

# HOW CAN WE ENHANCE CRITICAL INFRASTRUCTURE AND TRANSPORT SECURITY THROUGH AN INNOVATIVE METHODOLOGY OF OBSERVATION AND SHOCK WAVE TRACKING IN HARSH ENVIRONMENTS?

MICHEL-OLIVIER STURTZER<sup>1</sup> & SOPHIE TRÉLAT<sup>2</sup>

<sup>1</sup>Department of Explosive Protection, French–German Research Institute of Saint-Louis (ISL), Saint-Louis, France

<sup>2</sup>Department of Explosion and Weapons Effects, French Institute for Protection and Nuclear Security (DEND), Fontenay-aux-Roses, France

## ABSTRACT

The paper deals with an innovative methodology aimed at enhancing security of critical infrastructure and transport against the effects of explosive phenomena, in particular in the field of overseas and homeland security, as well as in the nuclear industry. In this context, the French–German Research Institute of Saint-Louis (ISL) and the French Institute for Protection and Nuclear Safety (DEND, previously IRSN) cooperate since 2017 by sharing their expertise and experimental capabilities. The methodology developed in this article consists of performing applied research studies and reduced-scaled experiments on reference targets facing representative threats. They rely on (i) the use of real-time pressure measurements to assess the mechanical loads at the targets surface and (ii) the capture of high-speed images of the supersonic flow interacting with the structures. One objective of the studies is to analyse efficiency of protective means and materials in terms of blast effects mitigation so as to propose guidelines on geometrical and structural dimensioning. This will contribute to building practical and normative recommendations for protection system design against explosive threats.

*Keywords: blast effects, pressure measurements, high-speed imaging, scaling effects.*

## 1 INTRODUCTION

The French–German Research Institute of Saint-Louis (ISL) is a bi-national research institute established by the Federal Republic of Germany and the French Republic on the basis of a treaty signed in 1958. The core mission of ISL is ‘Research, scientific studies and basic predevelopment in the field of defence and security’. Among other tasks, ISL focuses on the physical protection of personnel and assets against the effects of various explosive charges. To improve general survivability, fundamental studies on blast wave propagation and target interaction are continuously being conducted at ISL.

Nuclear security includes preventive measures to detect and counteract theft, tampering, illegal transportation of nuclear materials or any other malevolent act relating to nuclear materials, any radioactive substances or facilities harbouring them. In this context, the French institute for protection and nuclear security (DEND, Direction de l’Expertise Nucléaire de Défense et de sécurité in French) provides assistance and technical support for authorities in the field of sensitive activities, and assesses the safety of defence related facilities, the protection of civil nuclear installations and transports against any act of malevolence.

Both institutions consequently conduct research to study the effects of explosive phenomena (new mode of malevolence such as terrorism, unmanned aerial vehicles (UAVs), internal threats) on critical transport and infrastructure to ensure safety and security of either military assets or nuclear industry. The considered sources of explosions include weapons (metal fragments), industrial chemicals (ammo-nitrates) and emerging threats (homemade explosives). To achieve this goal, scaled-down experiments are being designed to analyse explosive blast propagation and interaction with reference targets such as parallelepipedic or



cylindrical shapes for instance, or to evaluate protection systems' blast resistance under real conditions. Diagnostic methods include pressure gauges and high-speed imaging.

Since 2017, DEND and ISL are cooperating on guidelines development relative to reduced-scale explosive tests. Both institutes are presently developing a high-speed imaging system demonstrating a large luminosity range capable to cope with intense light emission and pressure gradients, especially adapted to high-dynamic range and explosive phenomena. In 2022 a patent application was consequently filed. After focusing on the general experiments design methodology based on real information, the paper shows up some applications of the groundbreaking system: air blast propagation in the very close field of a cylindrical container or an access control system, subaquatic explosion, evaluation of actual and emerging threats, etc. Such applicative studies directly aim at contributing to maintain and further strengthen national nuclear security.

## 2 REDUCED-SCALE EXPERIMENTS: DESIGN METHODOLOGY

The BMAX (Bureau d'étude et Modélisation des effets des Armes et eXplosifs in French) office in charge of blast and weapons effects assessment at DEND develops models and tools to evaluate the effects of a malevolent explosion on nuclear facilities and transports. Different types of reference shapes are being investigated on a blast table: for instance, small explosive charges can be detonated in front of reduced-scale obstacles equipped with pressure sensors. Reference obstacles include vertical walls, cylinders, hemicylinders, protective barriers, etc., and can be representative of real infrastructures or containers thanks to the scaling principle of Hopkinson–Cranz [1], [2].

