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# An Abridged Review of Blast Wave Parameters

Manmohan Dass Goel[*#], Vasant A. Matsagar[^], Anil K. Gupta[#], and Steffen Marburg[!]

*[#]CSIR-Advanced Materials and Processes Research Institute, Bhopal - 462 064, India*
*[^]Indian Institute of Technology Delhi, New Delhi - 110 016, India*
*[!]Universität der Bundeswehr, Munich, Germany*
*[*]E-mail: mdgoel@ampri.res.in*

**ABSTRACT**

In case of blast loading on structures, analysis is carried out in two stages, first the blast loading on a particular structure is determined and second, an evaluation is made for the response of the structure to this loading. In this paper, a review of the first part is presented which includes various empirical relations available for computation of blast load in the form of pressure-time function resulting from the explosion in the air. Different empirical techniques available in the form of charts and equations are reviewed first and then the various blast wave parameters are computed using these equations. This paper is providing various blast computation equations, charts, and references in a concise form at a single place and to serve as base for researchers and designers to understand, compare, and then compute the blast wave parameters. Recommendations are presented to choose the best suitable technique from the available methods to compute the pressure-time function for obtaining structural response.

**Keywords:** Blast wave, empirical relations, Friedlander wave equation, peak pressure, impulse, wave parameters

## 1. INTRODUCTION

An explosion in air releases energy rapidly which generates a pressure wave of finite amplitude. These energy sources are physical, chemical, and nuclear that generates a violent reaction when initiated. This energy moves forward in air with a front and air properties cause this front to shock up or steepen as it progresses further. This shock front move supersonically, i.e. speed more than the speed of sound in air ahead of it, with discontinuity in pressure, density, and particle velocity across the front. The blast wave differs from acoustic wave as later moves at sonic speed and does not shock up. The movement of blast wave in air is a nonlinear process involving a nonlinear equation of motions, whereas largely wave propagation is a linear problem. Moreover, the process of reflection and diffraction for both the waves are significantly different.

The blast wave problem is dated back during World War II. Taylor[1] proposed numerical solution for an explosion in air by computing the energy of the blast and proposed scaling laws based on the experimental data. However, the need of research was felt to study the blast wave propagation in cold gas and general equation of state to describe it. Sedov[2] and von Neumann[3] analyzed the problem and independently proposed more general solution to the blast wave propagation. The science of blast over pressure measurement and its computation using various charts and empirical relations is available but scattered in many references. The main parameters describing blast wave include: peak positive over pressure ($P_{pos}$), positive duration ($t_{pos}$), under pressure ($P_{neg}$), negative duration ($t_{neg}$), wave decay parameter ($b$), and impulse ($I$). These parameters and reflected pressure are required to define the complete blast wave loading on any structure. All these parameters influence damage characteristics of the blast wave.

In engineering analysis, behaviour of explosion is simulated using pressure-time variation defined by above parameters and applied on the structures. This pressure-time function is further simplified by modeling the blast wave as triangular pulse in the protective system design of the structures. This triangular pulse is characterized by peak reflected over pressure and the reflected impulse. Moreover, it is general practice to neglect the under pressure phase of blast wave particularly for the hardened structures adding to further simplification. The actual blast wave is nonlinear and exponentially decaying in nature. There exist several empirical equations to describe its behaviour and all these equations are strictly based on observations[4-7]. The original Friedlander's equation is independent of atmospheric pressure. However, modified Friedlander's equation (with atmospheric pressure, $P_0$) is commonly used to model the blast wave being comparatively more accurate and reasonably simpler in comparison with the others.

As shown in Fig. 1, after the explosion occurs, the ambient pressure increases almost instantaneously and promptly begins to decay. Fig. 1 is an ideal blast wave representation and its characteristics are functions of the distance to the center of the charge, $R$ and the time, $t$. The

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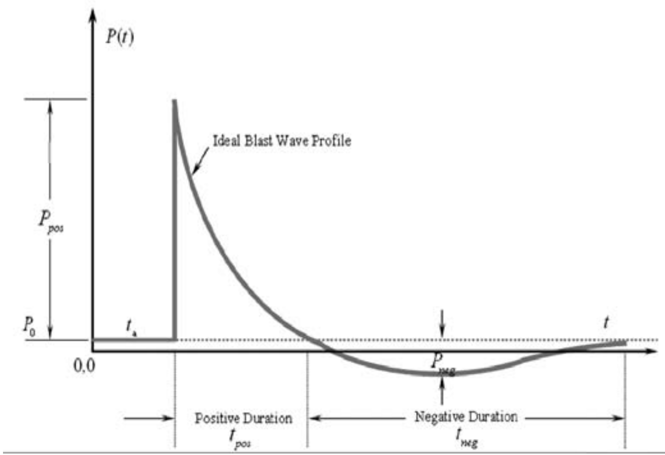


