Simulation of water gaps in detonic initiation trains

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Abstract. **A simulation tool was used to investigate the comparative effects of air and water in a gap between two detonic transfer elements. A specific model configuration was used to position a donor and acceptor in air and water environments, respectively, at different distances. Various transfer parameters were monitored in the simulation, such as peak pressure, specific impulse and arrival time. Although the effect in very small gaps could not be adequately resolved, it was counter-intuitively found for larger gaps that (for this specific configuration) transfer will occur at a larger distance through air in the gap than through water. A prototype hardware tool was designed based on the simulations, to execute confirmation experiments.**

Keywords—detonic; initiation train; gap test; simulation

I. INTRODUCTION

An increasing trend is the need for explosive charges to comply with international insensitive munitions (IM) requirements. The consequence of IM requirements is that it becomes increasingly more difficult to initiate the explosive charges. Therefore an appropriate initiation train is required to initiate the charge. The initiation train normally consists of a small, but sensitive detonator that will initiate a less sensitive relay, which will initiate a less sensitive booster, which may initiate yet another booster, which will initiate the main charge. For safety reasons the more sensitive elements are mechanically separated from the main charge until the system is fully armed. Therefore physical gaps will always exist between some of the elements in the initiation train - even when they are lined up for initiation. Gap tests need to be performed between consecutive elements to determine the probability of initiation transfer across each gap.

Depending on the design of an underwater demolition system, water may enter the system (intentionally or unintentionally) and form an additional barrier within the gap that may exist in the initiation train. The question arises whether water in the gaps will enhance the detonation transfer probability or be detrimental to the functioning of the initiation train. König and Mostert [1] have developed a gap test that uses a water filled tube to simplify the procedure of performing gap tests. It was not part of their research, however, to compare the detonation transfer probability in the water gap to that in a similar air gap. In this investigation, simulations were done in ANSYS® Autodyn® with a model similar to that of [1] and comparisons were made between relatively large water and air gaps.

It was postulated that air is the weaker transfer medium because it is highly compressible and the speed of sound is lower in air than in water. Simulations for relatively large gaps have indicated however that detonation transfer will occur from donor to acceptor over a longer distance in an air gap than in a water gap. Water is thus the weaker transfer medium and air the better transfer medium in this configuration. Very small gaps were not researched. This paper will discuss the large gap simulations and the reason for the phenomenon.

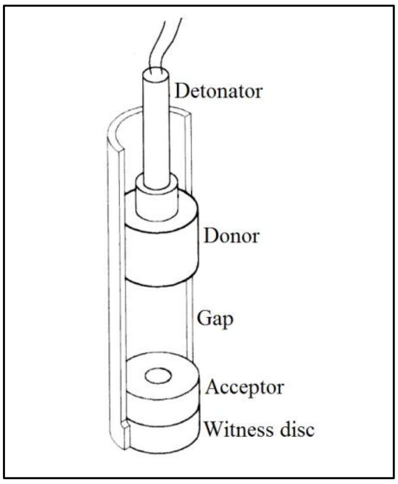

Fig. 1 Test setup of König and Mostert [1]

II. SENSITIVITY TESTING AND PROBABILITY

The sensitivity of an explosive material to a particular stimulus has far-reaching consequences in design practices of munition and other items used in the explosive industry. In some cases, it is crucial to know the minimum threshold for which the explosives would not react to the stimulus (i.e. for safe practices) and in other cases, it is important to know the threshold where it would react with high confidence for optimal reliable functioning of a device or product.

The estimation of the sensitivity of explosive items is problematic in the sense that repeated testing of a sample is not possible. Both in cases where the sample reacts, or when it does not, it is typically not reusable. It is therefore necessary to devise testing methods and analysis procedures with different samples of the same material in order to probe stimulus thresholds of interests. Normally, it is of interest to obtain a mean value in a postulated distribution of such stimulus where

50% of the samples would react, with some standard deviation and variance. With such information, it is then further probed for the confidence limits of both the minimum threshold level (i.e. no reaction with high confidence) and the maximum threshold level (i.e. reaction with high confidence) of the stimulus.

