# The Use of CFD to Support ALARP Designs for Energy Centres

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## ABSTRACT

Due to the increasing demand for energy in the UK both for housing and industrial needs in recent years, the government has incentivised 'distributed' energy generation in order to reduce the strain on central generation capacity and increase energy efficiency. Since these Energy Centres use natural gas, the installation must comply with the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR). Due to space constraints, many new developments are unable to house the energy centre in a totally separate building. The basement location for an energy centre is not ideal for reducing the risk from explosion to members of the public and workers; industry standards and guidance recommend against this location. However, it can still be considered for building design, provided that the risks have been suitably assessed and can be shown to be As Low As Reasonably Practicable (ALARP). Standards provide high level design guidance, but no information is given on "how to" or "need to" properly assess this design concept. By means of detailed consequence analysis based on CFD simulations, this paper presents Gexcon's methodology to help review mitigation barriers and allow the design to be optimised with respect to them, and so assisting to demonstrate compliance with regulations and reduction of risk in line with the ALARP principle. The impact of ventilation, dispersion and gas detection on the explosion risks are discussed in detail.

**KEYWORDS:** CFD, ALARP, risk assessment, mitigation barriers.

## INTRODUCTION

Due to the increasing demand for energy in the UK both for housing and industrial needs in recent years, the government has incentivised "distributed grid" energy generation in order to reduce the strain on central generation capacity and increase energy efficiency. This approach considers localised centres generating energy by means of Combined Heat and Power (CHP) systems and highly efficient boilers. CHP plants use waste heat to achieve efficiencies in excess of 80%, while traditional gas power stations range around 50% and coal 40%.

As a result of large urban building developments, combined with a desire to maximise the use of limited space within the construction area, the number of designs incorporating energy centres within multi-use occupied buildings (e.g. basements) have increased dramatically. These centres, which are normally unmanned, usually combine large amounts of congestion (due to a wide variety of piping and equipment sizes) within very confined areas. This could lead to significant explosion consequences following the ignition of an accidental gas release.

Gexcon have seen a rise in requests for assistance in these type of facilities over the past few years, in order to provide advice concerning explosion safety related to the use of natural gas. Ultimately our support was to ensure that the schemes are designed and built in compliance with standards to demonstrate:

1. That the risks have been suitably assessed and to assist with demonstrating that the risks are As Low As Reasonably Practicable (ALARP) [1], in line with UK law, and

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2. That the facility complies with the requirements of the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) [2]

Due to space constraints, many new developments are unable to house the energy centre in a separate building. The basement location for an energy centre is not ideal for reducing the risk from explosion to members of the public and workers whose place of work is located within the multi-use building, and certain standards (e.g. IGEM/G/5 [3]) recommend against this location. However, basements can still be considered for building design, provided that the risks have been suitably assessed and can be shown to be ALARP [1], in line with the general duties under the Health and Safety at Work Act 1974 [4] and reinforced in Regulation 6 of DSEAR [2] which calls for the elimination or reduction of risks due to hazardous substances. Standards provide high-level design guidance, but no detailed information is available within accepted good practice and literature to properly assess this design concept and demonstrate that risks are ALARP [1].

By means of detailed consequence analysis based on Computational Fluid Dynamics (CFD) simulations using FLACS [5], a methodology is presented to help review mitigation barriers and allow the design to be optimised with respect to them, and so assisting to demonstrate compliance with the regulations.

## FLACS CFD SOFTWARE

The simulations in the present study were conducted by means of FLACS [5], a specialised CFD tool for safety applications developed by Gexcon AS. One of the key features that distinguishes FLACS [5] from most commercial CFD codes is the use of the porosity / distributed resistance (PDR) concept for representing complex geometries on relatively coarse computational meshes. Simulations were setup in a manner consistent with specific user guidelines. The User's Manual provides comprehensive information on how to set up simulations, the modelling and theory underlying the code, its experimental validations and its limitations.

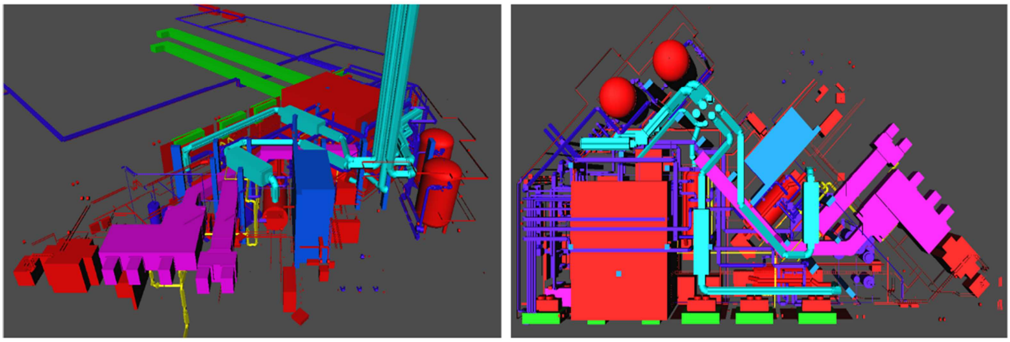


**Fig. 1.** Geometrical model created for the simulations of the energy centre (left, side view; right, top view).

## GEOMETRICAL MODEL

The first step in a simulation study is the construction of a geometry model. Gexcon has many years of experience in analysing onshore and offshore installations, at all stages of the project life cycle, from concept phase to decommissioning. An incomplete geometry model can be a significant source of uncertainty in the CFD analyses. For this reason, our studies tend to focus on building a representative model of the installation, paying close attention to congested regions, which contribute towards enhancing turbulence levels and mixing. This could result in higher overpressures in explosion scenarios or less effective ventilation and dispersion of gas clouds.

