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Design Accidental Load for Explosion Resistant Design

Sirous Yasseri[1*], Hamid Bahai[2]

[1] *Corresponding author: Brunel University London; Sirous.Yasseri@Brunel.ac.uk*
[2] *Brunel University London; Hamid.Bahai@Brunel.ac.uk*

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ABSTRACT

The accidental release and ignition of flammable vapours in petrochemical facilities generate overpressure and drag load which can impact the safety of installation and people. The intensity of the blast loads depends on many influencing factors including congestion, geometry, type & amount of fuel, leak size, and points of ignition among others. Given the stochastic nature of these parameters, it is obvious that the design for accidental load must be determined using a probabilistic method. This paper discusses a methodology known as "explosion exceedance diagram" and draws on recent developments in vapour cloud explosion research to determine the design accidental load (DAL). A case study demonstrates the application of the method.

1. Introduction

The accidental explosion is a design condition which must be considered for offshore oil and gas facilities; see e.g. UKOOA/HSE Fire and Explosion Guidance [21], or API-2FB [2]. Preventing fatalities, injuries and financial loss is the aim of this design condition. Obviously, it is not feasible to aim at designing for the worst possible case, hence using a reasonable design load with a low probability of occurrence is desirable; see e.g. Kim et al [15]. Moreover, credible scenarios cannot be uniquely defined; thus, all standards (e.g. ABS [1], NORSOK Standard Z-013 [18]) and all classification societies, (e.g. Lloyd's Register [12]), allow the dimensioning for explosion loads to be based on probabilistic risk assessment techniques. The Chemical Industries Association (CIA) issued revised guidance, in February 1998, on the location and design of occupied buildings at chemical manufacturing sites (see Goose, [10]). This guideline also promotes the use of exceedance curve. The advantage of the exceedance curve approach is that it displays the range of potential scenarios, rather than a single event.

Standards for the blast load design use a two-level design load definition, which is like the requirements for the seismic design (e.g. see ABS [1]). In principle, there is not much difference between various standards, but they use different terminologies for the same purpose. The current UK practice uses two-level explosion design loads, one with a higher frequency (say 100-year to 500-year return period) and another at much lower probability say 10^{-4} to 10^{-5} per year. The low probability explosion load is indented to prevent the total loss, while the higher probability explosion load is intended to protect the asset as well as injury to workers.

The Norwegian Standard NORSOK Z-013[18], requires design for an accidental design load (DAL), which is an abnormal loading condition whose probability of occurrence per year must be lower than 10^{-4}. This is equivalent to the higher-level blast load in API-2FE [2], termed as Ductility Level Blast (DLB). In this paper, a practical method for determining the design accidental load (DAL) is outlined. DAL is used to check the adequacy of the supporting structure as well as all safety critical elements. All equipment and piping are designed to resist the lower level explosion. The procedure to define the lower level blast load is the same as for the higher-level load.

2. Multi-level Design Process

ISO 19901-3 [9] requires installations to be considered for the effects of both a blast load with high calculated frequency as well as a severe event with a reasonably low calculated frequency of occurrence. The low blast loads should not cause excessive business disruption while more intense blast load aims to minimise fatalities and workers injury (Yasseri, [29]). The higher intensity blast load is known as the "Design Accidental Load", DAL in Norway, while it is referred to as the Ductility level blast (DLB) in the UK and US. However, the definition and safeguard against it are similar (Yasseri and Prager, [24] and Yasseri, [25]). The more frequent blast (i.e. the lower intensity blast) is referred to as the extreme level blast (ELB) in Norway or the Strength Level Blast (SLB) in the UK. This paper's focus is DAL, but the procedure for deciding on SLB load is the same.

Any choice involves making a fundamental trade-off between providing very costly high structural resistance and the risk of injuries, downtime and repair- while still avoiding collapse. The choice of frequency for DAL is generally driven by the regulatory requirements and to some extent by the operator's safety policy. However, the choice of the likelihood for the lower level event is purely economic; namely spending now to have a more resistive system or pay the cost of repair and downtime when such event should occur. There is one more difference between these two levels, namely only the safety-critical systems (the structure is one of them) and piping & equipment with high inventories are designed against the low-frequency event, i.e. DAL. But, which equipment to be designed for the higher frequency event is decided based on the tolerable economic loss. Performance requirements for each level of the blast intensity are discussed by Yasseri and Menhennett [23].

