Engager posted on 2-1-2011

There is common set of equations witch can be used for calculation of blast wave from explosive charges, it's called Sadovsky formulas. It works regardless on nature of explosion and depends only on TNT equivalent of explosive charge. All this calculations are based on energy similarity law for explosions witch stated that all blast wave parameters are function of two variables: first is explosion energy and second is distance from explosion origin.

Important thing is that if you rise energy of explosion (and correspondingly explosive mass) you will get the same drawing of property-range dependence but it will just be scaled, so you only need only one experimental dependence for some standard explosive charge then you can simply scale it to suit your particular case.

1. Sadovsky formula for blast wave from TNT explosion on open air at standard atmospheric pressure 1 atm and standart air temperature:

$$\Delta p_1 = 0,84\frac{\sqrt[3]{m}}{r} + 2,7\frac{\sqrt[3]{m^2}}{r^2} + 7,0\frac{m}{r^3}$$

In this formula mass (m) is in kilograms (kg), and distance from origin is (r) in meters (m), overpressure is in atm.

2. Sadovsky formula for blast wave from TNT explosion on earth surface at standard atmospheric conditions:

$$\Delta p_1 = 0,95\frac{\sqrt[3]{m}}{r} + 3,9\frac{\sqrt[3]{m^2}}{r^2} + 13,0\frac{m}{r^3}$$

In this formula mass (m) is in kilograms (kg), and distance from origin is (r) in meters (m), overpressure is in atm.

3. Same formulas can be applied to any explosive using TNT equivalent Kt = Qexplosive/Qtnt, where Q are energies of explosion for example in MJ/kg (Qtnt = 4.19 MJ/kg). Formula for air blast becomes:

$$\Delta p_1 = 0,84\frac{\sqrt[3]{k_T m}}{r} + 2,7\frac{\sqrt[3]{(k_T m)^2}}{r^2} + 7,0\frac{k_T m}{r^3}$$

In this formula mass (m) is in kilograms (kg), and distance from origin is (r) in meters (m), overpressure is in atm.

4. Sadovsky formula for positive shock phase duration for TNT blast wave:

$$\tau^+ = 1,3\sqrt[6]{m}\sqrt{r}\cdot 10^{-3}$$

In this formula mass (m) is in kilograms (kg), and distance from origin is (r) in meters (m), resulted time is in seconds (sec).

5. Theory of blast waves shows that all other blast wave parameters are can be expressed as functions of overpressure. Formulas below are for blast wave in air at standard ambient conditions:

Velocity of shock front (in m/sec, overpressure dP is in atm):

$$D = c_0\sqrt{1 + \frac{k+1}{2k}\cdot\frac{\Delta p_1}{p_0}} = 340\sqrt{1 + 0,86\Delta p_1}$$

Velocity of gas behind shock front (in m/sec, overpressure dP is in atm):

$$u_1 = \frac{\Delta p_1 v_0}{D} = \frac{\Delta p_1}{\rho_0 D} = \frac{8,3\cdot 10^4 \Delta p_1}{D} = 243\frac{\Delta p_1}{\sqrt{1 + 0,86\Delta p_1}}$$

Temperature of gas in shock wave front (in K, overpressure dP is in atm):

$$T_1 = \frac{p_1 v_1}{p_0 v_0}T_0 = \frac{p_0 + \Delta p_1}{p_0}\cdot\frac{p_0}{p_1}T_0 = 288\frac{(1 + \Delta p_1)(7 + \Delta p_1)}{7 + 6\Delta p_1}$$

Sonic velocity in shock wave front (m/sec, overpressure dP is in atm):

$$c_1 = \sqrt{kRT_1} = 20\sqrt{T_1} = 340\sqrt{\frac{(1 + \Delta p_1)(7 + \Delta p_1)}{7 + 6\Delta p_1}}$$

As one can see this set of equations allow you to determine all blast wave parameters for explosion of any explosive at any range from origin. However one should remember that sadovsky formulas are quite precise when overpressure is below 10 atm, for very proximity of origin this formula is not so precise but still can be used for aproximate calculations.