Figure 1 shows the geometrical model created for the study, where boilers, pipelines of different diameters, water tanks and even ventilation and flue extraction ducts (among others) were considered.

## VENTILATION ANALYSIS

An internal ventilation study was first conducted to provide the basis for the subsequent analysis. A detailed prediction of the internal flow patterns helps determine the effectiveness of the ventilation system and allows any potential dead spots to be identified. Ventilation patterns also provide valuable information to predict the potential behaviour of (low momentum) gas dispersion scenarios.

The energy centre accounted for several supply and extraction units distributed across the room and at different levels. Figure 2 provides an example of the flow velocity (UVW_3D) contour map at ground level. Good ventilation was observed in the room at different heights, particularly in the region in between boilers A and B and in front of boiler C, where there are gas lines and connections (i.e. flanges, valves, etc). Some areas of lower ventilation were observed around the water tanks and the lower right corner of the energy centre. This should not be a major issue, with respect to DSEAR [2], given that no gas lines were present in those regions.

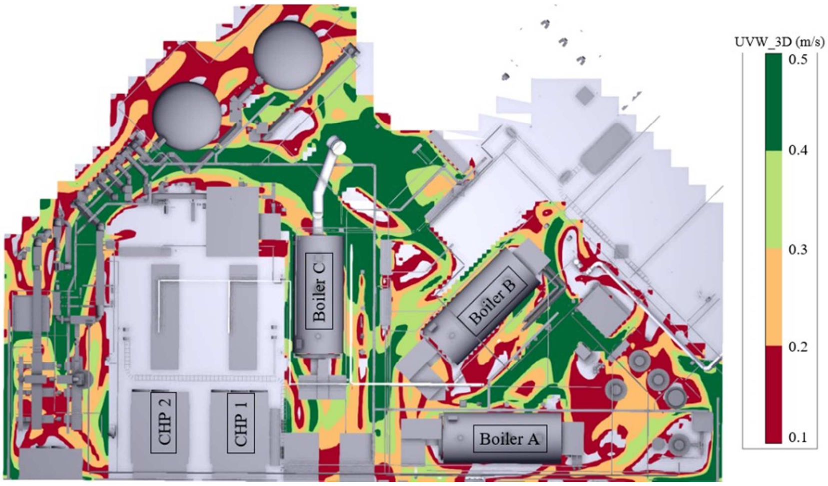


**Fig. 2.** Velocity contour map at ground level.

## DISPERSION ANALYSIS

The objective of the dispersion studies was to simulate a number of unintended gas releases that would provide realistic and accurate data on how gas might disperse and accumulate in different areas of the energy centre. Based on the gas line P&ID, a combination of leak locations, leak directions and leak rates were modelled so that the simulated gas clouds cover a representative number of realistic loss of containment scenarios. Leak scenarios were chosen based on those most likely to develop large clouds and those most likely to be challenging for the gas detection system. The flow patterns determined in the ventilation study were used to make this assessment. Figure 3 shows some of the leak locations and directions defined for the dispersion analysis at ground level. Releases were directed towards areas of ‘reduced’ ventilation, where dilution could be less effective.

Table 1 provides further details of the jet release pressures and hole sizes considered, which will directly affect the mass flow rate of the releases. A combination of full bore rupture (i.e. line diameter) and small hole size (30 mm) leak scenarios were considered.

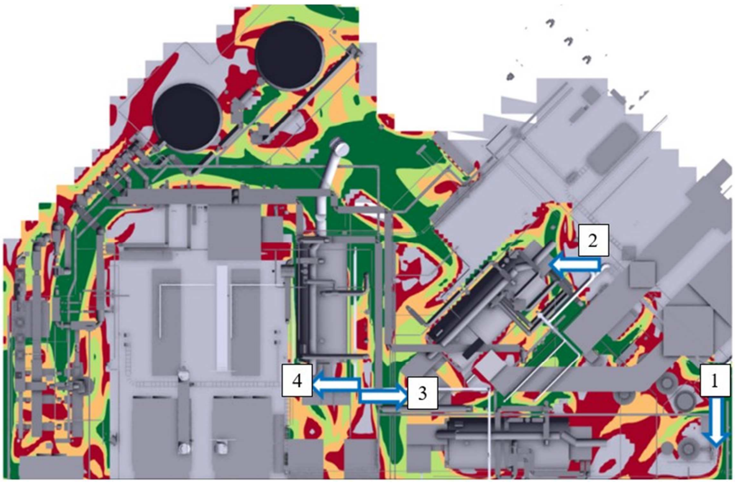


**Fig. 3.** Location and direction of leaks at ground level.

**Table 1. Combinations of release pressure and hole sizes considered for the study**

| Jet location | Release pressure (mbar) | Hole size (mm) |
|---|---|---|
| 1, 2, 5, 6 | 250 | 30 and 250 |
| 3, 4 | 250 | 30 and 100 |
| 7 | 150 | 30 and 125 |

The small hole sizes which statistically represent a typical installation are very demanding in terms of computational resources, hence a trade-off was made between the size of hole modelled and the time and resource required to model the scenario. Some design standards [3] consider hole sizes of 0.5 to 2.5 $mm^2$ depending on the type of installation when assessing the extent of hazardous areas for these types of facilities. This therefore results in the dispersion scenarios modelled being conservative when assessing small hole size releases. Item “FR 1.3 Pipework” [6] quantifies the frequencies for the small and large ruptures considered as $1x10^{-6}$ and $5x10^{-7}$ (per m per yr.) respectively for pipework diameter up to 149 mm, and $7x10^{-7}$ and $2x10^{-7}$ (per m per yr.) respectively for pipework diameter up to 299 mm.

