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Blast Mitigation by Water

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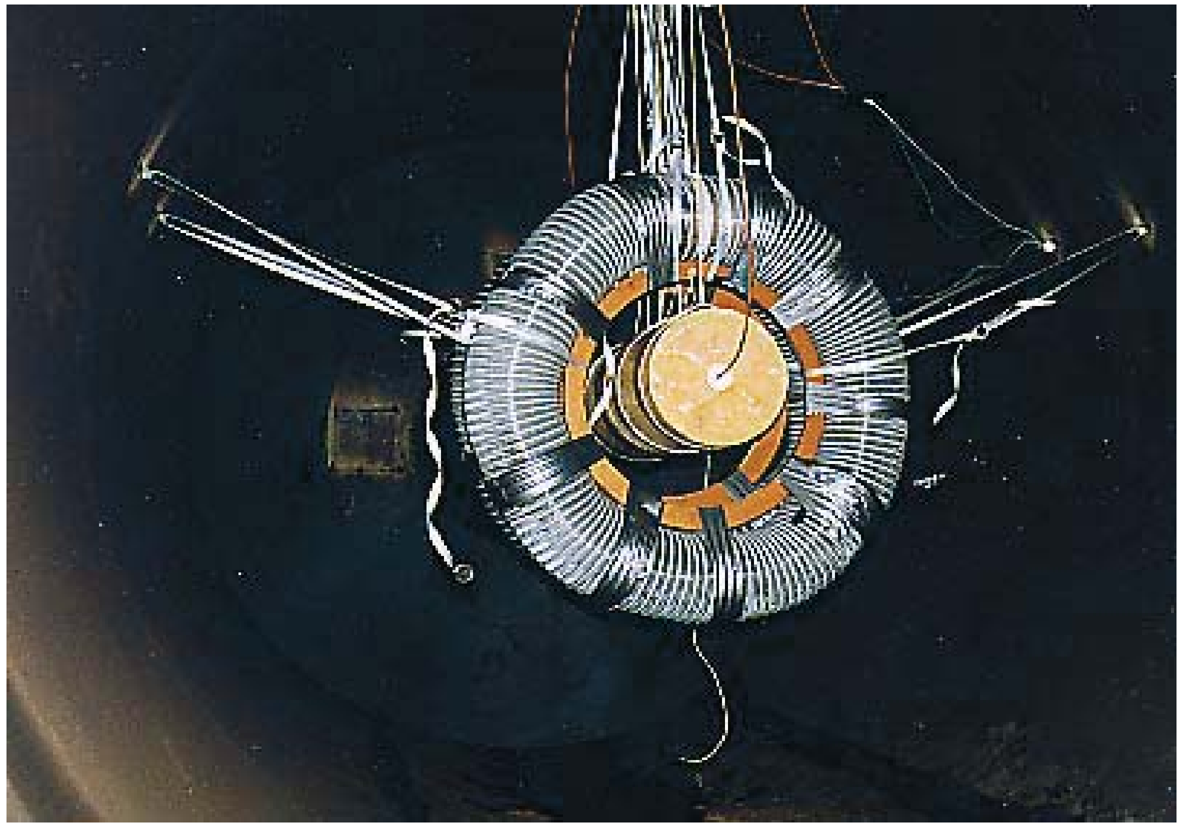

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BLAST MITIGATION BY WATER

Abstract

The water mitigation concept can be exploited in the design and operation of new and existing military facilities exposed to the threat of internal explosions, like ammunition handling and storage sites. It offers the potential for major savings in the cost for explosives safety of ordnance facilities from accidental explosions. In addition, the concept can be applied to the temporary storage of ammunition like is the case in Out-of-Area operations, e.g. during peace keeping missions.

In 1997, a co-operative research project was defined between FOA (The Swedish Defence Research Agency, since 2001 named FOI) and TNO-Prins Maurits Laboratory (PML, recently referred to as TNO Defence, Security and Safety) in The Netherlands, aimed at investigating the physics of water mitigation and to formulate instructions and standards of how to use water barriers. FOA/FOI was responsible for studying the effect of scaling laws and the influence of cased versus uncased charges, whereas TNO-PML was responsible for studying the influence of loading density, and the amount and location of the water for the mitigation effectiveness.

Keywords

Explosions, Pressure, Mitigation

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Dämpning av explosionstryck med vatten

Sammanfattning

Tekniken att dämpa explosioner med hjälp av vatten har en rad tänkbara tillämpningar för militära och civila anläggningar, t.ex. för att reducera riskområden vid ammunitionslagring i bergrum. Industriellt kan den även tillämpas för att reducera kostnader för erforderliga skyddskonstruktioner vid tillverkning och destruering av ammunition och sprängämnen. Ett aktuellt användningsområde är ammunitionsförvaring på camper i samband med internationella fredsbevarande insatser.

1997 inleddes ett samarbetsprojekt mellan dåvarande FOA (som 2001 uppgick i FOI, Totalförsvarets forskningsinstitut) och TNO - Prins Maurits Laboratory i Nederländerna (som numera benämns TNO Defence, Security and Safety), som syftade till att bättre förstå den fysikaliska bakgrunden till fenomenet samt att formulera standarder och rekommendationer för användningen av vattenbarriärer. FOA/FOI:s verksamhet inriktades på studier av skallagarnas giltighet samt att undersöka om höljesladdningar inverkade på fenomenet, medan TNO-PML främst studerade inverkan av laddningstätheten och vattenvolymernas storlek och placering för dämpningseffektiviteten.

Nyckelord
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Contents

1 Summary

Several experimental research programmes have indicated that explosion effects can be reduced by placing water in the vicinity of a detonating charge. Particularly, in case of a confined explosion, water has the potential to mitigate the shock pressure as well as the gas pressure loading developed inside the confining structure. This water mitigation concept can be exploited in the design and operation of new and existing military facilities exposed to the threat of internal explosions, like ammunition handling and storage sites. It can also be applied in sensitive facilities, thereby increasing the physical security of these facilities against terrorist bombings. In short, it might be a very practical, useful, cost effective concept for a very broad range of applications. Some of the advantages of using water are:

- that water is cheap and readily available in most cases;
- that the amount of water can be easily adapted to the explosive weight;
- and that it does not have large logistics demands, since it only requires the transport and storage of empty bags.

In 1997, a co-operative research project was defined between FOA (The Swedish Defence Research Agency, since 2001 named FOI) and TNO-Prins Maurits Laboratory (PML, recently referred to as TNO Defence, Security and Safety) in The Netherlands, aimed at investigating the physics of water mitigation and to formulate instructions and standards of how to use water barriers. TNO-PML focused their research on the spatial and temporal distribution of the different energy terms involved, and the influence of different parameters, e.g. the water-to-charge ratio and standoff distance, on the water mitigation effect. FOA/FOI has performed experimental and theoretical work to investigate the scaling laws for the water mitigation phenomenon, focused on mitigation effects for high loading densities in confined or almost confined spaces, and also on eventual effects from the casing of the exploding charges.

Some significant results from the performed experiments and analyses are:

- in small scale tests existence of the water mitigation effect was confirmed: in a closed vessel a maximum reduction in QSP (Quasi-static gas pressure) of about 80% was found;
- the reduction in QSP is increased when the *water-to-charge ratio* (w/e) is increased. The reduction shows an asymptotic behaviour and the highest reduction of 85% is found for w/e ratios larger than 5;
- no major deviation from simple Hopkinson scaling laws was observed;
- no reduced mitigation effect for tests with cased versus uncased charges was observed;
- at least 60% mitigation was observed at high loading density, 10 kg/m^3;
- the mitigation effect is sensitive for an increased ventilation area (A) of the confinement volume (V); it almost disappeared for $A/V^{2/3} = 0.4$.

2 Introduction

Several research programmes (Eriksson 1974, and Eriksson and Vretblad 1994) have indicated that explosion effects can be reduced by placing water in the vicinity of a detonating charge. Particularly, in case of a confined explosion, water has the potential to mitigate the shock pressure as well as the gas pressure loading developed inside the structure confining the explosion.

In case a high explosive detonates, a high pressure blast wave will be generated which moves outward in all directions. When the detonation takes place in a confined structure, due to the high temperature of the detonation gases, a pressure build-up inside the structure will take place. The magnitude of the peak gas pressure depends primarily on the charge weight (TNT equivalent) relative to the volume of the structure. The duration and total impulse of the gas pressure depends primarily on the degree of venting. From experiments it has been found that the blast pressure as well as the gas pressure can be reduced by placing water in plastic bags or containers next to the detonating charge. When the blast wave strikes the rupturable container the water will be aerosolized. It is assumed that the fine mist of water droplets prevents access to oxygen and cools down the gases, preventing a further combustion of the detonation products. In fact, a large part of the detonation energy will be dissipated by changing the water mist from liquid to vapor state, thereby absorbing detonation energy from the explosive. As a result, the blast overpressure and impulse, as well as the peak gas pressure and total gas impulse will be much lower than it would have been in case of the absence of water. Test results have demonstrated that, by placing water in the vicinity of the charge, the peak gas pressure and total gas impulse from a confined explosion can be reduced by up to 90%. It has been suggested (Eriksson, 1995) that a water supply of five times the charge weight, is equivalent to a reduction of the charge weight to approximately one-fifth when it comes to the blast. Since the gas pressure and impulse are mainly responsible for the high launch velocity of building debris and the maximum strike range of hazardous debris, smaller safety distances around storage facilities may be acceptable when employing the water mitigation concept.

Most tests conducted up to now, have been executed on relatively small scale involving bare charges of less than 100 kg of TNT, all indicating a significant mitigation effect by applying water. A large scale test involving the detonation of 1000 kg of TNT of ammunition and 2000 kg of water in a 75-m long tunnel, conducted at Älvdalen (Sweden) in 1996, however, showed only a minor reduction of the explosion effects (Forsen, Hansson and Carlberg, 1997). Hence, one goal of this survey is to confirm that the water mitigation concept also works at full scale and is not limited to small amounts of explosives.

Not all of the physics of water mitigation is well understood today, since inconsistent experimental results were obtained at different scale. Because of its complexity, it is not yet possible to provide an exact description of the different physical phenomena involved. The aims of this investigation can be summarized as:

- to investigate and understand the mechanism by which water absorbs energy from a confined explosion and how this phenomenon reduces the gas pressure loading from a confined explosion;
- to formulate instructions and standards of how to use water and how to calculate equivalency factors of masses of High Explosives when water is used;
- to investigate whether there exists a limit to the loading density Q/V for which a significant mitigation effect can be obtained.

Partnership between TNO and FOA/FOI

In 1996 a Memorandum of Understanding (MoU) was signed between FOA/FOI and TNO-PML in order to facilitate co-operation concerning defence research between Sweden and The Netherlands.

The current project, which is concerned with the use of water to mitigate the effects of accidental explosions in storage or other handling of high-explosives or ammunition, was executed within the framework of this MoU. Each country (Sweden and The Netherlands) has invested about 100 kEuro in the project over a minimum period of two years.

Background and historical review

In 1974, Eriksson was the first to show that the strength of the blast wave can be reduced by placing water in the vicinity of a detonating charge. A charge weight of up to 0.5 kg was used in the tests, with a loading density of up to 0.1 kg/m^3. A reduction of more than 50% in peak overpressure was found in case the water supply was 5 times the charge weight.

In 1991, several High Explosives tests were conducted at the Naval Surface Warfare Centre (Carderock Division US Army). These tests were designed to measure the benefit of constructing High Performance Magazines employing water-filled walls. These tests, conducted with up to 2 kg of TNT on 1/12th scale models of the storage cells, demonstrated that water can reduce the peak gas pressure and total gas impulse from a confined explosion by as much as 90%.

Keenan and Wager (1992) described the principle of how water mitigates the gas pressure loading developed inside the structure confining the explosion. In broad outline, their vision is given in the introduction. They further show how this phenomenon can be exploited in the design and operation of new and existing ordnance facilities exposed to a potential internal explosion. One possible way for deploying the concept is a water blanket which can be draped over the top of a pallet of ordnance. After the blanket has been ruptured by the shock wave, the water will be aerosolized, thereby allowing the water to absorb huge amounts of energy by vaporizing the water droplets.

Keenan and Wager (1992) further reason that the utility of the water concept is expected to diminish with an increasing ratio of net explosive weight to structure volume (Q/V). At high Q/V, first, there is insufficient space to accomodate the volume of explosive and water; and secondly, there is insufficient space inside the structure to allow the shock waves to aerosolize the water. Hence, they suggest that there is an upper bound of Q/V which defines the limit for the useful application of the water concept.

In 1994, tests have been performed with different explosives (balanced as well as underbalanced with respect to Oxygen) with a weight of up to 100 kg of TNT at different loading densities (0.1 - 4 kg/m^3) and with different additives, e.g. water, glycol and foam (Eriksson and Vretblad, 1994). These tests confirmed that water has a mitigation effect, and that the reduction in pressure works for both balanced as well as underbalanced agents. Furthermore, it proved to be independent of the loading density in the range tested and the degree of reduction showed to be dependent on the distance of the water bags to the charge. The effective charge was reduced by more than 50%.

In 1995, the British firm DELL Explosives patented a blast and splinter proof screening device, which is a liquid-filled rupturable flexible containment device which should be placed close to the explosive to reduce the effect of a detonation (Patent F42D 5/045). It can be used in the control of debris from building demolition, the disposal of munitions and unexploded weapons, and the suppression of terrorist bombs. For instance, the water bags can be quickly erected around a car as a protective shield to limit the effects of a subsequent explosion.

In 1995, some tests were conducted in the U.K. aimed at investigating whether the commercially available waterbags by the firm DELL Explosives can be used to reduce the explosion effects of a demolition set containing about 10 kg of explosives. The British EOD uses this set for the disposal of sea-mines. The investigation showed that the overpressure could be reduced by about 90% and that fragment distances were reduced. It has been suggested by Dutch EOD-personnel who visited the trials, to apply this technique during disposal operations of large GP bombs (e.g. 500 lbs-bombs) (Vermeulen, 1996).

In 1996, a large scale test was conducted by FOA/FOI at Älvdalen, sponsored by the KLOTZ-Club and Singapore. A total number of 180 15,2 cm artillery shells (5.5 kg TNT each), with a total charge weight of 1000 kg of TNT, were detonated in an explosion chamber attached to a 75 m long tunnel. In the vicinity of the charge 2000 kg of water was placed. The loading density in the explosion chamber was 3 kg/m^3. The pressure, ground shock and debris out-throw was recorded. The experiment was a repetition of an experiment executed in 1989, performed without water. The test with water added showed a minor reduction in pressure inside and outside the tunnel, in the vicinity of the entrance. At larger distance from the entrance, however, somewhat higher pressures and impulses were measured. The fragment density outside the tunnel was lower with water added, as expected.

Prior to the large scale test, a small scale test series (with a loading density of approx. 5 kg/m^3) had been conducted in the 1/20th scale model of the tunnel in Älvdalen (Forsen, Carlberg and Eriksson, 1995). The effect of the heat capacity of an agent, the water to explosive weight ratio, and the distance of the water to the charge was investigated. The small scale experiments indicated a much greater reduction in peak pressure and impulse both inside and outside the tunnel than was found in the large scale test.

In 1997 and 1998, at the Naval Facilities Engineering Service Centre in the US, small-scale tests were conduct to establish basic parametric relationships (Malvar & Tancreto, 1998). In addition, numerical simulations were made with hydrocodes to identify the best numerical models for prediction of the effects. The models need to account for such phenomena as heat absorption through phase change of the water, water dispersion, mixing and heat conduction between materials in various phase states, and combustion in the presence of oxygen for oxygen deficient explosives. Results are very encouraging, both for adequately predicting water mitigation effects and for the effectiveness of water mitigation even when venting reduces the internal gas pressure effects.

Lottero (1998) of the Aberdeen Proving Ground, Army Research Laboratory, describes the numerical modeling of the detonation of a simplified munitions stack, a “donor stack”, in a temporary storage area and the subsequent effects on the immediate surroundings of the stack, e.g. a water barricade and an “acceptor munitions” stack. The CTH hydrodynamics computer code was used for that purpose. The loading on and pressures within the barricade have been computed, as well as the whole body motion of the barricade.

Problem definition

The large scale test conducted in Älvdalen (Sweden) yielded somewhat disappointing results, and did not confirm the results from the small scale tests. This deviation might be explained by the differences between the small scale and full scale tests:

- different scale, i.e. the up-scaling of the water mitigation effect is questionable;
- imperfect scaling, e.g. the small scale experiments were made with uncased charges whereas in the large scale test, cased shells were used. Also the wall roughness of the large scale rock tunnel was not modelled in the small scale tests;
- the loading density (Q/V) in several small scale experiments was about the same as in the large scale experiment, based on the total charge weight. Considering the fact that a cased charge results in a lower pressure than an uncased charge, it should be accounted for the reduced weight of High Explosives in the full scale experiments, which results in a lower loading density. A comment made during the KLOTZ-Club meeting at Gulfport (Oct. 1996) was that the mitigation effect of water then decreased for this specific water-to-charge arrangement;
- during the first experiment in 1989 there may have been a significant amount of water on the floor of the tunnel due to cracks in the rock, which must be accounted for;
- different measuring techniques were used in 1989 and 1996, which might have influenced the accuracy of the pressure-time recordings.

Obviously, the water mitigation effect is so complex that a fundamental approach to the problem is needed to fully understand what the exact reduction mechanism is and what parameters play a major role in the process.

Based on previous investigations, the following important issues were identified and investigated in the present study:

- the scaling laws of experiments;
- the difference when using uncased High Explosives as compared to cased charges, such as ammunition;
- the influence of loading density, charge to water ratio, and charge to water distance on the mitigation effect.

Objectives
Not all of the physics of water mitigation is well understood today, since inconsistent experimental results were obtained at different scale. Because of its complexity, it is not yet possible to provide an exact description of the different physical phenomena involved. The aims of this investigation are:

- to investigate and understand the mechanism by which water absorbs energy from a confined explosion and how this phenomenon reduces the gas pressure loading from a confined explosion;
- to formulate instructions and standards of how to use water and how to calculate equivalency factors of masses of High Explosives when water is used;
- to investigate whether there exists a limit to the loading density Q/V for which a significant mitigation effect can be obtained.

The research conducted by FOA/FOI and TNO within the framework of joint research was reported in 4 separate papers, presented at the 28th and 29th Explosives Safety Seminar. These papers are included in this report as Annex A to D. In the main report the work conducted is described in Chapter 3. A discussion on the physical phenomenon of the water mitigation is given in Chapter 4. Guidelines for the use of water as mitigating material are given in Chapter 5 and applications are described in Chapter 6. Finally some conclusions will be drawn in Chapter 7.

3 Description of work

The joint research consisted of a combined theoretical and experimental study. The project was divided into the following two phases:

1. Fundamental research

The first phase was aimed at understanding the physics of water mitigation. Basic energy balance calculations using thermodynamic laws were applied, to get some idea about the balance between detonation and evaporation energy. This also gave some indication of the optimum ratio of charge-to-water weight. More elaborate computer codes, like the hydrocode AUTODYN, were used to study the water mitigation process in detail.

Next, available data were evaluated, validating the developed understanding of the physics of the mitigation process. Based on existing data, insight was provided into the parameters that mainly influence the mitigation effect. Most of the experimental data were provided by FOA/FOI. This led to a better understanding of the physics and the identification of knowledge gaps.

2. Experimental set-up

New scale experiments were performed to validate the understood physics and to eliminate the knowledge gaps.

Scaling: well-defined experiments were conducted at different scale.

Cased charges: well-defined experiments were conducted at small scale to study the influence of cased charges versus bare charges.

Loading density: well-defined experiments were conducted at small scale with a systematic variation of the loading density.

This research was combined with a theoretical approach and computer calculations. Based on these experiments, guidelines were developed of how to use water as mitigating material.

Overview of work packages

In the following the tasks will be summarized.

FOA/FOI was responsible for:

- studying the effect of scaling laws and
- studying the influence of cased versus uncased charges,

whereas TNO-PML was responsible for:

- studying the influence of loading density on water mitigation.

Each of these subjects was subdivided into the following tasks:

1. Fundamental research:
    - investigate the physics of the phenomenon;
    - validate the understanding of the physics by evaluating available data.

   Results: - understanding of the physics;
   - identify knowledge gaps.

2. Experimental set-up:
    - experimental validation of understood physics;
    - experimental and theoretical programme to eliminate knowledge gaps.

More specific description of work TNO-PML:

- 1995-1996 preliminary tests at small scale: to confirm the existence of the water mitigation effect;
- 1997 Literature survey; to inventory the given explanations for the mitigation effect found;
- 1997-1998 The thermodynamics codes CHEETAH and TIGER were used to get some idea about the relation between the different thermodynamic parameters (e.g. gas pressure, density and temperature);
- 1998 Computer simulations have been made with the hydrocode AUTODYN to reach a better understanding of the phenomenon. Dynamic aspects of shocks and detonation were modelled, like the spatial distribution and time development of many parameters, the propagation of shocks and the interaction with water and steel objects for different mass, distance to charge and surface blockage area.
- 1999 An experimental parametric study was conducted. Tests were conducted in two 1 m diameter, 1.3 m long cylindrical explosion chambers, one closed and one provided with a 25 cm diameter duct. The last vessel is similar to the one used by FOA/FOI. For a bare charge of 200 gram of HE with a length-to-diameter ratio of 3, the amount of water, the water stand-off distance and the capturing angle was varied, resulting in a total of 39 tests. The blast as well as the quasi-static pressure was measured inside the explosion chambers. From the measurement results guidelines for the use of water barriers could be derived.
- Attempts were made to visualize the break-up of water-filled containers under blast loading using X-ray.

More specific description of work by FOA/FOI:

- 1996 A literature search was made and results from earlier tests made by FOA/FOI and the Klotz Club were studied;
- 1997 A simple numerical model including two-phase EOS for water was suggested to predict the shock flow inside and outside a duct or tunnel attached to an explosion chamber. Pilot tests were made with an explosion chamber, 1 m long and 0.7 m in diameter, with an attached duct, 2.8 m long and 0.25 m in diameter. The tests were made with 1.5 kg cylindrical PETN charges, both uncased and cased with hollow 4.5 kg pre-fragmented steel cylinders. 3 kg water was arranged around the charges, i.e. the used water to explosive ratio (w/e) was 2.
- 1998 The small scale study was continued with the same geometry but with increased loading density. Successful measurements were made at 10 kg/m^3 with w/e= 2. Tests with the w/e ratio 5 were made at 4 kg/m^3 as well as with an increased ventilation area by a factor 4 and with w/e=2. Tests with the water replaced by other agents (steatite powder and carbon-tetrachloride) at the same weight ratio 2 were also performed.
- 1999 Tests were performed in a 3 times up-scaled specimen, similar to the geometry above with an explosion chamber volume of 10.8 m^3 with 40 and 100 kg explosives inside, in both cases with w/e=2.
- After 2000 the work has continued at somewhat lower intensity. Efforts have been made to study the break-up of water with rapid-filming and X-ray flash photography. Tests have been conducted with a new small-scale model similar to the test site in Alvdalen in which the roughness of the rock tunnel was modelled.

4 Discussion on the physics of water mitigation

The most commonly accepted explanation for the experimentally observed effect of the mitigation of a blast wave by water has been given by Keenan and Wager (1992). In their article they state that when the blast wave resulting from the explosion reaches the water, being contained in bags or plastic containers, these casings as well as the water will be fragmented, transforming the water into an aerosol, a mist of tiny water droplets. The aerosol will mix with the hot detonation gases. As a result of the heat transfer between the gases and the aerosol the water will evaporate, the gases will cool down and the gas pressure will decrease. A second effect, mentioned by Eriksson and Vretblad (1994), is that due to the lower temperature also no afterburning of the detonation products will occur with the oxygen, present in the air, and therefore no extra temperature and pressure increase of the gases will occur. Therefore, both the cooling down and the avoidance of afterburning result in a lower gas pressure, hence in a lower load on the construction. A third proposed mechanism is the transformation of the explosion energy into kinetic energy. Just like the casing of a munition article will absorb a considerable fraction of the detonation energy in the form of kinetic energy, also water containers, placed around the charge, can acquire much kinetic energy and thereby reduce the internal energy and pressure of the blast wave.

The description given above of the blast mitigation effect by water evaporation has been questioned. As remarked earlier by Eriksson and Vretblad (1994) the evaporation of water not only results in a decrease of the gas temperature and therefore a decrease of the partial gas pressure of the detonation products, but of course also produces water vapour, thereby increasing the pressure. But this partial pressure can easily be shown to be of minor importance by a simple thermodynamic calculation of a mix of hot High Explosive gases and water, reaching thermal equilibrium in a confined space. Such a calculation, using the detonation energy of the High Explosive, the general gas law, a table of heat capacity and C_p/C_v for different gases together with a table of pressure, volume and internal energy for water shows that, although a certain partial pressure do occur from the water vapour, the overall pressure is still largely reduced. This is due to the fact that the value of heat capacity for water is 4-5 times higher compared with the agents in common combustion products from a detonation (soot particles and gaseous CO, CO_2, N_xO_y, etc.).

It has also been questioned whether an important fraction of the energy, liberated by the detonation, can be used to evaporate water and whether such an evaporation process can occur within a short timeframe. It therefore seems unlikely that an evaporation process can account for a considerable reduction of the gas pressure. This, however, neglects the fact that the water does not need to be vaporized to absorb energy from the HE gases. As soon as the break-up into fast moving droplets occur, the water amount largely increases its total surface area which effectively absorbs energy from the HE gases due to heat conduction. Recent rapid-film recordings made by FOI shows that the break-up occur within tens of microseconds in small scale tests (0.2 kg of explosives) i.e. the water must be aerosolized within milliseconds also in large scale with a suitable geometry, provided that scaling laws are relevant. Obviously, some of the physics involved is not in accordance with simple scaling laws, e.g. the surface tension of water. From an energy perspective, such effects are believed to be of minor importance except for very small amounts of water and explosive.

The vaporizing might as well be delayed in a confined space by the high pressure, as water can remain in liquid phase at temperatures up to its critical point: 374 deg Celsius at 2.2 MPa. Also, water in gaseous phase still has a higher heat capacity than the detonation products i.e. it only contributes to a small degree to the pressure built-up in a confined space, while the water in liquid phase (droplets) continues to reduce the pressure by absorbing energy.

Afterburning of detonation products can for some explosives, as notably TNT, produce a considerable amount of extra energy but the avoidance of the liberation of this amount of energy is by far not enough to explain the experimentally observed mitigation effects of up to 90 %, see e.g. Chapter 3. Besides, afterburning can only occur if enough oxygen is available and if the temperature is high enough. Both conditions can not be fulfilled at the same time. The detonation gases will have to expand strongly in order to mix with a sufficient amount of oxygen. During the expansion the temperature of the gases will rapidly decrease by a value of several hundred centigrades. At these temperatures no afterburning will occur. In practice afterburning of detonation products only occurs in the first stage of the expansion and only at the interface of the detonation gases with the air. Although it creates a very spectacular effect the extra energy it supplies is usually negligible. Furthermore, if such an effect would occur, a clear difference should be observed between an explosive as TNT, with its very high oxygen deficiency, and other explosives that have a much lower oxygen deficiency. Experimentally such a difference has not been observed (Eriksson and Vretblad 1994).

The third proposed mechanism, the transformation of energy to kinetic energy of the water, is of course a valid one. A detonation will accelerate all materials in its immediate neighbourhood and the corresponding kinetic energy will come at the expense of the energy of the detonation products. Whether this effect can quantitatively describe the observed mitigation results will have to be further examined.

5 Guidelines for usage of water mitigation

From the parametric study reported in Paper 3, the following guidelines for the use of water mitigation in confined space and the influence of the different parameters on the reduction of Quasi-Static Pressure (QSP) could be drawn.

