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Recent Improvements in Dstl's Capacity for Modelling UNDEX and Associated Structural Response

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Abstract

The ever-increasing threat from underwater munitions has warranted the requirement for the ability to numerically simulate underwater explosions and the associated structural response. For many years Dstl has been using APOLLO Blastsimulator, a high-fidelity computational fluid dynamics (CFD) code developed for prediction of blast, for air blast simulations and has since worked to include functionality for underwater explosions, a capability that is still under development. To aid this, emphasis has been placed on attempting to understand the behaviour of non-ideal explosives typically used in this domain through experimental testing in various regimes. The cost implications of large-scale tests underwater, however, have meant that a combination of airblast and small-scale underwater tank tests have been carried out in order to validate modelling capability and provide confidence for upscaling; whilst models are showing promise the software is still under development.

Introduction

It has become apparent in recent years that the underwater battlespace is receiving increased attention, prompting UK Government to build an in-house high-fidelity modelling capability for simulating underwater explosion (UNDEX) events, including the shock response and bubble behaviour. Such events can occur throughout the water column (e.g. floating mines, seabed mines, torpedo) within which the behaviour can wildly vary depending on a number of factors. A notable feature of UNDEX behaviour is complex bubble physics that can develop over a period of seconds (as opposed to milliseconds for an air blast). One such example is bubble oscillation, characterised by multiple pressure pulses and jetting, caused by bubble collapse [1]. In addition to the initial shockwave, a structure can experience devastating impacts, due to the combination of cyclic loading from the oscillations and concentrated loading from a high-speed jet directed towards the structure [1]. Adding to the complexity, migration of the bubble occurs during the event, its direction dependent predominantly on proximity to and orientation of the local boundary(ies) [1]. When interaction with structures and boundaries is included the modelling difficulty is only increased; it is well known that interaction with the free surface is particularly complicated [2].

This paper presents the evolution of an UNDEX numerical modelling capability using APOLLO Blastsimulator – CFD code developed by Fraunhofer Ernst Mach Institut (EMI) – at the Defence Science and Technology Laboratory (Dstl) in order to better simulate events (and physics) described above. Comparisons will be made to the capabilities of LS-DYNA in relation to empirical data from various trials and experiments. Following on, considering the typical nature of UNDEX munitions, reference will be made to the importance of attempting to understand the unpredictable behaviour of non-ideal explosives before detailing the experimental developments for the purposes of small-scale testing. Finally, the ongoing work required to improve our knowledge and capabilities will be highlighted.

Background

In the past, within Dstl, this type of task would have been tackled using LS-DYNA and this was the case given its available functionality (see Figure 1 for initial comparison to APOLLO, using a relative scoring system), but issues existed with computational efficiency, robustness and missing functionality. Moving forward it was decided that a suitable approach to developing the capability would involve using a code with more scope to advance. For many years since Dstl has been using APOLLO to model air blast scenarios to great effect. As an Eulerian code it has proved to be very efficient and user-friendly; therefore, especially given Dstl's strong relationship with the APOLLO developer and future development potential of APOLLO, it seemed logical to incorporate an UNDEX capability. This capability did not exist prior to 2018 and so is relatively new – being still in its infancy with respect to functionality, development and validation – but there are ongoing efforts to improve the accuracy and ability of APOLLO to capture the full UNDEX behaviour. Figure 2 details the vast improvements made when compared to Figure 1, although it is evident that some capability gaps still exist.

