**UK MOD DEFENCE PROCUREMENT AGENCY,
TECHNICAL ENABLING SERVICES, SEA TECHNOLOGY GROUP,
NAVAL AUTHORITY EXPLOSIVES**

Explosive Effects Mitigation for 4.5 Inch Mk 8 HE Medium Range Naval Fire Support Munitions including a Platform Consequence Analysis Methodology.

Author: Mr Julian Taylor MSc, MIExpE, CpRINA,
STG NAExp4, Ash 3c #3311,
MOD Abbey Wood, Stoke Gifford,
BRISTOL, BS34 8JH.
Tel: 0117 91 35091.
STG-NAEXP4@dpa.mod.uk

Figure 1 –4.5 Inch Mk 8 Mod 1 Gun fitted to a Type 23 frigate.

INTRODUCTION AND AIMS

1. The Royal Navy (RN) has been using the 4.5 Inch (114-mm) weapon (as its standard medium calibre gun since World War II. In the mid-1960s RARDE began design development of a fully automatic version which was developed into the radar controlled 4.5-inch Mk 8 gun. The gun mounting itself is designed by Vickers and features a reinforced GRP gun shield with an ammunition feed system and remote power controls. A number of types of fixed ammunition can be fired including HE rounds. Fitted in all RN frigates (Fig 1) and destroyers the MK 8 gun is the RN's standard medium calibre general purpose gun.

2. The primary purpose of the gun is Naval Gunfire Support, the provision of artillery bombardment against shore targets. In this role the gun is capable of firing a 21kg shell at 25 rounds per minute in excess of 22,000m and can provide artillery support equivalent to three shore based batteries (Fig 2). The Mk 8 can also be

used effectively against surface targets at sea as well as a limited anti-air capability.

Figure 2 – 4.5 Inch Mk 8 Mod 1 Gun on firing.

3. The explosive safety risks caused by the operational imperative to stow large quantities of medium range gunnery munitions for Naval fire support in warships have always been challenging to address. The hundreds of rounds carried in confined warship magazines are, through necessity, packed in tightly together, giving rise to unavoidable Sympathetic Reaction (SR) risks. Historically it has been accepted that a full order initiation of one round would cause mass detonation, with the consequent loss of the ship, significant crew casualties and damage to the environment. The intrinsic safety performance of current legacy rounds support this analysis, and although improved resistance to SR has been seen from an alternative Insensitive Munitions (IM) fill, additional measures may be required to complement a systems approach in preventing propagation and reducing consequences.

4. Accordingly, two potential platform SR mitigation techniques have been investigated and developed by the UK MoD, Sea Technology Group, Naval Authority Explosives, in efforts to reduce risks to As Low As Reasonable Practicable (ALARP) and to achieve tolerable (Unitised) levels of consequence. This will give benefits to safety and capability and will reduce some of the pressures on berth management for Warships in Harbour.

5. The use of Anti-Fratricide (AF) bars, a novel magazine stowage enhancement, utilising carefully positioned steel bars surrounding shells which absorb and deflect hypersonic fragmentation, thus preventing SR, have been successfully trialled. This arrangement will “unitise” explosive effects in magazines to no more than one round detonating.

6. This simple mitigation technique has been developed into a bespoke system that may be retrospectively fitted between HE rounds when stowed both in the platform and when being transported in the N6 crate, without requiring upkeep downtime.

7. Secondly, a unitised stowage barrier has been derived and tested. This is a barrier system designed to be fitted between stowage racks preventing SR

propagation from one to the other. The unitised stowage barrier is available for development into new designs of stowage rack or for fitting into existing platform stowages, but requiring retro-fitting during upkeep periods. Each rack contains a unitised number of rounds stacked within the stowage.

8. The number of rounds stowed in each rack is calculated to limit the consequences to a pre-determined tolerable level. The stowage rack is designed into units of this amount measured by the Effective Net Explosive Quantity (ENEQ) of the ammunition stowed within. The unit level is the reduced amount of energy released to prevent propagation to adjacent magazines and minimises damage so that platform loss does not occur, with crew casualties and effects on the environment minimised.