- the small scale tests confirmed the existence of the water mitigation effect: in the closed vessel a maximum reduction in QSP of about 80% was found;
- the reduction in QSP is increased when the *water-to-charge ratio* is increased. The reduction shows an asymptotic behaviour and the highest reduction of 85% is found for water-to-charge ratios larger than 5;
- the QSP reduction is slightly increased when the *stand-off distance* of the water barrier to the charge is decreased. Overall, the stand-off distance was found not to be very critical;
- the *weight of the charge* did not have a large influence on the percentage QSP reduction, achieved with the same water-to-charge ratio and stand-off distance. It should be noted that the tests were conducted with relatively small charges;
- when TNT instead of DM12 was used, a lower QSP reduction was found, however, this variation in *type of explosive* only showed to have a minor effect on the mitigation;
- the *degree of enclosure* of the water barrier was also found to have an influence on the QSP reduction. As compared to the full enclosure, a 65% degree of enclosure showed a 15% lower QSP reduction. Hence, the optimum QSP reduction is achieved when the charge is fully enclosed by the water barrier;
- greatest reduction was found for the *full confinement* experimental set-up.

From the tests with partially confined charges reported in Papers 2 and 4, the following results can be derived:

- no major deviation from simple Hopkinson scaling laws was observed for tests with charges varying between 1.5 up to 100 kg of explosives. However, not likely to occur, such effects cannot be excluded when very large amounts of ammunition explodes;
- no reduced mitigation effect for tests with cased versus uncased charges was observed;
- at least 60% mitigation effect on the QSP was observed at the high loading densities 4 and 10 kg/m^3 with scaled ventilation area $A/V^{2/3}$ = 0.1.
- a severe reduction of the mitigation effect occurred when the scaled ventilation area was increased from 0.1 to 0.4.

6 Possible Applications of Water Mitigation Concept

Obviously, the water mitigation concept can be exploited in the design and operation of new and existing facilities exposed to a potential internal explosion, like ammunition storage facilities (see Keenan and Wager, 1992). The water concept offers the potential for major savings in the cost for explosives safety of ordnance facilities from accidental explosions. Particularly, when unhardened facilities as normally used for the production, maintenance and repair of weapons are considered. In addition, the concept can be applied to the temporary storage of ammunition like is the case in Out-of-Area operations, e.g. during peace keeping missions. However, the use of water blankets on top of ammunition pallets or hanging on the ceiling above stored ammunition needs a revolutionary change in mindset of the responsible military ammunition officer, since water and ammunition are often seen as a bad combination.

The water concept can also be used to increase the survivability of combat facilities, like command and control centers. In case an enemy weapon perforates the structure, the detonation of the warhead may result in a fully confined explosion, developing a gas impulse that might destroy the whole facility, comprised of several separate cells. By providing the ceiling or walls of the facility with water blankets, the peak gas pressure and total gas impulse can be reduced, limiting the direct effects to just one cell and increasing the survivability of the structure.

The water concept can also be applied in sensitive facilities, thereby reducing the physical security of these facilities against terrorist bombings.

Furthermore, the water concept can be used to enhance the safety and capability of EOD teams when transporting explosive devices, e.g. to disposal sites. Water bags can be installed in the transporting device or water blankets placed over pallets of ordnance to reduce possible explosion effects. Such protective measures can also be taken to explosives confiscated by the police or for the transport and temporary storage of explosives used for demolition work.

The advantages of using water are:
- that water is relatively cheap and readily available in most cases;
- that the amount of water can be easily adapted to the explosive weight;
- and that it does not have large logistics demands, since it only requires the transport and storage of empty bags.

So, it might be a very practical, useful, cost effective concept for a very broad range of applications.

Some typical conceptual ideas of applications of the water mitigation concept will be given in the following:

Applications for ammunition storage/transportation

Keenan and Wager (1992) have suggested the use of "water blankets", as shown in Figure 1, to reduce the explosion effects in the event of the mass detonation of a stack of ammunition. This concept has been studied in the US.

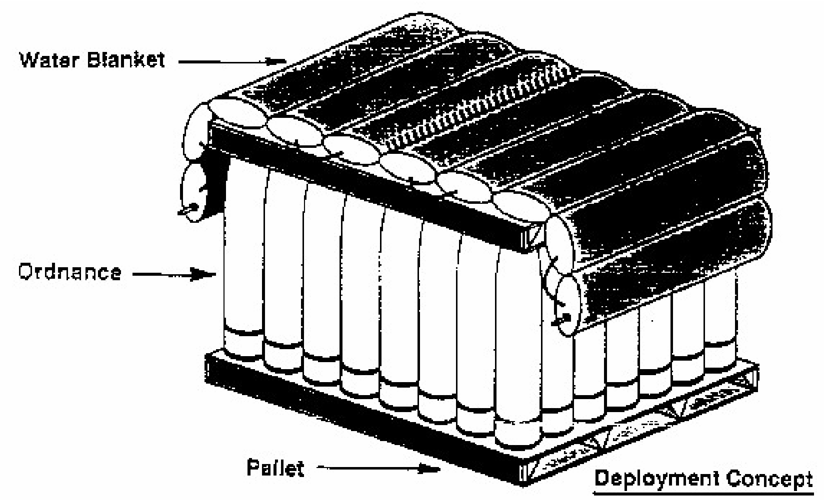

Figure 1 Concept of water blanket for shielding of pallet of shells

In October 2002 a large explosion trial was held in Woomera, South Australia, in which TNO participated together with research organisations and MoD from the UK, Australia, Norway, Singapore and the US (Van Dongen, 2003). The overall goal of the test was to develop new guidelines for the safe storage of ammunition and explosives in a military Out-of-Area compound. One of the sub-goals was to investigate sympathetic detonation, and means to prevent this. Several different barriers between the 5-tonne donor container, filled with 5 tonne TNT equivalent 88 mm grenades, and 4 surrounding acceptor container, filled with live acceptor ammunition, were tested, see Figure 2 for a view of the test set-up. Three out of the four barriers were conventional sand-filled barriers, and one was water-filled. None of the live acceptor ammunition was activated in the trial, indicating that all 4 barriers prevented sympathetic detonations. The concept of the water barrier worked overall as good as the sand-filled barriers. Hence, water filled barriers might be a good alternative for design of an ammunition storage site, when there is a shortage in sand.

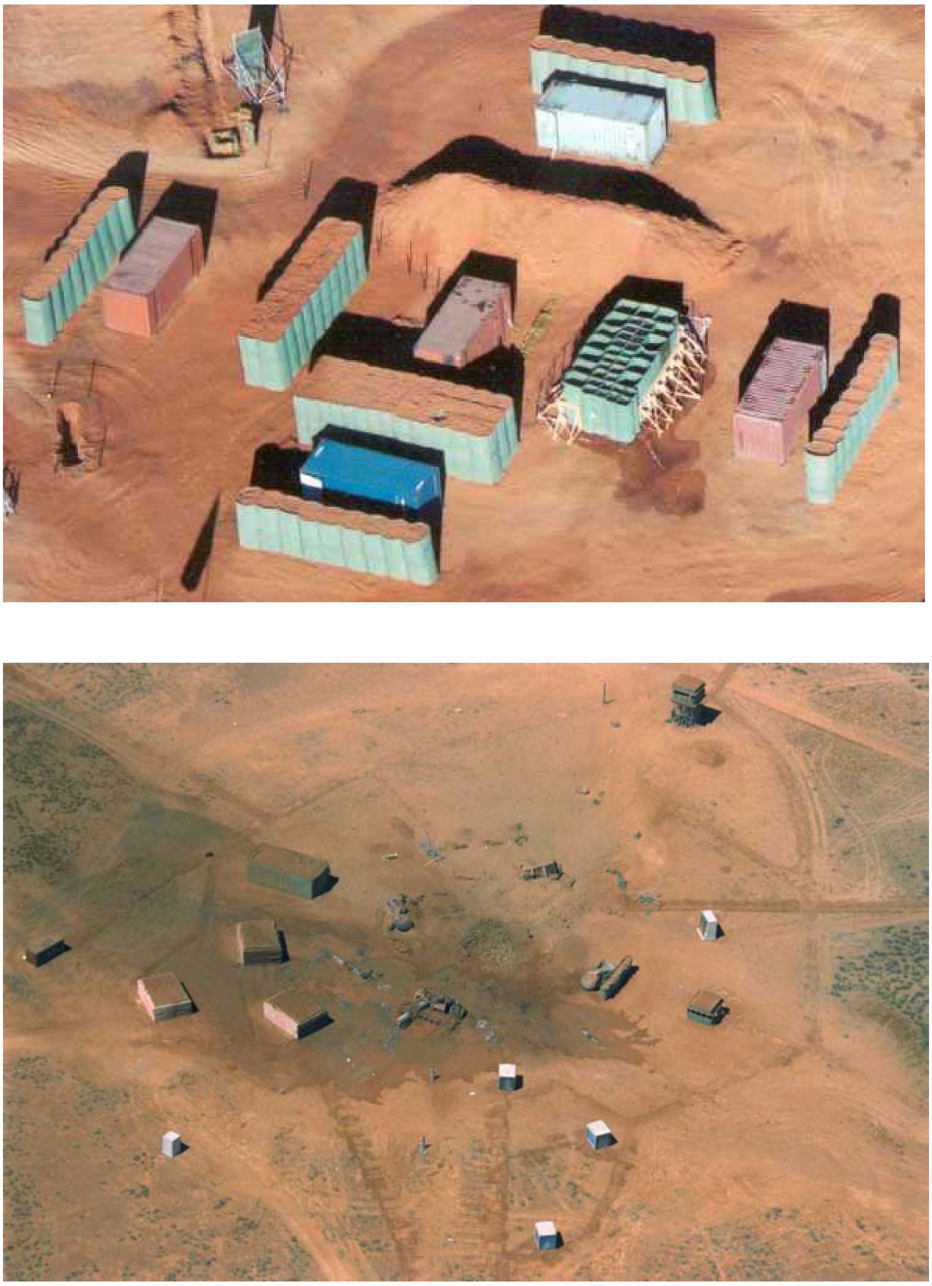

Figure 2 The donor-acceptor set-up of the 5-tonne trial, with the water barrier on the right, next to the donor container.

Applications for protection of vulnerable or explosion sensitive structures

The survivability of structures, like underground bunkers, can be enhanced by hanging water blankets to the ceilings of the rooms. Keenan and Wager (1992) have drawn this principle in Figure 3, showing an underground bunker hit by a penetrating weapon. The water mitigation concept will limit the damage to the room hit, and will significantly reduce the damage in neighbouring rooms.

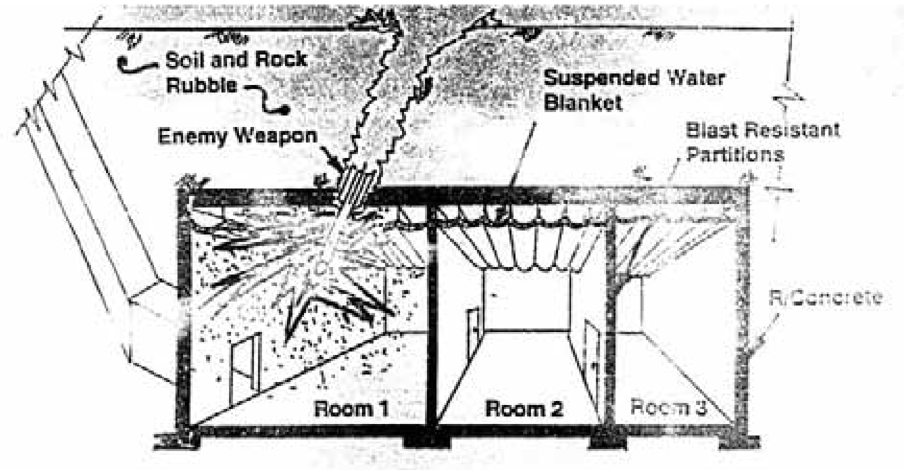

Figure 3 Concept of water blanket suspended from ceiling to enhance the survivability.

In analogy, water pillows can be used in ammunition work shops to reduce the explosion effects in case of accidental explosion of a missile, see a conceptual design in Figure 4, by Keenan and Wager (1992). By applying the water pillows the explosion effects can be limited to the test cell.

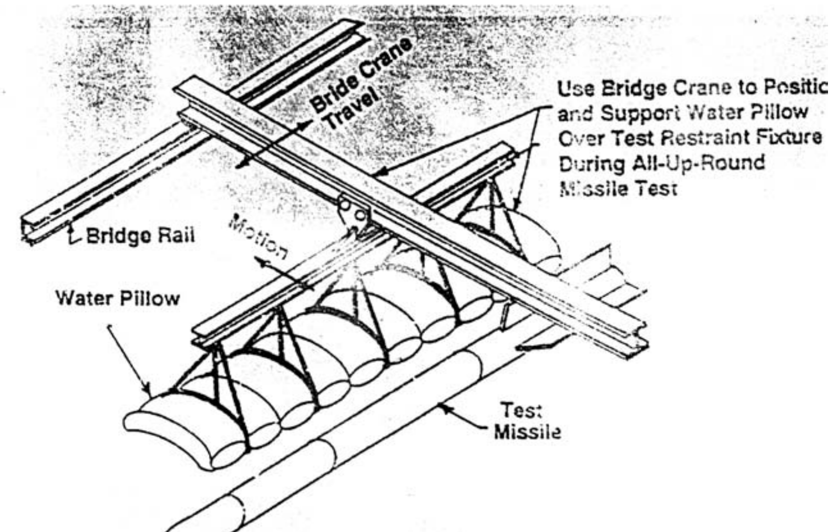

Figure 4 Concept of water pillow deployed above test missile.

In various countries, e.g. US, UK, GER and NL, research is ongoing in enhancing the survivability of ships against incoming missiles and torpedoes, using the water mitigation concept. For this scenario a very fast water mist generator is needed to activate the water storage containers in the ship compartment where the missile impacts. Tests have been conducted with cold gas generator technology, but also with small explosive charges that have been activated by the flash of incoming torpedo. Since most of these systems are still under development, not much information is available in open literature yet, but the concept is very promising.

Water barriers can also be used to protect expensive vulnerable structures like military aircraft, as shown in Figure 5. Military aircraft when parked on an airfield need large safety zones when loaded with weapons, which may explode by accident. The required safety zones can be reduced by placing barricades next to the airplanes. The use of water-filled plastic containers is suggested by Dell Explosives, which allow easy entry of shell-fragments and allow easy aerosolisation of the water under blast shock attack. Willcox (1998) has described various guidelines on the required thickness of the water layer to reduce the velocity of fragments of various HE munitions.

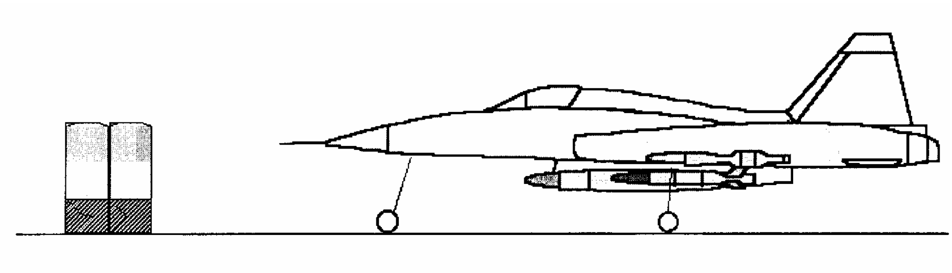

Figure 5 Concept of water barriers next to parked aircraft.

The US firm Battelle (Burky, 1999) has developed a Blast Suppression System. It consists of a water spray system that is capable of generating a “wall” of water in front of an object, e.g. a building, to be protected, as shown in Figure 6. Such a system can be used when a vehicle bomb is parked next to a building and is identified as a threat, i.e. by prior warning. The system is meant to be run until the threat is dealt with or the evacuation of the building is completed. The water spray system creates in a very short time (typical a few seconds response time), a water barrier which forms a resistance to the air blast generated, thereby reducing the blast load on the building facade. Various tests have shown that reductions of up to 50% in peak pressure and impulse can be achieved this way. This technology can be used to protect the vulnerable sides of buildings. This apparatus is also well suited to be applied next to a vehicle inspection area, e.g. next to a building or a military compound, as indicated in Figure 7.

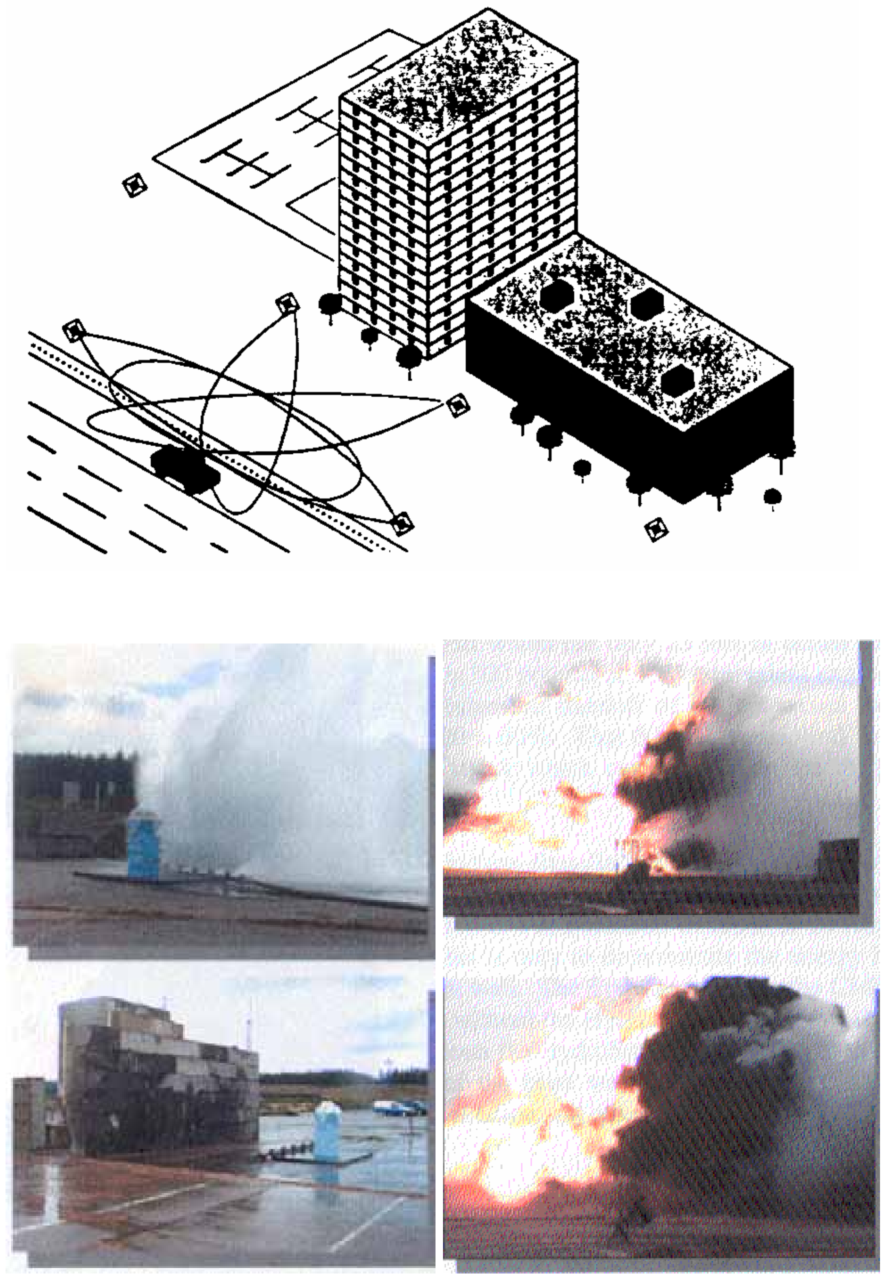

Figure 6 Hydro Suppressor System of Battelle, creating a "water barrier wall"..

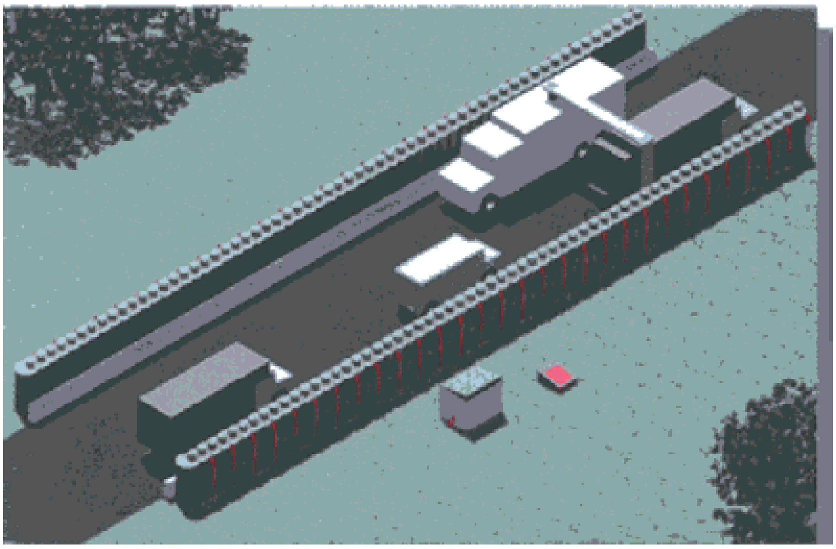

Figure 7 Protection of a Vehicle Inspection Area.

Janes Defence Weekly (April 1999) reported on developments ongoing at the Naval Surface Warfare Centre Dahlgren Division concerning operational effectiveness and technologies supporting a Water Barrier Ship Self Defence System. The barrier system, as shown in Figure 8, is designed to offer a last line of protection against incoming missiles. At a critical range of 100 m from the ship, a rocket launched line charge is deployed to form a wall of water. Trials conducted have demonstrated the ability of the water barrier to defeat incoming fragments and projectiles. The water plume had a destructive effect on a missile. NSWCDD says that the water barrier defence concept also has the potential in other mission areas, e.g. ship defence against torpedoes and mines, non lethal defence against small boats and light aircraft engaged in terrorist operations or drug smuggling.

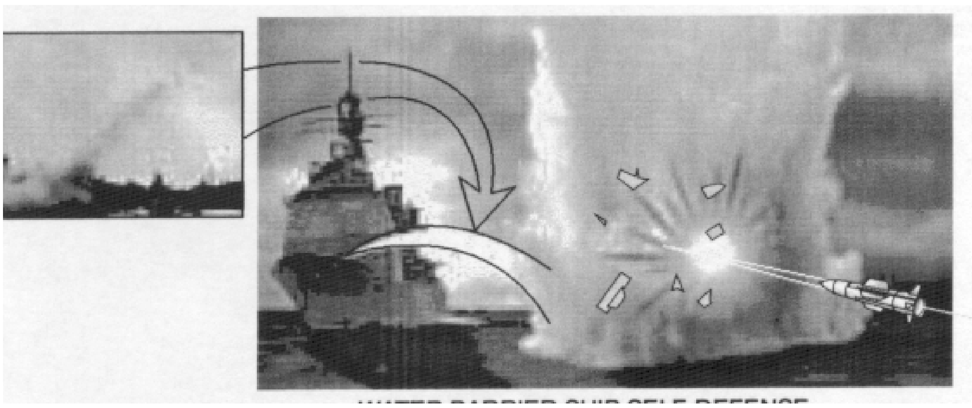

Figure 8 Concept of waterbarrier to intercept missile

Applications for EOD operations

Keenan and Wager (1992) have suggested the use of water-filled "hotdogs" in a bomb cart to transport small ammunition articles, as shown in Figure 9. The vessel is designed to fully contain the explosion effects if the ammunition were to detonate. The bomb basket holds the bomb at a minimum stand off distance from the walls of the containment vessel.

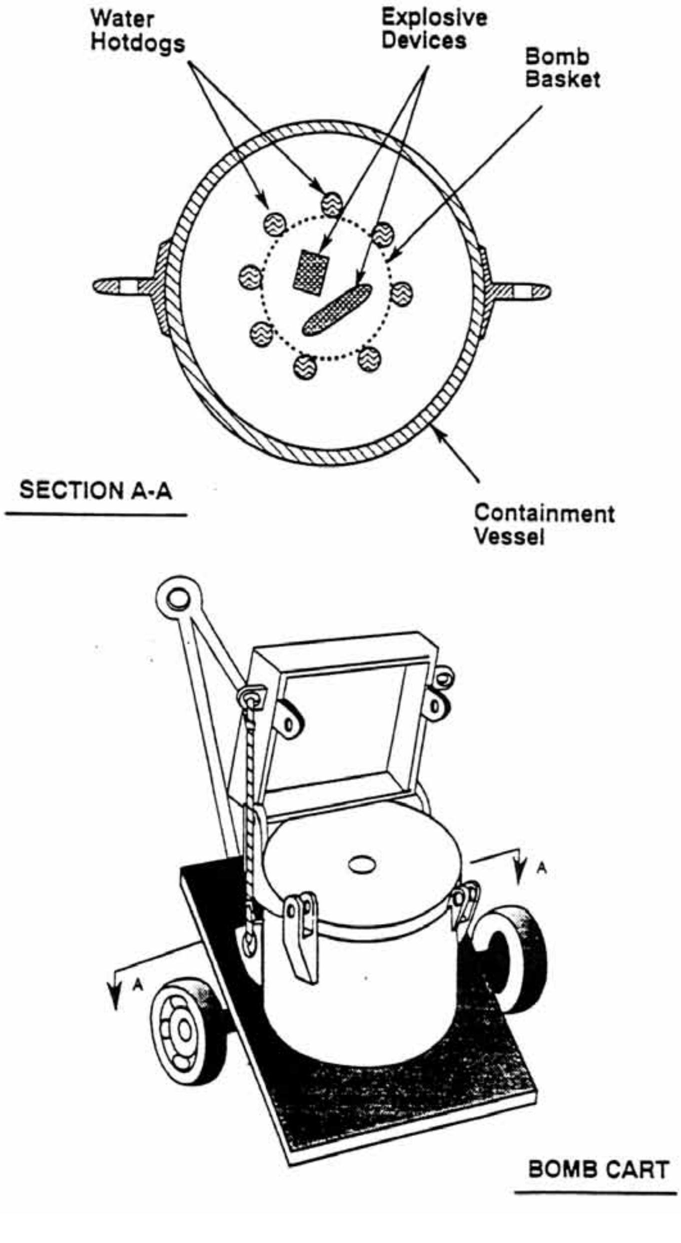

Figure 9 Conceptual design of bomb cart with waterhotdogs.

Blast reduction systems, based on water mitigation technology, are being used by UK EOD engineers nowadays. By building a "collateral blast damage reduction" system around the bomb pit, the evacuation distances can be reduced from typically 2.600 m to 500 m. This system was used for the first time in Britain in 2000 when a 1,000 kg wartime bomb, named “Herman”, had to be neutralized, next to a major railway line in Reading. Earlier trials with this system had been made in Kosovo. The support structure is made of foam blocks, laid like bricks, and hollow beams, carrying many pairs of water filled plastic saddlebags. Figure 10 gives an indication of the structure.

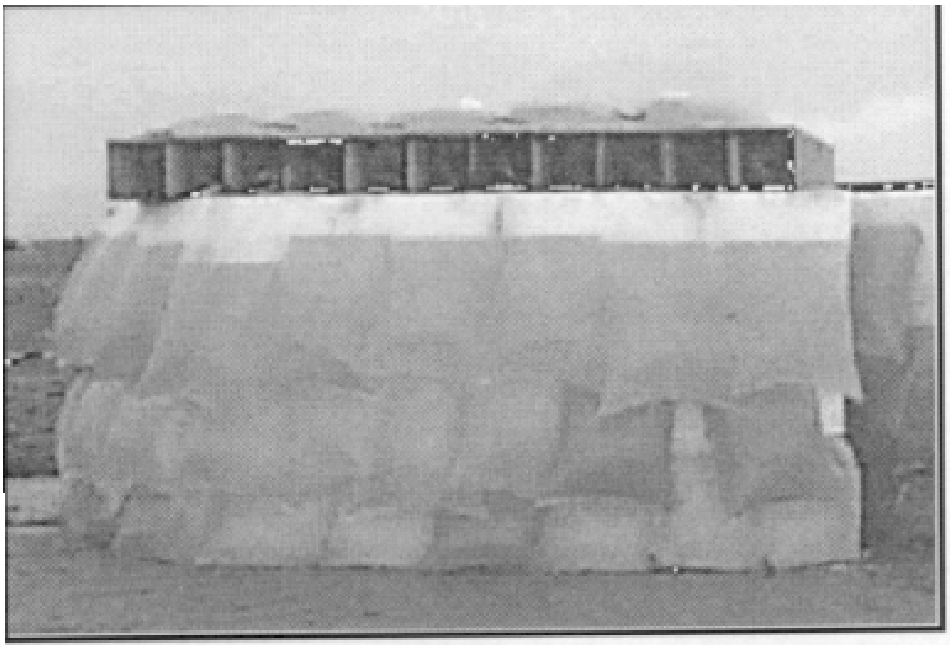

Figure 10 “Collateral blast damage reduction” system for EOD demolition operations.

