Warheads

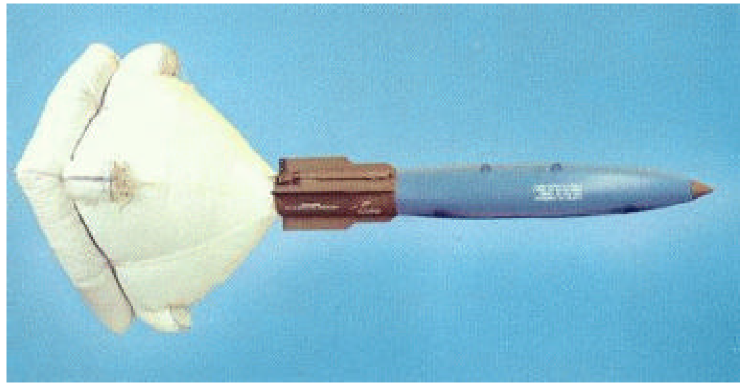
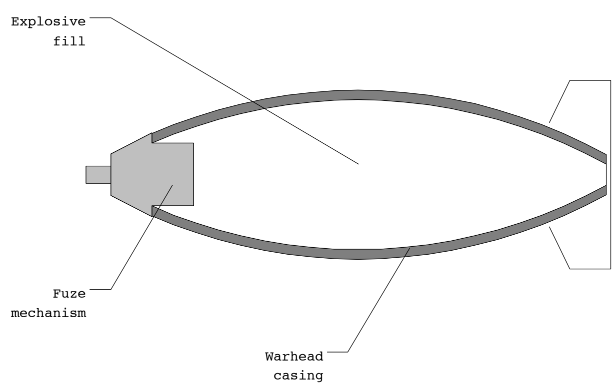


Figure 23-1. The MK83 (1000lb) General Purpose Bomb with Ballute retarding mechanism.

All of the sensors and guidance systems discussed so far have one goal, to deliver a warhead to the immediate proximity of the target. At this point, of course, the warhead will detonate and hopefully disable the target. Warheads come in a wide variety of designs, some only useful for special purposes. But the majority cause damage in one of two simple ways, either by concussion (blast effects) or by penetration with one or more fragments. In order to understand the function of the warhead, we must first learn what warheads can do and then how targets are vulnerable to their effects.

Warhead Construction

The typical warhead has three functional parts the fuze mechanism, the explosive fill, and the warhead casing.



The fuze mechanism performs many functions. It contains the equipment for detecting the proximity to the target and initiating the detonation sequence, called the *TDD device* (for Target Detection and Detonation). It also contains one or more safety mechanisms that prevent inadvertent detonation of the main charge. Lastly, the fuze provides the start of the high explosive train. It consists of the detonator, which is a small amount of primary high explosive, and possibly the booster charge.

When the explosive fill, which is a large amount of secondary high explosive, is detonated, a large amount of heat will be released. Initially, the explosion is contained within the casing. As heat is added, the gaseous products will raise the pressure until the casing can no longer contain it. At that point the casing will burst and the gases will rapidly expand. The casing will break up into fragments which will be propelled outward at great speed. The rapidly expanding gasses will compress the surrounding air and create a shock wave which will propagate outwards at near the speed of sound in air (~340 m/s).

There are two main effects, which cause damage to targets, the high-energy fragments of the casing and the shock (or blast) wave. Warheads are usually designed to maximize one of these effects. Fragments tend to be lethal to a greater range than the blast effects, but it depends on the particular target. Aircraft are particularly vulnerable to fragment damage, as are personnel. On the other hand, buildings can only be brought down by extensive blast effects. We now turn to a detailed account of each type.

Blast Effects

The rapid expansion of the gaseous products after the casing has burst creates a shock wave. The shock wave is an acoustic wave like ordinary sound, but of limited duration and great energy. Recall that the energy of the acoustic wave was a function of the amplitude, or peak pressure. In shock waves, the peak pressure is achieved only once, and is called the *peak overpressure*. The peak overpressure is reached very quickly as the shock wave passes, after which the pressure subsides more slowly.

