Determining the Equivalent Explosive Effect for Different Explosives

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ABSTRACT

Explosives with different amounts of available chemical energy per unit mass (specific energy) have the same explosive effect when the total available chemical energy (detonation energy) for the explosives are equivalent

$$e_{m1}\, m_1 = e_{m2}\, m_2 = E_t$$

where e_{m1}, e_{m2} are the specific energies and m_1 and m_2 are the masses for two different explosives and E_t is the total detonation energy. The mass of explosive 2 needed to produce the same explosive effect as explosive 1 is

$$m_2 = e_{m1}\, m_1 / e_{m2}$$

The specific energy can be estimated from $e_m = e_v/\rho_0$
where

$$e_v = -4.7613 + 1.6923\, D$$

is the amount of available chemical energy per unit volume, D is the unconfined detonation speed (km/s), and ρ_0 is the explosive initial density (Mg/m^3). The effectiveness of a low detonation speed explosive will be similar to that of a high detonation speed explosive when their total detonation energies are the same. The perception that high detonation speed explosives are more effective than low detonation speed explosives at causing snow avalanche failure is a result of comparing explosives with equivalent mass rather that equivalent total energy and the fact that the Chapman-Jouguet pressure of an explosive is strongly dependent on detonation speed.

INTRODUCTION

Avalanche control professionals may select an explosive based on its effectiveness at initiating snow avalanches, releasing cornices or creating fractures and settlement in snow. Concerns about safety, ease of handling, cost, or the need to perform a specialized task may also play a role in selecting an explosive. This selection process can be hampered by the lack of an accurate method to determine the equivalent explosive effect between different explosives. The effect that an explosive has on its surroundings depends on the impulse (integrated pressure over time) and maximum pressure that is generated upon detonation. These are generally determined by the total available chemical energy (detonation energy), detonation speed, and the level of confinement of the explosive. This paper presents a discussion of the explosive detonation process and describes a method for determining the equivalent explosive effect between different explosives. The perception that high detonation speed explosives are more effective at causing snow avalanche failure than are low detonation speed explosives is also discussed.

EXPLOSIVE DETONATION

In an idealized detonation, the detonation wave consists of four regions. The leading shock front of the detonation wave compacts the chemically unreacted explosive to a state on its Hugoniot curve (the locus of pressure-density states attained by shock loading from a single initial state) with a discontinuous high pressure. The reaction zone follows the shock front and releases most of the detonation energy producing extreme pressures, densities and temperatures. Subsequent chemical reactions cause the pressure and density to decrease, over a period of several hundred nanoseconds, to the equilibrium Chapman-Joguet (C-J) state located at the rear of the reaction zone. The expansion of gases following the C-J state produces a rarefaction wave, the Taylor wave (Dobratz and Crawford, 1985; Tarver, 1992). The detonation products are at the C-J state which is assumed to be at thermodynamic equilibrium. The C-J pressure (P_{cj}, detonation pressure) is slightly lower than the pressure at the detonation shock front (Dobratz and Crawford, 1985) and is the maximum bulk pressure that an explosive can achieve. The actual explosive pressure depends on its state of confinement and is generally less than P_{cj}.

Explosives are typically characterized by their P_{cj}, the C-J Grüneisen parameter (Γ_{cj}, the ratio of the thermal pressure to the thermal energy at the equilibrium C- J state), detonation speed, initial density, and energy per unit mass (specific energy) or energy per unit volume (energy density) (Table I in the Appendix). Explosive volume and energy density determine the total detonation energy that is available to be transferred as kinetic energy into the surrounding medium. The mass of an explosive and its specific energy are often used in place of volume and energy density. The detonation speed, density and Γ_{cj} determines the C-J pressure (P_{cj}, the pressure at the equilibrium C-J state). Detonation pressure is a function of explosive initial density (ρ_o, Mg/m^3) and the unconfined detonation speed (D, km/s) and can be calculated from

