Reducing HE Response Severity by Varying the Confinement around an Explosive Charge to Improve IM Signature

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1. Introduction

Insensitive Munitions (IM) are developed to reduce the possibility of unintended violent reaction throughout the munitions lifecycle either in accidents or as a result of malicious or enemy action. The test protocol for IM [1] requires the application of severe insults such as fast and slow cook-off, bullet, fragment, shaped charge impact and sympathetic detonation to the IM system in its packaging to demonstrate that the Energetic Material (EM) does not produce these violent responses. However, the most frequent accident that is likely to occur to a munition (insensitive or otherwise) are relatively low speed impacts from drops or during transportation accidents. For an IM system, low speed impacts will not cause the EM to produce a violent response as the stimuli experienced by the IM system in its packaging will be too small to cause ignition. However, safety needs to be examined for the complete life cycle of the munition and, during certain stages of the life-cycle (such as during manufacture, testing and disposal) there will be opportunities when the EM is vulnerable to low speed impacts. As a result of the low speed impact, the EM within the munition may initially suffer mechanical damage followed by the formation of localised hot zones (e.g. as a result of pinch or mechanical deformation) that could begin a burn (deflagration) within the damaged EM. If conditions are favourable, the deflagration can grow in volume and violence along the voids in the damaged EM. A major influence in this is the confinement surrounding the burn site. As the burn rate is pressure dependant and the internal pressure depends on the strength of the confinement preventing the release of the combustion gases, if the confinement is sufficiently strong, then violent events similar to explosions or even detonations may occur. The growth of the reaction from a burn to a detonation type event is known as Deflagration to Detonation Transition (DDT)

The development of a new munition needs to consider the Munitions safety throughout its lifecycle and this will include when it is outside of its packaging (improving the system safety outside any packaging will enhance the IM signature of the system when packaged). It would be prudent to attempt to minimise the potential of the munition to produce a violent response when subjected to any abnormal insults. As stated earlier, IM status is generally achieved through careful use of either one or a combination of the following; explosives (e.g. reduced sensitivity EM's), design features and improved packaging [2]. As this work is aimed at accidents involving low speed impacts when the munition is outside the packaging, the package option can be discarded. The choice in EM may be restricted given the requirements for performance, safety, longevity, cost and mechanical properties. It is also assumed that the EM, if ignited in ambient environments, will exhibit quiescent burning or self-extinguish and not undergo rapid reaction growth rate that rapidly develops into a very Violent Reaction (VR) once it has been ignited regardless of its environment). This means that the design of the munition would be a key factor in determining the response when subjected to low speed impact insults.
A major design influence on the explosiveness of an EM is the strength of the confinement surrounding the ignition site. Ignoring inertial confinement provided by the mass of the EM material (it will be assumed that the ignition occurs close to a surface/interface of the EM charge), the confinement would generally be provided by a case surrounding the EM. It is desirable from an IM perspective, to have a relatively weak (low failure strength) case surrounding the explosive so that the case fails, quenching the reaction, before it develops into a violent event. For some munitions, the confinement surrounding the EM acts as part of

the weapons functionality (e.g. fragment forming) or helps to maintain the integrity of the weapon as it is being delivered to the target and is thus a desirable feature when the munition operates in design mode. In this instance it may be desirable to introduce ‘seams or joints’ in the case that are substantially weaker than the main case body. It may even be possible to introduce vent ports to quench burning reactions without affecting the design mode functionality of the munition. Another option is to reduce the confinement strength of the case by using a thinner case (or a weaker case material).
This paper describes some concept tests that have been undertaken to examine to viability of using of weaker (thinner) confinement as a method of reducing the likelihood of obtaining a violent reaction from a munition when it is outside of its packaging if involved in a low speed impact.