3. Regulatory requirements for DAL

The NORSOK Z-013 [18] and NORSOK S-001[17] standards define DAL as "dimensioning accidental load". In several publications, the abbreviation DAL is defined as "design accidental load". Vinnem [21] refers to this abbreviation as the "design accidental load".

DAL which is used for the design of oil and gas installations in Norway is defined in terms of annual frequency of occurrence, thus implying quantitative risk analysis for the installation. Most codes typically associate DAL with an annual frequency of no more than 10^{-4}. The Section 11 in the Facilities Regulations (Petroleum Safety Authority Norway, [16]) states this requirement; and other codes such as ISO 13702 [8] and ABS [1] use the same figure.

The NORSOK S-001[17] defines and uses only the term dimensioning accidental load, but specifies that this is closely connected to the defined risk acceptance criteria. NORSOK Z-013 [18] defines dimensioning accidental loads similarly to the NORSOK S-001 [17] but specifies that the risk acceptance criteria used typically are an annual occurrence of a load of no more than 10^{-4}. Compared to the other standards and regulations mentioned above, revision 3 of NORSOK Z-013 [18], issued in 2010, also defines the term design accidental load, and states that this should be the "final" load, and that this load not be less severe than the load which is associated with an annual frequency of 10^{-4}; based on invoking the ALARP principle, namely requiring searching for risk reduction measures until the risk is ALARP (Yasseri [27 & 30]).

The UK regulations use the goal setting (or performance based) approach, meaning they express design goals, namely what the regulator wish the duty holder to achieve rather than how to achieve it. In the UK frequency of 10^{-4} as the maximum total allowance for a single hazard is used by practitioners, but require this choice to be proved the risk is ALARP, namely proving that the frequency (or consequence) cannot be reduced further without disproportional costs (Yasseri and Menhennett, [26]). A generally accepted principle is accidental loads and environmental loads with an annual probability less than or equal to 10^{-4}, shall not result in loss of any main safety function. The main safety functions are listed in Section 7 of the Facilities Regulations, and are listed below (adapted from Hamdan, [11]):

- Preventing escalation of accident so that personnel outside the immediate accident area are not injured,
- Maintaining the capacity of load-bearing structures until the facility has been evacuated,
- Protecting rooms of significance so that they remain operational until the facility has been evacuated,
- Protecting the facility's safe refuge areas so that they remain intact until the facility has been evacuated,
- Maintaining at least one escape route in every area where personnel are located until they are taken refuge in the safe refuge areas, and rescue of the personnel have been completed.

The installation must be partitioned into zones (or areas) according to the contribution of equipment to risks. These zones should be isolated so that accident in one zone does not affect other zones immediately next to it. The following main areas shall as a minimum be isolated (when relevant):

- Accommodation (living quarter)
- Utility
- Drilling and wellhead
- Process
- Hydrocarbon storage

Each zone must be separated from its neighbours with definable and secure boundaries.

DAL should be established using a recognized method (e.g. NORSOK Z-013, 2010) [18] and representative geometric explosion model of the installation. The loads should be defined for relevant local horizontal and vertical area dividers, i.e. pressure and impulse from explosion and equipment (pressure/drag forces). Explosion loads should also be defined for areas external to the initial explosion location (typical LQ, utility modules etc.);" (NORSOK Standards z-013[18]).

As explained above, pressure and impulse loads for walls and roofs should be established, as well as pressure/drag forces for equipment using tolerable frequency of occurrence. The rationale behind the drag forces for equipment is that the load that imposed on equipment inside an exploding gas cloud will not directly be resolved by the explosion simulation code.

4. Risk acceptance criteria

When establishing the design accidental loads, the loads should be developed through a Quantitative Risk Analysis (QRA) and compared with the risk acceptance criteria for the installation. The risk acceptance criteria that is used is normally the specified criteria given in regulations for the accidental loads with an annual probability of occurrence of less than 10^{-4}, which shall not result in loss of any main safety function. In addition, the design accidental loads shall not contribute to the total risk of the installation in question by being above the total risk acceptance criteria, which typically is in the form of PLL, FAR and AIR (see Vinnem [21].

The Fatal Accident Rate (FAR) represents the number of fatalities per 100 million hours of exposure, i.e.:

$$FAR = \frac{PLL}{Exposed\ hours} \times 10^8 = \frac{PLL}{N_m}\frac{10^8}{8760} \qquad (1)$$

Where PLL= potential loss of life, N_m=average annual manning level and 8760 is the number of hours in 1 year.