Once you have calculated overpressure and positive phase duration for your particular case you can convert it to psi and msec respectively and get a point on lethality diagram from posts above:
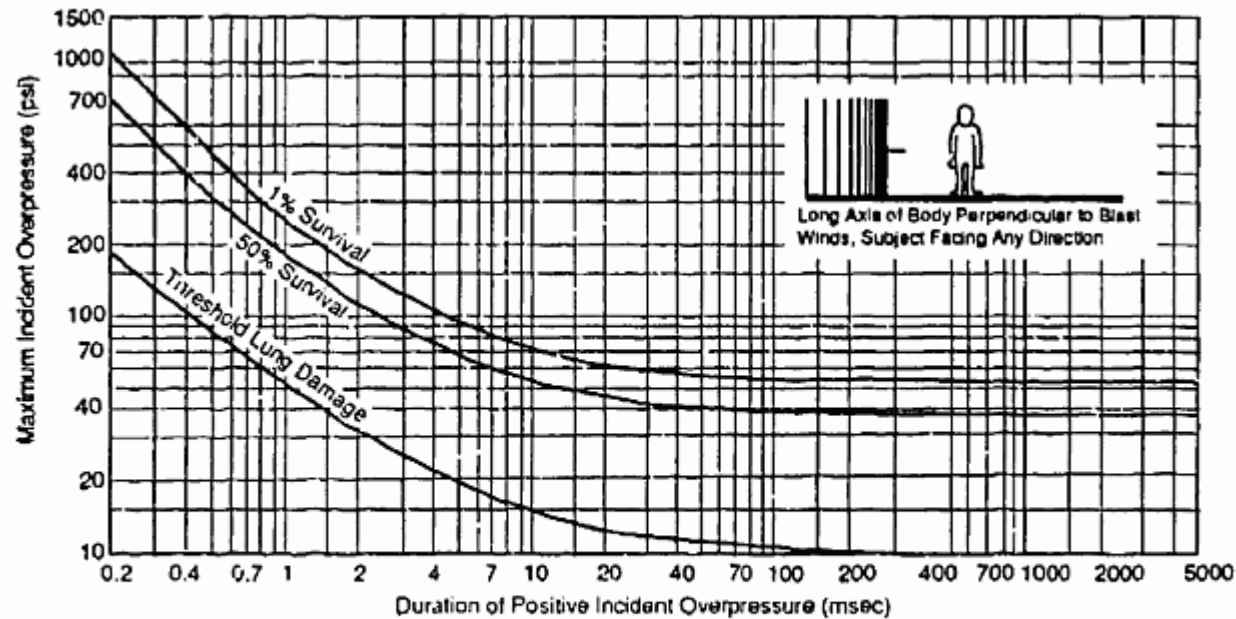
Survival curves predicted for a 70 kg man, applicable to free-stream situations where the long axis of the body is perpendicular to the direction of propagation of the blast wave

You can also use the following general observations on action of blastwave on overage human (1 kg/cm2 ~ 1 atm):

1. dP is > 26 kg/cm2. Instant death, full body disintegration.
2. dP is > 8 kg/cm2. Instant death, body throw back, disintegration of body parts.
3. dP is > 5 kg/cm2. Fatal damage, 99% chance of lethal outcome. Disintegration of body parts, massive damage to soft tissue and bone .
4. dP > 3.8 kg/cm2. Heavy damage, 75% chance of lethal outcome. In lucky case hospitalization for at least 2-3 months.
5. dP > 2.5 kg/cm2. Moderate damage, 10% risk of fatality or hospitalization for 1-2 months.
6. dP > 2.1 kg/cm2. Light injuries, hospitalization for 7-15 days.
7. dP > 1.6 kg/cm2. Disruption of neural system up to loss of consciousness.
8. dP > 1.1 kg/cm2. Rupture of tympanic membranes for average human.
9. dP > 0.5 kg/cm2. Minimal safe distance for artilleryman.
10. dP > 0.35 kg/cm2. Minimal distance of possible rupture of tympanic membranes.

Action on buildings. Note: Damages below are listed in assumption that all building lies within corresponding hazard radius, if parts of the building are in different hazard zones damage in different places of building will vary.

