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Estimating the consequences of an explosion on critical infrastructure
Określanie skutków wybuchowego obciążenia infrastruktury krytycznej

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Abstract. *The study is an analysis estimating the threat arising from the detonation products of a condensed explosive on the physical environment. It presents an analysis of fundamental detonation properties such as detonation height and Mach wave formation, related to their loading effects on critical infrastructure. Analytical equations as well as modelling were investigated to predict the effects of explosive loading on surroundings and people. Comparisons were made between the results from calculations with those of the equations, based on approximated experimental data. It was concluded that when applying the JWL equation of state to the reaction products of TNT, good agreement was obtained between modeling and experimental results for the detonation energy derived with the aid of thermodynamic calculations.*

Streszczenie. *Przedmiotem pracy jest ilościowa analiza zagrożeń powstających w wyniku oddziaływania produktów detonacji skondensowanego materiału wybuchowego na otoczenie materialne. Przedstawiona została analiza podstawowych właściwości pola wybuchu jak wysokość wybuchu nad poziomem gruntu, kształtowanie się fali Macha w aspekcie ich wpływu na obciążenie obiektów infrastruktury krytycznej. Rozpatrzone zostało zastosowanie wzorów analitycznych oraz symulacji numerycznej do prognozowania skutków wybuchowego obciążenia obiektów i osób. Przeprowadzono porównanie zgodności obliczeń numerycznych z wzorami analitycznymi opracowanymi na podstawie aproksymacji danych eksperymentalnych. Stwierdzono, że w przypadku zastosowania do opisu produktów detonacji trotylu równania stanu JWL, dobra zgodność symulacji numerycznych z wynikami eksperymentu uzyskiwana jest dla energii detonacji określonej za pomocą obliczeń termodynamicznych.*

Keywords: *free-air and surface burst explosion, blast field, numerical simulation*
Słowa kluczowe: *wybuch swobodny i kontaktowy, pole wybuchu, modelownie numeryczne*

Nomenclature and abbreviations:

Δp_s	Overpressure at front of blast wave [kPa]
R	Blast wave radius, distance from the centre of explosion to blast wave front [m]

m_{TNT}	Mass of trinitrotoluene (TNT) charge [kg]
A, B, R_1, R_2, ω	Parameters of Jones-Wilkins-Lee (JWL) equation of state
υ	Specific volume [m^3/kg]
Q_v	Heat of explosion [MJ/kg]
Z	Sachs variable [m/$kg^{1/3}$]
BKW	Becker-Kistiakowsky-Wilson equation of state of detonation products
MWEQ	Numerical programme designed for evaluating chemical composition and thermodynamic parameters of explosion and detonation of high energy materials

1. Introduction

Contemporary problems in safety engineering are the needs to recognise and prevent a variety of possible multi-hazard threats which exist in industry or may be provoked by homemade explosives. One of these is explosion which manifests itself as blast loading of engineering structures and persons. Explosively generated shock waves expand at supersonic velocity, making them difficult to escape. Usually, explosive events are more often accompanied with the loss of life rather than fires. Civil engineering and public safety need guidance on how to design engineering structures capable of withstanding such influences. The investigation and determination of the actual path of events is essential in the recognition of hazardous accidents. The proper identification of the possible progress of an incident build up justifies the forecasting of hazard prevention based on accountable quantification of their consequences.

In the paper, the application of analytical formulae obtained by approximation of experimental results as well as the use of numerical simulations for evaluation of blast wave overpressure, is considered. Results of numerical simulations are compared with experimental data. The employment of the Jacobs-Wilkins-Lee (JWL) equation of state to characterise detonation products of a trinitrotoluene (TNT) charge, is examined.

2. Characteristic features of blast loading imposed on built environment and critical infrastructure

A blast wave originates as an effect of energy release during explosion. The rapid compression of the surrounding atmosphere caused by expanding detonation products, results in the formation of a shock wave which proceeds at supersonic velocity. The sharp rise of overpressure occurring at the front of the shock wave, produces a threat to structures and persons it encounters. A general wave diagram of an external blast is presented in Figure 1.