7 Conclusions

In a joint study FOI and TNO have attempted to increase the understanding of the water mitigation phenomenon, which implies that explosion effects can be significantly reduced by placing water in the vicinity of a detonating charge. Various experimental studies and analytical and numerical investigations have been conducted within the framework of this investigation. Besides, confirming the existence of the water mitigation phenomenon, leading in some cases (confined structures) to reduction in gas pressures to up to 80%, this study has indeed overall increased the understanding of the phenomenon. It was found that various aspects, like the cooling effect, the avoidance of afterburning, and the transformation of explosion energy into aerosolizing the water particles and into the kinetic energy of the particles, and the evaporation of water, all contribute to some extent to the mitigation of the explosion effects. Due to the complexity of the joint occurrence of all these aspects, the current study did not succeed in giving a full explanation of all effects observed in the several trials and test set-ups. Yet, although not fully understood, the water mitigation concept still provides a promising technique for application in ammunition storage facilities, although it needs further investigation. Not only can it reduce the risk area from pressure and debris throw in case of an accident with exploding ammunition, there is obviously also a reduction of the fire hazard in the surroundings.

The water should be located in close proximity to the ammunition; a suggestion for ordnance manufacturers is to develop especially designed transport cases that can be filled with water.

A considerable mitigating effect can be obtained in underground ammunition storage magazines even if the water is not located in immediate proximity, e.g. for ammunition on pallets, where e.g. artillery shells can be covered by a water blanket or, if this seems unsuitable, an extra pallet with water containers is stored next to every pallet with ammunition.

The experiments and calculations show that the amount of water to net explosive weight should be at least a factor 2 to have a considerable mitigation effect. From the experiments conducted, the mitigation effect seems to increase with weight-ratios up to 5, but a further increase of the water amount seems to have only minor effects.

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Appendix A Paper 1

28th DoD Explosives Safety Seminar

Water Mitigation of Explosion Effects
Part II: Redistribution of Explosion Energy

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Abstract

Several experimental research programmes have indicated that explosion effects can be reduced by placing water in the vicinity of a detonating charge. Particularly, in case of a confined explosion, water has the potential to mitigate the shock pressure as well as the gas pressure loading developed inside the confining structure. This water mitigation concept can be exploited in the design and operation of new and existing military facilities exposed to the threat of internal explosions, like ammunition handling and storage sites.

In 1997, a co-operative research project was defined between FOA in Sweden and TNO-Prins Maurits Laboratory (PML) in The Netherlands, aimed at investigating the physics of water mitigation and to formulate instructions and standards of how to use water barriers. The TNO-PML focused their research on the spatial and temporal distribution of the different energy terms involved, and the influence of different parameters, e.g. the water-to-charge ratio and standoff distance, on the water mitigation effect.

In the paper, the results of some small scale tests will be presented. In addition, an inventory of explanations for the mitigation effect, as found in literature, will be given and evaluated. Mostly, the reduction effect is explained by the fact that large part of the detonation energy is dissipated by changing the water droplets from liquid to vapor state.

The thermodynamics codes CHEETAH and TIGER were used to get some insight into the relationship between the different thermodynamics parameters (i.e. gas pressure, density and temperature) during the detonation of TNT. Some calculations were made with water added. In addition, the hydrocode AUTODYN was used to model the dynamic aspects of the

detonation and the airshock propagation and its interaction with various materials placed in the vicinity of the charge, like water and steel solids. Next, the local and temporal distribution of the internal and kinetic energy of the detonation gases, of the blast wave and of the water and steel objects was calculated.

From this analysis it could be concluded that the mitigation effect is more complex than expected and that it can only be partly explained by the evaporation of the water droplets. In some cases the mitigation effect is mainly caused by the redistribution of the internal and kinetic energy over the detonation gases, the blast wave and the barrier material.

1. Introduction

Several experimental research programmes (Eriksson 1974, and Eriksson and Vretblad 1994) have indicated that explosion effects can be reduced by placing water in the vicinity of a detonating charge. Particularly, in case of a confined explosion, water has the potential to mitigate the shock pressure as well as the gas pressure loading developed inside the structure confining the explosion. This water mitigation concept can be exploited in the design and operation of new and existing military facilities exposed to a potential internal explosion, like ammunition handling and storage facilities. In addition, the concept can be applied to the temporary storage of ammunition like is the case in Out-of-Area operations, e.g. during peace keeping missions.

In 1995 and 1996, at TNO-PML some preliminary tests were conducted at small scale, which will be reported in Chapter 3, and which confirmed the existence of the mitigation effect (Absil and Verbeek, 1998). Not all of the physics of water mitigation, however, is well understood. Most tests conducted up to now, have been executed on relatively small scale involving bare charges of less than 100 kg of TNT, all indicating a significant mitigation effect by applying water. A full scale test involving the detonation of 1000 kg of TNT of ammunition and 2000 kg of water in a 60-m long tunnel, conducted at Älvdalen (Sweden) in 1996, however, showed only a minor reduction of the explosion effects (Forsén et al., 1996). In 1997 a co-operative project was defined between the Division of Vulnerability of Buildings and Fortifications of FOA and the Researchgroup Explosion Prevention and Protection of TNO-PML, aimed at investigating the physics of water mitigation and to formulate instructions and standards of how to use water barrieres. Another goal of this survey is to confirm that the water mitigation concept also works at full scale and is not limited to small amounts of explosives.

The aim of this first phase of the study, described in the present paper, was to gain some understanding into the physics of water mitigation. First, a literature survey has been conducted to inventory the given explanations for the mitigation effect found. In general, the reduction of the blast overpressure and quasi-static pressure is explained by the fact that large part of the detonation energy will be dissipated by changing the water droplets from liquid to vapor state, thereby absorbing detonation energy from the explosive. Then, at TNO-PML the thermodynamics codes CHEETAH and TIGER were used to get some idea about the relation between the different thermodynamic parameters (i.e. gas pressure, density and temperature). Next, in order to reach a better understanding of the phenomena occuring in a blast wave, computer simulations have also been performed using the hydrocode AUTODYN. The code was used to model the dynamic aspects of shocks and detonation, like the spatial distribution and time development of many parameters, the propagation of shocks and the interaction with water and steel objects for different mass, distance to charge and surface blockage area. In conclusion, some insight has been gained into the mechanism of water mitigation and the "white spots" still existing in the knowledge base.

2. Discussion of proposed mechanisms.

The most commonly accepted explanation for the experimentally observed effect of the mitigation of a blast wave by water has been given by Keenan and Wager (1992). In their article they state that when the blast wave resulting from the explosion reaches the water, being contained in bags or plastic containers, these casings as well as the water will be fragmented, transforming the water into an aerosol, a mist of tiny water droplets. The aerosol will mix with the hot detonation gases. As a result of heat transfer between the gases and the aerosol the water will evaporate, the gases will cool down and the gas pressure will decrease. A second effect, mentioned by Eriksson and Vretblad (1994), is that due to the lower temperature also no afterburning of the detonation products will occur with the oxygen, present in the air, and therefore no extra temperature and pressure increase of the gases will occur. Therefore both the cooling down and the avoidance of afterburning result in a lower gas pressure and therefore in a lower load on the construction. A third proposed mechanism is the transformation of the explosion energy into kinetic energy. Just like the casing of a munition article will absorb a considerable fraction of the detonation energy in the form of kinetic energy, also water containers, placed around the charge, can acquire much kinetic energy and thereby reduce the internal energy and pressure of the blast wave.

The description given above of the blast mitigation effect by water evaporation is a very questionable explanation. As remarked earlier by Eriksson and Vretblad (1994) the evaporation of water not only results in a decrease of the gas temperature and therefore a decrease of the partial gas pressure of the detonation products, but of course also produces water vapour, thereby increasing the pressure. It is also questionable whether an important fraction of the energy, liberated by the detonation, can be used to evaporate water and whether such an evaporation process can occur within a

short timeframe. It therefore seems unlikely that an evaporation process can account for a considerable reduction of the gas pressure.
Afterburning of detonation products can for some explosives as notably TNT produce a considerable amount of extra energy but the avoidance of the liberation of this amount of energy is not enough by far to explain the experimentally observed mitigation effects of up to 90 %, see e.g. Chapter 3. Besides afterburning can only occur if enough oxygen is available and if the temperature is high enough. Both conditions can not be fulfilled at the same time. The detonation gases will have to expand strongly in order to mix with a sufficient amount of oxygen. During the expansion the temperature of the gases will rapidly decrease to a value of several hundreds of °C. At these temperatures no afterburning will occur. In practice afterburning of detonation products only occurs in the first stage of the expansion and only at the interface of the detonation gases with the air. Although it creates a very spectacular effect the extra energy it supplies is usually negligible. Furthermore, if such an effect would occur, a clear difference should be observed between an explosive as TNT, with its very high oxygen deficiency, and other explosives that have a much lower oxygen deficiency. Experimentally such a difference has not been observed (Eriksson and Vretblad 1994).
The third proposed mechanism, the transformation of energy to kinetic energy of the water, is of course a valid one. A detonation will accelerate all materials in its immediate neighbourhood and the corresponding kinetic energy will come at the expense of the energy of the detonation products. Whether this effect can quantitatively describe the observed mitigation results will have to be further examined.

3. Small scale experiments at TNO-PML

3.1 Small-scale tests (1995)

To validate the existence of the water mitigation effect, several small scale experiments have been conducted in one of the bunkers of TNO-PML. The tests were conducted using 1 kg of cylindrically-shaped plastic explosives (PETN, 7 mm diameter x 14 cm length), initiated by an electric detonator nr. 8. The bunker used, sizes 2 m in diameter and 2.45 m in height, resulting in a loading density of 0.13 kg/m^3. The explosive was detonated at the centre, on the floor of the bunker. During the tests the doors of the bunker were closed to capture the detonation gasses and to obtain a significant quasi-static gas pressure after the detonation. At the steel hatch of the bunker, at about a distance of 1 m from the charge, the pressure-signal was measured using 2 pressure transducers. To obtain some reference data on the QSP, first, a number of detonation trials were conducted using bare charges which resulted in maximum QSP-levels of 130 kPa.

Then the explosive was placed in a plastic bucket of varying size filled with water. In these trials there was no air gap between the explosive and the water. In Table 1 some information is given on the size of the plastic buckets used, the amount of water used and the measured maximum QSP-levels. The results clearly indicate that:

- a reduction in maximum QSP from 50% to 20% was obtained;
- the mitigation effect increases with increasing volume of water, but there seems to exist an optimum water/explosive volume ratio.

test nr.	amount water [ltr]	measured max. QSP [kPa]	size plastic bucket (diameter x height) [cm]
7	0.5	60	9x18
5	1	45	11x22
4	3	25	15x27
6	6	25	24x50

Table 1. Tests with fully enclosed explosive.

Next, some trials were made placing the explosive in an inner plastic box, and filling an outer plastic box with water. Herewith, an airgap was created between the explosive charge and water. In Table 2 some information is given on the size of the boxes, the amount of water used and the measured QSP-pressure reduction. Figures 1 and 2 show photographs of tests nr. 8 and 9. In trial 10 the top of the inner box was removed offering the blast and gas-pressure to escape. From these trials it could be concluded that:

- a more effective reduction of the QSP is found when an airgap is created between explosive and water;
- a reduction from 130 kPa to about 15 kPa was obtained, yielding a reduction of 85% in maximum QSP-level;
- for a higher water/charge ratio, a larger reduction is obtained;
- the explosive should be fully enclosed by the water, otherwise it will escape through the path of least resistance.

test nr.	amount water [ltr]	measured max. QSP [kPa]	size plastic boxes inner box [cm] outer box [cm]	remarks
8	18	15	13x19x30 19x29x39	airgap 7 cm closed top
9	5	18	8.5x11x20 13x19x30	airgap 3 cm closed top
10	5	30	8.5x11x20 13x19x30	airgap 3 cm open top

Table 2 Test with airgap between explosive and water

In the next number of trials the influence of the distance between a waterbag and the explosive was investigated. In the first trial a waterbag (3 ltr) was placed right on top of the charge, yielding a QSP pressure reduction upto 20 kPa. Then the distance between the waterbag (6 ltr) and the charge was enlarged upto 10 and 50 cm, yielding a max. QSP-level of 45 and 50 kPa respectively. From these trials it can be concluded that:

- an optimum mitigation effect is found when the charge is fully confined by water;
- a reduction of the order of 50% in maximum QSP-level in a confined space can be obtained, even when the water is not in the near vicinity of the charge.

Figure 1 Test set up of test nr. 8.

Figure 2 Test set up of test nr. 9.

In conclusion: these small scale tests have indicated that a significant reduction, of upto 85%, in quasi-static pressure can be obtained by placing water in the vicinity of the charge in a confined space.

3.2 Small-scale tests (1996)

On behalf of the Explosives Ordnance Disposal Organisation of the Royal Netherlands Airforce, TNO-PML is developing a so-called bomblet attenuator. This device should be placed over small ordnance items, like bomblets and mines, and should be able to capture most of the fragments and vent the blast away from demining personnel, in case such an item explodes. The attenuator can also be used for the temporary protection of vulnerable objects situated close to such small UXO items or it can be used when mines have to be detonated in-situ, close to high value assets.

Within the framework of this research programme some tests were conducted to quantify the explosion effects of two representative types of bomblets and to gain some insight into the effectiveness of some simple off-the-shelf attenuators. In addition the effectiveness of water and sand bags to mitigate explosion effects has been examined experimentally by placing water/sand bags over the vent opening of the attenuator. Some of the relevant findings of this study will be reported in the following.

Two types of bomblets were detonated in these trials: the BLU-86 and the no.1 MK1 bomblet. The BLU-86 is a small 76.2 mm diameter fragmenting bomblet, consisting of a steel housing and a main charge of 113 g cyclotol. The no.1 MK 1 bomblet has a total length of 356 mm and a diameter of 70 mm. It is provided with a chaped charge with a charge weight of 227 g hexolite contained in a steel housing. During the tests the shaped charge was directed downward into the earth. The detonation of the bomblets was achieved by using an electrical detonator nr. 2C2, mounted to 20 g plastic explosives which was adapted to the bomblet.

In the tests relevant for this study, a 0.4 m diameter, 0.3 m high steel cylinder was used. It had a wall thickness of 13 mm and a weight of about 40 kg. Furthermore, two types of top-covers were used: 2 sandbags, containing 15 kg of sand each, and waterbags, containing 10 ltr. These top covers were placed over the ventopening of the cylinder, at a distance of 30 cm above the charge.

Figures 3 and 4 show the experimental set-up. Three pressure transducers were used to measure the overpressure signals at distances of 2.5, 5 and 7.5 m away from the charge. At the same distances 3 witness plates, 2 mm thick Aluminium, were positioned to measure the fragmentation impact. A video camera was used to record the events.

Subsequently, the following test programme was executed:

- the explosion effects of the two types of bomblets were recorded by detonating the bomblets on the surface;
- the explosion effects were recorded with the steel cylinder placed over the bomblets;
- the mitigation effect of the top covers was recorded, by repeating the trials with the sand and water bags on top.

By comparing these results the effectiveness of the attenuator could be evaluated.

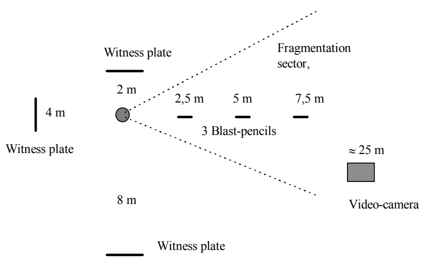

Figure 3. Experimental set-up.

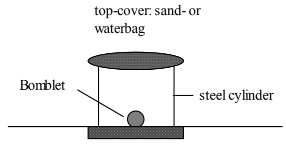

Figure 4. Bomblet, attenuator and top-cover.

The steel cylinder showed to be able to stop the penetrating fragments of the Blu 86 and Mk.1 bomblet. Although the cylinder was slightly lifted by the blast, over a few centimeters, it was not ruptured and stayed intact.

Figure 5 shows the reduction of the peak overpressure of the blast for the steel cylinder with and without top cover for the Blu 86 bomblet. The upper curve shows the unshielded situation. At 2.5 m the maximum overpressure is about 25 kPa, which is close to the threshold for eardrum rupture. From the curve measured for the situation with the cylinder placed over the bomblet it can be concluded that this yields a reduction in blast peak overpressure of about 10 to 20%. With top cover a reduction of the peak overpressure of upto 70% to 80% is found. The water bag seems to be only slightly more effective than the sandbag. The sandbag captured all fragments of the bomblets while in case of the water bag a few fragments were thrown out of the cylinder. The camera-recordings showed the generation of a sand and water jet, of upto 30 m, in the air.

Figure 6 shows the peakoverpressure decay as found for the Mk1 bomblet. For this bomblet somewhat higher pressure levels are found. Without shielding a peak overpressure of about 45 kPa was measured at 2.5 m distance. With the steel cylinder placed over the bomblet a reduction in peak overpressure of about 15% is found. The lower curves show the peak overpressures as measured with topcover. A reduction in peak overpressure of upto 80% is observed. Hardly any difference between the sand and waterbag can be seen.

In conclusion: From these trials it can be concluded that in this specific experiment water as well as sand bags were very effective means for reducing blast overpressure as well as capturing fragments. Because hardly any difference was found between the reduction by the sandbag and waterbag it is likely that the mitigation effect is due to the transformation of detonation energy into kinetic energy of the sandparticles and waterdroplets, as was confirmed by the water jet observed on the video-recording.

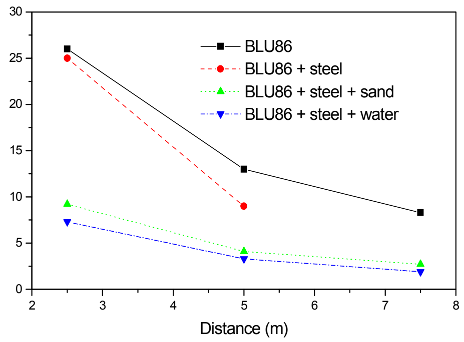

Figure 5. Blast attenuation for the Blu86 bomblet

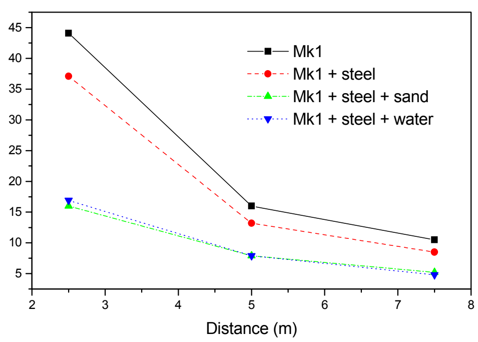

Figure 6 Blast attenuation for the Mk1 bomblet

4. Theoretical evaluation of mechanisms for blast mitigation

4.1 Thermodynamic computations.

In order to elaborate on the remarks made in Chapter 2 some thermodynamic calculations have been performed using the thermodynamic programs CHEETAH and TIGER. These programs can calculate the thermodynamic parameters and the composition of the reaction products for a detonation and the expansion of the reaction gases. The programs can calculate the (frozen) thermodynamic equilibrium states of the materials, but do not describe dynamic aspects like gas flow and reaction rates. With these programs the detonation of TNT has been calculated. The resulting Chapman-Jouguet values are: P_{CJ} = 19.4 GPa, T_{CJ} = 3685 K. Subsequently the thermodynamic state has been calculated after an isentropic expansion to specific volumes up to v = 200 cm^3/g. For a value of v of 200 cm^3/g the pressure and temperature have decreased during the expansion to: P = 0.73 MPa, T = 587 K. At this point the internal energy of the gases has decreased to 12.5 % of its starting value due to the work performed. The absorbed energy has been transformed into kinetic energy of the blast wave and possible fragments.

	P (kbar)	v (cm^3/g)	T(K)	e/e_0 (%)
unreacted	0.001	0.604	298	100
CJ point	194.4	0.454	3685	129
expansion	47.3	0.723	2607	76.2
	10.13	1.31	1905	55.6
	2.01	2.95	1479	36.2
	0.568	6.66	1221	28.5
	0.156	17.4	996	22.4
	0.041	50.0	799	17.3
	0.017	100	687	14.7
	0.007	200	587	12.5

Table 3 Expansion of reaction products of TNT

When at this point, preserving the total volume, an equal mass of water is added (mass ratio TNT/water is 1/1) the result is: P = 0.55 MPa, T = 388 K. So although indeed a strong cooling occurs the pressure has only decreased by 25 %. In this calculation it has been assumed that all available energy is used for the evaporation of water; it therefore gives the maximum effect obtainable by evaporation. Calculations for other values of v and for other amounts of water show that values higher than 30 to 40 % reduction can not be obtained, even for very large amounts of water. The reason is that soon the saturation point of water is reached and adding more water does not lead to more water evaporation, only the specific heat of the added water then has a small influence on the pressure and temperature. From Table 3 we can also conclude that no heat absorption mechanism can reduce the pressure an order of magnitude, since the temperature very soon decreases well below 1000 K and the maximum reduction of any heat absorption mechanism would be (T-298)/T, assuming a linear relationship between pressure and temperature.

4.2 Hydrocode simulations.

In the section above we have considered the effects of the loss of internal energy of the detonation gases due to their expansion. This energy will during the expansion process be converted into kinetic energy of the gases, into kinetic and internal energy of the blast wave in the air and into kinetic energy of any solid material, present in the neighbourhood of the charge. It is possible that at later times part of this energy can again be converted back into internal energy and be used to evaporate water. To further investigate this and other dynamic phenomena in a blast wave we have carried out computer simulations with use of the hydrocode Autodyn. With such a hydrocode it is possible to model the dynamic aspects of shocks and detonation, like the spatial distribution and time development of many parameters, the propagation of shocks, the interaction between various materials, etc. This hydrocode has been used to model the blast effects due to the detonation of a sphere of TNT with a radius of 200 mm and with a mass of 55 kg. The TNT sphere is surrounded by air at NTP conditions and the explosive is ignited in its center. A number of simulations have been performed, both with the mere TNT/air system described above, but also with other materials present in the immediate neighbourhood of the explosive. Both water and steel have been used as materials, while also variations have been applied in mass, distance to the explosive and surface covering area.

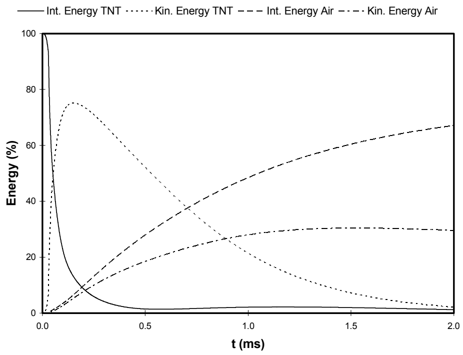

Figure 7 Energy distribution as a function of time for an unobstructed blast wave

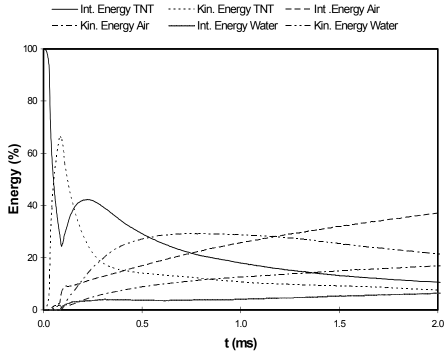

Figure 8 Energy distribution as function of time with water blocks

In the simulations the interaction of the blast wave with the water blocks has only been modeled in a general and coarse way. The breaking up of the blocks into particles has not been described and also a possible evaporation of the water droplets has not been taken into account. In the simulations no casings have been applied to the explosive charge, no walls of the storage room have been modelled and also no three-dimensional effects have been taken into account.

In Figure 7 a plot is given of the time development of the various energy fractions of the explosive and the air for a simulation where no water or other materials are present. The plot illustrates that the detonation energy is quickly converted into kinetic energy during the first 150 μs. At that time, when the blast wave has travelled almost 1 m, the shock wave in air has developed sufficiently and will further absorb the energy, both as internal energy and as kinetic energy. The slowing down of the detonation gases results in a decrease of their kinetic energy, which is converted into energy of the air. At 2 ms, at a distance of approximately 4 m from the explosive, the internal energy of the air has absorbed 67 % of the energy, the kinetic energy of the air has 30 %, while a few percent is still contained in the explosive. At longer time frames the kinetic energy of the air will decrease again and for long distances practically all energy will be converted into internal energy of the air.

In order to examine the influence of water barriers on the strength of the blast wave a number of simulations have been performed with blocks of water present in the neighbourhood of the explosive charge. Several blocks of water were placed at some distance of the charge. Both the mass of the water, the distance to the charge and the spatial angle, covered by the water, were varied in the simulations.

Figure 8 gives an overview of the influence of the water on the time development of the energy distribution for a simulation, where a mass of 114 kg water was placed at a distance of 500 mm from the center, covering 50 % of the spatial angle. Initially the conversion of internal into kinetic energy of the detonation gases is identical to that of the simulation, shown in figure 7, but when the blast wave hits the water this conversion is suddenly stopped. The kinetic energy of the gases strongly decreases while their internal energy temporarily increases again. Next a considerable amount of energy is converted into kinetic energy of the water. This goes at the expense of the energy transfered to the air but at later times the velocity of the water decreases again due to the interaction with the gas flow and the kinetic energy of the water is gradually converted into internal and kinetic energy of the air. Eventually the main part of the energy still ends up as internal energy of the air, but this occurs at a much later stage than for an unobstructed blast wave.

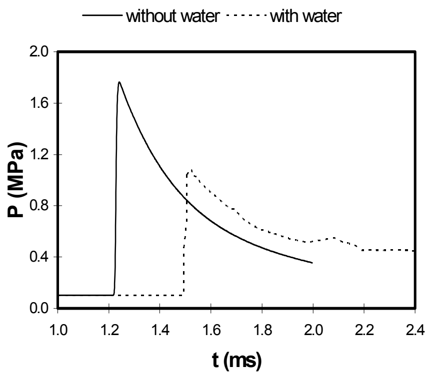

Figure 9. Shock pressure history with and without water at r= 3m.

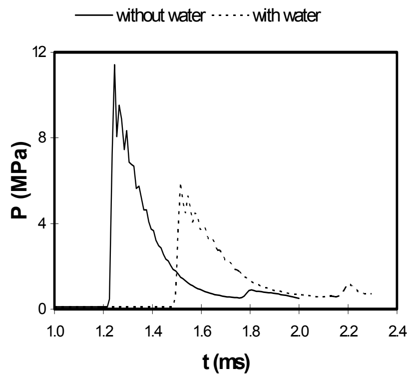

Figure 10. Stagnation pressure history with and without water at r = 3m.

In figures 9 and 10 the influence of the presence of the water obstruction is shown for the shock pressure and stagnation pressure. Here the plots are given for the time history of these variables at a point, 3 m from the center of the explosive. For comparison also the corresponding plots are shown for an unconfined blast wave. The plots show that the peak shock pressure is reduced to approximately 62 % of the unconfined shock pressure. It is also shown that the stagnation pressure is reduced more than the shock pressure to a value of 52 % of the stagnation pressure for an unconfined blast wave. This is apparently the result of a different spatial distribution of the kinetic energy of the shock. It also appears that the presence of the water blocks clearly slows down the propagation speed of the blast wave.
Variations in the simulations with the mass of the water, the distance of the water to the charge, the spatial angle, covered by the water, and the location where the pressure trace was obtained, showed a clear dependence of the pressure reduction on these parameters. Up to now no higher reductions of the shock pressure were obtained than about 50 %. Similar simulations have also been carried out for steel obstructions. It appeared that these only significantly influence the blast wave if the barrier is relatively thin and if a very large spatial angle is covered. In that case 40 to 50 % of the energy can be absorbed and shock pressure reductions of up to 60 % can be obtained.

