EXPLOSION GUIDANCE

Guidance on the Assessment of Explosion Hazards for Natural Gas Facilities

STOGIT

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1 INTRODUCTION

Stogit S.p.A., a subsidiary company of Snam S.p.A. operates eight strategic natural gas storage facilities in Italy. Given the quantities of gas stored on these sites, there is a need to assess the potential hazards to personnel both onsite and off-site including the potential explosion hazards due to a release of natural gas.

This report has been prepared by DNV GL to provide guidance on the methods that can be used to quantify the explosion hazards. The guidance has been developed in the context of information gained from a visit to the Stogit storage facility at Minerbio in Emilia-Romagna. This storage facility injects gas into a depleted natural gas field.

In developing the guidance, DNV GL has made reference to:

- The mechanisms involved in pressure generation in gas or vapour cloud explosions.
- Data from large scale explosion experiments conducted by DNV GL.
- Published 'simple' methods for assessing the severity of gas or vapour cloud explosions.
- Modelling of explosions using a DNV GL phenomenological explosion model.

In preparing this report, DNV GL has focused on the nature of the explosion hazards associated with natural gas, however in order to provide some context for this, reference is also made to the explosion properties of other common hydrocarbons.

2 GAS EXPLOSION MECHANISMS

Any leak from a pressurised natural gas pipework or equipment will form a flammable natural gas-air mixture around the leak location.

- If a natural gas air mixture is ignited in an open area it would burn without generating a damaging blast wave. This type of "flash fire" event would endanger personnel within the flammable cloud but not cause significant damage to equipment or personnel outside the cloud envelope.
- If the natural gas air mixture is ignited in a region of plant that is filled with obstacles (such as pipework) or in an enclosure (such as a compressor house) there is the potential for a blast wave to be generated that could have a damaging impact outside the immediate flammable areas.

An understanding of the mechanisms required to cause damaging levels of pressure to be generated is needed to identify situations where this explosion potential is of concern.

A brief introduction to explosion mechanism is given in this section.

2.1 Flammability and Combustion

For an explosion to occur following a hydrocarbon release, the proportion of gas or vapour in the air must fall inside a range where the mixture is flammable. If the mixture has too little fuel to support combustion then the mixture will be below the lower flammable limit. If the mixture has too much fuel (i.e. the mixture contains too little oxygen) to support combustion, then the mixture is above the upper flammable limit. The flammable limits vary between different hydrocarbons.

The combustion of a flammable mixture at ambient temperature produces hot combustion products at temperatures exceeding 2000K.

Burning velocity is a measure of how fast a flame front will burn through a stationary mixture of hydrocarbon gas and air. Burning velocity is an important indicator of the '**reactivity**' of any hydrocarbon-air mixture as the faster the burning velocity, the greater the energy release rate and rate of generation of hot combustion products will be.

There are three main factors that affect the burning velocity:

- Type of hydrocarbon
- Fuel Concentration
- Turbulence of fuel air mixture ahead of the flame front

It is important to note that the burning velocity of natural gas is less than that for other common hydrocarbons such as propane, butane and ethylene under equivalent conditions.

With regard to combustion, assuming that the unburnt gas is stationary, the flame propagates into the unburnt gas at a characteristic 'laminar' (i.e. non-turbulent) burning velocity. If the unburnt gas is turbulent, the burning velocity can increase and is then called the 'turbulent burning velocity'. The turbulence has the effect of mixing the flame with the mixture, increasing the rate of combustion. Turbulence could be created by unburnt gas being forced to move by the expansion of the burnt gasses due to their temperature increase, external conditions, or the gas movement caused by the release itself.

If the unburnt gas is moving, a stationary observer measures a **flame speed** that is the sum of the unburnt gas velocity and the burning velocity of the flame through the unburnt gas.

2.2 Explosions

Two classes of explosions relevant to this study are outlined below, specifically **confined explosions** and **vapour cloud explosions**.

2.2.1 Confined Explosion

Combustion of a flammable hydrocarbon-air mixture generates hot combustion products that, due to their higher temperature, would normally expand to occupy a larger volume. In controlled conditions, such as on a gas burner, the combustion products are free to expand behind the flame. However, if a flammable mixture fills a confined volume, then the hot combustion products cannot expand and, as a result, the pressure within the structure increases. This is generally known as a confined explosion.

With hydrocarbon-air mixtures, the typical flame temperatures for the combustion of hydrocarbons are in the range 2100K to 2300K, which corresponds to a thermal expansion ratio of 7.4 to 8.0. The maximum overpressure that can be generated is therefore about 7 barg. Structures such as buildings will fail long before this pressure is reached, effectively limiting the maximum overpressure, as once failure occurs, the hot combustion products can escape from the structure.

However, if the rate at which combustion products are being generated exceeds the rate at which the products or mixture are being expelled through available openings or vents in the enclosure, the pressure can continue to rise (up to the maximum of 7 barg) until further structural failure occurs. Pressure rise can also occur in partially confined volumes as a result of insufficient openings to vent the combustion products.

Confined explosions are characterised by flame speeds of the order of a few metres per second within the confined volume. However, high flame speeds may be achieved as the flame vents from the confining structure. This may lead to a secondary external explosion, in which the flame propagates into a highly turbulent mixture that has been expelled ahead of the flame.

Factors that can affect the pressure generated in a confined explosion include:

- Fuel composition and concentration.
- Ignition position.
- The amount and type of congestion within the structure (if any).
- The nature of the confinement, e.g. strength of the structure, size of any vents that might be present.
- Volume of the cloud within the structure and the volume of the structure.

Fuel type and concentration primarily change the burning velocity of the hydrocarbon air-mixture, which in turn affects the rate at which combustion products are produced. Generally, the higher the burning velocity, the higher the pressures produced in a confined explosion.

When the ignition position is close to an opening where gases can escape from the volume, the venting of hot combustion products will occur relatively early in the explosion process and the pressure generated will be less. However, when the ignition position is a relatively long distance away from the nearest opening (all other things being equal), the onset of venting of hot combustion products will occur later in the explosion process and the pressure generated will be greater.

In general, the lower the pressure at which structural failure occurs, the lower the maximum pressure generated by the explosion. As a consequence, the speed of the venting gases is also generally lower and the magnitude of any external explosion is also reduced.

Figure 1 shows a confined explosion in a test enclosure in which a window has been fitted over the only opening. Failure of the window has allowed the hot combustion products to vent from the enclosure.

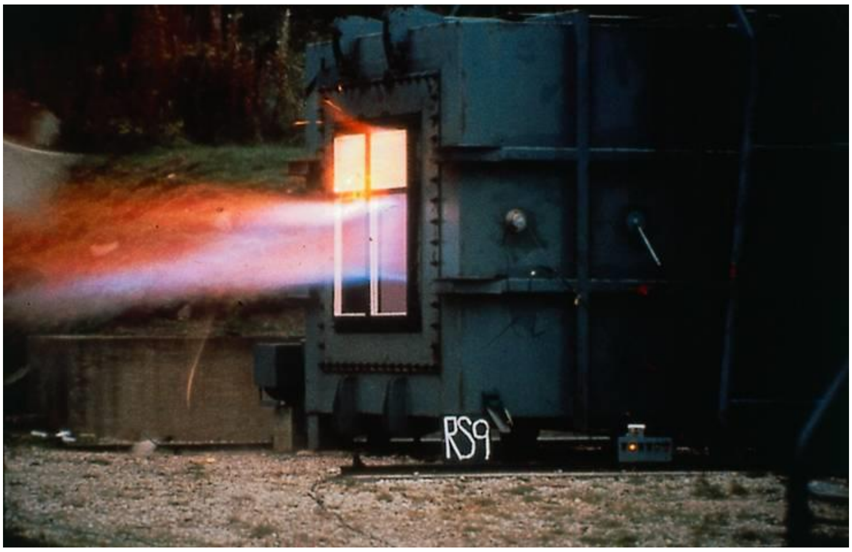

Figure 1: Confined Explosion Showing Venting Combustion Products

2.2.2 Vapour Cloud Explosions

Confinement does not explain all types of hydrocarbon-air explosions. There have been a number of major explosions involving large releases of hydrocarbons where the flammable cloud was not confined, such as at Buncefield in the UK in 2005. These explosions are generally termed vapour cloud explosions and a severe explosion of this type within the UK occurred in Flixborough in 1974 [1].

At the time of the Flixborough incident, the mechanism that generated pressure in a vapour cloud explosion was not understood. As a consequence, a significant amount of research was directed towards explaining these events during the late 1970s and 1980s.

One way pressure can be generated is by accelerating the flame to high speeds, typically over 200ms^{-1} (for comparison the ambient speed of sound is about 340ms^{-1}). The flame generates pressure because of the inertia of the unburnt mixture in front of the flame, in a manner similar to the way an object moving at high speed through the air can generate a pressure wave in front of it.

The exact relationship between flame speed and pressure depends on the conditions being considered, but a good guide to typical relationships is shown in Figure 2 taken from [2].

