Design and Operation of a Small Scale Set back Force Simulator and its Use in Investigation into Composition B Fillings Subjected to Hot Gun Scenarios

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Abstract: Ammunition fired from large calibre gun chambers may experience accelerations in the regions of 150,000 m s^{-2} and as a result are subjected to considerable force during the process of set back. During firing some of the energy may be transferred to the filling and any defects present in the shell filling can lead to local hotspots which may result in premature ignition of the warhead. A potential source of defects is the application of excessive heat to the ammunition either by storage in a hot environment or accidentally by leaving the ammunition in a hot gun scenario in the chamber of the gun. A hot gun scenario can be defined as arising after 50 rounds or more have been fired in a four hour period. In this scenario the filling may easily exceed the qualification temperature with two possible accidents occurring. Cook-off of the filling can result in spontaneous firing of the round or, when correctly initiated, the round may premature in the gun barrel both of which may have catastrophic results. Currently there is no standard test to evaluate the behaviour of composition B (60% RDX: 40% TNT) filled ammunition subjected to a hot gun scenario. Because of its low melting point 80 °C the liquid TNT can separate from the RDX increasing its sensitivity and increasing the probability of an in bore premature when fired.

This paper describes the design and operation of a small scale simulator for set back forces and its use to investigate the conditions under which composition B fillings, subjected to a hot gun scenario, could initiate. Samples of composition B were subjected to thermal treatments to mimic hot gun conditions and then subjected to simulated set back conditions and the level of impact energy required for initiation determined. This was compared with the level for untreated samples and a possible evaluation of current hot gun procedures undertaken. The indications are that the process can be cost effective in simulating set back induced premature ignitions.

Introduction

Experience has shown that large calibre, in service, naval gun fired projectiles are generally very reliable and safe. Careful attention to filling procedures and tight quality control procedures ensure that ammunition with filling defects do not enter service. However, once in service, either storage in inappropriate hot environments or deployment in hot gun scenarios, can produce potentially dangerous ammunition by inducing defects in the filling. Both situations can create potentially dangerous states, either for direct cook-off or, if the weapon is fired, for a premature misfire in the barrel to occur. The temperatures of the explosive fill in this investigation, Composition B (RDX/TNT/Wax), may easily exceed their qualification temperatures. Composition B softens at around 70 °C, begins to melt at 79.6 °C and has a cook-off threshold of nearly 180 °C [1]. Thus it is unlikely that direct cook-off will occur but the possibility of premature initiation in the barrel could be increased. Melting of the TNT could lead to separation of the more sensitive RDX and the set back forces could induce initiation in the RDX rich regions.

When firing a large calibre gun of greater than 76 mm, some of the mechanical energy can be concentrated in the explosive filling, particularly at defects, creating hot spots which can the cause accidental in-bore explosion. The ignition is considered [2] to be the result of the conversion of mechanical energy, generated by set back pressure during the firing, into heat within the explosive. A number of mechanisms as detailed below have been proposed:

- Adiabatic Gas Compression;
- Pore Collapse and micro-jetting;
- Friction;
- Shear and viscous flow.

These mechanisms, either singly or in combinations, can produce hot spots in the explosive filling which can eventually end up in a run away chemical reaction. However set back forces can also deliver a shock wave to the filling. If the shock wave has sufficient peak pressure then a prompt shock to detonation, SDT, will result. Normally gun systems are designed to keep the pressure and any associated shock energy below the threshold for SDT events to occur. However lower intensity shock waves can result in bond rupture, inducing a chemical reaction, which can release energy to the filling and thus support the shock wave

which, if the system is confined, will steadily accelerate the burning front over a period of time and distance and a deflagration to detonation transition, DDT, will result. The distance and time required for DDT to occur is a function of peak pressure and the explosive. This data is normally displayed as pop plots [3]. Factors affecting the DDT transition are confinement, particle size and density of the filling, configuration of the filling and the thermodynamics of the explosive, i.e. its 'Q' value. If the run up distance exceeds the ammunition dimension then DDT may not occur. Thresholds are affected by the duration of the pulse and the area over which the shock is delivered. For a flat cylinder impinging on an explosive sample the initial shock pressure can only be maintained over a conical region in front of the impactor [4]. Conditions that focus energy at localised regions within the explosive mix will give a higher frequency of initiation. Hence under the right circumstances the peak set back pressure can cause compressive heating of the gas voids in the explosive and may be sufficient to result in an in-bore explosion. Whilst careful attention needs to be paid to filling quality to eliminate air gaps, other sources of gaps, cracks and pores induced by melting and/or re-solidification of the Composition B will lead to a greater chance of accidental initiation of the explosive due to set back forces [5].