9. Both these techniques will support Integrated Project Teams (IPT) in managing their platform risks to achieve tolerable consequences maintaining capability and safety by reducing risks to ALARP. [1]

10. This paper summarises a consequence analysis methodology in deriving the maximum tolerable event and undertakes an assessment of the performance of the proposed mitigation options. The paper also describes the validation work completed and comments on the findings.

4.5 INCH MK 8 AMMUNITION ASSESSMENT.

11. The 4.5-Inch Mk 8 Gun system incorporates a medium range, high velocity gun, mounted in an automatic unmanned turret. A gunbay and a main magazine providing stowage for ammunition.

12. The Mod 0 gun fires 4.5 Inch Mk 8 HE Conventional Ammunition (CA). The Mod 1 gun fires 4.5 Inch Mk 8 HE Improved Ammunition (IA). Both rounds have UN Hazard Classification Code of 1.1E.

13. The ammunition was examined for its safety performance and it was concluded that it would initiate with a Type I detonation reaction from impact threats seen in the Naval environment and will propagate Sympathetic Reaction.

14. The effects were measured by examining arena trial results for fragmentation and from recorded over-pressure measurements. This was for both bare and packaged rounds.

15. The ENEQ is based upon the measured over –pressure produced upon detonation. Trials have demonstrated that the propellant does not propagate detonic shock waves and therefore does not contribute to the peak static and reflected over-pressure. This provided a measure which may then be compared to derived platform tolerable damage levels.

THREAT HAZARD ASSESSMENT METHODOLOGY TO MAINTAIN OPERATIONAL CAPABILITY AND SAFETY

16. To achieve the most appropriate strategy to reduce platform vulnerability, a logical assessment process is required to be followed. A Threat Hazard Assessment (THA) [2] focuses attention on identifying solutions to meet design

shortfalls, both platform and munition, and allows scope for both advised solutions and non-prescriptive design. The result is to formulate the Platform and OME Protection Strategy. This derives what is a tolerable event, options to minimise the effects of detonation and provides a target to develop unitised munition stowages and configurations.

17. To determine a tolerable detonation event within a naval platform requires an understanding of what is required from the platform in terms of its operational capability and in terms of safety, throughout the life of the platform, including all the scenarios and operations that will be undertaken. In effect this identifies and defines all threats posed.

18. The assessment determines the munition response to these threats and determines the likely consequences from these effects; on each other, the platform, to personnel and onto the environment.

19. The Platform and OME Protection Strategy then optimises the platform and system designs to include protection and mitigation measures to reduce consequences that meet the required tolerable level of damage. This is measured by the level of blast damage that can be sustained or withstood to maintain the required level of capability from the platform and to meet safety criteria. A suitable measure is the combined ENEQ of the munitions to produce this level of blast and fragment damage.

TOLERABLE LEVELS OF DAMAGE.

20. To determine the tolerable level of damage requires an understanding of the proposed magazine arrangements within the platform and the quantities of ammunition they will hold.

21. The Quasi Static Pressure (QSP) loading level can be used as a measure to define the blast withstand for platform structure allowing it to maintain a required function. As a minimum this could be to remain afloat, minimise the number of casualties, both crew and shore personnel when alongside or it may be to limit the size of an event to allow the platform to move or continue to operate, although at a reduced capacity. This measure assumes the loadings to cause failure are from the QSP phase. However, impulse loading and stand-off of an initiation event can be allowed for by determining whether localised shock holing or panel loading occurs and assessing its effect. Fragmentation damage is also considered.

22. The QSP phase will produce a panel loading onto structure causing it to displace to maximum and fail, allowing venting to adjacent volumes before there is significant decay [3]. This translates into failure of ship structure most likely to occur at weld seams and at points where stiffeners and longitudinals are welded to the plate (including decks and bulkhead junctions). These hard points, as a function of geometry and differing material properties, are the points at which the pressure loading (QSP) exceeds the panels ultimate yield stress due to restricted displacement [4].

23. Calculation were completed for these effects allowing for the platform scantlings and material parameters.

24. To determine the critical QSP (Pc) for each structural boundaries the Carroll equation (1) was used [5.]

$$\mathbf{Pc=1.88x10^{8}t/l} \qquad (1)$$

Where :
Pc = is the critical level of quasi-static overpressure in MPa
t = Plate Thickness (mm)
l = The effective panel structure span (M).