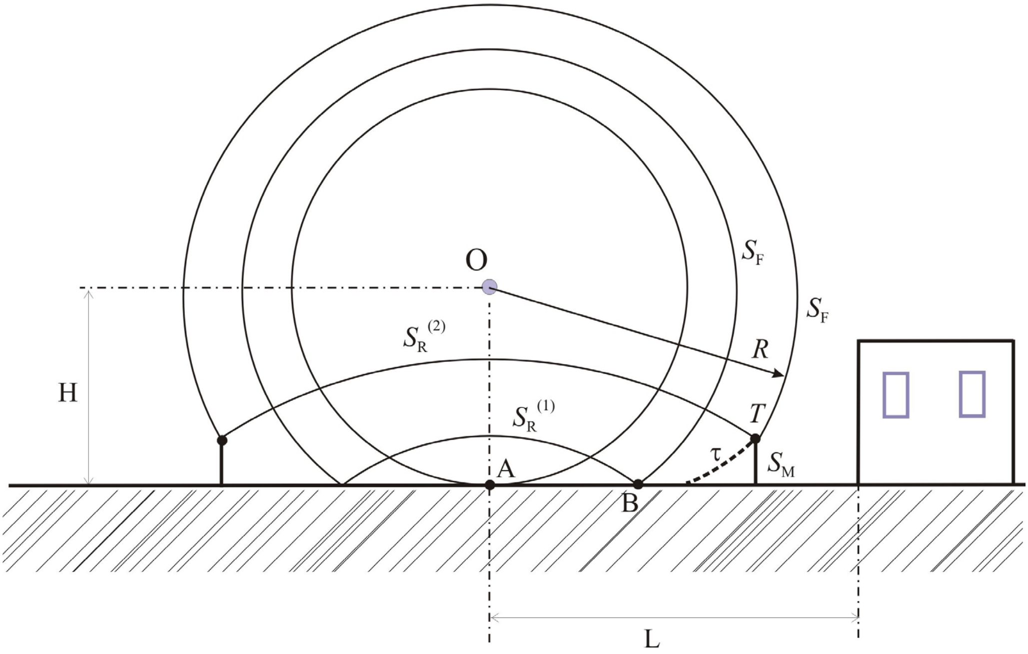

Figure 1. Reflection of spherical shock wave and formation of Mach wave: T – triple point, S_F – incident shock wave, S_R – reflected shock, S_M – Mach stem, τ – tangential contact discontinuity

Two lengths determine the subsequent evolution and character of the evolving pattern of the blast field. They are: H – height of burst (HOB) and L – the distance from origin of the reflected wave (point A) to the exposed object. The reflected shock wave $S_R^{(1)}$ propagates into heated and compressed air. Therefore, it moves faster than the incident shock wave S_F. As a result, at consecutive periods of time, the reflected wave $S_R^{(2)}$ pursues the incident shock and merges with it to form a single shock front S_M. The originating wave is called a Mach wave or "Mach stem". In the whole process of spherical shock reflection, two stages can be discerned. In the first period, just after the straight reflection occurring at point A, the incident and reflected waves travel at approximately equal velocities. The incident and reflected waves do not merge and only one common point B, at the reflecting surface, is observed. Only at later stages when the front of reflected wave becomes steeper, does the reflected wave overtake the incident wave and a single shock front S_M is formed. The point at which the three (incident, reflected and Mach waves) meet is called the "triple point" (T). The process of Mach wave formation is termed an irregular reflection. The origin and formation of the irregular shape of the wave pattern depends on many parameters, such as strength of explosion, height of burst, surface smoothness. The reflection of a weak shock will mainly proceed in a regular manner, with no formation of a detectable Mach structure. The proper understanding of factors contributing to the time and space structure of shock loading, ensures reliable estimates of blast effects on buildings and engineering structures, to gain.

3. Experimentally derived characteristics of blast field generated by detonation of explosive charge

Experimental investigations of blast field parameters are performed mainly in two geometries, *i.e.* when an explosion occurs in the open atmosphere ($H >> L$) and on the surface ($H \cong 0$) when the detonating charge is positioned on the ground.

Historically, extended experimental blast investigations were performed by Sadowski in the forties and fifties of the XX century. The overpressure in the post-explosion shock wave of a TNT contact charge ($H \cong 0$), as reported in monograph [1], was obtained in the form of Equation 1.