1. dP > 2.5 kg/cm2. Destruction of concrete steel constructions, bridges e.t.c.
2. dP > 1.75 kg/cm2. Destruction or heavy dammage to earthquake proof steel reinforced concrete constructions.
3. dP > 1.0 kg/cm2. Full destruction of all buildings, except earthquakeproof steel reinforced concrete constructions.
4. dP > 0.65 kg/cm2. Collapse of steel framework buildings and light steel reinforced concrete constructions.
5. dP > 0.25 kg/cm2. Significant damage to big city buildings.
6. dP > 0.15 kg/cm2. Partial collapse of buildings.
7. dP > 0.05 kg/cm2. Light dammage to buildings, break of glass in windows.

Formulas i've posted above are pretty easy to implement, however to make understanding their use easier I post practical example of their use. Let's calculate shock wave parameters for 1 kg PETN charge placed on the ground. Heat of explosion for PETN is 5.756 MJ/kg so Kt = Qexp/Qtnt = 5.756 / 4.19 = 1.373. Now we can use formula (2) from post above substituting M with Kt*M = 1.373 * 1 = 1.373, we can in same way use formula (4). For each distance from explosion origin we can use this formula to get overpressure (dP) and duration of positive (compression) phase in shockwave (T+), and then use dP to calculate other parameters at this range: speed of shock wave front (Vf), speed of gas behind shock wave front (Vg) and temperature in shock wave front (Tf). Results of calculations for case with 1 kg PETN are shown below (for convenience of use for damage estimation overpressure graphs are plotted in both psi and kg/cm2 units):

R(m)	1	2	3	4	5	6	7	8	9	10
dP (psi)	344.27	57.52	22.47	12.25	7.93	5.69	4.37	3.51	2.92	2.49
T+(msec)	1.37	1.94	2.37	2.74	3.06	3.36	3.63	3.88	4.11	4.33
Vf (km/s)	1.573	0.714	0.519	0.447	0.412	0.393	0.382	0.374	0.368	0.364
Vg(km/s)	1.246	0.459	0.246	0.156	0.110	0.082	0.065	0.054	0.045	0.039
Tf(K)	1465.37	509.24	385.17	345.32	327.02	316.91	310.67	306.50	303.55	301.37

R(m)	11	12	13	14	15	16	17	18	19	20
dP (psi)	2.16	1.91	1.71	1.55	1.41	1.29	1.20	1.11	1.04	0.97
T+(msec)	4.55	4.75	4.94	5.13	5.31	5.48	5.65	5.82	5.97	6.13
Vf (km/s)	0.361	0.359	0.357	0.355	0.354	0.353	0.352	0.351	0.350	0.350
Vg(km/s)	0.034	0.030	0.027	0.025	0.023	0.021	0.019	0.018	0.017	0.016
Tf(K)	299.70	298.39	297.33	296.46	295.74	295.12	294.60	294.14	293.74	293.40