The PCE (Protection contre les effets des Charges Explosives in French) team responsible for protection against the explosive charges at ISL conducts studies in the field of threat characterization, threat defeat and target protection to provide physical protection of personnel and assets. Two operational environments are considered: foreign and homeland security. Reference explosive charges are being investigated on dedicated blast pads equipped with characteristic scaled down structures and vehicles.

The facilities on which the design methodology is based are described in the following sections.

### 2.1 DEND test table

The blast table has been principally designed to study shock waves reflection phenomena and interaction with different non-deformable structures [3]. It measures  $1.60 \times 2.40$  m and features an array of mounting holes that facilitates the placement of modular  $0.40 \times 0.40 \times 0.05$  m wooden plates, and pressure transducers (Figs 1 and 2). Different types of pressure transducers (piezo-electric and piezo-resistive, Figs 3(b) and 3(c)) are mounted on an elastic support inserted into the holes (each separated by 133 mm) provided for this purpose. Each pressure transducer is calibrated prior to the tests. Explosive charges (Fig. 3(a)) are installed and ignited on a dedicated reinforced steel table plate to generate a hemispherical blast wave using a Davey-Bickford SA 4201A detonator [5].

Experimental campaigns are performed at the ArianeGroup's research centre located near Paris (Vert-le-Petit, France). ArianeGroup handles all the experiment pyrotechnics and also provides the data recording system (Nicolet Genesis data acquisition system, sampling rate of 500 kHz). During experiments, the modular table is mounted and placed at the centre of a closed bunker (Fig. 2), so as to avoid the perturbation from shock reflection on the bunker walls.



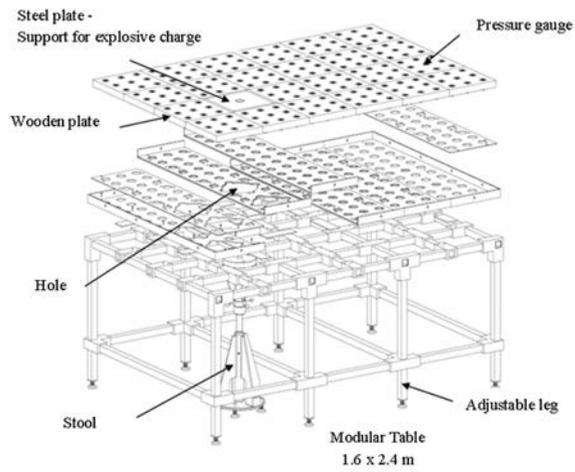


Figure 1: Schematic view of the DEND laboratory scale table [4].

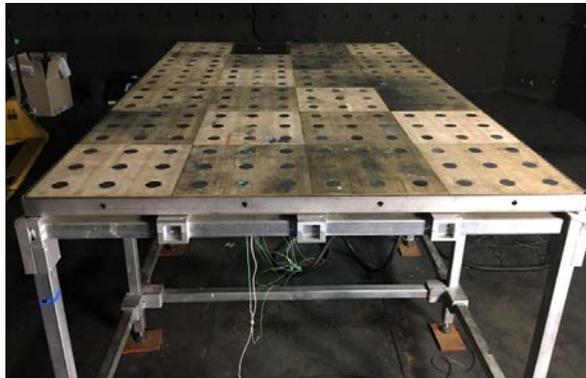


Figure 2: DEND blast table in its bunker [3].