Many different types of tests have been developed in the past that use statistical inference to analyse the parameters of interest in sensitivity. The most well-known ones are the Probit [2], Bruceton [3] and Langlie [4] tests. All these tests used sequential testing of samples in different ways and give reasonable estimates of the mean thresholds and the standard deviations if the sample sizes were sufficiently large and the initial estimates were within certain bounds. However, there are clear limitations with these methods [1] or large testing sample sizes are required to produce adequate results. A new method was first proposed in 1991 [5] and formally introduced in 1994 by Neyer [6]. The method is also based on sequential testing of samples but differs from the previous methods in the sense that the information matrix is computationally updated with every test result and that a new test stimulus level is recommended from an autonomous mathematical/statistical analysis in order to optimise the testing procedure. This procedure is called D Optimality Statistics and is contained in the SenTest™ software package.

Although the SenTest™ software quickly converges to the point of interest during a gap test, it is of little value if the test hardware does not accommodate the required range. Also, the closer to the 0.5 probability point the gap test can start, the least number of shots will be required to complete the test. Since all detonic tests inherently contain significant risks and testing is extremely expensive, it is best to estimate the dimensions of the test hardware and the position of the starting point first through modelling and simulation before firing any live explosives.

III. MODELLING AND SIMULATION

A. *Computational tool*

Simulations were performed with the ANSYS® Autodyn® numerical computational tool (also referred to as a ‘hydrocode’). This tool, as is the case with all hydrocodes, solves the Euler conservation equations for mass, energy and momentum for non-linear changes by the method of finite differences and specific use of empirical equation of state and material models. The tool is specifically suited for the treatment of high rate deformation problems, or to estimate effects from explosive/metal interactions.

There are many different equations of state (EOS) models for explosives but most of these are thermo-chemistry based and inappropriate for use in a mechanical hydrocode. The most popular EOS used for explosives, is the Jones-Wilkens-Lee (JWL) EOS [7], [8], [9]. This EOS is empirically based and obtained from copper cylinder test expansion experiments. It is well suited for hydrocode work since it requires only the internal energy of the explosives, the detonation pressure, density and velocity, together with empirical constants designating the expansion behaviour of the detonation product gasses. The most common form of the JWL EOS is:

$$P = Ae^{-R_1\frac{V}{V_0}} + Be^{-R_1\frac{V}{V_0}} + C(\frac{V}{V_0})^{-(1+\omega)} \qquad (1)$$

In equation (1) A, B, C, R_1, R_2 and ω are constants and the pressure can be found as a function of the compression of the gasses at any expansion ratio. In the form of equation (1), the coefficients indirectly account for the energy released by the explosive during detonation, but an alternative form can be used that contains an internal energy term.

The handiness of equation (1) is that it sidesteps the complex thermo-chemical nature of the detonation event and uses only the empirically measured effect of the work performed on the immediate surroundings. It has been found to be sufficiently accurate in many applications but care has to be taken to use this EOS out of context in complex problems such as far field blast loading. Most of the commonly used explosive JWL constants are supplied in the ANSYS® Autodyn® built-in library.

The other explosive EOS is the Lee-Tarver [10] initiation and growth model. With the JWL model, an initiation point is specified in the hydrocode and then spherical detonation paths are calculated at a fixed rate (the specified detonation velocity) outward from this point. With the JWL model, the explosives will therefore always detonate fully. The Lee-Tarver model, on the other hand, considers the possibility that full detonation will not occur in the explosive. It can be operated in two modes, i.e. only giving an indication whether detonation is possible, or it can be physically initiated at a particular threshold.

Both the JWL and Lee-Tarver EOS models were run without a material strength model. It makes no sense to attribute strength effects to a material that will experience Giga Pascal pressures when detonated.

