Comparative Analysis of Arbitrary Lagrange in Eulerian (ALE) and Adaptive Smooth Particles Hydrodynamic (SPH) Simulation of Rocket Propelled Grenade (RPG) on Armors

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Abstract

Military ground vehicles and helicopters are vulnerable to buried landmines, Improvised Explosive Devices (IED) and unguided ground launched threats particularly, the RPG-7 Rocket Propelled Grenade. Detonating IED's and landmines creates a blast pressure and propagating blast waves near the ground vehicles causing both structural damage and crew injuries. On the other hand, projectiles and RPG's cause the structural damage and crew injuries by their impacting velocities. RPG-7 with a top speed of 294 meters per second (660 mph), strikes the target with a velocity in excess of 1100 meters per second (2460 miles per hour) with its jet tip speed and pierces up to 400 mm of Rolled Homogenous Armor (RHA) steel. There are numerous technologies available to mitigate both mine blast and impacting projectiles from RPG's. High penetration of RPG's with a shaped charge is a big problem to protect against and to simulate. End to end full system blast simulation methods and methodology are fully matured and used widely to protect military ground vehicles and soldiers, whereas full system simulation methods or methodology to capture the kinematics of RPG and its effects on a vehicle structure is not as robust as that of buried mine blast or IED. Arbitrary Lagrange in Eulerian (ALE) method is well suited for blast and ballistics simulation due to very large deformation of the structures and fragmentation. In this study, two simulation methods of RPG are compared, namely ALE and ALE coupled with adaptive Smooth Particle Hydrodynamics (SPH). Capturing the proper slug and jet formation is a numerical challenge in RPG simulation. In order to capture with high degree of accuracy, it is necessary to model the RPG threat with fine details. This will be computationally very expensive, especially when it comes to simulating full system which often requires a very large domain. But it is necessary to model the full vehicle system or the platform and the RPG in detail to better to understand and quantify its effects on impact and engagement. There are many probabilistic models available to predict the chances, but they don't capture the accuracy. The simulation method addressed in this study aims at capturing the armor response with high accuracy on RPG impact and engagement. To perform these analysis, LS-DYNA based ALE and ALE-SPH (3D) methods were used. This will enable us to understand the RPG threat better and the effectiveness of the impact on the target, and helps to develop a suitable defeating mechanism and mitigating solutions

Keywords: *Rocket Propelled Grenade (RPG), IED, ALE, SPH, Armors, High Explosive*

1.0 Introduction

Improvised Explosive Devices pose a significant and growing threat to military ground vehicles, whereas Rocket Propelled Grenade (RPG) poses significant threat to aircraft, helicopters and also to military ground vehicles. Introduced in 1962, RPG's are now the mainstay airborne antitank weapons. Of all of the Soviet antitank weapons, the RPG-7 is probably, one of the best known to U.S. Commanders [1]. Heavy proliferation of RPGs in theaters are increasingly targeted at U.S. and allied aircraft carriers. Joint Aircraft Survivability Program Office (JASPO) [2] is continuously looking for viable strategies and solutions to mitigate the RPG damages on aircraft platforms.