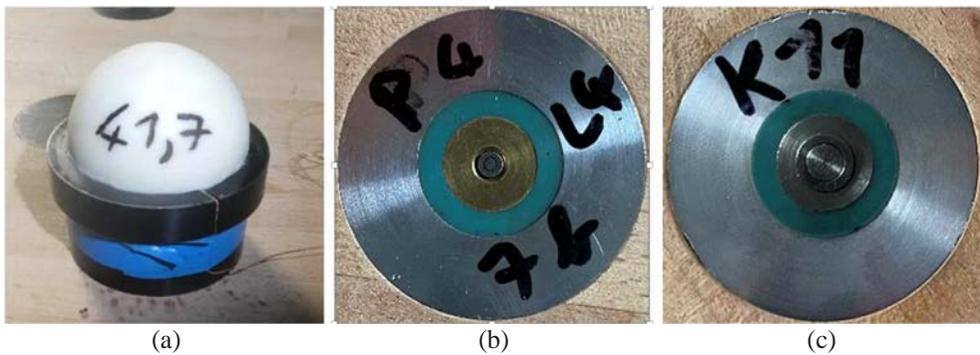


Figure 3: (a) Plastic explosive charge; (b) and (c) Pressure transducers [3].

## 2.2 ISL blast pad

ISL developed a dedicated outdoor blast pad located at its own explosive range: explosive charges are detonated in a factor 2 up-scaled version of DEND test configuration (position actually rated up to 10 kg of TNT equivalent). Sensors' integration is presented in Fig. 4 [3].



Figure 4: ISL hemispherical blast pad [3].

Different types of pressure transducers (piezo-electric and piezo-resistive) are mounted in a polypropylene support inserted in one of the integrated rail ports, each separated by 266 mm. Each pressure transducer is calibrated prior to the tests. All data are recorded using a Transcom system running at 2 MHz. Explosive charges are installed and ignited on a dedicated reinforced steel ground plate to generate a hemispherical blast wave (Figs 4 and 5), using a RP83 detonator [5].



Figure 5: Hemispherical explosive charges (C-4, Semtex, Hexomax and Comp-B) [3].

In addition, ISL offers the possibility of investigating spherical blast waves consecutive to above ground explosive charge detonation using similar pressure transducers installed on 1.5 m high poles as shown in Fig. 6.

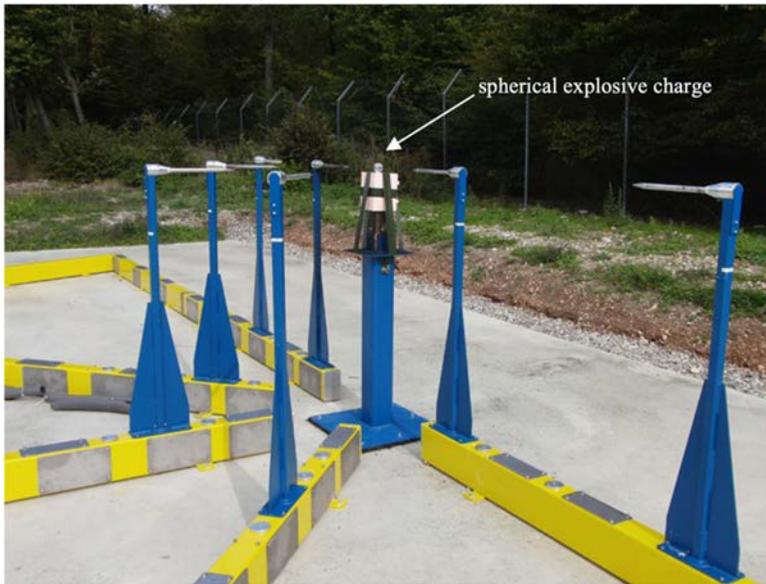


Figure 6: ISL spherical blast pad [6].

### 3 APPLICATIVE STUDIES

#### 3.1 Industrial chemical: ammo-nitrate detonation

On 4 August 2020, a large quantity of ammonium nitrate storage located in a hangar of the Beirut harbour exploded, causing few hundred deaths, more than 5,000 injuries, and dramatic fallouts for the Lebanese economy [7]. Following a legal procedure, a few thousand tons of ammonitrate had been ‘temporarily’ stored in a warehouse in non-adequate conditions: mixed with fireworks, motor oil, wooden pallet, and chemical products, etc. [8]. The explosion was preceded by a fire in the same warehouse. After some time, a large orange fireball became visible engulfing the storage building (Fig. 7(a)), followed by the transmission of a large blast wave materialized by the colossal white Wilson cloud seen in Fig. 7(b).

