Fundamental and Applied Studies of Fuel-Air Detonation
- A Quarter Century of Large-Scale Testing at DRDC Suffield -

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Historical Context

When the Fuel-Air Explosives (FAE) program at DRDC Suffield (formerly the Defence Research Establishment Suffield, DRES) began in the late 1970s, scientific investigations of gaseous detonation generally fell into two broad categories: (i) those dealing with the 'microscopic' features of detonation or the structure of the wave front, and (ii) those concerning the 'macroscopic' aspects of detonation or the gross dynamic behaviour of the wave.

Our understanding of the wave structure began with the classical works of Chapman[1] and Jouguet[2] at the turn of the 20th century. These authors were the first to postulate that a detonation wave consisted of a shock wave followed by a flame, and their thermodynamic analysis included a heat addition term to account for combustion energy. The later work of Zeldovich[3], von Neumann[4], and Döring[5] described the wave as a shock followed by a steady-flow, inviscid, reaction zone terminated by a plane at sonic conditions. An anomaly in the generally accepted view of detonation was the observation of a 'spinning' wave near the detonability limits, as first reported by Campbell and Woodhead[6] in the mid 1920s. It was not until the late 1950s when it became evident that spinning detonation was a limiting case of the universal cellular structure of detonation. Denisov and Troshin[7] used smoke foils to record this structure in the Soviet Union, while White[8] in the United States obtained interferometric photographs showing the non-steady 'turbulent' nature of detonation. A plethora of studies over the succeeding two decades attempted to understand the intricacies of the cellular structure and to measure the cell size for various fuel-oxidizer-diluent systems (e.g., Strehlow[9], van Tiggelen[10]).

Regarding the dynamic behaviour of detonation, it was known that the initiation and sustenance of detonation depended on an intimate competition between the rates of gasdynamic expansion and chemical energy release behind the leading shock front. Experimental investigations in this area fell into two general classes. In the first class, the flow entering the shock front is not globally steady to an observer riding on the front. Initiation of detonation by a spark or an explosive charge is one example (e.g., Zeldovich[11], Lee[12], Bull[13]). Transmission of detonation from a tube or a channel to a less confined region is another example (e.g., Mitrofanov[14], Lee[15], Knystautas[16]). The rate of gasdynamic expansion in these problems becomes less severe as the wave front diverges. In the second class, the flow entering the shock front is globally steady as viewed by an observer moving with the shock. Problems of this type include propagation of detonation in a column or layer of mixture bounded by an inert gas (e.g., Dabora[17], Vasiliev[18]), yielding boundaries (e.g., Tarasenko[19], Vasiliev[20]), or rigid walls (e.g., Fay[21]). Here, the rate of gasdynamic expansion is identical for each 'stream tube' of particles entering the front and the wave propagates with a velocity deficit that increases as the severity of the expansion increases.

A key challenge facing the academic community during the 1970s and 1980s was to quantify the link between the dynamic behaviour of detonation and the newly discovered cellular structure of the detonation front. A second challenge was to interrelate the observations from many seemingly diverse investigations. Only then would a unified description of detonation be possible.

