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Why is Water so Good at Suppressing the Effects of Explosions?

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Background

John Parkes of Dell Explosives started work on suppressing explosions with bags of water after hearing of the death of Helen Tinney, an innocent bystander, who was killed at the demolition of a block of flats in Glasgow in 1992.

When most experienced explosives engineers first observe a suppressed explosion they are convinced that there has been a misfire. Depending on the amount of water and the way it is contained, the overpressure can be reduced by a factor of ten, sometimes more than twenty (Salter and Parkes 1994). The number of fragments from shell cases can be cut by a factor of a hundred. Their velocities can be reduced by a factor of seven. Slugs from focal point charges are stopped within metres. Safety distances round magazines can be cut. The number of people evacuated from a bomb disposal site can be reduced. In June 1999, engineers from 33 EOD regiment saved an entire village in Kosovo from the detonation of a 2000 lb NATO bomb by using water bags.

This paper outlines some of the physics behind the effects. Latent heat, fast external pressure rise, drag of fragments, momentum transfer, the speed of sound in gas-liquid mixtures and interference with the combustion of carbon are all involved but perhaps other mysteries still remain. Some practical details of the technique are discussed.

Heat.

The latent heat need needed to evaporate a kilogram of water is 2.25 megaJoules. The explosive energy from a kilogram of TNT is 4.45 megaJoules, just less than twice as much. As water is cheap we can afford to place water weighing much more than twice the weight of explosives. An explosion breaks water into a fine spray. The surface area of spray is six times the water volume divided by drop diameter and can be very large. For example a cubic metre of water broken into 30 micron drops has a surface area of 200,000 square metres, equal to a square of 450 metres side. This large area provides a splendid chance for evaporation. We cannot be sure about the exact rate of heat transfer without knowledge of the distribution of drop diameters and their velocities relative to the surrounding hot gases. However by making reasonable guesses we can show that all the heat can be transferred to water drops in times of the order of a few milliseconds. Cooling the products of an explosion by a factor of ten on the absolute scale will give correspondingly large reductions in the pressure and volume of gases.

Sound speed.

The speed of sound in any medium is given by dividing the bulk modulus by the density and taking the square root. (The bulk modulus of a substance tells you how hard it is to reduce its volume by increasing pressure and is the ratio of an applied pressure to the resulting fractional change in volume.) Water at 15 C has a rather high bulk modulus of 2.05×10^9 N/metre^2 and a density of 999 kg/metre^3 giving a speed of sound of 1432 metres/second. At the frequencies of sound and explosion waves the bulk modulus of a gas is given by its pressure times the ratio of its specific heats at constant pressure and constant volume. This ratio is often given the symbol γ with the value 1.4 for diatomic gasses like air. The density of ambient air is about 1.22 kg/metre^3 giving a speed of sound of 341 metres/sec.

The speed of sound in a mixture of water and air is very interesting, (Karplus and Klinch 1964). A fifty-fifty mixture by volume would have double the bulk modulus of air, ie 283640 N/metre^{2,} and half the density of water, ie 499.5 kg/metre^3. This mixture would have a speed of sound of only 23.8 metre/second, a factor of 17 down on normal speed in waterless air. Figure 1 shows a graph of the speed of sound in water-air mixtures as a function of water-to-air fraction. The effect is very strong for ratios between 0.03 and 0.97.