RPG's are shoulder launched unguided grenades. RPG does not have any electronics to guide towards the target precisely and this weakness typically requires the operators to position themselves close to the target to ensure a direct hit towards a moving target. Effectiveness of the RPG's are based on shaped charge housed within the body or casing. Explosive in the RPG warhead is in contact with a high density elastoplastic copper liner material. Copper liner is connected to the piezoelectric fuse at the tip of the warhead via conductors. Detonation occurs as soon as the piezoelectric fuse contacts the target, developing electrical charge and detonation of explosive charge housed inside the casing. Upon detonation, very high pressure generated causes the copper liner which are usually conically shaped to collapse asymmetrically, at very high strain rates and forms into molten shaped charge. Jet tip formed from molten copper liner travels at velocities as high as 10 km/s depending on the chemical composition of explosive inside the casing. It is important to know that the jet tip velocity varies throughout its length, highest is being at the tip and lowest near the slug. There are several explosive chemicals available namely, TNT, PBXN, PETN, OKFOL with different Chapman Jouget pressure and detonating velocities. Higher the detonating velocities, higher the jet tip speed and more damages. Diameter and cone angles of the liner influences the final shape of the molten material. Closer the target to the warhead, destructive the damages are and far away from the target, shaped charge breaks into series of several segments. This phenomenon of continuous system to discontinuous system makes RPG to be ineffective at long standoff distances from the target. The jet continues to elongate until it literally breaks up, resulting in several jet segments with greatly diminished penetrative power. Diameter of the jet at the base where slug is formed is higher with lower velocity than the velocity at the jet tip. At closer standoff distances slug may penetrate the opening hole created by the jet tip at the target. Conical copper liner needs space to properly form after the HE detonation. This is called the standoff distance. Generally this standoff is expressed in terms of charge diameter as unit less quantity.

Complexity of materials, shapes and travel speed makes the RPG engagement to the vehicle platform very challenging. There are not many numerical simulation methods/approaches available. Very high pressure, high strain and high velocity associated with RPG detonations makes it impossible to model as Lagrangian formulation. Lagrangian formulation is not well suited for large deformation problems. Mesh entanglements, distortions will result in numerical instabilities. This leaves the researchers to choose either Eulerian approach of modeling as fluid, wherein the mesh is fixed and material flows through the grid as fluid. Alternatively there are several meshless and discrete methods that are emerging such as Smooth Particle

Hydrodynamics (SPH), Discrete Element Particles (DEP), and Smooth Particle Galerkin (SPG) to choose from. In order to capture the detonation and fragmentation accurately, all of these methods are computationally expensive and memory intensive. The research project described herein investigates numerical simulation methods aimed to capture the jet formation as accurately as possible, slug and damage mechanisms against armor on military vehicle platforms using LS-DYNA [7] ALE method and a hybrid ALE with adaptive SPH. This will help to develop an effective active protection system (APS) requirements for effectiveness and damage mitigation technologies.

2.0 RPG Threat Model

Figure 1 and 2 shows the picture of RPG-7. It has 3 main sections Warhead, sustainer motor and booster. Warhead houses the high explosive charge and conical copper liner. Once the RPG is launched, projectile accelerates to 117 m/s. approximately after 11m from the initial booster, rocket ignition boosts further the rocket to maximum velocity of 294 m/s. [2,4] This two stage launch is to reduce the back blast and to protect the gunner from inadvertent and catastrophic failures. Launch sequence of RPG is shown in figure 3. Most RPG's travel max distance of 900 meters [5-8] before being self- destructed. Stabilizer fins keep the airborne accuracy of rocket and warhead enhanced.