4.3 Confined explosions

The previous discussion was mainly concerned with unconfined explosions. In case of an explosion in a munition storage room some other effects may also play a role. Like the kinetic energy of the blast wave will in a confined space after several reflections partly be converted again into internal energy of the detonation products and of the air, present in the room. This energy might contribute to the evaporation of water so that the mitigation effect might be higher than computed previously. However, in a munition storage room a considerable fraction of the energy will be lost by the interaction of the blast wave with the wall and with other solid objects, present in the room. Furthermore, it will take quite some time for the motion of the blast wave to die out, while it will also take a considerable amount of time before any present water containers will be broken up, before the water will be aerosolized and before the aerosol will be sufficiently mixed with the air and the detonation gases in the room. Also in the case of cased munition, the casing of the munition will typically absorb 40 % of the detonation energy in the form of kinetic energy, which can never be restored as internal energy of the air. It therefore still seems very unlikely that evaporation effects can account for a major fraction of the large water mitigation effects, observed experimentally.

5. Conclusions

Small scale experiments conducted at TNO-PML have confirmed that water can, under certain conditions, effectively mitigate the blast peak overpressure and quasi-static pressure build-up by confined explosions. From the experiments the following conclusions could be drawn:

- in fully confined situations, a reduction of up to 85% in quasi-static pressure can be obtained;
- the mitigation effect increases with increasing volume of water, but there seems to be an optimum water to charge ratio;
- a more effective reduction in QSP can be obtained by creating an airgap between charge and water;
- the charge should be fully enclosed by the water barrier to obtain an optimum blast mitigation;
- the trials conducted with waterbags and sandbags as top covers of the cylinders, indicated that both media yield identical mitigation effects, e.g. reduction in blast overpressure of up to 80% and nearly completely capturing of the fragments. This confirms the idea that, in this particular situation, the mitigation effect is probably due to the transformation of detonation energy into kinetic energy of the sandparticles and waterdroplets.

From the theoretical analysis it follows that a water evaporation mechanism can at the most explain a fraction of the experimentally observed mitigation effects. Most likely the observed effects are a combination of different phenomena, where the most important mechanism seems to be the conversion of energy into kinetic energy of the water. In comparing results of water mitigation experiments it should further clearly be stated whether mitigation of the shock pressure, the stagnation pressure, the quasi-static pressure or the impulse on a wall is considered, since the mitigation effect will be different for each of these parameters.

6. References

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Appendix B Paper 2

28th DoD Explosives Safety Seminar

Water Mitigation of Explosion Effects
Part 1: The dynamic pressure from partially confined spaces

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Abstract
This work is a contribution to an ongoing co-operative research project between FOA in Sweden and TNO-PML in the Netherlands, aimed at investigating the physics of water mitigation and to formulate instructions and standards of how to use water barriers. FOA has focused on the scale-modeling laws and to investigate if the mitigation is affected when the charges are cased.

The technique of damping blast from high explosives with ”water barriers” of different types has recently been studied by some research institutes and consultants. Examples on practical applications are to reduce the most severe hazard area around an ammunition storage, on equipment for manufacturing or the destruction of ammunition etc. However, the results reported in this field indicate that the mitigation effect from water is not yet fully understood. Although it has been demonstrated to work well in many tests in small scale, unexpected results have occurred when tested in full scale.

This paper contains a somewhat closer look on the blast mitigation effect from water for geometries similar to a duct attached to a confined space, e.g. an access tunnel in to an ammunition storage. Of special interest is then the dynamic pressure inside the access tunnel, caused by the shock and quasi-static pressure from an explosion in the storage chamber, as well as the jet formed outside the tunnel entrance. An effort is made to explain some results from scale model experiments in terms of elementary thermodynamics and shock wave theory. This is illustrated by a set of numerical simulations with the hydrocode AUTODYN using its two phase material model for water. The calculated results are compared with the experiments, and it is concluded that the numerical model to some extent

describes the phenomena involved. Applied on real ammunition storage magazines these data, in short, indicate a substantial pressure reduction in the storage chamber, but possible problems with debris throw outside the access tunnel due to the high dynamic pressure in the flow.

1. Background

The technique of water mitigation of explosion effects has recently been studied by several consultants and researchers (/1/, /2/, /3/, /4/, /5/, /6/, /15/, /16/, /17/). Examples on practical applications are to reduce the most severe hazard area around ammunition storage magazines, around equipment for manufacturing or the destruction of ammunition, or even around suspected terrorist bombs etc. An alternative is aqueous foam, the same type as is commonly used by fire-squads. Foam has been investigated quite well both experimentally and theoretically and is found to have a considerable damping effect on shock-waves both in the free air, in confined spaces as well as in tubes and tunnels. But as foam has no long-time stability, pure liquid water in suitable packages is instead considered for ammunition storages and other situations with lasting hazard areas. The problem of potential leakage of water is nowadays eliminated, due to plastic containers of different types, which are intended to break up only when exposed to a detonation (e.g. in /7/, where tests of one such product is reported).

The mitigation effect from water has been demonstrated to work well in many situations, but some unexpected results have also been reported. One example is a full scale test simulating a detonating ammunition storage in a rock tunnel, performed by the KLOTZ-Club in Alvdalen, Sweden in 1996 /3/. The results when water barrels were placed close to the charge were compared with a former test without water, but with the same charge and tunnel geometry. It was then found that the pressure, especially outside the tunnel, rather increased slightly than was reduced, as intended.

In this paper, the dynamic pressure from the water vapor flow from a partially confined space is modeled for a case when the water mitigation technique is used for an explosion in a chamber with an attached duct (the “shotgun” geometry). It also intends to give a somewhat broader view on the physics of the water mitigation technique, as well as on some other experiments reported.

2. Review of applicable physics

2.1 Shock-wave pressure.

The air shock-wave is a complex, dynamic phenomenon which comprises both a wave and a flow simultaneously; its pressure can be measured and described in different ways. Figure 1 illustrates the fundamental difference between the *static pressure* and the *dynamic pressure* of a flow, inside and outside a tunnel. The static pressure, denoted p', is the pressure of the compressed gas inside the wave, caused by the gaseous combustion products from the HE, superposed on the surrounding air pressure. One way to measure p' is with a transducer mounted with the diaphragm flush with the propagation direction (thereby it is also called "side-on" pressure). The dynamic pressure, denoted q is actually the kinetic energy of the moving gas, which is related to the drag force that a fix object expirence when exposed to (i.e. surrounded by) the shock wave flow. The dynamic pressure is described by:

(1) $q = ½ v^2 x \rho$ where v denotes the velocity and ρ the density of the gas flow.

Clearly, this differs from the internal, static pressure of the gas as it depends only on the density and the velocity vector of the moving gas (although a relation between the dynamic and the static pressure do exist for shock-waves in defined situations).

A device to measure the dynamic pressure in a shock flow can be obtained if the above described "side-on" gage is supplemented with a transducer with its diaphragm mounted perpendicular to the flow direction, preferably on a thin nozzle with aerodynamic shape. This gage then senses the stagnation pressure p_{stag}, but according to /11/ p.45, a good estimation of the dynamic pressure is the difference between the stagnation pressure and the static pressure; it can therefore be calculated from the relation $q= (p_{stag}- p')$; this is relevant only in one direction, e.g. for one-dimensional flows.

In experiments with shock waves often only p' is measured; then one assumes that the properties of the gases in the shock flow are known. If the gases, however, have some unknown characteristics, it is important to measure also q to correctly describe the flow. This can be illustrated by a shock-wave in a tunnel that enters free air, figures 1 and 2. Inside the tunnel, the shape of the two different types of pressure traces coincide fairly well close to the wave front; at the rear part of the wave they differ a bit more and outside the tunnel they are entirely different.

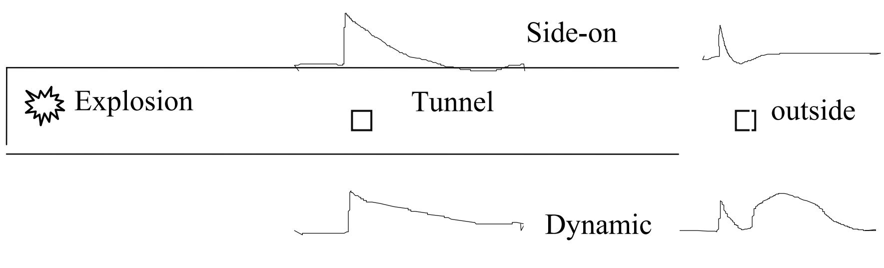

Figure 1. Air shock wave pressure traces from gages inside and outside a tunnel

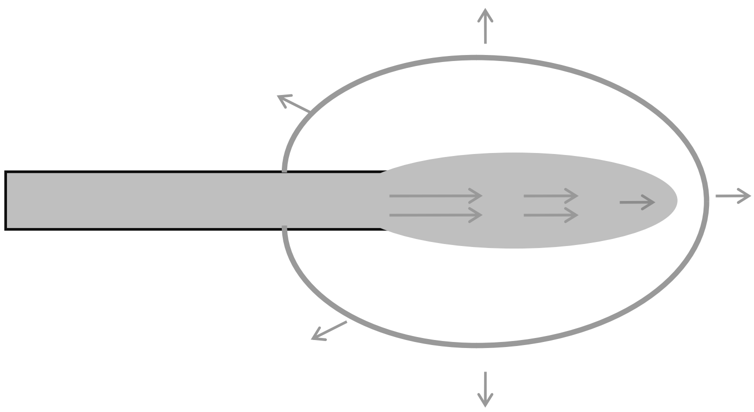

Figure 2. Shock-wave and flow outside a tunnel.

Two effects combine outside such a tunnel exit, as indicated in figure 2. When the shock wave reaches the open air, it immediately starts to expand in all directions as an almost spherical ”shell” (as waves have no inertia) while the moving gas, due to its inertia forms a jet outside the tunnel which follows right behind the shock wave in the centerline direction. This explains the pressure histories in figure 1 where the p’-gage outside the tunnel only senses the pressure when the thin shell-formed shock wave passes, while the q gage first senses a sudden movement in the air when the shock wave passes, and then the long-duration force when it is reached by the jet; this is shown by authentic pressure recordings in the Appendix, also in /13/, /14/ and /17/. In /14/, experiments are reported with a shock tube with gages located in front of the tube exit which, together with shadow-graphs, show a jet that is quite narrow (a few tube diameters) up to some distance and then dissolves into eddies and disappears at larger distances, as shown in figure 3.

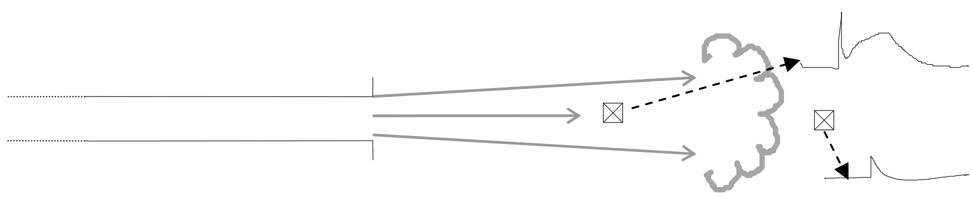

Figure 3. Stagnation pressure measurement on a jet, dissolved into eddies at large distances.

These experiments (with one-phase flow; helium was used as driver gas) indicate that the range of the jet is determined by the geometry of the duct, the exit pressure (i.e. the flow speed) and the duration of the flow. It was concluded, that several properties of the gases influence such a jet. Although the relations that describe all the situations above are complicated they can, to a large extent, be analyzed with well-defined ideal-gas models. Also, the behavior of the two-phase flow that occurs when a real gas like water vapor is added, is possible to analyze to some extent with simplified assumptions (as described in section 2.4).

2.2 Short about thermodynamics.
When a mass amount (n moles) of an ideal gas undergoes an adiabatic compression or expansion, the pressure p, volume V and temperature T are related by the following equations (from /8/):

(2) $pV = nRT$ (General Gas Law)
(3) $pV^{(Cp/Cv)}$ =constant (Poisson's Law)

where C_p and C_v are the heat capacities at constant pressure and volume, respectively, and the gas constant R = 8.314J/mol K. From the relation $C_p = C_v + R \Rightarrow C_p/C_v > 1$ together with equation (2) and (3) above, it can be seen that the temperature always increases when a gas is compressed and decreases when expanded. The ideal gas model is a quite good approximation for most cases with a mix of air and detonation products like CO, CO_2 , NO_x etc. at moderate pressure levels (i.e. a few MPa). A real gas, like water vapor, differs somewhat from the equations above, e.g. when a real gas is expanded its temperature decreases more, which in some cases turns it into liquid or solid phase, while an ideal gas by definition always remains in gaseous phase.

To describe an agent at different phases, tables on its density, temperature, volume, internal energy etc. at different pressure values are used. Some relations can also be presented graphically, as for water in figure 4. Among other things, this shows that there is a certain range in pressure and temperature where water exists as a liquid. For temperatures beyond the critical point (647 K) it can't be in the liquid phase, no matter the pressure increase. On the other hand: if the pressure is very low, all the water will remain in the gaseous phase even when the temperature is decreased (and then turns directly into ice crystals at a very low temperature). In figure 4b, derived from figure 4a, the pressure-volume relation for the liquid–vapor region is plotted more in detail; the temperature is here implicit. A similar curve is piecewise implemented in the two-phase material model of the hydrocode "AUTODYN" /9/.

It can be noted, that water vapor at high pressure and temperature has a higher density than air if the air is compressed from NTP (Normal Temperature and Pressure i.e. 273 K, 100 kPa) to a similar pressure. The opposite (i.e. lower density than air) is valid for HE gas, due to its high temperature.

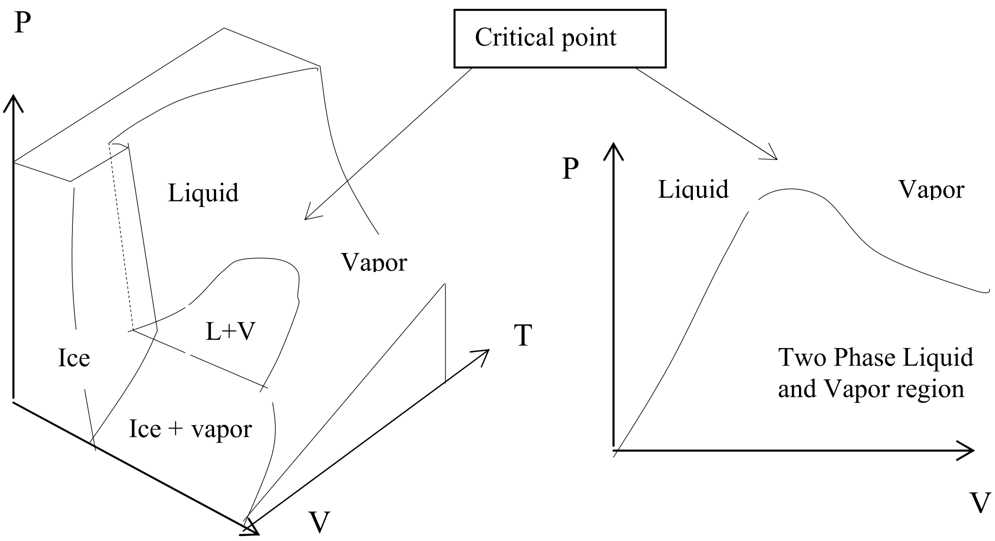

Figure 4. a) Pressure-Volume-Temp. relation for water. b) Simplified curve for two phases.

The Heat of Vaporization energy (HoV) for water is 2260 kJ/kg which is roughly one half of the energy release from HE per kg, e.g. TNT has about 4850 kJ/kg. Hence, the energy from 1 kg TNT has the ability to vaporize ca 1.8 kg cool, liquid water. According to table 1, the heat capacity for typical HE gases is 4 - 5 times less than for water, i.e. when mixed with a water mist, the overall temperature must decrease largely; so does also the pressure, according to the general gas law (2).

Agent	Formula	Heat capacity C_P kJ/kg K
Carbon-dioxide	CO_2	0.82
Carbon-monoxide	CO	1.05
Nitrogen	N_2	1.04
Nitrogen-monoxide	NO	1.00
Water	H_2O	4.2

Table 1: Heat capacities for some HE combustion products, compared to water (273K)

Different gaseous agents usually mix easily; this happens spontaneously due to the diffusion phenomenon. The mix has average values from the included agents on properties like density, heat capacity etc. As diffusion takes some time (depending on temperature, density etc.), a separation of the different gases can be maintained for some time during very fast events like shock waves, resulting in a contact surface between air and the combustion products. This can be experimentally visualized by high speed photography, and can also sometimes be traced in the pressure recordings. It is easier to observe in a simple geometry, as in a duct with smooth walls, or in free air with spherical expansion. Rough walls in a duct and obstacles inside will increase the diffusion and mixing of the gases; it will simultaneously decrease the static pressure p' of the wave front as well as its velocity.

2.3 Interaction explosive-water.

Consider a water volume in the proximity of a detonating HE charge, figure 5. The expanding gas volume will, as it hits the closest water surface, initiate a shock wave inside the water volume and cause ”spalling” on the opposite side of the volume.

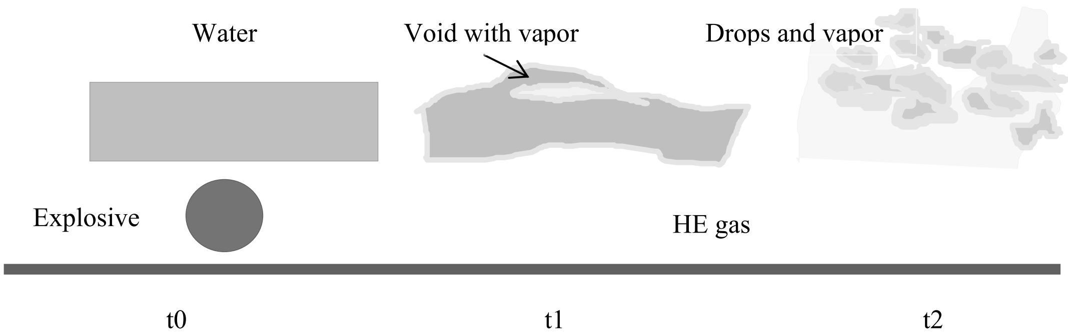

Figure 5. Possible initial behaviour of explosive-water at three stages: t_0, t_1 and t_2.

This will cause a void inside the water volume, which immediately fills with vapor. Due to the pressure gradient, the whole volume will also start to accelerate and be “smeared out”, and because of the different velocities in different locations inside, it seems likely that the volume is somewhat later broken up into a cloud of water drops of different sizes. During this process, heat is transferred from the hot HE gases to the water, both by heat radiation and by conduction. Simultaneously, a shock wave is developed in the gas between the drops which, in the case of a confined explosion, repeatedly will affect them with heat and acceleration when the wave is reflected against the walls. This will cause them to break-up into smaller droplets which, due to the resulting large increase of the total surface area of the water, also will increase the speed of heat transfer from the surrounding HE gas.

From the above, there is reason to believe that the heat transfer to (and vaporization of) water is of large importance for an explosion in a confined space. The cooling and phase transition will, despite of a slight pressure increase from the vaporization, result in a decrease of the overall pressure; the energy of the explosive is then to a large extent stored in the water as internal energy. In free air, on the other hand, large parts of the observed water mitigation effect might instead be caused by a mechanism when the water drops absorb a great deal of the kinetic energy from the expanding HE gas and thereby suppresses the air shock wave in the surrounding space.

2.4 Analyze methods.
Because of the above indicated differences in the water mitigation mechanisms due to the surrounding geometry, it is suggested to split the problem into three special cases according to figure 6. Case A: HE, water (and air) confined in a closed volume, case B: HE and water placed in free air, and finally case C: HE and water is partially confined, e.g. inside a tube with one end entering free air. Case B is only briefly treated here (more extensive in /5/, /7/ and /17); this paper concentrates on A and C and mixes between; i.e. a chamber with an attached duct.

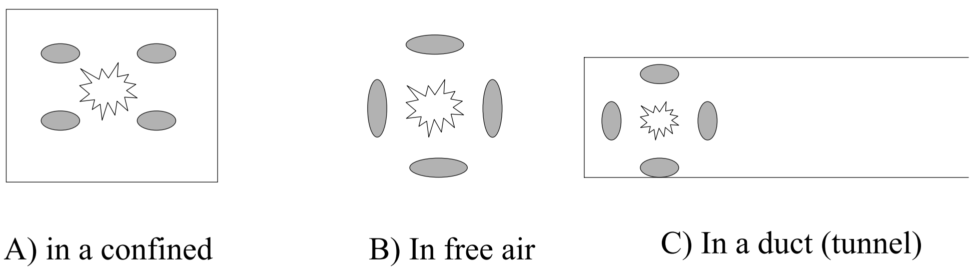

Figure 6. Suggested principal cases for the geometry around the HE –water arrangement.

A numerical model to completely simulate the situations above should consider diffusion and heat transfer, both from conduction and radiation between the HE gases, air and water. It should also deal with the formation of droplets when the water volume is crushed, accelerated and vaporized, as well as condensing of the vapor into droplets if cooled at a later stage. If the process takes place close to a structure (e.g. inside a duct or chamber) the model should deal with friction and heat transfer to the walls as well. All these extensions are today possible with advanced CFD codes, however at a high cost. As a first approach, a numerical method is suggested which is applicable for the case A and (possibly) C in figure 6. It is easily implemented by a hydrocode with a two-phase liquid-gas material model, as follows:

1. Assume that the water absorbs all of the energy released from the explosive (HE).
2. Replace HE with hot, pressurized water with similar energy, using the two-phase model.
3. Use an ideal gas model to fill the remaining space with air at NTP (”normal” pressure and temp)

When initiated, the water temperature should be close to the critical point (647 K) in order to provide a possibility for a maximum amount of water to vaporize (for a case with an excess of water compared to the HE energy, that part could be modeled as one phase material). After initiation, the water volume will start to vaporize, expand and ”push” the surrounding air into shock-waves. The method is very approximate, especially for the initial interaction water - explosive; still it can illustrate some important phenomena for an explosion with high loading density in a chamber and also inside and outside an attached tunnel. Implemented on AUTODYN /9/ the model neglects heat transfer, viscosity and friction.

In the Appendix an AUTODYN model according to the above method is applied on the FOA tests described in /17/. The steel-cased 1.5 kg plastic explosive was, due ca 25% expected initial losses when the case fragmentizes, modeled as 1.1 kg PETN without water. The test with water was modeled with a similar energy in 3 kg hot pressurized water as the only ”explosive”. Figure 9 in the Appendix shows the test set-up, figure 10 the numerical model and the following figures (11-17) shows pressure-time histories from the target points in the numerical model and recorded data from the gages in the experiment for comparison.

3. Review of experiments (referring to the geometry cases "ABC” in figure 6)

A was investigated at FOA Grindsjon in 1994 by Forse’n (reported in /2/) where 0.5 kg HE surrounded by 2.5 kg water in plastic bags was detonated in a 1.2x1.5x 2.0 (3.6 m^3) closed explosion chamber with pressure gages mounted inside. Two tests with water were compared with 0.2 kg HE without water. In both cases there was also a concrete slab mounted as one of the cubes’ six walls. From earlier tests it was known, that this wall collapses when 0.5 kg HE is detonated in the volume, but after these two tests it was almost unaffected. The pressure gages confirmed this result, and it was concluded that the water reduced the ”equivalent charge” by approx. 60 %. Similar tests were made by Ericsson /5/ in 1974, in smaller scale. However, all those tests must be regarded as a mix between case A and B because of their low loading density. Recently, a few small scale tests with higher density (4 kg/m^3) was made by FOA /17/. Full scale tests with ammunition magazines are reported by Keenan and Wager /1/.

B was investigated by Ericsson 1974 in small scale /5/, and by Vermuelen 1995 in larger scale /7/. Ericsson tested 50 gram TNT charges surrounded by 2x, 5x and 10x its’ weight by water. The charge was placed inside a balloon i.e. completely surrounded by water. The pressure was measured with gauges 0.7 meter from the charges. The results showed, that the peak pressure was reduced by approx. 5-20 % compared with bare charges, but one have to remember the scaling law for free field : $r / Q^{1/3}$; i.e. the actual

”equivalent charge” was reduced by at least 50%. Recently, also tests with 20, 30 and 40 gram plastic explosive surrounded by water hemispheres up to 1 kg have been reported by Rinaudo, Smith and Rose with similar results /15/. Tests reported by Vermuelen /7/ with 10 kg HE close to approx. 1 ton water stored in specially designed water-bags (”Dellex”), resulted in a 95% reduction of the side-on peak pressure near the site and a sound reduction of 12 dB on large distances (2000 meters).

C. A few tests were made by Ericsson 1974 /5/ but has recently been closer investigated by FOA in small, medium and large scale /2/,/3/,/4/. The tests are usually not ”clean case C” as they have a slight area change in the tube (large area changes are treated separately as “case A+C”, below)
In small scale, a 1:20 simplified model of the ”Klotz-tunnel” in Alvdalen was tested with 200 g HE surrounded by 400-600 g water in plastic cups (this corresponds to 1600 kg HE and 3200-4800 kg water in full scale). The explosion chamber was a tube with cross section 0.030 m^2, 1.25 m by length and was connected to a 3.75 m long steel pipe with cross-section 0.0144 m^2. Side-on pressure was measured in 3 locations: two gages were placed in the walls inside the pipe and one was located 1.25 m outside the pipe, right in front of the muzzle, where also a stagnation pressure gage was mounted in a few shots. Some of the results from the tests are published in /4/.
In medium scale, a number of tests have been performed with shock-tubes, most of them in ”tube4” (cross-section 1.8 m^2, FOA Marsta), a few also in ”tube3” (cross-section 4.4 m^2, also at FOA Marsta). The charge weight in ”tube4” was 1-5 kg HE , used with and without water bags and barrels in the range 1- 25 kg. With ”tube3”, tests were performed with charges up to 100 kg. The measured pressure-time histories, published in /2/ and /6/, are only from side-on pressure gages, which were located inside the tunnels at quite long distances away from the explosion chamber. No measurements of stagnation or dynamic pressure were made.
In large scale, one test was performed by the ”KLOTZ-Club” in Alvdalen 1996. The charge was artillery rounds, corresponding to 1000 kg HE in total. The geometry was similar to the small scale tests, but with some important exceptions: a) a tunnel crossing about 15 meters from the explosion site b) tunnel wall roughness was much larger, estimated to 0.2 m. c) the walls and the floor in the tunnel were (probably) wet. d) a barrier was built outside, in front of the tunnel exit. Measurements were made at several locations, both inside and outside the tunnel, but no gage was mounted close to the explosion site, and no measurement of stagnation or dynamic pressure was made inside the tunnel. The results (/3/) are ambiguous; the test is briefly discussed in section 4.

A+C: Some important tests made with models of ammunition storage magazines can be regarded as a ”mix” between geometry A and C. Their properties are expected to depend on some main geometry characteristics, as indicated in figure 7.

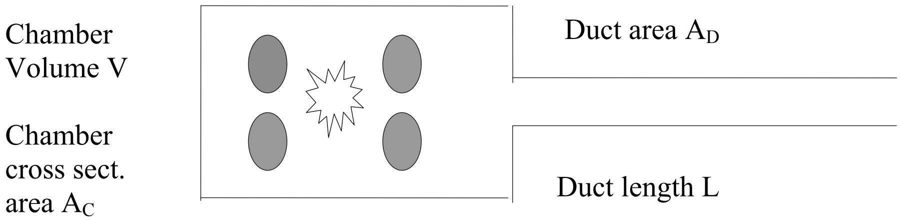

Figure 7. 'Mixed geometry' A + C (according to figure 6).

This type of structure has been tested by Joachim and Lunderman /16/. The chamber volume was 0.365 m^3, the duct area was 0.017 m^2 and its length 4.0 m. Charge densities in the range 1.67 to 5 kg/m^3 were tested with water / explosive ratios from 0.67 up to 3.3. The water was arranged so it completely surrounded the explosive. Measurements were made of the pressure inside the chamber, and in the duct both the side-on and the stagnation pressure gages were mounted. Similar gages were also located outside the test specimen. In short, the results indicate a lowering of the pressure in the chamber by about 70 % with water present, about the same figure also occurred for the *side-on* gages, both inside the duct and outside. The *stagnation* gages in the duct, however, showed less reduction with water: about 30-40 %. The results from the stagnation and side-on gages outside the duct (located on a plane surface ca 0.4 m below the exit) had no such large differences.