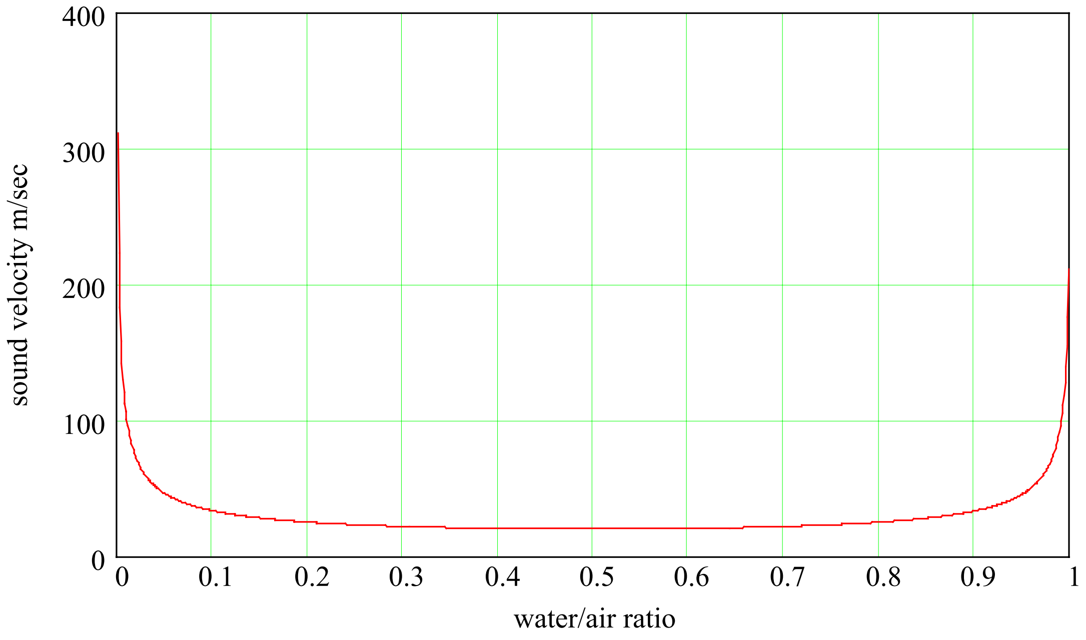

Figure 1. The speed of sound in mixtures of water and air as a function of water-air ratio.

A video sequence of a water-suppressed explosion shows that the rate of advance of the spray front is very close to the velocities shown in figure 1.

Momentum transfer

The conical geometry of a focal point charge can produce a slug of metal moving with a velocity which is considerably above the detonation velocity of the best explosives. The velocity is so high that very thick armour plate can be penetrated. However when such a projectile hits two bags of water, about the dimensions of a pillow, hanging on an easel made of domestic hollow core doors, the entire mass of water is blown out from the far side of the furthest pillow. Suppose that a slug weighing 0.1 kgm is approaching the target at 10,000 metres/second. The momentum is 1000 kg metres/second. This has to be conserved. When the slug hits the front wall of a water bag a positive pressure wave with a spherical front propagates through the water. When this reaches the far side of the bag there is an impedance mismatch because the mechanical properties of air and water are so different. This results in the reflection of the positive pressure wave as a negative front, but a liquid cannot sustain large negative pressures. The result is that water sprays out from the entire area of shock front. The process is repeated for the second bag.

If the momentum of the slug is transferred to a 100kg mass of water, the water velocity needed to accept the momentum will be only 10 metres/second. The water behaves like the executive desktop toy known as Newton's cradle consisting of a set of steel balls on pairs of strings swinging in a row. The intact slug in the shape of a carrot will be found very close to the easel position. Protection works because the expanding shock front transfers momentum to *all* the water.

Fragment drag

Imagine that you are part of a steel munition case round an explosive charge that has just exploded. The enormous internal pressure has caused cracks to appear between you and your neighbouring fragment at places chosen by the shell designer to produce the most damaging effect. You feel a much lower pressure outside the casing and the very large pressure difference means that you have to do some serious acceleration. Meanwhile explosive gases with a very high density under the same pressure gradient are pouring through the gap between you and the neighbouring fragments giving high aerodynamic drag forces to increase acceleration even further. Your shape is such that you will probably have rather a high drag coefficient.

We now repeat the event but with a large mass of water touching your outer wall. As soon as the cracks open, the pressure in the water outside rises very fast and quickly approaches the pressure inside. There is no pressure gradient so why should you bother to do any acceleration? The water from the outside of the enclosing bags can do it instead. Drops of water are held together by surface tension but movement relative to surrounding air creates a force to break them apart. This continues until they are very small and moving with almost the same velocity as the mixture of air and explosion products around them. If the water packing round the charge was incomplete and you did acquire some velocity relative to the water around you, the drag forces will be 800 times higher than if you were moving through air.

Parkes, Wilkinson and O'Dwyer did experiments on Howitzer shells at the DRA range at Shoeburyness using extremely sophisticated equipment for measuring fragment numbers and velocity. The results (Salter and O'Dwyer 1999) from two unsuppressed events at 6.05 metres range and two suppressed events at 4.5 metres range are shown in figure 2. The fragment screens intercept only a small fraction (1.95% and 3.54% respectively) of the total number of fragments produced by the shell casing but, with an unsuppressed detonation, still enough to be statistically significant.