Currently there are no standard tests that can be used to assess the behaviour of Composition B filled ammunition in a simulated hot-gun condition. A number of experimental assemblies have been designed to mimic set back force initiation. Both the Susan Test vehicle and the NSWC set back simulator rely on delivering a shock impact to a sample of explosive confined in a moving vehicle. In the Susan test [6] the explosively filled vehicle, containing ~200 g of explosive is fired from a propellant powered gun and impacts on an armoured target plate, HRA steel 102 mm thick. A range of projectile velocities starting at ~ 100 m s^{-1} are used and the resulting explosive output plotted as a function of impact velocity. Notice that the explosive filling is subjected to two set back type forces. The first occurs on launch of the projectile from the gun and the second, larger effect, due to the reduced distance over which the deceleration is applied, set forward is delivered by the impact on the target.

In the NSWC set back simulator [7] the vehicle, shown schematically in Figure 1, falls under gravity and impacts on a metal anvil. Pressure is applied to the sample by the plunger impact and sensors above and below the sample allow the shock wave progress through the sample to be monitored. The rate of application of the pressure is much slower because of the lower impact velocity compared to the Susan projectile.
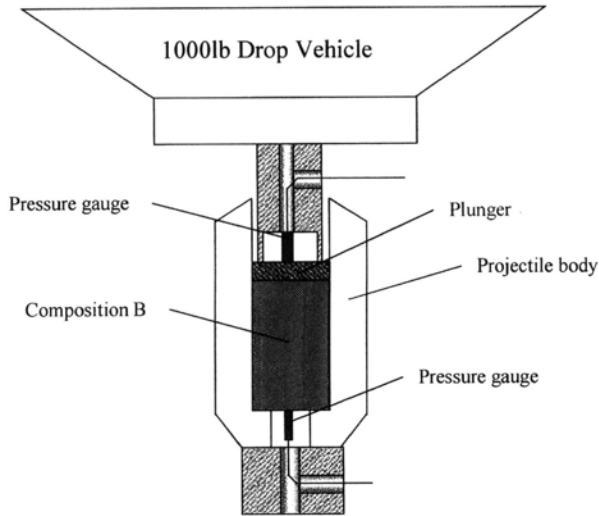
Figure 1. Schematic of the NSWC set back simulator.

A third system applies pressure to the sample by means of a propellant driven piston in an enclosed system shown schematically in Figure 2 [8].
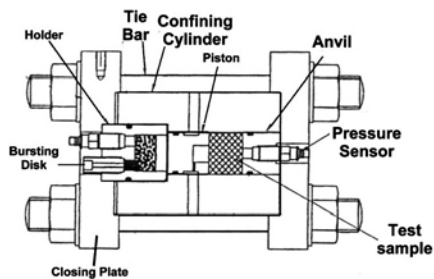
Figure 2. Limited scale propellant powered set back simulator.

A cylinder of explosive 25.4 mm diameter and 21 mm long is encased in a steel body and the pressure applied to the piston is generated by combustion of different quantities of selected propellants in an enclosure fitted with a bursting disk, which can be adjusted to a desired failure pressure by choice of disk thickness. A piezoelectric sensor measures the gas pressure generated. In an alternative system a tri-axial compression generated hydraulically is applied and allows some of the parameters necessary for modelling of the shockwave propagation to be determined but does not mimic set back forces accurately in the region of interest for our purposes.

A target assembly was designed to mimic set back forces by using projectile impact. The Cranfield designed system used here was originally developed as a spigot intrusion assembly for investigating initiation mechanisms as described in a previous publication [9]. However by judicious changes increase in the diameter of the spigot from 13 mm to 30 mm, thus matching the explosive sample diameter and restricting spigot movement to 5 mm penetration enabled an impact from a sabot to deliver effectively a set back force to a confined explosive sample. Impact by a compressed gas gun launched sabot on one end of the impactor could deliver a suitable set back shock to an explosive sample mounted directly in front of the opposite end of the impactor in a confined system. There is no free volume for the explosive to expand into thus mimicking the conditions inside a gun launched ammunition. Post firing simulation and analysis of materials were used to determine the mechanism of initiation and the severity of the event compared to the amount of force the samples were subjected to.