**Figure 1. Ideal blast wave resulting from explosion in air.**

peak pressure is known as peak positive over pressure, $P_{pos}$. A negative phase follows, in which the pressure is lower than ambient pressure known as under pressure, $P_{neg}$. The duration of peak positive over pressure and under pressure is known as positive, $t_{pos}$ and negative duration, $t_{neg}$, respectively. The integrals of over pressure and under pressure curves are known as incident over pressure impulse, $I_{pos}$ and under pressure impulse, $I_{neg}$, respectively. This information on blast wave is available in the form of charts and equations[8-11]. The blast wave profile described by the modified Friedlander equation depends on the time, $t$ which starts at the arrival of the pressure wave at this point, i.e. $t = t_0 - t_a$ as,

$$P(t) = P_0 + P_{pos}\left(1 - \frac{t}{t_{pos}}\right)e^{-b\frac{t}{t_{pos}}} \tag{1}$$

The parameter, $b$ describes the decay of the curve; $P_0$ is the ambient air pressure; and $t_0$ is the time at peak positive over pressure.

## 2. COMPUTATION OF PEAK POSITIVE OVER PRESSURE

After the detonation occurs, the ambient pressure increases almost instantaneously and promptly begins to decay, forming a nearly triangular over pressure pulse. This peak pressure is called the peak positive over pressure. It represents the pressure at a point in space when the shock wave is unimpeded in its motion. There exist various empirical equations developed by several researchers based on the analysis of large and small scale explosion data. In the present paper, various empirical relations developed based on the analysis of spherical charge detonated in air only are presented whereas as for hemispherical charge a factor of 1.8 can be applied directly to obtain the parameters in order to account the reflection from the ground.

Brode[6] analysed the differential equation of gas motion in Lagrangian form and presented the analytical solution for the peak positive over pressure in near-field and medium to far-field conditions as,

$$P_{pos} = \frac{6.7}{Z^3} + 1\,\text{bar}\ (P_{pos} > 10\ \text{bar}) \tag{2}$$

$$P_{pos} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019\,\text{bar}\ (0.1 < P_{pos} < 10\ \text{bar}) \tag{3}$$

Henrych[12], based on the analysis of several experimental data, presented the equations to compute peak positive over pressure. These equations are similar to Brode[6] equations. The following equations were presented which relate peak positive over pressure variation with scaled distance,

$$P_{pos} = \frac{14.072}{Z} + \frac{5.540}{Z^2} - \frac{0.357}{Z^3} + \frac{0.00625}{Z^4}\,\text{bar}\ (0.05 < Z < 0.3) \tag{4}$$

$$P_{pos} = \frac{6.194}{Z} - \frac{0.326}{Z^2} + \frac{2.132}{Z^3}\,\text{bar}\ (0.3 \le Z \le 1) \tag{5}$$

$$P_{pos} = \frac{0.662}{Z} + \frac{4.05}{Z^2} + \frac{3.228}{Z^3}\,\text{bar}\ (1 \le Z < 10) \tag{6}$$

Held[13], based on experimental analysis of explosion data, presented the following equation to compute the peak positive over pressure,

$$P_{pos} = 2\frac{W^{2/3}}{R^2}\,(\text{MPa}) \tag{7}$$

Kinney and Grahm[8], based on the analysis of large experimental data, presented the following equation to compute the peak positive over pressure,

$$P_{pos} = P_0\frac{808\left[1 + \left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{\left[1 + \left(\frac{Z}{0.048}\right)^2\right]} \times \sqrt{\left[1 + \left(\frac{Z}{0.32}\right)^2\right]} \times \sqrt{\left[1 + \left(\frac{Z}{1.35}\right)^2\right]}}\,(\text{bar}) \tag{8}$$

Sadovskiy[14] presented the following equation for the peak positive over pressure based on explosion data analysis,

$$P_{pos} = 0.085\frac{W^{1/3}}{R} + 0.3\left(\frac{W^{1/3}}{R}\right)^2 + 0.8\left(\frac{W^{1/3}}{R}\right)^3\,(\text{MPa}) \tag{9}$$