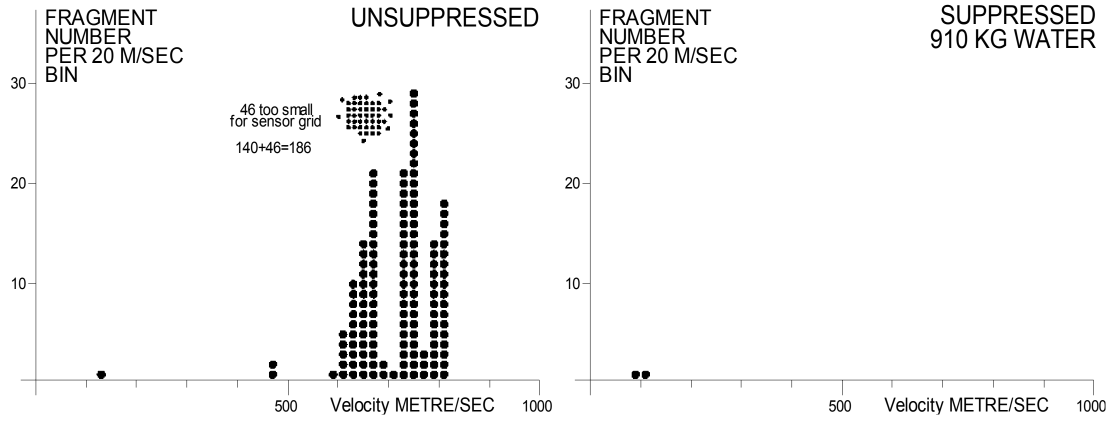

Figure 2. Fragment number and velocity from pairs of 155 mm M107 howitzer shells.

For both the unsuppressed shells the velocity distribution shows three distinct clusters between 600 and 800 metres per second for reasons so far unexplained. The two shells produced a total of 186 fragments. However, even with a higher interception angle there was only one fragment recorded from each of the suppressed events and both the velocities were about 100 metres per second. There were water bags around and above the shell but not below it and it is possible that the fragments which escaped had been moving downwards and had bounced off the ground. The base plate of an artillery shell must be thick enough to withstand the very high breech pressure and there are accounts of intact base plates being thrown over the heads of observers 1800 metres away from a shell burst. In the Shoeburyness trials broken base plates from 155 mm and 200 mm suppressed shells were found at the foot of the 18 mm plywood support of the velocity sensing screens.

Anyone who wishes to repeat the experiment but is not in possession of their own 155 mm howitzer shells and fragment-counting equipment can build a stockade out of four sheets of hardboard and cover a charge with a bag of granite chips from a garden centre. Examination of the boards after firing will show many hundreds of penetrations. However with a 200 mm thickness of water bags above the granite chips there will not be a single penetration of the hardboard screens and so the second part of the experiment can safely be tried at home.

Carbon combustion

Many explosives, TNT in particular, do not contain enough oxygen to react with all the other molecules and consequently an explosion generates a surplus of carbon in the form of a cloud of finely divided soot. Some of the energy in the soot cloud can still be useful if the carbon can take oxygen from air and act like a fuel-air explosion. This means that a negative oxygen balance is not regarded as a disadvantage. Alford (2000) has pointed out that the presence of water drops, water vapour and lower temperatures could interfere with the secondary carbon-oxygen reaction. This could provide yet another way for water to affect explosions. Evidence for this is that TNT explosions which have been suppressed leave behind very sooty water but relatively clean air. There are many electrostatic effects going on in an explosion and over short distances the forces between small, charged particles can be very strong. The water spray from a suppressed explosion is very effective at trapping the dust from a building demolition.

Practical structures

Suppression has now been tested with a wide range of charge weights and weapon casings up to a MK-84 Paveway bomb with a 2000 lb charge. Most of the practical work involves making a structure to contain and support a large weight of water without itself generating dangerous fragments. The experiments show that it is wrong to try to contain water in any structure which itself might tend to contain the explosion or to interfere with the outward movement of spay. We want to get intimate contact between explosion products and water as quickly as possible. Water bags made from layflat polyethylene tube are satisfactory provided that the welding is given careful attention. Even with a thickness of 250 microns they are sufficiently strong. I have seen a very fit, rugger-playing RLC major wearing steel-tipped combat boots viciously attack a water-filled bag to no effect. A tug-of-war team can drag a filled bag over rough gravel.