25. Using the Weibull equation (2) re-arranged to determine the ENEQ weight of explosive to produce that level of QSP within a determined volume may be found [4].

$$\mathbf{P_{qsp}=2.25x10^{6}(W_c/V)^{0.72}} \qquad (2)$$

Where :-
P_{qsp} = quasi-static overpressure in N/m^2
V = the volume of detonation compartment in m^3
W_c = the TNT equivalent quantity of explosives in kg

26. Shock holing calculations provided stand-off distances over which the local loading effect changes to full panel loading [6].

27. The result produces the maximum ENEQ, TNT equivalent weight of explosive, that a detonation event could be so that the damage is kept to a determined tolerable level.

RESIDUAL FRAGMENT ENERGY AT ADJACENT MAGAZINE BOUNDARIES

28. The initial velocity of the fragments emanating from the detonation of a 4.5 Inch HE Shell will impact the magazine boundary and surrounding internal compartment boundaries. The fragmentation analysis predicts the likely energy remaining either to be prevented from perforating into adjacent compartments or to perforate but at a residual level that is beneath the initiation threshold of the munitions or equipment within.

29. Predictions are made based on the path that fragments will take to Impact munitions stowed in adjacent magazines. This is described by the thickness and type of material, bulkheads and packaging, that lie in this path and THOR polynomials [7] are used to predict any residual velocity and mass of the defined fragment.

PREDICTIONS AND ASSESSMENT FOR MITIGATION OPTIONS

30. To determine the correct parameters to work with, trial data for 4.5 Inch Mk 8 HE CA and IA rounds were examined and where information lacked, trials were completed to measure the effects [8,9]. This produced comprehensive data on which to base predictions and performance requirements.

31. Intrinsic performance of the rounds was also determined, including Large Scale Gap Test (LSGT) data, giving detonation initiation pressure and fragment impact thresholds indicating the velocity levels for the onset of Shock to Detonation Transition (SDT) for the HE composition. This concluded it is fragment impact that

initiates SR in heavier cased 4.5 Inch HE shell and that blast shock can be discounted.

32. Theoretical assessment and predictions were made on the potential performance of the mitigation options and small scale testing was completed to refine this [8]. This led to prototypes being made and tested prior to full scale prototype development [9].

33. Appropriate instrumentation was deployed within the stack and test arenas to allow post firing assessment on the response of the reactions within the test set up, to assess the performance of the barrier options and to refine predictions. This included propagation timing recording, blast over-pressures, fragment velocity and mass measurement and high speed videos.

MITIGATION BARRIER PERFORMANCE TO PREVENT SYMPATHETIC REACTION.

34. The air shock wave generated by the detonation or the impact of fragments and packaging will all induce a shock load or impedance into casing of the adjacent munition. Whatever the source of shock impedance there are a number of ways of mitigating the effects: [8].

- by dissipation including changing the form of the shock wave from sharp impulse into a more rounded impulse of energy.
- by reflection.
- by the loss of energy due to the phase change of the material (water) and the loss of energy due to friction within the material (foam or gaseous water).
- for fragments this includes changing the shape and area (deform or break up) reducing the shock load impact and perforation ability or fully arresting the projectile.

35. Shock impedance is the produce of density and shock (pressure) wave speeds. The speed of a shock wave, U_s, in a material is given by the equation of state (Hughoniot) (3) [8].

$$\mathbf{U_s = C_o + S\ U_p} \quad (3)$$

Where C_o is the velocity of sound, S a constant and U_p the particle velocity.

ANTI-FRATRICIDE BARS

36. Tests in 1998 [11] demonstrated the principle that a symmetrically positioned round bar of mild steel, between two 4.5 Inch Mk 8 HE Conventional Ammunition, will prevent SR. The bar intercepts and deflects fragments emanating from the donor preventing them from impacting the adjacent shell case. The shape of the bar also changes the momentum induced from the loadings by altering internal vectors to cancel each other out, reducing momentum, theoretically, by some 30%. The area of the bar is also of a size that the loading produced into the adjacent shell is of a value less than that to induce ignition growth and prompt shock threshold of the acceptor [12].

37. Examination of the bars was conducted, utilising numerical modelling [13], which identified that the angle of fragment impact into an adjacent shell is critical in how the round will react. Above a critical angle of impact then fragments will ricochet resulting in no reaction.