This paper describes experiments designed to investigate the conditions of set back forces in a hot gun scenario, at the time the projectile is likely to be cleared from the gun, and if accidental initiation of Composition B could occur in a hot gun should clearing by firing be used. A series of tests conducted on these composition B filled targets, which had been subjected to hot gun conditions, were performed at the Cranfield Ordnance Test and Evaluation Centre (COTEC) to simulate set back effects at shot start. The sensitivity of Composition B after it has been thermally conditioned to varying temperatures for different lengths of time was investigated. These tests were performed in order predict filling vulnerability to accidental premature in-bore initiation within the Naval Gun environment and provide a fuller understanding of hot-gun clearance safety issues based on of the limitations of thermally shocked Composition B explosive fillings.

Calculation and measured pressures developed in a 4.5" naval gun suggest that peak set back pressures of around 270 MPa are normal [10] and this can be converted by Newton's law of motion; Force = mass x acceleration to determine the acceleration the shell experiences. This can be converted back to the acceleration of the impactor into the explosive. The advantage of the Cranfield design is the reduced quantity of explosive used (40 g compared to 400 g of some other test vehicles) and the simplicity of target assembly.

Experimental

Target Assembly
A cross section through the test rig and final assembly are shown in Figure 3.
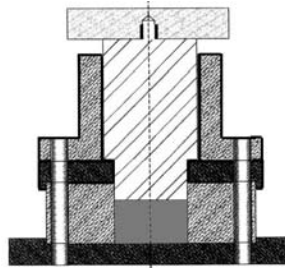
Figure 3. Cranfield set back simulator test vehicle with impactor driven to the stop.

The test rig contains the explosive cast in a polypropylene plastic ring, 35 mm diameter and 21 mm deep, which is an interference fit into a steel ring of the same depth and 100 mm diameter and provided the sample confinement. This ring and sample are fitted into machined recesses in the top and bottom target plates. Mounted on top of the top plate is the piston carrier plate. All components are interference fits reducing the possibility of slap as the impactor slides in the carrier. The whole assembly is bolted together with eight high tensile steel cap head, 13 mm diameter bolts. The impactor will travel 5 mm into the explosive sample, as shown in Figure 3, before it is arrested by the retaining lip on the top plate. This assembly is mounted on an A frame about one metre in front of the gas gun muzzle.

Gas Gun

The gun consists of a 2.5 m long steel tube, 50 mm diameter, which is closed at one end by a demountable steel plug. Around this end of the barrel is a concentric steel gas reservoir as shown in Figure 4. Vents in the side of the barrel which allow the gas to expand into the barrel are normally obscured from the barrel by the sabot which sits with the vents in between the two 'O' rings which seal the sabot in the barrel. The breech end of the gun is open to atmosphere as is the barrel in front of the sabot. Any gas seeping past the 'O' rings is thus vented to atmosphere. Operation of the firing button seals the breech and allows gas from the reservoir to fill the space behind the sabot forcing the sabot forward and uncovering the vents in the barrel wall producing a rapid gas expansion accelerating the sabot to the desired velocity.
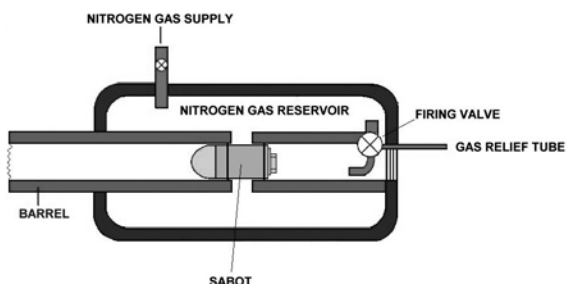
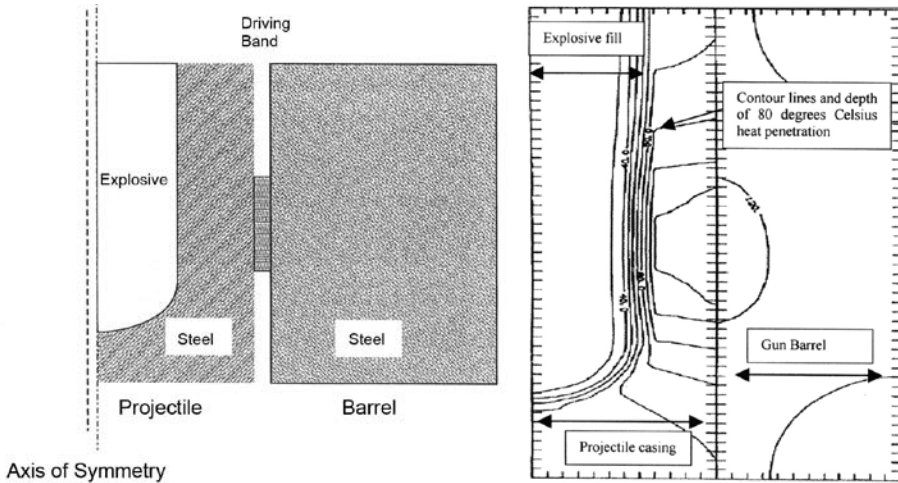**Figure 4.**   Schematic of the compressed gas powered gun.