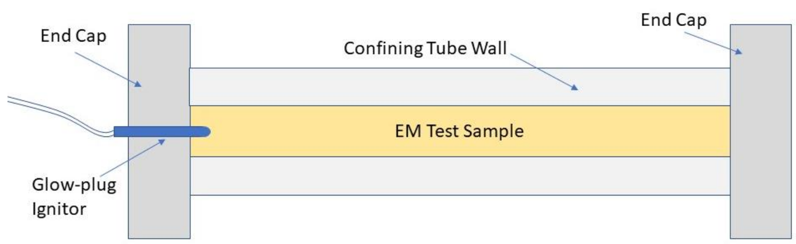
2. Variable Confinement Experiments

A series of experiments were undertaken to examine the concept of using variable confinement to restrict the potential for VR if ignition occurs in the EM. The design for the test vessel for these experiments was based on the generic thermal ignition DDT test which uses a heavily confined cylindrical EM sample that is ignited at one end with the reaction progressing along the length of the cylinder until detonation occurs. DDT type processes have been studied for many decades mainly with the aim of examining the effect of the porosity and particle size on the run distance to detonation for an explosive material under heavy confinement [Ref 3 to 13]. As a result of these studies it has been observed that, generally, DDT is more likely if the explosive has high porosity. In accidents involving munitions, it is conceivable that, as a result of the incident, the explosive main charge may increase its porosity due to the development of cracks or near complete break-up of the charge into rubble or powder. To simulate extreme damage to the EM in the munition, powdered EM was used in the experiments which provided high porosity in the HE (it is recognised that this may not be the optimum condition for promoting violent reactions but it should be remembered that these are concept experiments that can be honed if required at a later date).

The experimental vessels had a central tube section with internal cylindrical cavity of diameter of 25 mm and a 300 mm length which contained the EM sample. The end of the tube was secured with steel end caps (with a gasket providing a gas tight seal). An EM with a high (91% by wt.) HMX loading was used in the experiments and loaded (poured with gentle tap-tamping) into the cylindrical cavity in the test vessels so that the density of the powder was between 50 and 55% TMD. The particle size of the powder was in the range 1400µm to 2600µm. Two ignition methods were used in the experiments to provide different initial ignition and burn rates; one relatively gentle and the other more severe. The relatively gentle ignition method used a diesel engine glow plug to ignite the HE whilst the more severe ignition method used a spigot to pinch the HE between itself and one of the steel end caps. High Speed Video (HSV) cameras operating at rates of up to 600,000 f.p.s. were used to capture the experiments. The details and results of the two ignition method tests are given below:

2.1 Glow-Plug Ignition Method, Figure 1.

In the centre of one of the end caps, a threaded hole permitted the insertion of a diesel engine glow plug (tip temperature of about 700°C approximately 15 seconds after being powered by a 12V, 10 amp. supply). The tip of the glow plug was embedded approximately 10 mm into the HE powder. The tube section was varied (wall thickness and material) to obtain different confinement strengths. Initially steel tubes were used but later tests with tubes that enabled the flame front to be visually monitored (i.e. PMMA (Acrylic) tubes and steel tubes fitted with quartz windows). The ability to observe the flame front was intended to provide information on the build-up of the reaction (flame front) along the length of the EM test sample.



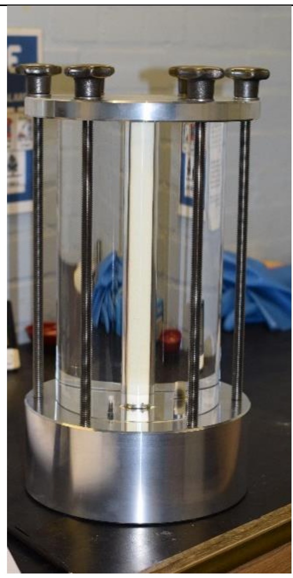


Figure 1. Left image is a schematic of the glow-plug ignited test vessel. The right image is a picture of the PMMA confining tube with 75 mm thick walls.

The tests conducted with steel tubular confinement all produced violent responses with significant fragmentation of the test vessel. The experiments conducted with PMMA confinement tubes either self-extinguished or the burn started to intensify and strengthen but the PMMA tube would fracture and deconsolidate before a violent reaction occurred. The experiments that exhibited this mild pressure burst type behaviour generally had the following burn characteristics: the burn would initially travel down the sample at about 1 $m.s^{-1}$ and after about 20 milliseconds would accelerate to about 100 $m.s^{-1}$ before the confinement failed and the reaction was extinguished. For the experiments with the quartz viewing windows along the length of the steel confinement tube, as the confinement strength was slightly higher than the PMMA vessels, the reaction was able to develop beyond a mild pressure burst with peak reaction rates of between 1 and 3 $km.s^{-1}$ being observed. Although these reactions not as strong as a detonation (measured at about 7.5 $km.s^{-1}$ for the powdered EM), they are very violent reactions that could pose a considerable threat to nearby munitions and personnel. The results from these tests are presented in Table 1.

Table 1 Results of the experiments conducted with a glow-plug ignition source.