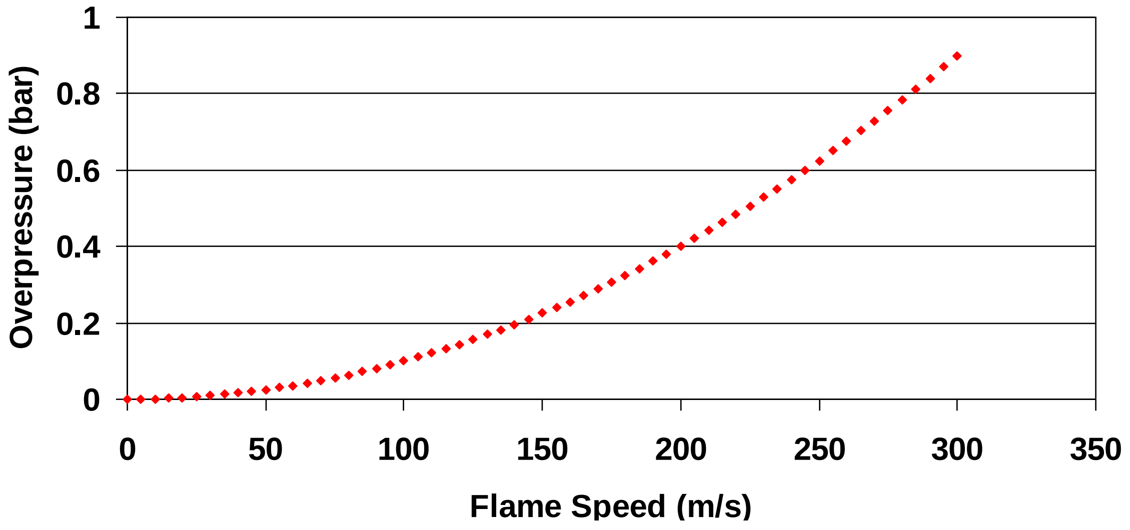

Figure 2: Example Relationship Between Flame Speed and Pressure

Large scale experiments showed that, if the flammable cloud engulfs a region of repeated pipework obstacles (such as process congestion), then flame acceleration occurs and that under certain conditions, the flame will achieve the high speeds required to generate damaging pressures.

The explanation for this flame acceleration lies with the interaction of flow generated by the combustion with the repeated obstacles. If the gas cloud is unconfined, the products behind the flame front are free to expand and will generate an outward flow ahead of the flame. The speed of this flow will be small initially but as the flame front encounters obstacles and follows the flow around them, the flame will distort, increasing its area and the rate at which combustion products are generated. This will increase the flow speeds ahead of the flame, leading to the generation of turbulence in the wake of obstacles. When the flame enters the turbulence, the local burning velocity of the flame will increase.

These factors combine to produce a higher rate of combustion at the flame front and more products behind the flame, which then increases the flow ahead of the flame. This can produce a positive feedback mechanism in repeated obstacles, producing successively higher flame speeds and increasing overpressures, as illustrated Figure 3 [3]. Under certain conditions, this can lead to continuous flame acceleration.

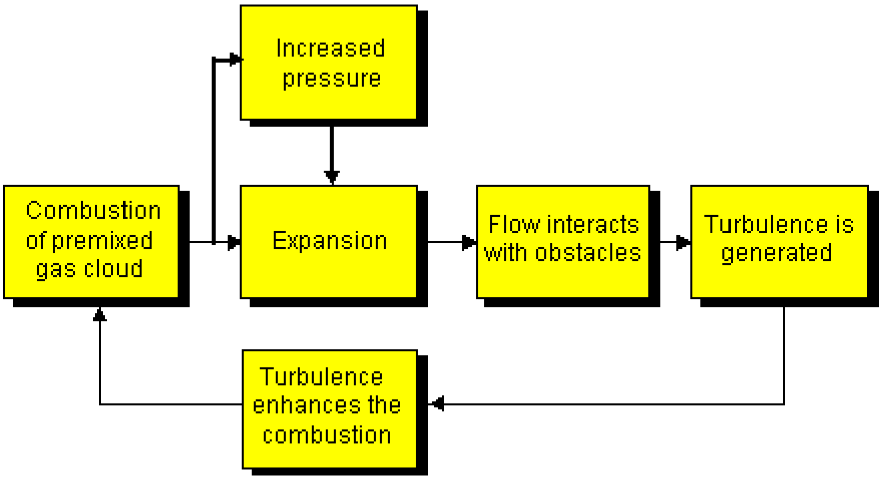

Figure 3: Positive feedback loop causing flame acceleration due to turbulence

This type of explosion generally involves flame speeds below the ambient speed of sound and is often termed as a **deflagration**.

In the absence of congestion capable of producing flame acceleration, ignition of a vapour cloud will result in low flame speeds and no significant generation of pressure. This is often termed a **flash fire** or **flash flame**.

Particularly severe explosions may result if the congested region is also partially confined as the flow field generated by the expanding combustion products can be directed through the pipework to a much greater degree, generating greater levels of turbulence.

The factors that influence the severity of a deflagration include the following:

- The concentration and composition of the gas within the mixture.
- The amount and type of any congestion present (size, orientation).
- The amount and type of confinement present (size, failure pressure).
- Nature of the ignition source.
- Size of the cloud within a congested region.

The degree of congestion can be characterised by the volume blockage (the proportion of any volume filled by obstacles) or area blockage and the average diameter of the obstacles. All other things being equal, explosions in congested regions with greater volume blockage (for the same diameter of obstacles) or smaller obstacle diameter (for the same volume blockage) will produce overpressures of greater magnitude.

In general, mixtures with higher burning velocities will produce greater magnitude overpressures.

An important aspect of deflagrations is that the high flame speeds are dependent on the continued presence of obstacles. Once the flame passes into an open area it rapidly decelerates. Pressure generation is therefore limited to regions of repeated obstacles with the magnitude of the pressure wave produced by the explosion decreasing as it propagates away from the congested region. The rate at which the observed pressure decays will depend to an extent on the nature of the actual explosion.

Deflagrations are defined as subsonic flame propagation. However, experimental work has shown that under more extreme conditions, shock wave interactions with the flame front can induce higher flame speeds in excess of the ambient speed of sound. Large scale experiments with these conditions have led to transition from deflagration to **detonation** for some hydrocarbons.

The key properties of a detonation, as compared to a deflagration are:

- The detonation front (analogous to the flame front in a deflagration) has an initial sudden rise in pressure, which then decays. This sudden rise in pressure is known as a shock front and the whole pressure wave as a shock wave.
- The shock front compresses the fuel/air mixture and in doing so, raises its temperature. In a detonation, the temperature rise is sufficient to initiate combustion as it exceeds the autoignition temperature of the mixture.
- Energy released from the combustion process maintains the magnitude of the shock front.
- This coupling of the shock wave and combustion process is self-sustaining and is not dependent upon the presence of obstacles.
- In an unconfined vapour cloud, the volume of the cloud that contributes to pressure generation is determined by the extent of cloud within the concentration limits that can sustain a detonation. Compared to a deflagration, this can be a significant increase if the cloud extends well outside areas of congestion.

The initial shock front typically has a magnitude in excess of 20 bar for hydrocarbon/air mixtures initially at atmospheric pressure. The detonation front travels at speeds of the order of $1800 ms^{-1}$.

Different fuels have different propensities for undergoing detonation. Common fuels can be considered in three classes:

- Fuels that readily detonate: such as hydrogen, acetylene and ethylene.
- Intermediate fuels where detonation is possible in practical situations but less likely: such as propane and butane. The vapour cloud formed at Buncefield falls into this category.
- Fuels that are very difficult to detonate: such as methane and natural gas.

The fuel/air concentrations that can sustain a detonation is a narrower range than the flammable range.

Recent studies have shown that vapour cloud detonation provides the only consistent explanation for some vapour cloud incidents [4], [5]. However, these incidents involved flammable vapour clouds formed from intermediate fuels, not natural gas. Large scale experimental studies conducted by DNV GL involving severe natural gas deflagrations did not result in a transition to detonation [6] and given the relatively low levels of congestion on the Stogit Minerbio site (see Section 3), a detonation of a natural gas-air cloud on the Stogit facilities is not credible. Vapour cloud detonations are therefore not considered within the guidance provided.

2.3 Blast Wave Propagation

The overpressure generated in the explosion region propagates away from that region. The level of overpressure decreases with distance. The rate of decay of overpressure with distance depends on the initial source overpressure and the energy in the source. That is, the larger the volume of the source explosion, the slower the rate pressure decays with distance, and the larger the area of damage. This is analogous to a large high explosive charge causing damage over a wider area compared to a small charge. Hence when considering the likely level of damage caused by the blast at a distance away from the source region, the volume of the source region needs to be considered as well as the severity of the explosion.

3 EXPERIMENTAL STUDIES

Large scale experimental studies have been carried out to both understand the mechanisms involved in pressure generation and to provide data for the validation of explosion models. Reference is made here to studies carried out at the DNV GL Spadeadam test facility in order to provide some background information against which the equipment on the Stogit Minerbio site can be viewed (see Section 4).

The experimental programmes referred to are:

- The EU co-founded MERGE and EMERGE projects [7], [8].
- Scaled vapour cloud explosion experiments in realistic congestion.
- Full scale offshore geometry experiments [9].
- Confined explosions venting into congested regions [10].

3.1 Projects MERGE and EMERGE

Projects MERGE and EMERGE were carried out by a consortium of research organisations throughout Europe. The objectives of the experimental programmes were to:

- Provide experimental data to aid the development and validation of explosion models.
- Investigate the potential to replicate large scale explosion behaviour in smaller scale test rigs.

Medium and large scale experiments were conducted at the DNV GL Spadeadam test site.