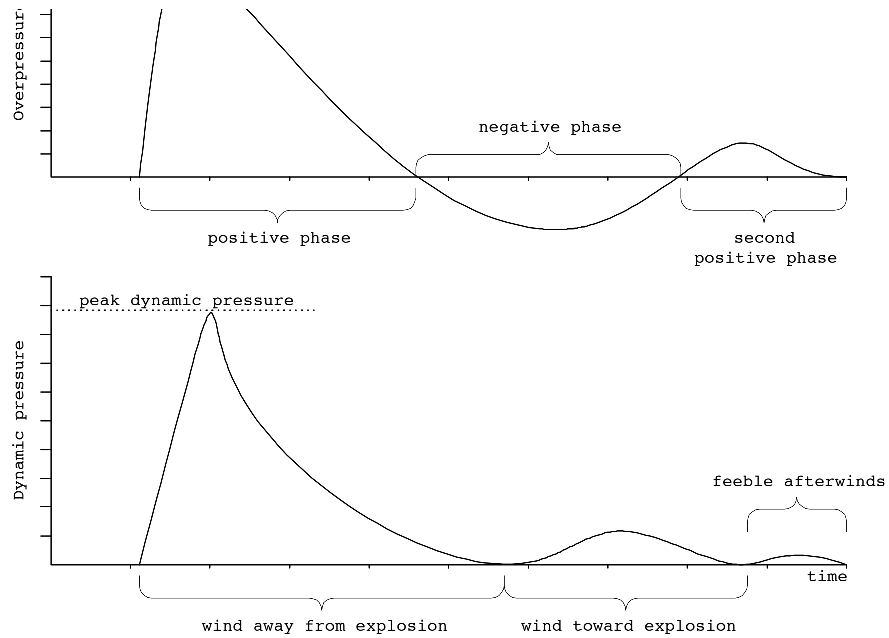


Figure 23-3. Peak overpressure and dynamic pressure in a shock wave.

As the wave passes the pressure oscillates one or more times between positive and negative phases. When the pressure is above the ambient, the shock wave is considered to be in the positive phase. The opposite condition is called the negative phase.

Due to the pressure differential within the shock wave, the air will flow from high to low pressure. This creates a blast wind, which can be of substantial velocity, well over 100 mph. The blast wind only lasts for a fraction of a second and changes direction during the negative phase. As the wind flows against objects, they will feel dynamic pressure from the drag. The dynamic pressure felt by an object follows the familiar equation for drag,

$$\boxed{P_{dyn} = C_d \, \tfrac{1}{2}\rho v^2,}$$

where:

C_d is the coefficient of drag for the particular object;

ρ is the density of air (normally ~1.2 kg/m^3); and

v is the velocity of the blast wind.

Due to the complex nature of explosions, it is not possible to easily predict the magnitude of these blast effects. However, there is a vast collection of experimental data from the explosion of 1 kg of TNT, which has been chosen as the reference explosion. The values for an arbitrary explosion can be found by relating it to the reference explosion through a relation known as the *scaling law*. It relates the distances at which the same effect will be felt for different explosive amounts. The scaling factor is $W^{1/3}$, where W = the equivalent amount of TNT (in kg). W is found by multiplying the mass of the explosive by its relative strength (RS). Explicitly,

$$\boxed{d_W = d_o \times W^{1/3}}$$

where:
d_o is the distance from 1 kg TNT; and
d_w is the distance from the W kg of TNT equivalent.

Example: If a particular peak overpressure, (example: 4 psi) is felt at 5 m from a 1 kg TNT explosion (the reference), estimate how far away from a 10 kg PETN explosion, the same effect will be felt.

The RS for PETN is 173% (from the Berthelot approximation).

W = 10 kg × 1.73 = 17. 3 kg

The actual distance d_w is therefore = $(17.3)^{1/3} \times 5$ m = 12.9 m

The same scaling law will also hold true for dynamic pressures. The peak overpressure and dynamic pressures are found from the graph in Figure 23-4.