FOA recently made a similar test /17/ (also treated as "case A", above). Figure 9 in the Appendix shows a drawing of the structure and the gage locations used. The chamber volume was 0.4 m^3 with an attached circular duct, area 0.053m^2 and length 2.8 m. The charge density was 4 kg/m^3 and the water to explosive ratio 2; the water was arranged as two 'rings' around the cylindrical charge. The pressure inside the chamber was measured in 2 locations, and 2 gages for side-on pressure were located in the first part of the duct. Outside, a stagnation pressure gage was mounted on a distance of 2 meters, right in front of the duct's exit, together with a side-on gage in the same location. Altogether, 6 gages were used in this experiment. The results are quite similar to the tests made by Joachim and Lunderman, except that stagnation pressure was not measured inside the duct. Instead, the gage that was located right in front of the duct's exit (this gage had no counterpart in the Joachim and Lunderman tests) showed almost no reduction in stagnation pressure when water was present. However, considering that the stagnation pressure *inside* the duct, measured by Joachim and Lunderman, also indicated rather small reductions with water, this seems quite plausible.

The aim with the FOA tests was also to investigate if the water mitigation was affected if the charges were steel-cased or not; this refers to the Alvdalen test /3/ where artillery rounds were used. The charge in the model tests were thereby cased in a hollow, pre-fragmented steel cylinder, weighing 4.5 kg. No such effect could, however, be noted with any significance, /17/ p.12.

4 Discussion

From the experiments, it seems likely that the water mitigation works well for the principal cases A and B, provided there is, by some means, a ”balance” in how the water and the explosive is arranged; the expression ”balance” is used because ”loading density” is only applicable to confined spaces as case A, possibly to case A-C, but not for the cases B and C.

Case A: The energy of the explosive vaporizes the water and is to a large extent stored in the HoV (this is valid for charge densities of some kg/m^3; low charge densities approaches case B below). The vapor is likely to cool down slowly in contact with the chamber walls, which also absorb the HoV when the vapor later is condensed to liquid water. If small leaks from holes and slots in the chamber occur, they contribute to increase the speed of the pressure decay; large leaks are treated below as case A+C. The effect of different loading densities on the mitigation capacity is briefly discussed by Keenan and Wager (/1/, Chapt.3.2).

Case B is somewhat more complicated. Only a small part of the water is likely to immediately evaporate by the heat energy from the explosive; the major part will probably remain as liquid water, accelerated by the expanding HE gases, broken up into droplets and thereby absorbing kinetic energy from the shock-wave, as described in section 2.2. Even later, evaporation and condensation may occur, close to the detonation point where the droplets and vapor relatively slowly flows out in all directions. This process will however not contribute to the fast shock-wave in free air, that is now far away from this area and hence will remain mitigated. With this explanation, it seems likely that the initial geometrical arrangement water-explosive will have a great influence on the result, which is in accordance with several experiments reported, e.g. /5/ and /15/. This is also valid for case A with low charge densities.

Case C might be the most complicated one; below some phenomena are suggested, believed to be of importance for this case. Assume that, similar to case A, the water is immediately heated by the HE, and a (partially) confined volume of air, HE gas, water drops and vapor at high pressure and temperature (however lower than without water) is formed. But, compared to case A one wall is missing, so the vapor- HE gas mix starts to expand in that direction through the tunnel, pushing the air that initially was there in front of it, which forms an air shock wave. In this situation, at least three sub-cases (C1, C2, C3) should be considered:

C1 The tunnel walls are smooth and dry; a contact surface might then occur between the mix of vapor and HE gases and the air inside the tunnel, as described in section 2.3. When the vapor behind the air shock front expands it might start to condense due to cooling from the tunnel walls, or when it expands in cool air outside the exit. When a shock-wave flow in gas phase leaves a tunnel exit, a jet is formed where the static and dynamic pressure differ significantly, as described in section 2.1. The static pressure in the wave front could be quite unaffected by the vapor, but the later arriving dynamic pressure increase is likely to be influenced, e.g. by a higher density and a change of gas velocity inside the jet. This is also in accordance with the calculated jet outside a duct attached to an explosion chamber, shown in the Appendix (figure 17).

C2 The tunnel walls are rough; the vapor and the surrounding air will now mix to a much larger extent which will put the vapor with its high internal energy closer the shock front; the front is also slowed down and mitigated by the wall roughness. It seems likely that this affects the shock front when it leaves the muzzle in some way. In order to separate such an effect from the mitigation due to the wall roughness, a comparison with expected data from a similar one-phase flow can be made, either from empirical data or from a hydrocode calculation with viscosity, friction and heat transfer included (e.g. the RCM code “OneD” /10/).

C3 The tunnel walls are wet before the explosion, which can increase the amount of water and vapor in the flow as the shock front might absorb water from the floor and walls as is ”sweeps” along the tunnel. This was indicated when the small scale tests (reported in /4/) were made. The experimentalists noted that in order to obtain reliable results, with and without water, it was important to get the test specimen completely dry between the tests. This is a memento when efforts are made to analyze the full scale test in Alvdalen, where the tunnel probably was soaked with an unknown amount of water inside, possibly also where the charge was located. This could have been the case, both for the “water mitigation” test /3/ in 1996 as well as the reference test “without water” /12/, made in 1989.

A+C ’mixed geometry’. In the Appendix, results from the experiments made by FOA /17/ and computer runs with this geometry are shown, together with the results reported by Joachim and Lunderman /16/ they form the background for the following comments (figure 8):

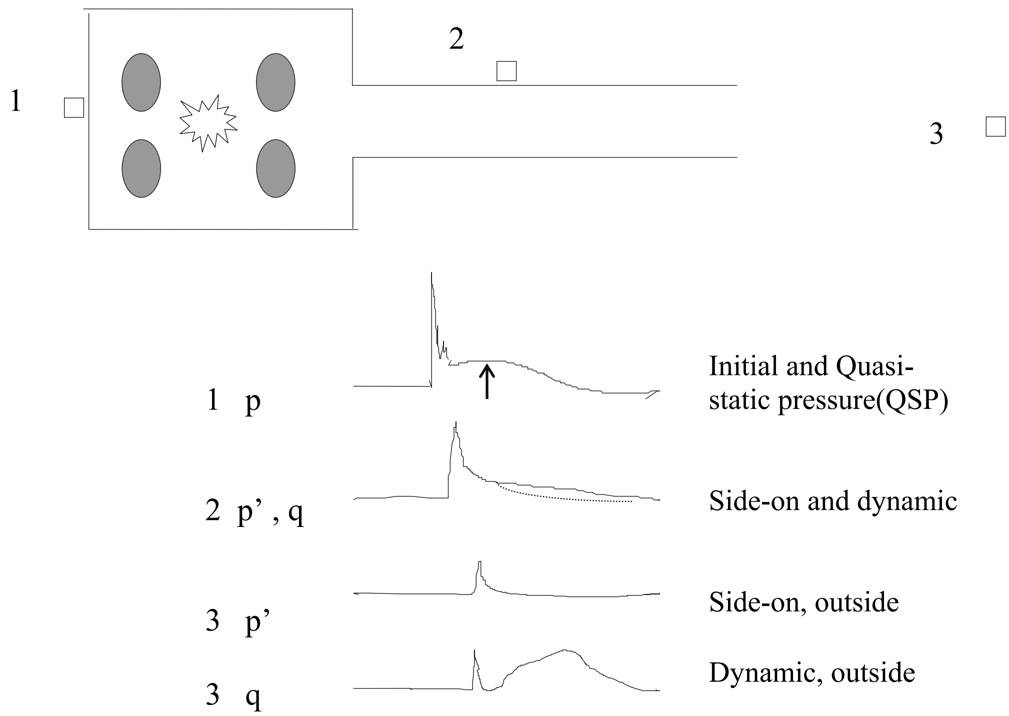

Figure 8. ‘Mixed geometry’ with typical pressure traces (not to scale)

Gage 1 first senses pressure peakfrom the initial wave front from the explosion, only partially affected by the water (its height is very dependent on the geometry arrangement explosive-water). Then, similar to case A above, the hot gases from the explosive builds up a Quasi-Static Pressure (QSP), as indicated in the figure. The QSP amplitude not only depends on the explosive to chamber volume ratio Q/V; it is also affected if the attached duct’s cross-section area is large (the geometry then approaches case C). With water present the HE gases are cooled which results in less QSP build-up. (This might look like a contradiction, as the water when vaporized demands more volume and causes a QSP increase itself, but when calculated this effect is found to be much less than the former, i.e. the pressure reduction due to cooling dominates).

Gage 2 first senses the (damped) initial peak, previously recorded by gage 1, followed by a gas flow caused by the QSP in the chamber. The relation between the side-on and stagnation pressure depends on the density of the gas, as described in section 2.1. A comparison between tests with and without water made by Joachim and Lunderman (/16/, Table 2) shows a large reduction of the side-on pressure but the reduction of the stagnation (and thereby the dynamic) pressure is less, which indicates that the density of the flow is higher when water is present. This is expected; as was stated in section 2.2 water vapor has a much higher density than the hot gases from the explosive.

The same explanation is also relevant for *gage location 3* when hit by the steam jet outside the muzzle. The tests reported in /16/, that don't have the stagnation gages right in front of the tube exit, showed about the same low pressure as the side-on gages in the same locations. This must indicate that they were outside the range of the jet; they were located on a plane, about 3 diameters below the tube centerline. The numerical model from the FOA tests also shows that the resulting jets are rather narrow (Appendix, figure 17). The results from target point 6 inside the jet show that the flow velocity is 3 times higher without water, but as the density is then only ca 1/8th the change in dynamic pressure is almost cancelled, see table 2.

Calculated, 20 milliseconds after expl. in target point#6	Flow velocity	Flow density	Dynamic pressure ($q = ½ v^2\rho$)
Without water	1800 m/s	0.1 kg/m3	324 kPa
With water	600 m/s	0.8 kg/m3	288 kPa

Table 2. Calculated properties of the flow outside the duct (for the FOA tests).

The dynamic pressure is approx. 300 kPa in both cases, which is in accordance with the traces from gage # 6 in the FOA experiments, shown in figure 13 in the Appendix.

4.1. Concluding remarks.

From the reported analyses and experimental data, it seems that the water mitigation technique works well, concerning the quasi-static pressure for confined explosions with loading densities in the range of some kg/m^3. But, if there is a small opening or an attached duct where the gases slowly leak out it can be noted that the *duration* of the QSP increases compared to a case without water. This is naturally caused by the lower gas flow velocity due to a lower pressure difference to the free air outside the structure, in combination with the larger mass present when the water vapor (and/or mist) is added to the HE gases. This increased total mass also causes a high dynamic pressure of the flow, both inside the duct and especially outside the exit; its amplitude might there be almost as large as for a case without water, despite of the reduced flow velocity. For a real situation with an exploding ammunition storage magazine with access tunnels, this dynamic pressure can cause a jet inside and outside the tunnel that is capable of throwing heavy debris quite a long distance. However, the total risk area for debris might still be reduced by the water mitigation technique, because the lower flow velocity will be unable to accelerate light debris to the very high velocities (thousands of m/s) that are typical from GP bombs detonating in free air.

Finally, it should be pointed out that there are several other mechanisms to consider for a risk analysis for ammunition storage with water than is treated here; there might as well be several possibilities to overcome the above indicated drawbacks of this technique.

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Results from numerical model, compared to experimental data

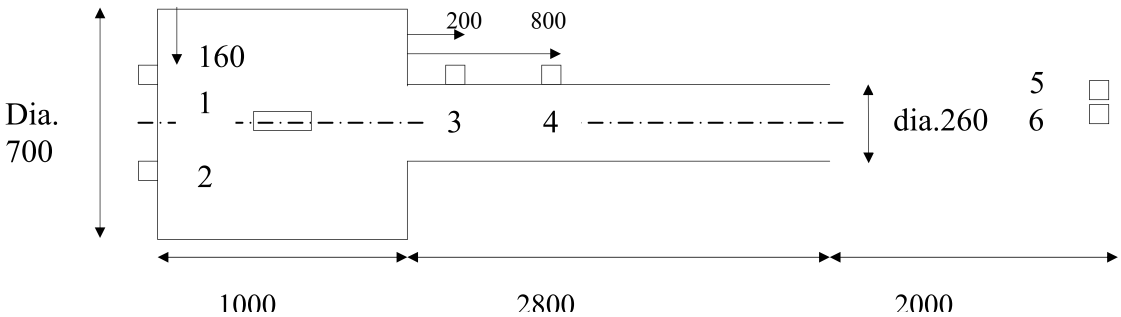


Figure 9. Test specimen (in mm). In the following pages, calculated pressure histories from target points 2 and 6 are compared with experimental traces in the corresponding gage locations

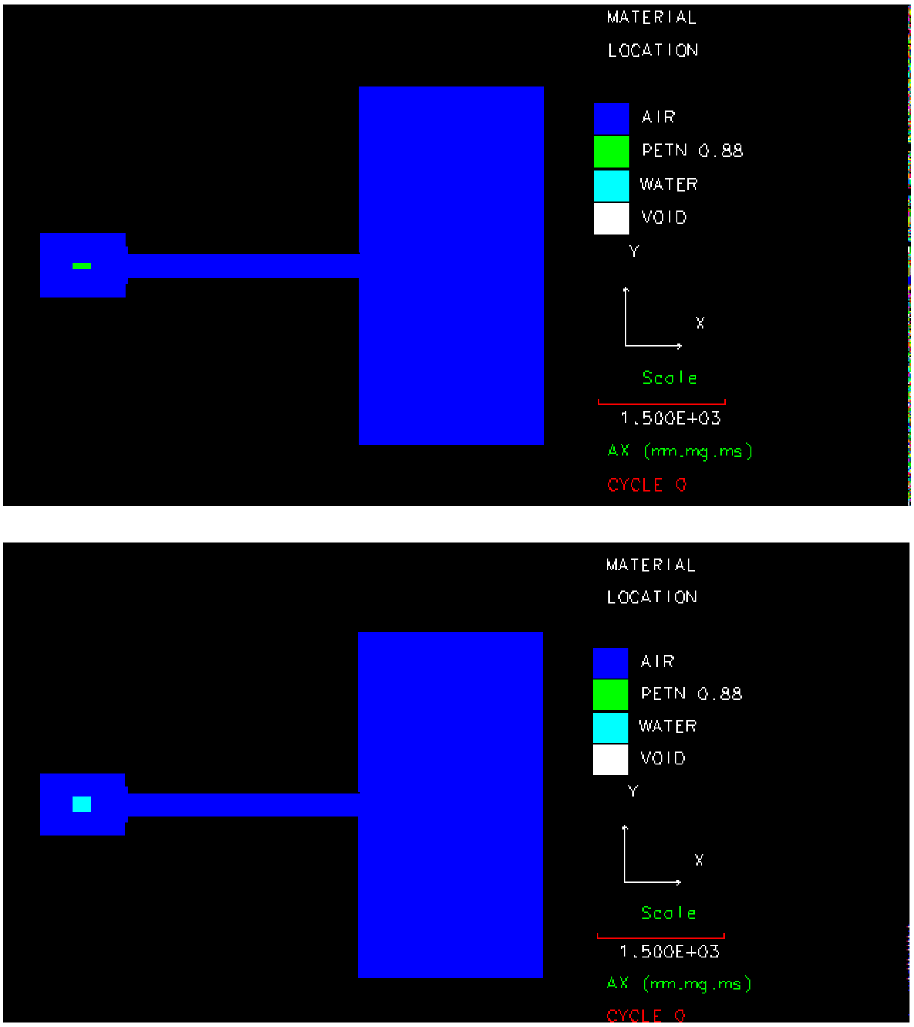
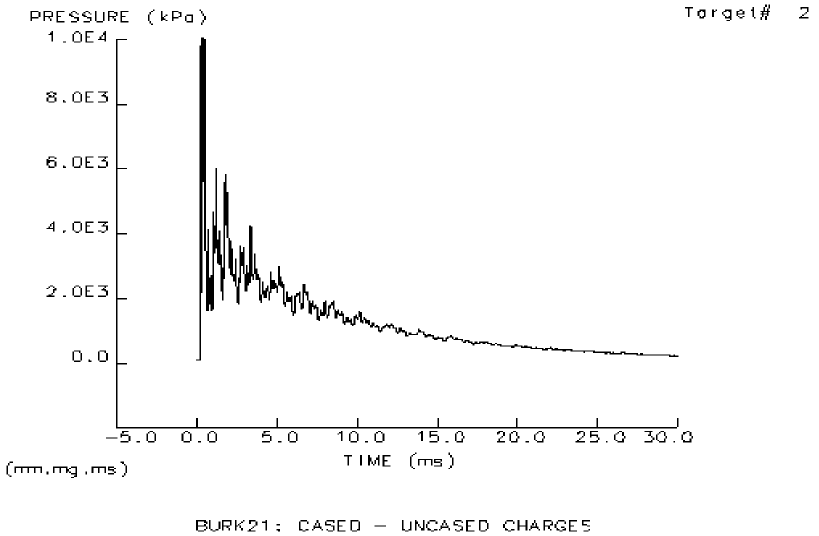


Figure 10. Numerical model on the FOA tests /17/, made with AUTODYN.



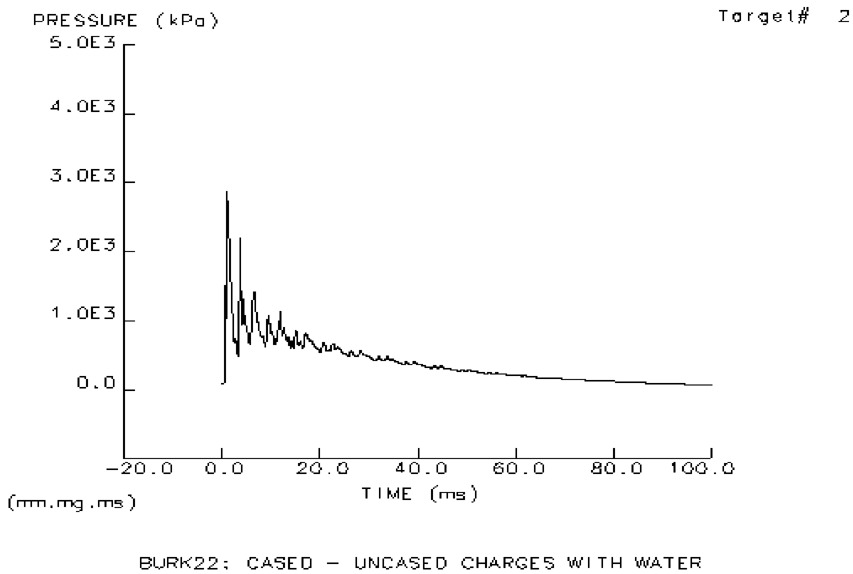


Figure 11. Calculated pressure-time history, inside explosion chamber without water (upper), with water (lower) ***; note: different scales***

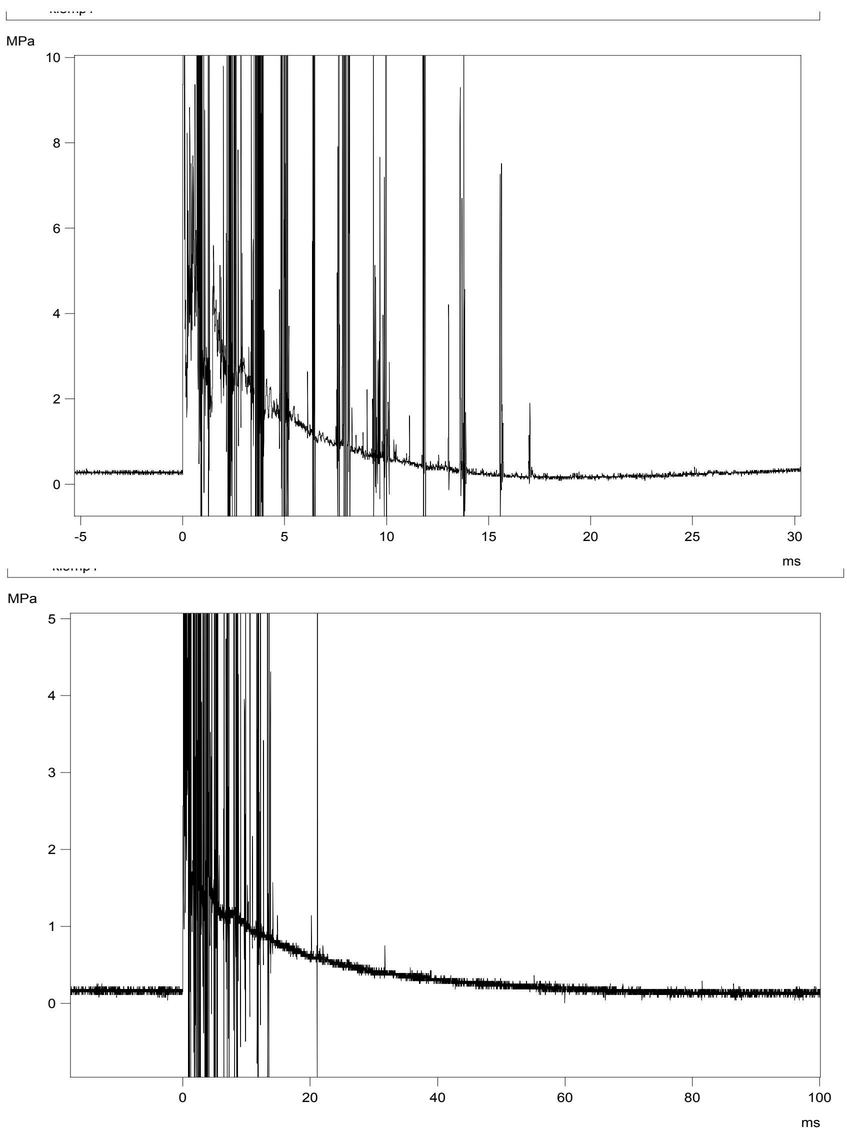


Figure 12. Experimental data: Pressure-time history inside explosion chamber gage#2, without water (upper), with water (lower)(Note the different scales, both on pressure and time axis between the registrations. The disturbances on the traces might be caused by debris impacts on the wall, near the gage)

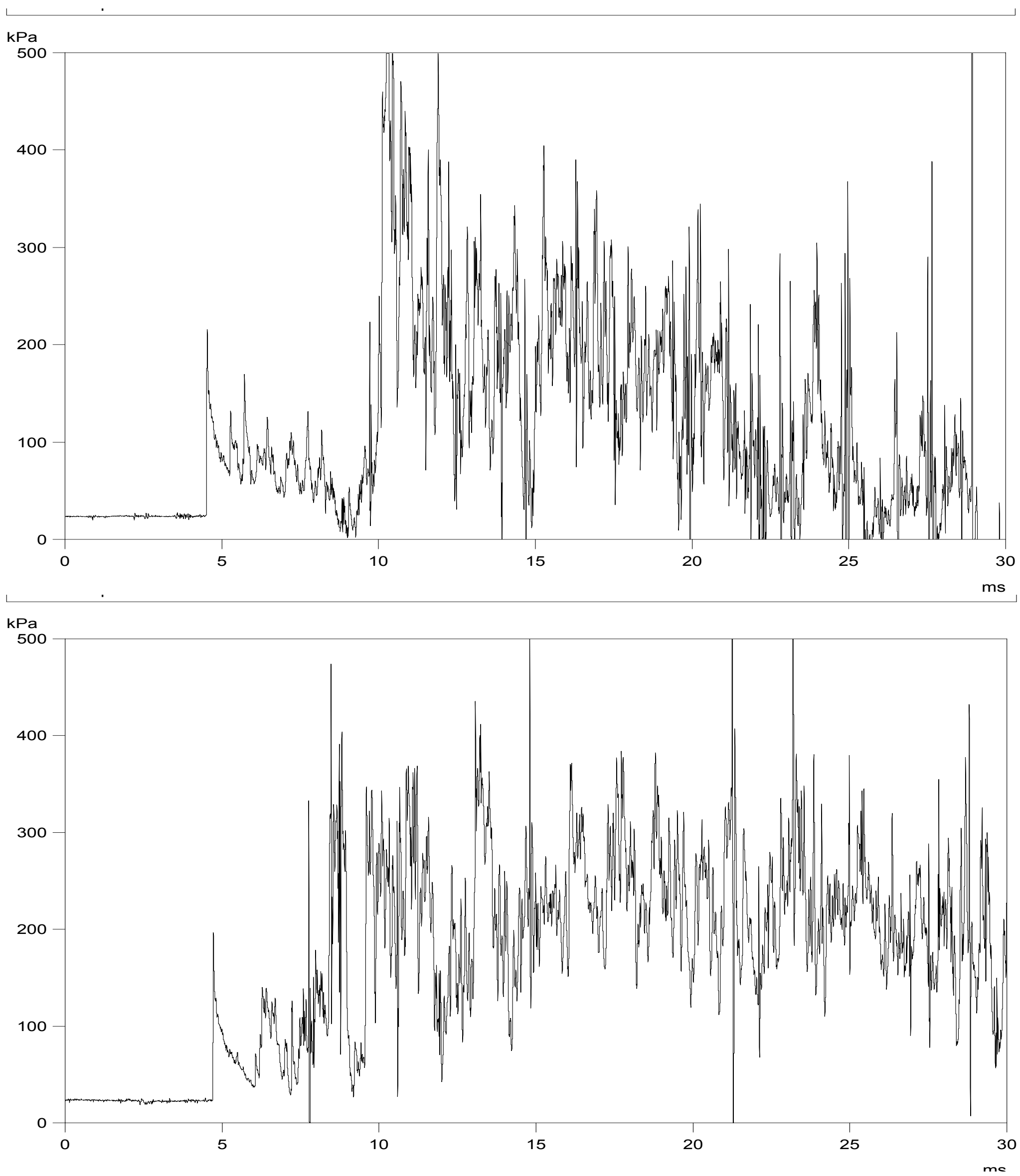


Figure 13. *Experimental data: Stagnation pressure 2 m in front of duct (gage#6) without (upper), with water (lower). Approximates the dynamic pressure, except the first peak at 5 ms.*

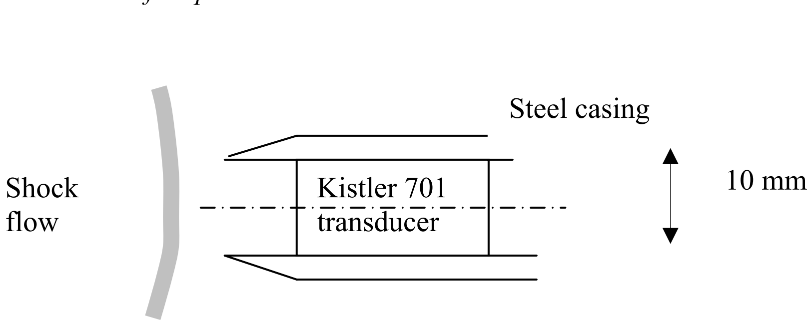
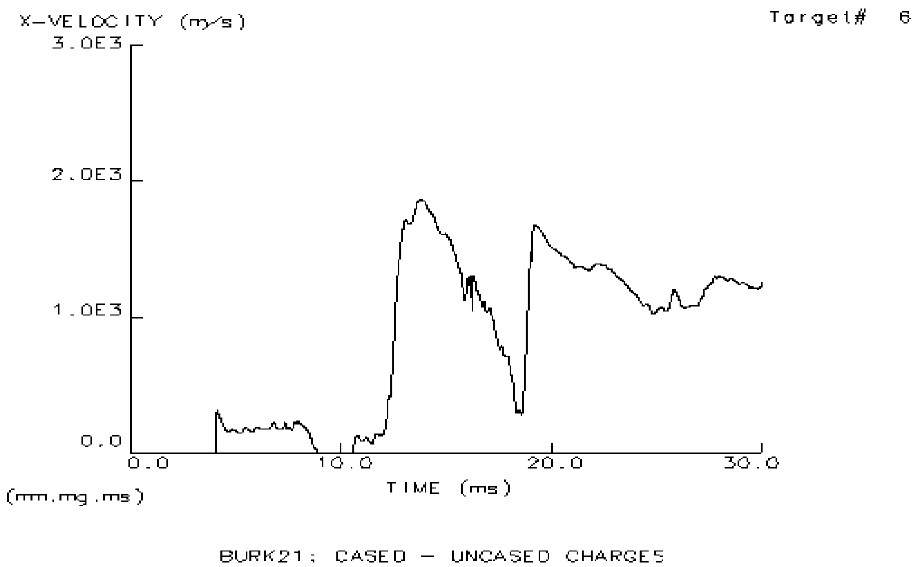


