UPGRADING THE EXPLOSIVE MODULE

21/07/2025

From Gases and Evaporators risk assessmeNt towards an Integrated management of sea and land pollution incidentS

D2.5 - Upgrading the explosive module
30/07/2025

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1. Introduction

The unconfined vapour cloud explosion phenomenon (UVCE) can involve serious damage to structures and people. It is therefore essential to accurately predict the effects of a UVCE in order to establish satisfactory preventive measures.

The analysis of the literature clearly show that the intensity of overpressures depends mainly on:

- The nature of the fuel mixture (the fuel involved and its concentration in relation to the oxidiser)
- The level of congestion (gas confinement and obstruction by obstacles)
- The ignition of the cloud (the energy of the ignition source and its position)

However, previous studies have shown that the factors influencing the intensity of this gas explosion are very different in nature, which is why it is not easy to define a simple and effective systematic method for predicting their combined effects.

The TNT model used in the previous MANIFESTS project was used to model the effects of a vapour cloud explosion in a very simple and practical way [1]. The advantage of this model lies in the empirical relationship between the explosion of a quantity of TNT and the resulting structural damage. This TNT equivalence is a simple tool for assessing the potential for material damage from a vapour cloud explosion. However, the proportional relationship between the amount of fuel available in the cloud and the mass of TNT expressing the explosive potential of the cloud may be open to debate. TNT equivalency yields for vapour cloud explosions are derived from statistical analyses of a limited number of major incidents. An average of 4% and an upper limit of 10% are generally used for predictions. The average value corresponds to an 'average major incident', typical of high-risk industrial contexts (refineries, chemical plants, railway marshalling yards). However, this approach is based on extrapolation and is only reliable if the actual conditions are similar to those of the average incident. However, TNT model is an imperfect model for representing vapour cloud explosions, as these generate longer and less intense blast waves than TNT. For applications such as assessing the impact of an explosion on structures or buildings, a more suitable model is needed, considering the shape and duration of the blast wave. The use of a statistical average for TNT equivalence limits the accuracy of predictions. A more deterministic approach becomes possible by identifying parameters related to the explosion formation mechanism, as is done in alternative models based on fuel-air charges.

As summarised in the Yellow Book [16], TNT equivalence models:

- state a proportional relationship between charge weight and cloud energy content,

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- use a TNT equivalence factor(proportionality) based on incident statistics which shows very wide and flat distribution. This correlation contradicts the basic assumption of proportionality,
- have therefore a poor statistical reliability,
- do not take into account the variability of explosion strengths,
- do not match with vapour cloud explosion blast characteristics (distance dependant efficiency factor),
- overpredict near-by pressure effects,
- predict only overpressures (not duration and blast-wave shape),
- are simple and easy to apply,
- are commonly used although there is common dissatisfaction.

This simple method was developed empirically based on observation of the phenomenon. The main objective was to evaluate at a correct, or at least conservative, estimate of the explosion energy, the pressure reached in the near field and its attenuation in the far field.

Although the TNT equivalence method is still widely used due to its simplicity, this method has the same weaknesses as its strengths: since it is a very simple method, many criteria are not considered, in particular:

- Only a single explosion is considered and there is no separation of the explosion energies of the different parts of the explosive cloud;
- The environment around the gas (obstacles, confinement, type of source) is not examined at all.

In summary, this method does not consider the combustion regime of the flame, but rather the amount of gas assumed to have exploded [11].

Furthermore, there is a physical difference between an explosion produced by an explosive charge such as TNT and one produced by a gas cloud. This means that the overpressures calculated using this method (based on a TNT charge) are too high for gas explosions in the near field and not high enough in the far field, and vice versa for the impulse.

This method can therefore be used to predict the maximum overpressures generated by detonations, but the TNT equivalent does not consider the difference between the pressure decay of a gas cloud detonation and that of a deflagration [10].

As a result, the TNT method is not the most suitable for correctly analysing a gas explosion.