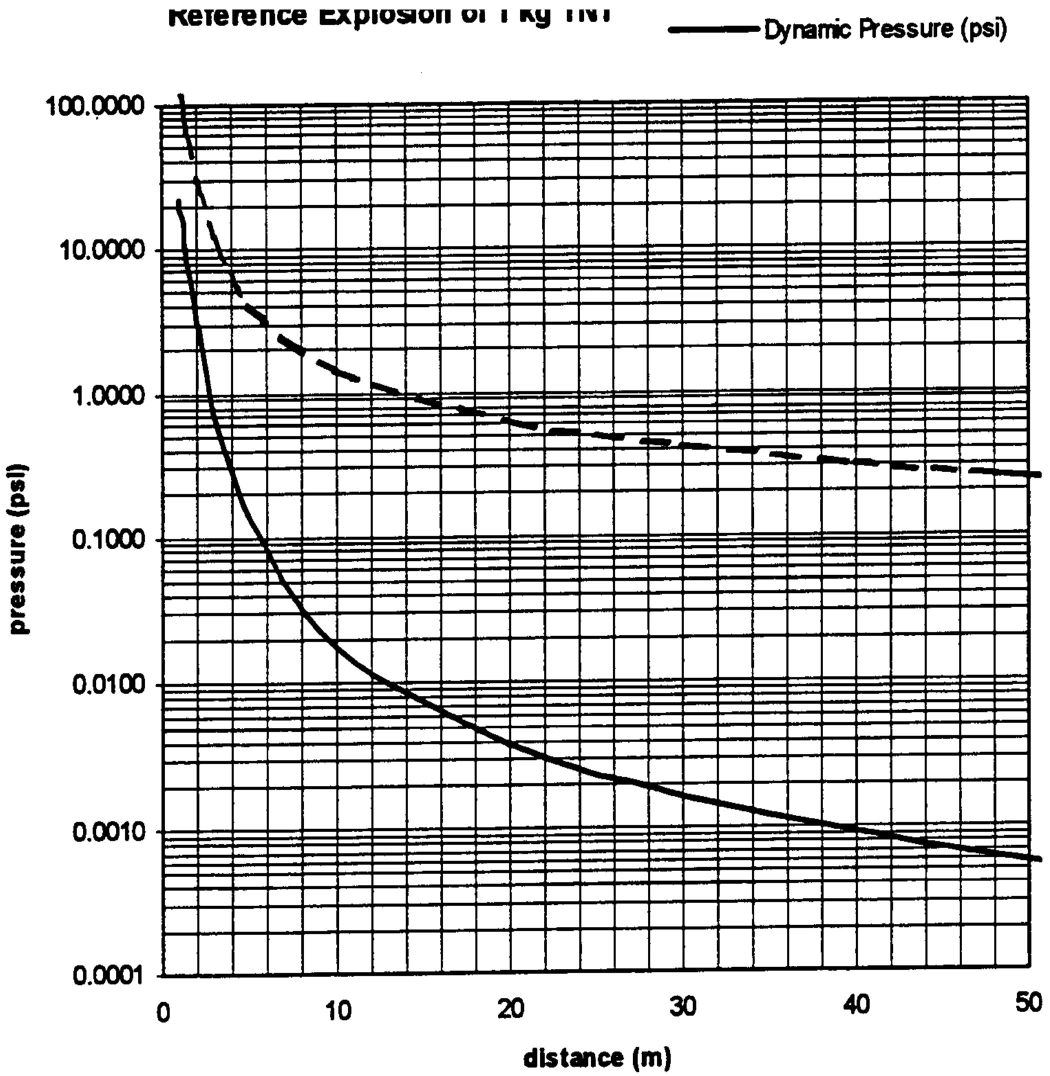


Figure 23-4. Peak overpressure and dynamic pressure for 1 kg TNT.

Example: Calculate the peak overpressure and dynamic pressure felt by a person facing a blast of 10 kg of TNT equivalent, standing 5 meters away.

To use the graph, the distance must be scaled down to the reference condition.

$d_o = d_w / W^{1/3}$
$d_o = (5\ m)/(10)^{1/3} = 2.3\ m$

Using the graph,
peak overpressure = 23 psi

Blast effect warheads are generally detonated above the ground. This is done intentionally in order to take advantage of constructive interference between the shock wave coming directly from the warhead and the shock wave that is reflected from the ground. The shock wave heats and compresses the air as it passes through it. This therefore, has changed the medium through which the reflected shock wave is traveling. The reflected shock wave travels faster than the original shock wave allowing it to overtake and combine with the original wave. At some distance away, the two waves will come together and create a region with even greater blast effects. This is known as the *mach stem* region.

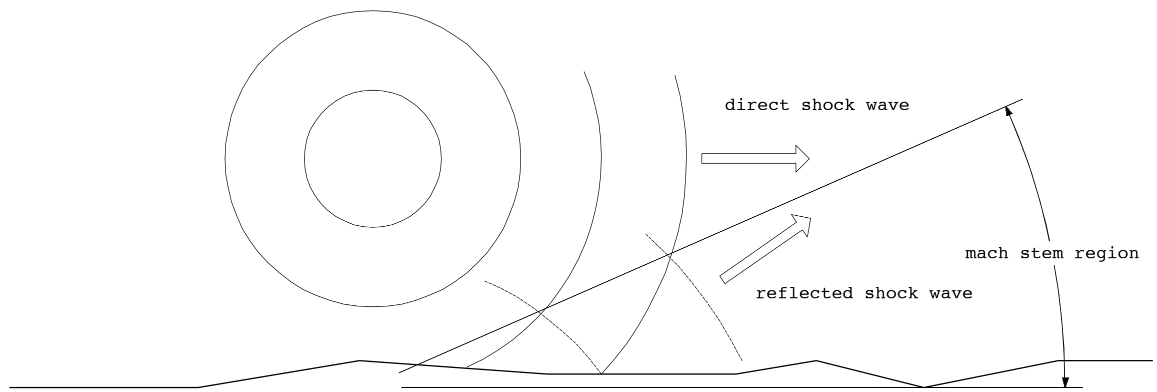


Figure 23-5. The mach stem region.

In this region, both the peak overpressure and the dynamic pressure will be almost double what would be felt if the warhead had detonated on the ground. The height above ground, which maximizes this effect at a particular range, is called the *optimum height of burst*. This is used to determine the setting for the detonator. Although this effect can greatly increase the effective range of some weapons, it only has practical application to very large bombs, and nuclear warheads. For smaller warheads, the extra distance from the target resulting from the detonation above the ground more than compensates for the increased pressures in the mach stem region.