PLL in equation (1) can be calculated by accident statistics including the total number of fatalities in one year or by the following equation:

$$PLL = \sum_n^N \sum_j^j F_{nj} \times C_{nj} \qquad (2)$$

Where F_{nj}= annual frequency of accident scenario n with people consequence j, C_{nj} = expected number of fatality for accident scenario n with people consequence j, and N=the total number of accident scenarios, J= the total number of fatalities, including immediate fatalities, fatalities during escape as well as evacuation & rescue fatalities.

AIR, also known as IRPA (individual risk per annum) is expressed as follows:

$$AIR = \frac{PLL}{Exposed\ indivudals} = \frac{PLL}{N_m \times \frac{8760}{H}} \qquad (3)$$

N_m and PLL are as define in Equation (1), H=annual offshore hours per individual, including both working and non-working hours, normally assumed to be 3360 hours per year.

The following five uncertainty-factors, as listed by Vinnem [21], among others, must be considered in the QRA of the installation (Yasseri, [28]):

- The actual location of the ignition points which may vary considerably, which have a strong influence on the resulting explosion overpressure.
- The strength of the ignition source which may vary depending on the type of the ignition source
- The volume of the gas cloud
- The homogeneity of the gas cloud
- The gas concentration in the cloud relative to a stoichiometric concentration

DNV-OS-A101 [6] gives recommendations for the Design Accidental Loads and associated performance criteria. The Accidental Loads in this standard are prescriptive loads. DNV Recommended Practice [6] may also be used in cases where the Design Accidental Loads are determined by a formal safety assessment (see DNV-OS-A101, Appendix C) [6] or Quantified Risk Assessment (QRA); see e.g. Vinnem, [21])

- the integrity of shelter areas,
- usability of escape ways,
- usability of means of evacuation,
- the global load-bearing capacity of the primary structure.

The selection of relevant design accidental loads is also dependent on the safety philosophy considered by the owner to give a satisfactory level of safety, but can't fall below the regulatory requirements. The generic loads defined in DNV-OS-A101 [6] represent the level of safety considered acceptable and are generally based on accidental loads affecting safety functions which have an individual frequency of occurrence in the order of 10^{-4} per year for a single hazard. This will normally correspond to an overall frequency of 5 x 10^{-4} per year as the impairment frequency limit of the installation. Table D1 of DNV-OS-A101 [6] lists an indicative nominal blast overpressure and their duration.

The following points must be remembered in conjunction with the risk budget of 10^{-4} for each category of accidental event (explosion, fire, etc.):

- 10^{-4} is the total risk budget, hence it must be divided judiciously between various zones of the installation. One crude way at the early stages of design would be to allocate equal budget to all zones. Thus, the budget for each zone is determined by dividing 10^{-4} by the number of zones requiring blast consideration. This approach is unlikely to yield an optimal design; hence it would require a few iterations. Judiciously allocating this budget to various zone according to the severity of explosion and effectiveness of mitigation measure, could help to obtain an optimal design faster.
- Also, this risk budget implies that the total impairment of the installation associated with blast loads is less than 10^{-4}, namely for a blast with a frequency less than 10^{-4} installation remain safe. It should be remembered that the structural system can be designed such a way that the probability of loss for DAL is not 100%.

5- Example

Consider a large oil and gas offshore platform which must be designed for the accidental level blast with an annual frequency of occurrence less than10^{-4} per year. First, the installation is partitioned into four zones, i.e. process (separation and compression), utility, lay-down & storage areas, and accommodation. No drilling on the platform.

The following steps are followed for determining the design accidental load

1. Divide the installation into distinct zones. The exposure to different blast scenarios is the deciding factor for each zone (there are four zones for the example problem). The aim is to determine realistic DAL for each zone.
2. The maximum acceptable frequency of 10^{-4} is divided between the above zones with a view to minimising the cost of blast-resistant design. To start the optimisation process, this budget may be equally divided between all zones, or a larger allowance is given to a zone with a higher expected blast overpressure. Several iterations are needed to determine the optimal allocation of the allowances. The allowance for each section is the contribution of that zone to the failure probability
3. The overpressure exceedance diagram (e.g. Figure 1) for each section is then calculated (see the appendix)
4. Using the impairment allowance of a zone (its share of 10^{-4}) and the exceedance diagram for that zone determine the design accidental load.
5. Investigate if sharing 10^{-4} differently between zones will lead to a lower cost.