2. Introduction to the Multi-Energy model

Van den Bosch [16] explains that the experimental research has shown that deflagration explosions in vapour clouds occur mainly in obstructed and/or partially confined areas ([6], [5], [17], [18]). These conditions promote rapid and violent combustion. However, areas of intense turbulence, such as those generated by jets of pressurised fuel, can also initiate a deflagration. In contrast, other parts of the cloud burn slowly without contributing significantly to the explosion.

This understanding has given rise to the multi-energy concept, according to which a vapour cloud explosion is a succession of sub-explosions, each associated with a specific area of the cloud. This concept differs from traditional approaches that consider the cloud as a single entity.

In the multi-energy model, the explosion effects are modelled separately for each source of deflagration. Although the effects are directional in reality, a simplified model represents them symmetrically. The BLAST model developed by Van den Berg [12] was used to simulate explosions and establish blast wave diagrams based on key parameters (maximum overpressure, dynamic pressure, duration of the positive phase) and according to a non-dimensional scale (Sachs scale). The strength of the explosion is then characterised by an index from 1 to 10 [16], ranging from weak to detonating explosion.

The intensity of the explosion influences the shape and decay of the blast waves: weak explosions generate gentler waves of constant duration, while strong explosions produce intense shock waves with decreasing overpressure and a longer positive phase.

To apply the multi-energy method, it is then necessary to know or estimate the volume and position of the flammable cloud, as well as the layout of the surrounding structures. Based on this data, multi-energy explosion tables can be used to assess the effects of an explosion more realistically.

2.1. The Multi-Energy concepts

The principle of the method assumes that the explosive cloud can rise to several elementary sub-explosions occurring in areas with a high degree of confinement, separated by a critical distance, and not just a single explosion [15].

The multi-energy methodology therefore consists of:

- Identifying potential high-explosion zones (assimilated in this method to confined zones) and calculating their volume;
- Calculating the air-hydrocarbon explosive charges: $E = 3.5 \times 10^6 \times$ Volume;
- Assigning a degree of violence to each identified zone;
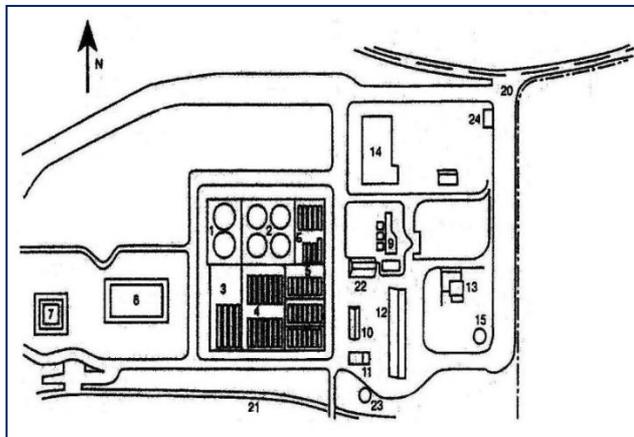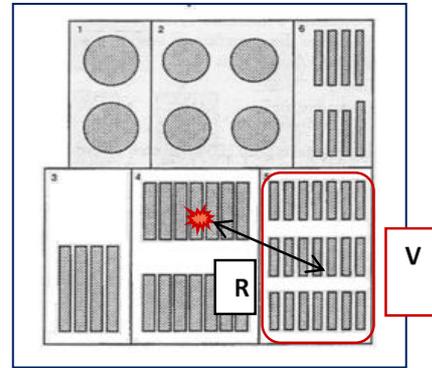- Calculating dimensionless distances for each charge;

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- Read the charts and estimate the overpressures for each area (the overall explosion overpressure will be the weighted average for each area[1]).

a) Identification of the different containment zones

b) Identification of the parameters of one zone

Figure 1: Application of the multi-energy method: example of the Mexico City filling centre [2]

The multi-energy model strategy provides a realistic estimate of the effects of vapour cloud explosions (VCE) by considering the local variability of conditions within the cloud. This strategy is based on the method proposed by Van Den Berg [13].

The multi-energy method is a model based on ideal explosions and assumptions that are not always justifiable: its concept assumes that an explosion can only occur in congested areas, which is not really the case, especially for highly reactive gases. This assumption implicitly excludes generalised gas detonations from this method [13]. The method also does not take into account the initial overpressure caused by the ignition source.

