WHY IS WATER SO EFFICIENT AT SUPPRESSING THE EFFECTS OF EXPLOSIONS?

by Stephen Salter [University of Edinburgh] and John Parkes

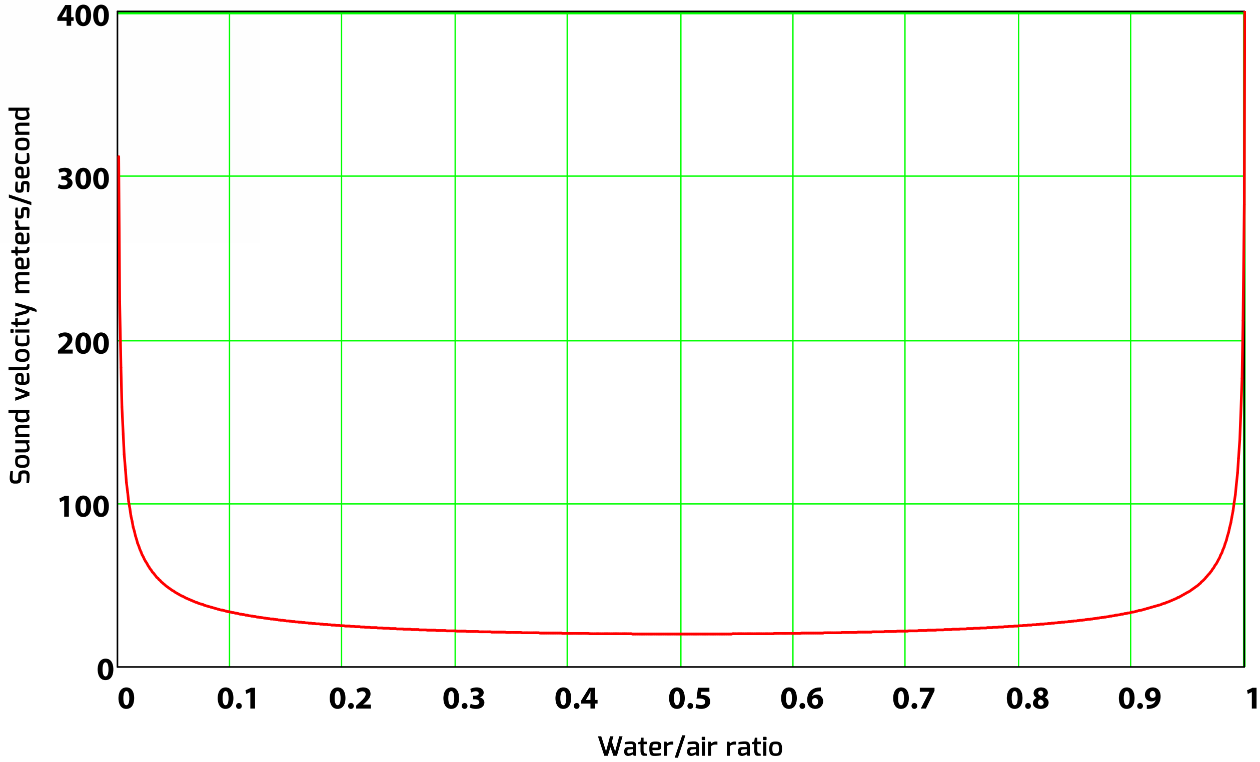

Figure 1. The speed of sound in mixtures of water and air as a function of the water/air ratio.
All graphics courtesy of the authors.

When most experienced explosives engineers first observe an explosion suppressed by bags of water, 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.[1] The number of fragments from shell cases can be one hundred times less. Their velocities can be seven times. Slugs from focal point charges are stopped. Safety distances around magazines can be cut. The number of people evacuated from a bomb disposal site can be reduced. In June 1999, engineers from 33 Regiment (Explosive Ordnance Disposal) saved an entire village in Kosovo from the detonation of a 2,000-pound NATO bomb by using water bags.

This article 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 also discussed.