The process zone has been considered for the demonstration purposes. Following the procedure outlined in the appendix, this zone was divided into six sections (Figure 3 of the appendix). Each section was assumed to share the same inventory. Each section should be divided into squares centred at a leak point, as explained in the appendix. Instead of the study 60 leak point were identified and care was taken all six sections and hole-sizes are fairly represented. Results of explosion frequency and overpressure analyses are given in Table 1. Results are arranged in ascending order (columns 2 and 3). The last column shows the complementary frequencies. A plot of Column 4 against column 2 is the exceedance diagram as shown in Figure 2

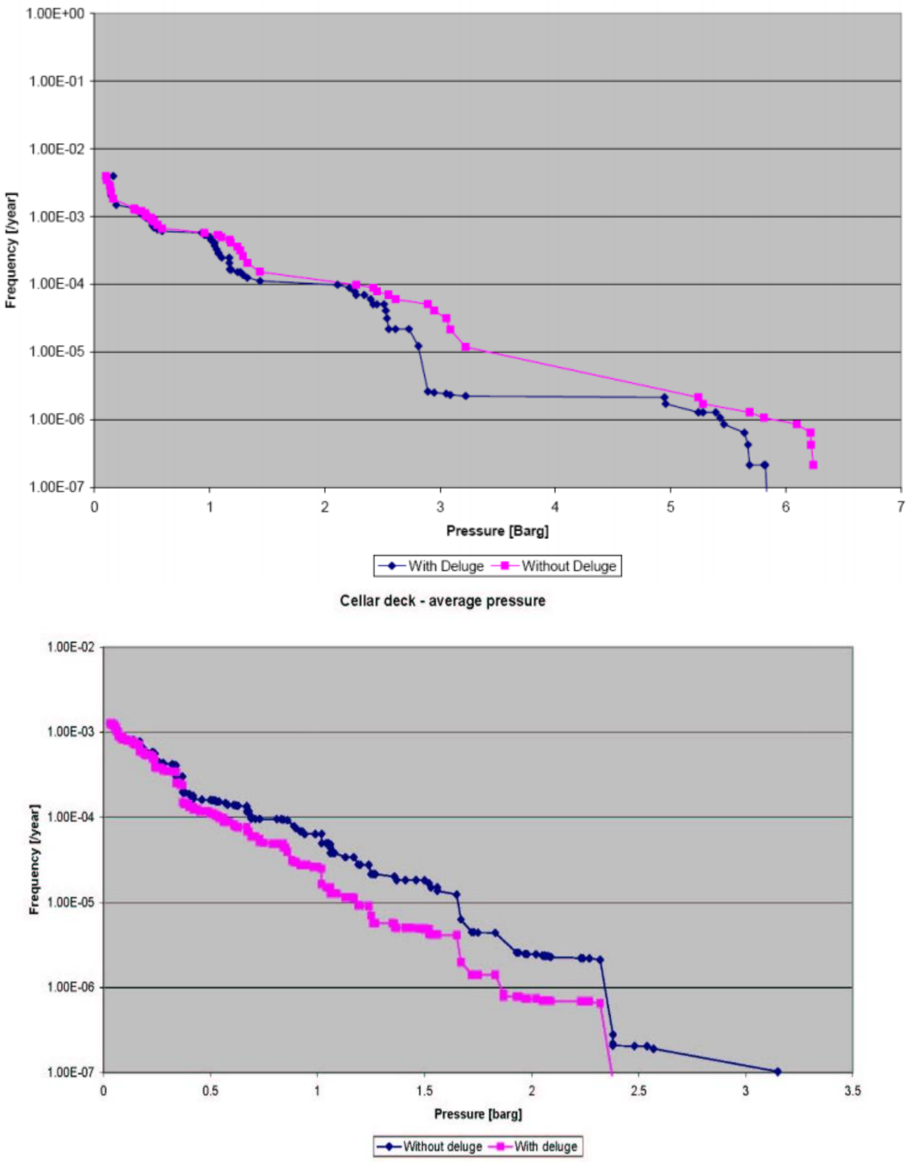

Figure 1: Two examples of pressure exceedance curve (From Talberg [19])