Bajić[15], based on experiments, modified Sadovskiy equation and presented a new equation to compute peak positive over pressure,

$$P_{pos} = 1.02\frac{W^{1/3}}{R} + 4.36\frac{W^{2/3}}{R^2} + 14\frac{W}{R^3}\,(\text{bar}) \tag{10}$$

where $W$ is the charge weight in kg, $Z$ is the scaled distance in m and expressed as,

$$Z = \frac{R}{W^{1/3}}\,(\text{m/kg}^{1/3}) \tag{11}$$

Kingery and Bulmash[9] presented polynomial equation to compute the peak positive over pressure. The results of these equations are presented in the form of charts.

The limitation of these charts is that, these charts are applicable up to a scaled distance of $Z$ = 40 m/kg$^{1/3}$. Fig. 2 shows charts to compute the peak positive over pressure as proposed by Kingery and Bulmash[9] for spherical charge detonated in air. Baker[10] also proposed

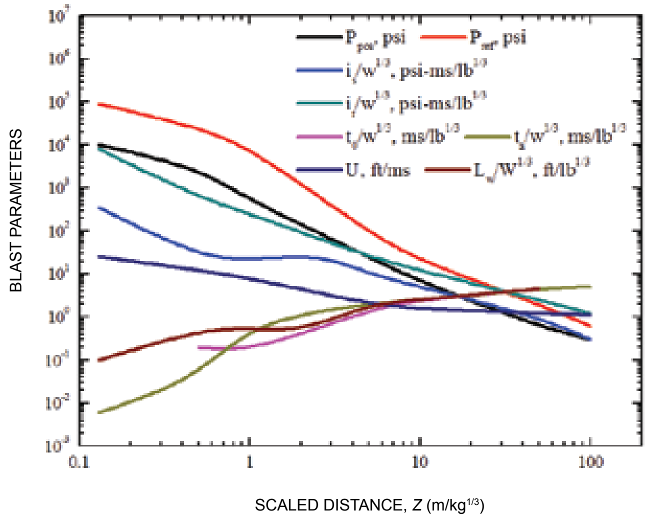


**Figure 2. Various blast wave parameters for spherical explosion in air (units in United States customary system).**

charts to compute peak positive over pressure and these are available up to $Z$ = 1000 m/kg$^{1/3}$. These charts can be used to compute the blast wave parameters. Figure 3 shows the comparison of all above mentioned empirical equations to compute the peak positive over pressure. It can be observed that for small scaled distance, i.e. $Z$ < 1 m/kg$^{1/3}$, there exists a wide variation in the peak positive

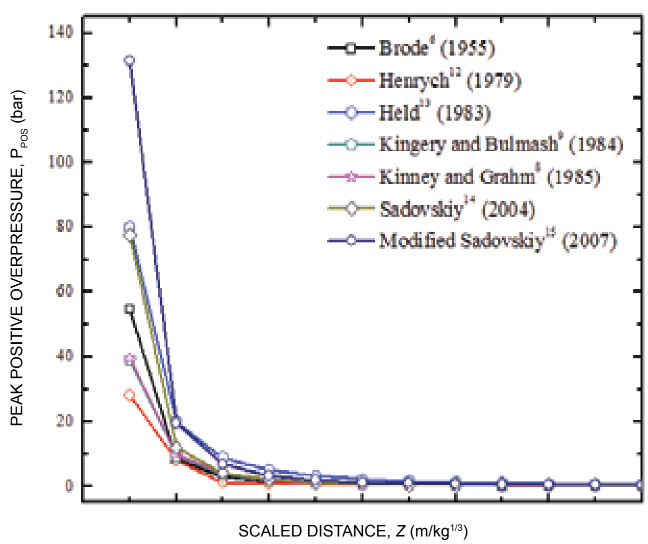


**Figure 3. Variation of peak over pressure with scaled distance.**

over pressure computed using these relations. Hence, it becomes utmost important to take special care when the scaled distance is smaller. The reason for this anomaly is attributed to the instrumentation in such near region of explosion which is always prone to error.