Confinement Material	Wall Thickness mm	Quasi-Static Confinement Strength MPa	EM Response
Steel	5 to 20	85 to 180	Violent Reaction
PMMA	25 and 75	22 and 28	Fail / Pressure Burst
Steel with quartz window	14 mm quartz	35	Violent Reaction

Images from the HSV from a couple of the glow plug ignited experiments illustrating typical reactions in the EM for different confinements and recovered (steel) test vessel remnants are shown in Figures 2 and 3.

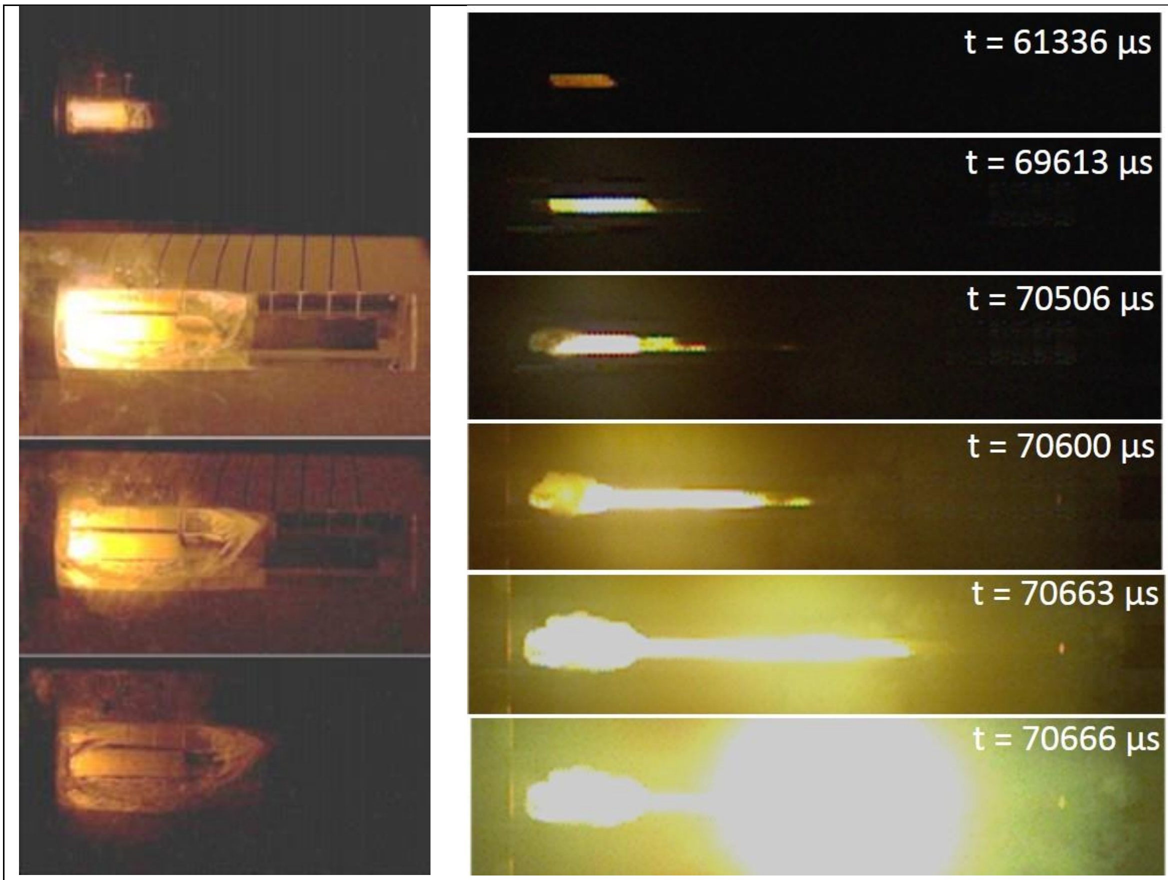


Figure 2. Images from the HSV of glow plug ignited tests. Left image shows four frames from a 25 mm thick PMMA wall experiment displaying break-up of the PMMA and quenching of reaction before the reaction reached half-way along the EM column. Right image shows six frames from a quartz window experiment showing the reaction front advancing sufficiently along the EM column and avoiding being quenched by the confinement failure near the ignition region. a more violent reaction

Figure 3. Still images of the recovered remnants from two experiments. Left image is from an experiment using 20 mm wall thickness steel tube and the right image is from a steel vessel with a quartz window.

