2010). Slightly higher (more conservative) pressures are predicted in explosion simulations using RCM (see lower plots, unit is kPa).

vapour clouds spanning more than one congested process unit. If the possibility of DDTs can be ruled out, the predicted explosion consequences can be used to generate worst-case blast contours (pressure or pressure impulse), including blast dynamic effects like reflections on buildings and shielding by walls or process units.

The realistic worst-case approach will require simulating numerous dispersion scenarios, by varying release location, rate, direction, wind direction and speed, for both gas and flashing liquid releases (if applicable), in order to identify one or more potentially worst-case scenarios among the range of release scenarios that may occur at the facility. This is an iterative process as the largest release rate may not give the worst-case consequences. Depending on the complexity of the facility, experienced modelers should identify such scenarios within 10-30 CFD dispersion simulations. The larger of these gas clouds will thereafter be ignited at different locations and exploded in order to evaluate the potential for DDT or high explosion pressures. Depending on possible release scenarios and the geometry layout, the outcome of the realistic worst-case study will either be comparable to the worst-case approach (if very large cloud sizes can be generated), or give lower consequences due to smaller cloud sizes or less ideal mixtures.

The third option will be a more comprehensive probabilistic study, which includes a ventilation study with 8–24 different CFD simulations, a dispersion study with at least 100–200 transient CFD simulations with a systematic variation in the release parameters mentioned above, and finally an explosion study with approximately 100 explosion simulations of idealized gas clouds of all sizes expected to be generated in the dispersion study (varying cloud location and ignition location). This approach is similar to typical offshore probabilistic approach studies. The dispersion study coupled with ignition intensity models will produce probability of ignition for the different gas cloud sizes, and the outcome of the complete study will include: risk of having a DDT; pressure-impulse or drag probability of exceedance curves at various targets, pipe work buildings, etc. This will provide a range of probability for intolerable events.

In the FLACS CFD model, which is the most commonly used consequence model for offshore explosion studies, a new parameter, DPDX – the maximum normalized spatial pressure gradient ahead of the flame – has been developed to predict the potential for DDT, see example Figure 4. Based on validation studies (e.g., Middha et al., 2007) the possibility of a detonation can exist when DPDX exceeds 1, and should be expected once DPDX exceeds 10. Another condition necessary to achieve a DDT is that the near homogeneous gas cloud that will support the detonation must have a relatively uncongested dimension of at least 13 × 13 detonation cell sizes. While methane clouds (likely from LNG for dense gas behavior) will require an approximately 4m thick layer, other relevant substances like propane and butane require a 1–2 m thick layer. The 1–2 m thick layers are often present in scenarios that can potentially detonate. This length scale criterion is therefore mostly relevant for methane and natural gas when it comes to DDT prediction for onshore facilities.

MITIGATION

Mitigation may be evaluated if intolerable risk is identified or if improvements are sought to render the risk as low as reasonably practicable. Mitigation measures include

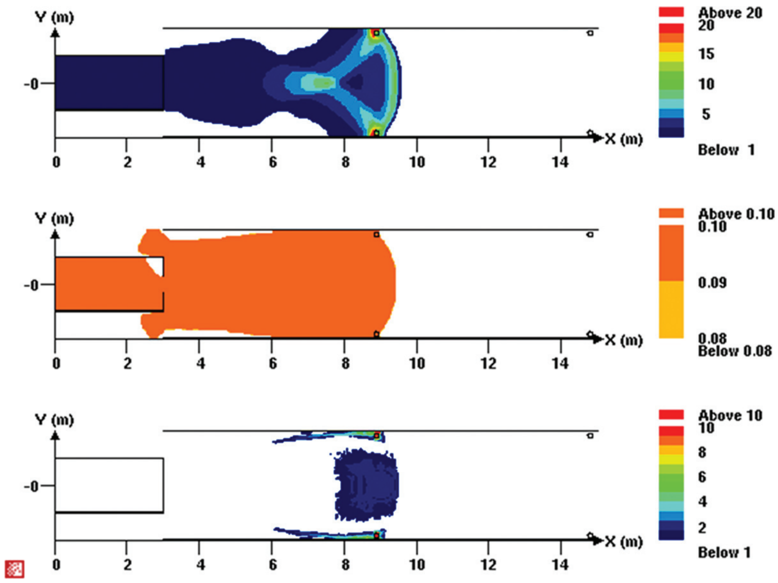

Figure 4. Illustration of DDT criterion DPDX, FLACS simulation of Fraunhofer-ICT hydrogen lane tests (Middha et al., 2007), upper plot shows pressures, middle plot flame position, while lower plot shows predicted DDT propensity DPDX as function of location.

reducing: the possibility for large gas clouds; the likelihood DDTs; and also high pressure levels inside and outside the facility.