## 3. COMPUTATION OF POSITIVE OVER PRESSURE DURATION

The duration of blast wave is the time between the passing of shock front and the end of the positive pressure phase as marked by zero over pressure. This duration and peak positive over pressure together determines effect of blast loading damage to the structure. Kinney and Grahm[8] presented the following equation to compute the positive over pressure duration,

$$t_{pos} = W^{1/3} \frac{980\left[1+\left(\frac{Z}{0.54}\right)^{10}\right]}{\left[1+\left(\frac{Z}{0.02}\right)^{3}\right]\times\left[1+\left(\frac{Z}{0.74}\right)^{6}\right]\times\sqrt{\left[1+\left(\frac{Z}{6.9}\right)^{2}\right]}} \quad \text{(milisecond)} \tag{12}$$

Henrych[12] presented the following equation to compute the positive over pressure duration as,

$$t_{pos} = e^{(-2.75+0.27\log_{10} Z+)+\log_{10} W^{1/3}} \tag{13}$$

Sadovskiy[14] presented the following equation for the positive over pressure duration as,

$$t_{pos} = 1.2\sqrt[6]{W}\sqrt{R}\,(\text{ms}) \tag{14}$$

Similarly, diagrams of Brode[6], Kingery and Bulmash[9], and Baker[10] can also be used to compute the positive over pressure duration. Kingery and Bulmash[9] polynomial equation can also be used to compute the positive duration. Fig. 4 shows the comparison of the above mentioned methods to compute the positive peak over pressure duration.

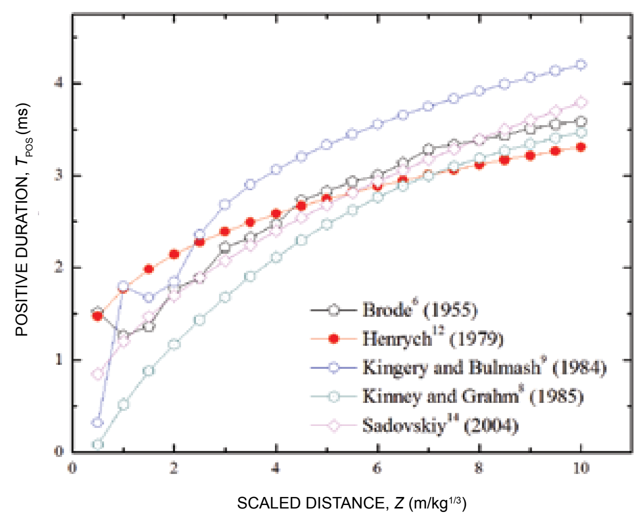


**Figure 4. Variation of positive over pressure duration with scaled distance**

## 4. COMPUTATION OF POSITIVE IMPULSE

Impulse ($I$) is an important parameter for blast damage capability. This is the controlling parameter for some situations especially for blast wave of shorter duration. It is defined as the area under the pressure-time curve and has the unit of force-time. Kinney and Grahm[8] presented the following equation to compute the positive impulse,

$$I_{pos} = \frac{0.067\sqrt{1+\left(\frac{Z}{0.23}\right)^4}}{Z^2\sqrt[3]{1+\left(\frac{Z}{1.55}\right)^3}} \text{(bar-ms)} \quad (15)$$

Held[13] presented the following equation to compute the positive impulse as,

$$I_{pos} = 300\frac{W^{2/3}}{R} \text{(Pa-s)} \quad (16)$$

Sadovskiy[14] presented the following equation to compute the positive impulse as,

$$I_{pos} = 200\frac{W^{2/3}}{R} \text{(Pa-s)} \quad (17)$$

Similarly, diagrams of Brode[6], Kingery and Bulmash[9], and Baker[10] can also be used to compute the positive over pressure duration. Kingery and Bulmash[9] polynomial equation can also be used to compute the positive impulse. Fig. 5 shows the comparison of the abovementioned methods to compute the positive impulse.