Sabot velocity was determined by measuring the time taken for the sabot to break a series of insulated copper wires stretched across a plastic tube, mounted in front of the muzzle on the guard assembly designed to provide protection to the muzzle, through which the sabot passed (see range Figure 7). Breaking the wires produced a voltage pulse which was measured by a fast recording oscilloscope. One of the wires also triggered the fast video recording.

Explosive samples
Composition B (60:40 RDX:TNT) was supplied by B.Ae. Systems Ltd Glascoed to MOD specification and was used without further treatment 400 g of the mixture was heated in a beaker on a boiling water bath at 90 °C. When the sample was completely molten it was poured into a series of the plastic supporting rings placed on a water bath heated metal plate. The plate was then removed from the heat and allowed to slowly cool in a cooling blanket. Any piping was filled with additional molten material. The samples were examined by SEM and x-ray for the quality of surface finish and absence of voids.

Thermal Conditioning
A study into hot-gun effects in larger calibre naval guns [2, 11] identified the region closest to the driving bands as receiving the heat transferred from the hot-gun and determined the advance of the molten contour line into the Composition B filling as a function of time. The calculations made an allowance for the change in thermal conductivity accompanying the phase change from solid to liquid. The resulting profiles are shown in the diagram below.

Figure 5.   Area of contact between projectile and barrel and the depth contour
                lines for the 80 °C heat penetration as a function of time.

The other factor is the number of rounds and the frequency of firing in the
salvo. There is only a significant effect of ambient conditions for a small number
of rounds. Typical projectile temperatures for salvos are shown in Figure 6 below.
These profiles were used to determine the most appropriate thermal conditioning
times for the test samples. The figure shows that about 10 minutes after firing
the first shot in a 60 round salvo, at 20 rounds per minute, the filling will have
a considerable molten TNT zone in contact with the projectile walls, which will
still be in contact with a barrel at > 85 °C.

Figure 6.   Time temperature profiles for the barrel and projectile in a hot-gun
                scenario.

As a result of these thermal studies, some of the targets in the confining ring and base plate were placed in ovens at 80 and 85 °C and heated for 10 or 15 minutes at each temperature since our calculations suggested that these were the critical hot gun conditions. Samples were then re-examined by optical microscopy prior to mounting in the target assembly. The target was mounted on the support frame in the test cell on the COTEC ranges at West Lavington as shown in Figure 7.
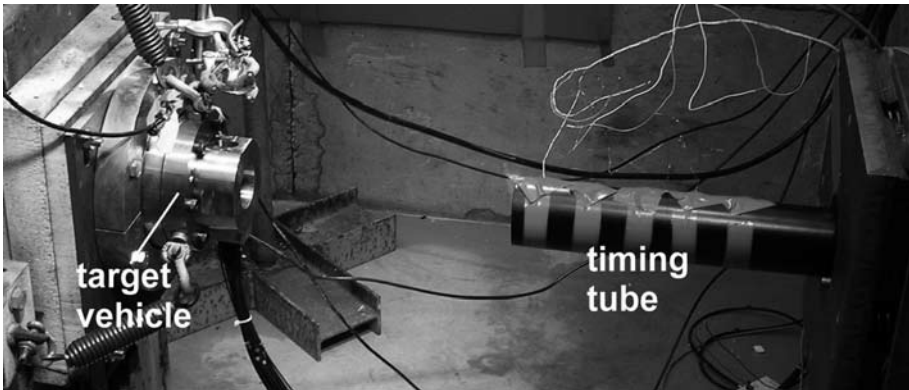