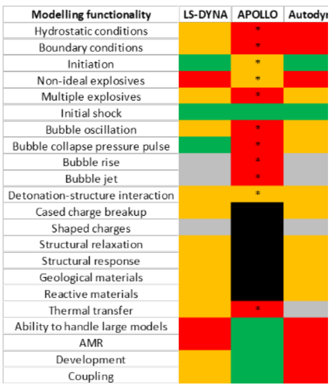

Figure 1. *Initial software capability*

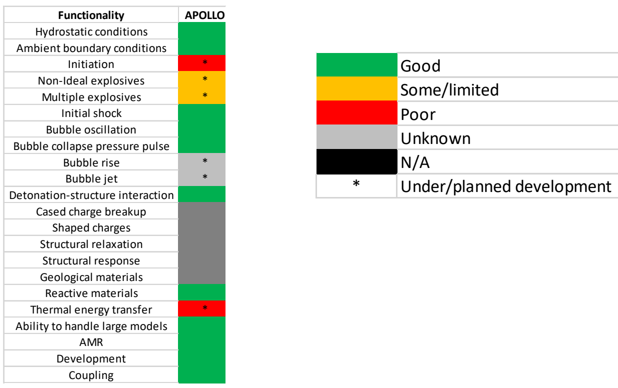

Figure 2. *Updated software capability of APOLLO*

Software Development

With reference to Figure 2, and as mentioned above, significant effort has gone into developing APOLLO in order to introduce UNDEX modelling functionality. This will be an ongoing endeavor that will be validated through a combination of simulating open-source and Dstl-commissioned trials, analysing as wide a range and number as possible for the most representative comparison.

A major difference between UNDEX and the air blast scenarios is the presence and influence of gravity on the bubble behaviour. Reference was made earlier to the impact of nearby boundaries on bubble migration but the end result is also affected by buoyancy forces influenced by gravity-induced pressure. According to the formula (1), the hydrostatic pressure P in a fluid increases with depth, resulting in a pressure gradient through the domain:

$$P = \rho g h \qquad (1)$$

As such a number of new functionalities have been implemented into APOLLO, namely gravity – for initial hydrostatic conditions – combined with improved ambient boundary conditions compatible with such initial conditions. Evidence of this can be seen in Figure 3 below wherein bands of pressure throughout the water column can be seen to move up the pressure gradient bar (i.e. tend towards red) with increasing depth. Effort has been applied to improving and expanding the Dynamic Mesh Adaption[1] (DMA) options to provide greater control over the efficiency of models through manipulation of model resolution behaviour with time. Due to boundary effects and/or the often large difference in scale between a charge and structure it is common to require an expansive model domain, a large proportion of which is frequently not in the area of interest but still has to be considered and included; therefore the control offered by DMA is incredibly beneficial in optimising the model to concentrate refinement in regions local to the area(s) of interest.

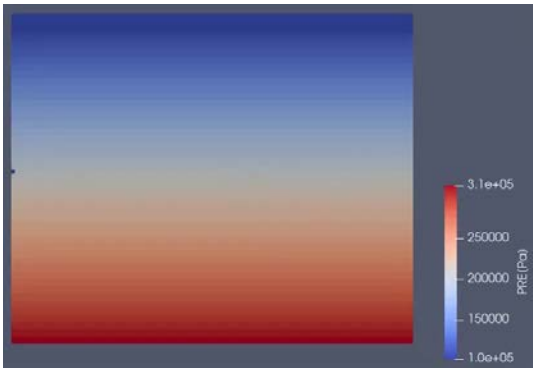

Figure 1. *Paraview extract - varying hydrostatic pressure with depth as an initial condition*

Since APOLLO is a strictly Eulerian code, development has also been focused on implementing open coupling to structural codes in order to allow assessment of structural response. This typically involves utilising separate meshing software (e.g. Hypermesh) in order to mesh the structure in question to then be analysed in the coupling system. The suite currently includes LS-DYNA, IMPETUS and SOPHIA that all possess their own strengths making them suitable for certain scenarios. A handful of examples will be presented in the following section to demonstrate this capability, albeit using static video extracts and not including SOPHIA as Dstl are only currently in the process of acquiring the software. The intentions moving forward are to focus attentions on developing SOPHIA to be able to deliver coupled functionality to a level that matches or betters those currently available to Dstl.

[1] Dynamic Mesh Adaptation (DMA) is a numerical capability within APOLLO which improves computational efficiency. The DMA algorithm selects at least one region, with the strongest gradient for the parameter of interest (e.g. pressure), resolves the region to the highest resolution specified, and applies a coarser resolution to areas with weaker gradients.

UNDEX Capability

As mentioned previously, whilst an UNDEX capability is present in APOLLO, ongoing efforts will look to validate this and identify areas where improvements inaccuracy can be achieved. The below graphs (Figure 4) demonstrate an example of the current capability of APOLLO and LS-DYNA in a free-field environment when compared to empirical data for a scenario of a 1.13kg TNT spherical charge at a depth of 152.4m with a gauge distance of 1.26m [3]. It can be seen that both APOLLO (green) and LS-DYNA (orange) capture the shock pressure to a reasonable degree and fairly accurately trace the Friedlander of the experimental output (red); APOLLO produces an excellent comparison only likely underpredicting pressure due to resolution – exacerbated by having to model in 3D, whereas LS-DYNA can model in 2D. The APOLLO trace closely matches that of the experiment for the first bubble but with a clear overprediction of the second bubble period.