Figure 4 and Fig. 5 show the evolution of the flammable gas cloud (i.e. between the Lower and Upper Flammability limits, LFL and UFL, respectively) based on the equivalence ratio as %LFL (ERLFL) for one of the release locations and different hole sizes. For a full bore rupture scenario, the upper half of the room is filled within a minute and a half following the release (see Fig. 4). But for a small hole size release, the extent of the flammable gas cloud remains within a 3 m radius of the release source (see Fig. 5). For a constant line pressure, the hole size plays a key role as the mass flow rate is significantly increased with a larger hole size. For this case, the mass flow rate achieved for a full bore rupture was 7.3 kg/s, while for a small hole size release this was just 0.1 kg/s (i.e. 73 times smaller).

Further information on the flammable gas cloud size for the different release scenarios simulated is shown in Fig. 6 (full bore rupture) for the release time modelled. To evaluate the hazard of a given gas cloud, Gexcon has developed methods for natural gas that aim at estimating an equivalent stoichiometric gas cloud (Q9) with comparable explosion consequences [7]. The resulting cloud is a scaling of the non-homogeneous gas cloud to a smaller stoichiometric gas cloud that is expected to give similar explosion loads as the original cloud (provided the shape and position of the cloud are chosen conservatively, as is the ignition point).

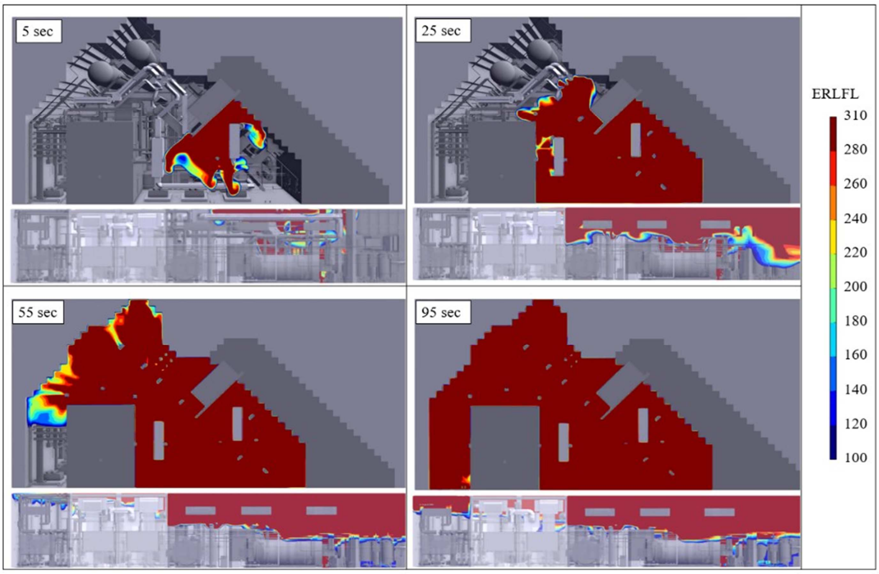


**Fig. 4.** Flammable gas cloud evolution from a 'full bore rupture' release at location #2 (LFL blue, UFL red).

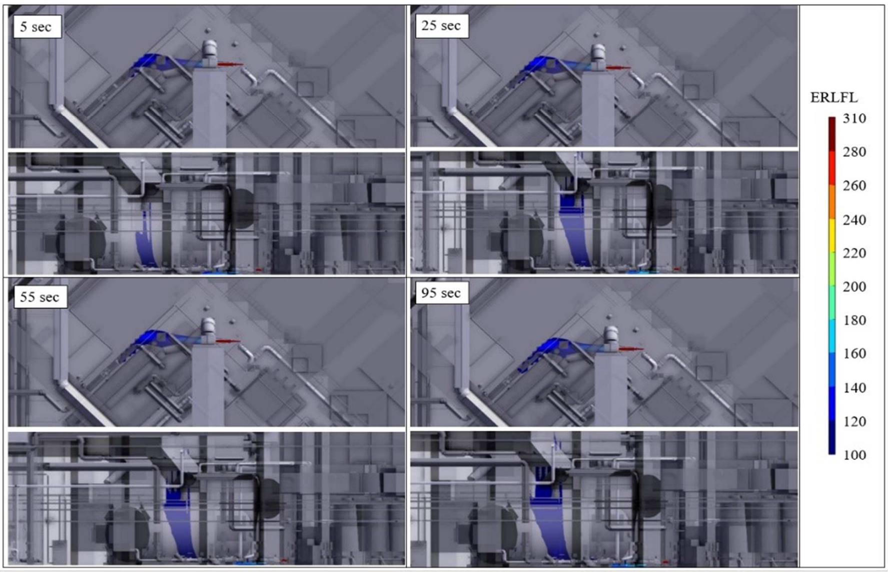


**Fig. 5.** Flammable gas cloud evolution from a 'small hole size' release at location #2 (LFL blue, UFL red).

A wide range of cloud sizes was obtained for full bore rupture scenarios as shown in Fig. 6, ranging from 175 $m^3$ up to almost 1200 $m^3$. These low frequency catastrophic scenarios are very unlikely to occur except in certain specific circumstances, such as physical impact or long-term vibration fatigue [6]. A good inspection and maintenance program coupled with control of activities in the area will substantially reduce the likelihood of these scenarios.