B. *Test hardware simulaion*

The design of the test hardware, analogous to reference 1, is shown in Fig. 2. The hardware consists of a holder for the detonator and the donor on one end of a tube, with a movable witness disc and acceptor inside the tube. The tube is slotted to accommodate the use of callipers to accurately measure the distance between donor and acceptor.

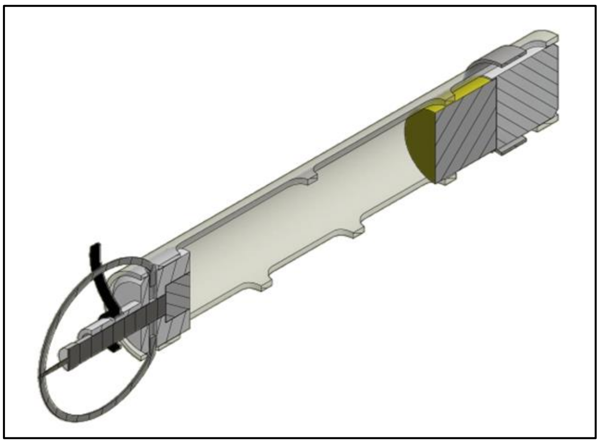

Fig. 2 Test hardware drawing

The donor is made of PBX9010 explosive and the acceptor PBX9404. Many simulations were performed to arrive at this design. A number of those simulations will be discussed in this section.

The contribution to the stimulus by the detonator was not taken into account during simulations since the output of the detonator is a small fraction of that of the donor.

Aluminium is the first material that comes to mind for the tube of the test hardware in Fig. 2. The simulations in Fig. 3 and Fig. 4 show however, that the detonation wave runs ahead through the tube and may pre-compress the acceptor through the tube. This may influence the response of the acceptor. Consequently it was decided rather to manufacture the tube from Plexiglass. The same simulations with Plexiglass show no similar concerns, thus Plexiglass was selected for the hardware in Fig. 5.

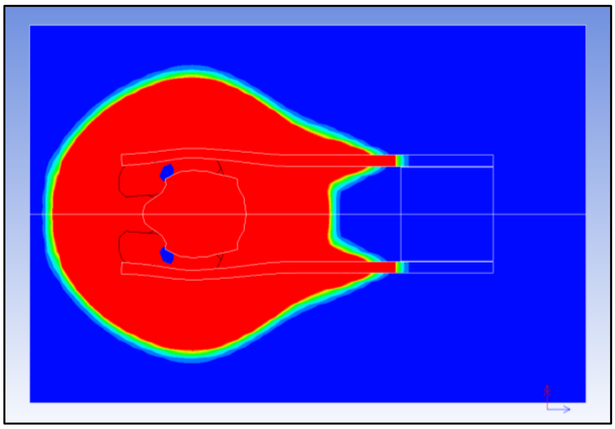

Fig. 3 Detonation wave running ahead in aluminium tube

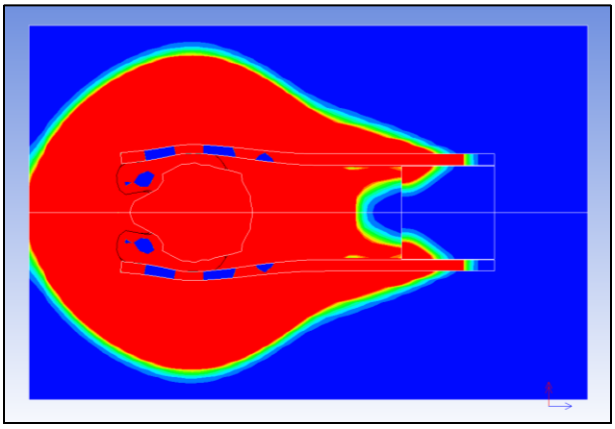

Fig. 4 Side compression in the explosive via aluminium tube

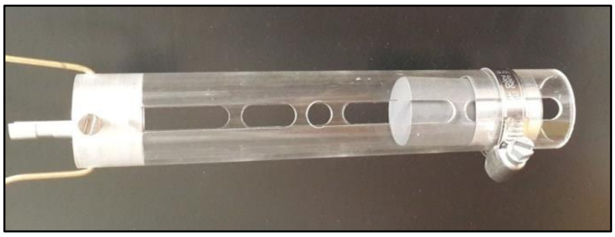

Fig. 5 Test hardware photo

C. *Hypothesis and large gap simulations*

The initial hypothesis for this work was that water is a better transfer medium for initiation transfer than air. The hypothesis was based on two well-known facts:

