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Prediction of gas explosion overpressure interacting with structures for blast-resistant design

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ABSTRACT

To evaluate the overpressure of a explosion, there are three kinds of models: an experimental (simplified or empirical) model, semi-experimental model, and computational fluid dynamics model. Each model has various methods, and is applied to slightly different cases. In this paper, three commonly used methods of the experimental model are introduced and reviewed, that is, the TNT equivalent method, TNO multi-energy method, and Baker-Strehlow-Tang (BST) method. The TNT equivalent method is a method using the equivalent charge of TNT. It is easy to use, but may be overly conservative for a gas explosion which has a different mechanism from that of TNT explosion. The TNO multi-energy method, suggested as an alternative to the TNT method, uses a class number to calculate the overpressure. This method, which is most commonly used in the onshore industry, leaves a planner, owner or designer the selection of the class number, and it lowers the objectivity. The BST method also still requires users to assume the Mach number. Therefore, there is a need for more detailed guidelines to improve the accuracy of the TNO multi-energy method and BST method.

1. INTRODUCTION

A school of New London, Texas experienced a gas explosion on March 18, 1937. Over 296 persons were dead, and over 300 persons were injured. In 1992 at Analco of Guadalajara, Mexico, a gas explosion killed over 252 people, and injured over 500 people. In addition, there was economic damage of about 300 million dollars. Two gas explosions shown in Figs. 1 and 2 are the most common cases of gas explosion accidents occurred in living regions (not an industrial complex). As anticipated, the gas explosions caused human, environmental, and economical damages. In many cities, as the human density and usage of gas increase, the potential for gas explosions also increases.

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Fig. 1 Landscape of school after the explosion (Daily mail 2012)

Fig. 2 Landscape of Guadalajara after the explosion (CNN Mexico 2012)

1.1 Blast load for blast resistant design

When blast occurs, a large amount of energy is emitted within very tiny time, so it needs other methods to estimate blast loads for blast resistant design unlike the wind or seismic loads. The peak overpressure (P_{so}), the reflected overpressure (P_r) and the dynamic pressure (q_0) are needed for the blast resistant design (Bounds 2010). In this paper, it is focused on reviewing and researching proper methods to estimate the peak overpressure especially for a gas explosion.

2. MODELS TO PREDICT PEAK OVERPRESSURE

To predict the explosion overpressure, three models can be used: simplified (empirical), phenomenological, and computational fluid dynamics (CFD) models. The simplified model calculates the overpressure using the scaled distance. The CFD model estimates the overpressure by solving the Navier-Stokes equation which considers the flow of fluid in field (Turner and Sari 2012). Each model has its own advantage, disadvantage and characteristics. This paper focuses on reviewing TNT equivalent method, TNO multi-energy method and Baker-Strehlow-Tang method used as part of the simplified model.

2.1 TNT equivalent method

TNT equivalent method, which is widely used for blast resistant design, estimates explosion pressure depending on the scaled distance. This method, first developed by the U.S. Navy and the U.S. Air force, uses correlations between explosives and damages based on the analysis of various military experiments. Results were included in the US Army Technical Manual TM 5-1300 and are illustrated in Fig. 3. Similarly, by observing damaged conditions in many gas explosion accidents, TNT equivalent method may be used to describe the degree of explosive damages of gas explosions. After calculating the combustion heat of leaked gas, the combustion energy of explosion can be set equal to that of the equivalent charge of TNT and then the range of overpressure is estimated according to the distance. Because of its convenience, the TNT equivalent method is widely used while it is generally conservative for the case of gas explosion. As it considers only one explosion at the center of a gas cloud, the TNT equivalent method is not suitable for the gas explosion, which has potential sources causing various overpressures within a vapor cloud. For this reason, TNT equivalent method is not recommended to determine the overpressure of a gas explosion (Bjerketvedt et al. 1997).