Fragmentation Warheads

Compared to warheads that propagate their lethal effect in the form of a shock wave, fragmentation warheads are generally cheaper and have a greater lethal range.

will the individual fragments have sufficient energy to damage the target and whether or not there is a high probability that a fragment will actually hit the target.

The design of a fragmentation warhead is quite simple. You only need to surround the explosive charge with a heavy casing, which can also act as its container. When the charge detonates it will build up sufficient pressure to burst the casing. If the casing is pre-scored to separate into small pieces, the individual fragments will be thrown outward at high velocity. One of the simplest designs is the hand-grenade. The exterior body of the explosive charge is made up of a serrated fragmentation coil inside a thin sheet metal casing with a straight-forward use of a high explosive train (comp-B is a secondary high explosive).

The kinetic energy of an individual fragment at some distance from the explosion will depend on two factors, the initial velocity, and the reduction in speed due to wind resistance. The fragments will be thrown outward at a velocity which depends on the nature of the explosive material (i.e. how energetic the explosion is) and the configuration of the warhead. By configuration we mean the mass of the explosive charge, the amount of material available for fragments and the physical arrangement.

A theoretical analysis that predicted the initial velocities of the fragments was done by R.W. Gurney in 1943. The velocity is a function of three factors. 1) The *heat of explosion per unit mass* of the explosive material, ΔE, in J/kg (to convert from kJ/mol, you must multiply by 10^6 and divide by the molecular weight).

For example, $\Delta E = 616.4$ kJ/mol of TNT.
Since TNT has a molecular weight of 227 g/mol
$\Delta E = (616.4 \text{ kJ/mol})\times(1 \text{ mol}/227 \text{ g})\times(10^3 \text{ J/kJ})\times(10^3 \text{ g/kg})$
$\Delta E = 2.715 \times 10^6 \text{ J/kg} = 2.715 \times 10^6 \text{ m}^2/\text{s}^2$

2) The *configuration*, which we will limit to three simple shapes: a flat plate, a cylinder and a sphere. Most warheads will fall into one of these categories. For example, a land mine is a flat plate, a 2000 lb. bomb is a cylinder and a hand-grenade is a sphere. 3) The *ratio of explosive charge to fragmenting metal*, C/M, which is also known as the charge-to-metal ratio. The theoretical result is:

$$v_0 = \sqrt{2\Delta E}\sqrt{\frac{\frac{C}{M}}{1 + K\left(\frac{C}{M}\right)}}$$

Flat plate:	K = 1/3
Cylinder:	K = 1/2
Sphere:	K = 3/5

The lead term, $\sqrt{2\Delta E}$, is known as the Gurney constant for the explosive material. The ΔE term is the heat of explosion in J/kg. The Gurney constant has units of velocity [m/s]. It is a rough measure of the speed of the explosion. For example, the Gurney constant for TNT is 2328 m/s. The expression after the Gurney constant generally is in the range of 0.5 to 2.0.

Example: Find the initial velocity of fragments from a M-61 hand grenade.

The M-61 uses 185 g of Comp-B (Gurney constant = 2843 m/s)
and 212 g of fragmenting metal casing.

The charge-to-metal ratio,
C/M = 185/212 = 0.87

Using the spherical factor for K = 3/5,

$v_o = (2843 \text{ m/s}) \times (0.760)$
$v_o = 2150 \text{ m/s}$

Reduction in Velocity with Range

As soon as the fragments are thrown outward from the casing, their velocity will begin to drop due to wind resistance (drag). The drag force is,

$$\text{Drag} = \tfrac{1}{2}\, \rho v^2\, C_d\, A$$

where:
ρ = the density of air (normally 1.2 kg/m^3);
v = the fragment velocity;
C_d = the coefficient of drag (depends on the shape of the fragment and to some extent, the velocity); and
A = the cross-sectional area of the fragment.

We can solve the equations of motion for the projectile and get the fragment's

$$v_S = v_0\, e^{\frac{\cdot \quad d}{2m}}$$

Where: **S is the range**, v_0 is the initial fragment velocity and m is the mass of the fragment.

Example- Find the fragment velocity 100 m from the detonation of a M61 hand grenade, given:

$v_0 = 2150$ m/s
A = 1 cm^2
$C_d = 0.5$
m = 2 g

We use the default value for the density of air. This gives a velocity of

v(at 100 m) = (2150 m/s) $e^{-(1.2 \times 0.5 \times 0.0001 \times 100)/(2 \times 0.002)}$
v = 480 m/s

JDAM is an inertially guided munition with GPS capability.

When a warhead detonates in the vicinity of a target, we may expect that the target will be damaged to some extent. However, there is no guarantee that the target will be destroyed or incapacitated. There are too many factors involved that may alter the outcome of the engagement. So it only makes sense to talk of damage in terms of probabilities.