An uneven thickness of water allows more ejecta along the direction of the thinner covering so the ideal would be a spherical water volume centred round the charge. A more practical hemispherical covering over a ground charge will increase ground shock but this could perhaps be reduced by a surrounding ditch. The key problem has been to build water bag structures with height. It is possible to draw systems in which the skin tension defines the shape but it is very difficult to control the shape of a partly filled structure. A water bag can roll down imperceptible slopes and the incompletely filled structures can show maddening behaviour. Expanded polystyrene foam, glass-fibre tubes in the form of hollow rectangular beams, cling-film, nets and the cheapest domestic doors with an internal paper honeycomb filling placed edge on are all suitable supports because they disintegrate into very light particles. Boyer et al (2000) developed a neat basket made from geo-textile mat shaped like a hat with a high rim to support water bags and replicated the Shoeburyness trials with grenades and mortars shells.

For larger structures, Dell Explosives lay duplex water bags so that they straddle a block of expanded polystyrene like saddle-bags over a horse and then fill each bag through a hole at the top. This allows walls with overlapping bags and an airspace between them. Roofs can be made by laying saddle-bags over thin-walled, rectangular section hollow tubes long enough to act as roof beams. The combination of walls and roofs allows the construction of 'habitats' in which large weapons can be made safe in the knowledge that any unintended high-order event (which occurs at about 10% of disposals) will be safely contained within a much shorter evacuation distance than required for an unsuppressed explosion.

While fragment stopping suggests that complete water coverage is desirable close to a weapon casing, the reduction of the speed of sound in water-air mixtures suggests that it might be useful to include some air deliberately in the outer region of the water volume. Polyethylene bubble pack can be used but has an inconveniently large buoyancy. The most satisfactory construction for walls, now supplied by Dell Explosives, uses bales of straw cased in polythene bags made from layflat polythene tubing. The unfilled bales are very light, far lighter than filled sandbags, so that structures are quick to build round objects like the bases of wind turbines. Holes for water pipes are then stabbed through the upper surface of each wrapped bale to allow filling from a hose. Each bale can hold 100 kg of water. Additional structural integrity can be obtained by wrapping the walls with a belt of cling film. There is the further advantage that while it is tedious to clean up thousand of fragments of expanded polystyrene after a suppressed explosion, the straw residues are bio-degradable.

More permanent structures for long term storage of explosives in crowded sites can be made from polystyrene with water filled polythene inserts.

For the many hundreds of thousands of suppressions needed for the disposal of surplus munitions, even the consumption of polythene would be undesirable. We have designed and carried out initial small-scale testing of 'water mortars' resembling giant water-pistols driven by compressed air which would be placed in a ring. Twenty tonnes of water would converge from all directions just as the charge was fired and the cycle would be repeated every few minutes.

Conclusions

Water bags are now in service for explosive ordnance disposal and civilian demolition adjacent to valuable installations. The reduction is safety distances and evacuation numbers can provide large savings.

Water suppresses explosions by:

- The rapid cooling of explosion products because of the large surface area of spray.
- The reduction of sound velocity in water-air mixtures to a few tens of metres per second.
- The transfer of the momentum of a fast projectile to the entire water mass.
- The rapid rise of pressure on the outside of a fragmenting weapon casing.
- The increase of drag of fragments in water because of its higher density.
- The suppression of soot combustion in low oxygen explosives.

To put numerical values on the possible factors listed above we should try to measure the number, velocity, temperature and size-distribution of drops inside the expanding water-air mix.

Structures to contain water must not impede the rapid mixing of water and gasses. They must not themselves present any fragmentation hazard. Achieving height is the chief difficulty.

Polythene bags, expanded polystyrene foam, low-density domestic doors, nets, geo-textile baskets, hollow GRP tubes and straw bales in polythene are all suitable materials.

Water and straw are very cheap, rapid to erect with small teams and bio-degradable. For the continuous production-line suppression needed for disposal of unused weapons, large volumes of spray can be generated by water mortars.

The author hopes that water and water-bags with the right supporting structures will make life for both civilian and military explosives engineers much less exciting.

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