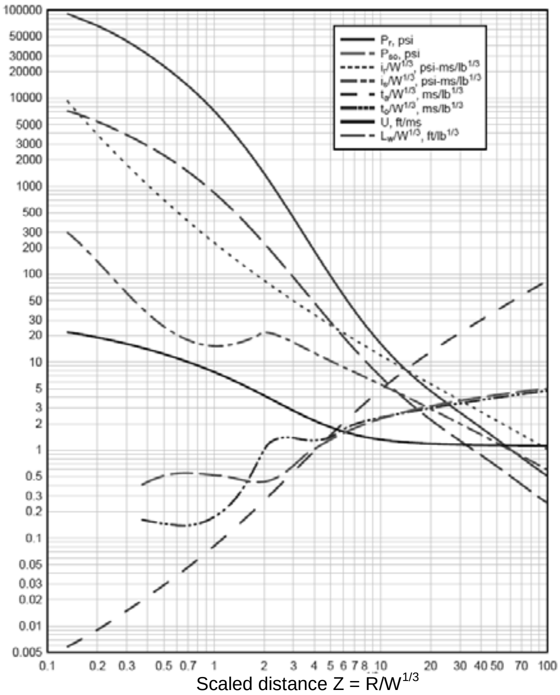

Fig. 3 Positive phase shock wave parameters for spherical TNT explosion (U.S. Army Corps of Engineers 2008)

2.2 TNO multi-energy method

TNO multi-energy method (TNO MEM) suggested by Van den Berg determines the peak overpressure considering the different strength of a gas explosion depending on confinement (Van den Berg 1985). Obstacles within a gases cloud can affect the degree of gas explosions by increasing the speed of flame, i.e., turbulence that is caused when fluid faces obstacles accelerates flames of explosions. Because TNO MEM assumes that turbulence governs the strength of a blast wave, it uses geographic conditions as a main factor to estimate the potential energy of gas explosions (e.g., whether obstructed or confined). From different ignition sources in a vapor cloud, sub-explosions having different strengths are determined, and then the positive overpressures and positive duration phases are defined. The procedure estimating the strength of explosions with TNO MEM is as follow (Melani et al. 2009):

(1) Determine the obstructed and/or unobstructed regions.
(2) Evaluate the class number and then estimate strength of sources in each region based on the class number.
(3) Determine the radius of a vapour cloud.
(4) Calculate the scaled distance, positive scaled overpressure and scaled duration phase (blast parameters).
(5) Calculate the positive overpressure, positive scaled duration and positive impulse (real parameters).

The blast parameters (Figs. 4 to 6, Van den Berg 1985) are determined based on the class number, and for the class number, the guidelines suggested by Kinsella (1993) and by Roberts and Crowley (2004) can be used (Tables 1 and 2). These guidelines, however, define the range of class number, not a certain value. The designer can make a final decision when choosing the class number, though it is not sufficiently objective. In order to supplement such an insufficient objectivity, several projects have been conducted, including the GAME (Eggen 1998) and GAMES (Mercx et al.1998) projects that provided the GAME correlation to correct the class number if the initial class number is conservative. Nonetheless, additional research on high-reactivity gas of hydrogen is needed as the GAME project was conducted in regard to low-reactivity gas such as methane.

Table. 1 Guidelines by Kinsella (1993) for the class number

Ignition energy		Obstacle density		Confinement			Strength
Low	High	High	Low	No	Existing	No	
	X	X			X		7 – 10
	X	X				X	7 – 10
X		X			X		5 – 7
	X		X		X		5 – 7
	X		X			X	4 – 6
	X			X	X		4 – 6
X		X				X	4 – 5
	X			X		X	4 – 5
X			X		X		3 – 5
X			X			X	2 – 3
X				X	X		1 – 2
X				X		X	1

Table. 2 Guidelines by Roberts and Crowley (2004) for the class number

Types of flame expansion	Mixture reactivity	TNOMEM charge strength		
		Obstacle density		
		High	Medium	Low
1-D	High	10	10	10
	Medium	9 – 10	9	7 – 8
	Low	9 – 10	7 – 8	4 – 5
2-D	High	9	7 - 8	6
	Medium	7 – 8	6 – 7	2 – 3
	Low	6	5 – 6	1 – 2
3-D	High	6	3	1
	Medium	3 – 4	2	1
	Low	3	2	1