On the other hand, for the smaller hole size with higher event frequency, representing releases at flanges and other connections, the cloud sizes were several orders of magnitude smaller than those for catastrophic full bore rupture scenarios. Here, the maximum gas cloud was approximately 0.33 $m^3$ for the scenarios considered. It is thus deemed that the ventilation system was effective at preventing the build-up of a dangerous flammable gas cloud within the room for these situations.

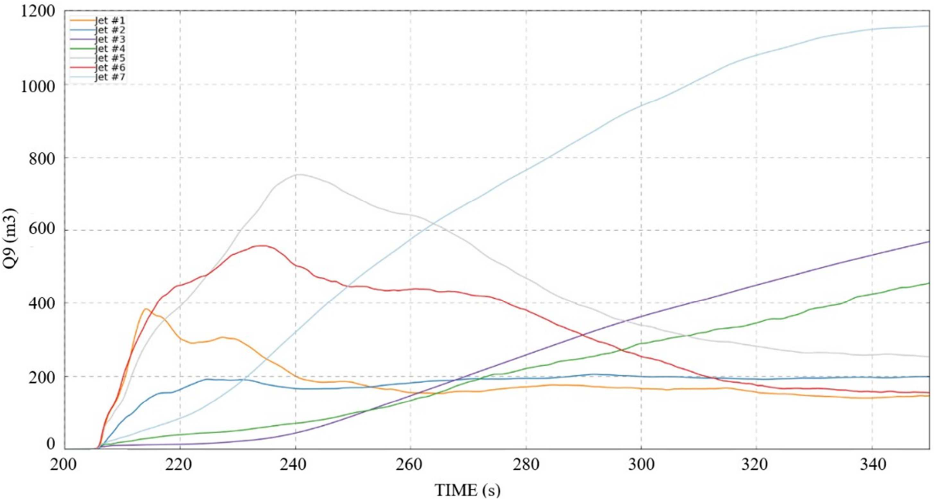


**Fig. 6.** Equivalent gas cloud sizes (Q9) obtained from full bore rupture release scenarios.

## GAS DETECTION ANALYSIS

From the dispersion scenarios modelled it was possible to observe that small hole size leaks created small clouds which remain localised to the leak source. However, catastrophic full bore rupture scenarios created a wider range of flammable gas clouds that could fill the entire room.

A gas detection study was conducted to analyse the most effective means to mitigate the formation of large gas clouds in the event of a release. Different gas detector layouts with a varying number of detectors and locations were considered as shown in Fig. 7.

The performance of the detectors was evaluated based on an actuation set point relative to the LFL (i.e. 20%). A 1ooN (i.e. 1 out of N detectors) voting criteria was considered, meaning that detection arising from a single detector is needed to trigger an action (e.g. emergency automatic isolation of the gas solenoid valve). The different gas detector layouts proposed and analysed were tested against the results obtained from the dispersion study. Table 2 summarises the performance for each layout in terms of isolation time, were a shut-off valve response time of 1 second was considered for this exercise and so added to the detection time.

While all the scenarios simulated were detected, some differences between layouts were observed with respect to isolation time. For the full bore rupture scenarios, detection times between the layouts did not change considerably, consistent with the formation of large gas clouds within a short period of time resulted in consistent and short time to detection. For small hole size releases, differences in detection time were observed in most of the dispersion scenarios. While the performance between a system with 4 detectors (i.e. Layout 1) and 8 detectors (i.e. Layout 2) was very similar, 5 out of 7 scenarios were detected earlier with a larger number of detectors (i.e. 10 for Layout 3 and 12 for Layout 4). In the scenarios considered, Layout 4 appears to detect faster than Layout 3 for most of the releases, and so it was the recommended layout based on the analysis.

It should be noted, however, that testing a larger number of and different leak locations/directions other than those considered here could provide a different outcome and hence these results are indicative only, although they have been selected based on reasonable assumptions on the likely leak locations. Detection performance will also ultimately rely on selecting the correct detector type, proper system design and installation, coupled with ongoing inspection and maintenance of the system.