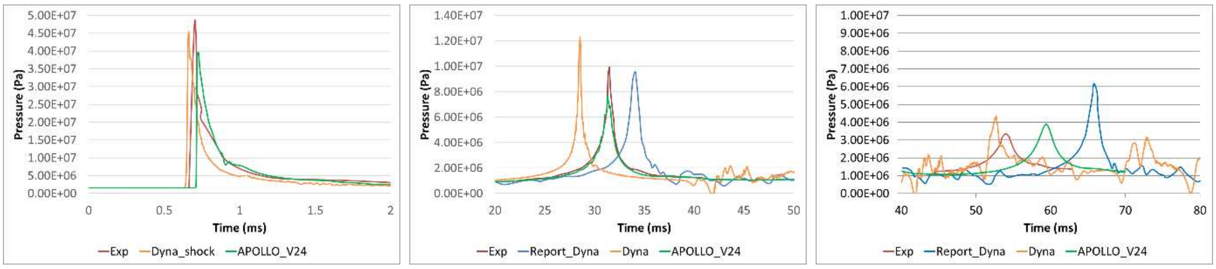

***Figure 2**. 1.13kg TNT sphere at a depth of 152.4m with a gauge distance of 1.26m; results displayed include test data, LS-DYNA and APOLLO*

The ability to include rigid objects in APOLLO allows for the modelling of water tanks typically used for small-scale tests, a subject that will be referenced in more detail in a later section of this report. Provided the model resolution is sufficiently fine the effects of a voxel approach for modelling objects are negligible when representing objects with non-uniform surfaces, a cylindrical tank being an example. The result is that the reflections from a tank of such shape can be accurately captured with limited interference. This behaviour is demonstrated in Figure 5 below, representing a 1m diameter steel tank with a 4g PE10 charge and gauge at 400mm.

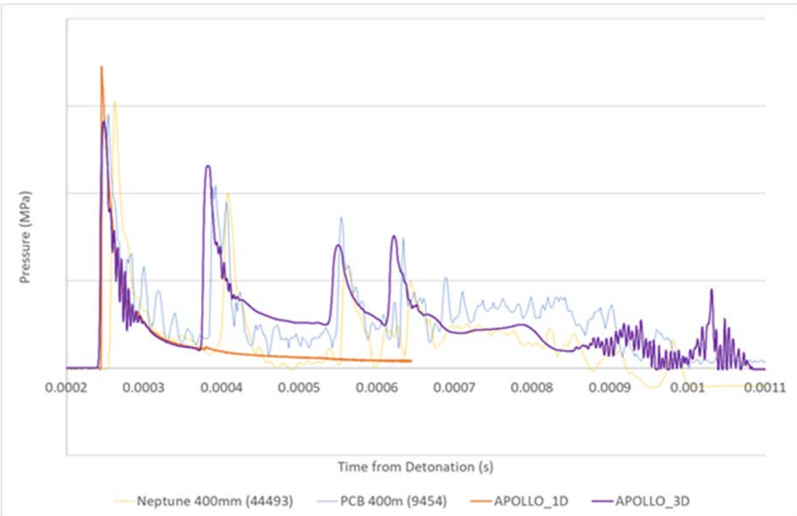

***Figure 3.** 4g PE10 charge in a 1m diameter steel tank with a gauge distance at 400mm; results compare APOLLO against test data*

Analysing this capability on a smaller scale – in a cylinder – has been shown to produce excellent results. Figure 6 below is the results of a 3g PETN charge in a 100mm diameter cylinder and 50mm standoff to the gauge [4]. The test data has been compared to APOLLO (2022/3) and LS-DYNA as well as DSYMAS – a joint US/German code – with DYSMAS (results extracted from the test report) and APOLLO closely matching the test trace, much more so than LS-DYNA.