$$P_{cj}\ (\text{GPa}) = \rho_o D^2/(\Gamma_{cj}+1) \qquad (1)$$

where $\Gamma_{cj} \approx 2.75$ can be used to obtain reasonable estimates when Γ_{cj} is unknown (Lee et al., 1968)[Fig. 1a]. The detonation speed of an explosive depends on its energy density, however, our interest is to estimate the energy density using detonation speed

$$e_v = -4.7613 + 1.6923\,D \qquad R = 0.92 \qquad (2)$$

where e_v (GJ/m^3) is the energy density (Fig. 1b). The specific energy does not correlate well with detonation speed since explosives often include an inert filler that decreases the energy density. Consequently, the value of the specific energy may increase or decrease depending on the density of the inert filler compared to the densities of the reactive materials.

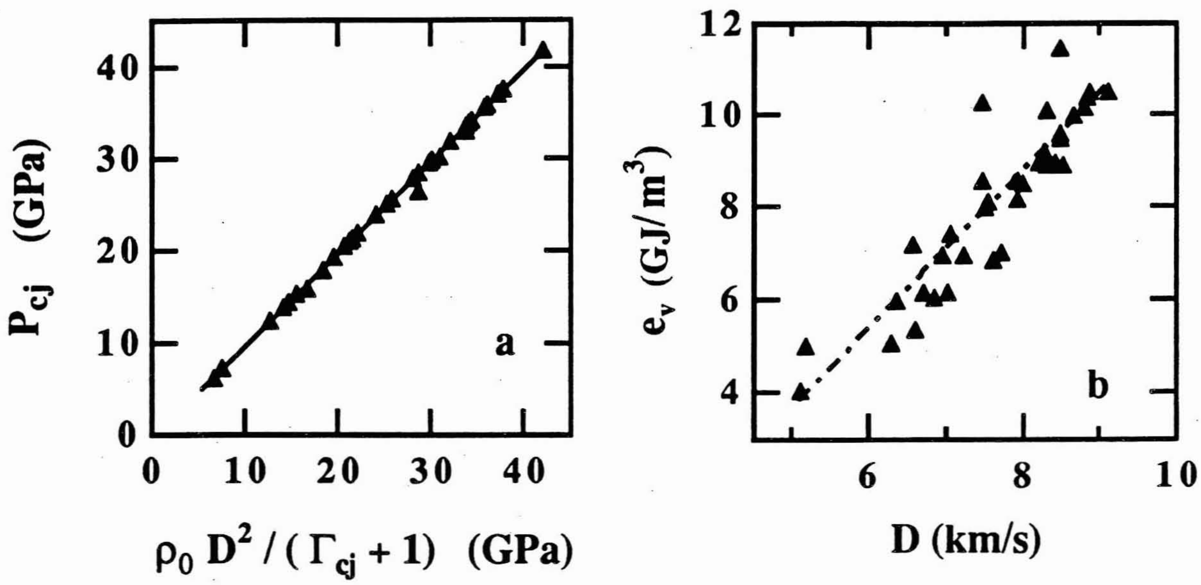

Fig. 1. (a) The C-J pressure as a function of explosive initial density, unconfined detonation speed, and C-J Grüneisen parameter and (b) the energy density as a function of unconfined detonation speed. Data from Dobratz and Crawford (1985).

EXPLOSIVE EFFECT

The effectiveness of an explosive is, in general, determined by its ability to fracture and/or move the surrounding material. For a given explosive this is determined from its P_{cj} and impulse. The P_{cj} is an indicator of the explosive pressure (the actual pressure depends on both the P_{cj} and strength or compressibility of the surrounding material) and the impulse is a measure of the momentum that is transferred into the material. For an explosive to be effective its pressure must exceed the fracture or yield strength of the surrounding material otherwise the pressure pulse will propagate through the material without significant effect. This is why explosives specialists use high detonation speed/high P_{cj} explosives in hard competent rock. When the explosive pressure exceeds the material's fracture or yield strength the extent of fracturing and permanent deformation in the material will be determined by the impulse. For low strength materials or materials with pre-existing fractures low detonation speed/low P_{cj} explosives are adequate, although high P_{cj} explosives will also work.