38. An AF bar in the correct position, symmetrically, between shells, (Fig 3) will intercept and deflect fragments so that they impact the adjacent shell above this critical angle. This position determines the most appropriate size of bar.

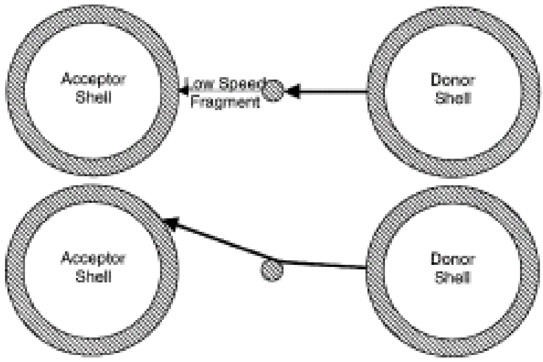


Figure 3 – Anti-Fratricide Bar showing its influence in reducing fragment impact into an acceptor.

39. Analysis, using Autodyne 2D and 3D, considered the kinetic energy of fragments impacting at various angles of attack and identified suitable sized bars placed in the correct configuration to prevent perforation of the casing (Fig 4). Using Autodyne post processor data plots of impact kinetic energy/time demonstrated the change in loading rate comparing no bar with various sized bars. This concluded that determining the actual force produced is an appropriate way to measure the loading and its ability to lead to prompt shock initiation.

40. Loading calculations then measured the force and pressure exerted by the AF bar on impact into the adjacent shell and concluded that this was significantly lower than the prompt shock threshold level.

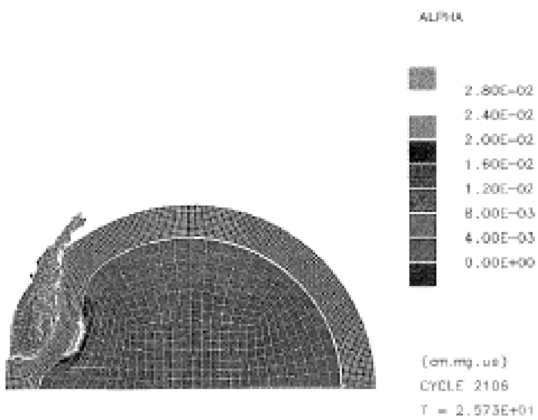
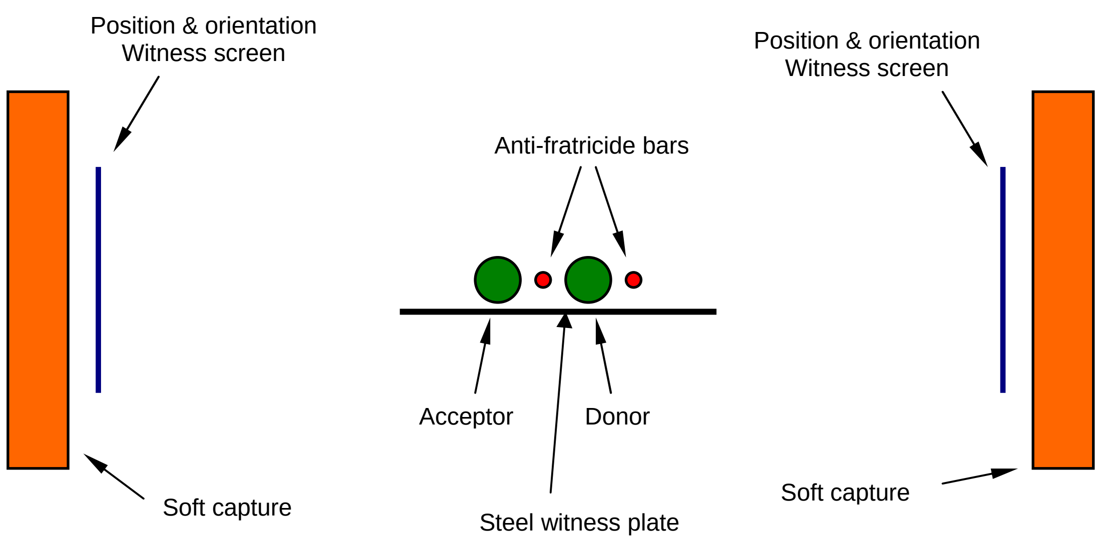


Figure 4 - Contour Plot for indirect impact of deflected fragment above critical attack angle.