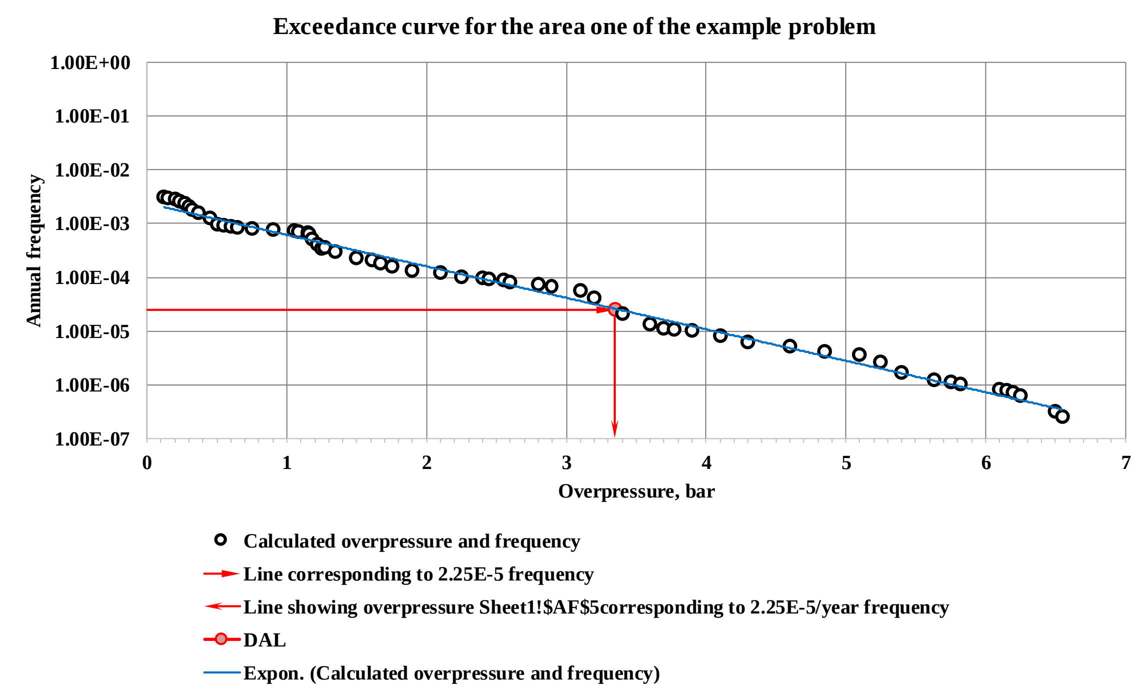

Figure 2: Explosion exceedance diagram for the zone one for example case.

The next step is dividing the budget 10^{-4} between the four zones. As a first attempt, this budget is divided equally between the four zones, hence each zone has a budget of $0.25*10^{-4}$. Entering Figure 2 with this frequency gives 3.35bar as DAL for this zone. This is too high a design load, it is better to allocate half of the budget to this zone, which yields 3.1 bar, which is still too high. More reduction may be achieved by considering, ventilation, leak and ignition sources, geometry and inventory size; or blow out panels as a last resort.