Fundamental Studies of Gaseous Detonation in Fuel-Air Mixtures

Influence of Confinement on Detonation Propagation

A novel experiment was conceived to improve our understanding about the competition between the rates of gasdynamic expansion and chemical energy release in the post-shock flow, and to quantify the critical conditions for detonation propagation. The apparatus, shown in Fig. 1, consisted of a cylindrical polyethylene tube (0.89-m diameter) filled with an ethylene-air mixture. Initiation of detonation was achieved at one end by a high-explosive charge or by transmission of detonation from a steel pipe of identical diameter. In these experiments, the rate of chemical energy release, as characterized by the cell size, was adjusted by changing the mixture composition. The rate of gasdynamic expansion was controlled via the selection of polyethylene wall thickness. With this set-up, it was possible to vary the degree of confinement from zero (i.e., an unbounded column) to infinity (i.e., a rigid pipe). Three wall thicknesses were used in the tests (1, 5 and 10 mil). As shown in Fig. 2, the wall accelerates outward in the radial direction following the passage of the leading shock. The thicker the wall, the less severe is the gasdynamic expansion imposed on the post-shock flow. A convenient means of quantifying the gasdynamic/chemical kinetic competition is to calculate the increase in cross-sectional area, $\xi = \Delta A/A$, of the 'stream tube' of particles entering the shock front as they migrate a distance from the shock equal to the detonation cell length, L_c. In order to calculate the former, the trajectory of the wall was computed using a piston-in-tube model adapted for cylindrical coordinates. The prediction was found to be in good agreement with high-speed film data. Using this approach, the critical stream tube area increase, ξ^*, was calculated to be near 20% for all critical conditions.

Figure 1. Set-up used to study yielding confinement

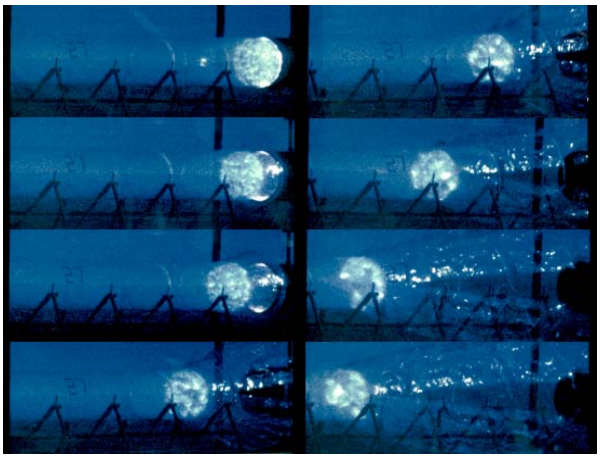

Figure 2. Cine frames showing propagation of detonation in a 10-mil plastic tube for 3.85% ethylene-air

The stream tube concept is also useful for describing the velocity deficits under supercritical conditions. Dabora's[17] adaptation of Fay's[21] 'nozzle' analysis yields the following expression for the velocity deficit if one assumes that the effective reaction-zone length for the wave is on the order of the cell length: $\Delta V/V_{C\text{-}J} = 1 - \{(1-\nu)^2 / [(1-\nu)^2 + \gamma^2(2\nu-\nu^2)]\}^{1/2}$ where γ is the ratio of specific heats for the detonation products and ν is defined as $\xi/[(1 + \gamma)(1 + \xi)]$. This expression was found to describe the velocity deficits from the author's yielding boundary experiments, as well as the deficits from the rigid tube tests of many other investigators, quite well. In rigid tubes, the expansion is caused by viscous boundary layers. Also noteworthy is that the limiting deficit of about 10% for $\xi^* = 20\%$ is in good agreement with most experimental observations and

with the value predicted by Edwards[22] based on Shchelkin's[23] instability criterion. Fay[21] had used the elemental induction-zone length in his model and severely under predicted the deficits.

Critical Tube Diameter for Detonation Transmission

The critical tube diameter, d_c, for transmission from a tube to an unconfined space has been proposed as a relative measure of the detonability of combustible mixtures (Matsui and Lee[15]). Mitrofanov and Soloukhin[14] first proposed that the critical diameter is linked to the cell width, λ, via the relation $d_c \cong 13\lambda$ based on experiments in low-pressure oxyacetylene. It was not known during the early 1980s if this relation held for less sensitive fuel-air mixtures, so a testing facility was constructed at DRDC Suffield to test this hypothesis. The facility consisted of a steel tube connected to a large plastic bag intended to simulate free space, both of which were filled with fuel-air mixture. A recirculation system was used to mix the gases, and the fuel concentration was monitored using an infrared analyzer. A detonation was formed at the closed end of the tube using either a high-explosive charge or an oxyacetylene slug. The instrumentation included pressure gauges, smoke foils, and high-speed cinematography. Four tube sizes were employed: 0.31, 0.45, 0.89 and 1.83 meters, the largest of which is shown in Fig 3. Acetylene, ethylene, ethane, propane and methane gases were tested. Near critical transmission of a propane-air detonation from the 0.89-m tube is shown in Fig. 4. Under critical conditions, reinitiation occurs near the tube axis just before the wave is quenched by the incoming rarefaction waves. The tests confirmed that the 13λ correlation is approximately valid for fuel-air mixtures, with the precise constant of proportionality being dependent on the regularity of the detonation cellular structure.