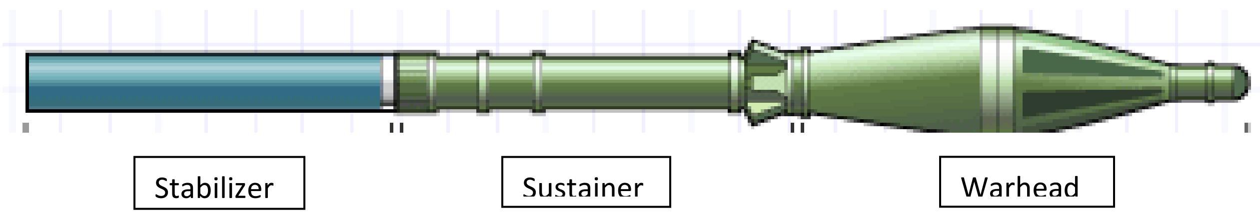

Figure 1: RPG-7 Model Pre-Launch mode

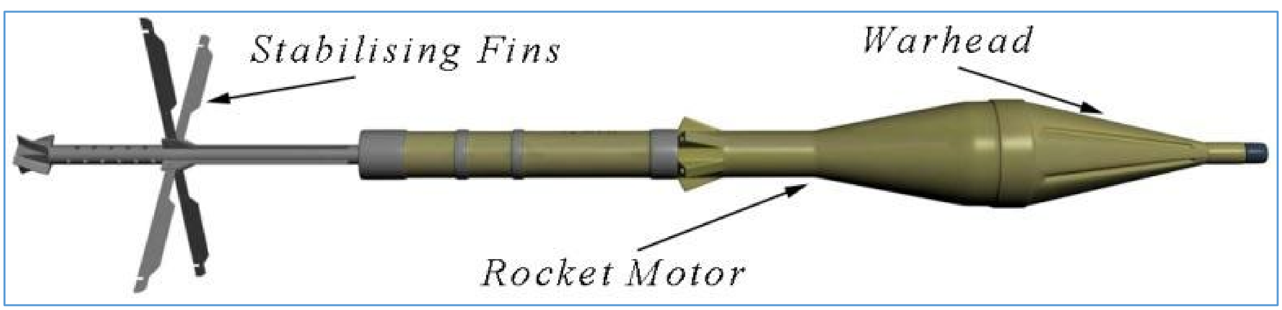

Figure 2. RPG-7 In-flight configuration mode

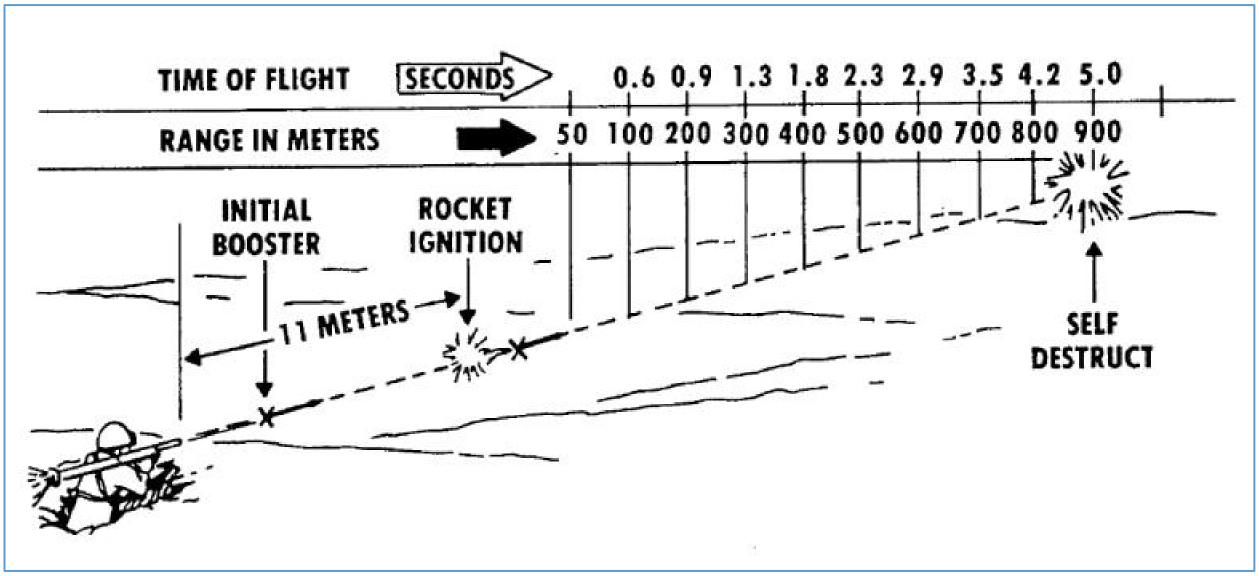

Figure 3. Launcher sequence

3.0 Finite Element Model of RPG Threat and Armor

RPG-7 finite element mesh was modeled using the generic CAD geometry. Very fine meshed RPG-7 model is shown in figure 4 with all the key components. In order to capture the jet formation and accurate shape charge, elements sizes needs to be as small as 0.5 mm. Numerically simulating such small elements is very challenging and also computationally expensive. RPG case is made with aluminum, conical liner is made with Oxygen free high conductivity copper (OFHC). Three different explosives are evaluated in this research namely, TNT, PBXN-109 and PETN. Mechanical and chemical properties are presented in the material model section. There are two piezoelectric fuses one at the tip of the nose cone 0.210 meters from the apex of the conical liner and another one at the base of the HE connected to the sustainer motor. These are modeled as polycarbonate materials. Stabilizing fins are not modelled in this research, however the effects of stabilizer spin is represented by giving a rotational velocity for the complete RPG model. Since the translational velocity is directionally controlled in simulation, effect of stabilizing fins are not significant. All the components in the model are under the influence of gravity loading. In addition to translational velocity, RPG experiences vertical velocity also due to gravity loading. Effect of air drag is not considered in this research, another variable affects the effectiveness of RPG. Both 2-D and 3-D models were evaluated and results from 3-D finite element models are presented in this paper.

Cross section of the meshed RPG model is shown in figure 4 and the dimensions of the RPG-7 used in this research are shown in figure 5 .82 mm caliber with 40 mm tube. Thickness of the copper liner is 2.00 mm. Dimensions and specifications of the model may not fit the exact specifications of RPG-7, since the mesh is generated by using morphed CAD geometry