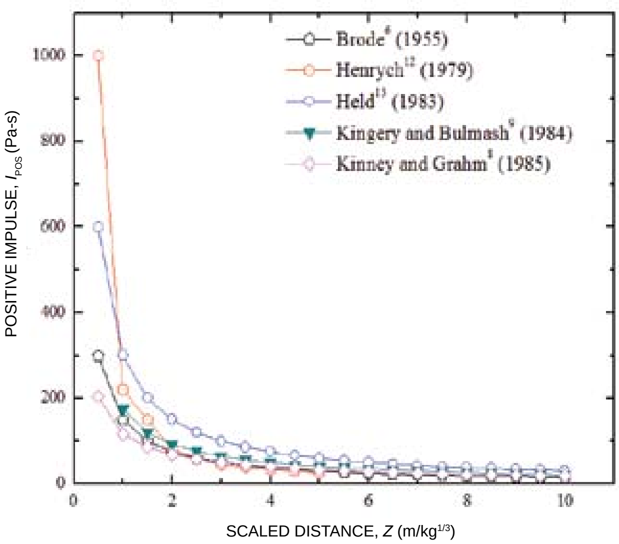


**Figure 5. Variation of impulse with scaled distance.**

## 5. COMPUTATION OF UNDER PRESSURE PHASE PARAMETERS

The under pressure phase is usually much weaker in nature and does not affect hardened structures[8,16]. Under pressure phase is more important for flexible structures as compared to the stiff structures. Modified Friedlander equation is used to compute the under pressure phase parameter also. Krauthammer and Altenberg[16] presented the following equation to compute the under pressure and negative duration,

$$P_{neg} = \frac{0.35}{Z}10^5 \text{ Pa } (Z > 3.5) \quad (18)$$

$$P_{neg} = 10^4 \text{ Pa } (Z < 3.5) \quad (19)$$

$$t_{neg} = 0.0104W^{1/3}\text{s } (Z < 0.3) \quad (20)$$

$$t_{neg} = (0.003125\log_{10}Z + 0.01201)W^{1/3} \text{ s } (1.9 < Z > 0.3) \quad (20)$$

$$t_{neg} = 0.0139W^{1/3}\text{s } (Z > 1.9) \quad (21)$$

Teich and Gebbeken[17] presented the following equation to compute the under pressure pulse and the time at which maximum negative pressure occurs,

$$t_{neg-peak} = \frac{b+1}{b}t_{pos} \quad (22)$$

$$I_{neg} = \frac{P_{pos}\,t_{pos}}{b^2}e^{-b} \quad (23)$$

Only for larger scaled distance ($Z > 20$) and more especially for scaled distance ($Z > 50$) the values of positive and negative phase are similar in magnitude.

## 6. COMPUTATION OF WAVE DECAY PARAMETER

The wave decay parameter, *b* describes shape of over pressure decay which governs the blast wave shape. It is an empirical adjustment to allow a quasi-exponential form to be given to pressure-time blast wave curve. This is also regarded as the adjustable factor which is selected such that the over pressure-time relations provide suitable values of blast impulse. This parameter is dimensionless similar to the intensity characteristics of the blast wave[8]. There exist various methods to determine this parameter based on pressure and impulse ratio. A superior method for determining the wave decay parameter, *b* is through computation of the area under the pressure-time curve for the blast wave.

Kinney and Grahm[8] presented values of wave decay parameter, *b* based on the ratio of instantaneous over pressure at time, *t* to the peak positive over pressure, $P_{pos}$. Fig. 6 shows the variation of ratio of instantaneous over pressure at time, *t* to the peak positive over pressure, $P_{pos}$ to the ratio of instantaneous time, *t* to positive time duration, $t_{pos}$. Another method to compute the wave decay parameter, *b* proposed by Kinney and Grahm[8] is by the use of impulse under positive phase as follow,

$$I/A = P_{pos}\,t_{pos}\left[\frac{1}{b} - \frac{1}{b^2}\left(1-e^{-b}\right)\right] \quad (24)$$

Figure 6 shows the variation of wave decay parameter using Eqn (24). Ismail and Murray[18] used this equation and proposed the following equation to compute the wave decay parameter, *b* as obtained by differentiating the Friedlander wave equation as follows,

$$b = 2.3\left(\frac{t_{pos}}{t}\right)\log\left(\frac{P_{pos}}{P}\right) - 1 \quad (25)$$

This formula differs from the Kinney and Grahm[8] relationship as,

$$b = 2.3\left(\frac{t_{pos}}{t}\right)\log\left(\frac{P_{pos}}{P}\right) \quad (26)$$