$$\Delta p_s = 0.95\frac{\sqrt[3]{m_{\text{TNT}}}}{R} + 3.9\frac{\left(\sqrt[3]{m_{\text{TNT}}}\right)^2}{R^2} + 13.0\frac{m_{\text{TNT}}}{R^3} \quad \left[\frac{\text{kG}}{\text{cm}^2}\right] \tag{1}$$

where: m_{TNT} – mass of TNT charge [kg], R – radius [m].
The original formulae are given in CGS units, which on conversion to SI units gives:

$$\Delta p_s = \frac{93.2}{Z} + \frac{382.5}{Z^2} + \frac{1275}{Z^3} \qquad 1.5 < Z < 10 \tag{2}$$

where:

$$Z = \frac{R}{m^{1/3}} \tag{3}$$

In view of the high experimental costs, the key task is to characterise the data obtained for a ground-based charge so that it can be applied in the reading of a free air explosion and *vice-versa*. As a first approximation, the ground surface may be taken as a perfectly smooth, rigid plane which reflects half of the explosion energy. Then, the free air charge of doubled mass is to be applied in order to attain the same blast parameters as those of the surface explosion. However, in most cases, the ground does not act as an ideal surface and some dissipation of explosion energy occurs. As a practical choice, a factor of 1.8 is recommended to multiply the mass of free-air blast in order to obtain equivalent effects of surface explosion [2, 3]. Thus, a charge of the same mass as in Equation 2 on exploding in open air, will produce the following overpressure:

$$\Delta p_s = \frac{76.59}{Z} + \frac{258.5}{Z^2} + \frac{708.3}{Z^3} \qquad [\text{kPa}] \tag{4}$$

A true assessment may be obtained by independent measurements. The results of spherical blast wave overpressures are quoted in [4] as:

$$\Delta p_s = 0.084\frac{\sqrt[3]{m_{\text{TNT}}}}{R} + 0.270\frac{\left(\sqrt[3]{m_{\text{TNT}}}\right)^2}{R^2} + 0.7\frac{m_{\text{TNT}}}{R^3} \qquad [\text{MPa}] \tag{5}$$

The validity of Equation 5 is specific to the range of $1 < \text{m/kg}^{1/3} < 10$. On the other hand, in [5] the formula for free air blast overpressure is given as:

$$\Delta p_s = 10g\left(7\frac{m}{R^3} + 2.7\frac{m^{2/3}}{R^2} + 0.84\frac{m^{1/3}}{R}\right) \qquad [\text{kPa}] \tag{6}$$

Clearly, Equation 6 originates from the same experimental data source as Equation 5 while acceleration due to gravity g is introduced in order to convert to SI units. Assuming $g = 9.8065$ m/s^2, we obtain

$$\Delta p_s = \frac{82.375}{Z} + \frac{264.8}{Z^2} + \frac{686.5}{Z^3} \qquad [\text{kPa}] \qquad 1.5 < Z < 10 \tag{7}$$

Some differences may be noted compared with Equation 4 which was obtained by assuming a factor of 1.8. A closer correlation may be obtained by introducing individual multiplying coefficients into Equation 7 in order to reproduce the wave profile as specified in Equation 2

$$
\begin{aligned}
&82.375\frac{\sqrt[3]{k_p^{(1)}\cdot m_{\mathrm{TNT}}}}{R}+264.8\frac{\left(\sqrt[3]{k_p^{(2)}\cdot m_{\mathrm{TNT}}}\right)^2}{R^2}+686.5\frac{k_p^{(3)}\cdot m_{\mathrm{TNT}}}{R^3}\\
&=93.2\frac{\sqrt[3]{m_{\mathrm{TNT}}}}{R}+382.5\frac{\left(\sqrt[3]{m_{\mathrm{TNT}}}\right)^2}{R^2}+1275\frac{m_{\mathrm{TNT}}}{R^3}
\end{aligned}
\qquad (8)
$$

Re-calculating, the following values of $k_\mathrm{p}^{(\mathrm{i})}$ coefficients may be obtained:

– $k_\mathrm{p}^{(1)} = 1.448$,
– $k_\mathrm{p}^{(2)} = 1.736$, and
– $k_\mathrm{p}^{(3)} = 1.857$.

The obtained $k_p^{(\mathrm{i})}$ coefficients differ from the averaged factor of 1.8. As the different terms of Equations 2 or 7 represent the intensity of the overpressure wave at varying distances from centre of the explosion, it may be concluded that the interaction of the expanding blast with the plane depends on the intensity of the shock wave. However, it should be noted that the average value of the multiplying factor of 1.8, as recommended in [2, 3], confirms its applicability at higher radii from the explosion centre, when the term including $k_p^{(3)}$ starts to become dominant. At shorter distances, a more accurate examination is necessary.