In snow, which has relatively low strength, most explosives will produce pressures sufficient to cause fracturing and deformation. As a result, the effectiveness of an explosive in snow will be primarily controlled by the impulse. For spherical explosive charges, the impulse at a given radial distance is

$$I = \frac{(2 M E_t)^{1/2}}{4 \pi R^2} \tag{3}$$

where I is the impulse, E_t is the total detonation energy, R is the radius from the center of the explosive to the pressure shock front and M is the mass of material engulfed by the shock wave. The ratio of impulses, at the same radius, for two different explosives is a measure of their relative explosive effect

$$\frac{I_1}{I_2} = \frac{E_{t1}^{1/2}}{E_{t2}^{1/2}} \tag{4}$$

The explosive effect of the two explosives is equal when their impulses are equivalent. Consequently their total detonation energies are also equal

$$E_{t1} = e_{m1}\, m_1 = E_{t2} = e_{m2}\, m_2 \tag{5}$$

where e_m is the specific energy and m is the mass of the explosive. The mass of explosive 2 needed to produce the same impulse as that of explosive 1 can be determined from

$$m_2 = \alpha_m\, m_1 \tag{6}$$

where $\alpha_m = e_{m1}/e_{m2}$. The specific energy can be determined from Table I (in the Appendix) or estimated using equation 2 and

$$e_m = e_v/\rho_0 \tag{7}$$

Fig. 2 provides a graphic method for determining α_m when the specific energies of the two explosives are known. As an example of usage consider the problem of determining the mass of PETN (ρ_0 = 1.77 Mg/m^3) explosive that has the equivalent impulse of 1 kg of TNT. The specific energies of PETN and TNT are 5.7 MJ/kg and 4.3 MJ/kg, respectively. From Fig. 2a, $\alpha_m \approx 0.75$ or 0.75 kg of PETN provides the same explosive effect as 1 kg of TNT. Fig 1b can be used to determine the mass of an explosive with specific energy e_{m2} that has the same explosive effect as 1 kg of TNT (The relationship of this curve to Fig. 2a is shown as a dashed line in Fig. 2a).