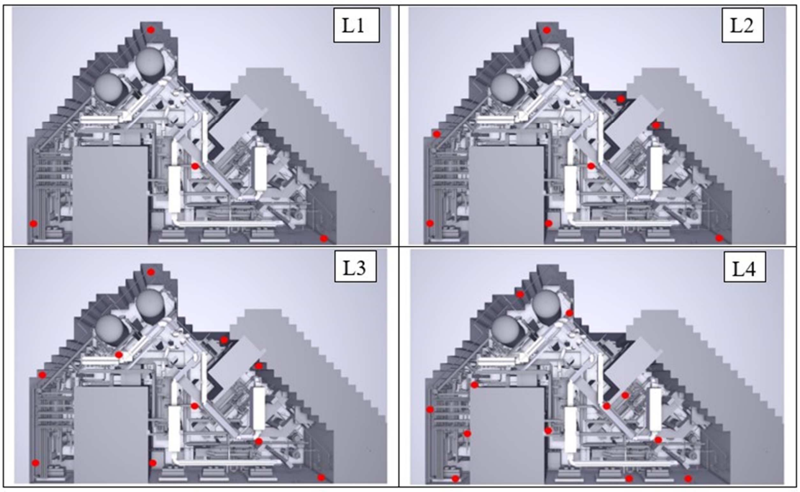


**Fig. 7.** Proposed point gas detector layouts. Red dots indicate the location of the gas sensors at ceiling height.

**Table 2. Gas detector layouts performance for different releases conditions**

| Jet location | Isolation time (s) – Full bore rupture release | | | | Isolation time (s) – Small hole size release | | | |
|---|---|---|---|---|---|---|---|---|
| | L1 | L2 | L3 | L4 | L1 | L2 | L3 | L4 |
| 1 | 2.5 | 2.5 | 2.5 | 3.0 | 7.5 | 7.5 | 7.5 | 26.0 |
| 2 | 6.0 | 4.0 | 3.0 | 2.0 | 117.5 | 21.0 | 13.0 | 7.5 |
| 3 | 6.0 | 6.0 | 6.0 | 6.0 | 52.5 | 52.5 | 52.5 | 38.0 |
| 4 | 6.0 | 6.0 | 5.0 | 6.0 | 46.0 | 46.0 | 37.5 | 20.0 |
| 5 | 3.5 | 3.5 | 3.5 | 2.5 | 23.5 | 23.5 | 23.5 | 11.5 |
| 6 | 3.0 | 3.0 | 3.0 | 3.0 | 57.5 | 57.5 | 57.5 | 53.0 |
| 7 | 2.5 | 2.5 | 2.5 | 3.0 | 5.0 | 5.0 | 5.0 | 5.0 |

## EXPLOSION ANALYSIS

Gas explosion simulations were conducted to ascertain the magnitude of the internal overpressures that could be generated if the cloud size (at the time of isolation) was ignited by a potential ignition source.

Table 3 summarises the gas cloud sizes obtained for full bore rupture and small hole size releases respectively for the different gas detection layouts. Clouds up to 110 $m^3$ were observed for full bore rupture scenarios, showing a significant decrease in the achievable maximum gas cloud compared to the values shown in Fig. 6. On the other hand, gas clouds from small hole size releases remained very small (maximum 0.33 $m^3$).

Figure 8 shows a comparison of the gas clouds for a full bore rupture and a small hole size release for dispersion scenario #2. The size of the clouds corresponds to the maximum value obtained for each corresponding scenario upon isolation (i.e. 91 $m^3$ for full bore rupture and 0.33 $m^3$ for small hole size release). The locations of the clouds were selected based on the dispersion patterns observed for the different release scenarios. The orange dot in the figures represents the ignition location, a combination of corner and centre-based positions were considered for the different dispersion scenarios studied.

**Table 3. Gas cloud size upon isolation for the different dispersion scenarios and detection layouts**

| Jet location | Full bore rupture release | | | | | Small hole size release | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | L1 | L2 | L3 | L4 | **MAX** | L1 | L2 | L3 | L4 | **MAX** |
| 1 | 90.0 | 90.0 | 90.0 | 106.0 | **106.0** | 0.06 | 0.06 | 0.06 | 0.06 | **0.06** |
| 2 | 91.0 | 58.0 | 38.0 | 19.0 | **91.0** | 0.33 | 0.22 | 0.21 | 0.16 | **0.33** |
| 3 | 11.0 | 11.0 | 11.0 | 11.0 | **11.0** | 0.09 | 0.09 | 0.09 | 0.09 | **0.09** |
| 4 | 21.0 | 21.0 | 19.0 | 21.0 | **21.0** | 0.09 | 0.09 | 0.09 | 0.08 | **0.09** |
| 5 | 98.0 | 98.0 | 98.0 | 75.0 | **98.0** | 0.08 | 0.08 | 0.08 | 0.08 | **0.08** |
| 6 | 109.0 | 109.0 | 109.0 | 109.0 | **109.0** | 0.07 | 0.07 | 0.07 | 0.07 | **0.07** |
| 7 | 20.0 | 20.0 | 20.0 | 23.0 | **23.0** | 0.11 | 0.11 | 0.11 | 0.11 | **0.11** |