More contemporary extensive investigations of post-detonation pressure waves are reported by Kingery and Bulmash [6]. They obtained independent equations for overpressure waves generated by open air and surface burst explosions. The results of the investigations were compiled in quite an extended equation of polynomial form dependent on $\log_{10}(Z)$ were the variable Z is that as defined in Equation 3. In the paper by Trzcinski [7] the method of least squares was employed in order to derive simpler equations which reproduce the results presented in [6].

The equivalent equations for overpressure in front of a spherical blast wave, not interacting with soil or other restrictions were obtained in the form of [7]

$$
\Delta p_\mathrm{s}=\begin{cases}
\dfrac{2034.08}{Z}+\dfrac{297.03}{Z^2}-\dfrac{24.76}{Z^3}+\dfrac{0.564}{Z^4} & 0.05<Z\le 0.3\\[2mm]
-\dfrac{389.32}{Z}+\dfrac{1512.32}{Z^2}-\dfrac{175.044}{Z^3} & 0.3<Z\le 1.5\\[2mm]
-0.6864+\dfrac{89.78}{Z}+\dfrac{200.56}{Z^2}+\dfrac{778.029}{Z^3} & 1.5<Z\le 40
\end{cases}
\quad [\mathrm{kPa}] \qquad (9)
$$

while overpressure induced by ground explosion as obtained by Kingery and Bulmash [6] may be described by Equation 10 [7].

$$
\Delta p_\mathrm{s}=\begin{cases}
-755.41+\dfrac{1459.27}{Z}+\dfrac{282.11}{Z^2}-\dfrac{76.86}{Z^3}+\dfrac{2.350}{Z^4} & 0.067<Z\le 1.5\\[2mm]
-0.780+\dfrac{120.41}{Z}+\dfrac{244.29}{Z^2}+\dfrac{1266.242}{Z^3} & 0.3<Z\le 40
\end{cases}
\quad [\mathrm{kPa}] \qquad (10)
$$

In view of the non-homogeneous form at smaller radii, Equations 9 and 10 may be compared for the range of $1.5 < Z < 40$, only. The re-calculation analogous to that performed by comparison of Equations 2 and 7, lead to the following set of multiplying factors:

– $k_\mathrm{p}^{(0)} = 1.14$,

– $k_p^{(1)} = 2.41$,
– $k_p^{(2)} = 1.34$,
– $k_p^{(3)} = 1.6275$

where the upper index of coefficient $k_p^{(i)}$ corresponds to the power of variable Z. Again, at greater distances, the multiplying factor $k_p^{(3)}$ tends to an average value of 1.8, however, no general resemblance with coefficients obtained by comparison of Equations 2 and 7, can be observed.

The performed analyses indicate that even in simpler cases, the straight adaptation of results obtained for *e.g.* free air explosion to other geometries, meets significant difficulties. The compilation of analytical predictions with a proper use of numerical techniques, enables a reliable estimation of blast effects on buildings and critical infrastructure, to be provided.

4. Test evaluations of accuracy of numerical simulation of blast wave progression

Numerical techniques offer a wide spectrum of programs and algorithms for prognosing the dynamics of load imposed by shock waves. In any case, the accuracy of numerical simulations is to be verified by experimentally obtained data. In the paper, numerical simulations are performed for a spherical blast wave generated by a free air explosion. The numerical algorithm of extended accuracy, based on the second order sequel to Godunov's method [8], is employed. The real features of the equations of state of both air and explosion products are assessed according to [9]. More extended characterisation of the method is presented in [10]. The results of evaluations were compared with the analytical equations of Sadowski (Equation 7) and Kingery and Bulmash (Equation 9). In close vicinity to the explosive charge, the equation derived by Henrych [11] was considered

$$\Delta p_s = \frac{1380}{Z} + \frac{543}{Z^2} - \frac{35.0}{Z^3} \quad 0.05 < Z \le 0.3 \quad [\text{kPa}] \tag{11}$$

As parameters of detonation and explosion products during evolution of the blast wave undergo quite extensive alteration, the performed evaluations were aimed at investigating the proper form of the equation of state to describe the thermodynamic state of the explosion products. Prospective application of the JWL equation of state was examined. The JWL equation of state is assumed in form:

$$p(\rho, \varepsilon) = A\left(1 - \frac{\omega}{R_1 \upsilon}\right) e^{-R_1 \upsilon} + B\left(1 - \frac{\omega}{R_2 \upsilon}\right) e^{-R_2 \upsilon} + \frac{\omega \cdot \varepsilon}{\upsilon} \tag{12}$$

were υ – specific volume [m^3/kg], ε – internal energy [J/kg], A, B, R_1, R_2, ω – coefficients estimated experimentally. Two JWL parameterizations were considered. Their characteristics are presented in Table 1.