Figure 7 showing target assembly in front of velocity measuring tube attached to the gun barrel. The impactor is inserted into the target vehicle immediately prior to firing.

A series of firings were performed at different sabot velocities and the events monitored by a high speed video camera.

Results

Microscopy
Electron microscopy of the as cast and thermal treated samples is shown in Figure 8.
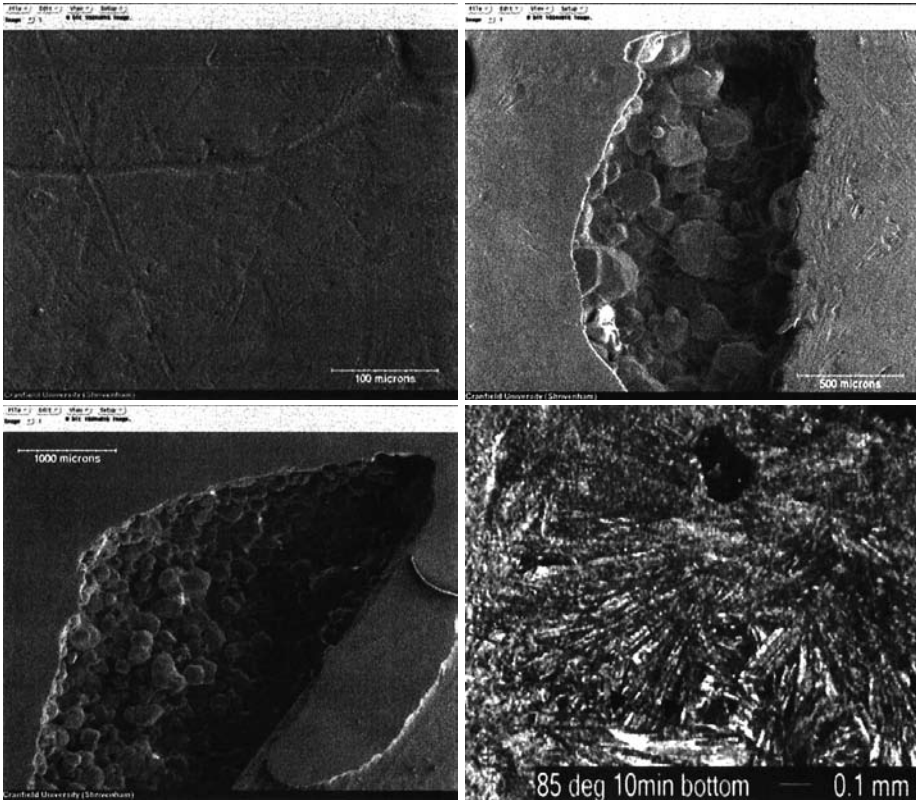
Figure 8.   Electron Microscopy of composition B castings top left as cast top right 10 minutes anneal at 80 bottom left 15 minutes at 85 °C and fragment after impact.

The defects present in the as cast samples are minute surface flaws resulting from the treatment to ensure no piping or excess material standing proud of the confining ring which could produce problems when the target was assembled. As the annealing time and or temperature are increased then the defects present increase. Annealing for 10 minutes at 80 °C showed significant problematic regions whilst 15 minutes anneal at 85 °C produced extensive migration of the TNT leaving almost pure RDX exposed on the surface. Notice these figures are obtained after the samples had cooled back down to ambient. Post impact analysis of the Composition B sample used in shot 4 showed extensive presence of shear banding and also granulation of the charge with possible recrystallisation of the TNT see Figure 8 bottom right hand image.