Figure 3. Set-up used to study transmission of detonation from a tube to an unconfined region

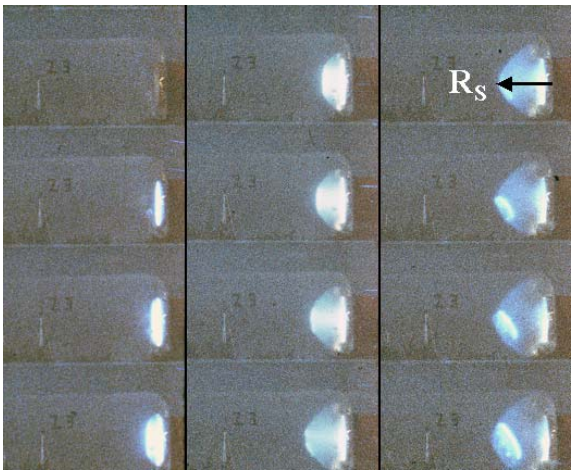

Figure 4. Cine frames showing near critical transmission of detonation from a tube in 4.7% propane-air

Based on the notion of a critical stream tube area increase ξ^* equal to 20% evaluated over the cell length, one can estimate the radius of a diverging wave front required to produce this condition. Consider a surface of particles entering a shock of radius R propagating at the Chapman-Jouguet (C-J) detonation velocity, $V_{C\text{-}J}$. Assuming that C-J conditions prevail throughout the reaction zone, these particles will fall behind the shock by a distance of one cell length, L_c, in time $\Delta t = L_c/C_{C\text{-}J}$ where $C_{C\text{-}J}$ is the sonic velocity of the burned gases. However, during this time, the particle surface expands to a radius of $R+(V_{C\text{-}J} - C_{C\text{-}J})\Delta t$ or $R+U_{C\text{-}J}\Delta t$ where $U_{C\text{-}J}$ is the C-J particle velocity. The stream tube area increase is therefore $\xi = \{[R + (U_{C\text{-}J}/C_{C\text{-}J})L_c]^j - R^j\}/R^j$ where $j = 1$ or 2 for cylindrical or spherical geometries. Noting that $U_{C\text{-}J}/C_{C\text{-}J}$ is typically 0.8, setting ξ to

0.2, and rearranging gives critical cylindrical and spherical radii of $R_c^* = 4L_c$ and $R_s^* = 8.4L_c$, respectively. Noting that $\lambda/L_c \cong 0.65$ in the literature, these radii can be expressed as $R_c^* = 6\lambda$ and $R_s^* = 13\lambda$. This means that $R_s^* \cong d_c$, a result substantiated by the cine sequence in Fig. 4.

Critical Energy for Direct Initiation of Detonation

The critical energy for direct initiation of detonation in fuel-oxygen mixtures has been investigated by many researchers. The energy source used in these studies has typically been a spark or an exploding wire produced by capacitor discharge. Fuel-air mixtures are significantly less sensitive than fuel-oxygen mixtures, so a powerful igniter such as an explosive charge is required to initiate detonation. While some initiation studies involving fuel-air mixtures had been reported during the 1960s and 1970s (e.g., Kogarko[24], Hikita[25], Bull[13]), useful data were relatively scarce. A testing facility was therefore constructed at DRDC Suffield for this purpose.