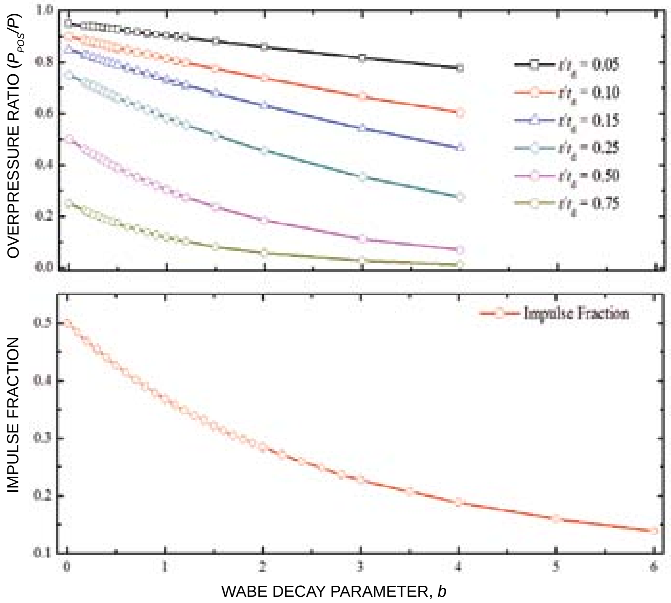


**Figure 6. Variation of wave decay parameter with scaled distance as per Kinney and Grahm[8].**

In deriving this equation Kinney and Grahm[8] took the slope of the limit of *ln p* as *t* tends to zero ($t \rightarrow 0$). The correct results are obtained by taking the limit of the slope[18]. Kinney and Grahm[8], and Baker[10] used the impulse method to compute the wave decay parameter, *b*.

Larcher[19], *et al.* studied the Kinney and Grahm[8] equation for wave decay parameter and used the impulse of positive phase to compute wave decay parameter, *b* as,

$$b = 5.2777Z^{-1.1975} \tag{27}$$

Lam[20], *et al.* used ratio of under pressure with positive over pressure to compute the wave decay parameter, *b* and proposed the following relations,

$$b = Z^2 - 3.7Z + 4.2 \tag{28}$$

$$\ln\left[ b \left| \frac{P_{neg}}{P_{pos}} \right| \right] + b + 1 = 0 \tag{29}$$

Recently, Teich and Gebekken[17] proposed a new formula to compute the wave decay parameter, *b* based on Borgers and Vantomme [21] work,

$$b = 1.5Z^{-0.38} (0.1 < \; Z > \; 30) \tag{30}$$

Kinney and Grahm[8] also presented the computation of wave decay parameter, *b* as the function of impulse fraction which is defined as,

$$\text{Impulse Fraction} = \frac{\int_0^{t_{pos}} P_{pos}\, t}{P_{pos}\, t_{pos}} \tag{31}$$

A comparison of above mentioned formulae is presented in Fig. 7.