Warhead Reliability

In order for the warhead to successfully detonate, a number of individual components must all function properly. For example, consider the high explosive train represented by the following figure:

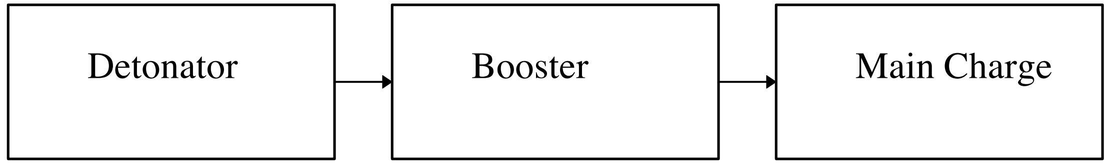


Figure 24-1. High Explosive Train

Successful detonation requires that the detonator, booster and main charge all function properly. Functional reliability is the statistical probability that the warhead will work. It is given the symbol P_s, where the "s" stands for success. Likewise each component will have a certain functional reliability associated with it. For example, through extensive testing, it might be determined that the detonator will operate correctly 999 times out of 1000. In this case, we would say that the functional reliability of the detonator was 99.9%.

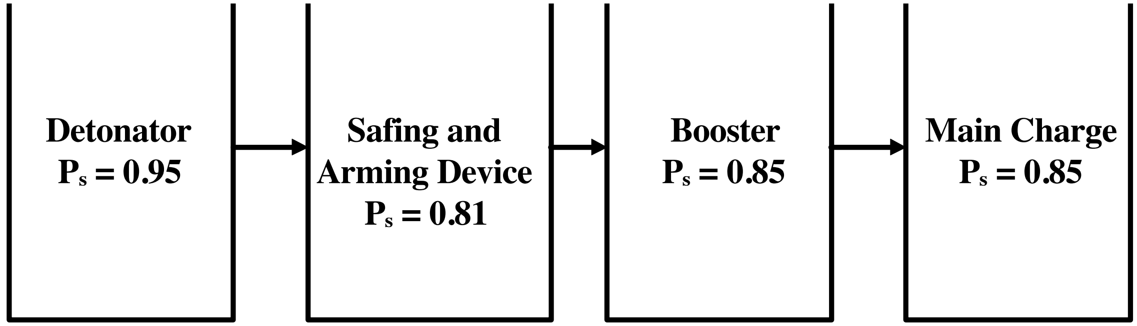
When the functional reliability of the individual components is known they can be combined and used to predict the overall reliability of the warhead. Consider the high explosive train with these three components and their associated functional reliability's:

Detonator : $P_s = 0.90$
Booster: $P_s = 0.85$
Main Charge: $P_s = 0.93$

When these components are connected together, each must function in order to complete the sequence. This is called a series configuration since each event precedes the next. The overall functional reliability is the combined probability that all three events will be successful, namely, P_s (overall) = P_s (detonator) x P_s (booster) x P_s (main charge). Therefore,

Ps (overall) = 0.90 x 0.85 x 0.93   0.71 or 71%

In the series configuration, the addition of other components tends to reduce the overall functional reliability. For example, if a safing and arming device (SAA), which is designed to interrupt the high explosive train until certain conditions are met, is placed



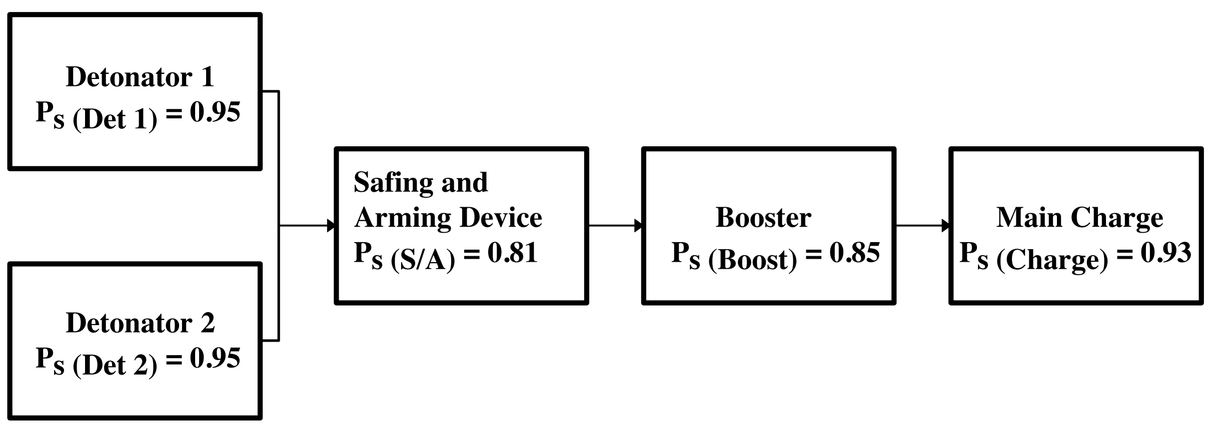
the overall reliability is reduced to, $P_s = 0.95 \times 0.81 \times 0.85 \times 0.93 \quad 0.61$ or 61%. Safety devices may reduce the functional reliability but are necessary to protect the people handling the warhead a before and during launch.

