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Vapor cloud explosion analysis of onshore petrochemical facilities

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1 INTRODUCTION

1.1 Historical evidence of VCE hazards

The paper describes an approach to predicting gas explosion loads and response which has been developed for offshore installations and which only recently has been adapted to onshore petrochemical facilities.

The paper consists of three parts:

Part 1: An overview of vapour cloud explosion hazards in petrochemical onshore facilities and a discussion of modeling approaches.

Part 2: A probabilistic explosion risk analysis for a petrochemical facility, based on the CFD code FLACS, where the focus is on determining risk of escalation in a future unit from explosions in an existing unit.

Part 3: An MDOF response analysis is presented for selected equipment (a loop reactor and a raised vessel) based on the loads predicted in the probabilistic analysis.

Onshore Hydrocarbon industry has a much longer vapour cloud accident history: On the 29th of July 1943 a release occurred from a rail car in a chemical plant at Ludwigshaven[Error! Reference source not found.]. The rail car contained 16,5 t of a mixture of 80% butadiene and 20% of butylene. A vapour cloud formed and ignited. 57 people were killed and 439 injured. The explosion demolished a block 350 m by 100m.

On the 23th of March 2005 a devastating explosion occurred in a refinery at Texas City. At least 15 people were killed and more than 70 injured.

The generic probability of a devastating explosion in a petrochemical/refinery process unit lies in the order of 5 \(10^{-7}\) per year – 5 \(10^{-3}\) per year depending on the type of unit [3]. The operating experience in steamcracking plants in Western Europe for instance for the period 1975 – 2004 is 1514 unit.years. In that period there have been 7 major explosions in these crackers which gives a generic
average probability of $4.6 \times 10^{-3}$ explosions per unit.year. It is obvious that this is a generic average figure which is characteristic for the population (1514 unit.years) and not necessarily for one particular unit. However it helps us to assess the risks of these type of operations and activities.

1.2 Vapor cloud explosions onshore

Petrochemical onshore installations can be characterised as follows in relation to VCE hazards:

- Large congested areas. An overall typical congested volume of a petrochemical unit could be $150 \text{ m} \times 80 \text{ m} \times 15 \text{ m}$
- Large quantities of flammable materials. A typical major vapour cloud can contain 10 – 50 tons of flammable products
- Several zones with dense congestion, see figure below.

![Figure 1.1 A congested area of an onshore unit](image)

1.3 VCE approach in onshore industry

The major concern for onshore installations has been the offsite risk. The Seveso legislation puts emphasis on accident prevention (for onsite and offsite people) and effective mitigation for off site people.

Simple methods (TNT equivalent, ME, Baker Strehlow, etc.) allow good (i.e. conservative) predictions for damage potential in the far field.

In the explosion region and the near-field, however, simple methods are not sufficient and CFD models like FLACS are required to predict overpressures with a sufficient degree of accuracy. Differences between these methods are illustrated in Figure 1.2.

![Figure 1.2 Comparison of overpressure vs. distance between simple methods and FLACS simulations [3]](image)

Accurate prediction of the explosion loads in the near field is however of paramount priority in order to avoid undue exposure of personnel near hazardous installations and to prevent domino effects between nearby equipment installations.
2 EXPLOSION RISK ANALYSIS

This part of the paper describes the results from an explosion risk assessment performed in a propylene unit. The CFD simulator FLACS is used for all simulations [4], [5]. It is planned to install a new propylene unit (PPnew) next to the present unit (PPold). The purpose of the analysis is to evaluate the risk for escalation in PPnew from an explosion in PPold.

The probabilistic explosion risk assessment has comprised of the following main tasks:

1. Import a Microstation 3D model of the PPold unit into FLACS, and complete the model with anticipated congestion to account for the lack of details.
2. Make a copy of the PPold unit to represent the future PPnew unit.
3. Perform ventilation simulations for 12 different wind directions in order to establish the ventilation conditions in the PPold unit.
4. Perform dispersion simulations with varying leak conditions and ventilation conditions in order to establish the potential gas cloud build-up in the PPold unit.
5. Perform explosion simulations in the PPold unit with varying gas cloud sizes, gas cloud locations and ignition locations and calculate blast loads in the future PPnew unit.
6. Perform explosion simulations in the PPnew unit and calculate blast loads in PPold.
7. Calculate the ignition frequency based on a time dependent ignition model.
8. Calculate the explosion risk on various equipment in both the PPold and the future PPnew units.