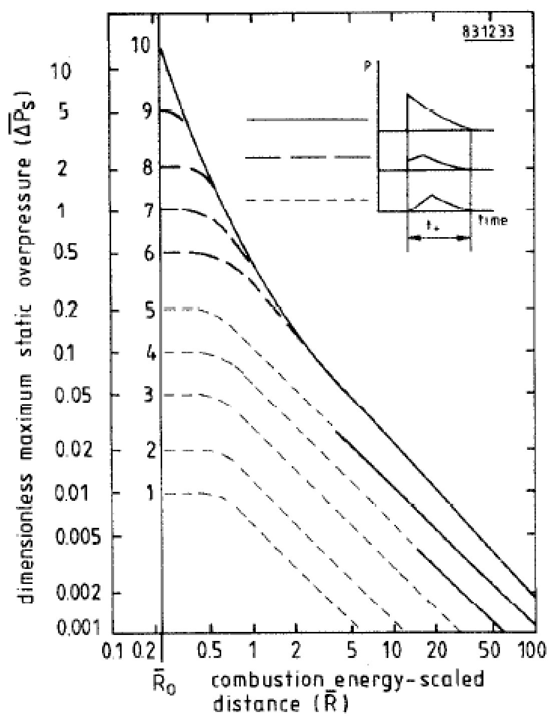

Fig. 4 Scaled distance versus dimensionless maximum static overpressure relationship (Van den Berg 1985)

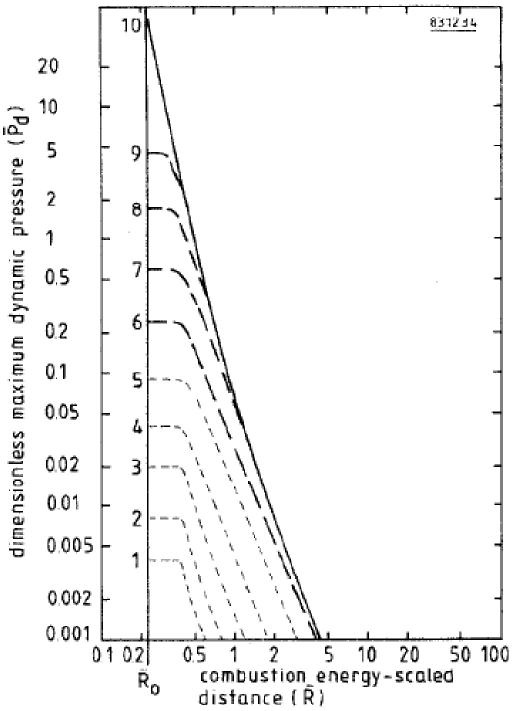

Fig. 5 Scaled distance versus dimensionless maximum dynamic overpressure relationship (Van den Berg 1985)

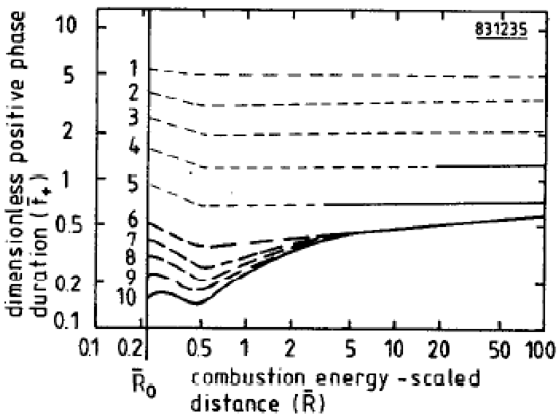

Fig. 6 Scaled distance versus duration relationship (Van den Berg 1985)

2.3 Baker-Strehlow-Tang method

Baker-Strehlow-Tang (BST) method has been developed by Baker et al. (1996), by Tang and Baker (1999) and by Pierorazio et al. (2005), dealing with overpressures and impulses in relation with energy-scaled distance. Baker et al. (1996) carried out a literature review to determine the flame speed of an explosion according to the Mach number. As a result, Baker-Strehelow (BS) method, the basis of three BST methods, was created. Designers can choose one of the following three methods: 1) Baker-

Strehelow (BS) method (1996); 2) Baker-Strehlow-Tang 1 (BST1) method (Tang et al. 1999) using new sets of curves; and 3) Baker-Strehlow-Tang 2 (BST2) method (Pierorazio et al. 2005) using a new matrix. All these methods are originally from the work conducted by Strehlow (1975).