41. The detonation of a donor within a stack of rounds was examined [14] to determine if fragments of enhanced velocity are produced by the acceleration of expanding gas flow passing between adjacent rounds. This concluded that some enhancement can be expected but that this is dependant on simultaneous detonation between shell, which in this case will not occur.

42. Modelling and assessment was also completed on the relative positioning of bars when placed in a stack at the second layer out from the donor and whether bars will intercept and deflect fragments above the critical impact angle at this dimension. This concluded that at this alternative geometry, fragments are deflected to above the critical angle. Tests then confirmed this assessment [14].

43. Small scale tests [9,11,14,16] were conducted examining the potential for using selected sizes of bar and material types including mild steel, stainless steel and aluminium between both types of HE rounds CA and IA (Fig 5 & 6). This determined that mild and stainless steels were the preferred choice and that a total of 23 single donor to acceptor firings, using these materials, have resulted in no reaction with adjacent acceptors.



Figures 5 & 6 – Firing set up and recovered acceptor post firing showing markings from bar impact and deflected fragment strikes above the critical angle of perforation.

44. Momentum induction into bars was measured and compared to predictions with reasonable comparisons being found for the heavier metal bars.

45. 6 stack firings [16,17] have been completed, 3 each for CA and IA using mild steel bars (Figs 7 & 8) . One donor was initiated with 7 acceptors surrounding. The configuration provided sufficient surrounding layers to represent all geometries to test the AF bars performance. Ballasted containers were then placed around the donors and acceptors to provide restraint and mass effect and replicate a N6 transport crate and typical onboard stowage.

46. All 6 firings resulted in no propagation of SR and all acceptors were recovered. On some firings one or two acceptor propellant ignited and burned in atmosphere.

47. All debris was mapped and compared to lobbing predictions. The calculations and experiment results were assessed against drop and spigot tests and concluded that KE transfer of momentum into lobbing adjacent shell into magazine structure is unlikely to lead to a secondary initiation.


Figures 7 & 8 – End on Set up for stack tests. Donor is second from bottom on left column. 7 Acceptors surrounding and 9 ballasted containers are placed on the periphery. Right - 7 Recovered acceptor shell and cartridge post firing.

48. A prototype AF assembly has been developed (Fig 9) which allows bars to be placed in the correct position surrounding the shell, between packaged rounds, when stacked in their stowage or when placed within the N6 transportation crate. Functional testing is currently being progressed with ship handling trials having recently been completed.

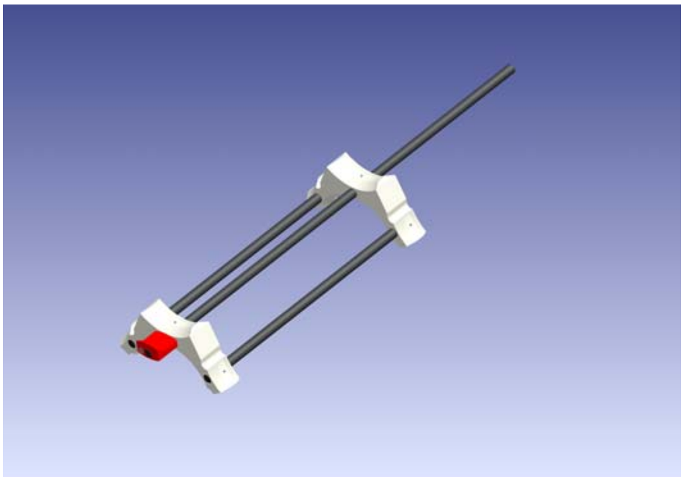


Figure 9 – Asymmetric sketch of 4.5 Inch Anti-Fratricide assembly

49. Implementation will require no retrospective work to current Naval Platforms with the AF assembly being fitted into transport crates, within depots, providing protection through the logistic cycle. The AF assemblies are struck down into ship magazines on embarking the ammunition. They will remain within the stowed stacks throughout the time the rounds are onboard ensuring that any un-planned incident does not escalate into a mass explosion and catastrophic loss of platform and life.