Table 1: Explosion overpressures and frequencies

Scenario (selected)	Overpressure (bar)	Frequency (annual)	Complementary frequency
1	0.12	1.20E-04	3.00E-03
2	0.15	1.80E-04	2.88E-03
3	0.2	2.00E-04	2.70E-03
4	0.23	2.50E-04	2.50E-03
5	0.27	2.50E-04	2.25E-03
6	0.3	2.50E-04	2.00E-03
7	0.32	2.50E-04	1.75E-03
8	0.37	3.00E-04	1.50E-03
9	0.45	2.50E-04	1.20E-03
10	0.5	7.00E-05	9.50E-04
11	0.55	3.00E-05	8.80E-04
12	0.6	5.00E-05	8.50E-04
13	0.65	2.00E-05	8.00E-04
14	0.75	2.00E-05	7.80E-04
15	0.9	6.00E-05	7.60E-04
16	1.05	3.00E-05	7.00E-04
17	1.08	2.00E-05	6.70E-04
18	1.15	3.00E-05	6.50E-04
19	1.16	1.20E-04	6.20E-04
20	1.18	1.00E-04	5.00E-04
21	1.22	7.00E-05	4.00E-04
22	1.25	-2.00E-05	3.30E-04
23	1.27	6.00E-05	3.50E-04
24	1.35	7.00E-05	2.90E-04
25	1.5	2.00E-05	2.20E-04
26	1.61	2.00E-05	2.00E-04
27	1.67	2.50E-05	1.80E-04
28	1.75	2.50E-05	1.55E-04
29	1.9	1.50E-05	1.30E-04
30	2.1	1.50E-05	1.15E-04
31	2.25	5.00E-06	1.00E-04
32	2.4	7.00E-06	9.50E-05
33	2.45	4.00E-06	8.80E-05
34	2.55	6.00E-06	8.40E-05
35	2.6	8.00E-06	7.80E-05
36	2.8	5.00E-06	7.00E-05
37	2.9	1.00E-05	6.50E-05
38	3.1	1.50E-05	5.50E-05
39	3.2	2.00E-05	4.00E-05
40	3.4	7.00E-06	2.00E-05
41	3.6	2.00E-06	1.30E-05
42	3.7	5.00E-07	1.10E-05
43	3.77	6.00E-07	1.05E-05
44	3.9	1.90E-06	9.90E-06
45	4.1	2.00E-06	8.00E-06
46	4.3	1.00E-06	6.00E-06
47	4.6	1.00E-06	5.00E-06
48	4.85	5.00E-07	4.00E-06
49	5.1	1.00E-06	3.50E-06
50	5.25	8.50E-07	2.50E-06
51	5.4	4.60E-07	1.65E-06
52	5.63	9.00E-08	1.19E-06
53	5.75	1.00E-07	1.10E-06
54	5.82	2.00E-07	1.00E-06
55	6.1	4.70E-08	8.00E-07
56	6.15	5.30E-08	7.53E-07
57	6.2	1.00E-07	7.00E-07
58	6.25	3.00E-07	6.00E-07
59	6.5	6.00E-08	3.00E-07
60	6.55	2.40E-07	2.40E-07

6. Conclusions

The current industry practice is to ensure the total frequency of explosion events should be below 10^{-4}, but depending on the results of the assessments, additional risk-reducing measures should be studies to ensure that risks are ALARP (Yasseri [27 & 30]).

The load associated with 10^{-4} is not the final or the target design load, it is just a starting point. In fact, DAL is not the target, but it is a method to break iteration loop (i.e. the start of iteration to achieve an optimal design) so that the design process can be started, thus it acts a ceiling that the excursion of load frequency beyond it, is not permitted. In fact, the ALARP principle determines if the design goals are achieved (Yasseri, [30]. The experience has shown that breaking the loop with 10^{-4} leads to the shortest path to ALARP.

The contribution of the exceedance diagram doesn't end with the determination of DAL. It can assist with reduction of explosion hazard when considering if the risk is as low as reasonably practicable (ALARP). To reduce the overpressure, ignition sources may be removed or protected, leaks are prevented, or their frequency reduced by using a better material or more inspection and the inventory may be reduced and so on. These considerations either shifts the exceedance curve downwards or changes its slop downward leading to less intense DAL. Thus, in this context, it becomes a valuable tool in hazard mitigation. However, the analysts must be mindful of uncertainties in the estimation of parameters influencing DAL.

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Appendix A

A1. General

This appendix presents a methodology for calculation of exceedance diagram (Walker & Yasseri [22], Chamberlain [3] and Chamberlain and Puttock 2006 [4]). The method can consider all possible gas release scenarios using the Monte Carlo simulation.

The zone (module, compartment, etc.) are divided into areas/sections with similar characteristics. In general, a minimum of 4 to 8 explosion sections are identified as having unique characteristics which affect the severity of explosions (Figure A1). Using one section only means designing the entire zone for the higher load. Each zone is examined for the number of equipment and probable leak locations. In addition, all data needed to define the leak scenario such as the type of fuel, operating pressure & temperature, and hole-sizes are identified. The selection of the hole-size, leak location, wind speed, wind direction and stability class are decided randomly in a Monte Carlo simulation.