The experimental methodology was used to replicate the effects of the Beirut explosion, particularly the fireball development and the propagation of the blast wave into the



Figure 7: Webcam views of Beirut explosion [9]. (a) Fireball; and (b) Wilson cloud.

surrounding complex environment. A publicly available Lebanese webcam video (Fig. 7) was analysed to extract the trajectory of the blast wave and a consequent approximate TNT equivalent of the ammonitrate explosion. Based on these data, a non-deformable parallelepipedic wooden mock-up (Fig. 8(a)) was designed to provide a simplified model of the vertical cylindrical concrete silo stack seen in Fig. 7(a): its dimensions are 721 mm in length, 223 mm in height and 126 mm in width.

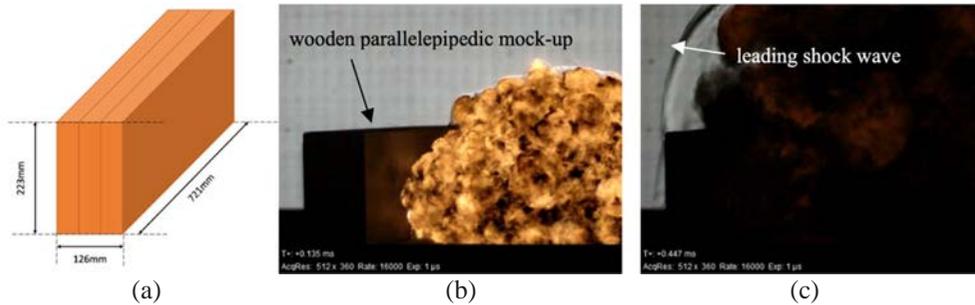


Figure 8: Beirut reduced-scale test. (a) Wooden mock-up; (b) Fireball development; and (c) Leading shock.

The scaled-down structure was exposed to the detonation of a few hundred grams of plastic explosive charge: the hemispherical fireball can be precisely observed as it impinges the front face of the stack of silos (Fig. 8(b)). In Fig. 8(c), the leading shock wave, invisible on the original video, is rendered visible once it has cleared from the post-combustion products. It is then enveloping the rear face of the concrete structure, undergoing diffraction phenomena from the building surfaces. High speed imaging highlights the importance of such observations for the assessment of urban structures vulnerability and protective characteristics, as well as the evaluation of prevention or mitigation measures.

## 3.2 Weapons effects

### 3.2.1 Contact explosive charge

The effects of a high explosive charge detonating (by accident or malevolence) directly on contact with a steel plate were studied. Prediction of the dynamic response and failure modes of a metallic protection represents a key knowledge notably in the field of critical infrastructure and vehicle protection and design. To that extent, both institutes recently joined their efforts in improving the knowledge in this field by conducting experimental and analytical work.

A series of tests was conducted using S235 steel plates commonly used for metallic structures (and similar to the outer steel jacket used for some storage container design [10], [11]). A cylindrical shaped plastic explosive weighing a few grams was placed at the surface of the metallic plate, as shown in Fig. 9.

Real-time deformation and metal fragments projections were analysed by the mean of high-speed images presented in Fig. 10. On the first image, we observe deformation and tearing of the steel plate rear surface leading to the formation of a large flying spall. A leading shockwave visible from the second image on corresponds to the shock transmitted to the air through the metallic plate by the detonation wave. A second visible shock is certainly

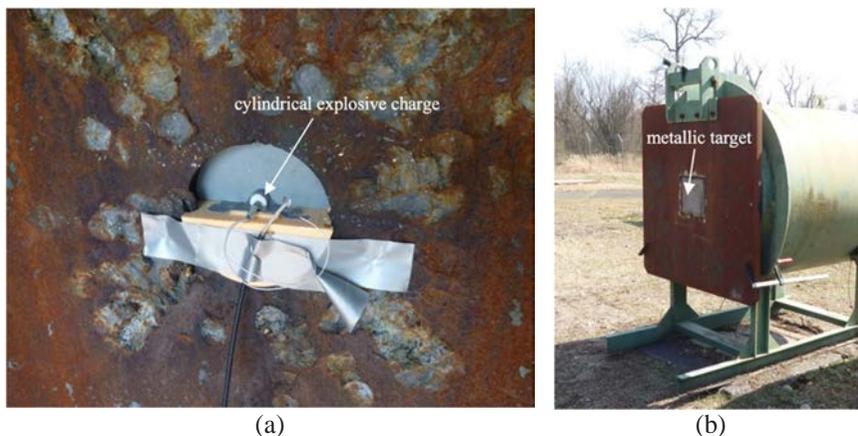


Figure 9: Contact explosive blast pad. (a) Explosive charge; and (b) Experimental setup [5].