Nevertheless, this method can be used in both the near and far field for gases with low to medium reactivity.

The difficulty with this approach lies in choosing the index of the degree of violence of each sub-explosion, which is assessed on the basis of the factors influencing flame acceleration seen earlier[2].

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[1] Wave superposition may occur under certain conditions but it is not necessarily useful to take this into account in the initial analysis, as the results will still be representative of the risks involved [7].

[2] these factors are: confinement and bulkiness, turbulence level, ignition source, cloud geometry and composition, and gas reactivity.

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2.1.1. Choice of the violence index

The explosion violence index is defined on a scale of 1 to 10. Index 1 corresponds to flash fires, 10 to a force similar to a detonation in the area under study, and the intermediate indices are used for deflagrations classified according to their propagation speeds[3]: index 3 for slow deflagrations and 6 for fast deflagrations (Figure 2).

The choice of index is therefore essential in order to obtain a correct estimate of overpressures. Several studies have been carried out with the aim of arriving at a fair recommendation for the appropriate degree of violence.
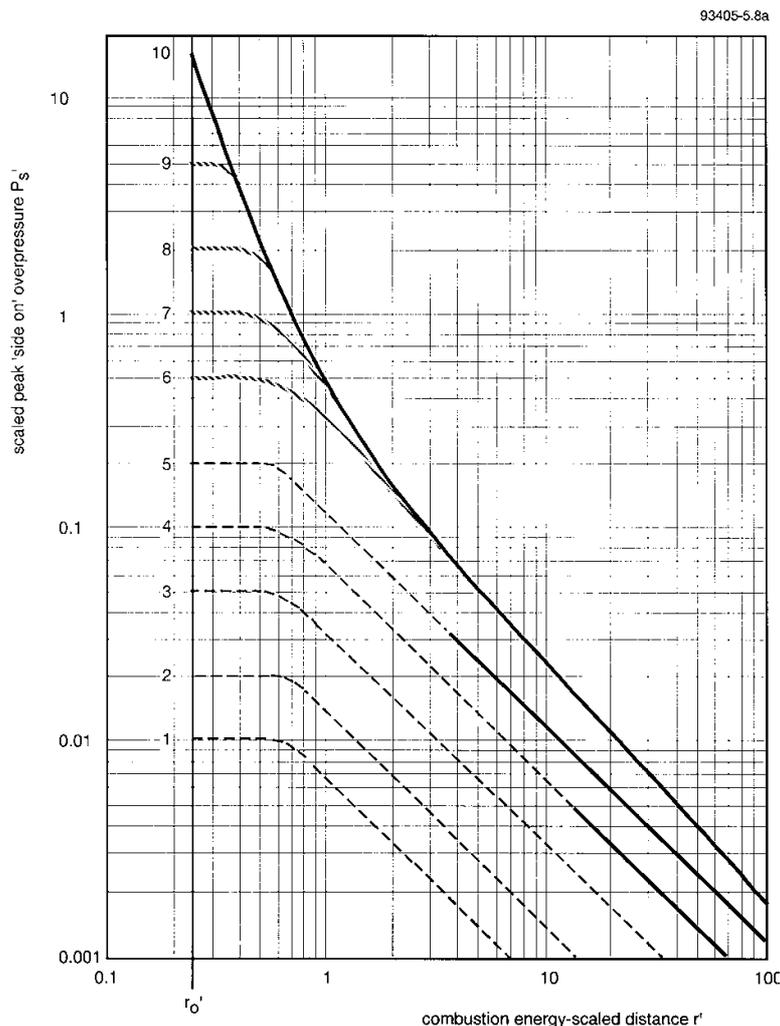

Figure 2: Multi-Energy method blast chart: peak side-on overpressure (Van den Bosch [16])

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[3] the induced overpressure is strongly linked to the flame propagation speed.