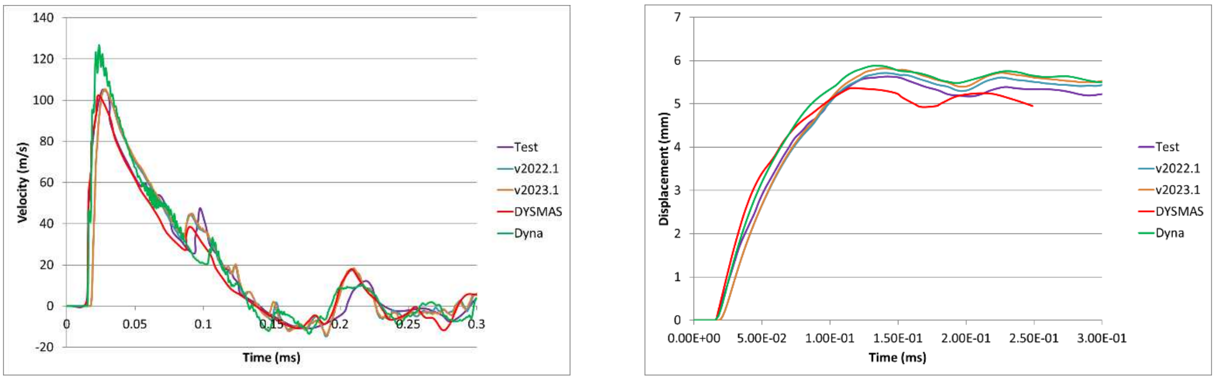

Figure 4. *3g PETN charge in a 100mm diameter cylinder with a gauge distance at 50mm; results compare APOLLO with test data and DYSMAS*

The ability of APOLLO to two-way couple to structural codes was mentioned earlier and is demonstrated below (Figure 7) with two video extracts: a simple blast against a structure and a charge confined within a water-filled cylinder. The concept of coupling is that the Euler code outputs pressures (caused by the explosion) experienced on the surface of the structure to be read by the structural code and translated into cell deformations, this information is subsequently fed back to the Eulerian code with an updated surface and associated velocity influencing the pressure waves and the cycle continues. The benefit of this approach is that the superior efficiencies of the Euler code can be combined with the Lagrangian capabilities of the structural code to produce answers in a much shorter time frame.

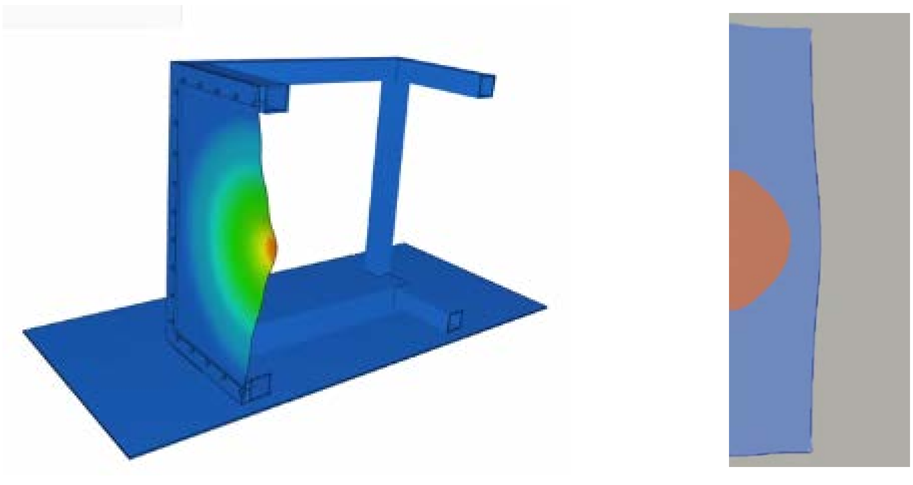

Figure 5. *Examples of APOLLO coupled to structural code: blast against a structure, coupled to IMPETUS (left); charge in a water-filled cylinder, coupled to LS-DYNA (right)*

Non-ideal Explosives

UNDEX explosives are typically manufactured with non-ideal compositions (i.e. additional oxidisers and fuel such as ammonium perchlorate and aluminium) as the behaviour leads to a longer reaction time and subsequent increase in the frequency and length of bubble oscillations [5]. The reason this behaviour can be favoured is due to the associated whipping effects that induce a fatigue loading capable of ‘snapping’ vessels in half [6]. As such it is imperative to understand the phenomena as well as the underlying physics and chemistry of such events in order to be able to better represent them in numerical models.

A series of near-field, far-field and confined tests (Figure 8) have been carried out at the test facilities at Blastech assessing a variety of charge shapes, masses and standoffs to allow analysis of the full range of behaviour experienced. When viewing the videos associated with the below extracts the long burn time is particularly evident for the (KS57) charge in far-field conditions, also displaying imperfections in the fireball during this period.