The probabilistic explosion risk assessment has been performed in accordance with the guidelines given in NORSOK Z-013, Annex G [6]. NORSOK is applied for gas and oil installations on the Norwegian continental shelf, and the methodology described in this paper was developed on the basis of NORSOK requirements. Simpler explosion analysis methods are not acceptable according to NORSOK.

2.1 Geometrical model

The geometrical model of the PPold propylene unit was transferred from a Microstation 3D model to FLACS. The model was updated with anticipated congestion in order to account for lack of details in the Microstation model. The unit is about 100m long and 50m wide.

The FLACS model of PPold was then duplicated to represent the future PPnew propylene unit. The duplicated PPnew unit was translated 101m north of the PPold unit. Figure 2.1 shows both PPold and the future PPnew units.
2.2 Input and assumptions in the analysis

2.2.1 Statistical weather data

The wind statistics indicate 3 predominant wind directions (see Figure 2.2), wind from 60°, 240° and 300°. Within a range of ±30°, these 3 wind directions represent 82% of the total wind direction frequency. These 3 directions were used as a basis for the dispersion analysis.

2.2.2 Leak sources

34 isolatable segments were identified in the PPold propylene unit. Each segment is associated with a specific main piece of equipment. For each segment, the total mass available for release, the leak frequencies for 3 hole sizes, and the associated gas release rate for each hole size are given.

![Figure 2.2 Frequency for wind direction](image)

Due to a limited number of simulations to be performed, not all segments can be studied individually. The segments were grouped in 6 release locations which were used as a basis for the dispersion analysis.

Several gas mixtures are found in the PPold unit, however only propylene, the most abundant gas in the unit, was used in the analysis.

The leak frequencies are distributed over 8 different leak categories and 6 release locations in the explosion risk analysis.

For each release location there is more than one segment with the potential for generating a flammable cloud from an accidental leak. In order to keep the work at a manageable level, one representative segment (the largest) has been picked for each release location.

2.2.3 Ignition modelling

The Time Dependent Ignition Model (TDIM) [7] has been applied for the probabilistic explosion analysis. The basis for the model is a number of recorded leaks, where most of the leaks were small and with mean duration estimated to 5 minutes.

Ignition intensities are separated into two classes, continuous and discrete ignition sources:

- Continuous ignition sources will ignite flammable gas as soon as it reaches the source.
- Discrete ignition sources can ignite a combustible gas cloud at any moment.

Ignition intensities are grouped by types of source (hot work, pumps, compressors, generators, electrical equipment, other equipment, other and personnel). For hot work, it is the number of hours per year that is relevant. For pumps, compressors and generators, it is the number of active sources that is taken into account. For the rest, exposed deck areas are used.

Gas alarm will be activated upon detection and it has been assumed that ignition intensities associated to personnel will be reduced 5 minutes after leak start (i.e. the personnel has normally evacuated the unit).

For continuous ignition intensities, the ignition sources associated to personnel and hot work will not contribute any more 5 minutes after leak start. Other ignition sources are not reduced upon gas detection, but will not be active anymore once the gas cloud has reached a steady state (typically within a few minutes).

For discrete ignition intensities, the ignition sources are still active as long as flammable gas is present in the unit. For personnel, the ignition sources are reduced to 50% 5 minutes after leak start. The personnel should normally have left the unit, but people might still be present around the unit to evaluate the situation. For other ignition sources, it has been assumed that after a relative long period of exposure, if a flammable gas cloud has not been ignited the probability of ignition should be reduced.