HEAT

The latent heat needed to evaporate a kilogram of water is 2.25 megajoules. The explosive energy from 1 kilogram of TNT is 4.45 megajoules. Water is cheap and can be affordably placed weighing much more than twice its weight in 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 meter of water broken into 30 micron drops has a surface area of 200,000 square meters. This large area provides a splendid chance for evaporation. The exact rate of heat transfer cannot be known without knowledge of the distribution of drop diameters and their velocities relative to the surrounding hot gases. However, by making reasonable guesses, one 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 ten times on the absolute temperature 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 indicates 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 degrees Celsius has a rather high bulk modulus of 2.05 x 10^9 newton per square meter and a density of

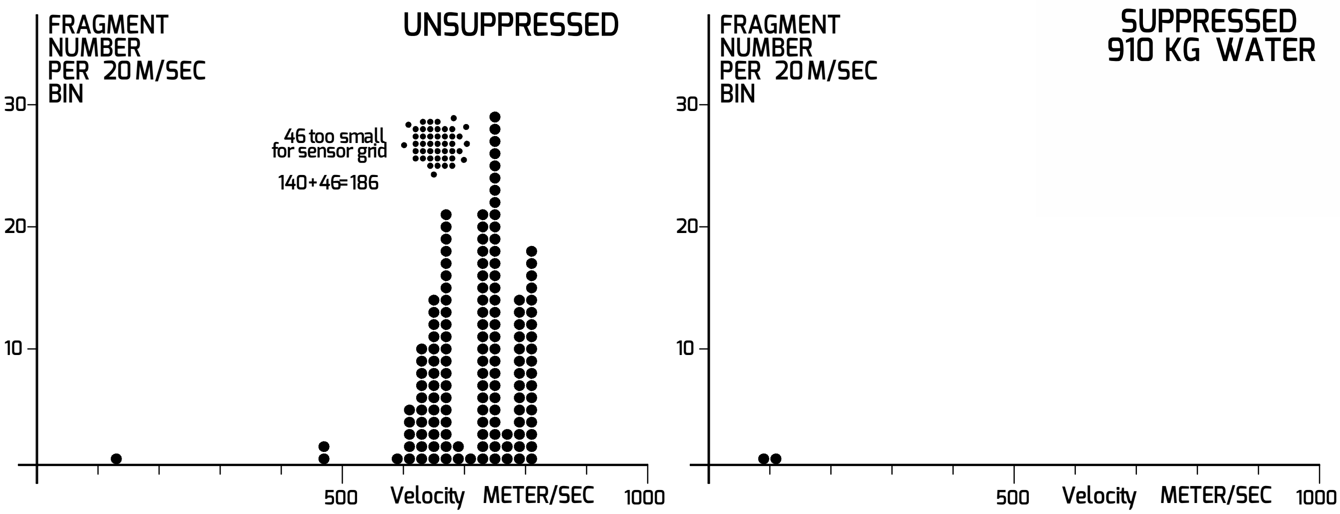

Figure 2. Fragment number and velocity from pairs of 155 mm M107 howitzer shells.

999 kilogram per cubic meter, giving it a speed of sound of 1,432 meters per second. At the frequencies of sound and explosive waves, the bulk modulus of a gas is given by its pressure times the ratio of its specific heat 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 kilogram per cubic meter giving it a speed of sound of 341 meters per second.

The speed of sound in a mixture of water and air is very interesting. A fifty-fifty mixture by volume would have double the bulk modulus of air (i.e., 283,640 newton per squared meter) and half the density of water (i.e., 499.5 kilogram per cubic meter).[2] This mixture would have a speed of sound of only 23.8 meters per 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.

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 that is considerably above the detonation velocity of the best explosives. The velocity is so high that a very thick armor 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 kilogram is approaching the target at 10,000 meters per second. The momentum is 1,000 kilogram meters per 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 100 kilogram mass of water, the water velocity needed to accept the momentum will be only 10 meters per second. The water behaves like the executive desktop toy known as Newton's cradle, which consists 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 a steel munition case round has just exploded. The enormous internal pressure causes cracks to appear between the munition's case and the neighboring fragment at places chosen by the shell designer to produce the most damaging effect. A much lower pressure outside the casing and the large pressure difference means that the case has to do some serious acceleration. Meanwhile, explosive gases with a high density under the same pressure gradient are pouring through the gap between the case and the neighboring fragments giving high aerodynamic drag forces to increase acceleration even further. The casing's shape is such that it will probably have a high drag coefficient.

Now imagine that the event is repeated with a large mass of water touching the outer wall of the case. As soon as the cracks open, the pressure in the water outside rises very fast and quickly approaches the pressure inside. With no pressure gradient, why should the munition 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 around the charge was incomplete and the round did acquire some velocity relative to the water around the munition case, the drag forces will be 800 times higher than if it were moving through air.