Maximum flame speed mainly dependent upon the Mach number (M_w) is finalized according to the sources, confinement, and obstacle density, and is used to calculate positive overpressures and positive impulses of two sets of pressure-curves. The same way of the TNO MEM can be adopted to determine the overpressure. The impulse can be directly obtained from reference curves along with a given equation (only for the case where M_w is greater than 0.25).

2.3.1 Selection of matrix

There are two usable matrixes for selecting the Mach number: 1) Baker et al. matrix (1996, Table 3); and 2) Pierorazio et al. matrix (2005, Table. 4). The Mach number is determined using either one of these matrixes which consider the correlations among congestion (or obstacle density), fuel-reactivity, and flame expansion (or confinement).

(a) Baker et al. matrix (1996)

This matrix is based on the literature review of experiments on flame speed. The obstacle influence is defined depending on different kinds of obstacles, the volume blockage ratio (VBR) and the pitch. According to the categories of the TNO MEM, fuel-reactivity of gas is classified as L (low reactivity), M (medium reactivity) or H (high reactivity) (see Table 3). The confinement or flame expansion is classified as 1D, 2D or 3D flame expansion, reflecting the way of the flame spreading.

Table. 3 Baker et al. matrix (1996) for selection of Mach number (M_w)

1D flame expansion (planar flame)			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	5.2	5.2	5.2
M	2.265	1.765	1.029
L	2.265	1.029	0.294
2D flame expansion (cylindrical flame)			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	1.765	1.029	0.588
M	1.235	0.662	0.118
L	0.662	0.471	0.079
3D flame expansion (spherical of hemispherical)			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	0.588	0.153	0.071
M	0.206	0.100	0.037
L	0.147	0.100	0.037

(b) Pierorazio et al. matrix (2005)

This matrix is based on previous experiments in medium scale. The congestion region and obstacles are designed as modular sections of 1.8 m^3 cubes or circular tubes. The number of cubes/tubes and VBR (volume blockage ratio) are divided into three categories: 1) Low; 2) Medium; and 3) High congestion. However, it is not easy to determine the level only based on the VBR. Yet, the difference between categories is smaller than the previous matrix. In the Pierorazio et al. matrix (2005), different kinds of gases are used to establish a fuel-reactivity, and the BS matrix is adopted for classification. In the Pierorazio et al. matrix (2005), the 1D flame expansion is eliminated because it hardly occurs in the actual industrial field. The 2.5D flame expansion is added, instead, for environmental conditions blocked with fragile panels or solid confining plane.

Table 4. Pierorazio et al. matrix (2005) for selection of Mach number (M_w)

2D flame expansion (cylindrical flame)			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	DDT	DDT	0.59
M	1.6	0.66	0.47
L	0.66	0.47	0.079
2.5D flame expansion			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	1.765	1.029	0.588
M	1.235	0.662	0.118
L	0.662	0.471	0.079
3D flame expansion (spherical of hemispherical)			
Fuel reactivity	Obstacle density		
M_w	H	M	L
H	0.588	0.153	0.071
M	0.206	0.100	0.037
L	0.147	0.100	0.037

2.3.2 Selection of curves

After the Mach number is determined from the matrix referred above, positive overpressures and positive impulses are calculated using sets of curves. Two sets of curves available in the BST method are as follow: 1) the Baker et al. curves (Figs. 7 and 8, Baker et al. 1996), as a function of M_w and a function of Lagrangian Mach number; and 2) the Tang et al. curves (Figs. 9 to 13, Tang et al. 1999), as a function of M_f and a function of Eulerian Mach number. The latter sets of curves are commonly used. There are two ways to calculate the positive overpressure and positive impulse. For the BS method, the positive overpressure and impulse are defined from the graph given the selected M_w. For the BST1 and BST2 methods, the value of M_f, calculated using the selected M_w, is used to define the positive overpressure and impulse.