2.2.4 Explosion scenarios

In the PPold and the future PPnew units, the potential explosion loads from several gas cloud sizes have been investigated.
In the probabilistic assessment, GexCon have used the explosion loads from the smallest gas cloud category, e.g. 4% filling, as representative for all clouds from 0.1% to 4% filling. Similarly the results from a gas cloud filling 15% will be used as representative for all clouds filling 7% to 15% of the unit. This is conservative.

2.3 Ventilation simulations

FLACS wind simulations for 12 wind directions have been performed, and the resulting flow rate inside the PPold unit was calculated (see Figure 2.3). The simulations were performed for an external wind speed of 3.5 m/s.

![Figure 2.3 Ventilation conditions in PPold–Air Changes per Hour at 3.5 m/s external wind](image)

Based on the assumption that there is a linear correlation between the external wind speed and the internal flow rate, the internal flow rate is calculated for all other wind speeds.

2.4 Dispersion simulations

2.4.1 Investigated scenarios

288 dispersion simulations were performed in order to establish representative gas clouds likely to be generated for various wind and release conditions. Using the frozen cloud assumption, 1440 scenarios were estimated.

2.4.2 Results

The main results from the dispersion simulations are summarised in the following graphs. The dispersion simulations are used to calculate the frequency of ignited gas cloud using the time dependent ignition model.

Figure 2.4 illustrates the average and the maximum sizes of the equivalent stoichiometric gas clouds for different leak rates. The maximum gas cloud generated has an equivalent stoichiometric volume of 27000m$^3$ (38% filling of the unit)

Figure 2.5 shows the inverse cumulative frequency of gas cloud size. The release scenarios have been linked with the leak and wind frequencies to produce this graph.

![Figure 2.4 Average and maximum equivalent stoichiometric gas clouds from the dispersion simulations](image)
2.5 Explosion simulations

2.5.1 Investigated scenarios

A total of 59 explosion simulations have been performed in the PPold propylene unit as part of the probabilistic assessment, these were repeated in the future PPNew unit. The explosion simulations have been performed for varying gas cloud sizes, gas cloud locations and ignition locations. The investigated scenarios are summarised in the Table below.

<table>
<thead>
<tr>
<th>Gas cloud category</th>
<th>Size (l x w x h) (m)</th>
<th>Volume (m³)</th>
<th>% filling of unit</th>
<th>Amount of gas (kg)</th>
<th>Net volume of cloud (m³)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15 x 15 x 15</td>
<td>3375</td>
<td>4%</td>
<td>254</td>
<td>3120</td>
</tr>
<tr>
<td>2</td>
<td>19 x 19 x 15</td>
<td>5415</td>
<td>7%</td>
<td>411</td>
<td>5140</td>
</tr>
<tr>
<td>3</td>
<td>29 x 25 x 15</td>
<td>10875</td>
<td>15%</td>
<td>837</td>
<td>10270</td>
</tr>
<tr>
<td>4</td>
<td>33 x 33 x 15</td>
<td>16335</td>
<td>22%</td>
<td>1255</td>
<td>15380</td>
</tr>
<tr>
<td>5</td>
<td>36 x 50 x 15</td>
<td>27000</td>
<td>36%</td>
<td>2067</td>
<td>25370</td>
</tr>
<tr>
<td>6</td>
<td>50 x 50 x 15</td>
<td>37500</td>
<td>50%</td>
<td>2870</td>
<td>35250</td>
</tr>
<tr>
<td></td>
<td>100 x 25 x 15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>100 x 30 x 15</td>
<td>75000</td>
<td>100%</td>
<td>5740</td>
<td>70490</td>
</tr>
</tbody>
</table>

* The net volume is the real size of the cloud, i.e. the total volume minus the volume blocked by equipment.

In the PPold unit, gas cloud categories 1, 2, 3, and 4 were located at 6 different locations, with ignition in the centre of the cloud and at the south edge (except for gas cloud category 1 which was only ignited in the centre).

In the future PPNew unit, gas cloud locations and centre ignition locations were kept, but the clouds were ignited at the north edge instead of the south edge.