Figure 14. *Principal sketch of the used stagnation pressure gage.*



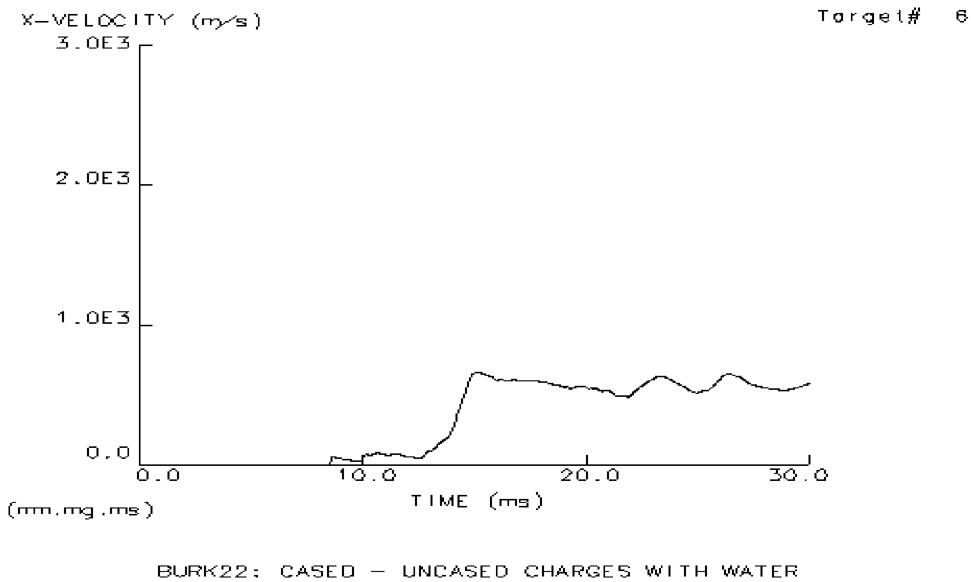
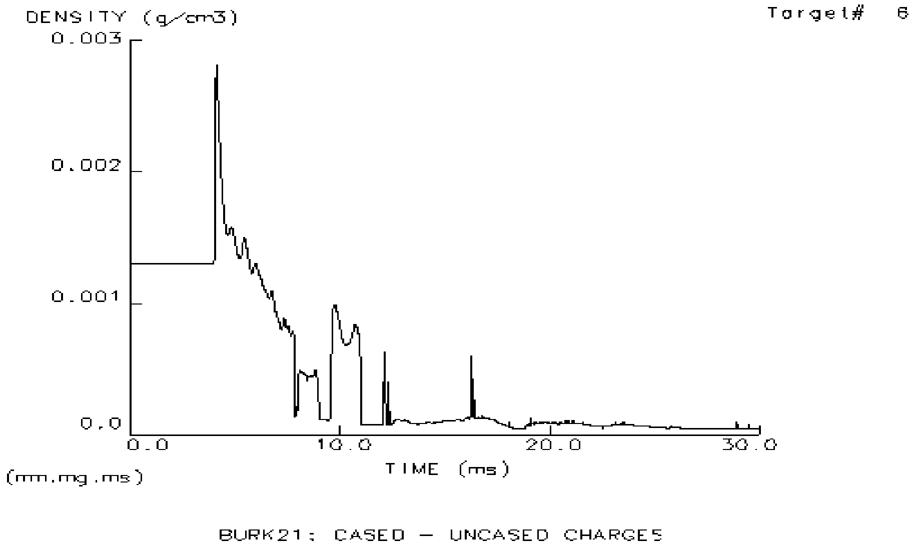


Figure 15. Calculated histories of flow speed in target #6 for the two cases: without water(upper)/ with water (lower)



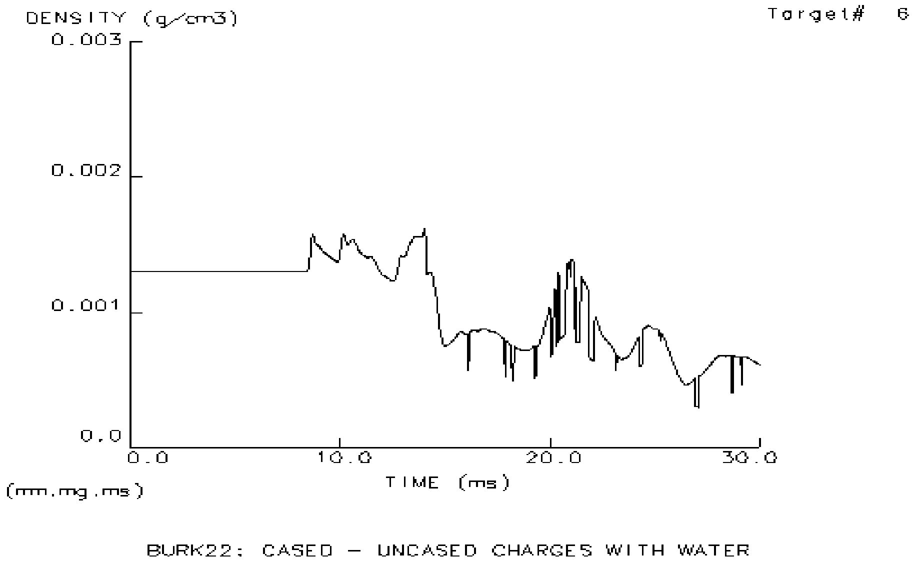
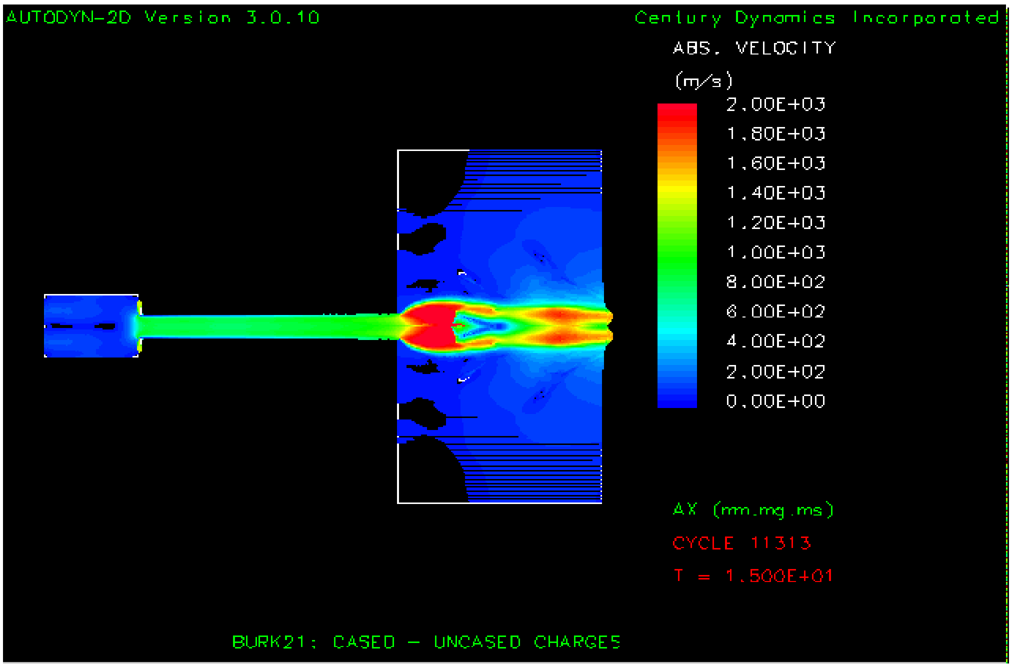


Figure 16. Calculated histories of density in target #6 for the two cases: without / with water. Note: The notches in the density curves are caused by the different agents (HE gas, air, water/vapor) present in the target location at different times.



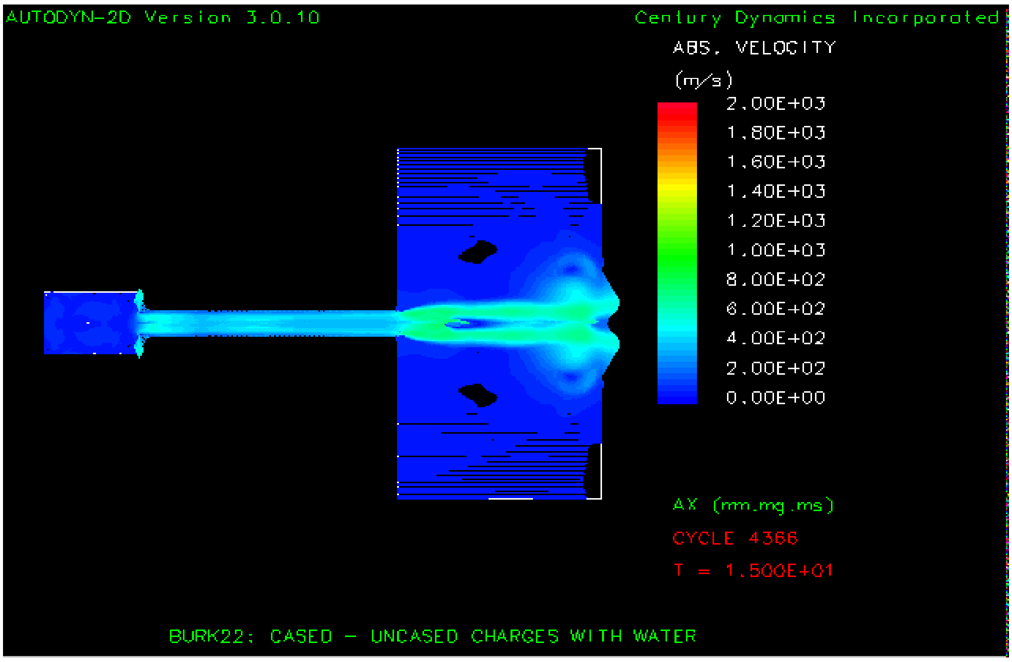


Figure 17. Calculated jets outside the muzzle after 15 milliseconds, without / with water. Note: target #6 (inside jets) was located 90 mm from the centreline of the duct (dia. 260 mm).

Appendix C Paper 3

29th DDESB ESS, 18th –20th July 2000, New Orleans, USA

WATER MITIGATION OF EXPLOSION EFFECTS
EXPERIMENTAL PARAMETRIC STUDY

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1. Introduction

Several experimental research programmes have indicated that explosion effects can be reduced by placing water in the vicinity of a detonating charge. Particularly, in case of a confined explosion, water has the potential to mitigate the shock pressure as well as the gas pressure loading developed inside the confining structure. This water mitigation concept can be exploited in the design and operation of new and existing military facilities exposed to the threat of internal explosions, like ammunition handling and storage sites.

In 1997, a co-operative research project was defined between FOA in Sweden and TNO-PML in The Netherlands, aimed at investigating the physics of water mitigation and to formulate instructions and standards of how to use water barriers. The TNO-Prins Maurits Laboratory focused their research on the spatial and temporal distribution of the different energy terms involved, and the influence of different parameters, e.g. the water-to-charge ratio and the stand-off distance, on the mitigation effect.

At the 28th ESS conference in Orlando the results of the first phase of the study, involving calculations with the thermodynamics codes CHEETAH and numerical simulations with the hydrocode AUTODYN, were presented (Absil et. al. 1998). From this analysis it could be concluded that the mitigation effect can only be partly explained by the evaporation of the water droplets, and that in some cases the mitigation effect is caused by the redistribution of the internal and kinetic energy over the detonation gasses, the blast wave and the barrier material.

In the present paper, the results of an experimental parametric study will be presented. Tests were conducted in two 1 m diameter, 1.3 m long explosion chambers, one closed and one provided with a 25 cm diameter duct. The last vessel is similar to the one used by FOA. For a bare charge of 200 gram of HE with a length-to-diameter ratio of 3, the amount of water, the water stand-off distance and the capturing angle was varied. The blast as well as the quasi-static pressure was measured inside the explosion chambers. From the measurement results guidelines for the use of water barriers can be derived.

Attempts were also made to visualise the break-up of water filled containers under blast loading by using X-ray. Although it proved hard to record any pictures, from the few successful recordings it could be concluded that the container was only slightly damaged by the blast and that the water is ejected out of the container as water jets.

2. Experimental set-up

The parametric study has been conducted in two cylindrical vessels. The vessels were identical, except that one was provided with a venting tube. Figure 1 shows a schematic of the two vessels with the instrumentation. Both vessels have a diameter of 1 m and a length of 1.3 m. Vessel 1 was closed, while vessel 2 was provided with a 1 m long, 25 cm diameter duct.

Both vessels were provided with 2 face-on pressure transducers, mounted 90° apart, at the middle of the vessel. A pressure transducer was also mounted in the wall of the duct. These pressure gauges are piezo-electric sensors of the Endevco 8511 A type. The sensors were protected with silicon grease against the high thermal radiation. The pressure readings were recorded using Digistar II recorders. In order to measure the dynamic pressure just outside the duct, a pitot-tube, consisting of a face-on transducer and a side-on pressure gauge was placed in the flow field, just outside the duct. Unfortunately, this transducer was demolished during one of the first tests, due to the debris blown out of the vessel.

The charges were placed at the centreline of the vessel. In the first tests, the charge was hung in the middle. Due to the debris originating from water container-material, in a number of trials the face-on pressure gauges were damaged. Therefore, in later tests it was decided to place the charge out of the centre of the vessel, at a distance of 32.5 cm from the back plate of the vessel. Two types of explosives were used: plastic explosive DM12 and compressed TNT. DM12 consists of 85% mass fraction of PETN and 15% oil and has a TNT equivalence of 1.09. Different charges-weights of 50, 100 and 200 gram of DM12 were used and 220 gram of TNT. The length-to-diameter ratio of the charges was selected approximately 3:1, as is the case for most ammunition articles, like shells and grenades. An electric detonator

nr. 8, containing 1 gram of explosives, was used to initiate the charges. The detonator was placed in the middle of the DM12 charge.
Reference tests were conducted with bare charges as well as with charges surrounded by container-material. Next, to study the mitigation effect, tests were also conducted with water barriers. These cylindrical water barriers were made out of 0.4 thick cardboard support cylinders, enclosed by "icecube" packs filled with water. The icecube packs were used to obtain an approximate homogeneous distribution of the water over the cylinder as to achieve a water layer of constant thickness over the cylinder. Figure 2 shows the experimental set-up.

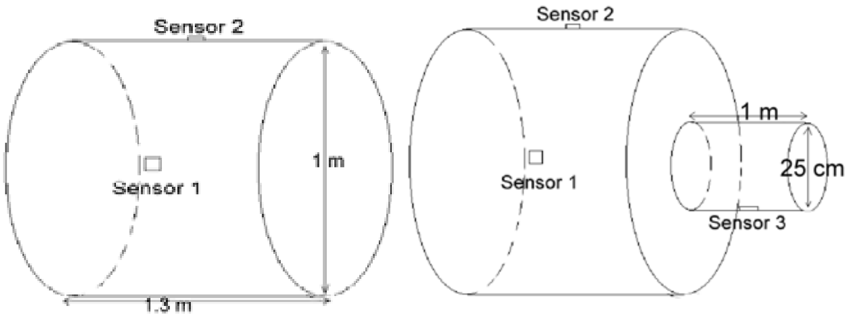

Figure 1. Schematic of the two vessels

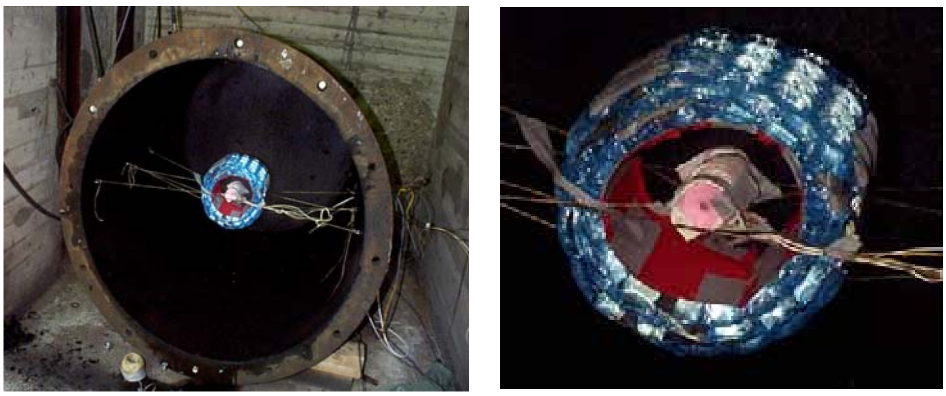

Figure 2. Experimental set-up of charge enclosed by water barrier

3. Measurement programme
To investigate the influence of the water-to-explosive weight ratio (W/Q), stand-off distance, weight of explosive and type of explosive, in total 39 tests were conducted. First 6 preliminary tests were conducted to determine the maximum loading density Q/V the vessel could take and to investigate the possibilities and limitations of the test set-up. Then, 25 tests were conducted in vessel 1 and 5 tests in vessel 2.

From the preliminary tests it could be concluded that with this test set-up the maximum QSP-level could be reproduced to within 5%. Due to overshoot and ringing of the pressure signals and the fact that the measurements were taken so close to the charge, the reproducibility of the peak overpressure however was only of the order of 20%. In addition, the way the cardboard water support cylinder was fixed around the charge also showed to affect the peak pressure measurement. This can be explained by the directional effect of the blast for the cylindrical charge and because of the variable blast resistance of the cardboard support cylinders. The impulse reproduces to within 5%.

The test conditions are summarised in Table 1.

Table 1. Test conditions

Test no.	charge				support cylinder	stand off distance	water before testing		
	type	weight	diameter	length	diameter		amount	length	thickness
		gram	cm	cm	cm	x * D_{charge}	x * W_{charge}	cm	mean (cm)
1	DM6	50	2.2	6.5	--	--	--	--	--
2	DM6	100	2.8	8	--	--	--	--	--
3	DM6	100	2.8	8	--	--	--	--	--
4	DM6	150	3	10	--	--	--	--	--
5	DM12	200	3.8	11	--	--	--	--	--
6	DM12	200	3.8	11	11.4	1.00	5	13	
7	DM12	200	4.2	9.5	--	--	--	--	--
8	DM12	200	4.2	9.5	--	--	--	--	--
9	DM12	200	4.2	9.5	17.5	1.6	--	--	--
10	DM12	200	4.2	9.5	17.5	1.6	--	--	--
11	DM12	200	4.2	9.5	17.5	1.6	4.9	13	2.6
12	DM12	200	4.2	9.5	17.5	1.6	10.1	13	5.0
13	DM12	200	4.2	9.5	17.5	1.6	15.7	13	7.3
14	DM12	200	4.2	9.5	10.5	0.8	--	--	--
15	DM12	200	4.2	9.5	10.5	0.8	3.1	13	2.6
16	DM12	200	4.2	9.5	10.5	0.8	7.1	13	5.3
17	DM12	200	4.2	9.5	10.5	0.8	11.3	13	7.7
18	DM12	200	4.2	9.5	11	0.8	1.3	9.75	1.5
19	DM12	200	4.2	9.5	10.5	0.8	1.8	9.75	2.0
20	DM12	200	4.2	9.5	12.6	1.00	--	--	--

21	DM12	200	4.2	9.5	21	2.00	--	--	--
22	DM12	200	4.2	9.5	12.6	1.00	3.8	13	2.6
23	DM12	200	4.2	9.5	21	2.00	5.7	13	2.5
24	DM12	200	4.2	9.5	17.5	1.6	1.3	9.75	1.0
25	TNT	220	4.2	11.2	12.6	1.00	0		-
26	TNT	220	4.2	11.2	12.6	1.00	3.2	13	2.5
27	DM12	100	3	9	9	1.00	0		-
28	DM12	50	2.7	8.1	8.1	1.00	0		-
29	DM12	100	3	9	9	1.00	3.3	9.75	2.2
30	DM12	50	2.7	8.1	8.1	1.00	3.9	9.75	1.4
31	DM12	200	4.2	17.5	17.5	1.6	3.00	9.75	2.1
32	DM12	200	4.2	10.5	10.5	0.8	3.1	13	2.6
33	DM12	200	4.2		10.5	0.8			-
34	DM12	200	4.2		10.5	0.8			-
35	TNT	220	4.2		12.5	1.00			-
36	DM12	200	4.2		10.5	0.8	1.8	9.75	2.0
37	DM12	200	4.2		10.5	0.8	3.1	13	2.6
38	TNT	220	4.2		12.5	1.00	3.2	13	2.5
39	DM12	200	4.2		10.5	0.8	7.1	13	5.3

Table 2. Test Results

Test no.	QSP			Peak values			
	QSP_{maxf} ace-on P1	$QSP_{max,}$ face-on P2	$QSP_{max,}$ side-on	P1	P2	P3	P4
	kPa	kPa	kPa	KPa	kPa	kPa	kPa
7	586	586		2400	2400		
8	546	546		3500	3000		
9	800	750		2750	2750		
10	734	734		2000	2400		
11	170	170		1250	1750		
12	141	141		750	1100		
13	111	111		2000	1000		
14	803	803		2250	2250		
15	184	184		1700	1700		
16	115	115		900	1100		
17	-	90		500	600		
18	397	-		2750	-		
19	405	405		1750	2000		
20	783	783		2500	3500		
21	818	818		3700	3500		
22	175	175		1800	1500		
23	204	-		1500	1750		
24	366	366		2600	2300		
25	869	869		2000	2000		
26	432	432		2500	6250		
27	553	553		1400	1000		
28	264	264		550	700		
29	95	95		850	950		
30	70	70		775	625		
31	208	208		1700	1700		
32	300	300		2500	1300		
33	529	540		1500	2200		
34	519	519	300	3100	2250		30
35	561	561	300	2000	2000	2000	28
36	275	275	85	4000	2400	750	14
37	145	145	2.4	1600	2000	600	12
38	188	188	12	2100	2300	1000	14
39	105	105	5	750	750	550	11

Test 1-6: preliminary tests; Test 7-32: closed vessel 1; Test 33- 39: vessel 2 with duct.

4. Measurement results

All test results, i.e. measured maximum quasi-static pressure and peak overpressures, are summarized in Table 2.

4.1 The influence of the water support cylinder

By comparison of the QSP and peak pressures as measured in tests 7 and 8 and 9 and 10, it is found that the casing material has a distinct effect on the values measured. Due to the cardboard support cylinder an increase in QSP of about 40% is found. This increase can be explained by the extra confinement of the charge and the strong directional effect of the cylinder. Hence, the effect of the support cylinder has to be accounted for in evaluating the water mitigation effect.

4.2 Mitigation of QSP-values

In Figure 3 and 4 the measured maximum QSP values are plotted as measured with pressure transducers P1 and P2 respectively. It includes all data as obtained from the tests conducted with 200 g DM 12 and 220 g TNT in closed vessel 1.

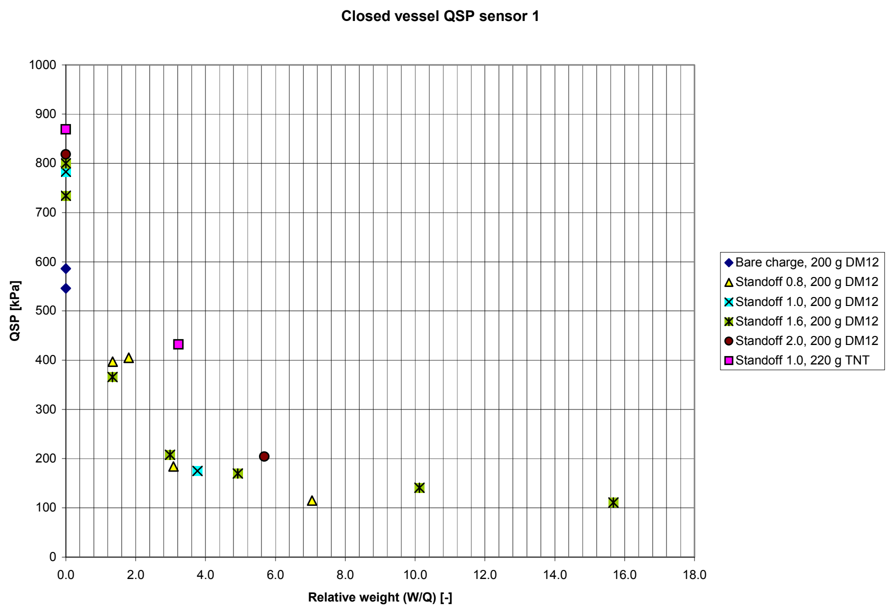

Figure 3. Maximum QSP values as measured with sensor 1 (vessel 1).

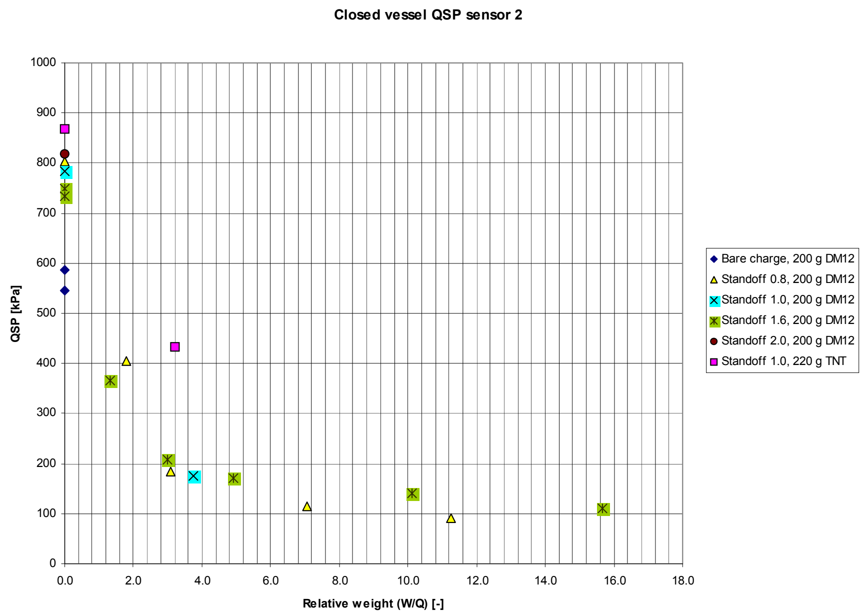

Figure 4. Maximum QSP values as measured with sensor 2 (vessel 1).

From these Figures it can be concluded that:

- the water mitigation effect is mainly determined by the water-to-charge weight ratio. The reduction shows an asymptotic approach with a maximum reduction of about 80%, which is reached when the water-to-charge ratio is larger than a factor of about 4.
- The stand-off distance only has a minor effect on the QSP reduction. The largest reduction is found when the water barrier is close to the charge.
- A smaller reduction is found for the TNT charge as compared to the DM21 charge, which has a TNT equivalence weight factor of 1.09. Hence, the reduction also depends on the type of explosive.

Figure 5, 6 and 7 show the measured maximum QSP values as measured with pressure transducers P1, P2 and P3 for the tests conducted in open Vessel 2. It includes all data as obtained from the tests conducted with 200 g DM 12 and 220 g TNT.