A ventilation and dispersion software (preferably a CFD software) is used to estimate the volume of the gas cloud based on the release rate and leak location as well as weather conditions. The calculated cloud volume and the calculated distance from the centre of the cloud to the point of interest (within the considered zone) are used in a software to calculate the overpressure (preferably a CFD software). The frequency of each scenario is calculated by multiplying the calculated frequency of leak in the module and the probabilities of leak size, leak location, weather conditions, and ignition. This process is repeated thousands of times to achieve a tolerable uncertainty. The level of uncertainty also depends on the sophistication of software used. In each simulation, the calculated overpressure and frequency are recorded. The recorded overpressures and frequencies are used to generate the exceedance diagram.

The characteristics of the release or leak, such as the fuel type, operating conditions or sizes of probable leaks, is crucial for estimating the release rate and hence, the size extent of the gas cloud. Each zone on an installation comprises of different types of leaks such as leaks from flanges, connections, fittings, piping, and seals. One should add also catastrophic or rupture and general leak. Leaks can be assumed uniformly distributed over the entire zone; especially when piping is involved. When the number of analyses is limited, generally specific leak locations are assumed. The leak types are identical since all leaks share the same fuel, flammable, and process conditions. Thus, the main distinguishing feature between release scenarios is the hole-sizes.

The probability distribution of hole-sizes is used to generate the cumulative probability distribution which is used for randomly selecting the hole-size. Numerous resources that contain data on hole-size distribution are available in the literature (e.g. see E&P Forum, [7]).

A2. Leak locations

An approximate approach to simplify calculations is to assume the inventory is infinite and available for release from any leak. This leads to excessive conservatism for larger hole-sizes. A less conservative method would be first to dived installations into zones of similar explosion characteristic as all regulations require. The next step is to divide each zone into sections (Figure A1) which share the same inventory with definable size.

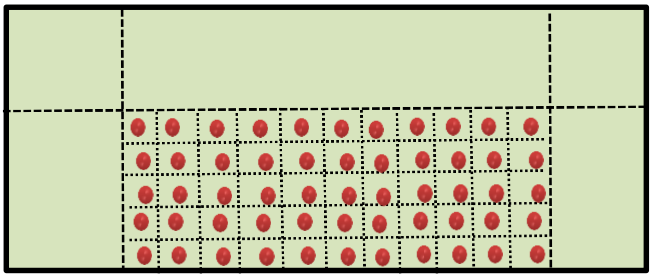

Figure A1: This figure shows one zone. Each zone is divided into areas/sections which share the same inventory (six in this case). Then each area divided into squares centred on the point of ignition as shown in the figure.

The release and frequency characteristics of the equipment can be approximated by a uniform distribution, which means the leak source can be anywhere in the section. To obtain fairly good results many leak locations must be included.

The leak locations can be approximated by dividing each section into squares of reasonable size. It is assumed the leak location is at the centre of each square; shown as dots in Figure A1. For congested sections, this assumption is not far from reality.

The choice of location is then performed using Monte Carlo simulation. It should be noted that the larger the number of a defined leak sources, the lower the probability of a leak from each source, and hence the lower the probability of damage which underestimates the risk. Therefore, the optimum number of leaks which should be based on the size of the module. A 1mx1m to 3mx3m should give reasonable results.

A3. Frequency Analysis

Frequencies are always presented on an annual basis. Several thousands of scenarios based on the hole sizes, leak locations, weather conditions and so on should be generated.

The frequency of each scenario resulting in explosion can be calculated using Equation (1)

$$F_i = f_{leak} \times P_{hole\ size} \times P_{leak\ location} \times P_{Wind\ direction} \times P_{wind\ speed} \times P_{stability\ class} \times P_{ignition} \quad \text{Eq. (A1)}$$

where,

F_i is the frequency of explosion,

f_{leak} is the frequency of leak in the zone,

$P_{hole\ size}$ is the probability of hole-size,

$P_{leak\ location}$ is the probability of the leak location,

$P_{Wind\ direction}$ is probability of the wind direction,
$P_{wind\ speed}$ is probability of the wind speed,
$P_{stability\ class}$ is probability of the weather stability class, and $P_{ignition}$ is probability of the ignition.
The frequency of leak in a zone, f_{total} is calculated by summing all the frequencies for each type of equipment using the following equation:

$f_{leak} = \sum N_k f_k$ ……Eq. (A2)

Where
N_k is the number of equipment of type k,
f_k is the frequency of leak for equipment k.
The probability of leak locations, $P_{leak\ location}$, is calculated based on the number of specified leak locations. As an approximation, one can consider a given number of leaks, making sure that all sizes and locations are fairly represented. Alternatively, the zone may be divided into equal size squares. The number of square is the number of leak locations. Thus,

$P_{leak\ location} = 1/(No. Leak\ point)$ ......Eq. (A3)

The number of leak points is equal to the number of squares, or the number of assumed leaks.
The probability of ignition may be calculated using a correlation suggested by Cox, et al [5], or another suitable approach. The correlation assumes that the probability of ignition is proportional to the power of the mass flow rate for continuous gas releases.
The explosion overpressure for each scenario may be calculated using a simplified approach such as TNO multi-energy method or TNT equivalent, however, use of a suitable CFD software is preferable (Talberg et al [19]).