The experiments were undertaken in half cube-shape regions, containing a rectangular pipework array. MERGE and EMERGE used eight types of arrays formed by tubes with the same diameter forming a regular 3D grid. The grid had a single regular spacing between the pipes in each orthogonal section. Figure 4 illustrates the test configuration, showing a view of the medium scale test rig.

Figure 4: Medium Scale Test Configuration for MERGE and EMERGE (Obstacle Type C)

Table 1 shows the details of the congested regions used in the experiments. The fuels used were methane, propane, ethylene and methane/propane mixture. All these fuel were mixed with air to an approximate stoichiometric concentration.

Table 1: Details of the congested regions MERGE/EMERGE experiments

Grid type	Dimension of the Congested Region (m)	Pipe diameter (m)	Pipe spacing (m)	Volume Blockage (in %)
A	4×4×2	0.043	0.2	10
B	4×4×2	0.041	0.133	20
B*	3.5×3.5×1.7	0.041	0.133	20
C	4×4×2	0.086	0.4	10
D	4.3×4.3×2.1	0.082	0.267	20
E	**8×8×4**	**0.168**	**0.8**	**10**
C*	**7.6×7.6×3.7**	**0.082**	**0.384**	**10**
F	4×4×2	0.043	0.283	5

The volume blockage is defined as the proportion of the overall congested region volume that is filled by the pipes.

Though the full experimental programme provides a comprehensive set of data, it is the large scale experiments with obstacle type E and C* that are the most relevant to this guidance. Figure 5 shows the congested regions used in these experiments. The dimensions of the congested pipework regions were up to 8mx8mx4m high.

The overpressures generated within the congested regions in methane tests were 140mbar and 910mbar for Types E and C* congestion respectively. For 75%/25% methane/propane mixture, the equivalent overpressures were 160mbar and 990mbar. Natural gas might be expected to give slightly higher overpressures than methane, given the presence of higher hydrocarbons, but not as much as the increase for the methane/propane mixture. The difference between methane and natural gas would therefore be only a few percent.

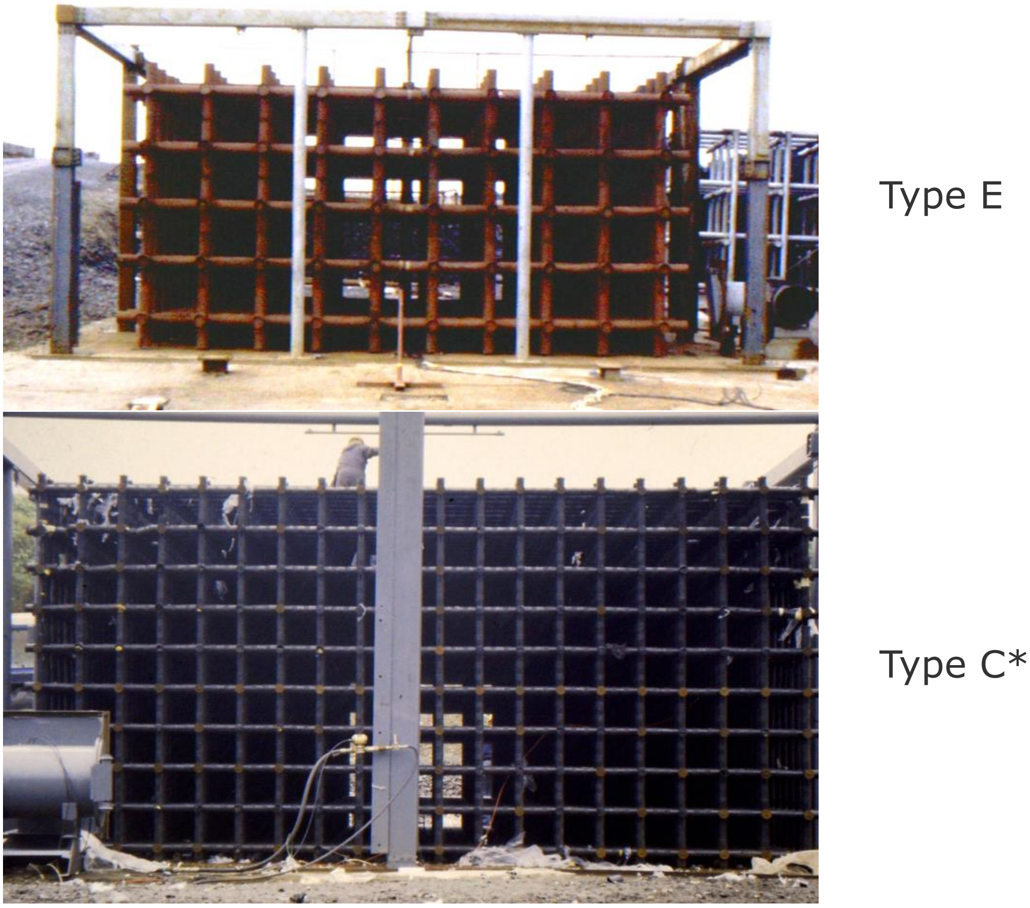

Figure 5: Pipework Congestion Used in Large Scale MERGE and EMERGE Experiments

3.2 Scaled Vapour Cloud Explosion Experiments

DNV GL has conducted a significant amount of research into the scaling of vapour cloud explosion experiments [7], [11]. This was required as the if the scale of an experiment is reduced, keeping all other things equal, then lower pressures are generated in the smaller scale test compared to the larger one.

The research showed that the scale effects could be counteracted to a reasonable degree by oxygen enriching the natural gas air mixture. This technique was then applied to a range of reduced scale models of real process regions. Figure 6 shows one of the test facilities used in this research, which is a one-fifth scale model of a pipe rack and LNG pump region on an LNG storage facility. The maximum width (at the LNG pump region) was about 4m, with a maximum height of about 2m, with most of the pipe rack elevated at a height of just over 1m. This experimental rig represented a full scale pipework region measuring up to 20m across and 10m high.

Figure 7 shows a representation of the experimental test facility from a 3D geometry file.

Figure 6: One Fifth Linear Scale Model of a Real Process Region

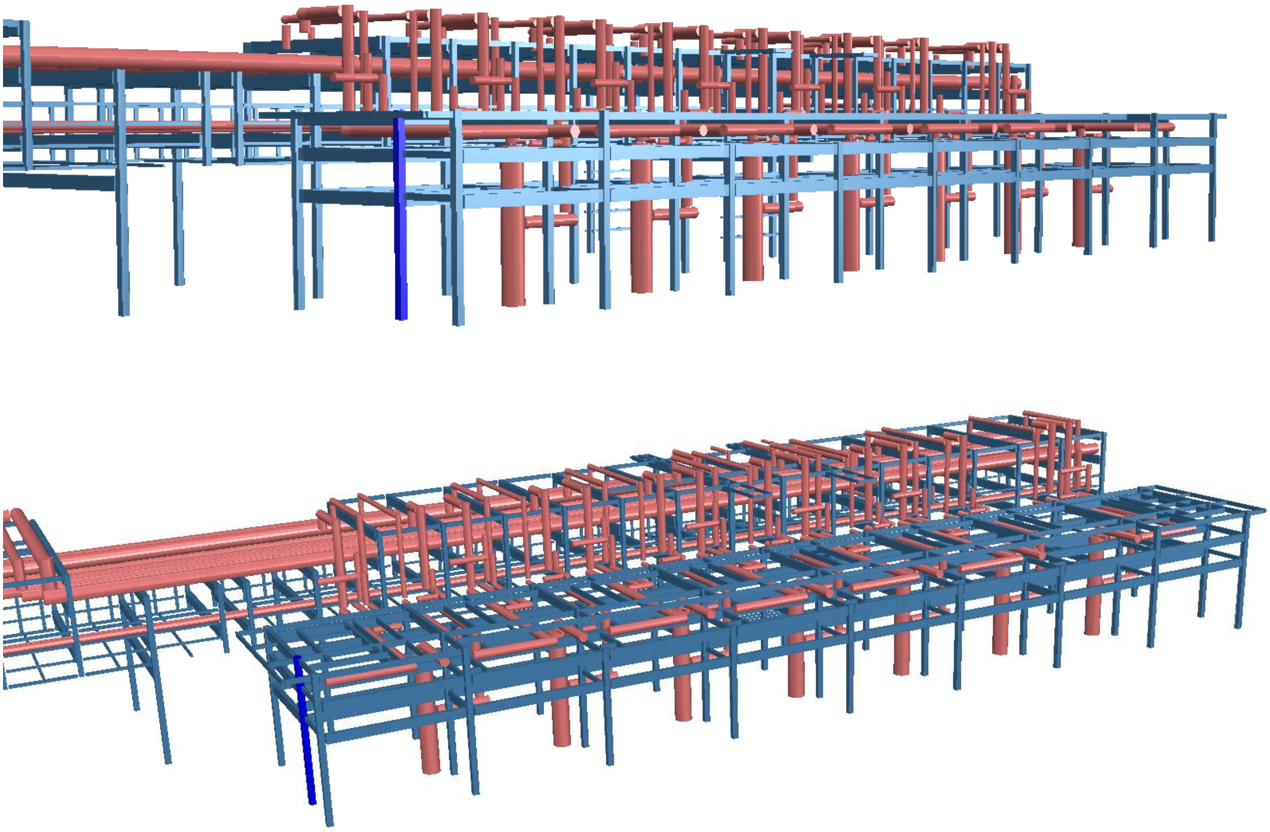

Figure 7: 3D Computer Geometry of LNG Pump Region

In experiments where the natural gas-air mixture was oxygen enriched to adjust for scale effects, the maximum overpressure was generated in the LNG pump region, being approximately 150mbar. If a box is defined around the elevated part of the LNG pump region and associated pipe rack, as shown in Figure 8, the volume blockage and a representative mean equipment (including structure, pipework and vessels) diameter can be calculated. This allows some relationship to be generated between the idealised geometries in the MERGE/EMERGE experiments and the realistic geometries.