- The speed of sound through water (1 498 m/s for fresh water) is more than 4 times its speed through air (343 m/s).
- Air is a highly compressible medium, while water is nearly incompressible.

Detonation of an explosive acceptor is most likely when an exploding donor causes a pressure that is higher than the initiation threshold of the particular acceptor. A range of simulations were done to determine the pressure inside the acceptor material for increasing gap sizes. The pressure values at three measuring points along the x-axis of the acceptor were recorded. Fig. 6 shows a peak pressure of 0.28 GPa in the acceptor when it is positioned at a distance of 50 mm from the donor in water. Fig. 7 shows a peak pressure of 2.3 GPa in the acceptor for 50 mm in air. This indicated that the tube that was used for the simulations in Fig. 3 and Fig. 4 was most probably too short to separate the donor and acceptor to a large enough distance to prevent initiation transfer. Consequently the tube length was increased to make provision for a 100 mm gap.

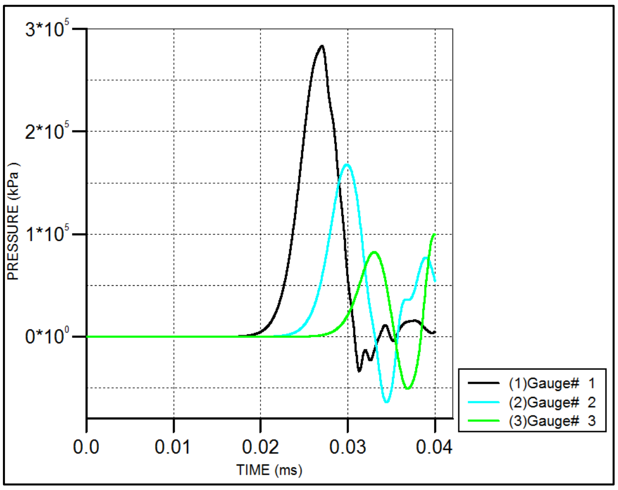

Fig. 6 Pressures inside acceptor with 50 mm water gap (0.28 GPa peak)

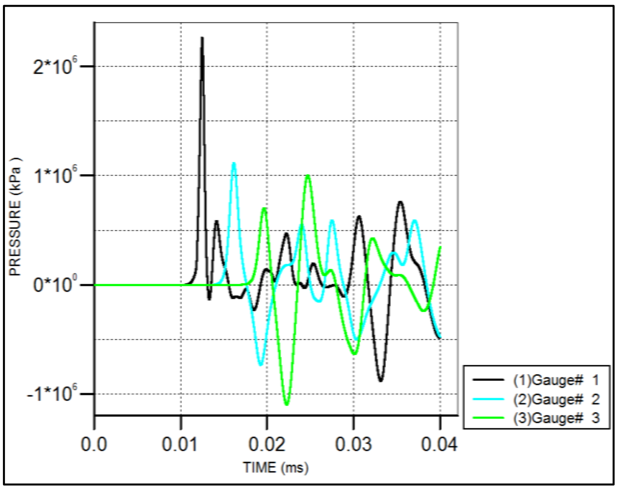

Fig. 7 Pressures inside acceptor with 50 mm air gap (2.3 GPa peak)