For a general series combination of n components, the overall functional reliability is;

$$\boxed{P_s\,(\text{series}) = P_{s1} \times P_{s2} \times P_{s3} \times \ldots P_{sn}}$$

Where P_{sn} = the reliability of the n th component.

On the other hand the functional reliability can be improved by adding additional components in ***parallel***. For example, consider a warhead design that uses two detonators, either of which can initiate the explosive train.



Considering just the detonator portion of the train, there are four possibilities:

2. Detonator 1 works and detonator 2 fails
3. Detonator 1 fails and detonator 2 works
4. Detonator 1 fails and detonator 2 fails

The high explosive train will be initiated in all cases except number four. So the probability of failure is merely, $P_{f\,(both\ fail)} = (P_{f\,(det1)} \times P_{f\,(det2)})$. But remember, $P_s + P_f = 1$ so then $P_f = 1 - P_s$. Which leads to,

$P_{f\,(both\ fail)} = (1 - P_{s(det1)}) \times (1 - P_{s(det2)})$ and therefore ;

$P_{s\,(overall)} = 1 - P_{f\,(both\ fail)} = 1 - \{(1 - P_{s(det1)}) \times (1 - P_{s(det2)})\}$

This leads to the generalization that for n components connected in parallel,

$$P_{s\,(parallel)} = 1 - \{(1 - P_{s1}) \times (1 - P_{s2}) \times (1 - P_{s3}) \times \ldots (1 - P_{sn})\}$$

or

$$P_{s\,(parallel)} = 1 - \{(P_{f1}) \times (P_{f2}) \times (P_{f3}) \times \ldots (P_{fn})\}$$

Using the methods outlined above, an apparently complicated combination of components can be reduced to serial and parallel elements, which can be simply solved to provide warhead reliability.

Probability of Kill (P_k)

In order to make sense out of the infinite spectrum of outcomes, it is useful to view it in black-and-white terms. For most military engagements, it only matters that the target is removed from action. It is in this sense that the target is considered "killed." The probability of kill (P_k) is a statistical measure of the likelihood that the target will be incapacitated. For a warhead, the P_k will depend on the nature of the target, specifically how vulnerable it is to the effects of the warhead (i.e. the shock wave, fragments, etc.), and the proximity of the warhead to the target.

The probability of kill can be defined conditionally. For instance, we can speak of the P_k if a fragment hits the target. To clarify the situation, the following notation will be used when needed to express the conditional probability of kill,

$$P_k|_{hit} = \text{the } P_k \text{ if the fragment hits the target.}$$

In this case the overall P_k will be the product of two factors,

Where P_{hit} is the probability of the fragment hitting the target.
In practice, there may be many factors contributing to the overall P_k. For example, the target must be detected and localized, the weapon launched and delivered to the target and then detonates reliably. Each of these factors will add conditional terms to the overall P_k.

Circular Error Probable

The proximity of the warhead to the target is also statistical in nature. We may speak of the average distance from the point of impact and/or detonation to the target if many warheads were launched at it. Alternatively, we may speak of the most probable outcome from a single launch, which turns out to have the same value. Therefore, the measure of the most probable distance from the point of impact and/or detonation to the target is the *circular error probable (CEP)*. It is defined as follows:

CEP = the radius of a circle about the aim point inside of which there is a 50% chance that the weapon will impact and/or detonate.

For the purpose of estimating the probability of kill, we will use the CEP as the distance from the point of detonation of the warhead to the target.

Levels of Damage

There are two ways to think of the process. In one case, there will be varying levels of damage to the target. For instance, the target may sustain minor damage which does not affect its operation, or the target may be completely destroyed. In the other view, there is some probability that the target will be removed from operation, which is the P_k. The two views are related, of course. For descriptive purposes, we make the associations shown in Table 24-1.

Damage Level	**Description**	**$P_{k\|hit}$**

	Operation still possible but at reduced effectiveness	
heavy	unable to operate	0.9

Table 24-1. Levels of damage and probability of kill.

Damage Criteria for Blast Effect Warheads

There are two main ways that blast effects may damage targets, *diffraction and drag loading*. Diffraction loading is the rapid application of pressure to the target from all sides as the shock wave passes over it. It is associated with diffraction because the shock wave front will bend around and engulf the target as it passes. In diffraction loading, the overpressure of the shock wave is applied to several sides of the object nearly simultaneously. For instance, a square building facing the blast would feel the shock wave arrive on the front sides and roof at nearly the same time. Ductile targets (for example made of metal) will be crushed. Brittle targets (for example made of concrete) will shatter. The loading can be estimated from the peak overpressure.