50. The development of an IM variant of the 4.5 Inch Mk 8 HE Improved Ammunition will significantly reduce the potential for the onset of SDT with reduced SR propagation. However, the threats seen in the Naval Environment provide a significant challenge to IM filled rounds. The benefits of the AF assemblies may be used for all variants to ensure that only one round will detonate with no sympathetic reaction propagation occurring.

WATER BARRIERS ASSESSMENT

51. For water, the interfaces between phases in the near field are complex with a number of mechanisms contributing. As water provides a discontinuity from density (speed of sound) and initial compression resistance then this will provide reflection but will allow some dissipation of blast, before water break up results in the water droplets, via increasing surface area, interacting with the gas phase allowing latent heat transfer [8].

52. The position of water has to be carefully considered, as direct coupling to the explosive can result in an increase in the shock pressure through the medium. Predictions were made and refined via trials [9] which concluded that by inducing air gaps between the barrier and the rounds this will prevent coupling and will enable the barrier to attenuate shock pressure by reflection and dissipation.

53. A further benefit of using water is its interaction with the expanding gas fire ball, cooling and quenching. This interference in the gas re-combination phase and reduction of after burn (by preventing oxygen scavenging) results in reduced over-pressure loading. Water quench has been shown [18] to reduce QSP inside the compartment where the initiation event occurs but the main benefit is experienced in the adjacent compartments where the reduced pressure is vented to significantly lower levels.

54. Prediction of residual velocities of fragments travelling through water and the container material were made using the Schonberg Projectile Penetration method (4). This applies the principles of fluid drag in retarding velocities which compares density, presented area and co-efficient of drag and gives predictions when in a hydro-dynamic interface regime.

$$Vr=Vi \, Exp\,[-Cd^* \, rm^*A^*S/(2m)] \qquad (4)$$

Where :
Vr = Residual Velocity after travelling S distance in fluid medium (m/s)
Vi = Initial fragment velocity at detonation (m/s)
Cd = Drag Coefficient of Fragment (co-efficient Cd = 0.7-1.5 depending on shape and velocity regime)
M = Fragment mass (kg)
A = Cross Section Area of Fragment (m^2)
Rm = Density of Fluid Material (kg/m^3)

55. Prediction through water, allowing for a reduction in barrier performance of 20% due to back face reflections from the shockwave, [10] were included. The predictions also made allowance for the barrier container and the ammunition container.

56. The prediction provided upper and lower residual velocities based on the least and greatest presented area of the fragment as it travels through the barrier allowing for the shape of the natural fragments produced. These are plotted at Figure 10.

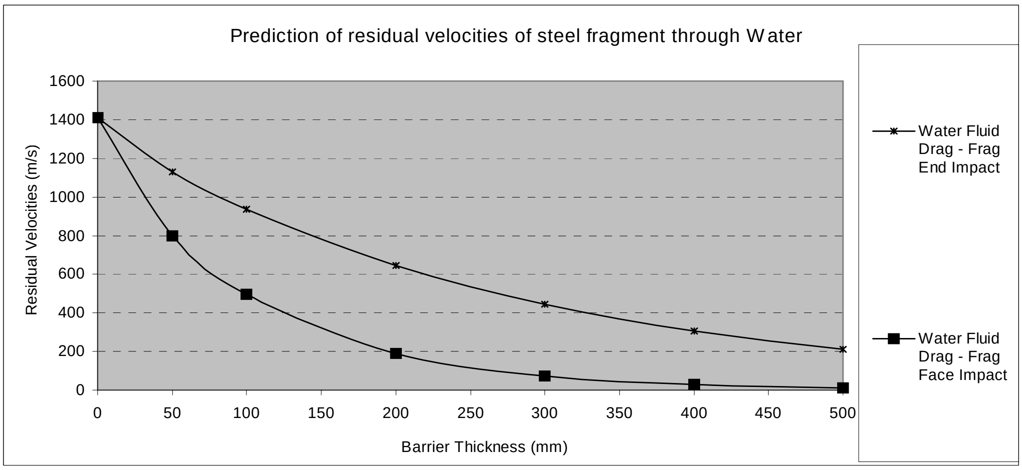


Figure 10 – Predictions for Unitised Barrier using Schonberg Projectile Penetration method. A comparison is made between fragment face impact with the larger presented area and fragment end impact, allowing for natural fragment formation.