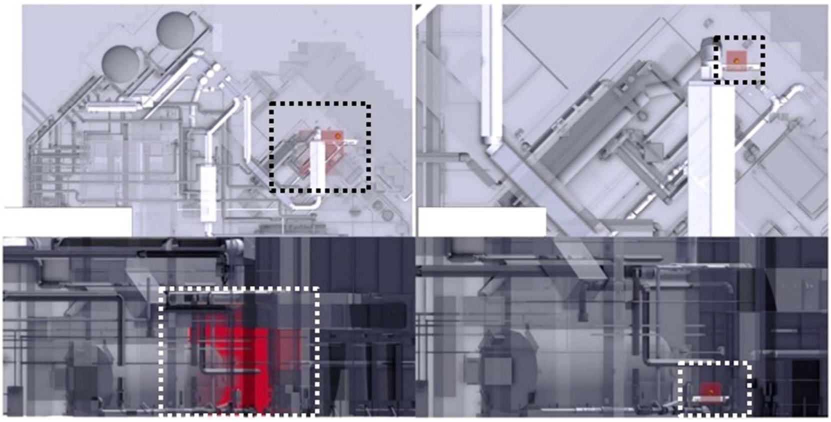


**Fig. 8.** Clouds (in red) defined for dispersion scenario #2 (left, full bore rupture; right: small hole size).

Figure 9 shows the approximate internal pressures reached following ignition of the different maximum gas cloud sizes (upon isolation) from full bore rupture scenarios. Pressure magnitudes (P) ranged from 0.02 barg for the smallest cloud considered (~11 $m^3$) up to 0.23 barg for the largest clouds (~109 $m^3$), remaining below the building slab resistance (~0.35 barg). No heat transfer through the walls was considered for the explosion analysis, hence the reason why the pressure does not decay in time after reaching a peak value. On the other hand, and for small hole size releases, very low internal pressures in the room were obtained for all the scenarios analysed and did not exceed 0.002 barg (i.e. typical pressure required to shatter a large glass window [8]).

A closer look at the internal pressure distribution inside the energy centre is shown in Fig. 10, where it is possible to observe that this peak pressure was only seen around the lower left corner area.

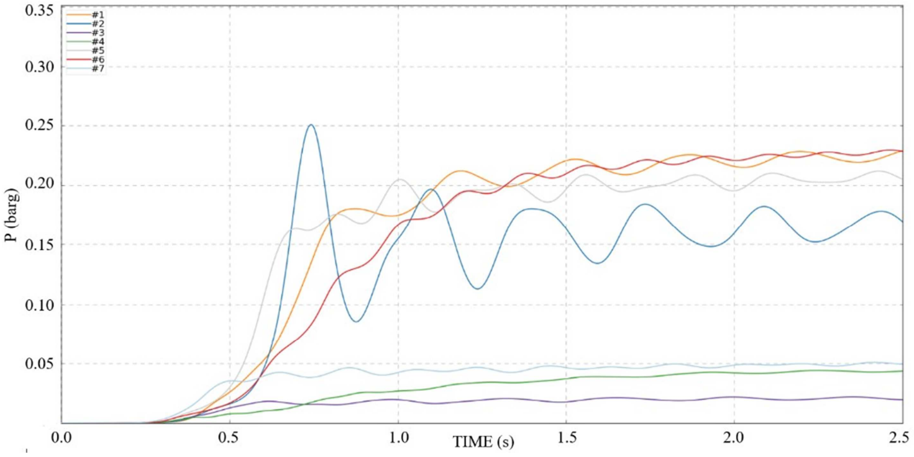


**Fig. 9.** Internal overpressures inside the energy centre following a gas explosion after full bore rupture.

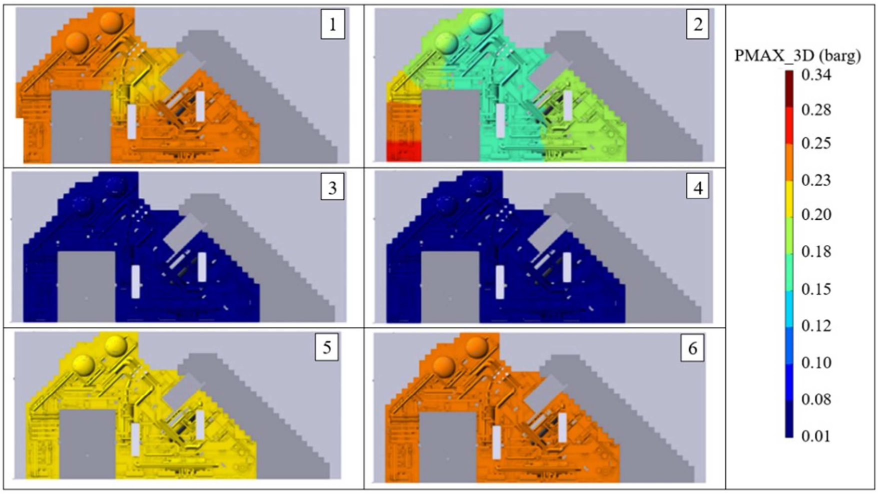


**Fig. 10.** Maximum pressure distribution (PMAX_3D) following a gas cloud explosion - full bore rupture.

## DSEAR COMPLIANCE AND RISK ASSESSMENT

Since the facility (multi-use building) incorporates workers and uses natural gas, which has the potential to create a flammable or explosive atmosphere, the installation must comply with the DSEAR regulations [2]. These require amongst other things to conduct a Hazardous Area Classification (Regulation 5) and a suitable and sufficient Risk Assessment (Regulation 7). While catastrophic releases should be considered as part of the Risk Assessment, the Hazardous Area Classification focuses on “reasonably foreseeable” releases, which may occur during normal operation.

### Hazardous Area Classification

Regulation 7 of DSEAR [2] requires that all employers shall classify places at the workplace where an explosive atmosphere may occur into hazardous or non-hazardous places. Detailed ventilation, dispersion and gas explosion simulations were conducted with FLACS [5] to determine the magnitude of the internal overpressures that could be generated if the cloud size (at the time of isolation) arising from a small hole size release was ignited by a potential ignition source.