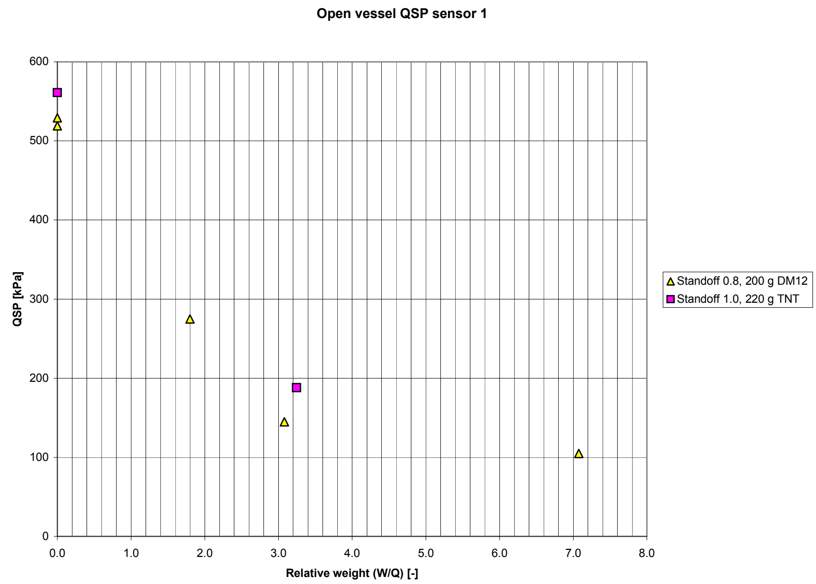

Figure 5. Maximum QSP values as measured with sensor 1 (vessel 2).

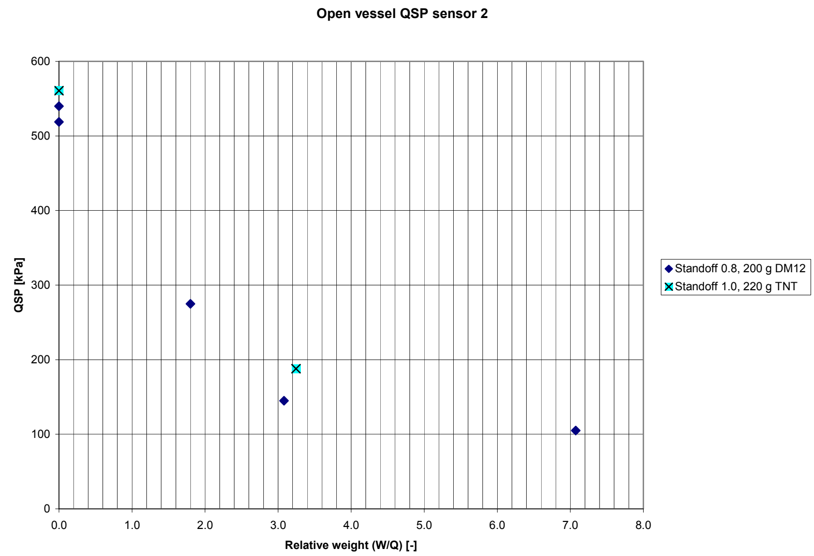

Figure 6. Maximum QSP values as measured with sensor 2 (vessel 2).

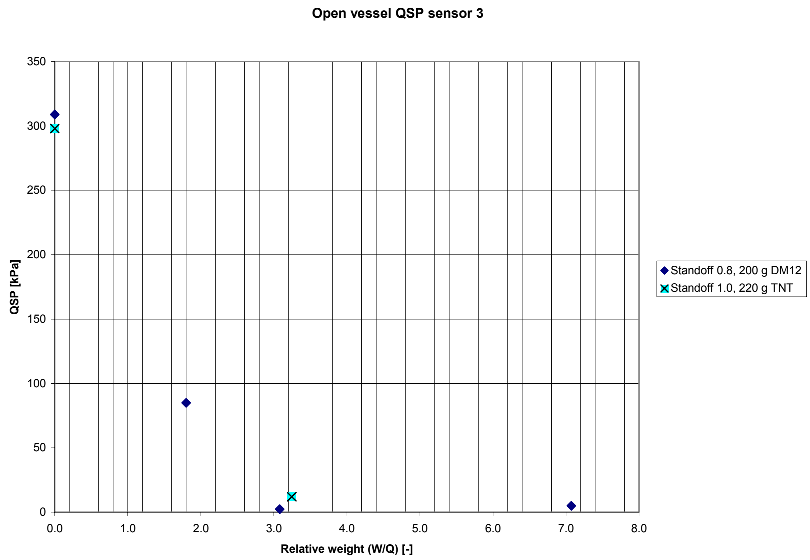

Figure 7. Maximum QSP values as measured with sensor 3 (vessel 2).

From these figures it can be concluded that:

- Also for the open vessel the reduction seems to depend highly on the water-to-charge ratio. Again an asymptotic approach is found, very similar to the one found for the closed vessel, and the maximum reduction seems to be reached at a water-to-ratio of about 4. The QSP as obtained in the duct as measured with transducer 3 is almost completely reduced when the water-to-charge ratio exceeds a factor of 3.
- For 220 g TNT a similar mitigation effect is found as for 200 g DM21.

4.3 Mitigation of peak overpressure values

In Figure 8 and 9 the measured peak overpressures are plotted as measured with pressure transducers P1 and P2 respectively. It includes all data as obtained from the tests conducted with 200 g DM 12 and 220 g TNT in closed vessel 1.

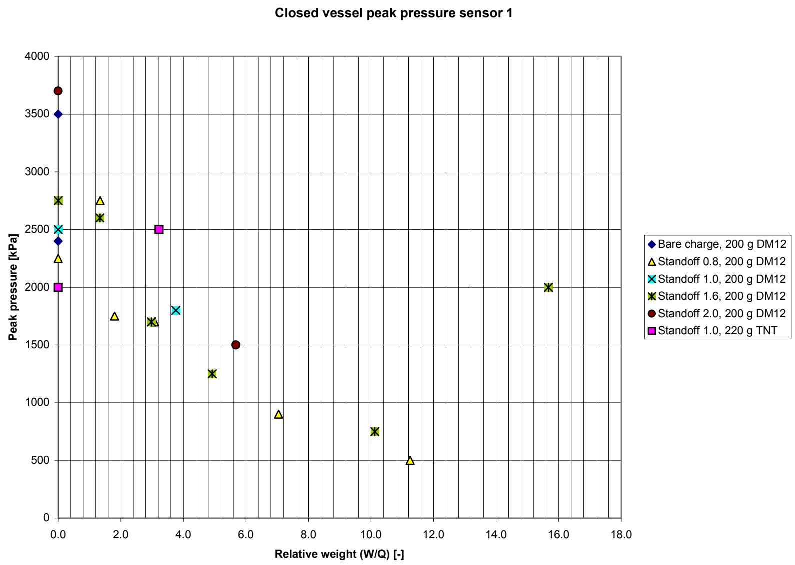

Figure 8. Maximum peak overpressure values as measured with sensor 1 (vessel 1).

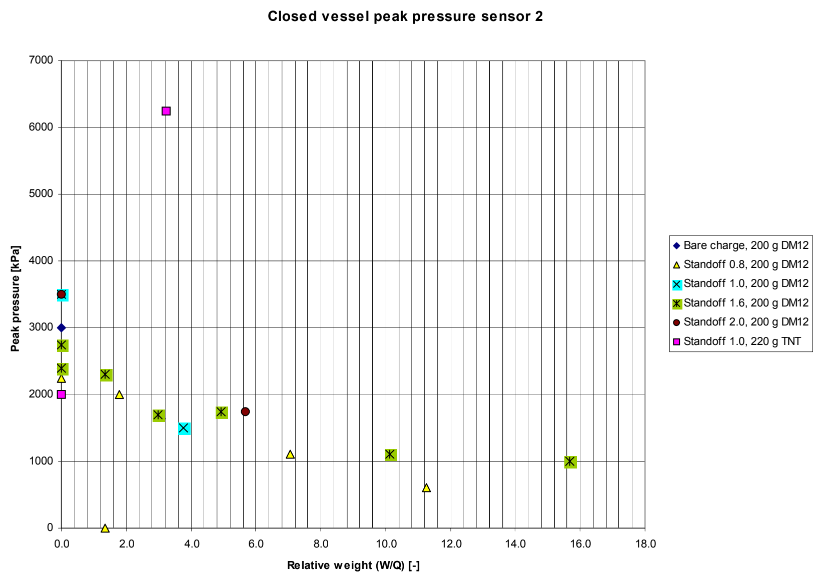

Figure 9. Maximum peak overpressure values as measured with sensor 2 (vessel 1).

From these figures the following conclusions can be drawn:

- The reduction in peak overpressure highly depends on the water-to-charge ratio. Again an asymptotic decay is found and the optimum reduction of about 85% in peak pressure is reached for W/Q>5.
- The stand-off distance only has a minor effect on the mitigation effect. The smaller the stand-off distance, the larger the reduction.

- The tests with 220 g TNT result in higher overpressure levels on both transducers. Too little experiments have been conducted with TNT in the open vessel to enable the drawing of firm conclusions.

The relatively high pressure level measured with sensor 1 for stand-off distance 1.6 and W/Q= 15.7 is probably due to an impacting piece of debris.

In Figure 10, 11, 12 and 14 the measured peak overpressures are plotted as measured with pressure transducers P1, P2, P3 and P4 respectively. It includes all data as obtained from the tests conducted with 200 g DM 12 and 220 g TNT in the open vessel 2.

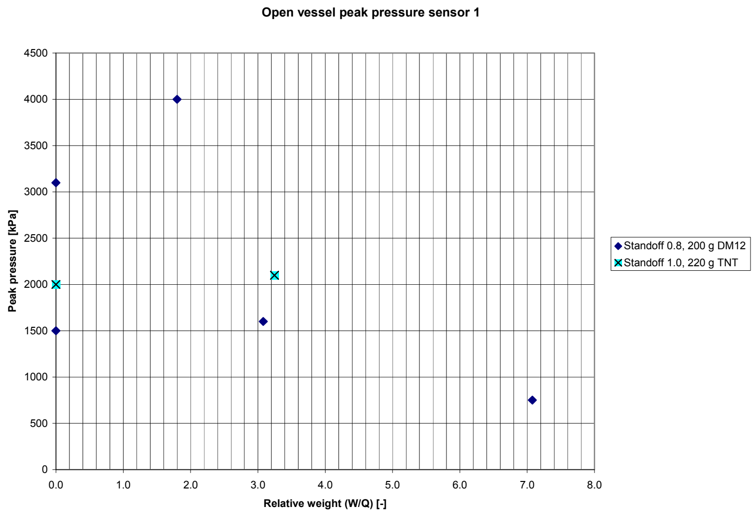

Figure 10. Maximum peak overpressure values as measured with sensor 1 (vessel 2).

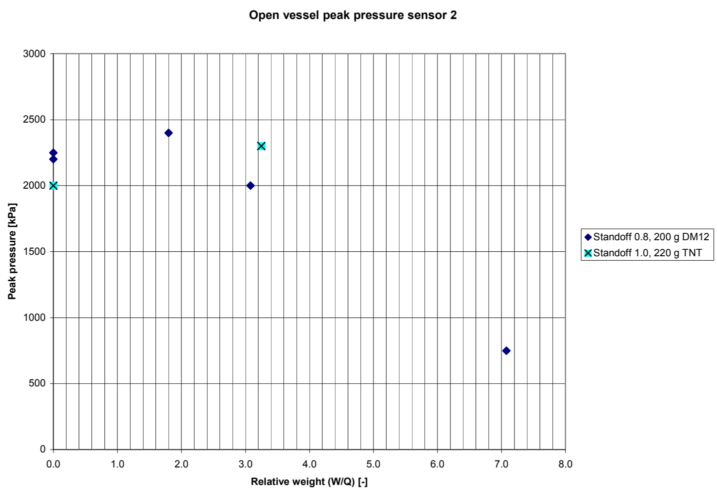

Figure 11. Maximum peak overpressure values as measured with sensor 2 (vessel 2).

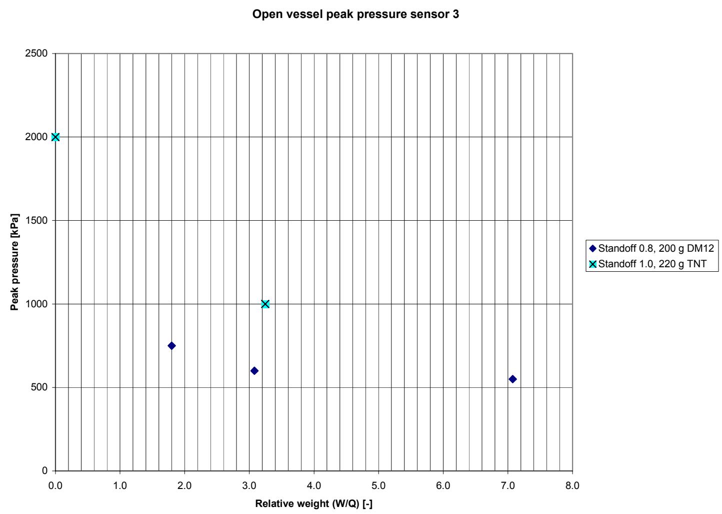

Figure 12. Maximum peak overpressure values as measured with sensor 3 (vessel 2).

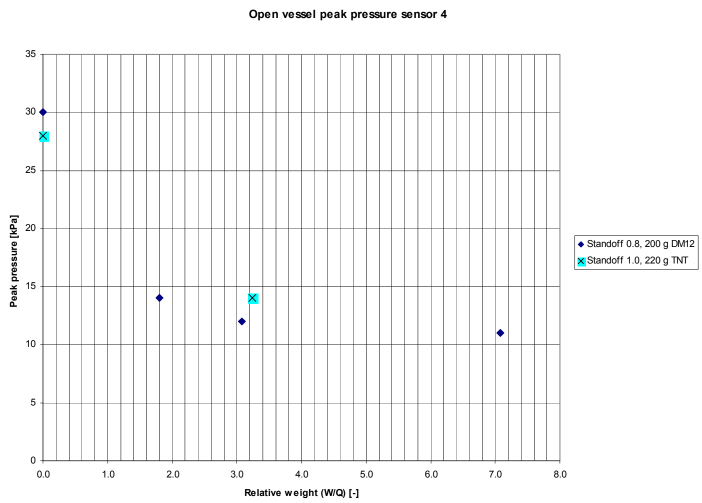

Figure 13. Maximum peak overpressure values as measured with sensor 4 (vessel 2).

From these Figures the following conclusions can be drawn:

- Overall, again the tests show an increase in pressure reduction with increasing water-to-charge ratio. Sensor 1 shows a typical high pressure level for the test with a water-to-charge ratio of 1.8. An asymptotic reduction of the peak pressure is also observed for sensors 3 and 4, which measure the side-on pressure in the duct and the dynamic pressure in the duct flow respectively. The maximum reduction is achieved for a water-to-charge ratio of about 5.
- For the tests with TNT, sensors 1 and 2 record only a minor mitigation effect, while sensors 3 and 4 indicate a decrease in pressure, though not as large as for DM21.

From the measured pressure signals also the impulse was calculated. Again a reduction in impulse was observed and was found to depend highly on the water-to-charge ratio. Like the pressure reduction, the impulse curve shows an asymptotic behaviour and the maximum impulse reduction is found for water-to-charge ratios larger than 5.

From the temperature measurements in the vessel it could be concluded that the temperature in the vessel changed from about 500 °C to about 100 °C when water was used. Hence, a clear cooling effect was observed. For water to charge ratio's of over a factor of 5 the temperature was cooled to about 50 °C.

4.4 The influence of the charge weight

To study the influence of the charge weight on the reduction, tests were conducted with 50, 100 and 200 gram of DM12 explosive. The water-to-charge ratio was kept constant in these trials, at W/Q=3.5. The results are summarised in Table 3. The reduction is expressed as the percentage of the pressure-level without water to the value with water barrier. From this table it can be concluded that the charge-weight only has a minor effect on the percentage reduction in QSP. The peak-overpressures, however, vary significantly without showing a clear trend. It should be noted, however, that these peak values showed a bad reproducibility.

Table 3. Influence of charge weight on pressure reduction

test	%QSP P1	%QSP P2	% peak value P1	% peak value P2
200 g DM12	22	22	72	43
100 g DM12	17	17	61	95
50 g DM12	27	27	141	89

4.5 The influence of the water capture angle.

One test has been conducted to obtain an indication of the influence of the capture angle of the water barrier. A photograph of the set-up is given in Figure 14. A comparison of the QSP and peak pressure results as obtained with this set-up with an enclosure degree of 63% to the full 100% enclosure is shown in Table 4. Again the results are expressed in percentage of mitigation. While a full enclosure results in a mitigation of down to 22.9%, the test with a capture angle of 63% results in a QSP reduction of 37.4 %. For the peak pressure reduction no clear trend was observed, much dependent on the location of the pressure transducer.

Table 4. Influence of the degree of enclosure

test	% QSP P1	% QSP P2	% Peak value P1	% Peak value P2
100 %	22.9	22.9	75.6	75.6
63 %	37.4	37.4	111.1	57.8

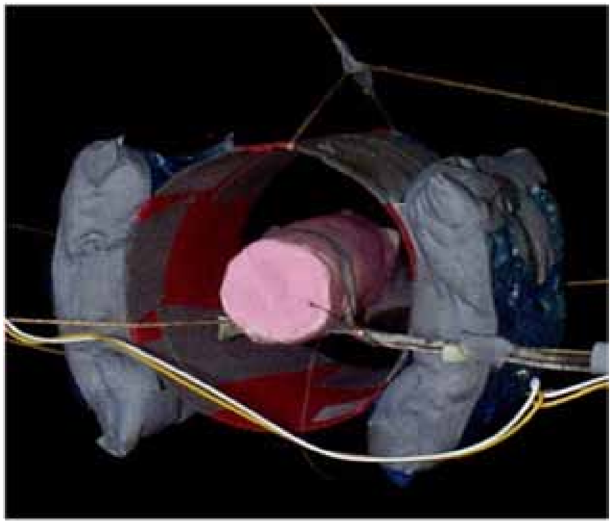

Figure 14. Test with an enclosure of 63% of the charge by the water barrier

5. Conclusions

From these tests the following overall conclusions can be drawn:

- the small scale tests confirmed the existence of the water mitigation effect: in the closed vessel a maximum reduction in QSP of about 80% is found;
- it is very challenging to conduct such "close-in" experiments, i.e. there is the threat of the pressure transducers getting damaged by debris;
- the water container and support material might also influence the peak pressure and QSP readings, and its effect should therefore by accounted for in assessing the actual mitigation effect;
- The QSP measurement showed to have a much better reproducibility than the peak overpressure. Therefore, the influence of the different parameters will be related to the QSP, though the influence on the peak pressure showed similar trends.

Concerning the influence of the different parameters on the QSPO reduction, the following conclusions can be drawn:

- the reduction in QSP is increased when the *water-to-charge ratio* is increased. The reduction shows an asymptotic behaviour and the highest reduction of 85% is found for water-to-charge ratios larger than 5;
- the QSP reduction is increased when the *stand-off distance* of the water barrier to the charge is decreased. Overall, the stand-off distance was found not to be very critical;
- the *weight of the charge*, varied from 50, 100 to 200 g in the tests, did not have a large influence on the percentage QSP reduction, achieved with the same water-to-charge ratio and stand-off distance.

- when TNT instead of DM12 was used, a lower QSP reduction was found, however, this variation in *type of explosive* only showed to have a minor effect on the mitigation.
- The *degree of enclosure* of the water barrier was also found to have an influence on the QSP reduction. As compared to the full enclosure, a 65% degree of enclosure showed a 15% lower QSP reduction. Hence, the optimum QSP reduction is achieved when the charge is fully enclosed by the water barrier.

The authors of the paper want to acknowledge the contribution of mr. Heinders and mr. van de Kasteele to the work.

6. References

1. L.H.J. Absil, H.J. Verbeek, Water mitigation of explosion effects. Part II: Redistribution of explosion energy, 28th DoD Explosives Safety Seminar, Orlando, 1998.

Appendix D Paper 4

29th DDESB ESS, 18th –20th July 2000, New Orleans, USA

Mitigation of Explosion Effects with Water: The pressure in partially confined spaces

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Abstract
The technique of damping blast from high explosives with ”water barriers” of different types has recently been studied by some research institutes and consultants. Examples on practical applications are to reduce the most severe hazard area around an ammunition storage, on equipment for manufacturing or the destruction of ammunition etc.

This work is a contribution to a co-operative research project defined in 1997 between FOA in Sweden and TNO-PML in the Netherlands, aimed at investigating the physics of water mitigation and to formulate instructions and standards of how to use water barriers. FOA has focused on the scale-modeling laws and to investigate if the mitigation is affected when the charges are cased.

The paper describes and analyses some experiments to study the blast mitigation effect from water for geometries similar to a duct attached to a confined space, e.g. an access tunnel in to an ammunition storage. Efforts has been made to reliably measure the pressure peaks as well as the quasi-static pressure (QSP) from pre-fragmented, steel-cased charges in an explosion chamber with loading densities up to 20 kg/m^3; the resulting static and dynamic pressure inside and outside a modeled access tunnel was also studied. Two test specimen that differed 3:1 in size were used in order to check for scale-modeling effects of the mitigation; the explosion chamber of the largest one measures 2 meters in diameter and 3.45 meters by length.

1. Background

On the 28th DDESB seminar in 1998, two papers were presented by FOA and TNO-PML in this research project with some ideas of the physical background for the water mitigation mechanism, illustrated by preliminary experimental results and calculations (/1/, /2/). Since then, new experiments and calculations has been performed, which have illustrated and verified those proposed mechanisms, with a few modifications.

In short, the proposed mechanisms for water mitigation of explosions are the following:
When a water volume is located close to a detonating charge, the expanding HE gas will, as it hits the closest water surface, initiate a shock wave inside which causes ”spalling” on the opposite side of the volume. The pressure gradient will also accelerate the water, and because of the spalling effect and different velocities inside the volume, it seems likely that the whole volume within a moment will break up into a cloud of drops of different sizes. During this process, heat is transferred from the hot gasses to the water, both by radiation and conduction. The shock wave in the gas between the drops will, in the case of a confined explosion, repeatedly affect them with heat and acceleration when the wave is reflected against the walls. This will increase the break-up into smaller droplets, and increase the speed of heat transfer from the surrounding HE gas. As the heat capacity for typical HE gases (CO CO_2 N_2 N_xO_y) is 4-5 times less than for water, the temperature of the hot gases must decrease largely when mixed with the water mist, hence the pressure in the constant volume of the explosion chamber also decreases, according to the general gas law: $pV \sim T$.

From the above, there is reason to believe that the heat transfer to the water is of large importance for an explosion in a confined space. The cooling and phase transition will, despite of the partial pressure from eventual vaporization, result in an overall pressure decrease; the energy of the explosive is then to a large extent stored as internal energy of the water. For explosions in free air the water might instead absorb kinetic energy from the expanding gases, which possibly explains the observed mitigation effects in such experiments (reported in e.g. /2/, /9/ and /10/).

In this paper, some recent experiments with partially closed spaces made by FOA are presented. The test set-up is described in Chapter 2, the results are presented in Chapter 3 and in the Appendix. In Chapter 4, the results are discussed and compared with the proposed mechanisms for water mitigation.

The subject has also been studied by several other consultants and researchers; a sample of titles from the literature are listed in Chapter 5.

2. Set-up of the experiments

Small Scale. The experiments were made with a partially closed axi-symmetric structure: a cylindrical explosion chamber with an attached duct, according to Figure 1. (The same structure was used in former tests, briefly described in /1/ and in detail in /3/ and /6/).

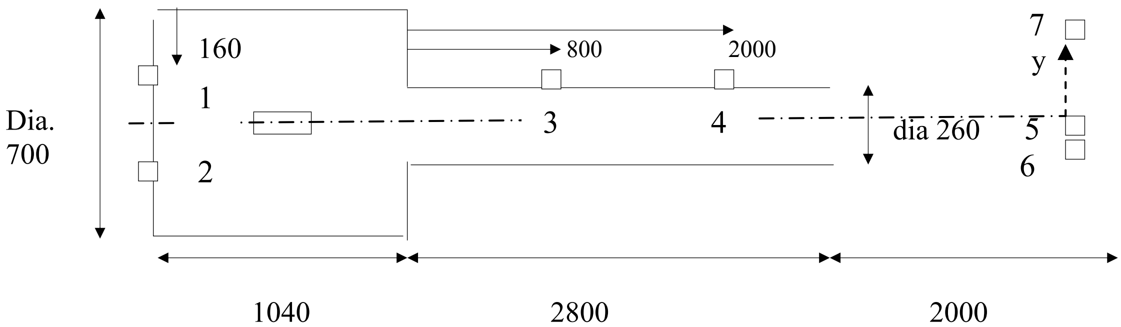

Figure 1. Test specimen for small scale tests with gage locations.

The used gage types were for mp1:Entran epxo5kp, mp2:PCB113a02, mp3-4 PCB113a24, mp5 PCB 113a51, mp6-7: Kistler701. Mp1 and 2 were protected by 50x50x10 mm steel plates 15 mm in front of them. One side-on gage, mp5, and two stagnation gages, mp6-7 were mounted 2 m in front of the duct exit to study the jet; the distance from centreline for mp7 (y) was varied between tests. The transients were captured with the sampling frequency 200 kHz.

The axi-symmetric charge and water arrangement was hung in the center of the explosion chamber. Similar to the former tests /3/, /6/ the water was contained in 'rings' (circular torus) located around the cylindrical charge, Figure 2. The charges were made of plastic explosive, containing 85% PETN. Tests were performed with both cased and uncased charges; the casing was a pre-fragmented hollow steel cylinder, weighing 3 times the HE packed inside.

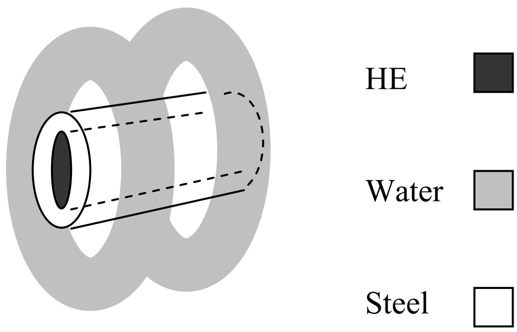

Figure 2. Principal sketch of cased charge with water arrangement.

For a loading density of 4 kg/m^3, repeated tests were made with all the combinations cased/uncased charges and with/without water, the water to HE ratio (W/Q) was 2 by weight.
For the loading density 10 kg/m^3, one test was made: an uncased charge with water, W/Q = 2.
For the loading density 20 kg/m^3, one test was made: a cased charge with water, W/Q = 2.

In the 20 kg/m^3 test, the pressure gages inside the chamber were heavily disturbed and destroyed after a few milliseconds, yet mp2 gave an indication of a QSP max value.

Two miscellaneous tests were made with this structure with other agents than water: Carbon-tetrachloride and Steatite powder; both arranged similar to the water (circular torus) with the weight ratio 2 to the explosive.

Two tests were also performed with the structure above modified by changing the diameter of the attached duct, from 260 mm to 500 mm. The ratio of cross-section areas between chamber and duct was thereby reduced from 8 to 2. The tests were made with uncased charges and loading density 4 kg/m^3, with and without water, W/Q = 2.

Large Scale. In order to check for scaling effects of the water mitigation technique, tests were made in a structure that was up-scaled ca 3 times compared to the structure above. The explosion chamber of the FOA test machine for nuclear blast simulation “Shock Tube III” was used, modified with concrete rings inside. A structure with only small deviations from a true replica scaling was then obtained; the volume of the test chamber became 10.8 m^3 i.e. 27 times larger than the 0.4 m^3 of the smaller structure (3^3=27). The inside diameter was 2.0 m, the length 3.45 m and the diameter of the simulated ‘duct’ inside the concrete rings was 0.7 m, see Figure 3. Only the first half of the 2.8 m length of the duct could be up-scaled as the space in the test machine was limited to 4.4 m. Also, instead of entering free air as in the small scale object, the large scale ‘duct’ entered in a 2 x 2 m wide and 240 m long tunnel. This geometry change was, however, believed to have a very small influence on the pressure history inside the explosion chamber.

The same up-scaling was made for the cylindrical charges and the water arrangement with water contained in torus shaped ‘rings’ as in Figure 2. The rings were made of 160 mm diam. reinforced plastic tubes, bent in circle with 900 mm outer diameter. The charges, 230 mm in diameter, were made of Hexotol instead of the PETN explosive used in the small scale tests.