2.5.2 Measurements

Based on client requirements, local pressure measurements have been performed on a range of equipment, both in the PPold and future PPNew units. Points have also been located in open spaces at different height levels both in PPold and the future PPNew units, to monitor the dynamic pressure (or drag value).
2.5.3 Results from explosion simulations

Overpressure and duration combinations for all pressure monitor points and all cloud sizes ranging from 4% to 100% are shown in Figure 2.6 and Figure 2.7. These are for explosions in PPold. The highest overpressures correspond to the largest gas clouds. Similar results were produced for the explosion simulations in PPnew.

Figure 2.6 Pressure vs. pulse duration in the PPold unit

Figure 2.7 Pressure vs. pulse duration in the future PPnew unit

2.6 Explosion risk calculations

The large variation in overpressure (and pulse duration) illustrated in the previous section clearly indicates that it is necessary to determine the likelihood of the different overpressure levels, which closely corresponds to performing an assessment of cloud size frequency.

2.6.1 Frequency of ignited gas cloud

Once the ignition intensities are processed with the dispersion simulations, the frequency of ignited gas clouds is determined. The results are illustrated in Figure 2.8.
The total frequency of ignited gas clouds in the PPold propylene unit is $1.99 \times 10^{-3}$. The average ignition probability is 0.37%.

### 2.6.2 Explosion risk in PPold

The results from the explosion risk calculations are given in Table 2.2 for selected elements. The results are expressed as the $10^{-4}$ and $10^{-5}$ overpressures, both in the PPold and future PPnew units.

#### Table 2.2 Local pressures in the PPold and future PPnew units

<table>
<thead>
<tr>
<th>Equipment ID</th>
<th>PPold unit $10^{-4}$ overpressures</th>
<th>PPnew unit $10^{-4}$ overpressures</th>
<th>PPold unit $10^{-5}$ overpressures</th>
<th>PPnew unit $10^{-5}$ overpressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>D302</td>
<td>0.47</td>
<td>0.19</td>
<td>0.89</td>
<td>0.32</td>
</tr>
<tr>
<td>R201-R202</td>
<td>2.71</td>
<td>0.11</td>
<td>3.29</td>
<td>0.16</td>
</tr>
</tbody>
</table>

#### Table 2.3 Drag values in the PPold and future PPnew units

<table>
<thead>
<tr>
<th>Measurement height (m)</th>
<th>PPold unit $10^{-4}$ overpressures</th>
<th>PPnew unit $10^{-4}$ overpressures</th>
<th>PPold unit $10^{-5}$ overpressures</th>
<th>PPnew unit $10^{-5}$ overpressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.56</td>
<td>0.01</td>
<td>1.60</td>
<td>0.04</td>
</tr>
<tr>
<td>12.5</td>
<td>0.40</td>
<td>0.01</td>
<td>0.68</td>
<td>0.03</td>
</tr>
</tbody>
</table>

### 2.6.3 Explosion risk in PPnew

The results from the explosion risk calculations are given in Table 2.4 and Table 2.5. The results are expressed as the $10^{-4}$ and $10^{-5}$ overpressures, both in the PPnew and PPold units. It has been assumed that the frequency of ignited gas cloud in PPnew is similar to PPold.

#### Table 2.4 Local pressures in the future PPnew and PPold units

<table>
<thead>
<tr>
<th>Equipment ID</th>
<th>PPnew unit $10^{-4}$ overpressures</th>
<th>PPold unit $10^{-4}$ overpressures</th>
<th>PPnew unit $10^{-5}$ overpressures</th>
<th>PPold unit $10^{-5}$ overpressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>D302</td>
<td>0.84</td>
<td>0.06</td>
<td>2.14</td>
<td>0.12</td>
</tr>
<tr>
<td>R201-R202</td>
<td>3.35</td>
<td>0.11</td>
<td>10.15</td>
<td>0.22</td>
</tr>
</tbody>
</table>