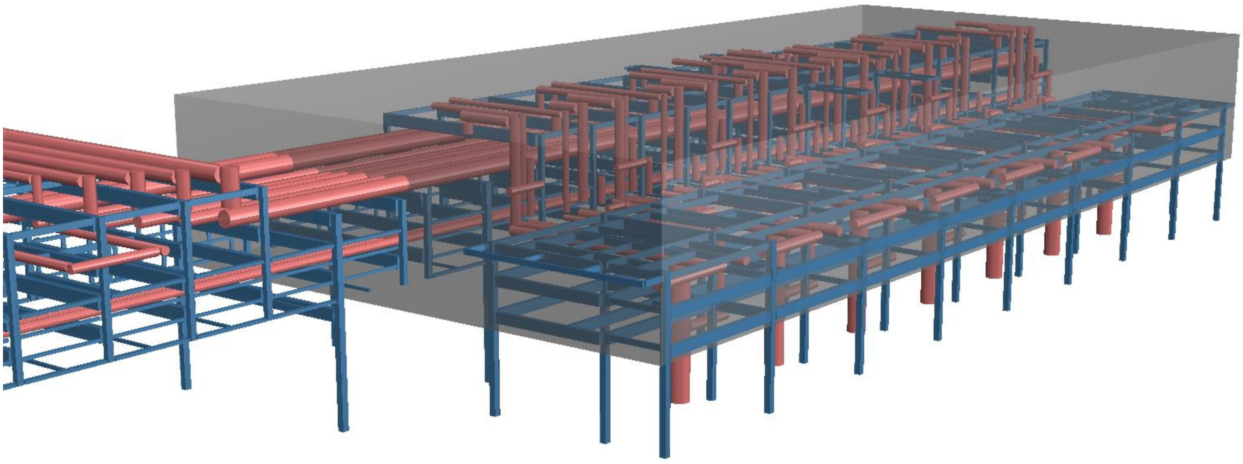

Figure 8: Domain Used for Volume Blockage Calculation

The volume blockage is calculated as:

$$B_V = \frac{V_o}{V_r} \times 100$$

Where:

B_V is the percentage volume blockage.

V_o is the combined volume of the equipment in the domain defined by the box.

V_r is the volume of the domain.

The mean diameter is calculated as an average of the equipment diameters weighted by their respective length:

$$D_m = \frac{\sum d_i . l_i}{\sum l_i}$$

Where the summations are carried out over all of the items of equipment with diameters within the specified range and:

D_m is the mean diameter

d_i is the diameter of an item of equipment

l_i is the length of the item of equipment

In calculating the mean equipment diameter, obstacles with rectangular cross-sections are given a representative diameter which conserves the cross-sectional area. In addition, I-beams have been considered as having a rectangular cross-section with the dimensions of the sides corresponding to the width and depth of the beam.

Using this approach, the volume blockage of the experimental test rig is calculated as 2.26% and the mean equipment diameter as 0.045m, which equates to a full scale mean equipment diameter of 0.225m.

A second region used in scaled explosion experiments is shown in Figure 9. This was a region that measured approximately 30m square and about 15m high. It was also adjacent to a wall. The volume blockage was approximately 1.6% with a mean equipment diameter (excluding the large green box) of 0.22m at full scale. The maximum overpressure generated in the oxygen enriched natural gas-air experiments was 400mbar.

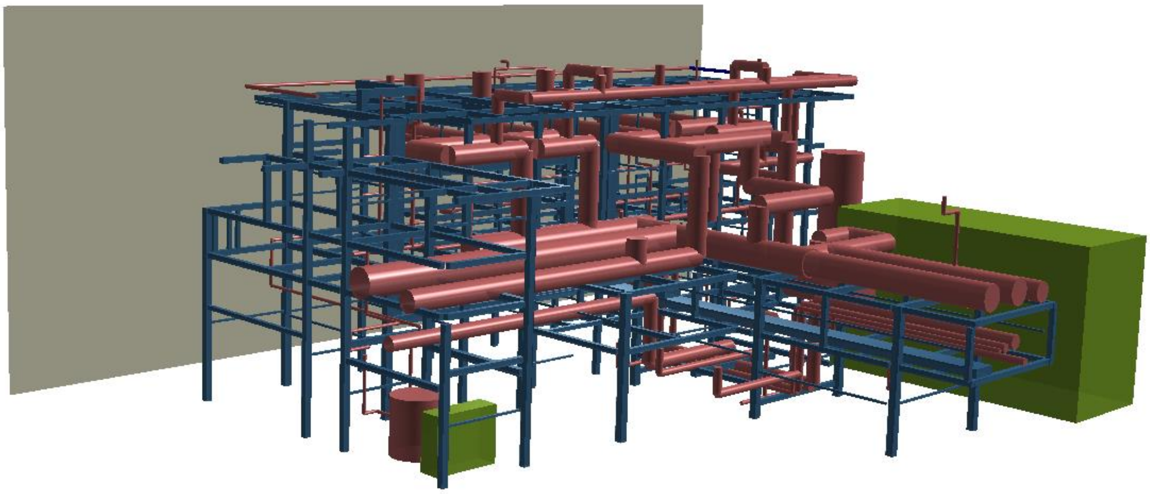

Figure 9: One Quarter Scale Congested Region with Wall

3.3 Full Scale Offshore Geometry Experiments

Following the Piper Alpha disaster in 1988 [12], there were a number of projects carried out with the objective of providing guidance on the design of offshore facilities against fire and blast. As part of this work, full scale experiments were carried out at the DNV GL Spadeadam test facility. The test rig measured, at its maximum 28mx12mx8m high and is shown in Figure 10.

Figure 10: Full Scale Offshore Test Rig

Over one hundred experiments were carried out in this facility and though most of them involved a significant amount of roof and wall confinement, a small number of experiments were conducted with no walls and only two thirds of the roof confined [13]. The experiments can used as a guide to the overpressures that can be produced by a large densely congested process region with a small degree of confinement.

The experiments used a number of different process congestion configurations and also different ignition locations. Two process congestion configurations, named O2 and O5 in the report, are referred to here and two ignition positions are considered (I2 and I3 in the report). The details of the process congestion are given in Table 2.

Table 2: Process Congestion Used in Full Scale Experiments

Congestion Configuration	Maximum Diameter Included (m)	Volume Blockage (%)	Mean Diameter (m)
O2	All	9.62	0.131
	0.5	3.40	0.106
O5	All	8.27	0.127
	0.5	3.31	0.116

The two ignition positions I2 and I3 were located at mid-height in the centre and at one end of the test rig respectively.

The overpressure generated in these configurations varied significantly across the test rig particularly for the end ignition point I3 which had the maximum flame acceleration path of 28m. Table 3 gives the range of peak pressures and average for each congestion and ignition location. There were over 30 pressure measurements taken in each experiment. It can be seen that though high overpressures are generated in some parts of the test rig, the average is very similar in both cases. The high overpressure pulses were of short duration, lasting just a few milliseconds.

Table 3: Overpressures Generated in Full Scale Offshore Experiments

	Ignition at I2 Congestion O2	Ignition at I3 Congestion O5
Maximum (mbar)	5,580	10,240
Minimum (mbar)	458	172
Average (mbar)	1,250	1,245

It should be noted that the experiments were carried out with a near stoichiometric homogenous natural gas-air mixture throughout the full test rig. This is the worst case both in terms of the fuel concentration and the extent of the natural gas cloud. It should also be noted that the roof of this process region was confined over 2/3rds of its area.

3.4 Confined Explosions Venting into Congested Regions

The combination of confinement and external process pipework occurs on actual process facilities. A series of large scale experiments, carried out by the former DNV GL examined the effect of pipework congestion located outside confined regions.

Two explosion chambers were used in the programme, one being approximately cubical, with a volume of 112 m^3, the second being a cuboid with a 2:1:1 aspect ratio and a volume of 182 m^3. The test facilities are shown in Figure 11.

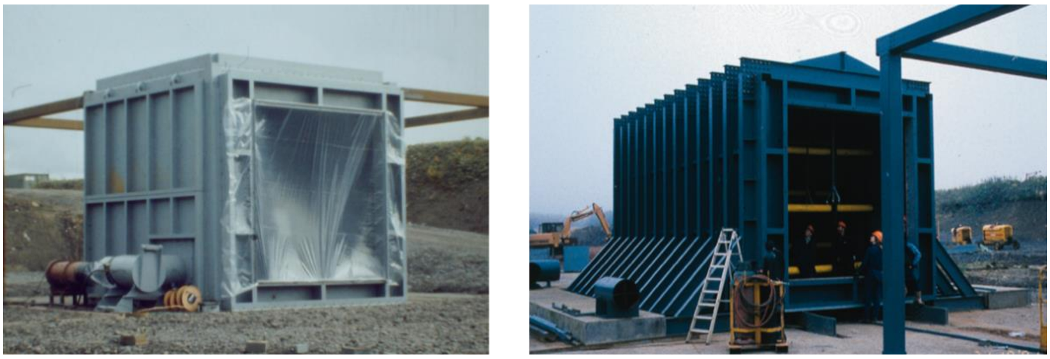

Figure 11: Explosion Chambers

The external congested regions were formed from 80 and 170mm diameter pipes to give 5% and 10% volume blockage. This gave four combinations of external congestion, with examples of three of these shown in Figure 12.