generated by the spall supersonic flight. In the wake of the leading shock, a cloud of ejecta particles is being progressively dispersed. Conducted tests allowed the determination of some elements linking the charge/plate characteristics to the topology of the projected materials and the formed crater. The position of the leading shock could also be tracked, as well as that of the fastest visible ejecta and the spall to determine their trajectories. By estimating their relative weight through direct measurements of collected fragments or visual analysis, it is then possible to contribute to the knowledge of backside effects behind a protection solution based on a metallic plate.

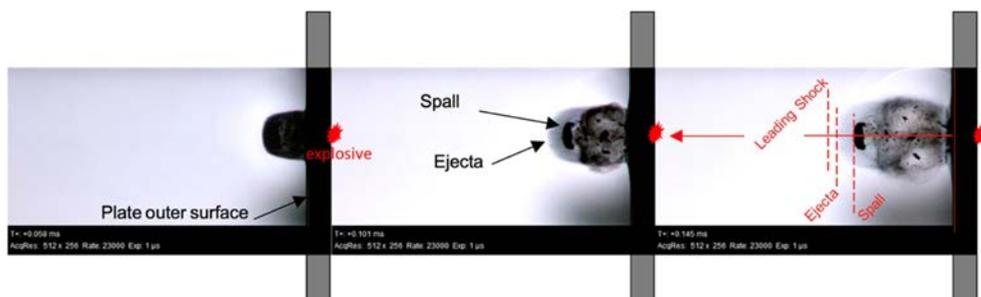


Figure 10: Series of three high-speed images of contact detonation [5].

### 3.2.2 Near-field explosive charge

DEND brings its expertise in the assessment of security levels for defence facilities, and protection of civil nuclear installations and transports against any act of malice. To achieve these goals, the institute manages active research projects in various nuclear safety and security fields in order to maintain top-level expertise and ensure on a long-term perspective the necessary knowledge and skills. ISL on the other hand has been investigating the effects of multiphase explosives for more than 15 years. The delayed combustion of reactive particles and the bare impulse of projected unreacted or partially reacted significantly modify the blast load characteristics in close range on vehicles panels or infrastructure walls.

The research work of both institutions contributes for example to developing or validating models, and identifying the most adapted tools or methods for assessing vulnerability of critical targets under explosive loading, in light of the fact it is a complex topic to deal with: walls of a shipping cask, as well as security doors or armoured vehicles panels by the way, are indeed made of one or several materials including steel, lead, resins, etc. [10]. These challenges in explosion area of expertise notably require determining the TNT equivalency of various explosive compositions or devices in peak overpressure, which represents a usual way of measuring the magnitude of an explosive event, accidental, experimental or terroristic. The determination of TNT equivalency in close range may be critical when the objective is to assess the effects on infrastructures. Fig. 11 shows an example of an ISL blast test for material resistance evaluation. A test plate is attached to the side of a test-bunker designed to lateral side blast effects.

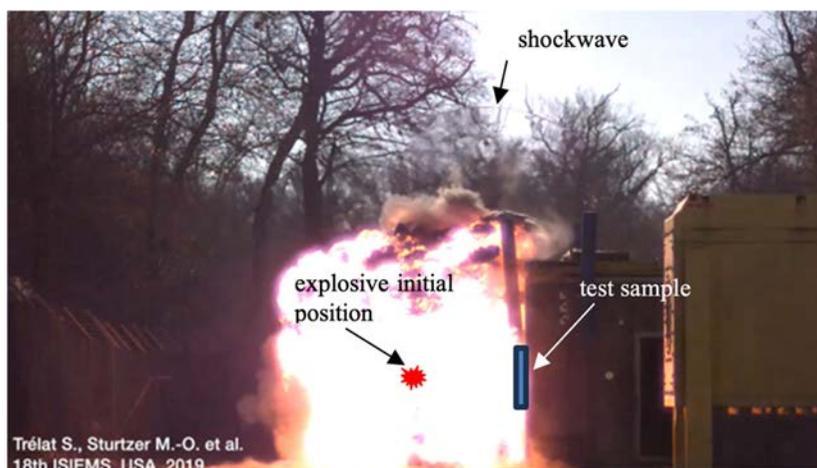


Figure 11: Near-field detonation test [5].