Figure 6. *Video extracts from testing of non-ideal explosives (left to right): near-field, far-field, light confinement, heavy confinement*

The variability in the explosive performance becomes evident when viewing graphical outputs that suggest a spectrum across the range of non-ideal explosives; PBXN-111 is more non-ideal than PBXN-109 due to its lower content of high explosive in addition to the presence of aluminium fuel, it also contains an oxidiser to allow underwater combustion. PE10 is an ideal plastic explosive with a high PETN content that shows similar behaviour to PBXN-109 and yet the other two charges in the graph below (Figure 9) display a substantially different overpressure and arrival time despite possessing an identical mass and shape, repeat tests with similar explosives displayed to avoid doubt of inaccurate empirical data.

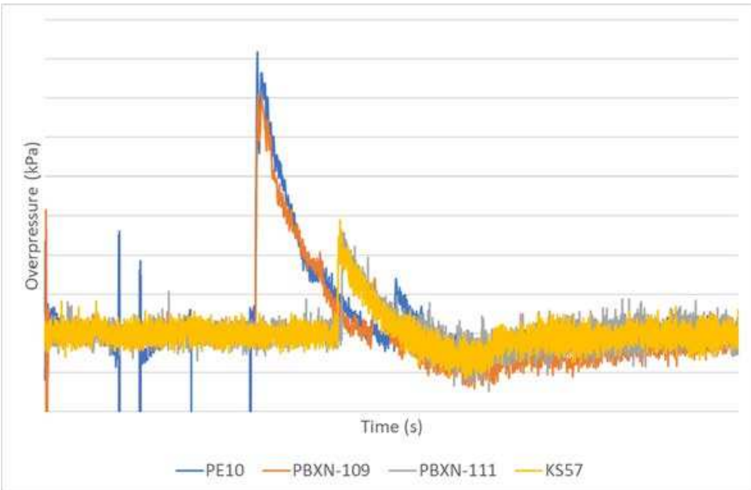

Figure 7. *Comparison of test data for non-ideal explosives*

The current absence of a valid method to explicitly simulate the behaviour of non-ideal explosives demontsrates the need to incorporate such behaviour into current numerical models. Nevertheless, Dstl is continuously exploring ways to improve in this domain, both with further experimental testing and by implementing new software functionality, with examples to be detailed in a later section.

Experimental Development

It is well established that verification and validation of numerical modelling is imperative to providing confidence in the software and its outputs. Typically this would involve performing trials of increasingly larger scale in order to capture the range of behaviour experienced with a varying charge mass. However, the logistics and complications imposed by a large-scale UNDEX trial significantly decrease the feasibility and, as such, Blastech – an explosive testing arm of the University of Sheffield – were commissioned to design and build a tank to provide the capability to undertake small-scale tests. This allows for much greater repeatability and control over the conditions (water clarity, lighting etc) and instrumentation such as high speed video (HSV) that generates excellent validation data, particularly in relation to bubble behaviour. Although yet to be modelled, a number of tests have been completed in the tank including bare charge, tests with geological materials and cased charge tests.

Below (Figure 10) is a rendered representation of the tank with a simulated UNDEX explosion using the physics included in the software Blender to provide an idea of the type of reaction that may be experienced. It measures 2m x 2m (diameter x height) with a number of portholes to the 'front' of the tank that provide windows for the cameras viewing from various heights and angles; it can handle charge masses up to 30g, making it suitable for repeat tests without a time-consuming reset process.

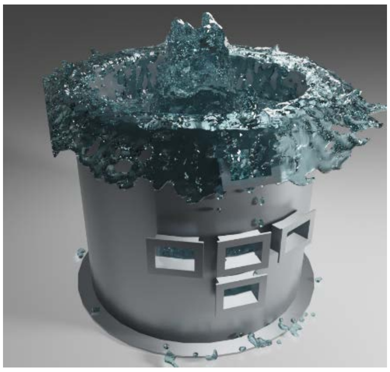

Figure 8. *Extract from Blender simulation of UNDEX in 2m diameter tank*

Whilst the HSV setup is able to capture the bubble behaviour with great resolution, issues persist with visibility at certain points in the explosive event. Figure 11 below contains extracts from a video at various stages: on the left is the initial detonation and expansion of the spherical shockwave; in the middle is the first bubble pulse at maximum volume with sharp details of the imperfections at the bubble surface; on the right is an example of the visibility issues faced, due to cavitation bubbles attracted to the porthole window in this case.