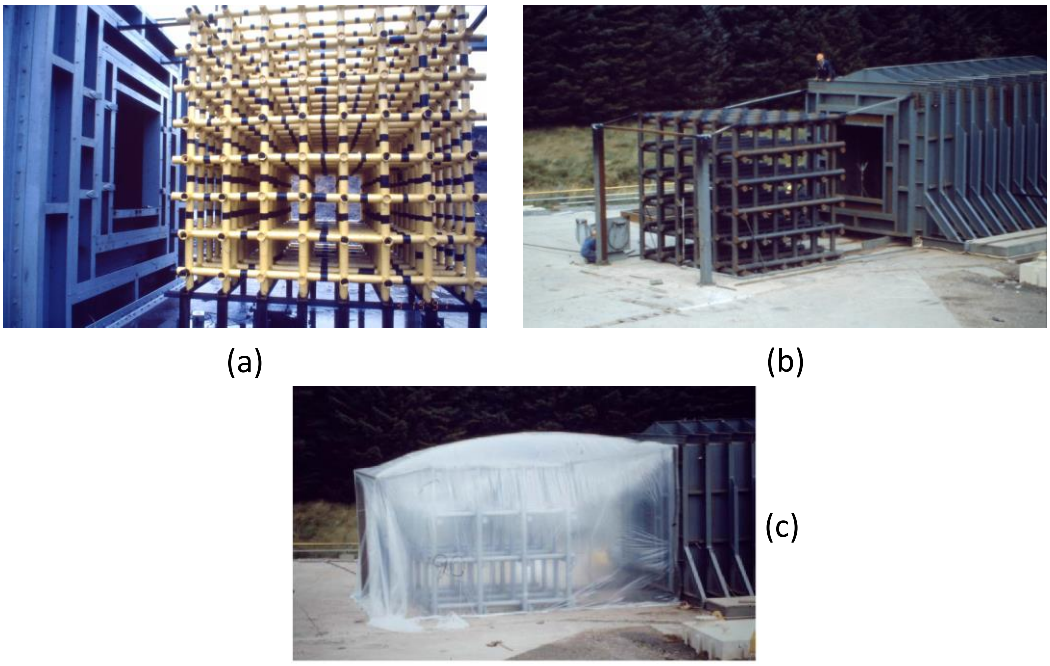

Figure 12: Experimental Arrangement Showing Examples of External Congestion

In natural gas-air experiments, the pressure generated in the external congestion varied considerably depending on the size of the vent from the explosion chamber and the congested region used, however overpressures exceeding 1bar were generated in many of the configurations. Comparison with the MERGE geometries indicates that the pressures are significantly higher than would occur if a cloud engulfing the congested region only were ignited.

These experiments indicate that Stogit need to give particular attention to any significant congested regions present immediately adjacent to confined volumes where there is a possibility of the flammable cloud being present inside and outside the confinement.

4 SURVEY OF MINERBIO EXPLOSION REGIONS

A visit was made to the Stogit Minerbio gas storage facility on 7th August 2014 in order to gain an appreciation of the potential for gas explosions on the storage sites. The photographic record taken during the visit has been used to faciliate commentary on potential regions where explosion overpressures could be developed.

4.1 Confined Regions

The primary confined regions are the six compressor enclosures, an example of which is shown in Figure 13. Given that the degree of pipework congestion within these enclosures is not severe, the overpressure produced by an explosion in this building will most likely be determined by the failure pressure of the enclosure itself. Essentially, the building will be pressurised internally by the combustion inside the building until structural failure occurs.

Figure 13: Compressor Enclosure

In order to be able to assess the overpressures that might be generated at distance from the enclosure the failure pressure of the walls, doors and roof need to be estimated. If the structural element that has the lowest failure pressure has a small area (e.g. the doors) it is likely that this will be insufficient to properly vent the explosion and the pressure will continue to rise until the next boundary confinement element fails. The roof may well be the weakest boundary confinement, but this would need to be confirmed.

There is no significant pipework congestion immediately adjacent to the enclosure, so the potential for an enhanced external explosion (as described in Section 3.4) does not need to be considered.

As structural failure will occur in this type of explosion, there is the potential for missiles to be generated. It is considered that missiles would not represent a hazard to the public off site given the distances to the site boundary, but could represent a hazard to onsite personnel. In this respect it would be preferable if the compressor enclosure boundary elements that fail first are not on the side facing the administration and control buildings as this should prevent missiles being projected towards the buildings. The location of the enclosures in relation to these buildings is shown in Figure 14.

Figure 14: Location of the Compressor Enclosures in Relation to the Admin/Control Buildings

There are number of other buildings on site that in general do not have any natural gas supply within them. For these buildings, there is the potential that a natural gas leak from another location could ingress into the building and cause a confined explosion if ignited. However, given that emergency shutdown should reduce the duration and size of any release quickly and that gas ingress would take time if windows are normally closed, then the risk of gas ingress into these buildings is considered to be low.

The main exception to this is the building containing the firewater pumps, shown in Figure 15. The door for this building was open at the time of the visit. If a gas cloud were to disperse towards this building, there is the potential that the firewater pumps may be activated as a result of the release and cause ignition. This is the actual sequence of events that caused the ignition of the vapour cloud in the Buncefield incident in the UK in 2005 [14]. It would be advisable to confirm that either the building is located outside the range of any flammable gas clouds or that the doors are kept closed when not in use (preferably spring loaded to close) and it is confirmed that they provide a reasonable seal against gas ingress.

Figure 15: Building Containing Firewater Pumps

4.2 Regions of Congestion

The site at Minerbio has two distinct areas; the area around the compressor enclosures; and the gas treatment area (primarily dehydration) for the natural gas produced from the storage reservoirs. These areas are considered separately.

4.2.1 Compressor Enclosure Area

A view of the area around the compressors is shown in Figure 16.

Figure 16: Compressor Area of the Minerbio Site

There is a small amount of pipework between the compressor buildings, shown in Figure 13 and Figure 17.

Figure 17: Pipework Between Compressor Enclosures

Comparison of this pipework with the experimental geometries in Section 3 shows that the size of the regions and degree of congestion is substantially less than those test facilities, where the overpressures generated were just over 100mbar. The pipework between the compressor enclosures would generate minimal flame acceleration and as the overpressures are dependent on the square of the flame speed, the overpressures generated would be negligible. These pipework regions need not be considered in any assessment of vapour cloud explosion hazards.

Air coolers are also located in the compressor area of the site. An example of one of these is shown in Figure 18. This region is more substantial than the pipework between the compressor enclosures and additionally has some degree of confinement above. The degree of congestion is still low in comparison to the experimental enclosures and it is considered that 100mbar would be a conservative estimate for the pressures that would be generated by the ignition of a stoichiometric natural gas-air cloud engulfing the whole of this region.

Figure 18: Air Cooler in Compressor Area

There is also some pipework in the vicinity of the air coolers, as shown in Figure 19. Again, the small size of these regions and the low degree of congestion means they should be excluded from any vapour cloud explosion analysis.

Figure 19: Pipework Adjacent to the Air Coolers

It should be noted that there were some buildings and pipework regions in the compressor area that were viewed but are not in use and it is understood that they will be removed. These regions have not been included within this assessment.

4.2.2 Gas Treatment Area

The gas treatment area is located in separate part of the site and can be considered as a completely independent area to that around the compressor enclosures. The area comprises two nominally identical process trains whose primary function is to dry the gas produced from the storage reservoir.

Figure 20 shows the pipework adjacent to the dehydration towers. This pipework is mostly at a single level with some occasional pipework at higher levels. In terms of scale, the pipework region is comparable to the LNG pump region described in Section 3.2 (at full scale) but only has a single layer of pipes. Compared to the two layers in the LNG pump region, there is also less structural support steelwork. However, the pipework is close to the ground which will tend to give higher overpressures compared to an elevated pipe rack. Overall, it is considered that the 150mbar overpressure generated in the LNG pump region will provide a cautious estimate of the overpressures that would be generated by ignition of a stoichiometric natural gas cloud engulfing this area.

Figure 20: Pipework Adjacent to Dehydration Towers

Figure 21 shows another region of process pipework in this area. This unit is larger than the MERGE/EMERGE test rigs but much less congested. This makes estimation of the worst case natural gas explosion in this area more difficult. However, the region is clearly much smaller and less congested than the full scale offshore geometry but may be closer in size to the second scaled explosion rig geometry, though without the wall present. Given this, it is considered that an overpressure of 400mbar would be conservative for this region, with a pressure of 200mbar probably being closer to realistic. However it is recommended that this is checked using the methodology given in Section 5.

Figure 21: Process Unit in Dehydration Area

Finally in this area, there were a number of road crossings where pipe runs passed underneath the site road. These will provide confinement of the pipework, potentially producing a situation where more rapid flame acceleration could occur.

Figure 22 shows an example of where a pipe run passes beneath a road. The congestion mostly consists of pipework in line with the pipe run with little obstruction orthogonal to it. The orthogonal obstructions would contribute most to any flame acceleration and so it is considered that these road crossings do not represent a region that could generate damaging overpressures.