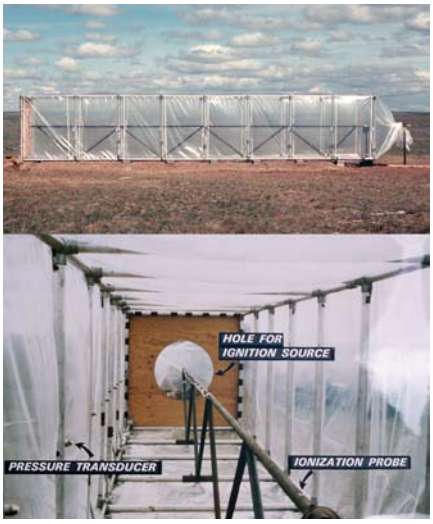

Figure 5. Set-up used to study initiation of detonation by a high-explosive charge

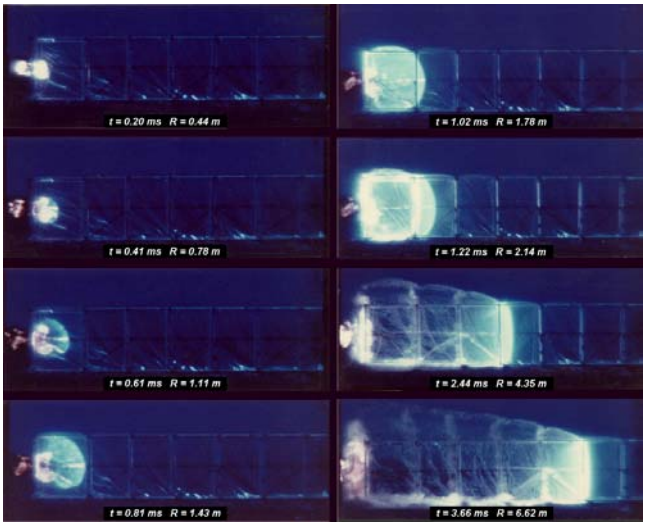

Figure 6. Cine frames showing initiation of detonation in 6.4% ethylene-air using an 18-gram PETN high-explosive charge

The facility (Fig. 5) employed a large plastic bag 10 m in length and 1.83 m by 1.83 m in cross section. The bag was filled with a fuel-air mixture that issued from a nozzle at one end. The mixture composition was controlled using calibrated mass flow controllers. A high-explosive PETN charge fastened to the end wall of the bag was used to produce a powerful shock wave. The instrumentation used in the tests included pressure gauges, ionization probes, and high-speed cinematography. If the charge was too small, the shock wave propagated through the mixture and ignition took place, but a detonation wave did not form. For a sufficiently large charge, detonation initiation was successful and, at a sufficient distance from the charge, the wave propagated through the mixture near the C-J velocity (Fig. 6). Several experiments were required to identify the critical charge mass for a given mixture composition. The process was then repeated for several compositions over the range of interest.

In the previous section, the critical shock radius required for reinitiation to occur in the critical tube problem was described. Bearing this critical radius in mind, the critical energy requirement boils down to determining what size of explosive charge must be detonated in order to produce a shock wave of approximately C-J strength by the time the wave reaches the critical radius. This reasoning suggests that a relationship must exist between the detonation cell size and the

Figure 7. Set-up used to study cylindrical initiation of detonation by an axial high-explosive detonating cord