Impact Results

The results of the impact firings are summarised in Table 1 below. The velocity of the sabot is a measured velocity from the breakwire signals and the impactor velocity is calculated from the video footage and also from the conservation of momentum before and after impact. Notice that the set back pressures calculated are around the maximum design pressure for a 4.5" naval gun with the exception of the first shot which was around the design set back acceleration but in excess of the design pressure. This firing was used as a calibration of the measuring and firing systems and produced the worst case scenario in terms of the resulting event.

**Table 1.** Details of sample conditioning and firing parameters for Composition B targets

Shot	Velocity of sabot	Impactor Velocity m s^{-1}	Set back acceleration m s^{-2}/10^5	Set back pressure MPa	Thermal conditioning	Event type
1	98.0	41.4	1.61	944	Ambient	Go(DT?)
2	76.1	32.2	1.04	569	10 min 80 °C	Go(DF)
3	67.3	28.4	0.81	444	10 min 85 °C	Go(DF)
4	51.9	21.9	0.48	265	15 min 80 °C	No Go
5	51.9	21.9	0.48	265	15 min 85 °C	Go(DF)
6	54.4	23.0	0.53	290	Defect 20 °C	Go(DF/T)

Shot 1 was above the predicted set back acceleration for a 4.5" naval gun and the simulated set back pressure was well in excess of the normal conditions in the gun and as a result a major event was observed. The test rig was destroyed and metallographic analysis of the fractured bolts indicated an energetic failure on the boundary of deflagration / detonation confirming the appearance of the base plate Figure 9. Shot 2 also destroyed the test rig but the event was much less vigorous and definitely a deflagration. Shot 3 was similar but with a longer duration and some material being ejected from the target and continuing to burn in the air.
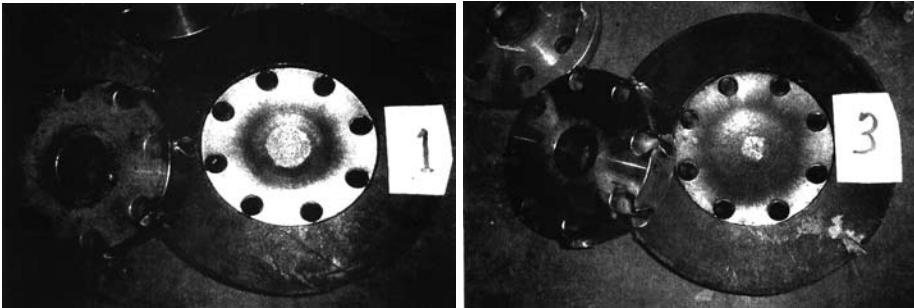
Figure 9 showing the base plates and confining rings for firings 1 (l) and 3 (r). The first firing has run to detonation whereas the third firing is only a deflagration/burn.

Shot 4 produced no event of any description the filling was hydraulically squeezed in the space between the confining ring and the base plate as a result of the stretching of the high tensile bolts by ~2 mm allowing the thin disk to form (see Figure 10 below).
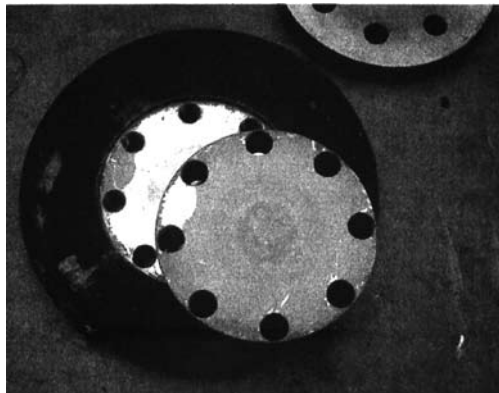
Figure 10 showing the hydraulic squeezing of the composition B filling between the base plate and the confining ring with no ignition evidence apart from a slight odour.

Shots five showed a limited event which occurred after the end of the impactor travel indicating that this trial may be on the threshold for initiation. A number of large fragments of charred composition B were recovered indicating a very limited event.

Shot 6 was by way of an anomaly in that our earlier examination had shown that, post casting, it contained defects and air pockets. So this sample was fired to

show that under normal firing pressures the presence of cracks or voids rendered the filling unsafe.