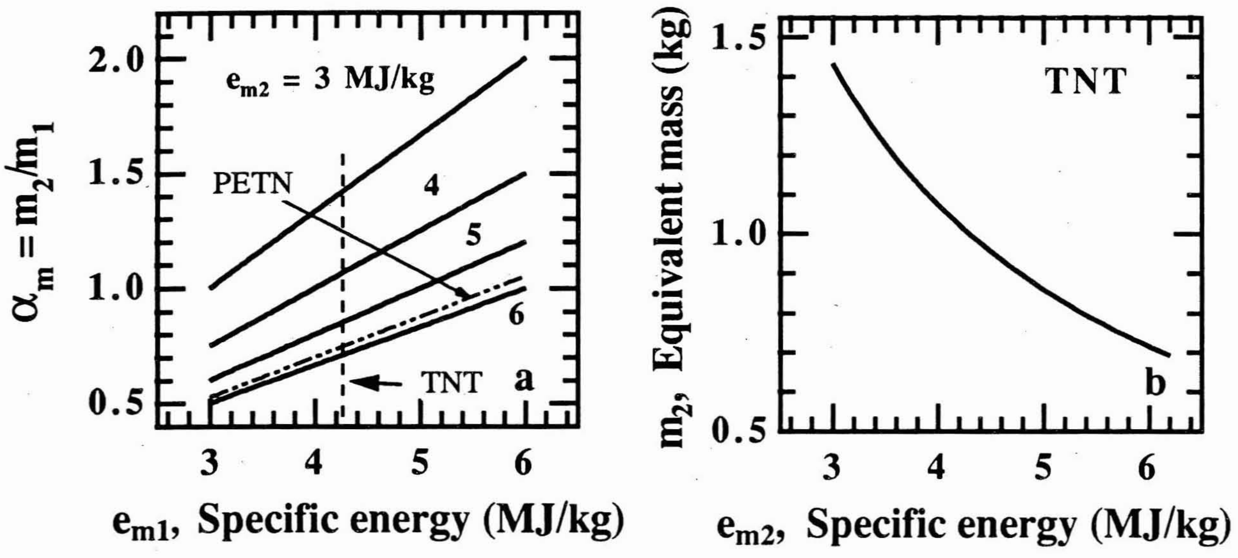

Fig. 2. (a) The mass ratio (α_m) required to produce an equivalent explosive effect for two different explosives where e_{m1} and e_{m2} are, respectively, the specific energy of the reference explosive and explosive of interest. (b) The equivalent explosive mass of an explosive with specific energy e_{m2} to that of a 1 kg TNT charge (shown as a dashed line in Fig. 2a).

Eq. 4 can be used to determine the amount of additional explosive mass needed to increase the impulse by a given amount where

$$\frac{I_1}{I_2} = \frac{m_1^{1/2}}{m_2^{1/2}} \tag{8}$$

is the impulse ratio between explosives with different mass but the same specific energy. Calculations using Eq. 8 indicate that doubling the impulse of an explosive requires that the explosive mass be increased by a factor of four while increasing the impulse by a factor of three requires nine times more explosive mass (Fig. 3).

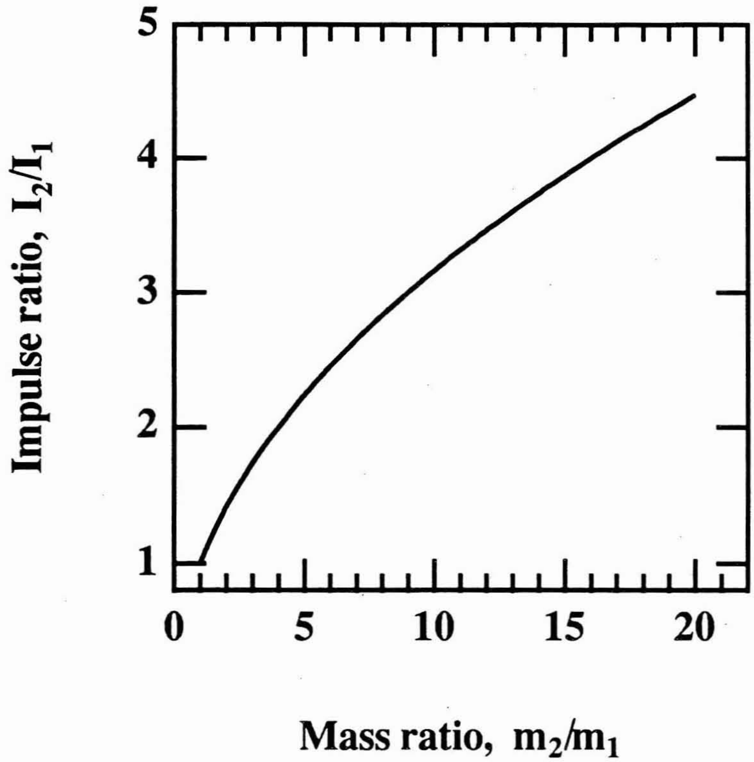

Fig. 3. The relative increase in explosive effect (Impulse ratio) achieved by increasing the relative mass (Mass ratio) of a spherical explosive charge.