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2.1.2. Procedure for the application of the Multi-Energy method

The procedure of vapour cloud explosion blast modelling according to the Multi-Energy concept can be subdivided into a number of steps. This procedure is based on the methodology described and more detailed in [16] This procedure of vapour cloud explosion blast modelling according to the Multi-Energy concept can be subdivided into a number of steps (Figure 3).
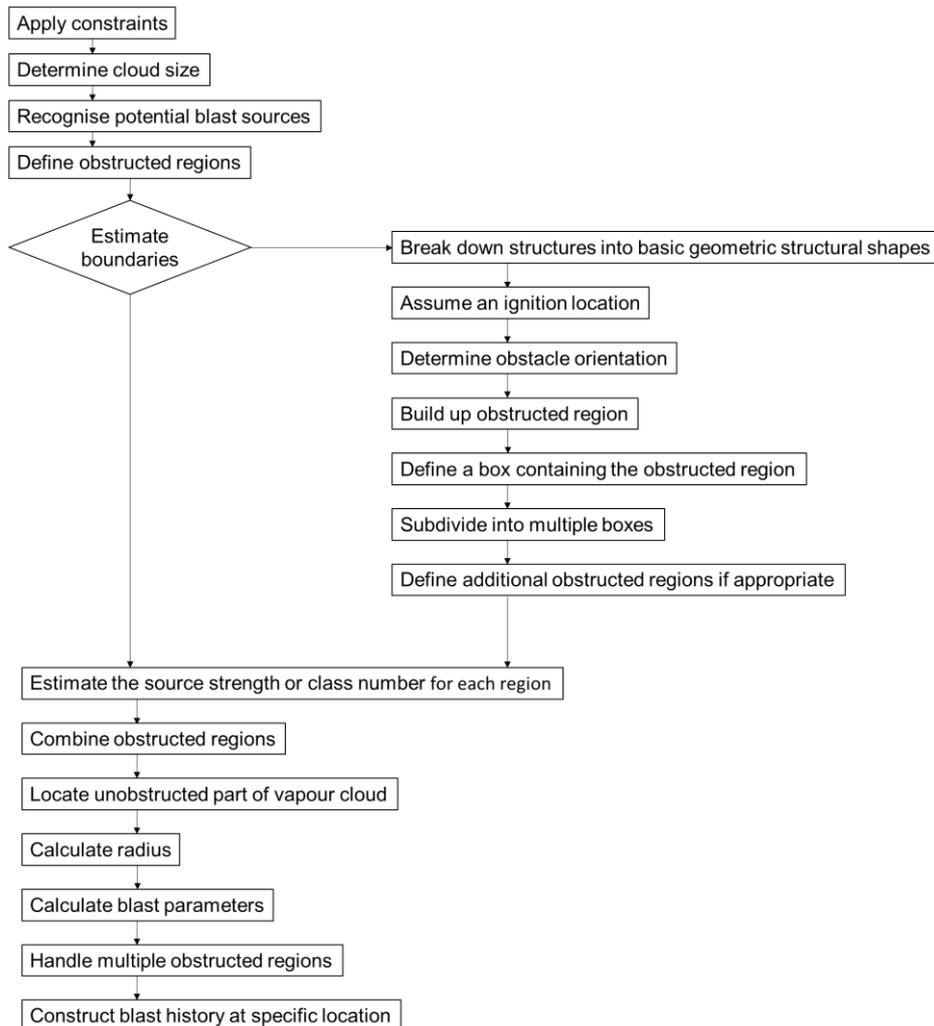
Figure 3: Flow diagram for application of the multi energy method proposed by Van den Bosch [16])

All the steps present in this diagram are detailed in the following paragraph

Step 1. application constraints

- The Multi-Energy method is only used for determination of the blast parameters from 'unconfined' vapour cloud explosions.
- The Multi-Energy method is a simplification of reality. It does not take into account directional blast effects due to the inhomogeneous distribution of

confinement and obstruction of the vapour cloud or due to the non-point symmetrical shape of the vapour cloud.