Discussion

Only a limited number of trials were performed but nevertheless there has been a significant effect demonstrated. The attempt to simulate set back forces with the impact rig design has proved very effective. Both the acceleration and the set back pressure can be simulated by the experiments with the rig described. It would be beneficial to measure the impact load with some strain gauges to see how the pulse is delivered. The results confirm the calculations based on measurements of the heat delivered by the hot barrel to the projectile and also the anticipated effect of these temperatures on the filling. Even extended exposure in a hot gun barrel is unlikely to produce temperatures at which cook-off will occur, <180 °C but more likely the filling will be sufficiently sensitised to produce premature initiation in the barrel should such a projectile be fired after a 10 minute exposure to 80 °C. The pressure at which no event was obtained in this study is well below the operating pressure of a 4.5" naval gun hence the probability of a premature initiation under normal operating conditions is significantly increased as a result of the projectile being subjected to hot gun exposure. There is no doubt that the thermal conditioning described here mimics the effects in hot guns calculated for projectile conditioning. Without exact determination of the defects present in the thermally conditioned samples it is impossible to assign the increased sensitivity to a particular mechanism i.e. gas heating or shear etc. It is likely that a combination of mechanisms is responsible for the increased sensitivity. Results obtained in this study compare very well with the data provided by the NSWC drop set back simulator, as shown in Figure 11. Perhaps because of the reduced confinement present in the COTEC target, lower pressures and reduced rate of pressure change are required for an event in this study but follow parallel lines to the NSWC data. A study of lower velocity impacts in the previous work [12] has shown that the rate of input of the energy is important and this may be one of the reasons for the differences between the NSWC data and this studies data. Our projectile velocities are higher than the falling mass velocities so lower energy inputs could be required for initiation.
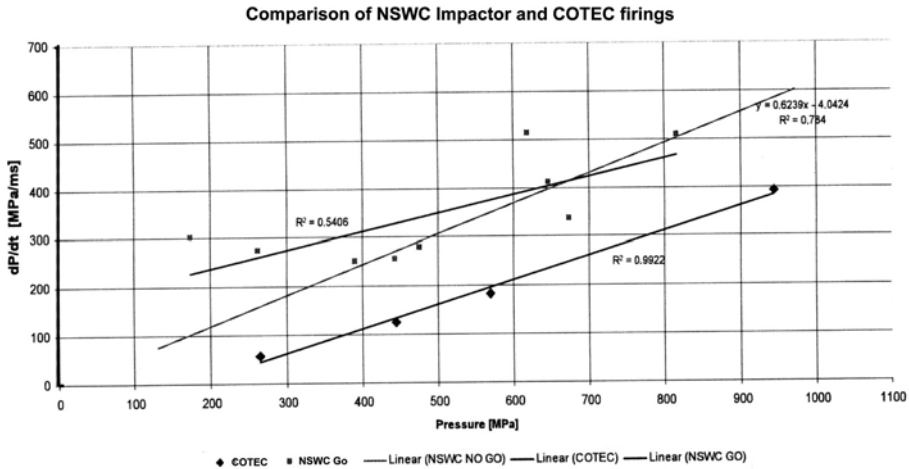
Figure 11. Comparison of NSWC and COTEC results for Composition B.

Additional tests need to be performed to give good statistical reliability to the data but the principle conclusions about the hot gun scenario are unlikely to be changed by further data. Further trials in which the sample is held at 85 °C during the firing process will more exactly mimic the hot gun scenario but that is a more demanding task. Modification of the confining ring to mimic the cup arrangement present in a shell would give enhanced confinement under impact perhaps providing a closer model to set back conditions. A system in which the confinement does not depend on the impactor remaining in the target is under consideration.

Altering the aspect ratio of the sample could also provide further data about the effect of set back. As preliminary modelling has shown, considerable pressure is generated at the bottom of the target and this may be affected by the length of the sample filling.

Conclusions

The impact rig designed for this study can accurately mimic the set back forces delivered by a large calibre naval gun to a projectile.

Thermal conditioning of the target samples used in this study can also mimic the conditions experienced by a projectile in a hot gun scenario.

Increase in exposure time to the hot gun conditions increases the sensitivity of the Composition B filling.

Projectile exposed to hot gun conditions are unlikely to cook-off but after 10 minutes exposure are likely to suffer premature initiation if fired under normal propellant conditions.

The effect will depend on the number of rounds and the rate at which they are fired but as an elementary precaution rounds left in a hot gun scenario for 10 minutes should not be fired.

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