TABLE I. PRESSURE (KPA) IN ACCEPTOR VS. GAP SIZE

Gap size (mm)	Air			Water		
	1	2	3	1	2	3
5	9.80E+06	1.50E+06	5.90E+05	4.30E+06	2.40E+06	1.20E+06
10	7.80E+06	1.80E+06	7.60E+05	1.90E+06	1.20E+06	7.20E+05
15	6.40E+06	1.60E+06	7.50E+05	1.20E+06	7.20E+05	5.00E+05
20	5.70E+06	1.50E+06	7.20E+05	7.70E+05	5.20E+05	3.50E+05
25	5.30E+06	1.30E+06	8.10E+05	6.20E+05	4.60E+05	2.80E+05
30	4.50E+06	1.20E+06	7.00E+05	5.50E+05	3.90E+05	2.20E+05
35	4.30E+06	1.30E+06	8.40E+05	4.90E+05	3.20E+05	1.70E+05
40	3.40E+06	1.20E+06	7.60E+05	4.20E+05	2.60E+05	1.30E+05
45	3.00E+06	1.20E+06	7.50E+05	3.30E+05	2.10E+05	1.00E+05
50	2.30E+06	1.10E+06	7.00E+05	2.80E+05	1.70E+05	8.20E+04
75	2.10E+05	1.90E+05	1.00E+05	1.30E+05	7.30E+04	3.20E+04
100	1.80E+05	1.60E+05	8.30E+04	7.00E+04	3.90E+04	1.70E+04

The simulation results over a gap range of 5 mm to 100 mm are summarized in TABLE I. The 1 GPa point of pressure for the acceptor is between 15 mm and 20 mm for a water gap. For an air gap, it is much further – between 50 mm and 75 mm. Therefore, the simulation results suggest that the hypothesis that water is a better transfer medium than air does not hold true for large gaps. No physical gap tests have yet been performed to validate the simulation results.

A possible explanation for why air is the better transfer medium in the simulation configuration, is because the damping effect of water on the detonation wave outweighs any of its other benefits over larger distances. The damping effect of water can be seen clearly by comparing Fig. 6 and Fig. 7. Not only is the peak pressure lower, but the shock wave time duration to bridge the gap is twice as large for water than for air. In contrast, the air is compressed in a constricted area and the combination of the high velocity detonation product gasses and compressed air impinging on the acceptor create an high initial peak pressure pulse.

D. Small gap behaviour

To gain further insight into the propagation of the shock wave in the gap, five measuring points were placed along the x-axis inside a 100 mm gap between donor and acceptor to measure the x-velocity of the particles in the transmission medium (Fig. 8 and Fig. 9). The measuring points were placed at distances of 10, 30, 50, 70 and 90 mm from the donor.

Fig. 8 shows how the maximum velocity of the water particles drops exponentially along these measuring points. The velocity of the air particles on the other hand drops linearly as shown in Fig. 9. If one graph changes exponentially and another graph linearly, then theoretically there could be a point (closer to the origin) where the two graphs coincide. If the same is true for pressure than for velocity, then there could exist a point closer to the donor where water will be a better transfer medium than air. Thus, the hypothesis may still hold true for small gaps. To further substantiate this possibility, Fig. 9 shows that the velocity of air particles closer to the donor are lower that its velocity 30 mm away from the donor. As an illustration of the theory: taking the data from TABLE I. and extrapolating it to a zero gap size, yields the anticipated graph in Fig. 10. The small gap behaviour was not further investigated through simulation in this work.