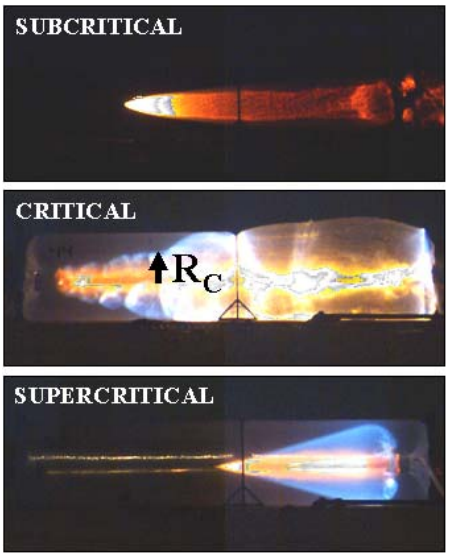

Figure 8. Video frames showing sub-critical, critical, and supercritical initiation

explosion length for the initiation charge under critical conditions. A recent collaboration between McGill University and DRDC Suffield was carried out to clarify the nature of this relationship. Once again, the apparatus consisted of a plastic bag filled with fuel-air mixture (Fig. 7). However, rather than initiating a spherical detonation wave, a line initiation source consisting of a high-explosive detonating cord was used to initiate cylindrical detonation in the mixture. Figure 8 illustrates the three regimes of initiation captured by high-speed video. In the subcritical regime, the detonating cord is not sufficiently powerful to initiate detonation and only the products from the detonating cord are visible (orange colour). In the supercritical regime, the shock produced by the detonating cord is strong enough to initiate detonation in the gas (light blue colour). The critical regime is characterized by the appearance of numerous explosion centres at a radial location fairly consistent with the predicted critical radius of $R_c^* = 4L_c$ for cylindrical geometry. The experiments also confirmed that the relationship between the explosion length and the cell size under critical conditions is linear.

Applied Studies of Detonation in Fuel-Air Mixtures

DRDC Suffield has been actively engaged in numerous applied studies over the years. Some of the earliest work for the Canadian Forces was aimed at neutralizing land mines. A canister device filled with propylene oxide and fitted with an axial fuel dispersal charge was developed for possible mine field clearing operations in the Falkland Islands (Fig. 9). The fuel is explosively dispersed to form a large 'pancake' shaped cloud that is subsequently detonated by a high-explosive secondary charge. The strong shock wave is sufficient to trigger or destroy the fuzes in many types of first generation land mines. A tactical minefield breaching system was later developed and demonstrated which utilizes a rocket-deployed hose that is subsequently filled with propylene oxide (Fig. 10). Again, the fuel is explosively dispersed to form a 200-m long cloud that is then detonated to create a safe lane for the passage of troops and vehicles.

Defending against FAE weapons is an important capability for any armed force. Figure 11 shows a deliberate ignition system mounted at the entrance to a simulated ventilation duct for an

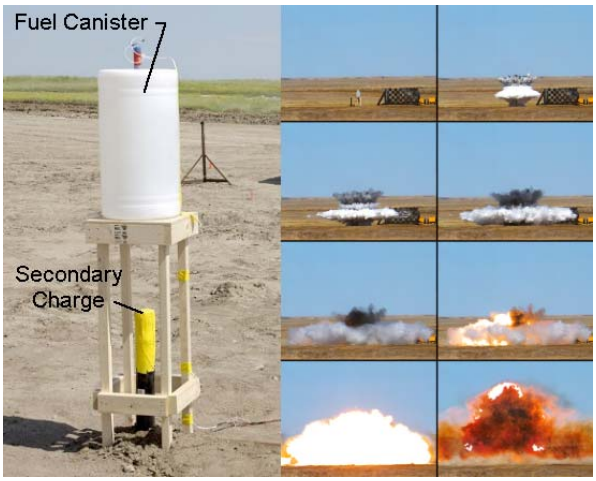

Figure 9. 66-liter fuel-air canister device and video sequence showing fuel dispersal and detonation

Figure 10. Rocket deployment of 300-m line-charge hose followed by fuel dispersal and cloud detonation

Figure 11. Deliberate ignition device in duct and cine sequence showing ignition of cloud during fuel dispersal