- Assume that blast modelling on the basis of deflagrative combustion is a sufficiently safe and conservative approach. Keep in mind that unconfined vapour cloud detonation is extremely unlikely

Step 2. determination of cloud size

- Determine the mass quantity after an accidental release that can contribute to the formation of a flammable cloud.
- Calculate the volume V_c of a cloud with a density ρ containing the flammable mass quantity Q_{ex} at stoichiometric concentration c_s (c_s in vol.%) with:

$$V_C = \frac{Q_{ex}}{\rho \times C_c} \qquad (1)$$

Step 3. recognition of potential blast sources

- Identify potential sources of blast in the vicinity of a postulated location of the centre of the cloud.

Step 4. definition of obstructed regions

- Define obstructed regions using the procedure or estimate boundaries of obstructed regions and determine the free volume V_r of each obstructed region.
- Determine the maximum part of the cloud V_{gr} that can be inside the obstructed regions.
- Calculate the volume V_o [m³] of the unobstructed part of the vapour cloud with:

$$V_0 = V_C - V_{gr} \qquad (2)$$

- Calculate the energy E of each region, obstructed as well as unobstructed, by multiplying V_{gr} and V_o by the combustion energy per unit volume.

Step 5. estimation the source strength or class number for each region

A conservative approach would be to choose a class number of 10 for each obstructed region. Other numbers may be chosen based on additionally obtained information if required. A low initial blast strength for the remaining unobstructed regions can be estimated by number 1. In case initial low turbulence motion is expected in unobstructed regions, for instance, due to the momentum of the fuel release, a number of 3 is advised.

Step 6: combination of obstructed regions

In case more than one obstructed region has to be considered:

– Define an additional blast source (obstructed region) by adding all energies of the separate blast sources together and by assuming a centre for the additional blast source. This centre can be determined by considering the centres of the separate blast sources and their respective energies.

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Step 7: location of unobstructed part of vapour cloud

- – Determine a centre for the unobstructed vapour cloud volume. This centre can be determined by considering the centres of the separate unobstructed regions and their respective energies. For each centre the blast parameters as a function of distance to its centre can be calculated using the blast charts given in
- – Figure 4.

Step 8: calculation radius

- – Model the blast from each source by the blast from an equivalent hemi-spherical fuel-air charge of volume E/Ev m³ (Ev = 3.5 MJ.m-3 is an average value for most hydrocarbons at stoichiometric concentration). Form an impression of the scale by calculation the radius r_0 for each blast source from:

$$r_0 = \sqrt[3]{\frac{3}{2} \times \frac{E}{E_v \times \pi}} \qquad (3)$$

Step 9: calculate blast parameters

The blast parameters at a specific distance r from a blast source can be read off Figure 2and

Figure 4 after calculating the scaled distance *r'*.

- a. calculate the scaled distance *r'* [-] which is the distance *r* [m] of the location under consideration to the centre of the explosion divided by the energy available E and the ambient pressure P_a:

$$r' = \frac{r}{\sqrt[3]{E/P_a}} \qquad (4)$$

- b. assume an explosion strength (class 1 to 10) and read off the charts the scaled peak side-on overpressure P_s', the scaled peak dynamic pressure P_{dyn}' and the scaled positive phase duration t_p'

- c. calculate the peak overpressure P_s [Pa] from:

$$P_S = P_S' \times P_a \qquad (5)$$

- d. calculate the positive phase duration t_p [s] from:

$$t_p = \frac{t_p'}{c_0} \times \sqrt[3]{E/P_0} \qquad (6)$$

Where c_0 represents the atmospheric sound velocity in the surrounding air, under ambient conditions [m.s⁻¹] and *E* is the *e*xplosion energy [J] with E=V₀ x 3.5 MJ.m⁻³
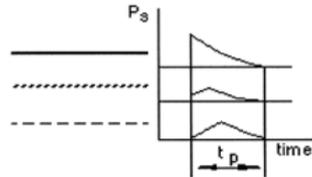
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  e. calculate the peak dynamic pressure P_{dyn} [Pa] from:

$$P_{dyn} = P_{dyn}{}' \times P_a \tag{7}$$

determine the shape of the blast-wave from

  f. Figure 4:

  g. calculate the positive impulse is by integrating the overpressure variation during the positive phase resulting in multiplying the side-on overpressure with the positive phase duration and with a factor 1/2:

$$i_s = \frac{1}{2} P_a \times t_p \tag{8}$$

These abacus (

Figure 4) were established using approximate numerical methods rather than analytical methods [13] whose initial assumptions for each zone were defined as follows:

- A hemispherical cloud;
- A homogeneous mixture of gases with stoichiometry;
- A spherical deflagration at constant speed;
- A heat of combustion E set at 3.5 MJ.m^{-3}, which corresponds to an average value for most air/hydrocarbon mixtures in stoichiometric proportions.