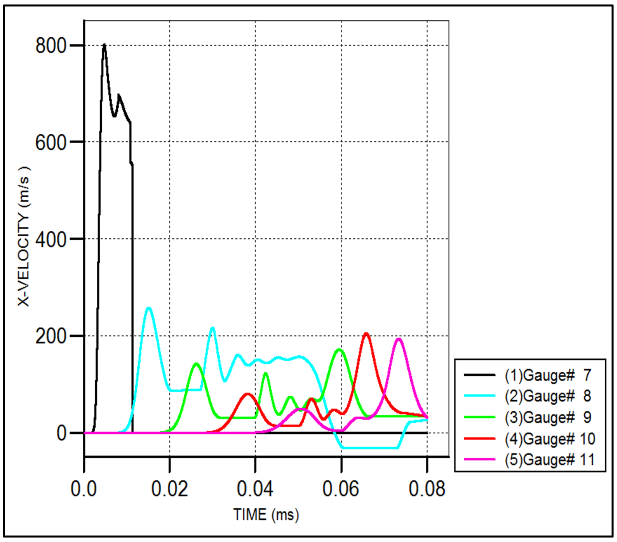

Fig. 8 X-velocities in 100 mm water gap

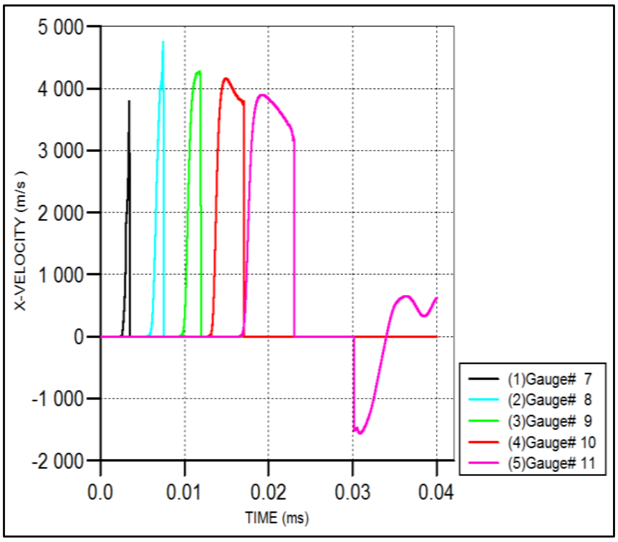

Fig. 9 X-velocities in 100 mm air gap

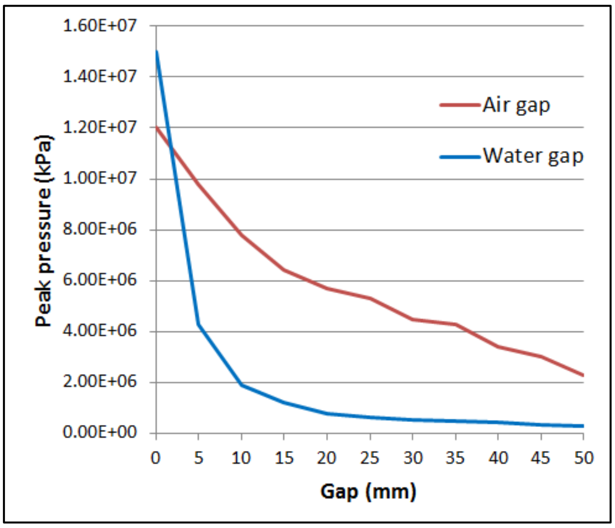

Fig. 10 Extrapolated graph for pressure vs. gap size

E. *Witness block simulaions*

It is standard practice to detonate explosive elements against a witness plate to determine its power. The depth of the indentation that the explosion makes in the witness plate is a good indication of the detonation power of that explosive. The witness plate can be made of lead, aluminium or steel, depending on the power of the explosive to be tested. Physical test results were available for a standard indentation test that was done previously with a similar donor. A representative model was created in ANSYS® Autodyn® to simulate the prior physical test. The physical indentation is shown in Fig. 11 and the simulated dent in Fig. 12. The simulated indentation depth is within 10% of the physical measurement. This result provides credibility to the indentation simulation and also increases the researcher's confidence in the outcome of the simulation tool for this work.