| R(m)	21	22	23	24	25	26	27	28	29	30
dP (psi)	0.92	0.87	0.82	0.78	0.74	0.71	0.68	0.65	0.62	0.60
T+(msec)	6.28	6.43	6.57	6.71	6.85	6.99	7.12	7.25	7.38	7.51
Vf (km/s)	0.349	0.349	0.348	0.348	0.347	0.347	0.347	0.346	0.346	0.346
Vg(km/s)	0.015	0.014	0.013	0.013	0.012	0.012	0.011	0.011	0.010	0.010
Tf (K)	293.08	292.81	292.56	292.33	292.13	291.95	291.78	291.62	291.48	291.34
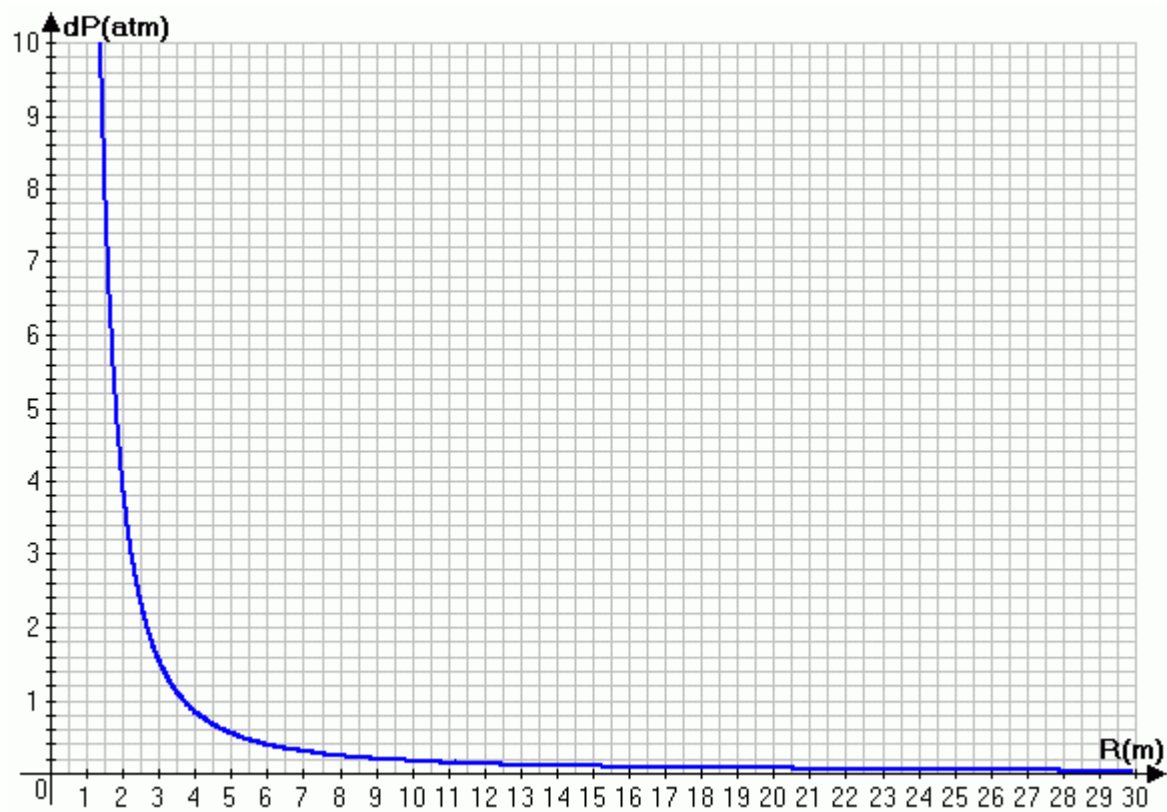
Overpressure vs range graph for 1 kg PETN explosive charge (in atm ~ 1 kg/cm2).