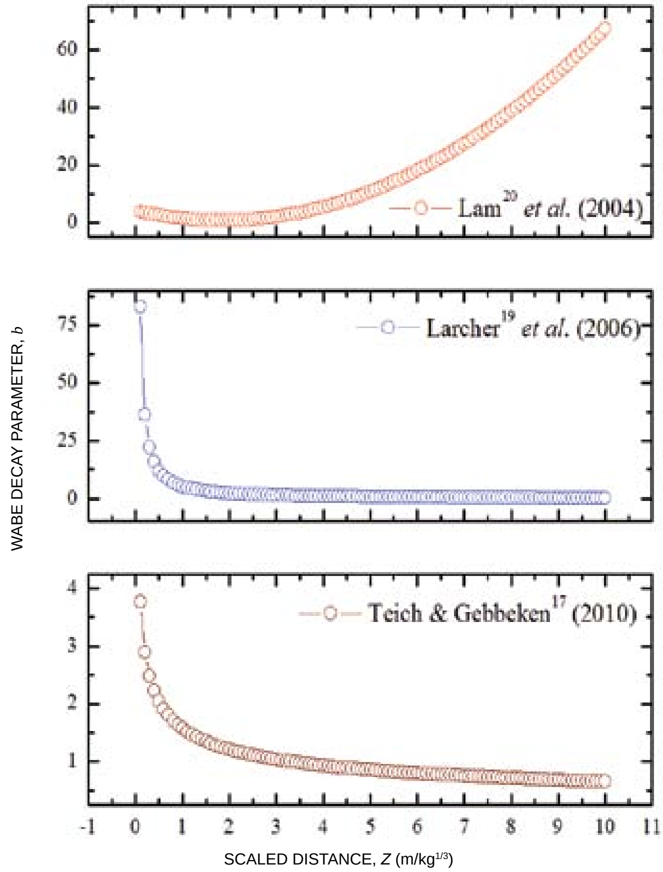


**Figure 7. Variation of wave decay parameter with scaled distance.**

## 7. SUMMARY AND DISCUSSIONS

Design engineers performing assessments or designs of the structures to the blast effects usually begin by computing blast loads for the explosive event under consideration. In almost all the cases, this computation involves the use of one of a number of simplified empirical relations, curves, and computer codes as discussed herein. However, there exists a wide variation in results computed using these available measures. Hence, it is crucial to analyse the particular situation from various viewpoints and choose the best possible combination rather than to prefer one particular method over the others, which often leads to discrepancies. As a result, design engineers are often faced by a dilemma when determining loads: which relation should be used? If results are to be compared with other models and find differences, which one should be considered? How much difference is there in the blast loads being used as compared to the other methods? and ultimately, how conservative is this relation?

This paper aimed to address the aforementioned queries at a single place in a concise form for the designers so that they can choose the best possible method to compute various blast wave parameters rather than simply relying on one method. Based on the study of various empirical relations available, it is observed that Kinney and Grahm's equations are most commonly used by researchers due to their close agreement with the experiments. To characterise the positive phase of blast wave, the Kinney and Grahm's equations are most suitable and the negative phase can be characterised by a triangular form with peak negative pressure and its time of occurrence is computed using the formulae presented herein. Thus, the complete blast wave profile would be as shown in Fig. 8 with the exponentially decaying positive phase and triangular in negative phase. Similarly, other combinations in the form of rectangular and double slope triangular profile for the positive phase can also be used depending upon the analysis methods. Once this profile is computed, one can compute reflected pressure and dynamic pressure using standard the formulae available[8]. The Kingery and Bulmash's equations for the computation of pressure seem to be misleading for the reflected, hemispherical case and hence needs to be used carefully.

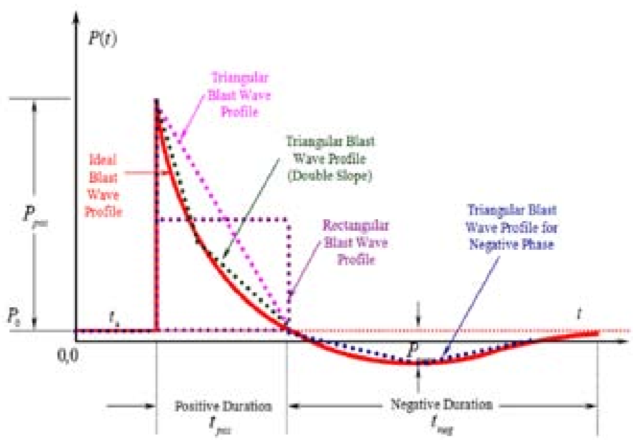


**Figure 8. Modified blast wave profile using triangular shape for both positive and negative phase.**

Hence, the main parameters describing blast wave positive phase, i.e. peak positive over pressure ($P_{pos}$), positive duration ($t_{pos}$), and impulse ($I$) can be computed using the Kinney and Grahm's equations. The negative phase parameters, i.e. under pressure ($P_{neg}$) and negative duration ($t_{neg}$) can be computed using Krauthammer and Altenberg[16] equations. The wave decay parameter ($b$) can be computed using equation presented by Teich and Gebekken[17]. Moreover, the under pressure pulse and the time at which maximum negative pressure occurs can be computed using the equation proposed by Teich and Gebbeken[17]. Thus, by using the above mentioned equations whole description of the blast wave can be achieved.