#### Table 2.5 Drag values in the future PPnew and PPold units

<table>
<thead>
<tr>
<th>Measurement height (m)</th>
<th>PPnew unit $10^{-4}$ overpressures</th>
<th>PPnew unit $10^{-5}$ overpressures</th>
<th>PPold unit $10^{-4}$ overpressures</th>
<th>PPold unit $10^{-5}$ overpressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.93</td>
<td>&lt; 0.01</td>
<td>2.31</td>
<td>0.02</td>
</tr>
<tr>
<td>12.5</td>
<td>0.82</td>
<td>&lt; 0.01</td>
<td>1.42</td>
<td>0.02</td>
</tr>
</tbody>
</table>
2.7 Discussion of explosion risk analysis

The ventilation analysis shows good ventilation in the PPold propylene unit, which was to be expected due to the very open configuration and the low degree of congestion of the unit.

From the dispersion analysis, it is seen that leaks up to 6kg/s only generate relatively small clouds with an equivalent stoichiometric gas volume below 2600m$^3$. This is in accordance with the open configuration of the unit allowing good ventilation.

For leaks above 12kg/s however, the size of the equivalent stoichiometric gas clouds increases significantly, with a maximum of 27000m$^3$ (38% filling of the unit) for a 96kg/s release. As the propylene gas is heavier than air, it stays close to the ground giving the possibility for large clouds to be formed.

High pressures can be obtained in both PPold and PPnew, especially for gas clouds filling 36% or more of the unit. For those clouds, deflagration to detonation transition (DDT) is not unlikely. The pressures generated decay quite rapidly with distance, so that the blast pressures in the other unit are much lower, but still a possible risk of escalation for the largest gas clouds (from 36% filling) exists.

Overpressures associated to the $10^{-4}$ frequency in the PPold unit are relatively high. These pressures correspond to the explosion of a gas cloud filling 15% of the unit. The $10^{-4}$ blast overpressures in the PPnew unit are lower.

Several conservative assumptions have been made in this analysis, and the following modifications to the analysis could reduce the calculated explosion risk:

- The representative segment size for each leak location is the largest of all segments associated to a leak location. Most of the segments are much smaller and this is therefore a very conservative choice. More representative (smaller) segments could be more appropriate to use.
- Blowdown, following ESD, has not been considered. With blowdown, the segments would be emptied more quickly and the gas clouds would be exposed to ignition sources for a shorter time.
- Decay of leak rate following ESD has not been included, leading to large clouds being exposed longer to ignition sources.
3 RESPONSE ANALYSIS

In order to better understand the risk of secondary explosions and escalation, finite element analyses were carried out to determine the global dynamic response of the D302 tank and the R201-R202 reactor loop structures to the $10^{-4}$ probability blast scenario. The non-linear, dynamic, explicit finite element (FE) code LS-DYNA [8] was used for these Multi-Degree-Of-Freedom (MDOF) analyses.

Due to the nature of the analyses, geometric non-linearity (i.e. large displacements) was intrinsically included in the calculations. Only the primary components of the structures were modelled explicitly. The foundations for the structures were assumed to be rigid and immovable. Gravity loading was included in both of the models and was applied in a staged analysis, with gravity applied to the structures prior to the application of the blast load.

3.1 D302 Tank Structure

The D302 tank structure consisted of a large tank, approximately 11.5m long and 3.5m wide, sat on steel saddles and reinforced concrete supports, as shown in Figure 3.1.

3.2 R201-R202 Reactor Loop Structure

The R201-R202 reactor loop structure consists of the R201-R202 reactor loops, which sit on the A201 concrete structure. The adjacent I201 steel structure, containing the D202 tank, is also supported by the A201 reinforced concrete structure along one of its column lines. The model is shown in Figure 3.2.

The reactor pipes were considered to be rigidly connected to the floor of the A201 concrete structure. The D202 tank was also considered to be rigidly connected to the adjacent supporting beams within the I201 structure.

3.3 Blast Loadings

The loading information for the blast scenario consisted of blast and drag pressure time-histories at various locations around the structures. For conservatism, a load factor of 1.5 was used for the pressures from the blast.