2.2 Spigot Impact Method, Figure 4

The spigot impact experiment design used similar test vessel components to the glow plug experiment except the end cap with the glow pug was replaced by a steel end cap that had a central smooth bore hole slightly (approx. 0.5 mm) larger than the diameter of the spigot to be used. The spigot was approximately 400 mm long and was inserted into the test vessel and held approximately 10 mm short of the end cap at the other end of the tube. The HE powder was poured into the test vessel with the spigot in this position (before the end cap was attached). The spigot is driven by the impact of a 1.5 kg steel projectile fired from a gas gun. The spigot impact speed and diameter were varied to observe the effect that this change may have on the violence of reaction. As with the glow plug ignited experiments, steel tube sections were used initially as confinement to the EM but were changed to PMMA in later tests to enable the observation of the reaction along the length of the EM column.

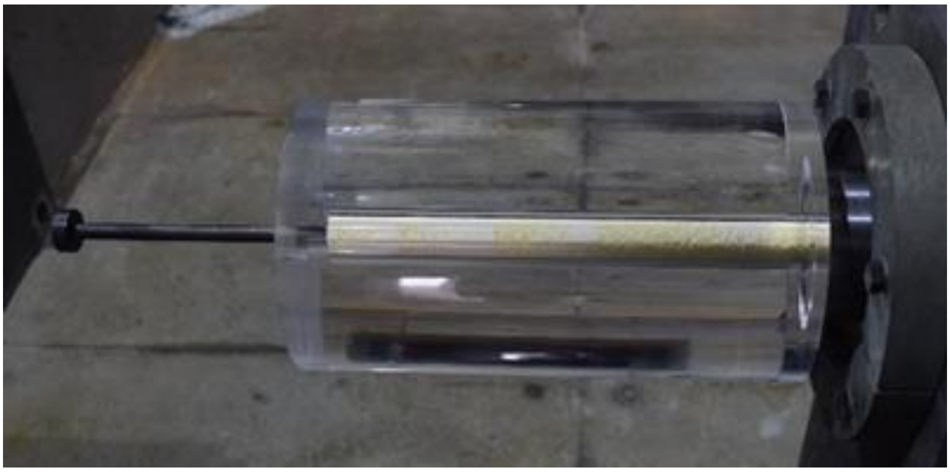


Figure 4. Top image is a schematic of the spigot impact ignited test vessel. The bottom image is a picture of the PMMA confining tube with 75 mm thick walls.

As with the glow-plug ignited tests, the tests conducted with steel tubular confinement with spigots of at least 12mm diameter all produced violent responses with significant fragmentation of the test vessel for pinch speeds of about 90 $m.s^{-1}$. No response was observed at these pinch velocities when spigots of 9 mm or less were used. The possibility of sensitized EM within the test vehicle precluded taking the test vessel apart to observe if any reaction had occurred.

The experiments conducted with PMMA confinement tubes 25 mm thick and with spigots of at least 12 mm diameter impacting at about 70 $m.s^{-1}$ either self-extinguished or produced a mild pressure-burst type event before a violent reaction occurred. Impacts with 11 mm diameter spigots pinching at speeds greater than 55 $m.s^{-1}$ with PMMA tubes that had 75 mm thick confinement walls produced violent responses with reaction rates between 3 and 7.5 $km.s^{-1}$ being observed. When the spigot impact speed was less than 55 $m.s^{-1}$ with 11 mm diameter spigots, the reactions in the EM either self-extinguished or developed at a slow enough rate that the test vessel integrity failed extinguishing the reaction before a violent reaction developed. Experiments with various small diameter spigots with the 75 mm thick PMMA test vessels confirmed that the ignition is too weak to self-sustain with the burn extinguishing within 20 mm for 4 mm diameter spigots and no ignition was detected when a 2 mm diameter spigot was used. Interestingly, impact by a 6 mm diameter spigot produced a pressure burst type event with the ignition being seen to get established before reducing in severity and then increasing in reaction rate, travelling the length of the EM column reaching a speed of about 1.5 $km.s^{-1}$ with the PMMA tube deconsolidating just behind the reaction wave front. It is considered that this result is due to the 6 mm diameter spigot being created from a 11 mm diameter spigot with approximately 12mm of the end of the 11 mm spigot being machined down to form the 6 mm impactor. It is thought that the 6 mm part of the spigot produced the initial burn but that this would have self-extinguished (as in the steel confinement experiments with 6 mm spigots) except that the reaction was re-invigorated when the 11mm diameter portion of the spigot pinched against the end cap. The results from these tests are presented in Table 2. Images from the HSV from a 11 mm diameter spigot impact ignited (>55 $m.s^{-1}$) experiment illustrating DDT in the EM when confined in 75 mm thick PMMA vessel and the plot of reaction rate progress along the EM column are shown in Figure 5.