Step 10: handling of multiple obstructed regions

  – If separate blast sources are located close to each other, they may be initiated more or less at the same time. The coincidence of their blasts in the far-field may not be ruled out and the respective blasts should be superposed. This should be accomplished by taking the respective quantities of combustion energy of the sources in question together. To determine the parameters in the blast-wave at a specific distance, one should use the blast source as defined in step 6.

Step 11: construct the blast history at a specific location

 – Combustion in the unobstructed region is considerably different from combustion in an obstructed region. Blast from an obstructed region will result in sharp and relatively short peaks (shock-waves). The relatively slow combustion in an unobstructed region will result in pressure waves of long duration. Due to the influence of the respective energies, however, either of the blast-waves can be of importance at a specific location.

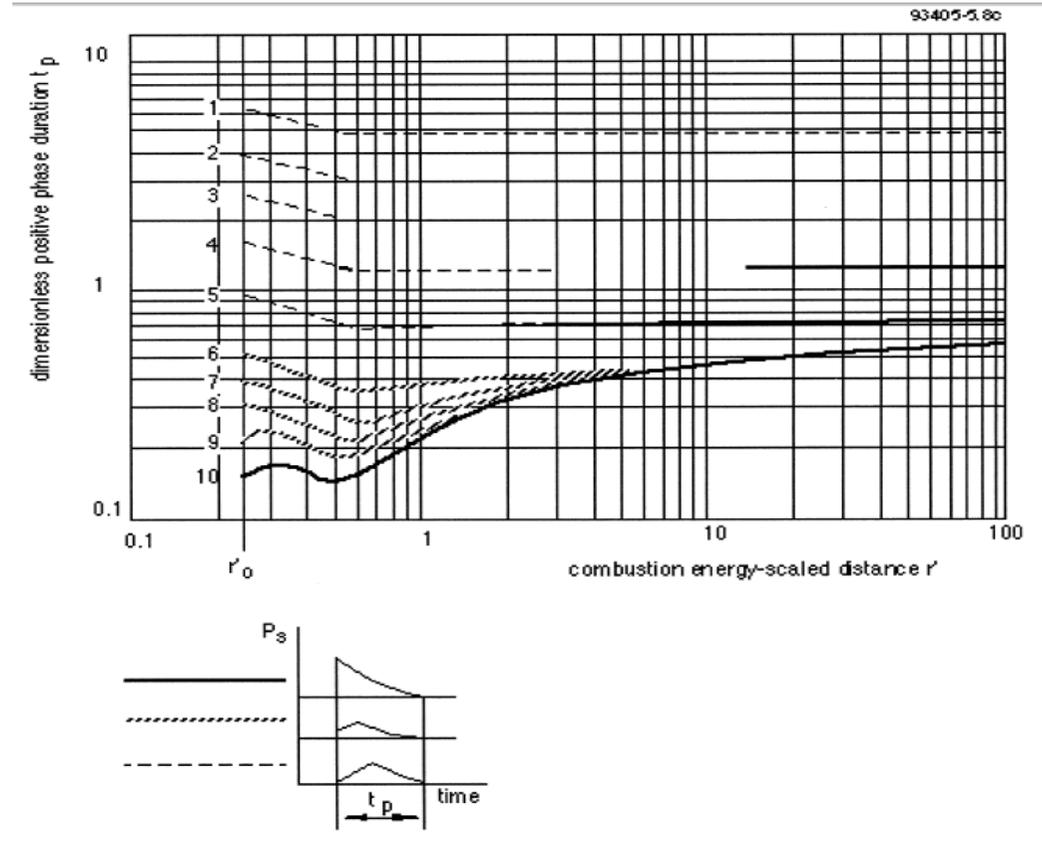UPGRADING THE EXPLOSIVE MODULE

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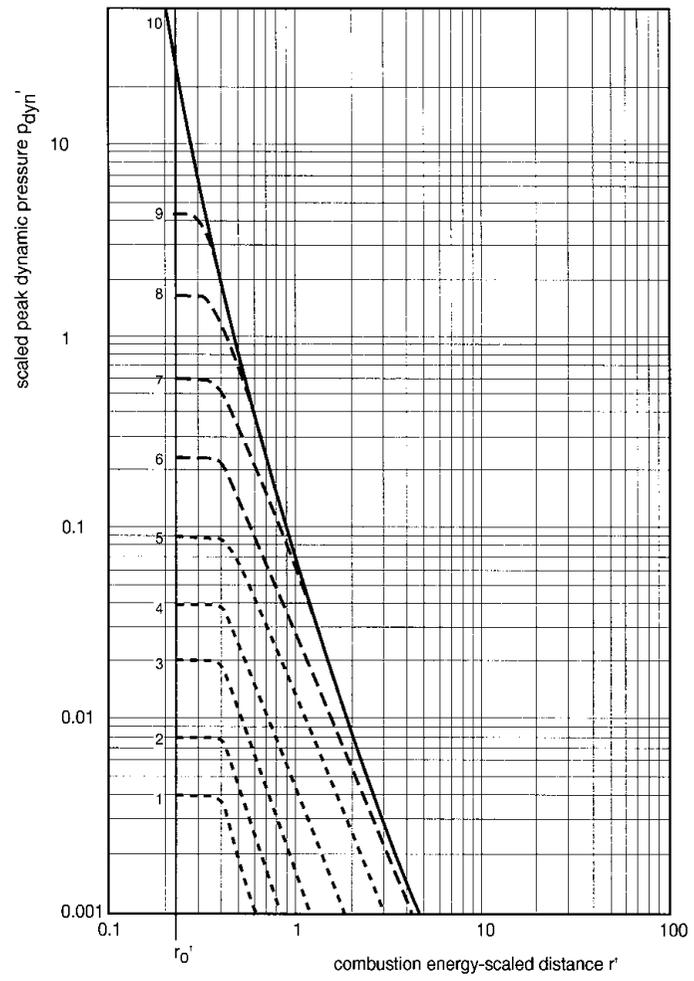
Multi-Energy method blast chart: peak dynamic pressure   Multi-Energy method blast chart: positive phase duration and blast-wave shape

Figure 4: Multi-energy method tables based on the reduced distance r' = r/(E/P₀)¹ᐟ³, where r is the centre of the explosion (m), E is the explosion energy (J) and P₀ is the ambient pressure (Pa). Van den Bosch [16]

3. Discussions

3.1.   Limitations of the multi-energy model

Although the multi-energy method allows for reasonable prediction of overpressures (high or low) in realistic contexts, **several limitations remain**, preventing the development of a fully robust application procedure. These limitations mainly concern:

– **Overpressure in obstructed areas**– Uncertainty about the choice of *source strength* (also known as *number of classes*), which affects the accuracy of predictions.
– **Definition of an obstructed area**– Lack of clear criteria for identifying and characterising an area as obstructed.
– **Minimum distances between explosion sources** – Lack of guidelines on the minimum *separation distance* at which multiple sources can be considered to be acting independently.

3.2.   Guidance for choosing the source strength

Since the method was introduced by Van den Berg in 1985 [15], the lack of clear guidelines on determining source strength has been recognised. Some guidance has since been proposed to address this uncertainty and is now available in summary form.

Scientific publications provide some guidance on choosing the strength of the explosion source, highlighting the crucial influence of three parameters:

– Obstruction (volume or blocked surface area),
– Confinement,
– Reactivity (considered to varying degrees depending on the author).