Figure 3.1 – D302 Tank Model

Figure 3.2 – R201-R202 Reactor Loop Model
these structures are mainly due to the drag pressure. The D302 tank is relatively large and so the blast pressure time-histories were directly applied. For the smaller D202 tank, a combination of the blast and drag pressures were applied.

### 3.3.1 Loading – D302

The relatively large dimensions of the surfaces of the D302 tank structure result in the blast pressures, rather than drag pressures, being the main loading. The blast loading pressure time histories, shown in Figure 3.3, were applied directly to the surface of the structure; the blast wind drag load was relatively small.

![Figure 3.3 – Blast pressures time-histories around D 302 Tank](image)

It was assumed that the blast pressure on the front and rear faces of the concrete support structures corresponded to that on the front and rear faces of the tank. A further increase of 10% (in addition to the factor of 1.5) to the blast pressures was applied to allow for the increase in surface area due to the presence of insulation and the increase in the loading due to secondary structures and pipes (primarily on top of the tank).

### 3.3.2 Loading – R201-R202 and I201 Structures

The R201-R202 reactor loop structures and the I201 structure are relatively open structures. Therefore, the main loading is derived from the drag pressures. For increased conservatism, at each elevation level, the drag pressure with the largest impulse was applied to all of the structural elements at that elevation (see Figure 3.4).

![Figure 3.4 – Drag Pressure Time-Histories for R201-R202 Reactor Loop Structures](image)

The loads on the structure were calculated using the drag pressures time-histories, estimates of the projected area of each component and a drag coefficient for each component. Drag coefficients of 1.2 and 2.0 [11] were used on circular and rectangular cross sections, respectively.

The increase in the blast loading due to the secondary components was accounted for by applying an approximate, but conservative, factor (in addition to the 1.5 factor) to the loading on the primary structure.

### 3.3.3 Loading – D202 Tank

The loading on the D202 tank consisted of both blast and drag pressure loading, applied simultaneously. The drag loading was calculated as for the other components within the model, using a drag coefficient of 1.2.

The blast loading is effective in the time period between when pressure has built up on the front face and when this has been equalised on the back face. The time-history for the nearest blast pressure measurement location was considered to approximately represent the ‘side-on’ blast pressure. Using the methods given in [9] and [10], this was used to approximate a resultant blast pressure time-history, taking into account both the ‘reflected’ pressure off the front of the tank and the equalisation of the blast pressure on the front and back faces of the tank.

The conservatively estimated blast loading represented approximately 75% of the total load on the D202 tank, while the drag loading represents the remaining 25%.
3.4 Material Properties

3.4.1 Steel Properties

The steel used in the structures was either SA-516-Gr.70 steel or grade S235JRG2 carbon steel. Material properties for these steels were derived from [12] and [13]. Since the structures generally remained elastic, a basic linear-elastic material model was employed for the majority of the components. Where the stresses were found to exceed the yield stress, an elastic-perfectly plastic material model was used (i.e. no strain-hardening). Yield stresses were based on the minimum allowable by the standards. Although typical properties are generally much higher, the minimum properties were assumed for conservatism. Strain rate effects were not included in the models.

3.4.2 Concrete Properties

Initial linear-elastic analyses indicated that the bending moments due to the blast loading in the reinforced concrete supports for the D302 tank and the concrete columns in the A201 structure would exceed their cracking moments (the point at which the concrete starts to crack), but remain within the ultimate capacities of the sections.

This meant that a reduced EI value for the section would be required to reasonably represent its stiffness. The concrete sections were analysed to estimate the moment-curvature relationship for the section for large deflections. It was then necessary to adjust the Young’s modulus so as to produce the effective EI value of the section that corresponded to the bending moments imposed by the blast loading. This was achieved by using an iterative process.

3.5 Inertia Distribution

Since the models were only required to represent the global response of the structures, the secondary structures, stairs, etc. were not modelled explicitly. However, the mass of these secondary items was included by adding their mass to the primary structure. In most cases, overall estimates of these masses were made, since the large number of these items meant that detailed information was not available.