If the potential for DDT is identified as a major challenge in the risk study, there may be a range of different approaches to solve this. Quite often the most powerful approach will be to reduce the likelihood of the significant gas clouds that could potentially experience DDT or high pressures, while another approach would be to modify the design so that explosions are less likely too accelerate to detonation. Some possible measures are discussed below.

At least two explosion accidents mentioned in the introduction seem to have experienced DDT's, likely caused by flames accelerating through trees. Vegetation inside and near facilities should clearly be considered in a risk study, and it may be recommended to remove trees and bushes near a facility, keep only tall trees with single trunks and congestion above 4–5 m, or use 3–4 m tall vapour fences to prevent gas from entering arrays of trees and bushes. FLACS simulations of the Buncefield explosion showed that the effect of these three mitigation measures all reduced the simulated explosion pressures by 1-2 orders of magnitude (Davis et al., 2010).

Inside the congested region of the plant, methods like soft barriers may be utilized. A soft barrier is a set of gas tight curtains, which will control gas migration, yet yield and vent in the presence of an explosion. If designed properly, a system with soft barriers may limit the cloud size inside a congested unit, and thus reduce the propensity for DDT and high pressures. However, as the soft barrier also will reduce ventilation, there is a potential for somewhat stronger explosions from smaller releases, and a proper study should be performed to evaluate this method. BP is using soft barriers on some of their offshore oil and gas platforms.

Many layout changes can be considered in the plant to reduce explosion risk, such as:

- Evaluate wall removal or change major decks from solid to grated or vice versa. Less confinement will usually reduce risk by influencing the cloud size distribution and limit flame acceleration, however, in many cases the opposite effect is observed;
- Evaluate spacing between units, as well as optimize their size and shape LxWxH;
- Flashing liquid releases (e.g., LPG) may represent a major concern as release rates and inventories can be large. A strong cabinet can be built around the main sources of release (e.g., tanks) so that any flashing release will impinge and lose its momentum before leaving the cabinet as a very fuel rich mixture from the bottom (with additional liquid particle collection systems). This could in most cases prevent the generation of massive vapour clouds filling a large facility at very reactive concentrations;
- Another potentially risk-reducing design for dense vapours is to elevate units with congestion 4–5 m above ground. This will leave an open area below the units, with significantly better ventilation. As most flammable gas/aerosol clouds will be quite dense, the cloud will fall down after losing momentum, and be efficiently diluted and transported away below the congested volumes. If an explosion occurs in the elevated units, there will be additional pressure venting downwards to limit flame acceleration. Such ideas have been implemented on gas processing plants.

Water deluge activated by threshold gas detection limits, are used to mitigate explosion consequences on many offshore oil and gas platforms. In fact, ISO 13702

(1999) requires the potential effect of water deluge on explosion mitigation to be evaluated as part of the risk assessment for offshore platforms. Large scale experiments (Al-Hassan et al., 1998) demonstrated that water mitigation was even more efficient for onshore type facilities than for typical offshore modules, due to less confinement. Explosion pressures were reduced from more than 10 barg to less than 0.5 barg. Tests also demonstrated that water curtains at regular intervals could potentially control flame speeds. For onshore facilities, which could have access to sufficient amounts of water (~10 l/sqm/min), it would be recommended to evaluate the potential benefits from water deluge.

To summarize this section, there are numerous ways to mitigate an explosion, which include influencing the gas cloud build-up, the explosion severity or both. Oftentimes the combination of two or more mitigation measures is better than the sum of their individual effects. One example of such an occurrence will be the combined effect of reducing confinement and applying water mitigation. Mitigation will typically have a negative effect for some scenarios and positive effect for other. In order to assess total combined effects of mitigation, a comprehensive study will be recommended, preferably with some kind of design-based or probabilistic approach.

While comprehensive studies may be considered expensive for facilities that have been relying on traditional blast curve approaches, their cost will be low compared to any design modification. If design change for mitigation is based on inappropriate consequence studies, the modification may have limited or no risk reducing effect, and there may likely be much more cost effective ways to limit the risk. More comprehensive safety studies throughout the onshore industry will also stimulate innovation, since it will be possible to evaluate the effects of design changes.