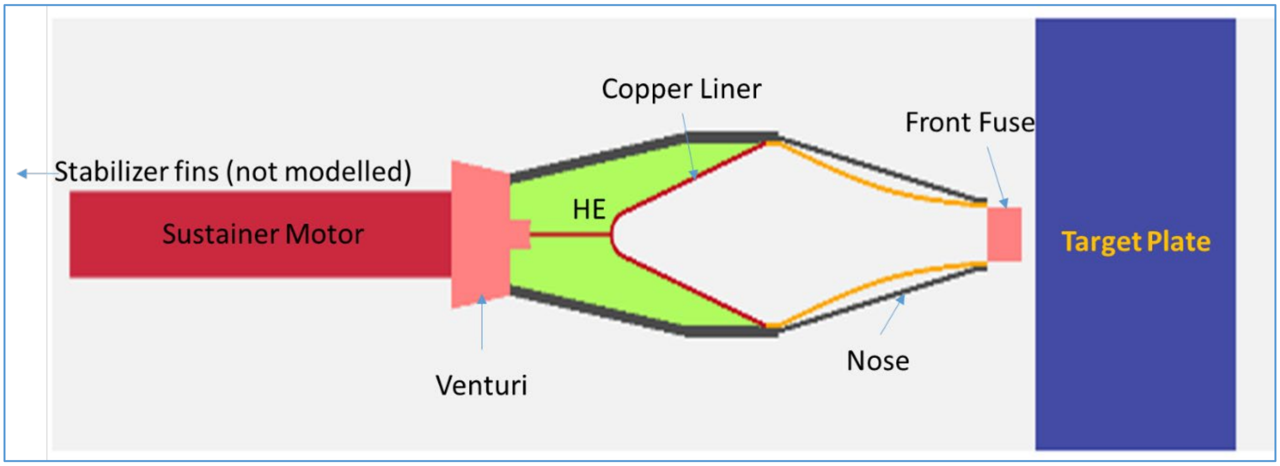

Figure 4. Meshed finite element model of RPG -7

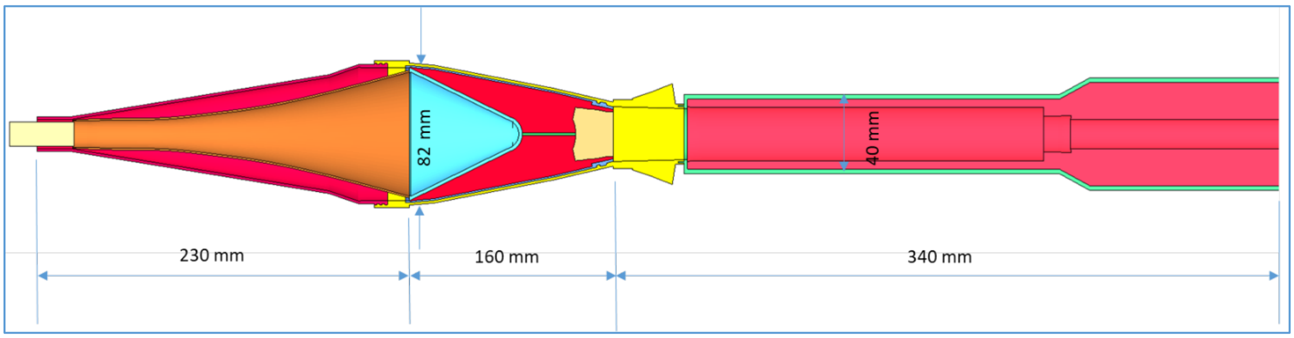

Figure 5. Dimensions of RPG -7

Technical specification of the RPG -7 are specified in table 1 [1]. All the threat data is derived from open sources

Table 1: RPG-7 Characteristics

Characteristics	
Length	960 mm
Weight	
Unloaded	14.5 lbs (6.5 kgs)
Loaded	19.5 lbs (8.85 kgs)
Caliber	
Tube	40 mm
Round	85 mm
Range	
Arming	5 meters
Sighting Range (max)	500 meters
Maximum Range	900 meters (self-destructs)
Velocity	
Initial	117 m/sec
Rocket Assist	294 m/sec
Armor Penetration at Zero Degrees	13 inches (330 mm)

3.1 Material models

Two sets of numerical simulations were performed, one with all Multi-Material ALE (MMALE) approach and the second one with hybrid approach using Multi-Material ALE and Lagrange with adaptive SPH for selected Lagrange parts. One of the main reason for using hybrid approach is, to capture the fragmenting effects of metal parts, which cannot be captured effectively in MMALE approach. HE, is modelled with *MAT_HIGH_EXPLOSIVE_BURN with JWL equation of state, copper liner is modeled with *MAT_POWER_LAW_PLASTICITY, aluminum and steel parts are modeled with *MAT_JOHNSON-COOK with GRUNEISEN equation state parameters and piezoelectric fuses were modeled as *MAT_PLASTIC_KINEMATIC. Surrounding air is represented as *MAT_NULL with POLYNOMIAL equation of state parameters. Detailed description and parameter used in the model are shown in tables 1 to 5.

TABLE 1: Mechanical Properties of Al 2024

Property	**Value**
Density (kg/m3)	2,780
Modulus of elasticity (Pa)	73E09
Poisson's ratio	0.33
Yield stress (Pa)	97E06
Tensile stress (Pa)	210E06
Failure strain	0.12

TABLE 2: Atmospheric Properties of Air

Property	**Value**
Density (kg/m3)	1.229
Viscosity (N s/m2)	1.83E05
Specific heat at constant volume (kJ/kg/K)	0.715
Ratio of specific heats	1.4

TABLE 3: JWL Parameters of Pentaerythritol Tetra nitrate (PETN)

Property	**Value**
Detonation velocity (m/s)	8,300
Density (kg/m3)	1,700
C-J pressure (Pa)	33.5E09
A (Pa)	617.3E09
B (Pa)	16.29E09
R1	5.25
R2	1.6
Omega	0.28
Detonation Energy/volume (Joules)	10.0e-09