Researchers such as Kinsella [8] include ignition strength, while Baker et al. [3] and Cates [4] add gas reactivity. However, despite these efforts, the practical application of these criteria remains highly uncertain, with a significant risk of underestimating overpressures (sometimes by a factor of 10 to 30 according to Mercx et al. [9]).

3.2.1. Limitations and recommendations

Current methods do not allow the influence of obstruction to be quantified correctly, which prevents reliable classification of reactivity.

Even if scaling laws allow the relative effect of different gases to be assessed, a reference (e.g. methane) is still necessary for an absolute estimate. This limits classification to explosion classes 9 or 10, as most gases are more reactive than methane.

3.2.2. Recommended approach (cautious and conservative)

1. Differentiate between obstructed and unobstructed areas.
2. Assign a high source strength (class 10) to obstructed areas.
3. Assign a low source strength (class 1) to unobstructed areas.
   – If initial gas movement is expected (e.g. high release velocity), use class 3.
4. Do not modulate according to the reactivity of the gas.

If overpressures are considered too high using this method, it is recommended to rely on:

– Reliable experimental data, or
– Tests specific to the situation under consideration.

Note: Applying an explosion force of class 10 in the multi-energy method gives results similar to those obtained by the TNT method with an efficiency factor of 20%, applied only to the obstructed area of the cloud.

3.2.3. Kinsella guidelines for the multi-energy method

In order to illustrate a methodology for assessing the strength of an explosion source, it is proposed to use the Kinsella method, which is the simplest method to implement. Kinsella [8] proposes criteria for determining the strength of the explosion source in the multi-energy method, based on the analysis of major accidents. Three factors are considered:

Obstruction:

– High: Dense obstacles with a blocking fraction > 30% and spacing < 3 m.
– Low: Obstacles present but with a blocking fraction < 30% and/or spacing > 3 m.
– None: No obstacles in the gas cloud.

Containment:

– Yes: The cloud is partially or totally contained (walls, barriers).
– No: The cloud is only contained by the ground.

Ignition energy:

– High: Powerful ignition source (e.g. confined explosion, internal ignition).
– Low: Low ignition source (e.g. flame, spark, hot surface).

These combinations of conditions are then used to determine the power level (or class number) in a specific table adapted to the multi-energy method (Figure 5).

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Blast strength category	Ignition energy		Obstruction			Parallel plane confinement	Multi-Energy Unconfined	Class
	Low	High	High	Low	No			
	(L)	(H)	(H)	(L)	(N)	(C)	(U)	
1		H	H			C		7-10
2		H	H				U	7-10
3	L		H			C		5-7
4		H		L		C		5-7
5		H		L			U	4-6
6		H			N	C		4-6
7	L		H				U	4-5
8		H			N			4-5
9	L			L		C		3-5
10	L			L			U	2-3
11	L				N	C		1-2
12	L				N		U	1

Figure 5: Table to determine the multi-energy index developed by Kinsella [8]

4. Conclusion

The integration of the multi-energy method into the explosive module of the MANIFESTS project represents a significant advance over the TNT model previously used. Although the latter remains simple and widely used, it is based on statistical assumptions that are not very robust and does not accurately reflect the physical characteristics of vapour cloud explosions.

In contrast, the multi-energy method offers a more realistic and differentiated approach, taking into account the complexity of explosive clouds, including the spatial variability of confinement, turbulence and ignition conditions. It thus makes it possible to model explosion effects in the form of localized sub-explosions, each with its own level of violence, according to a defined scale (index from 1 to 10). This approach improves the accuracy of predictions of overpressures, pulse durations and blast wave shapes, particularly in complex industrial or port contexts.

However, this method remains a simplification of reality and requires structural assumptions (e.g. homogeneous mixture, hemispherical geometry, stoichiometric combustion). Its correct application therefore depends on the quality of the data available on the gas cloud and its environment. Despite its limitations, it is a powerful and operational tool for enhancing risk assessment and planning protective measures in scenarios involving gas explosions in the open air.

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The integration of this model into the MANIFESTS project will contribute to more reliable and integrated management of technological risks associated with maritime and industrial pollution.

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