Figure 22: Example Road Crossing

5 ASSESSMENT METHODOLOGY

The purpose of this section is to build upon the comparisons made between experimental studies and pipework regions on the Minerbio site to provide more general guidance suitable for more application to other similar sites.

In providing this guidance, it is noted that there is no international standard on the methods to be used in assessing explosion hazards, though there is guidance on various aspects provided by a number of industry organisations (for example [17], [18], [19]). The guidance provided in this report is based on an understanding of the approaches given in the industry guidance combined with DNV GL's experience gained from conducting experimental research, developing explosion models and applying this knowledge to actual facilities.

5.1 Overview of Explosion Assessment

The objective of explosion assessment is to estimate the potential for harm to people and damage, both onsite and offsite, as a result of explosions. The assessment can be carried out in two ways:

- **Consequence Based** – where calculations are carried out on specific scenarios, with a single or small set of conditions. These may, for example, be worst case calculations where a specified explosion region is completely engulfed by a stoichiometric vapour cloud. Alternatively, the analysis may be based on a 'maximum credible event', where only a proportion of an explosion region is engulfed by a cloud. The main difficulty with this latter approach is that the definition of the maximum credible event is at best uncertain.
- **Risk Based** – which is often used where design against the worst case event is not practicable. In this approach, many gas release and dispersion events are analysed to determine the likelihood of a flammable cloud engulfing part or all of an explosion region. Explosion consequence calculations are carried out for each of these cases and combined with the dispersion analysis to produce an exceedance curve, which gives the frequency of an explosion exceeding a particular severity. Designs loads can then be specified in the knowledge that they will not be exceeded more often than, for example, once in 10,000 years. Such exceedance analysis also provides an input to assessing the risks to people.

The guidance provided here is intended to assist with the conduct of the explosion consequence calculations; it does not extend to the risk based analysis.

There are two aspects to the prediction of the explosion consequences on an onshore site:

- The overpressures developed in the source of the explosion, be it a congested process region or a confined enclosure.
- The decay of this pressure from the source.

Though complex CFD modelling can be used to assess both of the aspects above, for installations such as Minerbio, this level of analysis is generally not justified and simpler methods can be used. These aspects are considered separately in the following sections.

5.2 Explosion Source

There are a number of issues that need to be included when assessing the potential explosion source strength:

- Is the region confined or is it a congested region (that may then be partially confined)?
- What are the boundaries of the explosion source? This is required to allow the volume of the explosion source to be defined and also generic parameters that describe the region to be calculated. This requires some judgement for open congested regions, which can be quite irregular.
- How are the shapes of the explosion sources taken into account? This is particularly important for explosion regions with a high aspect ratio such as pipe racks.
- Can adjacent regions interact to give a larger explosion?

Each of these aspects is considered in the following sections.

5.2.1 Confined or Congested?

As noted in the previous section the pressure generating mechanism is different for confined or congested regions. The approach to defining the dominant explosion mechanism has been derived through comparison of the predictions of DNV GL explosion models against data obtained from experiments involving representations of the type of congested and confined regions that might be present on Stogit facilities

Firstly, if the explosion region has no wall or roof confinement, it should be considered to be a congested region.

If there is some boundary confinement on a congested process area, the next step is to estimate the area of any permanent wall or roof openings as a proportion of the total wall area. There are then three categories of classification of the explosion region:

- If the open wall/roof area is more than 70% of the area of the top and sides of the region, the region should be considered as a **congested** region and appropriate modelling or assessment should be used.
- If the open wall/roof area is less than 10% of the wall area, the region should be considered as a **confined** region, with the vent parameters for each wall and the roof taken into account in the analysis.
- For cases with an open wall/roof area is between 10% and 70%, the region should be considered a **mixed** region and modelled as both confined and congested and the worst case of these two options selected.

In the case of a partially confined **congested** region, if the congestion substantially occupies the full interior of the enclosure, then the explosion region should correspond to the entire enclosure volume. The congestion parameters should be calculated based on the entire enclosure volume. The effect of the partial confinement on the explosion should be taken into account in this case.

If the congestion occupies substantially less than the full interior the enclosure, then the explosion region should correspond to the region of congestion only. The congestion parameters should be calculated based on the region of congestion only. Boundary confinement need only be included if it blocks a face of the congestion.

It is noted that all of the explosion regions on the Minerbio identified in Section 4 are clearly in the category of **congested** or **confined**, with none of the areas defined as mixed regions.

5.2.2 Explosion Severity for a Confined Explosion Region

For confined explosion regions where there is not a substantial amount of congestion within the enclosure, such as the compressor enclosures at Minerbio, the severity of the explosion source will be defined by the failure pressure of the boundary structure, defined as the critical building pressure.

The critical building pressure represents the minimum internal overpressure sufficient to cause the fabric of the enclosure to fail. A critical building failure pressure of about 140 mbar is appropriate for most brick or sheet-clad buildings. For other types of structure it is advisable to carry out some degree of structural analysis to determine the failure pressure. Guidance on building strengths case be found in references such as [17].

Decay calculations can be carried out using the TNO multi-energy method (MEM) explosion strength curve most closely corresponding to the critical building pressure (see Section 5.3). The volume of the vapour cloud should be set to be the total volume of the enclosure, even if the volume of the cloud inside the enclosure is less than the full volume. This is because the explosion is defined by the failure of the boundaries, not combustion of the cloud. Once the boundaries fail, any remaining combustion will not contribute to pressure generation.

If the confined volume contains a significant amount of process congestion, then explosion modelling is recommended. One option is the use of the DNV GL MORSE explosion suite within the ORDER and FROST packages. CFD modelling is also an option. It should be stressed that no confinement requiring modelling was observed during the visit to Minerbio.

5.2.3 Explosion Severity for a Congested Region

The discussion of the experimental data in Section 3 highlighted volume blockage and mean equipment diameter as two parameters that can be used to characterise process congestion. These parameters do not provide a completely perfect description of a congested region as it is likely two congested regions with the same mean equipment diameter and volume blockage but comprising very different distributions of equipment, may well result in different overpressures being generated. However, they provide an adequate guide for the selection of MEM explosion strength curves.

DNV GL has a phenomenological explosion model for congested explosion regions with an aspect ratio (maximum dimension to minimum dimension) of less than three within the MORSE explosion model suite. In order to provide some data to Stogit, DNV GL has prepared a set of plots based on output from the model to allow the source overpressures to be estimated. The plots are given in Appendix A. The main steps in the procedure are described in the following sections.

5.2.3.1 Calculation of explosion parameters

The volume blockage and mean equipment diameter should be calculated using the method described in Section 3.2. Definition of the domain to be used for the calculation requires some judgement. The domain should be defined as a cuboid that encompasses the main items of congestion but excludes single items that extend significantly beyond this.

For example, for the process unit shown in Figure 21, the cuboid would include the congestion up to the top platform but would exclude the top of the tower on the right hand side of the picture.

Large scale items would also normally be excluded. Typically items with a diameter significantly more than one metre would be excluded as they do not provide the same enhancement of the explosion process and significantly distort the explosion parameters.

If the congested region is elevated, then the domain defining the explosion region should also be elevated to meet the bottom level of the congestion, as shown in Figure 8.

5.2.3.2 Effect of confinement

The plots given in Appendix A are for congested regions at ground level. If the congested region is elevated of the ground to a level that is greater than the depth of the congestion, then the pressures will be lower as a result of the reduced confinement allowing additional venting of combustion products from the underside of the region.

The means for accounting for this is to halve the congested region volume for the calculation of the source overpressure, though for any distance scaling in MEM, the full volume of the congestion should be used. The basis for this approach is that for congestion on the ground, the ground acts as a boundary of symmetry. For elevated congestion, this boundary of symmetry can be restored if a horizontal plane is placed at half of the height of the explosion region, halving the volume of the congestion.

Where confinement of one side of the congestion is present, then this can be accounted for by doubling the volume of the congestion. In this case, the confinement of the side provides an additional boundary of symmetry, effectively making the region double the size. Again, this is just for the calculation of the source pressure, the volume used to scale distances in MEM should be the actual volume of the explosion region.

It there is confinement on the top of an elevated section of congestion, similar to the air coolers shown in Figure 18, then the top confinement acts as the boundary of symmetry in a similar manner to the ground and the volume of the explosion region should not be changed.

If there is a more complex arrangement of confinement on the congested region, then it is likely that some explosion modelling will be required. Examples would be the use of the MORSE model in ORDER. It is noted that no such complex arrangement of confinement was observed on the Minerbio site.

5.2.3.3 High aspect ratio explosion regions

Where the ratio of the minimum dimension of the congested region to the maximum dimension is significantly greater than three, then the approach needs to be modified. This is because there is experimental evidence that for long regions such as pipe racks, the flame speed will not continue to accelerate but will reach a stable near constant speed. For example, if the domain around the LNG Pump region is considered, it is clear that the ratio of *a* to *c* is more than three.