Table 3 above shows the gas cloud size upon isolation for the different dispersion scenarios and detection layouts modelled using a leak orifice diameter of 30 mm. This is a very conservative leak orifice diameter, since generally 0.56 mm (calculated from a 0.25 $mm^2$ cross sectional orifice area) is used in IGEM standards [3], which is already considered to provide conservative results. The modelling results showed that the maximum gas cloud which could be formed is 0.33 $m^3$, which would have a diameter of 0.85 m assuming a spherical cloud. As the leak orifice diameter used for modelling is so conservative, the volume of gas cloud formed from a typical secondary grade of release (e.g. a flange leak) would typically be significantly smaller than this in reality.

The ventilation study concluded that good ventilation was present in the room at different heights, particularly in the region around the boilers, and around connections (i.e. flanges, valves, etc) on the gas lines. The degree of ventilation can then be considered as high relative to the potential gas cloud volume with fair availability for this installation, therefore the installation can be classified and maintained as Zone 2 NE (i.e. a hazardous zone in theory which would have negligible effect if ignited) in line with European Standard EN 60079-10-1 [9].

### Evaluation of the Guidance from IGEM/G/5 Edition 2

An evaluation has been made in respect to the industry guidance document IGEM/G/5 [3]. The standard makes use of the terms ‘must’, ‘shall’ and ‘should’, when prescribing requirements according to the law. Several sections of the standard, that advise against the location of an Energy Centre in the basement, could be challenged based on the information provided by the simulations:

- Section 8.1.3 Note 2 deals with the response of the building structure to a range of releases. It has been demonstrated that even large leaks (i.e. 30 mm diameter hole size, which at 707 $mm^2$ are much greater than the typical size of 0.25 $mm^2$ recommended by IGEM guidance [3]) do not form a gas cloud which would compromise the structure of the energy centre.
- Section 8.2.1 deals with the location of the EC in the building. Leak detection, emergency isolation and robust ventilation systems are considered to reduce the risk to ALARP for the chosen location. FLACS [5] modelling shows that if an explosion occurs, then the structure will be protected as the peak overpressure is below the maximum allowable slab resistance.

### Risk Assessment

In order to demonstrate ALARP, risks must be assessed, and additional risk reduction measures should be put in place to reduce the risks, where it is reasonably practicable to do so. An explosion following a catastrophic full bore rupture or a small hole size release is a credible worst-case consequence. Various barriers exist to either prevent or mitigate against this, including ventilation (to disperse gas clouds) and detection (to identify leaks and isolate the gas supply).

### Barrier Assessment by means of bowtie diagrams

A 'bowtie' is a diagram that visualizes the risk in one easy to communicate picture. The diagram is shaped like a bowtie, where the ‘hazard’ sits on top, followed by the ‘top event’ (moment when control is lost over the hazard). Described on the left are the ‘threats’ (whatever will cause the top event), while on the right are the ‘consequences’ (results from the top event). Finally, in between, the ‘barriers’ controlling (on the left) and mitigating (on the right) unwanted scenarios.

The bowtie diagram in Fig. 11 [10] shows the relationship between the potential causes and consequences of a gas leak in the pipework of the energy centre, together with the barriers identified and required under European Standard EN 60079-10-1 [9] and the IGEM/G/5 [3]. While an explosion was identified as a credible worst-case consequence, the assessment shows that maintenance and inspection are of critical importance in preventing the degradation of the facility over time. It was assumed that the pipework and gas and fire detection systems are inspected and maintained periodically, and that the equipment will be commissioned by a competent person so that, where appropriate, the gas supply will be promptly and safely isolated upon an alarm being triggered.

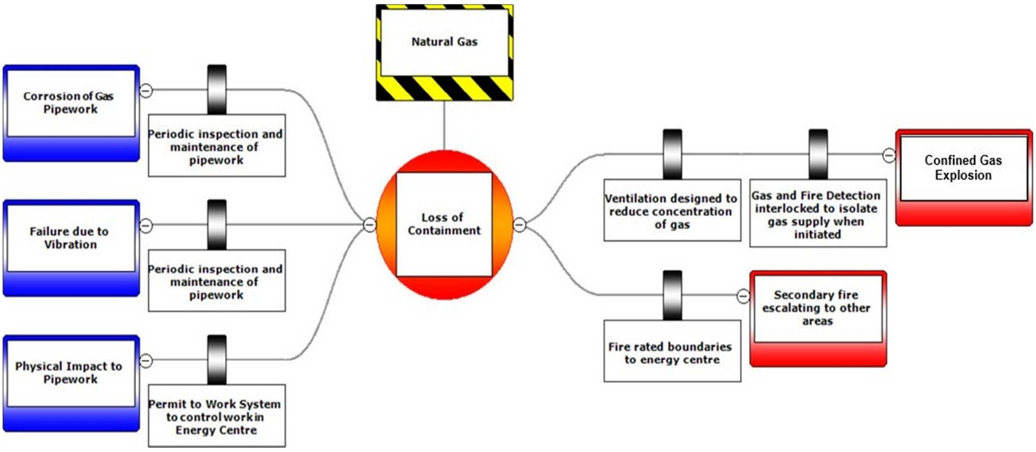
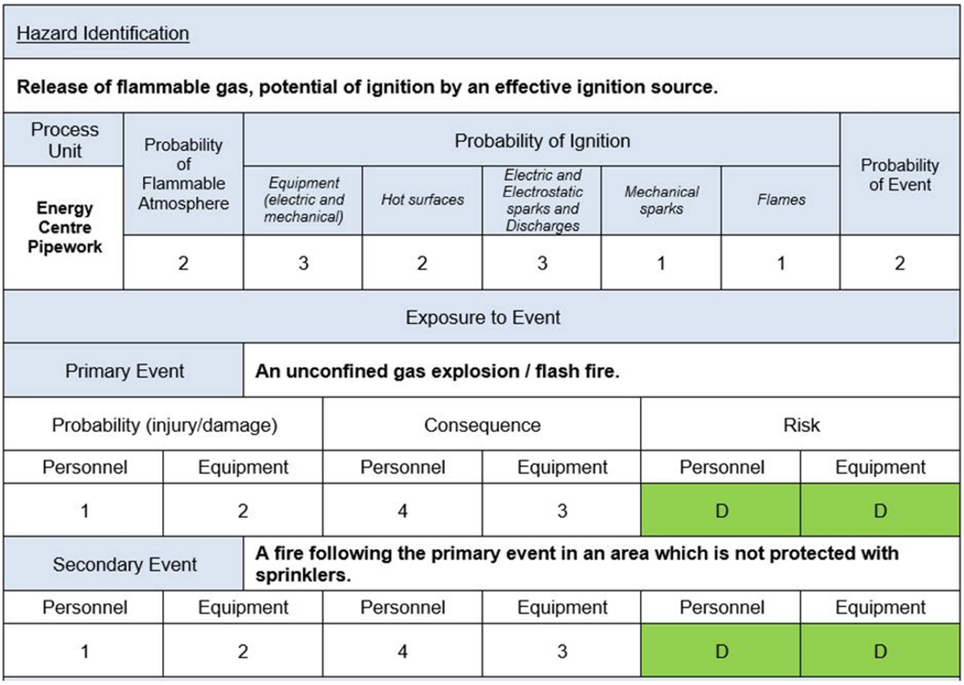