Table 2, results from experiments conducted using spigot impact ignition method.

Confinement Material	Wall thickness mm	Quasi-Static Confinement Strength MPa	Spigot Diameter mm	Spigot Speed at pinch $m.s^{-1}$	EM Response
Steel	25	200	6 9 12 15 20	90 90 90 90 90	Fail Fail VR VR VR
PMMA	25	22	12 15	70 70	Fail Fail /Pressure burst
PMMA	75	28	2 4 6 11 11	60 60 60 < 55 >55	Fail Fail Pressure burst Fail/Pressure burst VR

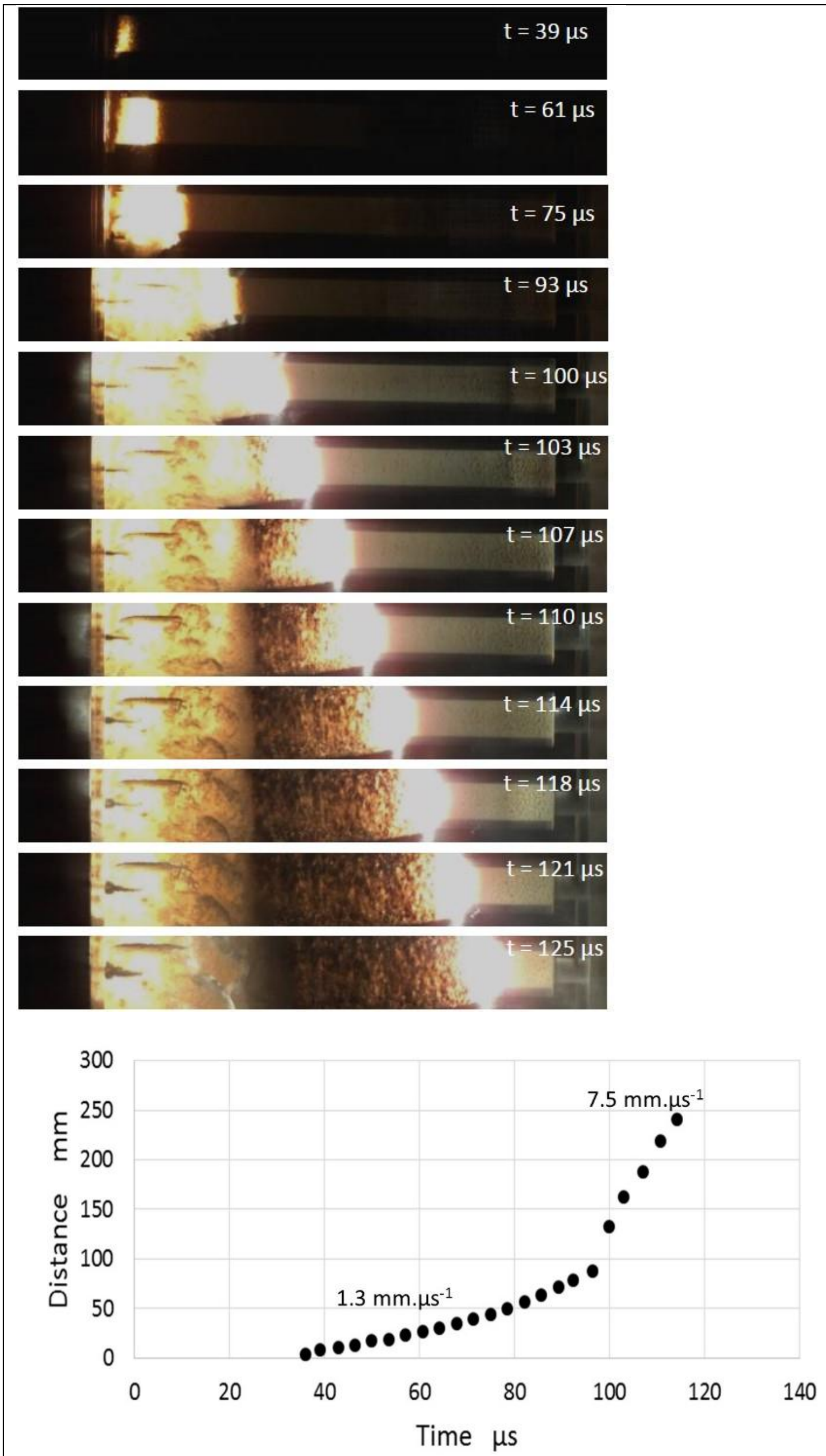


Figure 5. Top shows images from the HSV of a spigot ignited experiment in a 75 mm thick PMMA test vessel. The burn can be seen transiting from left-to-right with detonation breaking-out approximately a third of the distance along the EM column. The bottom images shows a plot of the burn front progress, initially at about 1.3 km.s^{-1} before undergoing DDT.

3. Review of Tests

The experiments reported in this work were developed to study the concept of preventing violent reaction from developing if a small localised ignition was to occur in severely damaged, but confined, EM. The experiments are to be viewed as a learning tool and not as a test methodology for examining the role of confinement on VR in EM. However, much has been learnt from the successes and failures experienced during the course of this work. Two examples of this is are:

a) the selection and use of PMMA as the material to provide confinement to the EM test sample. Although PMMA (and to a lesser extent, quartz) has the benefits of being commercially available, readily engineered to the correct form and enables high-speed video imaging of the reaction progression in the test sample, the material does suffer from micro-structural surface flaws which can significantly diminish its strength [14] that cannot be predicted with high accuracy. As such, the failure strength figures provided for the test vessels using PMMA and Quartz confinement are to be viewed as indicative rather than absolute values.

b) The use of long spigots. It was noticed that if the gas gun projectile did not impact along the axis of the spigot, the spigot tended to flex which resulted in a non-planar impact of the spigot end onto the steel end cap. This would result in irregular ignition of the EM and complex reaction growth patterns. When this was observed, the test result was ignored. In future, any work on spigot ignited EM will be conducted with a redesigned test vessel to enable short spigots to be used.

These concept experiments have shown that, for ignitions in the EM material (in powder form), the violence of the response can be moderated by altering the strength of the confinement. The experiments examined two ignition types which provided different initial rates of reaction in the EM. It has been demonstrated that the type of ignition (and resulting reaction growth rate) is a factor if mitigation of a violent event by reduction in the confinement surrounding the EM is desired. The use of different spigot diameters and impact pinch speeds and their effect on reaction development has shown that there are significant variables that need examination for different EM if an experimental programme is to be pursued.