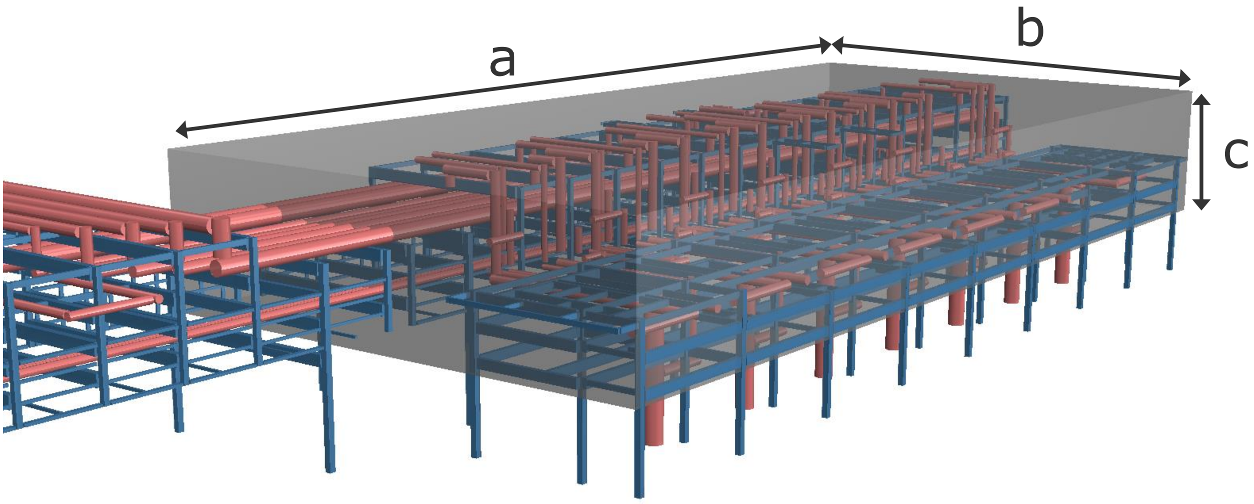

Figure 23: Explosion Domain of LNG Pump Region

In this case the volume of the explosion region used in the estimation of the source overpressure should be:

$$6.b.c.\sqrt{}(b.c)$$

Again, this is to be used in the calculation of the source overpressure, scaled distances should be calculated on the basis of the full volume of the explosion region (or that portion of it filled by the vapour cloud).

5.2.4 Interactions

If two congested regions are close enough to each other, there is the possibility that an explosion can develop in one and then enter the second at an elevated speed, thus enhancing the explosion in the second explosion region.

Interactions can occur if one congested region is close to a second such that the gap between them is less than the mean diameter of the explosion region.

If it is possible for interactions to occur, then specialist modelling may be required.

5.3 Pressure Decay from the Source

There are a number of methods that allow the decay of the overpressure from the source to be calculated. Examples of these techniques are the TNT Equivalence Method [6], [15] and the TNO Multi-Energy Method (MEM) [16]. Application is of these approaches is relatively straightforward.

The scaled-energy TNT free field model uses a correlation based on blast curves from high energy explosives. By correlating with a mass of TNT however, the explosion source is effectively assumed to be 'severe' in that it will generate shock waves.

The MEM uses correlations fitted to the results of CFD model predictions to define the decay of pressure and change of wave shape as a function of distance from the source. The correlations were produced for a range of explosion severities, categorised as 1 (least severe) to 10, as shown in **Error! Reference source not found.**.

Actual distances are calculated by scaling by a factor proportional to the cube root of the combustion energy within the vapour cloud in the explosion region. The scaled pressure essentially equates to the actual pressure in barg.

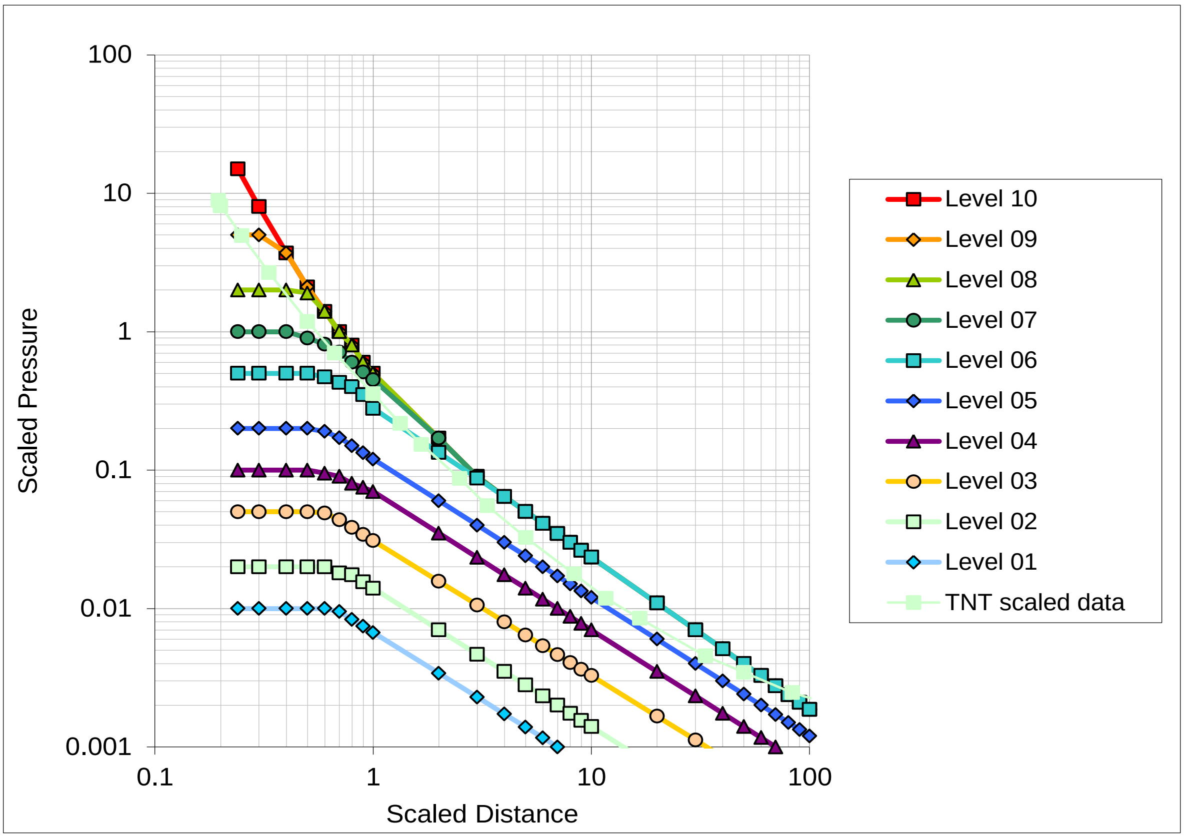

Figure 24: TNO MEM Decay Curves (Also showing TNT Scaled Data)

The MEM allows a less cautious overpressure decay to be used than in the TNT Equivalence model. However, the selection of the source strength is a user input hence it requires an "expert" user or some additional information, for example from a previous study or relevant experimental data to assess the best value to use for this parameter. In the absence of such additional information, the analysis often defaults to a cautious assumption of using curve 7, which assumes an approximate 1 bar source explosion. It can be seen from **Error! Reference source not found.** that it is only in the very near field that there is any difference between curves 7 to 10, however, if a lower explosion severity can be justified based on the type of analysis outlined in the previous section; this will make a significant difference to the far field pressures.

5.4 Summary

The overall approach to the assessment of potential explosion regions has been described in this section. Figure 25 summarises the assessment methodology in a flowchart for cases that are clearly congested or confined regions.