The densities of the components were factored to account for the masses of the tank and pipe contents and the secondary masses associated with the structures (insulation, outer plating, pipes, platform on top, fireproofing, etc.).

3.6 Discussion of Response Analyses Results

3.6.1 D302 Tank Model

The displacements of the tank structure during and following the blast were relatively low. The displacements (shown in Figure 3.5) along the length of the tank (longitudinally, approximately in the direction of the blast) reached about ±7mm and about ±3mm laterally, across the tank. These displacements were largely as a result of the rigid body motion of the tank with all of the deformation concentrated in the saddles and concrete support structures.

![Figure 3.5 – Dynamic Displacements of D302 Tank](image)

The stresses in the D302 tank were generally very low with some small stress concentrations around the connection with the saddle. Within the saddle structure, the highest stresses were observed in the vertical stiffening ribs and in the reinforcing plate forming the saddle connection to the tank. These stresses in the D302 tank and saddle structure were well within the minimum yield of the material (i.e. the material remains elastic).

The stresses in the concrete supports for the D302 Tank were relatively low and it is expected that only small cracks might develop during the blast. However, these cracks are likely to close-up again since there was no yielding of the reinforcement.

The connection between the steel saddles and the reinforced concrete supports were made through 4 bolts for each saddle. Using the results from the FE analysis, it was shown that the forces in this connection detail would not produce significant tensile or shear stresses in the bolts. Therefore, failure of this connection detail is not considered to be likely.

Therefore, the tank is expected to return to its original position once the blast has passed and structural failure of any part of the D302 tank structure is considered unlikely.
3.6.2 R201-R202 Reactor Loop Structures

The largest displacements in the R201-R202 reactor loop occur at the top of the structure during a sway response to the drag impulse loading. The displacements here are up to ±33mm, as shown in Figure 3.6, corresponding to 1 in 2000 or 0.05% of the height of the structure. The fundamental sway mode of around 0.75Hz and some higher frequency modes are both evident.

The peak bending moments in the loop reactor pipes, shown in Figure 3.7, were well within their elastic capacity, with utilisation factors of about 20%.

The reactor loop pipes were also subjected to ‘push-pull’ axial forces, as the structure swayed back and forth. However, both of the loop reactor pipes remained in compression with relatively low axial stresses.

The bracing members spanning between the reactor pipes were subjected to bending as the reactor tower swayed. However, the bending moments in these cross members were well within their minimum elastic capacity, with utilisation factors of about 20%. The shear forces in the reactor loops and the bracing members were also low.

The R201-R202 reactor loop structure remained elastic under the drag loading. It displayed neither signs of instability nor any indication that the structural integrity was compromised.

3.6.3 I201 Structure with D202 Tank

The I201 structure is a shorter and stiffer structure than the R201-R202 structure and responds to the blast loading with a higher frequency response. The peak deflections were about 12mm at the top of the I201 structure, as shown in Figure 3.8. The overall structural response of the I201 structure corresponds to a frequency of about 4Hz.

The D202 tank is only supported on the I201 structure through the relatively flexible floor beams. This support is not located at the vertical centre of the tank and so the combined blast and drag loading on the D202 tank produced a rocking motion of the tank relative to the I201 structure. The peak relative displacement between the D202 tank and the I201 structure at the upper level was found to be about 22mm. However, it is anticipated that any contact between the D202 tank and the I201 structure would only damage the outer shell of the tank covering the insulation and it is unlikely that this would cause any significant damage to the pressure vessel.

The highest loads in the I201 structure were in the region of the D202 tank support, due to the rocking motion of the D202 tank. However, no yielding or plasticity is expected in the I201 structure.

3.6.4 A201 Concrete Structure

The maximum displacement of the A201 structure was about ±3mm. The concrete columns experienced significant bending moments and push-pull forces during the swaying of the R201-R202 reactor loops. The peak bending moment in the...
columns were at the base of the columns, as shown in Figure 3.7. The column sections are expected to crack with these loads, but the demand was well within the ultimate capacities of the sections. Any cracks are likely to close-up afterwards since there was no yielding of the reinforcement. All of the columns remained in compression throughout the dynamic response.