Parkes, Wilkinson, and O'Dwyer did experiments on howitzer shells at the Defence Research Agency (DRA) range at Shoeburyness using extremely sophisticated equipment for measuring fragment numbers and velocity. The results from two unsuppressed events at 6.05 meters range and two suppressed events at 4.5 meters range are shown in Image 1.[3] 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.

For both the unsuppressed shells, the velocity distribution shows three distinct clusters between 600 and 800 meters 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 meters per second. There were water bags

A pair of water bags mounted on a chip-board easel. The HB 876 has a self-forging fragment that is absolutely lethal and designed to knock out bulldozers as they attempt to fill in bomb craters on runways. The weapon functions when tipped over and sends the self-forging fragment through the bulldozer blade, engine, and the operator. The weapon carries many smaller "pea charges" for AP effect. In the trial, the fragment was actually shattered and its pieces were recovered from the ground at the foot of the range's safety blocks. No damage was occasioned to the blocks. Self-forging fragments are used in many roadside bombs and kill tanks and armored vehicles (and their crews) with ease.

around and above the shell but not below it. It is possible that the fragments that escaped had moved downwards and bounced off the ground. The base plate of an artillery shell must be thick enough to withstand the high breech pressure, and there are accounts of intact base plates being thrown over the heads of observers 1,800 meters away from a shell burst. In the Shoeburyness trials, broken base plates from 155 to 200 mm suppressed shells were found at the foot of the 18 millimeter 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 center. Examination of the boards after firing will show many hundreds of penetrations. However with a 200 millimeter 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. 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 has pointed out that the presence of water drops, water vapor, and lower temperatures could interfere with the secondary carbon-oxygen reaction.[4] This could provide yet another way for water to affect explosions. Evidence for this is that TNT explosions that have been suppressed leave behind 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 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 2,000 pound charge. Most of the practical work involves making a structure that can 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 that itself might tend to contain the explosion or to interfere with the outward movement of spay. Achieving intimate contact between explosion products and water as quickly as possible is ideal. 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. A fit, rugby-playing Royal Logistics Corps major wearing steel-tipped combat boots could viciously attack a water-filled bag to no effect. Similarly, a tug-of-war team could drag a filled bag over rough gravel without consequence.

An uneven thickness of water allows more ejecta along the direction of the thinner covering, hence a spherical water volume should be centered around 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 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 behavior. Expanded polystyrene foam, glass-fiber tubes in the form of hollow rectangular

Image 2. Saddle bag and polystyrene construction.

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. 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 mortar shells.[5]

For larger structures, Dell Explosives laid duplex water bags so that they straddled a block of expanded polystyrene like saddle-bags over a horse and then filled each bag through a hole at the top. The arrangement is shown in Image 2. This method 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 that are 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 around 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 kilograms 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 thousands of fragments of expanded polystyrene after a suppressed explosion, the straw residues are biodegradable. 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. A team at the University of Edinburgh designed and carried out initial, small-scale testing of water mortars resembling giant water pistols driven by compressed air that would be placed in a ring around a charge. 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 (EOD) and civilian demolition adjacent to valuable installations. The reduction in 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.
- Reduction of sound velocity in water/air mixtures to a few tens of meters per second.
- Transfer of the momentum of a fast projectile to the entire water mass.
- Rapid rise of pressure on the outside of a fragmenting weapon casing.
- Increase of drag of fragments in water because of its higher density.
- Suppression of soot combustion in low-oxygen explosives.

To put numerical values on the possible factors listed above, researchers should 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 glass-reinforced plastic (GRP) tubes, and straw bales in polythene are all suitable materials.

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

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

See endnotes page 63

As presented at the UK Explosives Mitigation Workshop, RCMS Shrivenham, 19 June 2002.

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John Parkes

John Parkes joined the British army in 1963 at the age of 17 and was promoted to the rank of sergeant at the age of 20 making him the youngest to hold that rank since the end of WWII. He carried out counter terrorist work in Aden in 1966–1967 and was in command of the Brigade's Engineer Support Troop. He has supplied bomb suppression equipment around the world and, in 1996, protection for the demolition of a railway bridge at Yaxley near Peterborough, which was 18 inches away from its replacement.

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