A4. Exceedance Calculations

In the early 1980s, Kaplan and Garrick [13] proposed an approach for defining risk. They referred to this definition as “the quantitative definition of risk”. The quantitative definition of risk is based on the notion of scenarios. A scenario is a possible way that a system can behave and formally it can be “viewed as a trajectory in the state space of a system” (Kaplan, 1997) [14]. Thus, a scenario can be described as a succession of system states over time. Since there are uncertainties regarding the behaviour of the systems, there exist many possible scenarios. The type of scenarios of interest for risk analysis is referred to as *risk scenarios*. The first step in a risk analysis is, therefore, the identification of risk scenarios.
Each scenario is defined by three components, namely a scenario designation and associated frequency and overpressure. These are known as the triplets- equation (A4).

$\langle S_i, L, C_i \rangle; \quad i = 1,2,\cdots,N$ Eq. (A4)

Where
S_i is the scenario i
L_i is the likelihood of scenario i
C_i is the consequence of scenario i
It is also assumed N scenarios have been identified (Table A1)

Table A1 Triplets sorted in order of increasing consequence

S_i (scenarios)	f_i	C_i (ascending order)	Complementary cumulative frequency
S_1	f_1	C_1	$F_1^c = f_1 + f_2 + f_3 + \cdots + f_{n-1} + f_n$
S_2	f_2	C_2	$F_2^c = f_2 + f_3 + \cdots + f_{n-1} + f_n$
S_3	f_3	C_3	$F_3^c = f_3 + \cdots + f_{n-1} + f_n$
…..	…..	…..	…..
S_{n-1}	f_{n-1}	C_{n-1}	$F_{n-1}^c = f_1 f_{n-1} + f_n$
S_n	f_n	C_n	$F_n^c = f_n$

Scenarios must be exhaustive and non-overlapping. The set of scenarios is seldom exhaustive. Perhaps, the triplets being incomplete may not be a big handicap, if the hole-size distribution is fair. Favouring either small or large hole can change the exceedance curve slope, leading to unrealistic DAL.
To create the exceedance curve, the triplets must be arranged in increasing order of consequence, i.e. $C_i > C_{i+1}$, see Table A1. The exceedance curve can be plotted as a step function as shown in Figure A2. The frequency,f_i, in this figure are the event frequency. The maximum value on the vertical axis is therefore equal to 1.0, as
$F = \sum_1^n f_i = 1.0$ ......Eq. (A5)
Equation (A4) indicates the set of scenarios are complete; this condition is not achieved.

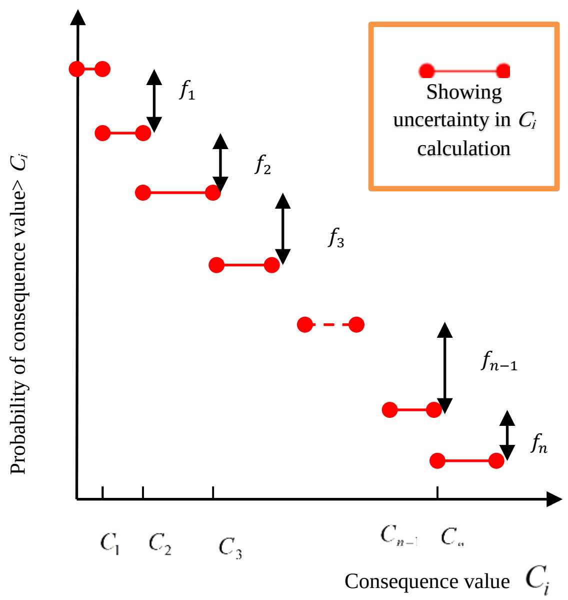

Figure A2: Construction of exceedance diagram