Fig. 11 Indentation test on 16 mm aluminium plate

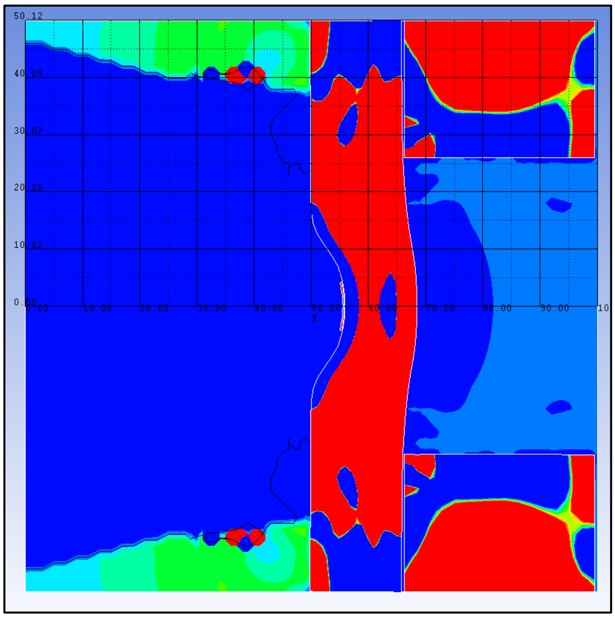

Fig. 12 Simulation of indentation test on 16 mm aluminium plate

The position of the acceptor in the gap test must be continuously adjustable inside the tube. Therefore, it cannot be placed directly against a witness plate and a disc was used instead of a plate. The disc can remain in direct contact with the acceptor anywhere inside the tube.

The purpose of the witness disc in this test is not to provide an indication of the explosive power as such, but rather to prove whether the acceptor detonated or not, i.e. whether initiation transfer occurred. The question is whether the aluminium disc will deform enough to distinguish the damage of an exploding acceptor from the damage that the donor alone will inflict.

The simulation in Fig. 13 shows that the witness disc is slightly deformed by the donor when an inert acceptor is placed against the disc. Fig. 14 indicates a much larger deformation of the witness disk when the acceptor detonates. The simulations illustrate that there will be no doubt after a test whether the acceptor detonated or not.

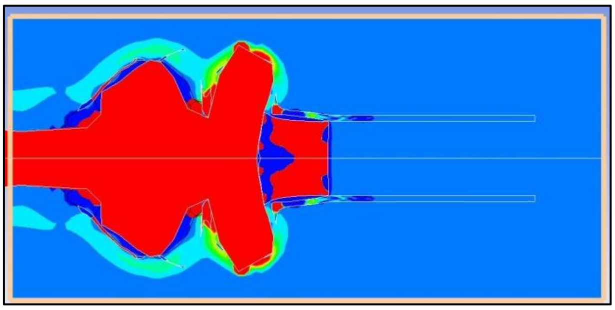

Fig. 13 Deformation of witness disc with inert acceptor

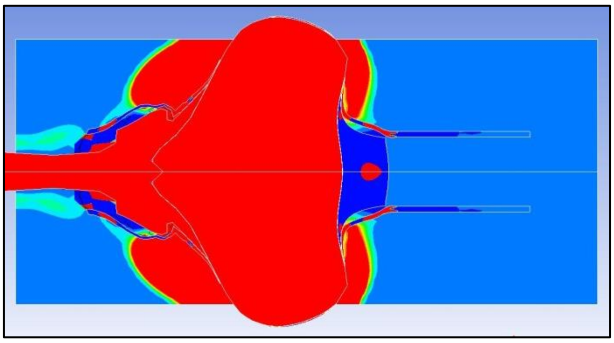

Fig. 14 Deformation of witness disc with exploding acceptor

IV. CONCLUSION

Rudimentary simulation of detonic tests with a hydrocode provides the user with much insight into the mechanisms that are involved in detonation. It illustrates how the shock wave propagates and how the shockwave is influenced by the transmission medium and obstacles.

Most importantly, the simulations reveal that the hypothesis, that water is a better transfer medium than air, does not necessarily hold true for large initiation gaps. The hypothesis may however still hold true for small gaps.

Future work should include physical tests to confirm the large gap simulation results and small gap simulations to determine whether the hypothesis holds true for small gaps and at what distance air becomes the better transfer medium.

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