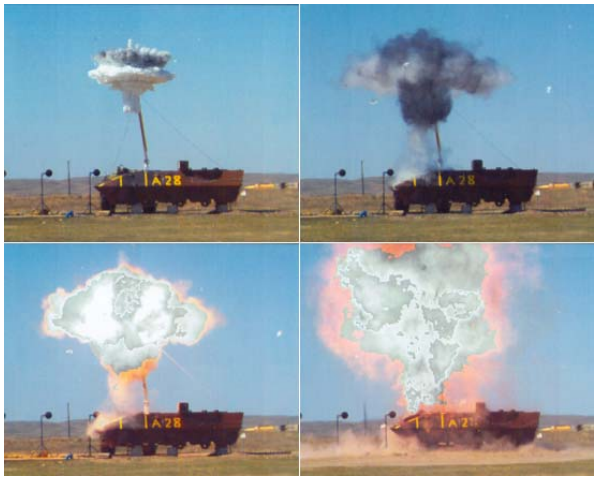

Figure 12. Test employing 10-liter FAE canister device to assess the blast vulnerabilities of armoured vehicles

underground military installation. The system is designed to prevent large amounts of combustible vapour from being ingested into the installation, and to burn off the developing fuel-air cloud before the secondary charge has an opportunity to detonate. This system is currently in use by an allied nation. DRDC Suffield has also assessed the blast vulnerabilities of numerous military vehicles (Fig. 12), equipment, and field fortifications. Once specific vulnerabilities have been identified, countermeasures are devised and proven in follow-on trials.

Multiple FAE canisters can be used to create enhanced blast effects. Figure 13 shows liquid fuel being dispersed from three individual canisters arranged in a 'V' shaped array. The clouds are subsequently detonated simultaneously to produce a strong directional blast wave that emerges from the open end of the V. In some regions, the peak pressures and impulses correspond to those that would be created by a single TNT charge having 20 times the mass of the fuel in the three canisters. This concept could be weaponized or used as an inexpensive blast simulator.

The secondary charges used to initiate FAE clouds are expensive and unreliable. It would be ideal if the fuel could be dispersed into a cloud that automatically detonates after a prescribed time delay. So-called 'non-explosive' or 'chemical' initiation of detonation has been a topic of

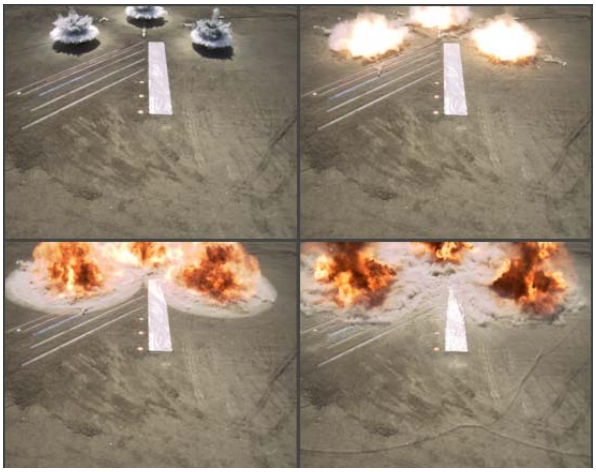

Figure 13. Evaluation of triple FAE canister array as a high-TNT-equivalency blast simulator

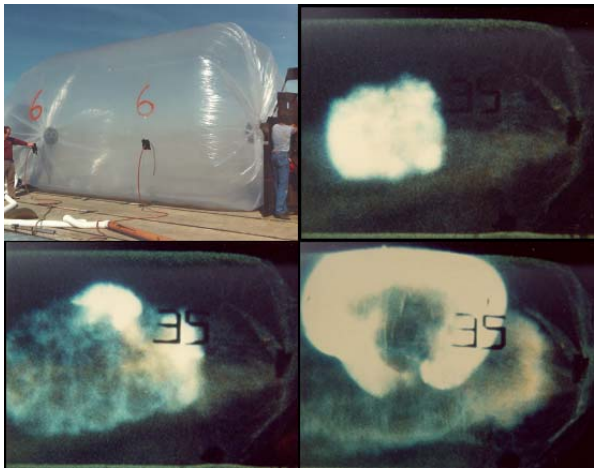

Figure 14. Initiation of detonation in ethylene-air by a turbulent fluorine-air jet from a pressurized chamber