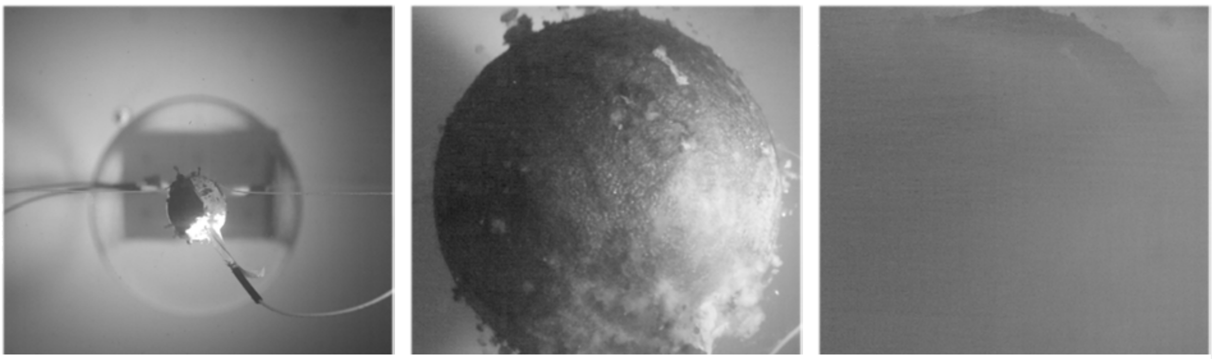

Figure 9. *High-speed video extracts showing detonation and bubble behaviour*

Ongoing Work

As is the case with any capability, it is important to progress and improve on the current proficiency in order to produce more accurate results that are better informed. Ongoing efforts fall into two distinct areas: numerical modelling and overall understanding (primarily through trials). It is important to combine learning and testing in both of these areas so one can inform the other and vice versa for validation purposes.

Dstl intends to expand the coupling capacity of APOLLO to allow for analysis of the full range of required structural response for a variety of UNDEX scenarios. The introduction of Smooth Particle Hydrodynamics (SPH) will extend the capability to include the modelling of charge casing fragmentation and interaction with geological materials, for example. Further developing the element type range for 1D, 2D and 3D will allow a greater selection of structural types to be assessed. No known method currently exists for explicitly simulating the behaviour of non-ideal explosives synonymous with UNDEX explosives (such as PBXN-111 and KS57). As part of this development Dstl is investigating the implementation of a multiple rate Guirguis-Miller (GM) model, a simplified method to allow simulation of non-ideal explosives in UNDEX by accounting for multiple rates of energy release from various components of an UNDEX explosive [5]. With regards to the general capabilities of APOLLO, and noting Figure 2, efforts are ongoing to validating bubble behaviour – rising and jetting – to more accurately simulate the physics involved. This will be achieved through a combination of trials and software development. Also, as UNDEX models tend to be significantly larger and longer running than air blast models, further improving the efficiency is very favourable.

Reference was made in an earlier section to the significant costs and logistics involved with large-scale UNDEX tests, so the opportunity to be involved in such tests in open water is of exceptional value. Plans are currently being developed to conduct a series of large-scale tests as part of the ANNC agreement (with Norway and Netherlands) using charge masses in the range of 50-200kg for both ideal and UNDEX explosives in three distinct sections of the water column: floating, submerged (mid-depth) and seabed. It is hopeful that this will provide invaluable data for shock and pressure histories, bubble oscillation, and structural response.

Conclusions

This paper presents the developments of a high fidelity UNDEX modelling capability at Dstl in partnership with EMI, both from a software and experimental viewpoint. It is clear from the evidence presented that significant progress has been made in developing APOLLO from a code that previously only modelled airblast to now possessing the capability to model UNDEX events, acknowledging that further refinements are still required in order to model the full behaviour experienced (bubble jetting and rise, for example) in such a scenario. Advancements in trials exposure is aiding in this development phase through small-scale trials performed at Blastech utilising the newly installed tank facility capable of testing a variety of scenarios, with plans to venture further into medium and large-scale trials to capture the full range of behaviour; planned trials for charge masses up to 200kg in open water at various depths in the water column will provide invaluable data and insight. Investigations are also ongoing into the behaviour of non-ideal explosives that are not currently well understood and for which no known method for explicit modelling currently exists.

Acknowledgements

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