A plastic explosive charge is detonated above ground in the vicinity of the test metallic sample. A large fireball is enveloping the target as the leading shockwave (rendered visible thanks to the contrast of the dark trees on the bright background) has already departed from the afterburning region. If the resulting effects are lower than predicted (i.e. an overestimation of the plastic explosive TNT equivalent), survival of the candidate protective system being evaluated may be misinterpreted.

### 3.3 Emerging threats: aluminized home-made explosive

The research institutes may also be required to issue their opinion on the threat characterization and sensitivity studies for critical assets or several fuel cycle facilities. In this context, DEND must be able to assess the assumptions adopted by a nuclear operator to model its capacity for action for the design-basis threats of sabotage as defined by the national security directive applicable to nuclear facilities [11]. These are rapidly changing fields with regard to threat evolution on communication networks, which implies a continuous effort on the part of the institutes to maintain their expertise. ISL on the other hand may be asked to assess the physical effects of certain types of explosive compositions in characteristic configurations such as its mobile-roof internal detonation bunker [12].

For instance, in order to characterize the effects generated by the same mass of C-4 and an aluminized explosive composition (Al-Ex), the propagation of a hemispheric blast wave in free environment was studied. One charge of each type with the same mass was detonated at the centre of ISL hemispheric blast pad (Fig. 12). Side-on pressure gauges placed at a few meters from the charge centre recorded the pressure evolution for both explosive compositions. High-speed images presented in Fig. 13 demonstrated the fundamental difference in the fireball behaviour of the two explosives: the reactive aluminium particles ensure a long-lasting light emitting combustion reaction leading to enhanced quasi-static pressure effects. This observation was confirmed by the overpressure and positive impulse evolutions with distance. Results thus proved to be critical to estimate this new type of explosive threat's degree of strength in free field in comparison to a reference plastic explosive such as C-4 (or even TNT) used for previous vulnerability studies.



Figure 12: ISL hemispheric blast pad [5].

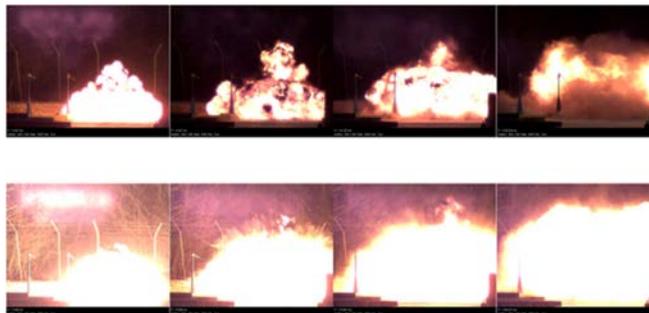


Figure 13: Two series of high-speed images: C-4 on top, Al-Ex on bottom [5].

### 3.4 Air blast propagation close to a cylindrical shape

Understanding the effects of a blast generated by an accidental or a terroristic explosion nearby a critical structure is a main concern for both DEND and ISL. Hemicylindrical shapes are commonly encountered on industrial sites, military facilities and also representative of certain infrastructures and transport containers in the nuclear sector. Full-scale reactive phenomena are however seldomly compatible with long-term studies due to cost and regulation issues. Blast wave interaction with a convex structure was consequently investigated through a twin reduced scale experimental approach. The effects of explosive

charges were characterized at the surface of a hemi-cylindrical obstacle, shown in Fig. 14, inspired by nuclear and radioactive containers, or at larger scale, by the nuclear reactor building or a hangar to store vehicles or aircrafts. Based on the 50 g TNT equivalent DEND installation described in Section 2.1, ISL designed a factor 2 up-scaled setup by using 400 g TNT equivalent explosive charges. Blast wave propagation was analysed through the peak overpressures recorded along the hemi-cylindrical structure's central line with numerous sensors placed at its surface. An innovative parameter named the reduced shifted direct distance (RSDD) was introduced to take into account the geometry of the obstacle and the 3D free-field pressure decay. A physical model (Model S) [13] allows then the prediction of the peak overpressure evolution on whole circumference of the hemi-cylinder. Further results confirmed the extension of this conjecture to other charge masses and ratio between the distance to the charge and the hemicylinder radius. This rapid tool will be useful to perform structural analysis or to assess the resistance of transport and infrastructure.