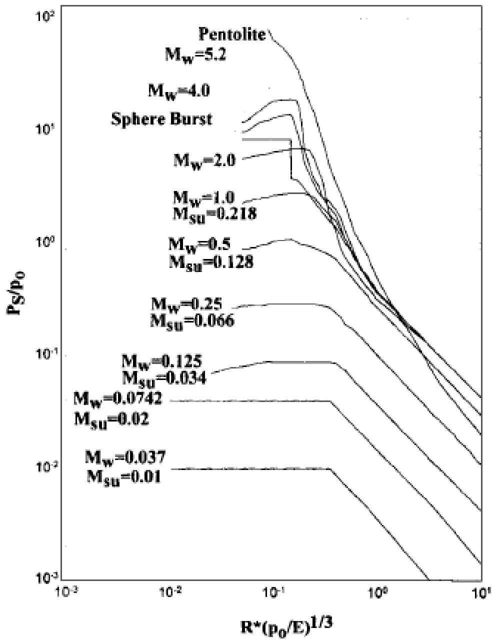

Fig. 7 Scaled overpressure curves for spherical vapor cloud explosions (Baker et al. 1996)

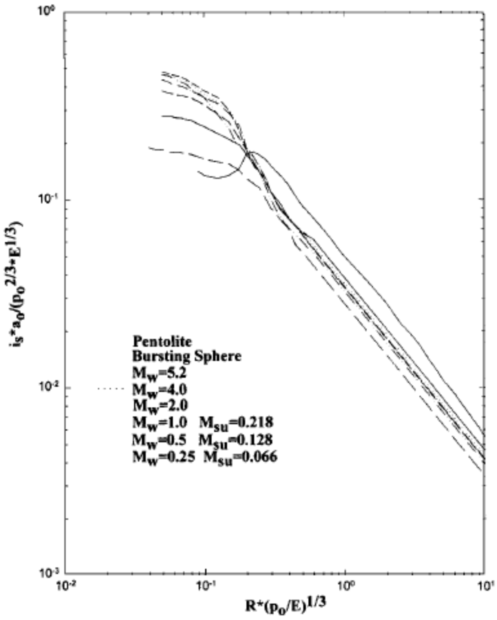

Fig. 8 Scaled side-on specific impulse curves for spherical vapor cloud explosions (Baker et al. 1996)

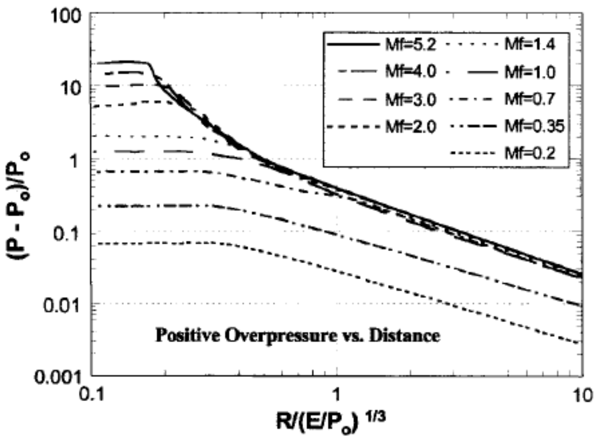

Fig. 9 Positive overpressure versus distance relationship for various flame speeds (Tang et al. 1999)

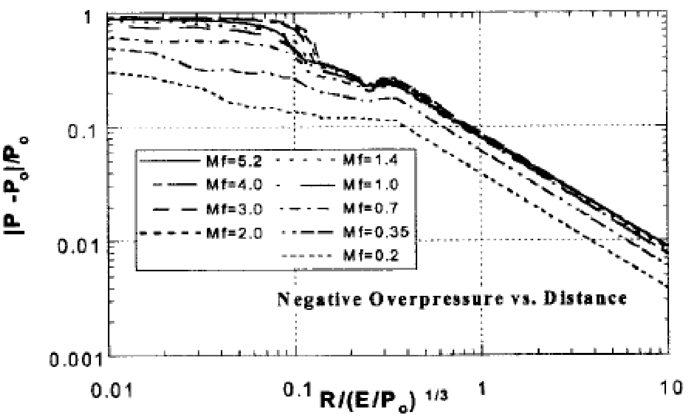

Fig. 10 Negative overpressure versus distance relationship for various flame speeds (Tang et al. 1999)