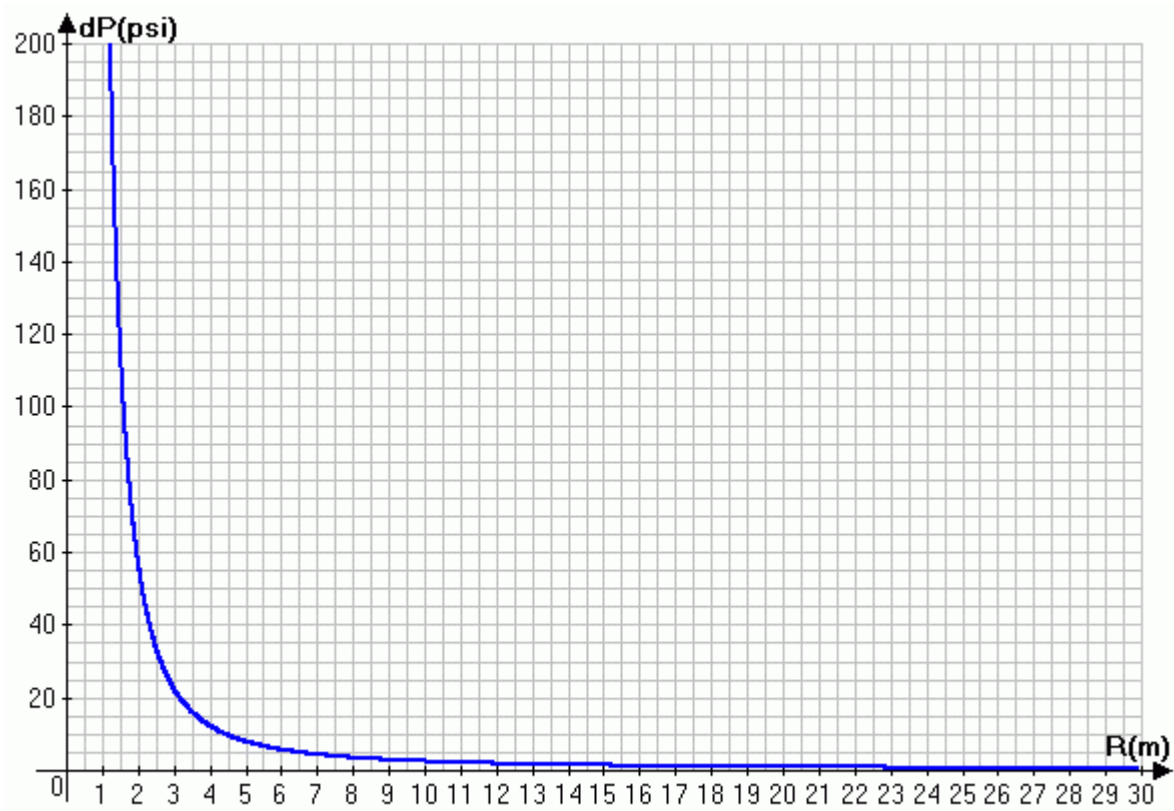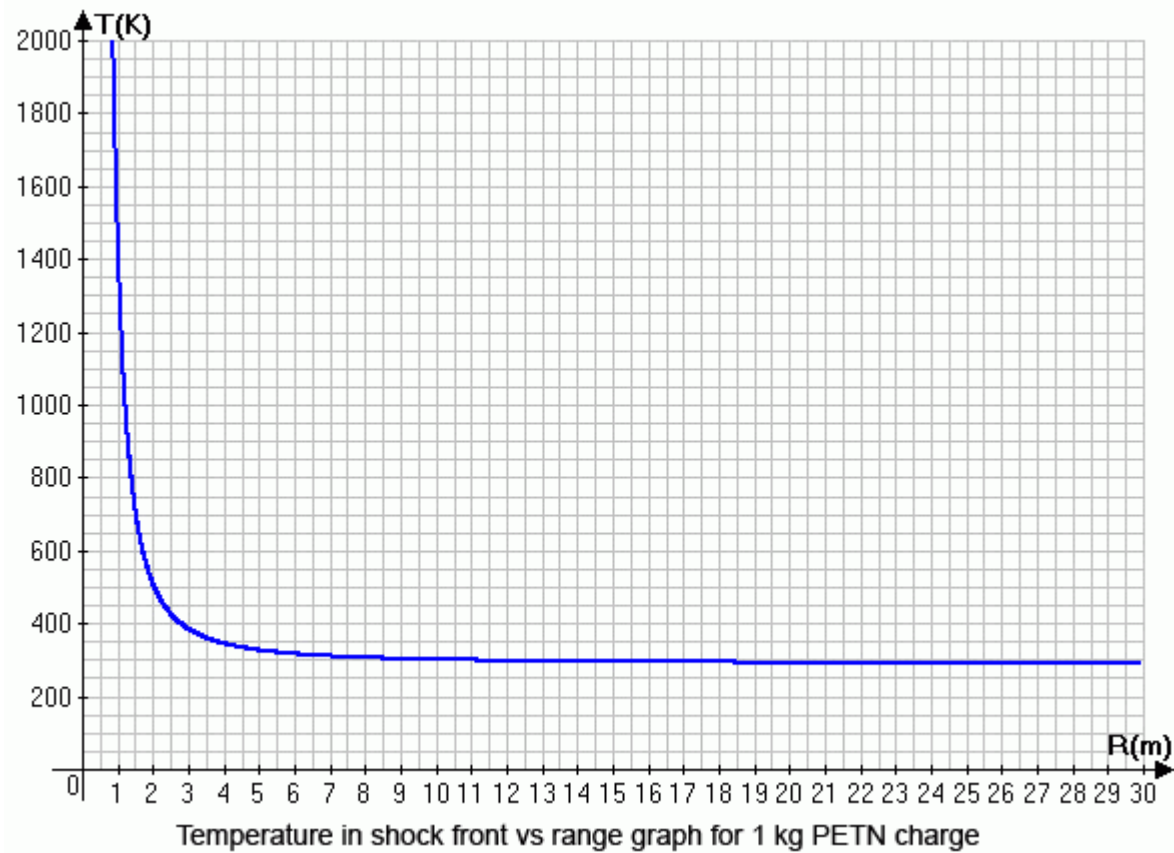
Overpressure vs range graph for 1 kg PETN charge
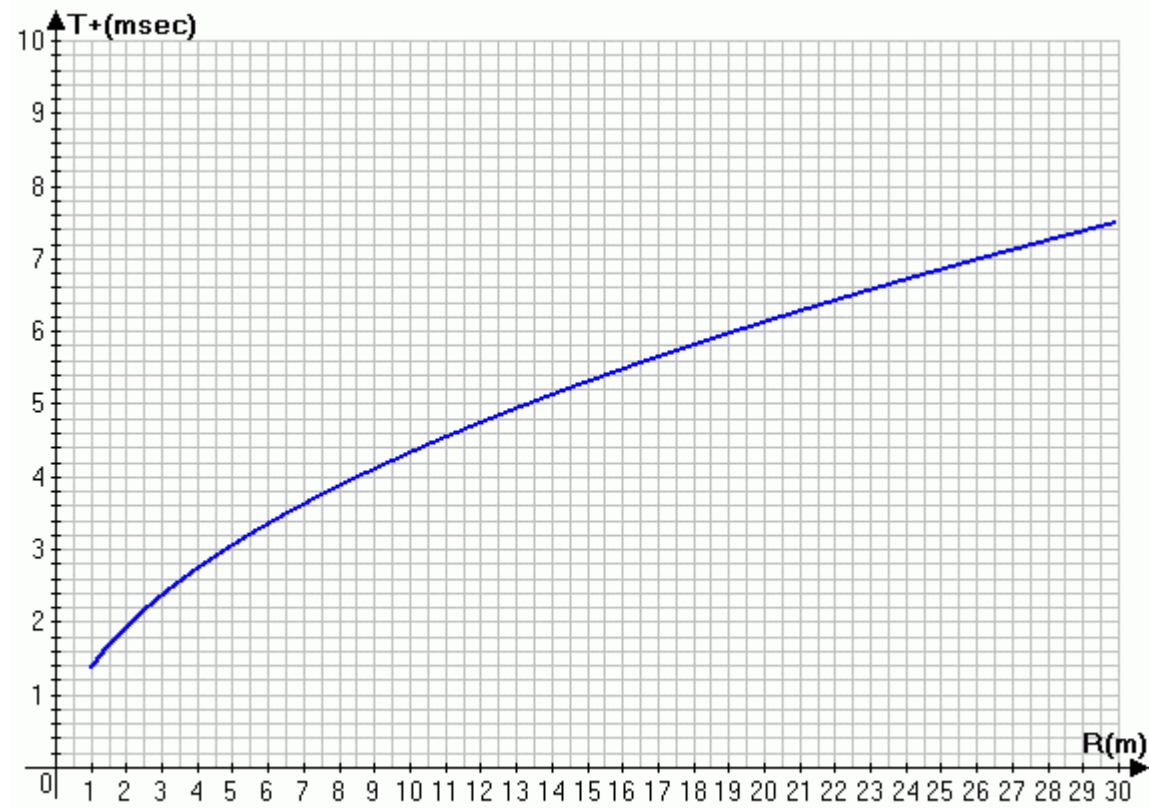
Positive phase duration vs range for 1 kg PETN charge
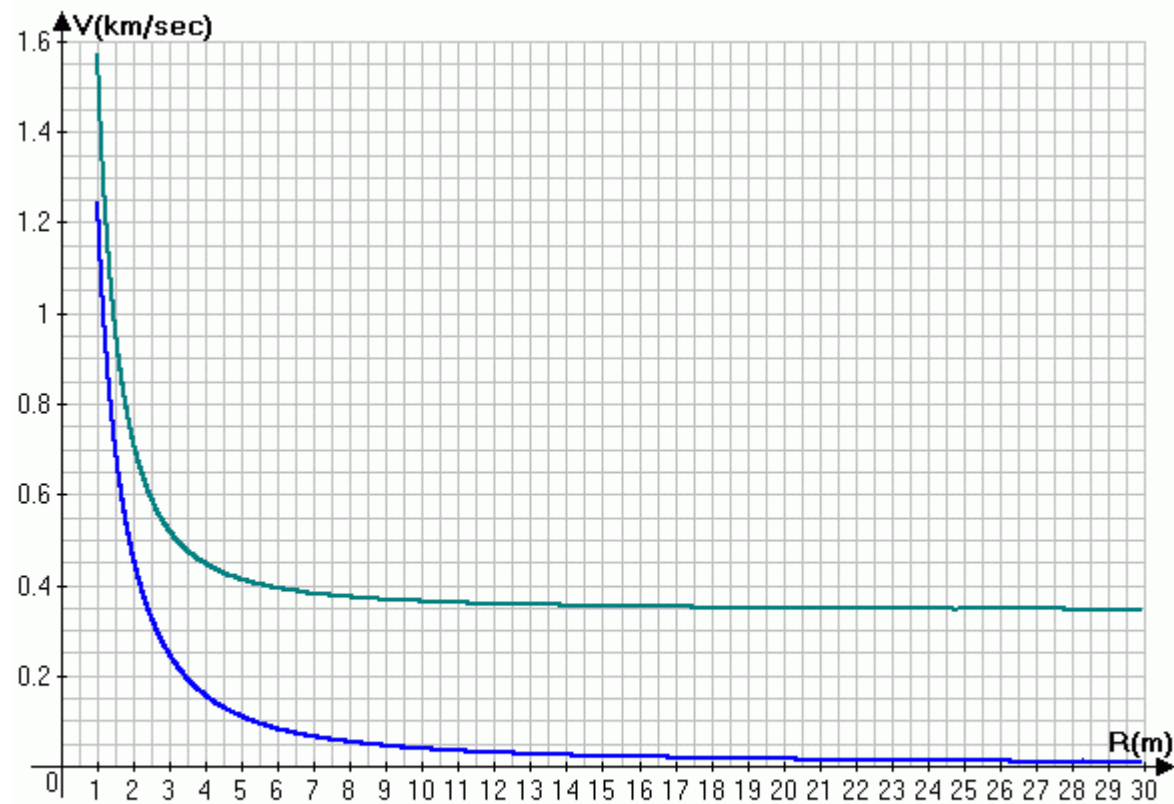
Velocities of shock wave front and gas behind front vs range grapth for 1 kg PETN charge

Temperature in shock front vs range graph for 1 kg PETN charge

Now let's look how much safe can be a man who stands in 1.5 meters from explosion origin, and how safe can be another man standing 4 meters away from origin. Graphs above for 1.5 meter distance show overpressure ~8.137 atm (kg/cm2) witch is equal to ~118 psi with ~1.67 msec positive shock phase, at distance of 4 meters we get overpressure ~0.844 atm (kg/cm2) witch is equal to ~12 psi with ~2.741 msec positive shock phase duration.

Comparing results with tabled values in post above we can conclude that first person must suffer instant death with throw back of body with possible body part disintegration, while second one is relatively safe but can suffer rupture of tympanic membranes.

Note: Don't forget that this calculations assume that explosive charge was without shell and there are no shell fragments around. Fragments of charge shell are far more deadly and in case if shell was metallic will surely kill at such close distance. Calculations above take to account only pure damage done by shockwave itself.