If major accidents can be prevented, this should also be of significant value to the facility. Buncefield,

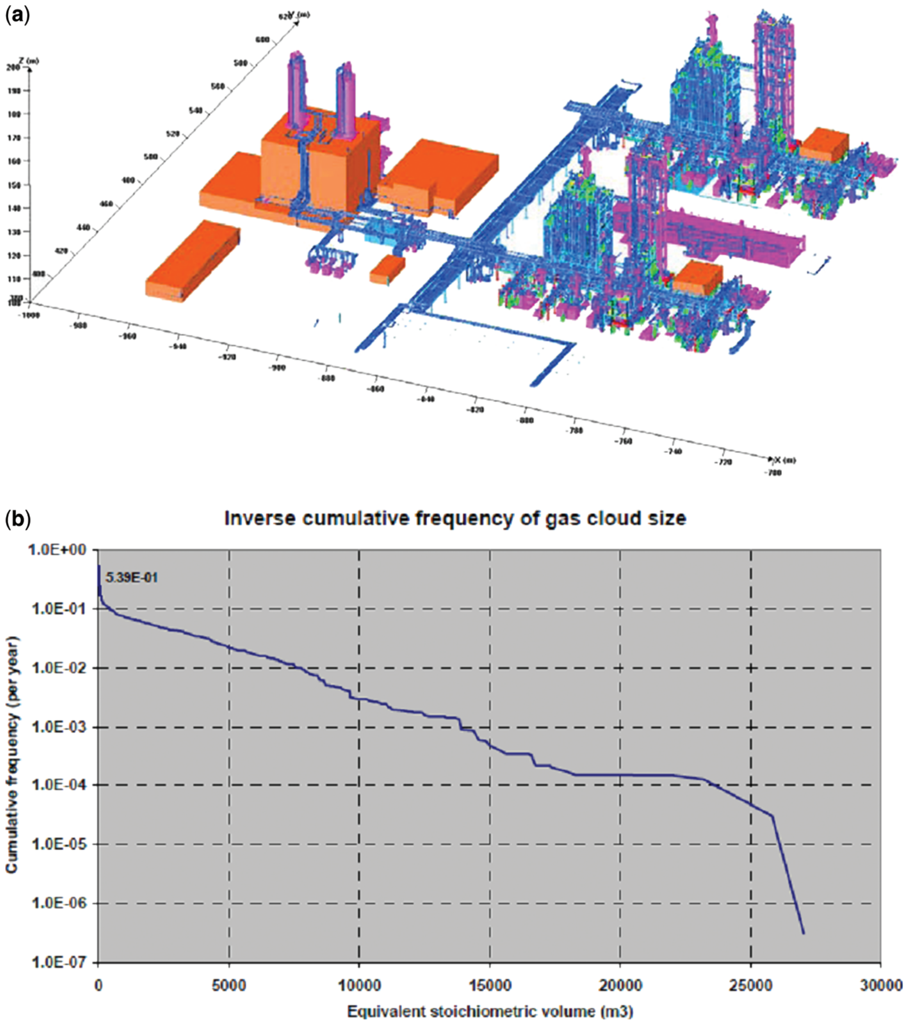

Figure 5. Example of probabilistic risk study on an onshore facility (Hoorelbeke, 2006), upper picture shows simulation model of propylene unit while lower picture shows cumulative frequency of gas cloud size based on CFD ventilation and dispersion study.

BP Texas City and Deepwater Horizon have reminded us about the potential losses when experiencing a major accident.

DISCUSSION AND CONCLUSION

Explosion risk assessment approaches for onshore facilities have been discussed. Based on several serious recent accidents, where DDTs were concluded to have occurred in two of the incidents, we raise the question whether the current simplified risk assessment approach for onshore facilities is adequate. In most cases, risk assessments never consider the possibility of DDT in their risk studies.

Current approaches for onshore facilities, which use quite simplified consequence tools that do not address how design and layout changes can reduce explosion risk, do not stimulate innovation towards safer designs and concepts. In that respect, the offshore oil and gas industry generally has a very different philosophy using more functional or risk based design and requirements for validated tools and methods.

The Seveso-II directive requires member states to ensure that "*operator is obliged to take all measures necessary to prevent major accidents and limit their consequences*". It is quite difficult to achieve this goal using simplified approaches.

The Netherlands recently standardized the onshore risk assessment approach, so that everybody has to use the same package of integral tools for dispersion and blast-curves for explosion, neither of which can account for details in the geometry (i.e., plant layout and design). In France, there is currently a discussion whether to rule out the use of 3D CFD tools for onshore blast and dispersion studies, with the reasoning the French authorities (and advising research organizations) think these are non-conservative and have a too high degree of user-dependency. At the same time, some major oil companies seeing the benefits with the more comprehensive risk assessment approaches used offshore, are gradually starting to use these approaches for their onshore facilities, see Figure 5 (Hoorelbeke, 2006).

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