Although the confinement failure strength of the PMMA and quartz test vessels were pressure tested to provide quantitative strength-failure values, it needs to be recognised that these failure strength values are quasi-static. Direct correlation of these quasi-static values to the failure strength of the confinement in a munition undergoing reaction in its EM is a non-trivial exercise as the failure strength of materials (measured in a quasi-static pressure test) often change as pressurisation rates increase [15,16]. Even though the loading rate in the instrumented pressure tests was conducted at the highest rate achievable (in the MPa/s regime), it was still several orders of magnitude lower than the pressure rise-rate in the experiments (in the MPa/ms regime). Correlation of the confinement failure strength in the experiments is further complicated if a different material is used in the test vessels compared to the case material in the munition as there is often difference in the dynamic increase factor for failure strength between materials. It is concluded that, if possible, the test vessels used to determine the confinement failure strength should be manufactured from the same material as the case providing confinement. This would enable the test vessel and munition case thickness to be compared as a measure of confinement strength without reliance on misleading quasi-static data. Regardless of the issues about scaling the quasi-static failure strength with the dynamic failure strength, knowledge of the quasi-static failure strength required to reduce the likelihood of violent reaction from the EM will provide an approximate value against which margins for safety can be estimated against (e.g. use munition case failure strength that is a factor of 2, 5 or 10 lower than the measured threshold confinement strength required to prevent violent reaction with the munition EM).

Some munitions will have EM / case material combinations that, in order to reduce the likelihood of VR occurring, would require the case thickness to be so thin that it becomes impractical to pursue this course of action.

If munition designers wish to improve the safety characteristics of the system in low speed impact accidents, reducing the thickness of the case confinement may be a possibility for achieving this safety gain. As mentioned earlier in this report, the introduction of deliberate weak zones (such as case joints) or vent paths in the case may be alternative options worth investigating.

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