**Fig. 11.** Bowtie diagram for natural gas leak in the energy centre pipework.



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hazard Identification | | | | | | | |
| **Release of flammable gas, potential of ignition by an effective ignition source.** | | | | | | | |
| Process Unit | Probability of Flammable Atmosphere | Probability of Ignition | | | | | Probability of Event |
| **Energy Centre Pipework** | | *Equipment (electric and mechanical)* | *Hot surfaces* | *Electric and Electrostatic sparks and Discharges* | *Mechanical sparks* | *Flames* | |
| | 2 | 3 | 2 | 3 | 1 | 1 | 2 |
| Exposure to Event | | | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Primary Event | | **An unconfined gas explosion / flash fire.** | | | |
| Probability (injury/damage) | | Consequence | | Risk | |
| Personnel | Equipment | Personnel | Equipment | Personnel | Equipment |
| 1 | 2 | 4 | 3 | D | D |
| Secondary Event | | **A fire following the primary event in an area which is not protected with sprinklers.** | | | |
| Personnel | Equipment | Personnel | Equipment | Personnel | Equipment |
| 1 | 2 | 4 | 3 | D | D |

**Fig. 12.** Risk assessment for a natural gas release inside the energy centre.

### Summary Risk Assessment

The risk assessment presented in Fig. 12 summarises the estimated explosion risks for this installation, taking into account the barriers and risk reduction measures that were identified based on the Zone 2 NE classification (supported by the CFD results). Gexcon's risk assessment uses a semi-quantitative approach [11] designed to meet the requirements of DSEAR [2]. The risk assessment not only considers risks to people as required by health and safety law but also the risks to the business (plant and equipment).

Generally speaking, both the probability of formation of a flammable atmosphere and of an effective ignition source are ranked between 1 (very unlikely) to 5 (very likely), resulting in a probability (or the frequency) of an event occurring with a similar scale. Finally, different risk levels are assessed, ranging from E (very low and acceptable) to A (very high and unacceptable).

## CONCLUSIONS

This paper presented a methodology following detailed consequence analysis based on CFD simulations to help review mitigation barriers and allow the design to be optimised with respect to them, and so assisting to demonstrate compliance with regulations.

An Energy Centre has undergone a significant technical safety assessment in order to determine a suitable level of safety for the installation and to support in demonstrating that the risks are reduced to a level which can be considered ALARP [1], in line with UK law and industry guidance in IGEM/G/5 [3]. Although this study considered a specific building design, it is straightforward to extend the proposed methodology to other configurations.

Hazardous area classification was supported by a comprehensive CFD study including ventilation, dispersion, gas detection and gas explosion analysis, in order to demonstrates that a Zone 2 NE classification was appropriate in line with the relevant European Standards [9].

The risk assessment indicated that the risk is tolerable, considering the implemented measures for risk reduction. Based on CFD analysis, it is believed that the basis of safety analysed (i.e. ventilation plus gas detection) was adequate in that the more likely (yet still very conservative) releases generate very small flammable clouds resulting in low internal overpressures in the event of ignition.

Finally, the barrier assessments showed that maintenance and inspection is of critical importance in preventing the degradation of the facility over time. It is then essential that the facility operator has rigorous inspection and maintenance procedures and that these are followed.

By means of CFD simulations, it was possible not only to assess the impact of ventilation and gas detection upon realistic dispersion scenarios, but also to determine the impact of explosion consequences from both likely (small) and unlikely (catastrophic) releases, in order to properly quantify risks to personnel and equipment and help to select appropriate mitigation barriers. This approach to risk analysis and management provides valuable information to the engineer or operator, helping to better represent the risk picture, and so assisting to improve the design of the installation and potentially reducing its CAPEX and OPEX.

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