Table 1. Considered JWL parameterizations

Ref.	$\rho_{0\mathrm{exp}}$ [kg/m^3]	D [m/s]	E_0 [kJ/cm^3]	A [GPa]	B [GPa]	R_1	R_2	ω
[3]	1630	6930	7.0	371.21	3.231	4.15	0.95	0.30
[12]	1630	6930	7.0	362.033	2.492	4.07257	0.88784	0.25

The parameterization as quoted in [3] was chosen. Internal energy estimated in cylinder tests (E_0) is referred to as the unity of volume. After recalculating to mass unit, we obtain $Q_v = 4.29$ MJ/kg.

A TNT charge of mass $m_{\mathrm{TNT}} = 8$ kg was considered. The results of evaluations in the ranges of $2.5 < Z < 5$ and $1 < Z < 2.5$ are presented in Figures 2 and 3. The shock overpressure of about 30 kPa attained at $Z = 5$, may be considered as a moderate health hazard threshold. Below this, personal injuries of various degree with minimal probability of life loss are to be expected [7].

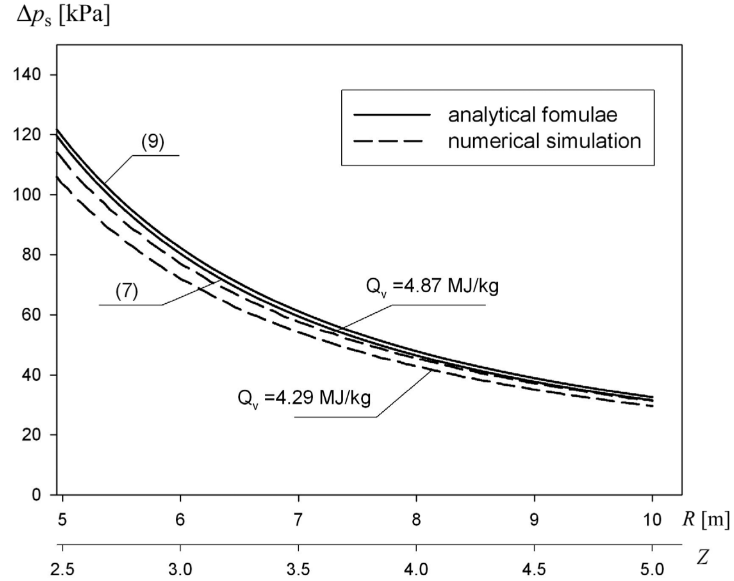

Figure 2. Blast wave parameters by explosion of 8 kg TNT charge: $2.5 < Z < 5$ – moderate overpressure range

The chemical composition and thermodynamic parameters, among them the magnitude of explosive energy, may also be estimated using thermodynamic calculations. Thermodynamic calculations of TNT detonation and explosion were performed using the MWEQ programme [14]. The Becker-Kistiakowsky-Wilson (BKW) equation of state with an adjusted set of BKW covolumes [15], was used. An explosion energy of Q_v = 4.87 MJ/kg was obtained. Numerical simulations with initial energy of TNT explosion products equal to 4.87 MJ/kg, give good agreement with analytical equations derived from experiments.

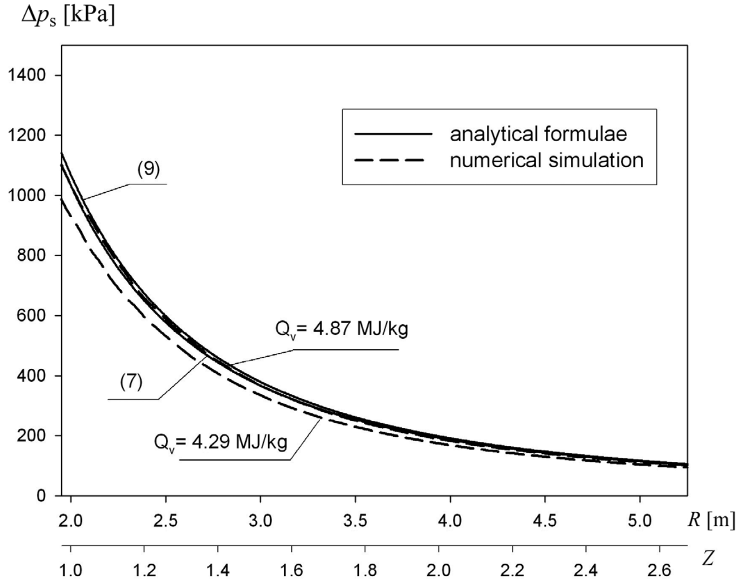

Figure 3. Blast wave parameters by explosion of 8 kg TNT charge: $1 < Z < 2.5$ – severe damage range

From the obtained results, it may be inferred that the rapid expansion, as it occurs from the explosion in open air, thermodynamic state of detonation products as obtained at the C-J point, may play the decisive role in determining the blast field parameters.