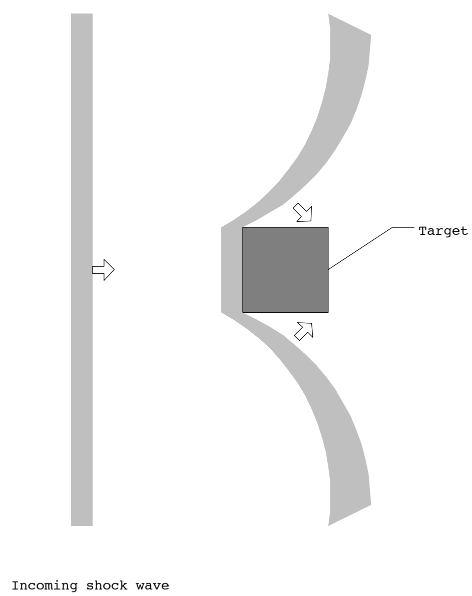


Figure 24-2. Diffraction loading.

Suppose a shock wave of 25 psi peak overpressure is incident upon a standard one-story residential house. The surface area of the house could be estimated as follows:

Side area = 25 ft. x 10 ft.

Roof area = 40 ft. x 13.3 ft. (front half only of roofline at 20)

Total area = 1432 ft^2 x (144 in^2/ft^2) = 206,200 in^2.

The total loading if all the peak overpressure were applied simultaneously to the front, sides and roof,

Load = 25 psi x 206,200 in^2 = 5.2×10^6 lb.

That's a load of roughly 2600 tons. It's highly unlikely the structure would survive.

Drag loading, on the other hand, comes from dynamic pressure. It is the aerodynamic force, which acts on surfaces that are perpendicular to the shock wave front. For example, if we subject the same residential structure to 3 psi of dynamic pressure, it would feel

Drag load = 3 psi x 400 ft^2 x 144 in^2/ft^2 = 172,800 lb., or

Drag load = 86 tons.

In general, the drag load will be much less than the diffraction loading. However, it is applied for a longer period of time. The drag load also reverses direction, which tends to rip objects apart.

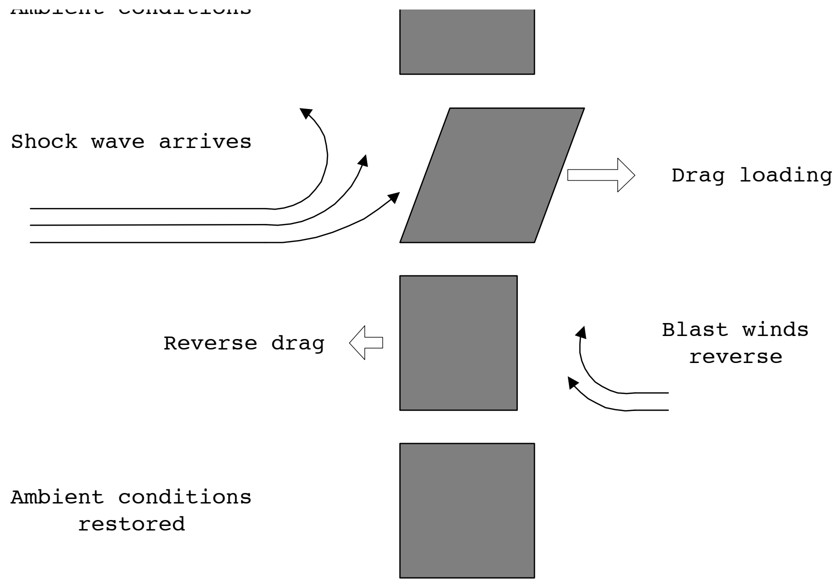


Figure 24-3. Drag loading.

Some targets, which are relatively flexible, are not damaged by diffraction loading. These same targets may be vulnerable to drag loading damage. Targets that are not rigidly affixed will be thrown by the force and may be displaced by several meters. Personnel are very vulnerable to this type of damage as well as the secondary threat of being hit by other objects and debris thrown by the blast. Aircraft and light equipment are also likely to be damaged by drag loading.

For purely academic purposes, Table 24-2 is a list of possible targets which indicates which effect they are most vulnerable to and the values of peak overpressure or dynamic pressure required to achieve three levels of damage.

Target	**Damage mechanism**	**Light** (psi)	**Moderate** (psi)	**Heavy** (psi)
Industrial buildings	Diffraction	3	5	15
Roads and Bridges	Diffraction	5	8	12
Light armor	Drag	1	4	7
Heavy armor	Diffraction	10	100	200
Troops in open field	Drag	1	3	5
Troops in bunkers	Diffraction	5	30	100
Shallow buried structures	Diffraction	30	175	300
Parked aircraft	Drag	0.7	1.5	3
Ships	Drag	2	5	7

Example: Find the distance to which light armor might be destroyed from a 2000 lb TNT equivalent bomb.

Referring to the dynamic pressure vs. range curve for a reference explosion (1 kg TNT) we find that 7 psi of dynamic pressure will be felt at about 1.5 m.