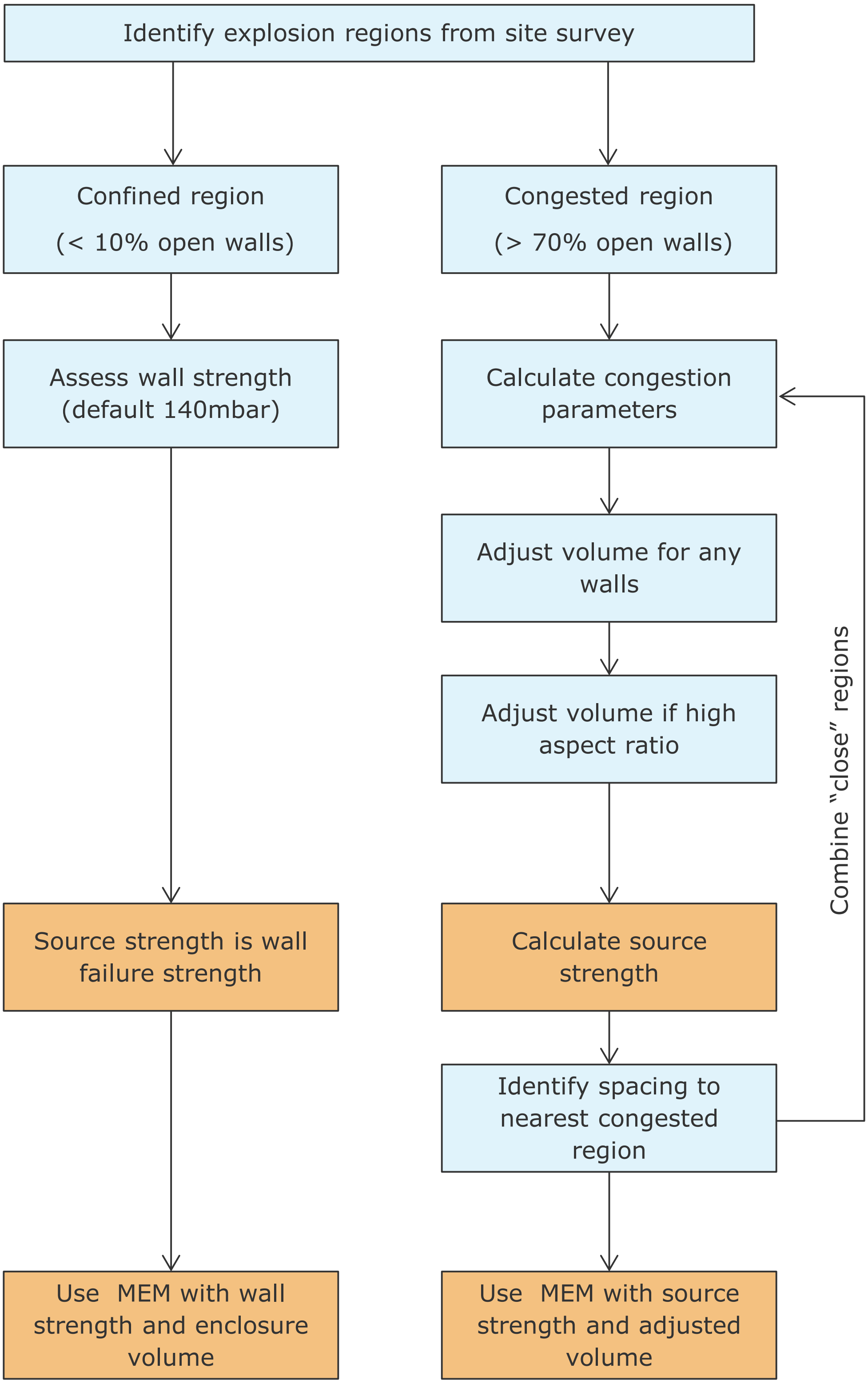

Figure 25 Overview of explosion assessment process

6 CONCLUSIONS

Guidance has been provided on the assessment of natural gas-air explosions on sites comparable to the Stogit Minerbio facility. This guidance has been based on a combination of DNV GL's understanding of both confined and vapour cloud explosions, data obtained from large and full scale experiments and explosion models available to DNV GL.

It should be noted that this guidance is relevant to natural gas-air explosions only and it should not be applied without consultation with DNV GL to explosions involving heavier hydrocarbons such as propane.

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APPENDIX A

Source Overpressures for Congested Explosions

The following plots give the explosion overpressure calculated for congested regions using the DNV GL explosion model MORSE. Plots are provided for various volume blockages and mean equipment diameters for explosion regions over a range of sizes. Two plots are given for each data set, one with a wide size range and the second with a smaller size range to allow better resolution for small explosion region sizes.

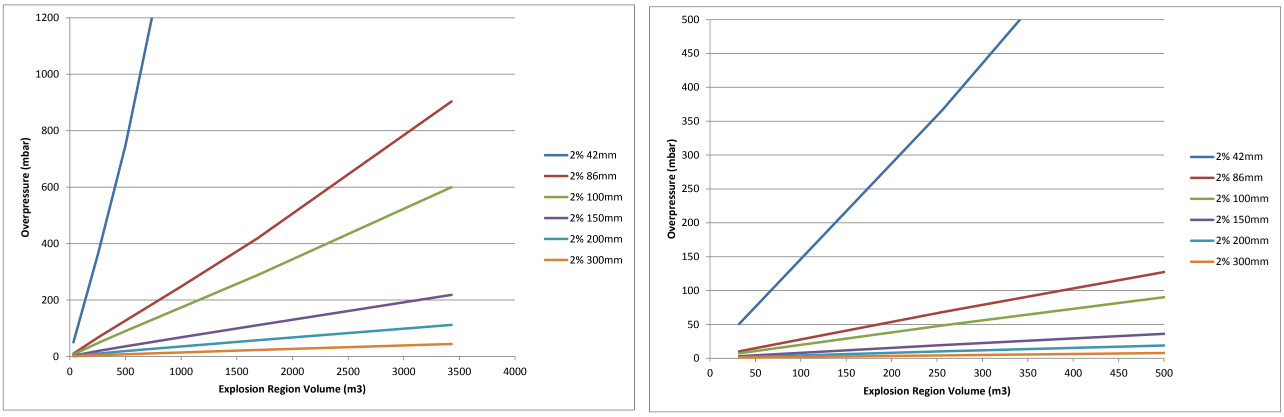

Figure 26: 2% Volume Blockage

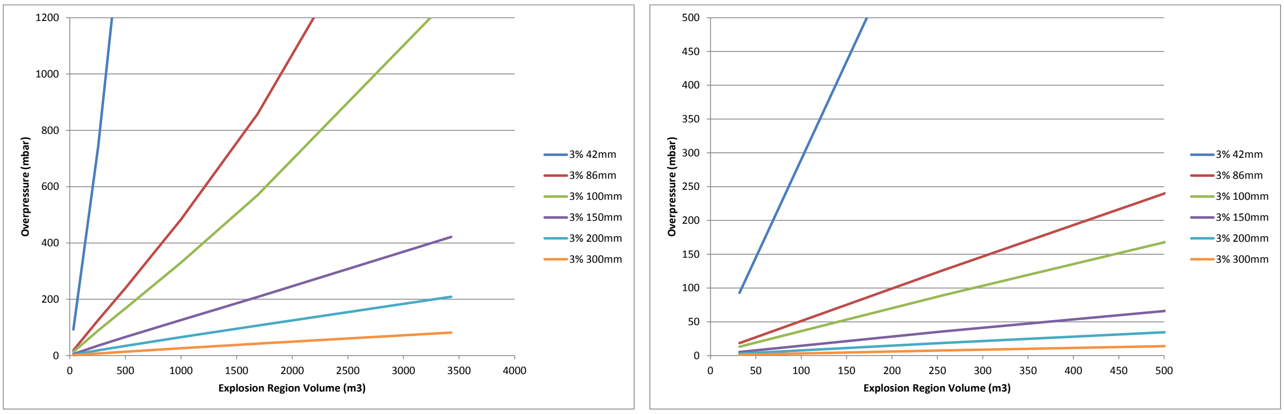

Figure 27: 3% Volume Blockage

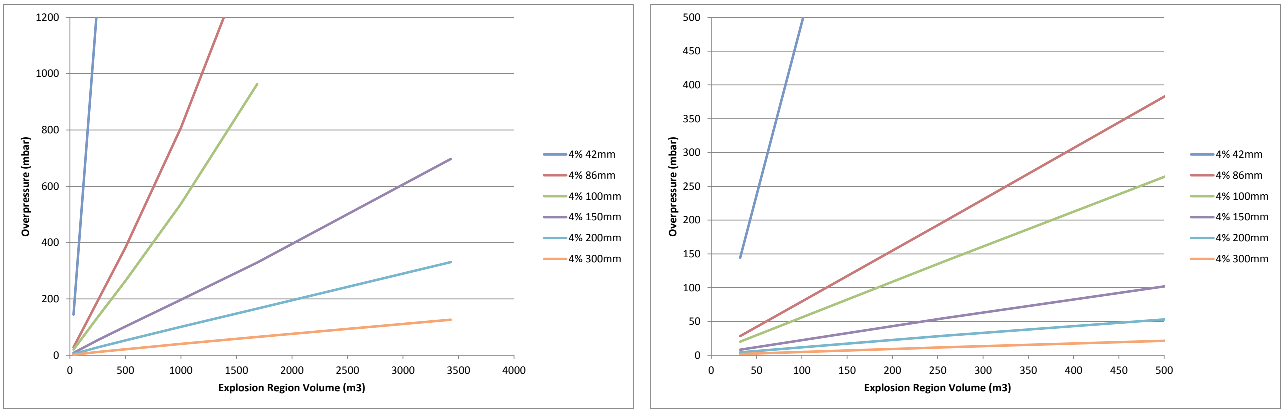

Figure 28: 4% Volume Blockage

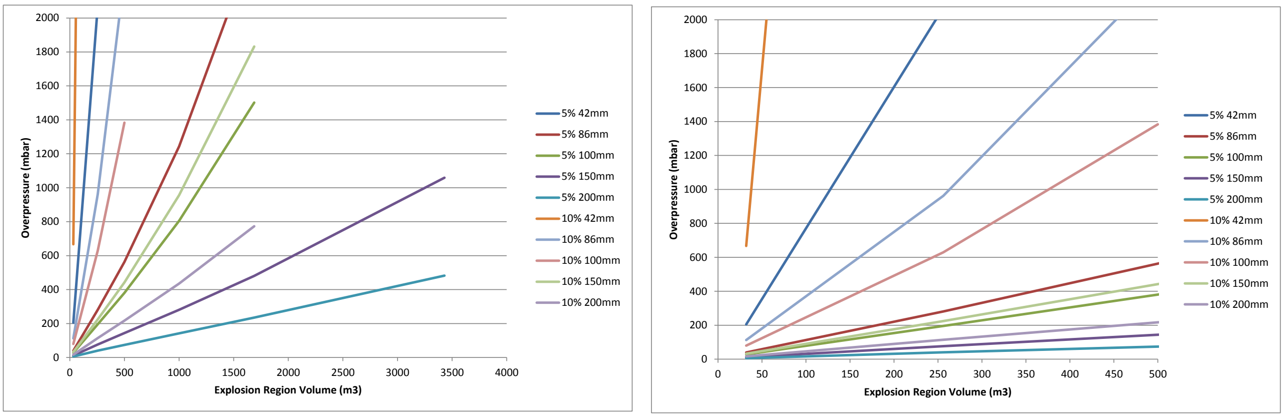

Figure 29: 5% and 10% Volume Blockage (note different pressure scale)

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