TABLE 4: JWL TNT

Property	Value
Detonation velocity (m/s)	8,300
Density (kg/m3)	1,630
C-J pressure (Pa)	21.0E09
A (Pa)	371.3E09
B (Pa)	3.23E09
R1	4.15
R2	0.95
Omega	0.30
Detonation Energy/volume (Joules)	7.00e-09

TABLE 5: JWL PBXN-110

Property	Value
Detonation velocity (m/s)	1,672
Density (kg/m3)	1,630
C-J pressure (Pa)	27.5E09
A (Pa)	950.3E09
B (Pa)	10.9E09
R1	5.05
R2	1.40
Omega	0.40
Detonation Energy/volume (Joules)	8.75e-09

3.2 Equation of State

Thermodynamic state of the material is described by mathematical expression using equation of state variables (EOS). EOS interconnects the various internal material behaviors such as changes in density, volume and pressure. Gruneisen EOS is used for aluminum covers and Jones-Wilkins-Lee (JWL) used for all HE materials. Surrounding air is represented as an ideal gas with EOS_LINEAR_POLYNOMIAL function. The coefficients C used in EOS_POLYNOMIAL is generated by curve fitting the, volumetric parameter mu and initial internal energy per specific volume E. For air E is 25325.0 Joules/m^3. Pressure P is expressed as follows

$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)$ E. For air, C_0, C_1, C2, C_3, C_6 are all zero and $C_4 = C_5 = \gamma - 1 = 0.4$

4.0. Boundary conditions

All the RPG components are encompassed in a large air domain. Outer segments of the air constrained with non-reflecting boundary conditions. This is to eliminate the waves at the boundaries reflecting back and creating numerical instabilities and negative volumes. This will assure that the dilatational and shear waves at the boundaries will not be reflecting back into the

ALE domain. All the other parts of the RPG are free to move and rotate depending on their trajectories before and after impact.

4.1 Initial conditions

Initial RPG launch velocity of 117m/s up to 11 meters is not considered to speed up the simulation time. All the RPG components were given the rocket velocity of 294 m/s in the forward direction towards the target. To account for stabilizes fin effects, a rotational velocity of 840rad/sec was given to the RPG components. All the components are under the influence of gravity loading. Target plate was constrained in all translation and rotation degrees of freedom.

ALE simulation is based on multi-material, contact definition was not necessary. For the ADAPTIVE_SPH simulation contact between the ALE parts such as HE, copper liner it was necessary to define CONSTRAINED_LAGRANGE_IN_SOLID (CLIS). This CLIS option allows the coupling between one or more of ALE multi-material groups (AMMG) to the Lagrange parts. There are several parameters to control the leakage in CLIS. Two of them which are important are NQUAD and PFAC. NQUAD defines the number coupling point's distribution over each Lagrangian segment. For uniform mesh sizes NQUAD = 1 should be fine, but for non-uniform mesh sizes NQUAD=2 will be sufficient. In addition to NQUAD leakage coefficient PFAC also has to be defined. Most often default values set forth in LS-DYNA user manual will be a good starting point, but many times PFAC values needs to be adjusted to the problem specific. PFAC is a scale factor for scaling the estimated stiffness of the interacting fluid parts to the Lagrange parts. In this case, PFAC value of 0.06 was sufficient enough to eliminate the leakage and establish numerical stability. One of the common issue in simulating solids with a very small time step, is negative volume during the simulation. To overcome this negative volume, HOURGLASS type 9 was used with default hourglass coefficients.