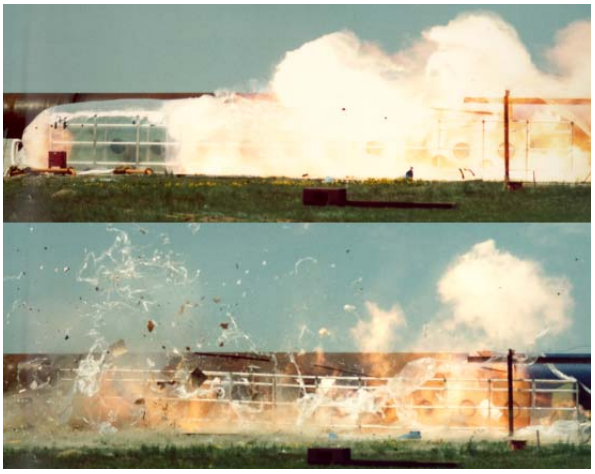

Figure 15. Transition from deflagration to detonation in an obstacle array filled with acetylene-air mixture

Figure 16. Gun firing of 155-mm hollow projectile through fuel-air mixture in detonation propulsion study

interest to weapon designers for decades. In one of the early fundamental studies of chemical initiation, a fluorine-air mixture at 20 atm was vented rapidly from a chamber into an ethylene-air mixture by rupturing a diaphragm (Fig. 14). Under optimal conditions, an induction-time gradient is formed in the jet vortex leading to ignition and rapid run-up to detonation via the SWACER (shock wave amplification by coherent energy release) mechanism.

DRDC Suffield has conducted a number of hazard prevention studies for the petrochemical and nuclear industries. In one such study, the detonability of hydrogen sulfide-air mixtures was of concern. Hydrogen sulfide is a by-product of heavy water production. However, little was known about its detonability and there was concern that the pipe racks present in heavy water production facilities might be capable of promoting deflagration-to-detonation transition (DDT). Figure 15 shows a test involving flame acceleration and DDT under confinement and obstacle conditions deemed to be representative of a heavy water production plant. These tests concluded that the detonability of hydrogen sulfide in air is similar to propane-air.

DRDC Suffield has been involved in several detonation propulsion studies. For example, a comprehensive assessment of the 'pre-detonator' concept proposed for use in pulse detonation

engines has recently been completed. In a separate study, the feasibility of propulsion based on steady detonation is being evaluated. A gun-launched hollow projectile is being used for this purpose. The projectile possesses a converging inlet, a throat, and a diverging nozzle. Numerical modeling has shown that if the inlet angle and throat diameter are judiciously chosen, detonation initiation will occur just behind the projectile and the wave will move forward and anchor itself in the throat. Figure 16 shows a facility in which a 155-mm howitzer gun is used to launch the hollow projectile through pre-mixed fuel and air contained in a plastic bag. This work is still in progress.

The Way Ahead

The work on fuel-air explosions continues today, but it is only one element in the overall energetic materials and explosive effects program at DRDC Suffield. Other past studies include detonation in foamed explosives, liquid explosives, liquid-explosive saturated inert-particle beds, high-explosive dust clouds, metallic dust clouds, monopropellant droplet clouds, and gas/particle hybrid mixtures. The current research focus is on super-compressed detonation in energetic liquids, overdriven detonation induced by cascading events, advanced thermobaric concepts, hybrid detonation, enhanced novel (i.e., terrorist) explosives, solid-state detonation, metastable and other and new energetic materials, and molecular dynamics modelling.

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