Figure 14: Hemispherical mock-ups at two different scales [13].

### 3.5 Subaquatic blast propagation

This section delves into understanding the impact of detonations caused by underwater explosives, with a specific focus on shallow water-filled nuclear pools and liquid-filled containers as parts of various vehicle fuel systems. These reservoirs are designed to maintain water tightness, often achieved through the presence of a thin stainless-steel liner. The need for research relies on investigating the potential loss of this functionality due to damage to the concrete structure and perforation of the liner. Such damage could result from local deformations caused by the overall response of the structure as well as the direct effects of the explosion. While the former aspect can be explored using techniques like, for instance, the method of images (MOI) [14], the latter occurs only when the explosive device is close enough to generate pressures capable of causing volumetric damage to materials.

This secondary effect complements the primary one and is exemplified through experimental simulations that analyse local conditions, combining pressure measurements and high-speed images recordings, thereby enhancing the understanding gained from global analyses. As an illustration, the series of images in Fig. 15 presents the initial propagation of the shock generated by the detonation of a small underwater high-explosive charge. The orange fireball of detonation products is visible on the first two images whereas the shock is transmitted to the surrounding water until it reaches the water tank walls leading to their rupture visible on the last image. Shock waves' reflection on the free surface can also be analysed thanks to the high quality of the capture image.

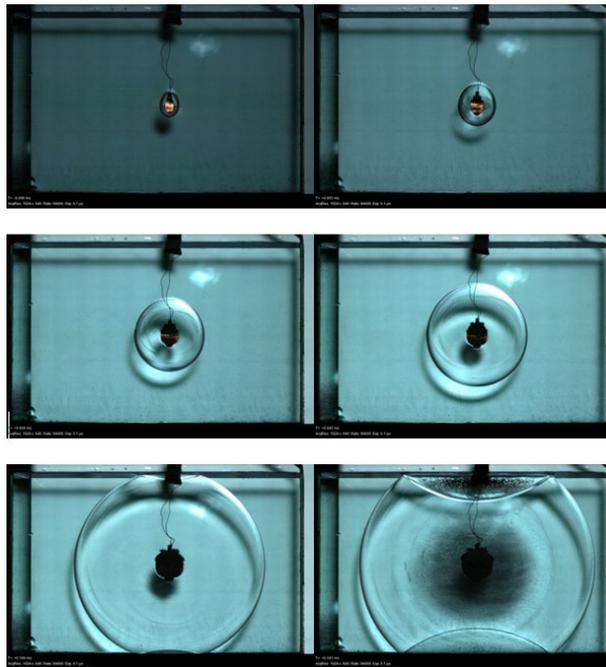


Figure 15: High-speed images for the free-field (i.e. without obstacle) subaquatic tests [5].

#### 4 CONCLUSIONS

In conclusion, the paper sheds light on an innovative methodology aimed at enhancing the security of critical infrastructure and transportation systems against explosive threats, particularly in the military and nuclear industry domains. The methodology involves conducting applied research studies and reduced-scaled experiments on reference targets to assess blast effects and evaluate the efficiency of protective measures and materials. By utilizing real-time pressure measurements and high-speed imaging techniques, the study aims to provide guidelines for protection systems design and normative recommendations development to mitigate the impact of explosive phenomena. The collaboration between the French–German Research Institute of Saint-Louis (ISL) and the French Institute for Protection and Nuclear Security (DEND) has been instrumental in advancing this research, with a focus on developing a high-speed imaging system capable of capturing the dynamics of explosive interactions with critical structures. The paper also presents several applicative studies, including investigations into industrial chemicals, weapons effects, and emerging threats such as homemade explosives. These studies provide valuable insights into the behaviour of structures and materials under explosive loading conditions, facilitating the development of robust protection strategies and enhancing national nuclear security.

Overall, the research outlined in this paper contributes to advancing the understanding of explosive phenomena and provides practical tools and methodologies for enhancing the safety and security of critical infrastructure and transports in the face of evolving threats. Further research in this area will continue to strengthen authorities' ability to contribute mitigating the impact of explosive events on vital assets and personnel.

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