3.6.5 Relative Movement between R201-R202 and I201 Structures

The relative displacements between the R201-R202 reactor loop structure and the I201 structure are important as a number of pipes are connected to both structures. Figure 3.9 shows the relative displacements between the top of the I201 structure and the R201-R202 structures at the same elevation (i.e. the region of maximum relative displacement). This shows that the maximum relative displacement between the two structures was about 15mm.

Figure 3.9 – Relative Displacement between R201-R202 and I302 Structures

3.7 Conclusions of Response Analyses

It was concluded that structural failure of the D302 tank, the R201-R202 and I201 structures and the D202 tank due to the blast loading is unlikely. All of the structural elements are expected to remain elastic with no permanent deformation to the primary structures resulting from the blast. Therefore, it is unlikely that there would be any escalation or “domino” effects due to a structural failure.

The response analyses only simulated the global response of the structures. Although the displacements of the structures would not cause any significant damage to the structures themselves, there is the possibility that these displacements would cause damage to some of the pipes within the structures (or pipes that cross-over from one structure to another). The potential for damage or leaks in these pipes due to the relative displacements of the structures or their performance under blast loading has not been evaluated within the scope of this work.
4 CONCLUSIONS

The situation till say 5 years ago was:

• Simple methods allowed to cope with the main concerns (i.e. offsite risk assessment)
• Onshore hydrocarbon process industries did not make the same profits as offshore facilities and advanced technologies (3D modelling) were considered expensive

Even today there is still an important gap between explosion research (theoretical and experimental investigations) and application of this research in the plants.

CFD and MDOF analyses, compared to the use of simple methods, typically generate information which is more realistic, more accurate and less conservative. This leads to a better understanding of behaviour as well as assessment of risks. They also enable the user to more accurately quantify the effects of mitigation measures.

An advanced analysis may well take more time and cost more than a simpler one, but it also generates a more complete picture of the issues involved and often gives information that is not available from simpler methods (like drag forces, location of maximum pressures, how to re-enforce supporting structures etc). This may be crucial because questions like how do we re-enforce to make the project acceptable, exist. Whether from a scientific point of view the answer is "better" may in some cases almost be irrelevant – it is the fact that necessary information is provided by the advanced method that is important.

The present study can be viewed as a verification exercise, where the purpose is to determine what level of damage is likely for loads having a probability of being exceeded of \(10^{-4}\) per year.

The analysis shows that very high explosion overpressures are seen for large gas clouds. However, a probabilistic assessment of explosion loads in conjunction with the application of proper risk acceptance criteria to determine dimensioning overpressures leads in most cases to design loads significantly less than the worst case loads found in most analyses. Often predicted damage levels are tolerable, as seen in the present analysis.

If unacceptable damage is predicted based on the \(10^{-4}\) load levels, the effect of mitigation measures may be evaluated using the same methodology. Their implementation may then be considered based on an assessment of cost and contribution to risk reduction.

It is often local effects of measures (like changes in confinement) that lead to the global overpressure reduction, hence predictive methods need to account for these local effects. Simple methods are therefore often not suitable when effects of different measures need to be quantified. One then has to resort to tools that resolve local effects, i.e. CFD-codes like FLACS.

In the case of the present MDOF analysis, one of the main benefits was that the advanced analysis showed that escalation due to structural failures was unlikely, whereas the simple methods indicated that there might have been a problem.

This illustrates one of the benefits of using more advanced and precise tools, namely that a more precise analysis may reduce the conservatism typically associated with simpler methods. Its use contributes to a more representative assessment of risk and the effect of risk reducing measures. Hence both protection level and type of protection may be optimised based on precise analyses of cost as well as benefit.
5 REFERENCES


7. DNV Technical report JIP Ignition Modelling: Time Dependent Ignition Probability Model, Report no. 96-3629, Rev. 04, Det Norske Veritas