To find the scaling factor $W^{1/3}$ convert the warhead size into kg:

2000 lb. = 910 kg TNT

$W^{1/3} = 910^{1/3} = 9.7$

Therefore the effect (7 psi dynamic pressure) will be felt to a range of

R = 1.5 m x 9.7 = 14.5 m

Damage Criteria for Fragmentation Warheads

As a general rule, the vulnerability of some targets to damage caused by fragments from a warhead depends on the kinetic energy. The initial energy can be found from the Gurney analysis and the velocity as a function of range can be found from the drag equation. For a typical fragment, about the size of a 120 grain, 9-mm bullet, the velocity at 200 m is about 1/3 of its initial value, and therefore the kinetic energy is down to 10% of its original value.

Personnel

Based on typical ballistics numbers, 100 J is the minimum lethal kinetic energy. This is roughly equivalent to a .22 long bullet (40 grains) from a rifle at 1000 fps. The next level of damage is about 1000 J, which corresponds to a .357 jacketed soft-point (158 grains) bullet at 1400 fps. This is fairly lethal (depending on where it hits) to unprotected personnel. Lastly, around 4000 J is sufficient to penetrate body armor. This is equivalent to a 7.62 full metal jacket or .30-06 armor-piercing bullet (166 grains) at 2750 fps. Roughly dividing this into three broad categories:

Light (.22 cal) = 100 J
Moderate (.357 cal.)= 1000 J
Heavy(.30-06 cal) = 4000 J

Aircraft are generally constructed of light metals. Giving a conservative estimate, you could treat the aircraft skin as the equivalent of body-armor. Thus it requires about 4000 J to penetrate the aircraft skin.

Armored Vehicles

It is probably unwise to assume an armored vehicle could be stopped by a fragmentation warhead. Any substantial amount of armor would require a specialized projectile. For light armor, saboted shells, which have a .50 cal outside shoe (sabot) containing a .30 cal shell (penetrator) that is hardened and shaped to pierce armor. At almost 4000 fps, this can penetrate ¾” of steel. Armor up to about 15”, can be pierced by special rounds that weigh upwards of 3.5 kg and travel at 700 m/s (making their kinetic energy about 850 kJ). As a crude rule of thumb, we can estimate that it takes about 10 kJ of kinetic energy per cm of steel in order to penetrate it. Table 24-3 is a summary of the damage criteria for targets vulnerable to fragmentation warheads.

	Fragment Energy in kJ		
Target	**Light Damage (P_{klhit} = 0.1)**	**Moderate Damage (P_{klhit} = 0.5)**	**Heavy Damage (P_{klhit} = 0.9)**
Personnel	0.1	1	4
Aircraft	4	10	20
Armored vehicle	10	500	1000

Table 24-3. Sample damage criteria for fragmentation effects.

Probable Number of Fragments Hitting the Target

It can be proven that the fragments from a typical warhead are generally lethal at long range, far in excess of the lethal effects from blast weapons of equivalent size. Drag reduces the energy slowly. For example, fragments from a hand-grenade can be dangerous to a range of about 100 m. However, the likelihood of being struck by a fragment at 100 m is small. There are only so many fragments that are distributed in all directions. The average number striking a target will reduce proportionally to $1/R^2$, where R is the range. We can express this as

$$N_{hits} = \frac{AN_0}{4\pi R^2}$$

N_{hits} is the expected number of fragments hitting the target;
N_o is the initial number of fragments from the warhead;
A is the frontal area of the target presented to the warhead; and
R is the range of the target to the warhead.

When estimating the P_k from a fragmentation warhead, you must take into account the number of fragments that are expected to hit the target. Multiple hits must be handled by correct manipulation of probabilities. For multiple hits the overall P_k is found from

$$P_k = 1 - (1-P_K|_{hit})^{N_{hits}}, \text{ if } N_{hits} > 1, \text{ or}$$
$$P_k = N_{hits} \times P_k|_{hit}, \text{ if } N_{hits} < 1$$

Example: Find the P_k from a hand-grenade against personnel at 2 m from the detonation, assuming there are 200 fragments at about 3000 J each (you may neglect drag at this short distance).

The closest value $P_k|_{hit}$ given in the table is 0.9 at 4000 J, so it would be reasonable to expect a probability of some where between 0.5 and 0.9 for a single 3000 J fragment. Take 0.8 as an estimate.

Assuming a person presents about 1 m^2 to the warhead, the expected number of hits will be :

$N_{hits} = 1(200)/(4\pi 2^2)= 4.$

Therefore,

$P_k = 1 - (0.2)^4 = 0.9984.$

This is a crude measure, however this calculation suffices to prove that virtually no person 2 m from a hand grenade will survive, which is known to be true.

Compare this, on the other hand to the P_k at 5m. Here there will only be

$N_{hits} = 1(200)/(4\pi 5^2) = 0.6$

This can be taken directly as the probability of being hit, so that

$P_k = 0.6 \text{ x } 0.8 = 0.5.$

the *lethal range* of the warhead.