DISCUSSION AND CONCLUSIONS

The effectiveness of an explosive in fracturing and deforming a material depends on the maximum pressure and total impulse generated upon detonation. High detonation pressure explosives, which also have high detonation speeds, are used in high strength brittle materials to maximize fracturing. Detonations that produce pressures less than the strength of the surrounding material may have little or no effect. For low strength ductile materials, like snow, any explosive (either high or low detonation pressure) should produce adequate results. High pressure explosives may be somewhat less effective as they lose energy to the production of excessive fractures that are unnecessary to cause bulk failure in a material. Most explosives produce sufficient pressure to produce fracturing and deformation in snow. Consequently, the primary factor determining explosive effectiveness in snow is explosive impulse which is controlled by the specific energy and mass of the explosive, not its detonation speed. This is counter to the perception among many avalanche control personnel that high detonation speed explosives are more effective at causing snow avalanche failure than are low detonation speed explosives.

Gubler (1976, 1977, 1978) conducted a study on explosive effect in snow, where the relative explosive effect was defined as a ratio of pressure or snow particle velocity produced by a given explosive as compared to Plastit explosive. The results of his study can be used to examine explosive effectiveness as a function of total detonation energy and detonation speed for the same explosive (Fig. 4). Although the data show significant scatter, Gubler's results indicate that relative explosive effect increases with increasing total detonation energy (Fig. 4a). No simple relationship exists between relative explosive effect and detonation speed (Fig. 4b).

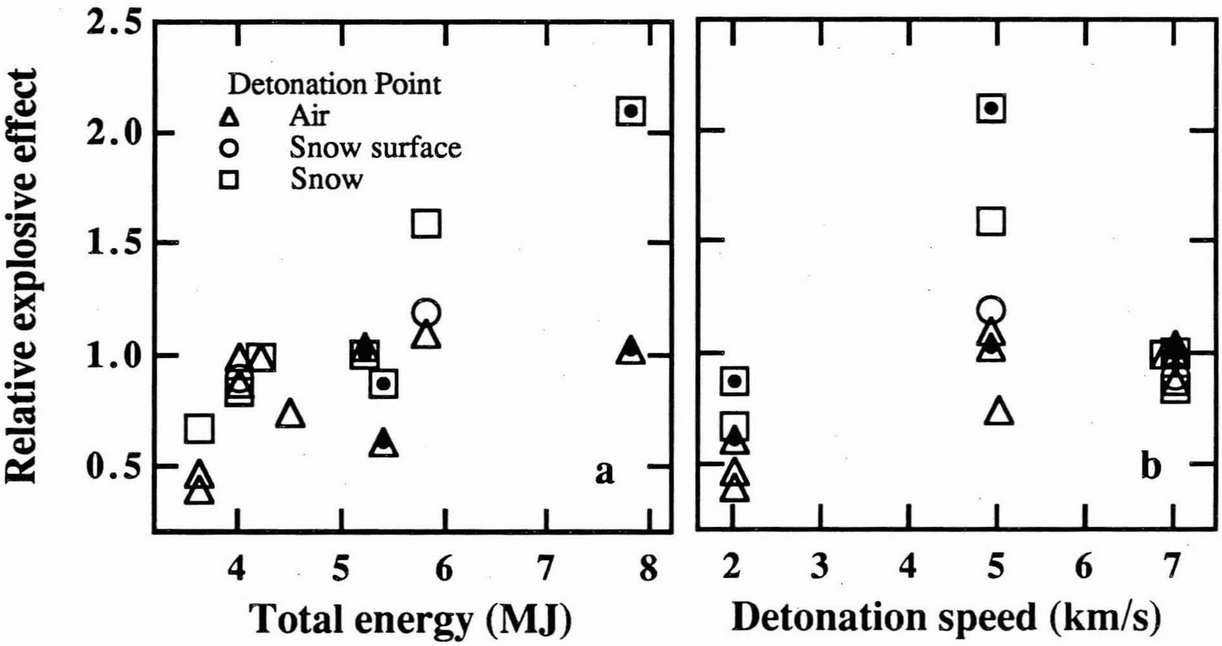

Fig. 4. (a) Relative explosive effect for various explosives as compared to plastit explosive as a function of the total detonation energy and (b) as a function of the explosive detonation speed (data from Gubler 1976, 1977, 1978). The explosives were detonated 1 to 1.5 m above the snow surface (Air), on the snow surface (Snow surface), and buried in the snow (Snow). All data symbols represent results for 1 kg explosives except for those marked with a center dot which where either 1.3 or 1.5 kg charges.