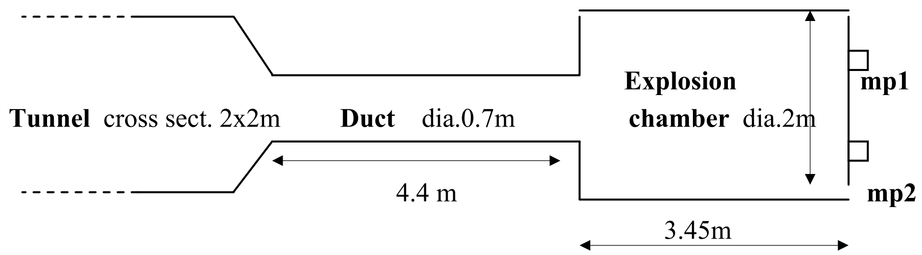

Figure 3. Geometry of the structure for the large-scale tests.

Gages of type Entran epxo were used in mp1 and 2. To protect the gages, 60x60x10 mm steel plates were mounted 15 mm in front of them. Also, a 8 mm layer of molybdenum grease was applied to protect them from the heat transient. Successful tests were made with uncased charges with the loading density 4 kg/m^3 and a water/explosive ratio W/Q = 2. An effort was made with a test with the loading density 10 kg/m^3 (100 kg HE) but then the gages failed.

3. Results from the Experiments

Evaluated max values of the quasi-static pressure (QSP) from the pressure histories from gage 1 an 2 in the explosion chambers are shown in the tables below. The evaluated values are obtained by averaging with the time constant 3 ms and the initial peaks at 0-2 ms neglected. (for the large scale test, the time constant 10 ms was used). A sample of unfiltered traces are shown in the Appendix; some initial peaks are cut by the scaling to clarify the QSP build-up.

Q/V kg/m^3	**case**	**W/Q**	**Specification of test set-up, Chamber / Duct area ratio 8** **HE casing mitig. agent**	**QSP_{max}** (MPa)	**Dura-tion** (ms)	**Im-pulse** (kPas)
4	X	-	1.5 kg 4.5 kg steelcase no agent	2.2	25	20
4	X	2	1.5 kg 4.5 kg steelcase 3 kg water	0.9	50	15
4		-	1.5 kg uncased no agent	4.0	20	30
4		2	1.5 kg uncased 3 kg water	1.5	60	40
4		2 (CCl_4)	1.5 kg uncased 3 kg carbontetrachl.	5.0	30	45
4		2 (Steatit)	1.5 kg uncased 3 kg steatite powder	2.2	30	20
10		2	3.75 kg uncased 7.5 kg water	4.0	65	65
20	X	2	7.5 kg 22.5 kg steelcase 15 kg water	4.0 *	-	-

Table 1. Measured QSP values in the 0.4 m^3 explosion chamber, small scale tests

Q/V kg/m^3	case	W/Q	Specification of test set-up Chamber / Duct area ratio 2	QSP $_{max}$ (MPa)	Duration (ms)	Impulse (kPas)
4		-	1.5 kg uncased no water	3.5	20	15
4		2	1.5 kg uncased 3 kg water	3.0	25	15

Table 2. Measured QSP in 0.4 m^3 explosion chamber, attached duct with 500mm dia

Q/V kg/m^3	case	W/Q	Specification of test set-up 3:1 Chamber / Duct area ratio 8	QSP$_{max}$ (MPa)	Duration (ms)	Impulse (kPas)
4		-	40 kg Hexotol no water	4.0 *	100 *	200 *
4		2	40 kg Hexotol 80 kg water	1.9	300	200

*Table 3. Measured QSP in 10.8 m^3 explosion chamber, from the large scale test (* denotes unreliable values from heavily disturbed traces)*

4. Discussion

From the results in Table 1 above, and Figure 4, 5 and 6 in the Appendix, it can be seen that the water mitigation technique works well in the small scale structure (0.4m^3 volume) with ca 60% QSP reduction both with cased and uncased charges, also at the very high loading densities 10 and 20 kg/m^3. In the larger 10.8 m^3 structure, the result from the uncased charge showed a good similarity to the corresponding small scale test (Figure 9) i.e. no obvious scaling effect of the mitigation phenomenon was observed. This does not preclude such effects in very large volumes, thousands of m^3 as in real ammunition storage magazines.

The results in Table 2, however, indicate a severe limitation of the water mitigation method. When a duct with doubled diameter was mounted and the ratio of cross section area chamber to duct thereby was changed from ca 8 to 2, a much less mitigation effect was observed (Figure 7). Referring to Chapt.1 “Background”, a suggested explanation is that because the evacuation of gas through the larger duct is faster, the time for the water mist to cool the HE gasses in the chamber is less, hence the QSP build-up is less affected. It should be pointed out that the used arrangement of water with ‘rings’ around the HE is probably far from the most effective, concerning mitigation effectiveness; other tests have been made with the charge completely surrounded by the water e.g. /2/ /5/ /9/ /10/. The poor mitigation effect obtained from this test was similar to the full scale test in Alvdalen in 1996 /8/, where the ratio of the cross-section area chamber/tunnel also was ca 2. The used water arrangement, in containers placed some distance from the charge, was also possibly unfavorable for the mitigation effect.

The test with the water replaced by Carbon-Tetrachloride gave spectacular results. From Table 1 it can be seen that the QSP increased with Carbon-tetrachloride. The intention was to demonstrate the suggested mechanism of the water mitigation by cooling of the HE gasses by the water mist. Water has an unusually high heat capacity as well as a high HoV (Heat of Vaporization), but as Carbon-tetrachloride has much lower values on these properties the mitigation effect was expected to be poor. The increase of the QSP that was obtained instead of mitigation can be explained by the partial pressure from the agent when it vaporizes. Chemical effects from this reactive agent when subjected to the explosion has also been suggested to explain some of the QSP increase.

The results from the test with Steatite powder makes this or similar agents thinkable for practical applications. Steatite has a high heat capacity of ca 1.3 kJ/kg K in relation to other minerals (compare with e.g. granite used in sandbags: ca 0.8 kJ/kg K), but it is inferior to liquid water: 4.2 kJ/kg K. Still, it gave a notable mitigation effect, both by QSP (ca 40 %) and also by impulse density as only a small increase of the duration was observed (Figure 8). A suggested explanation is that the spread-out of the powder around the exploding HE is effective and that this agent is less vaporized than water, and thereby does not contribute to the QSP by a partial pressure. In other words, this 'dusty' agent occupies about the same volume after the explosion when it cools the HE gasses, as it did before the event.

The results and conclusions above are preliminary, based on a limited number of experiments. To perform reliable measurements in structures with high loading densities is very difficult. Further experiments and large scale tests in this field will therefore be of great value when recommendations for ammunition storage are proposed.

5. References

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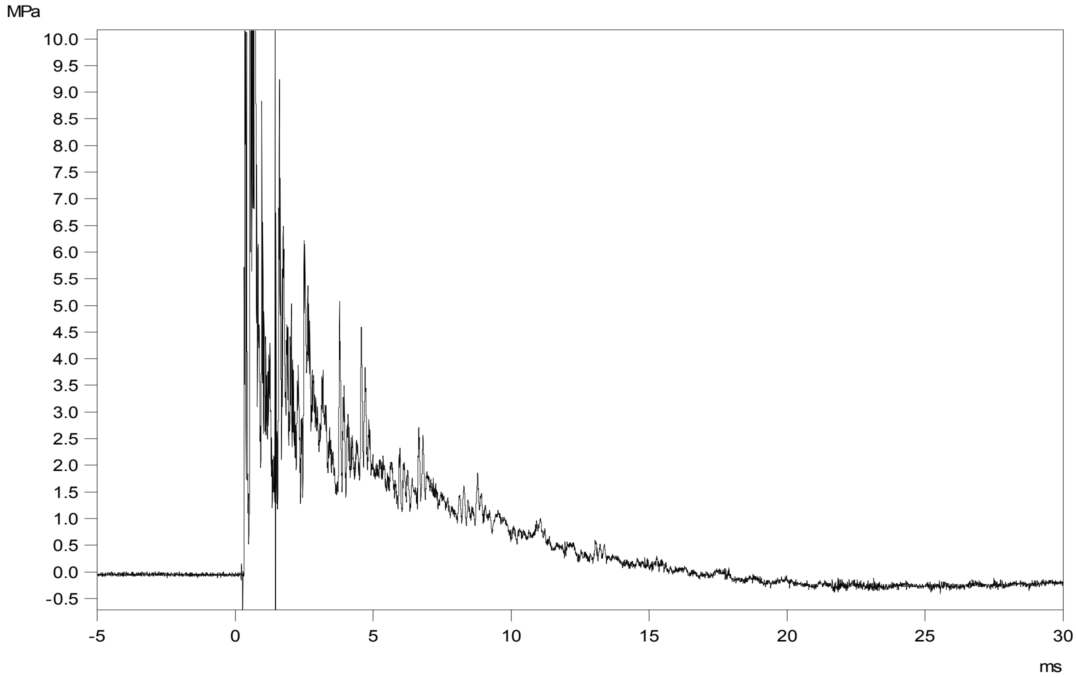
A Sample of Pressure Traces from the Experiments



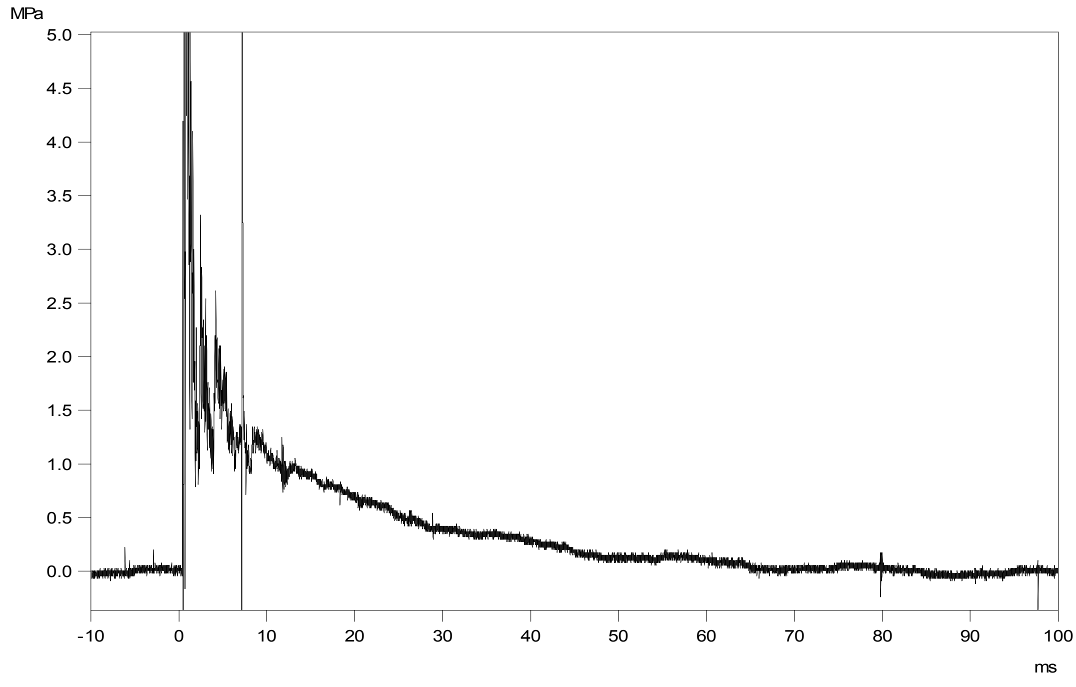


Figure 4. Pressure-time histories inside small scale explosion chamber: 1.5 kg uncased charges without water (upper), with 3 kg water (lower). Loading density: 4 kg/m^3

Note: different scales on both time and amplitude axes between the traces.

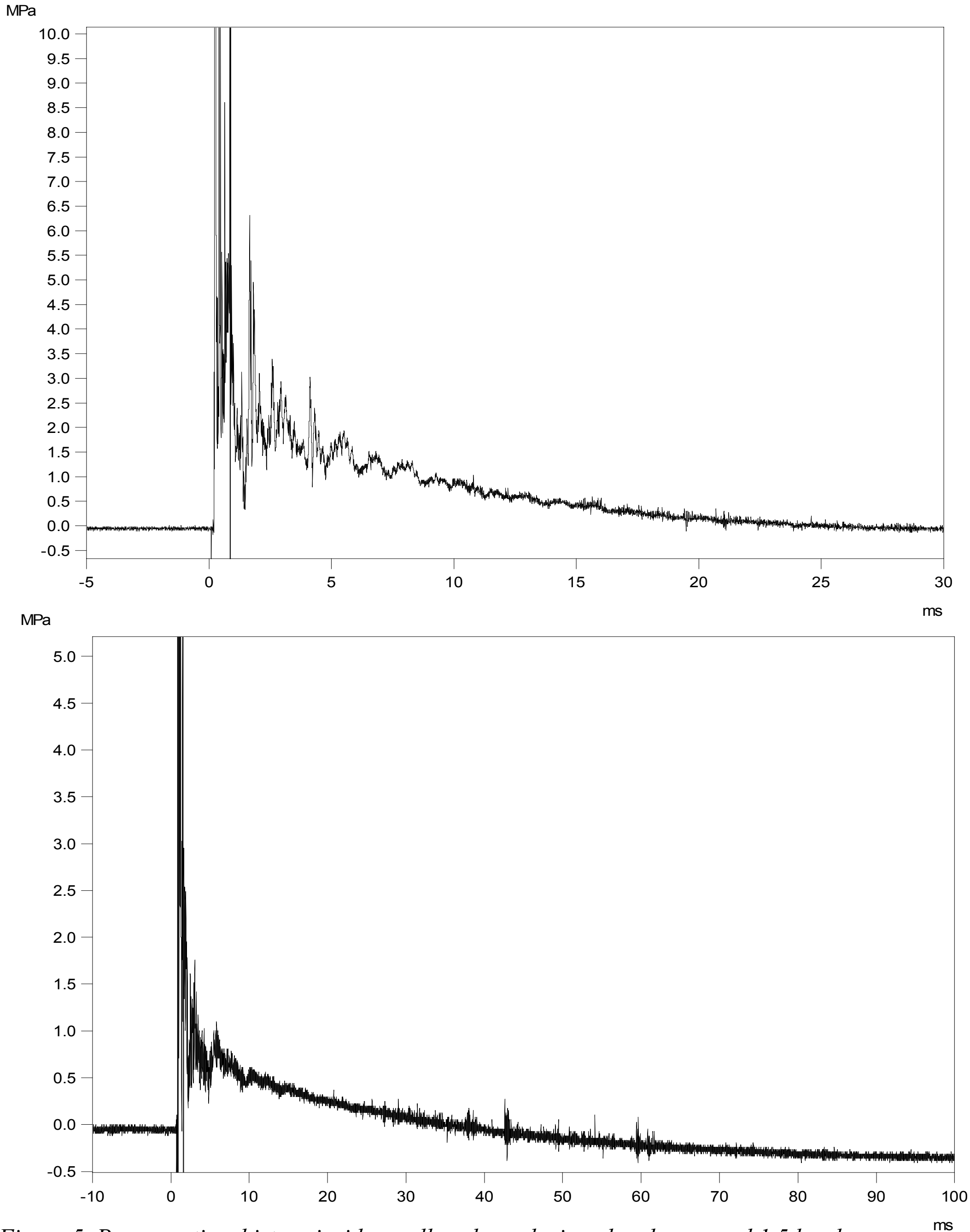


Figure 5. Pressure-time history inside small scale explosion chamber: cased 1.5 kg charges without water (upper), with 3 kg water (lower). Loading density: 4 kg/m^3

Note: different scales on both time and amplitude axes between the traces.

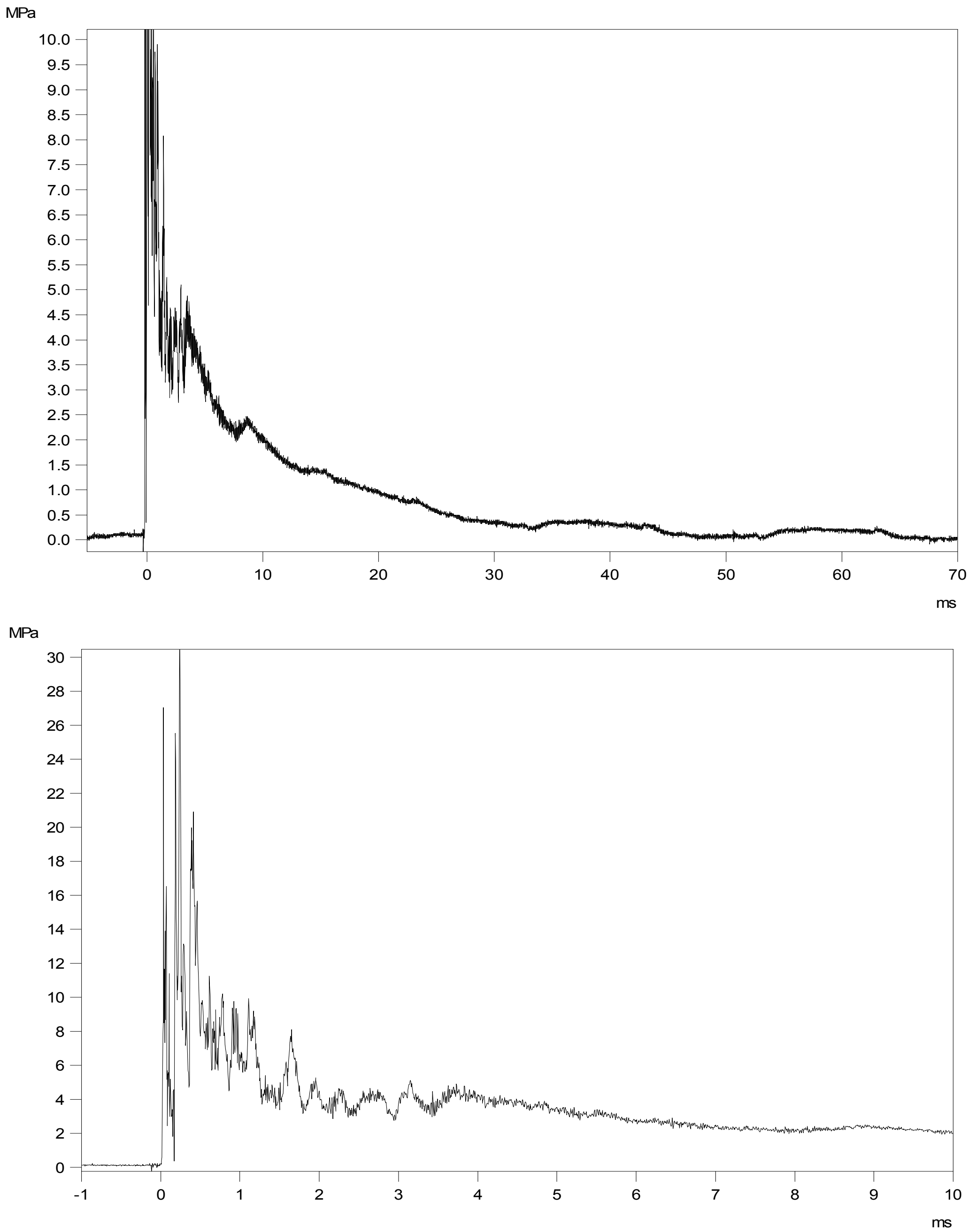


Figure 6: Pressure-time history inside small scale explosion chamber: uncased 3.75 kg HE with 7.5 kg water. Loading density: 10 kg/m3. The lower trace is a close-in on the first ten milliseconds. Note that the QSP stabilizes at ca 4 MPa after ca 2 ms. The initial peak reaches ca 30 MPa.

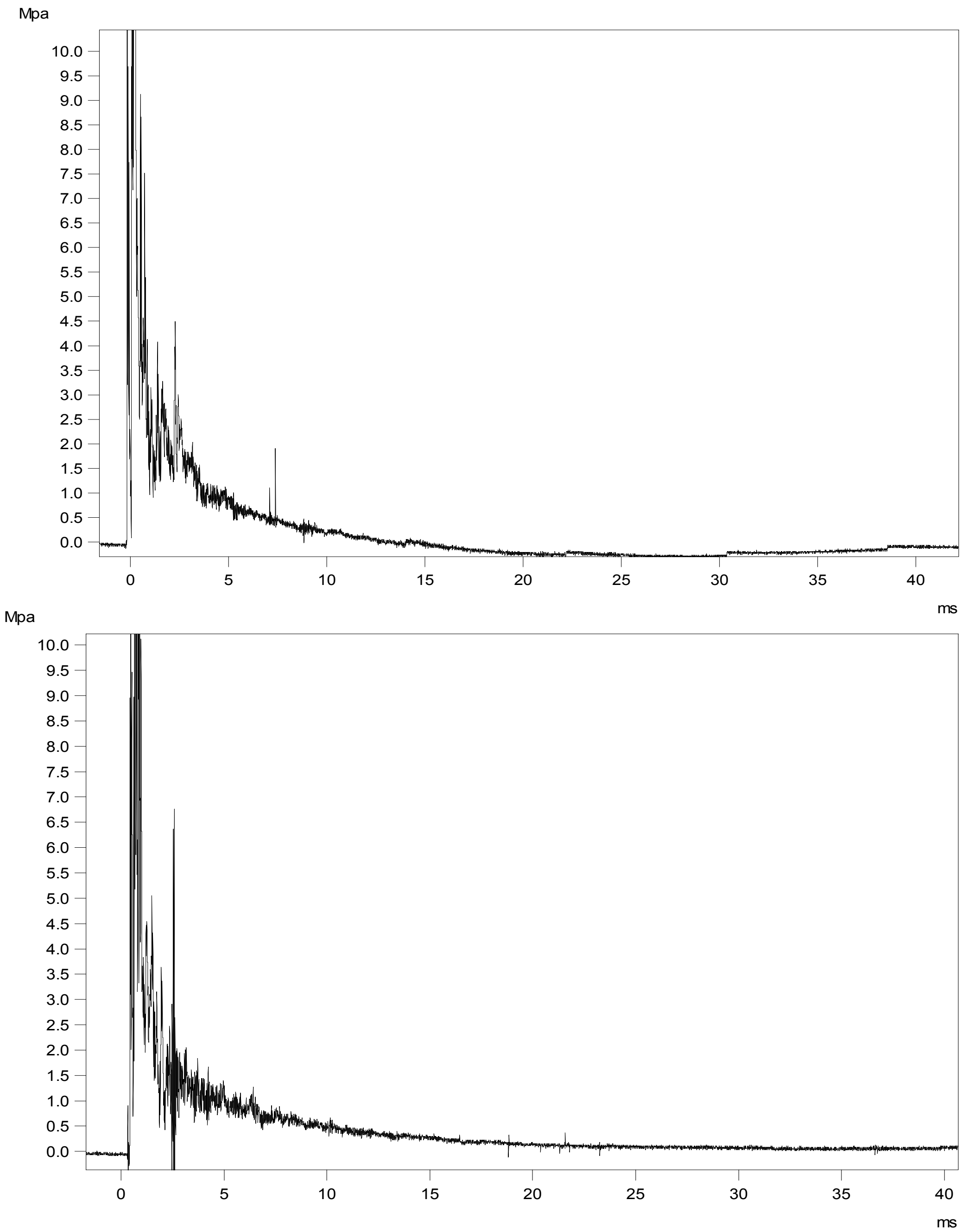


Figure 7. Pressure-time history inside small scale explosion chamber, duct with larger diameter (500mm) mounted. 1.5 kg uncased charges, without water (upper),with 3 kg water (lower). Loading density: 4 kg/m^3

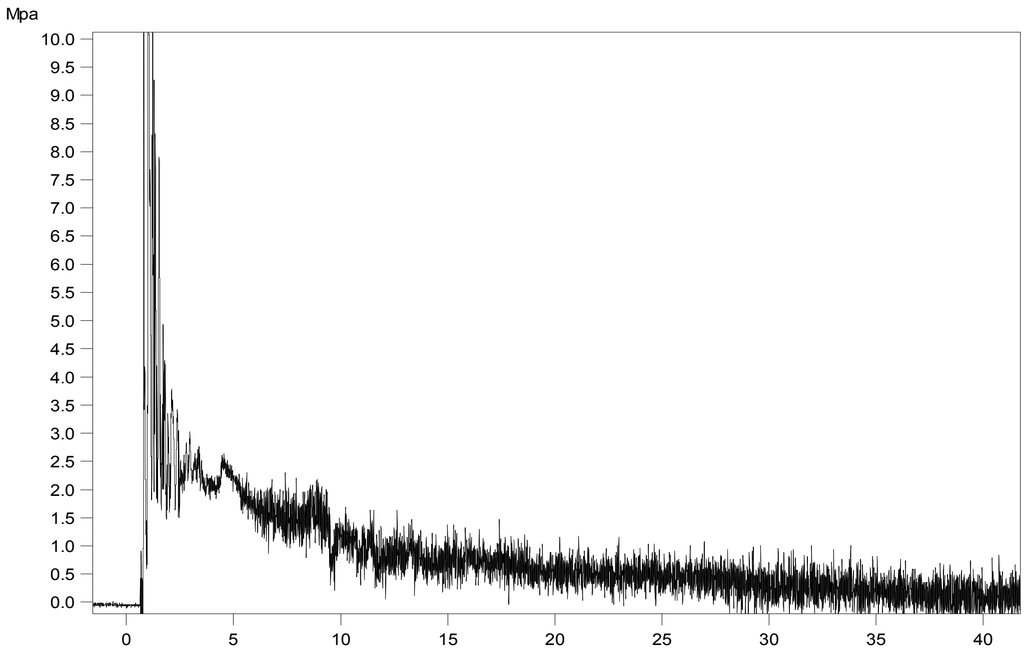


Figure 8. Pressure history inside small scale explosion chamber. Uncased 1.5 kg charge with 3.0 kg Steatite powder. Loading density: 4 kg/m^3

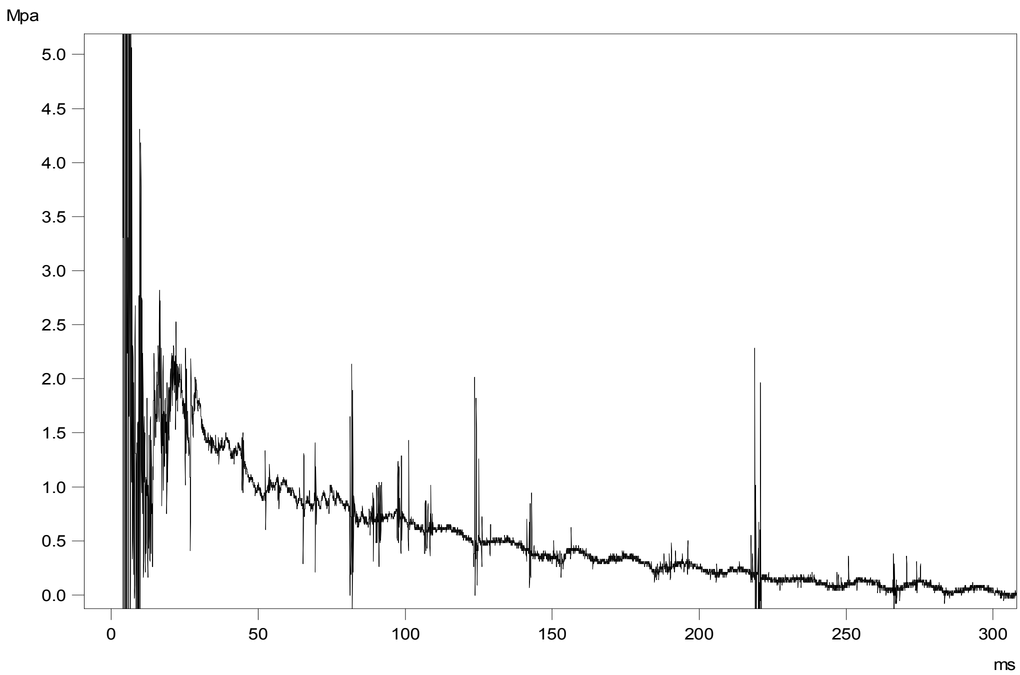


Figure 9. Pressure history inside explosion chamber. Large scale, uncased charge with 40 kg Hexotol and 80 kg water. Loading density 4 kg/m^3. Compare with the result from the corresponding small scale test in Figure 4, the lower trace.

NOTE: The test setup for the result above is on the front page of this report