5.0 Model Matrix

Numerical simulation was performed for six different Stand-Off Distance to Detonation (SODD) to understand how the impact of RPG on 350 mm thick RHA steel armor. High strength and high stiffness makes RHA one of the most widely used material for military vehicle armor and was chosen also in this research. There are many other lightweight composite materials have been developed for armor materials to reduce the weight of the vehicles. Airforce and Navy uses extensive carbon fiber based composite materials in addition to steel and aluminum. Further research will be conducted to evaluate these composite materials for RPG and other kinetic energy threats. Smallest element size in the model was 0.50 mm near the HE and copper liners and gradually increased to 3 mm further away from the HE. Ideally it would be beneficial to maintain the constant mesh size throughout the model. However this will significantly burden the computational resources and also result in excess of 50 million elements and over 300 million degrees of freedom. Simulating such a large model is one challenge, and post processing will be another huge challenge. Moreover once the shaped charged is formed, simulation will be stable and a coarser mesh size of 3 mm will be sufficient. The simulated model consists of 6 million 8 node solid elements. Simulation was evaluated with both ALE, and ALE with adaptive SPH methods. One of the advantages of adaptive SPH methods is, fragments from detonating RPG can be captured effectively.

6.0 Results

6.1 ALE simulation

RPG was detonated and impacted on 350 mm RHA armor for SODD 0, 1, 2, 3, 5, and 7 meters from the fuse. Distance between the copper liner apex to the fuse in this research is at 0.30 meters and this is considered as SODD 0. RPG was given an initial velocity of 294 m/s and depth of penetration on 350 mm RHA was compared for different SODD. Figure 6 shows the TRADOC published data for RHA Depth of Penetration (DOP) against SODD. 229 mm DOP observed for PETN explosive at SODD zero, and 179 mm for TNT explosive. As the SODD increases to 7 meters, DOP decreases to 87 mm. Farther the SODD, jet breaks into several segments and reduces the impact velocity and with reduced mass. This will result in reduced depth of penetration (DOP) as the SODD increases. Figure 7 is the comparison of the simulation results to that of the U.S Army TRADOC [3] published test data. Simulation responses capture very nicely the overall trend. However the magnitudes differ at several standoffs distances. This can be attributed to lack of air drag in simulation compared to that of test, where air drag influences the jet speed. Test data has the effect of air drag, which clearly shows at standoff distances of 6 ft. and beyond resulting in significant decrease in depth of penetration.