The findings of this study are consistent with observations that increased charge mass produces a greater effect (Livingood et al., 1990), but at a diminishing efficiency as the mass is further increased (due to the nonlinear relationship between the impulse and charge mass). Explosives with high specific energy will be the most effective for a given mass. Explosives with the same total detonation energy should have approximately the same effect at causing avalanche failure and snow deformation. The detonation speed of an explosive does not, in general, influence the effectiveness of an explosive in snow unless the particular application requires unusually high pressure.

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Table I. Parameters for characterizing common explosives (compiled from Dobratz and Crawford 1985).

C-J parameters						
Explosive	**Density** ρ_0 (Mg/m^3)	P_{cj} (GPa)	**Detonation speed** (km/s)	e_V (GJ/m^3)	e_m (MJ/kg) (GJ/Mg)	Γ_{cj}
BTF	1.859	36	8.48	11.5	6.2	2.717
COMP A-3	1.65	30	8.3	8.9	5.2	2.79
COMPB, GRADE A	1.717	29.5	7.98	8.5	4.95	2.706
COMP C-4	1.601	28	8.193	9	5.6	2.838
CYCLOTOL 77/23	1.754	32	8.25	9.2	5.2	2.731
DIPAM	1.550	18	6.7	6.2	4	2.842
EL-506A	1.480	20.5	7.2	7.0	4.7	2.752
EL-506C	1.480	19.5	7	6.2	4.2	2.719
EXPLOSIVE D	1.42	16	6.6	5.4	3.8	2.75
FEFO	1.590	25	7.5	8.0	5.03	2.578
H-6	1.76	24	7.47	10.3	5.9	3.092
HMX	1.891	42	9.11	10.5	5.55	2.740
HNS	1.0	7.5	5.1	4.1	4.1	2.468
HNS	1.40	14.5	6.34	6	4.3	2.881
HNS	1.65	21.5	7.03	7.45	4.5	2.804
LX-01	1.23	15.5	6.84	6.1	4.96	2.711
LX-04-1	1.865	34	8.47	9.5	5.1	2.935
LX-07	1.865	35.5	8.64	10	5.4	2.922
LX-09-01	1.84	37.5	8.84	10.5	5.7	2.834
LX-10-1	1.865	37.5	8.82	10.4	5.6	2.868
LX-11	1.875	33	8.32	9	4.8	2.868
LX-14-0	1.835	37	8.8	10.2	5.56	2.841
LX-17-0	1.90	30	7.6	6.9	3.6	2.658
NM	1.128	12.5	6.28	5.1	4.5	2.559
OCTOL 78/22	1.821	34.2	8.48	9.6	5.3	2.830
PBX-9010	1.787	34	8.39	9	5.03	2.700
PBX-9011	1.777	34	8.50	8.9	5.01	2.776
PBX-9404-3	1.840	37	8.80	10.2	5.5	2.851
PBX-9407	1.6	26.5	7.91	8.6	5.4	2.513
PBX-9501	1.84	37	8.80	10.2	5.5	2.851
PBX-9502	1.895	30.2	7.71	7.07	3.7	2.648
PENTOLITE 50/50	1.7	25.5	7.53	8.1	4.8	2.78
PETN	0.880	6.2	5.17	5.02	5.7	2.668
PETN	1.26	14	6.54	7.19	5.7	2.831
PETN	1.50	22	7.45	8.56	5.7	2.788
PETN	1.770	33.5	8.30	10.1	5.7	2.640
TETRYL	1.730	28.5	7.91	8.2	4.7	2.798
TNT	1.630	21	6.93	7	4.3	2.727