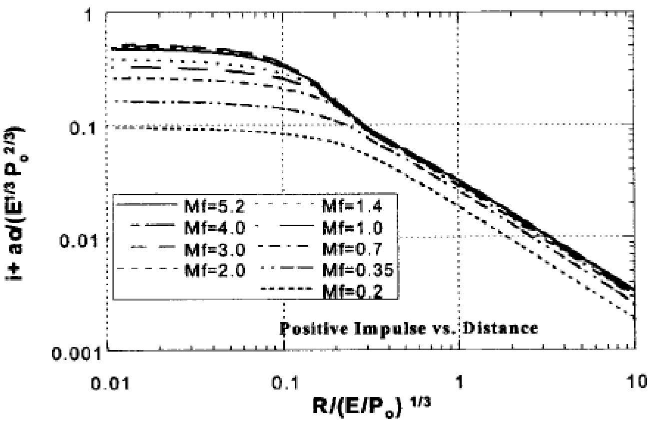

Fig. 11 Positive impulse versus distance relationship for various flame speeds (Tang et al.1999)

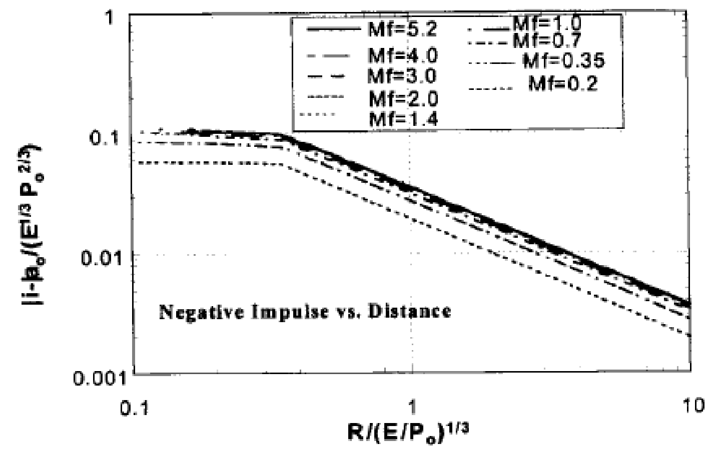

Fig. 12 Negative impulse versus distance relationship for various flame speeds (Tang et al. 1999)

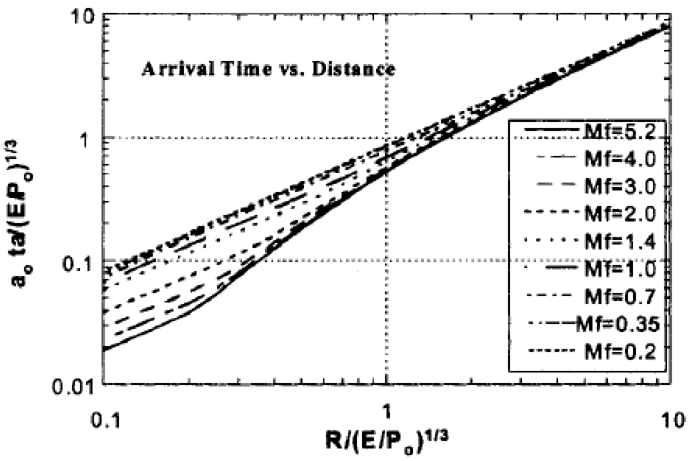

Fig. 13 Arrival time versus distance relationship for various flame speeds (Tang et al. 1999)

3. CONCLUSIONS

The TNT equivalent method which uses the correlation between explosion power and TNT equivalence provides most simplified equations. Although it is a mainly used method for the blast resistant design, it is difficulty to apply the TNT equivalent method to evaluate the overpressure of a “gas explosion” due to its conservative result and inappropriateness to explain sub-explosions. The alternatives to the TNT equivalent method are TNO MEM and BST methods. The former is described by using the positive pressure and time duration, whereas the latter explained by the positive pressure and impulse. The TNO MEM considers environment where a gas explosion occurred (i.e., congestion and confinement) and sub-explosions within a vapor cloud. After selecting the class number, overpressure, duration, impulse, and a degree of explosions (e.g., deflagration or detonation) could be obtained. The BST Method, which is similar to TNO MEM, offers information via a set of curves along with the Mach number determined from a valid matrix. These methods, however, leave the selection of the class and Mach number to the designers. The class and Mach number are affected by many important assumptions such as fuel-reactivity, a degree of the obstacled or confined environment. This lowers the objectivity of estimating peak overpressure. Therefore, to ensure the subjectivity of methods, further research studies that may provide some guidance on how to assume need to be conducted.

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