57. Trial results [9] recorded residual velocities and masses after travelling through the water barrier and tested barrier configuration in preventing propagation (Fig 11 & 12). This showed that the residual velocities were around the lower boundary and that fragment masses produced were greater than seen in arena trials. It was concluded that the donor shell casing break up was interfered with by the barrier changing the compression loads on the case and hence the position of fracture. This results in a higher drag value and a reduction in the residual velocities.

58. Prediction made, using refined parameters of presented area and higher co-efficients of drag, to allow for the larger size, resulted in predictions within 10% of recorded results.

59. The fragment velocities recorded are under the fragment impact threshold levels for the 4.5 Inch HE ammunition by some 40%.

Figures 11 & 12 – Test set up for water barrier with 3 donors on right (initiated simultaneously) with 1 acceptor to the left. Fig 12 shows recovered acceptor showing no fragment impact markings and little casing compression due to blastwave loading.

60. Barriers may be applied into stowage racks to separate stowed rounds. The number of rounds (unit size) are based on what is the tolerable size of an event derived from the Threat Hazard Assessment and consequence analysis.

61. A full scale prototype was tested to validate the unitised size of detonation principle [19] and ability of the barrier to prevent propagation between stacks. The stowage rack was designed to hold the tolerable unit size of rounds with a barrier being fitted between stacks. The test also examined the sympathetic reaction performance of un-protected 4.5 Inch Mk 8 HE IA rounds when stowed in a unitised stack.

62. Appropriate instrumentation was deployed within the stack and test arena to allow post firing assessment on the response of the detonation within the stack, the performance of the barrier and on the total combined effects from the event and compare to the required tolerable level.

63. Post firing analysis has concluded that 4.5 Inch Mk 8 HE IA will propagate SR within a stowage bay and that the propellant did not contribute any significance to the over-pressures recorded. It was concluded that the barrier prevents SR propagation into the acceptors in the adjacent stowage bay. The recorded over-pressures support this and confirmed the size of the event was less than the platform tolerable level. The records obtained from the burst detecting probes, which recorded the progressive detonation wave within the stowage, gave strong evidence that this sequence did not transfer to the protected shell in the adjacent stowage. This was also backed up by the recovered shell and cartridges and the residual fragment velocities obtained emanating through the barrier. This gave a narrow range of flight times of averaged fragment velocities which were slightly less than predicted and significantly under the known initiation threshold of 4.5 inch HE Shell [19].

64. In terms of minimising platform damage, a full order detonation of one 4.5 Inch IA shell results in releasing effects, of a measured ENEQ, which is less than the required tolerable level of damage. The water will contribute to lowering the gas pressures on internal structure, further reducing the extent of the damage volume.

SUMMARY

65. A methodology has been described enabling “high consequence” munitions to be integrated into Naval platforms by developing a Platform and OME Protection Strategy. This derives a tolerable size of initiation events to meet required levels of Operational Capability and Safety.

66. Methods to determine tolerable levels of damage within Naval Platforms have been described. This has shown that tolerable levels of damage to platforms may be measured by ENEQ, TNT equivalent weight of explosives, which may be used as a target to derive and design SR mitigation measures to limit the size of a detonation.

67. Current 4.5 Inch Naval ammunition has been tested and shown to propagate SR leading to intolerable levels of damage within Naval platforms if un-planned initiation takes place.

68. Development work has been described to identify and examine potential mitigation options which identified two candidate techniques.

69. A 4.5 Inch Anti-Fratricide assembly has been developed. This simple and effective mitigation system has been validated to prevent propagation of SR between rounds, limiting the consequences to one round only. The design has been prototyped and implementation requires no retrospective upkeep work to Naval platforms as the assembly is simply fitted between rounds when stowed in transport crates or magazine stowages. This provides benefit throughout the logistics chain.

70. Water barriers to unitise the size of a stowage to keep an unplanned initiation to less than the Naval platform tolerable levels has been developed and validated. The barrier is fitted into stowage racks and implementation would be by including into new designs or retrospectively fitting into existing Naval platform stowage racks.

71. Both measures are compatible with the introduction into service of future IM compliant ammunition and will further reduce their effects when in the Naval environment where threat levels may exceed IM test requirements.

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