5. Evaluation of blast field in close vicinity to TNT charge

Results of numerical simulation of blast overpressure in close proximity to the explosive charge, are presented in Figure 4.

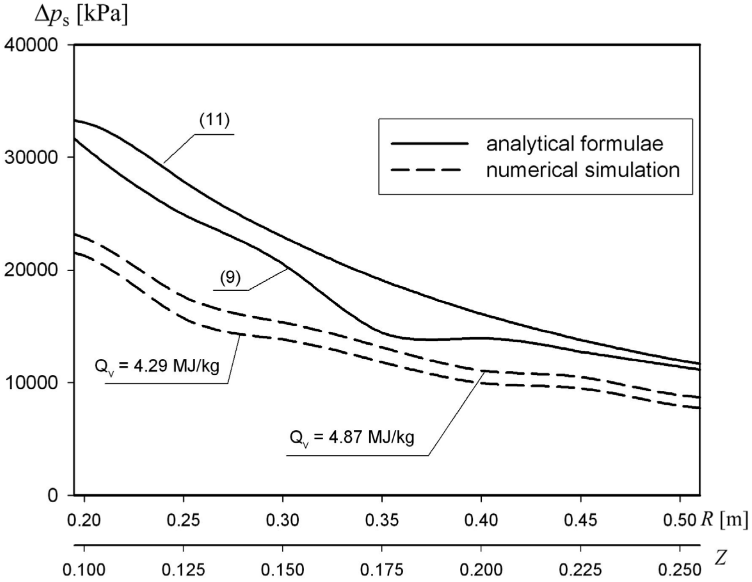

Figure 4. Blast wave overpressure in close proximity to the explosive charge, $m_{\mathrm{TNT}} = 8$ kg

Contrary to the results presented in Figures 2 and 3, an important discrepancy is obtained, even for the explosion energy of Q_v = 4.87 MJ/kg. The important feature to be noted is the significant disconformity between experimentally derived analytical equations *i.e.* those of Kingery and Bulmash (Equation 9) and those obtained by Henrych (Equation 11). It may be concluded, from observations performed at small distances from the explosive charge, that factors such as the method of initiation and the mass of the charge, may also influence the experimental results.

Also, a more extended numerical approach is necessary. The non-stationary field of flow which forms after the detonation zone (C-J point), needs to be accounted for *i.e.* the angle of incidence of the detonation wave upon the charge surface will influence the pressure field in their close surroundings.

6. Conclusions

The development of the blast field of an explosive charge detonating at ground surface and in free air, is considered. The base features of explosive load imposed on built-up environments and engineering structures, are characterised.

♦) Analytical equations, obtained by approximation of experimental data describing overpressure at the blast wave front, are reviewed and analysed. The equations of Sadowski [1, 4], Onderka [5], Kingery and Bulmash [6], estimating overpressure generated by the explosion of a TNT charge, are analysed and compared.

♦) The estimation of equivalent mass of a free air charge which will produce effects equivalent to those of a surface explosion, is considered. The general applicability of the ‘rule of thumb’ multiplying factor equal to 1.8, as recommended in [2, 3], is confirmed but at rather further distances from the explosion centre. At closer proximity, different analytical equations or numerical simulations of post-detonation shock wave, are to be employed.

♦) A numerical simulation of blast wave generated by explosion of TNT charge, was performed. Detonation products were described by the JWL equation of state. Good agreement of numerical simulations with analytical equations derived from experimental data, was attained. However, the explosion energy of 4.29 MJ/kg of a TNT charge as obtained in cylindrical tests, appeared to give lower blast wave parameters compared to experimentally obtained data. The initial energy of TNT explosion products equal to 4.87 MJ/kg, estimated by thermodynamic calculations, enables a better fit to experimental data.

♦) Test evaluations of the blast field in close proximity to an explosive charge, indicate the necessity of further investigations.

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