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## REFERENCES

1. Taylor, G.I. The formation of a blast wave by a very intense explosion I: Theoretical discussion. *Proc. Roy. Soc. London*, 1950, **A 201(1065)**, 159-74.
2. Sedov, L.I. Propagation of strong shock waves. *J. App. Math. Mech.*, 1946, **10**, 241-50.
3. Neumann, J.V. The point source solution. *In* John von Neumann: Collected Works, edited by A.J. Taub, Vol. 6, Pergamon Press, Elmsford, New York, USA, 1963. pp. 219-237.
4. Flynn, P.D. Elastic response of simple structures to pulse loading. Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland, USA, BRL Memo Report No. 525, November 1950.
5. Ethridge, N.M. Blast effects on simple objects and military vehicles II operation SUN BEAM.US Army Armament Research and Development Center, Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland, USA, Project 1.3, POR-2261, 1964.
6. Brode, H.L. Numerical solutions of spherical blast waves. *J. App. Phys.*, 1955, **26**(6), 766-75.
7. Dewey, J.M. The air velocity in blast waves from T.N.T. explosions. *Proc. Roy. Soc. London*, 1964, **A 279**(1378), 366-85.
8. Kinney, G.F. & Grahm, K.J. Explosive shocks in air. Springer, Berlin, 1985.
9. Kingery, C.N. & Bulmash, G. Airblast parameters from TNT spherical air burst and hemispherical surface burst. US Army Armament Research and Development Center, Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland, USA, Technical Report ARBRLTR-02555, April 1984.
10. Baker, W. Explosions in Air. University of Texas Press, Austin, USA, 1973.
11. Smith, P.D. & Hetherington, J.G. Blast and ballistic loading of structures. Butterworth Heinemann Limited, U.K., 1994.
12. Henrych, J. The dynamics of explosion and its use. Elsevier, Amsterdam, 1979.
13. Held, M. Blast waves in free air. *Prop. Exp. Pyro.*, 1983, **8**(1), 1-8.
14. Sadovskiy, M.A. Mechanical effects of air shockwaves from explosions according to experiments. *In* Sadovskiy M.A. Selected works: Geophysics and physics of explosion. Nauka Press, Moscow, 2004.
15. Bajić, Z. Determination of TNT equivalent for various explosives. University of Belgrade, Belgrade, 2007. Masters Thesis.
16. Krauthammer, T. & Altenberg, A. Negative phase effects on glass panels. *Int. J. Imp. Eng.*, 2000, **24**(1), 1-18.
17. Teich, M. & Gebbeken, N. The Influence of the under pressure phase on the dynamic response of structures subjected to blast loads. 2010, *Int. J. Prot. Str.*, **1**(2), 219-34.
18. Ismail, M.M. & Murray, S.G. Study of the blast wave parameters from small scale explosions. *Prop. Exp. Pyro.*, 1993, **18**(1), 11-17.
19. Larcher, M.; Herrmann, N. & Stempniewski, L. Explosions simulation leichter Hallenhüllkonstruktionen. *Bauingenieur*, 2006, **81**(6), 271-77.
20. Lam, N.; Mendis, P. & Ngo, T. Response spectrum solutions for blast loading. *Elec. J. Str. Eng.*, 2004, **4,** 28-44.
21. Borgers, J. & Vantomme, J. Improving the accuracy of blast parameters using a new Friedlander curvature α. *In* Department of Defense (DoD) Explosives Safety Seminar, Palm Springs, CA, USA, 12-14 August 2008.

**Contributors**

**Mr Manmohan Dass Goel** obtained his MTech (Offshore Engineering) from the Indian Institute of Technology (IIT) Bombay, Mumbai, in 2003. Currently pursuing his PhD from IIT Delhi, Delhi. He is currently working as a Scientist at the CSIR-Advanced Materials and Processes Research Institute, Bhopal, India. His areas of interest include : Numerical simulation, blast resistant structures, structural dynamics and vibrations, impact and crash, high strain rate characterization of lightweight materials, aluminium foam, and composites.

**Dr Vasant Matsagar** obtained his BE (Civil Engineering) from Government College of Engineering, Aurangabad, in 1997 and ME(Structural Engineering) from the University of Pune, in 1998. And PhD from IIT Bombay in 2005. Currently working as Assistant Professor at Department of Civil Engineering, IIT Delhi, Delhi. His areas of research include: Structural dynamics and vibration control, earthquake, wind, fire and blast engineering, and multi-hazard protection of structures.

**Dr Anil K. Gupta** obtained his PhD (Engg.) in Mechanical Metallurgy, from Delhi College of Engineering, University of Delhi, in 1987. Currently working as Director (Technical) at Shivam Autotech Ltd., New Delhi. His research interests include: Materials development, fabrication technology, study of structure and properties and deformability characteristics of materials. He is Fellow of Indian National Academy of Engineering.

**Dr Steffen Marburg** obtained his PhD from the Technische Universität (TU) Dresden in Germany. Since 2010, he holds the professorship for Technical Dynamics at the Universität der Bundeswehr (University of the Federal Armed Forces) in Munich, Germany. His research interests include: Simulation of vibrations and waves in structural dynamics and acoustics. He is a well-known expert in computational acoustics.