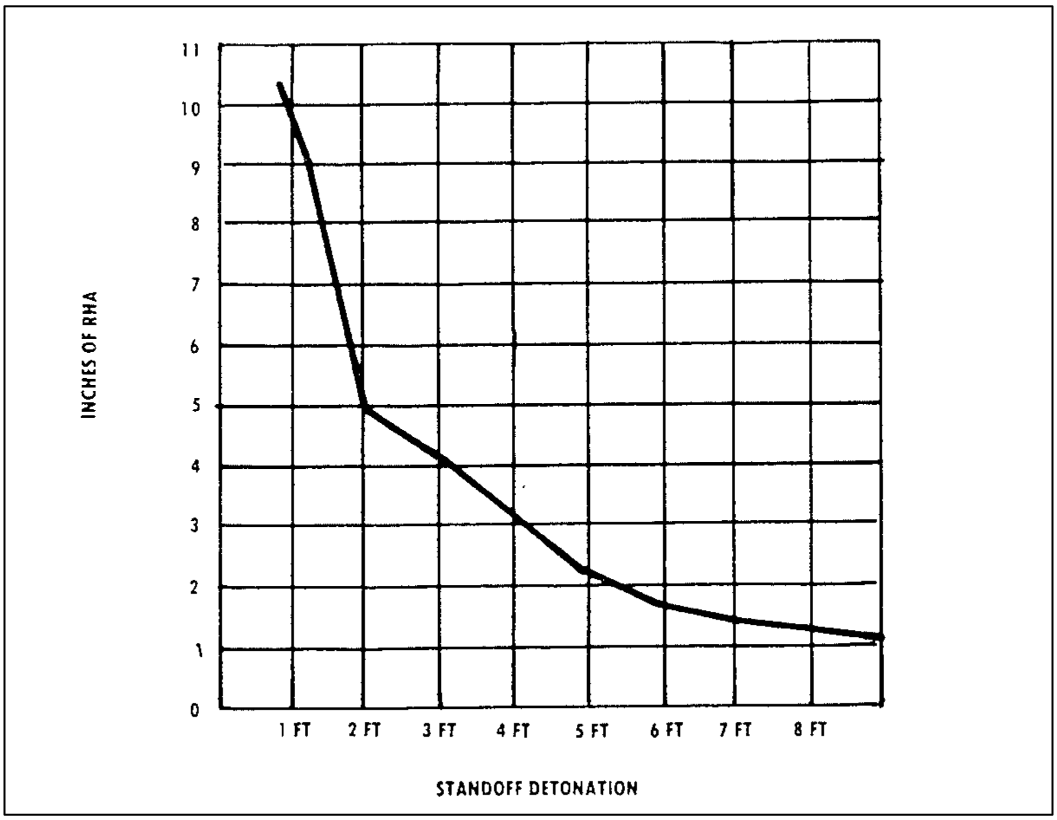

Figure 6: Standoff Detonation Vs RHA penetration

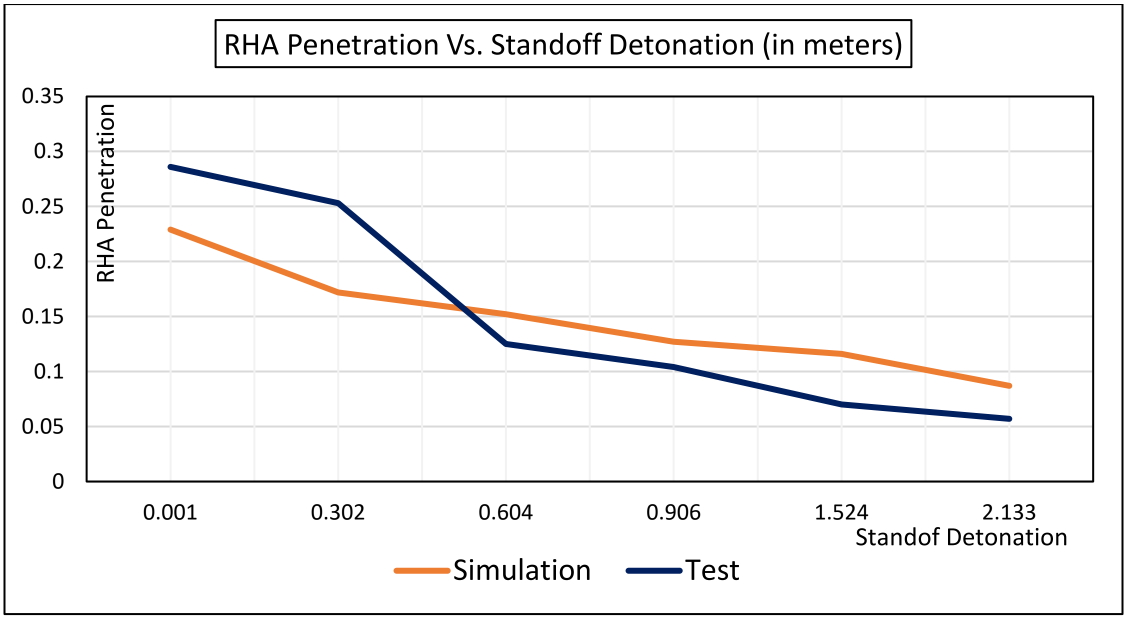

Figure 7: Standoff Detonation Vs RHA penetration comparison

RHA penetration for two explosives TNT and PETN are shown in figure 8. PETN has higher detonation velocity and higher specific energy compared to TNT and PBXN. PETN explosives results in higher depth of penetration. As the SODD increases penetration depth tends to converge for both TNT and PETN. Analysis was performed for PBXN explosives also, which has higher detonation velocity than TNT but lower than PETN.

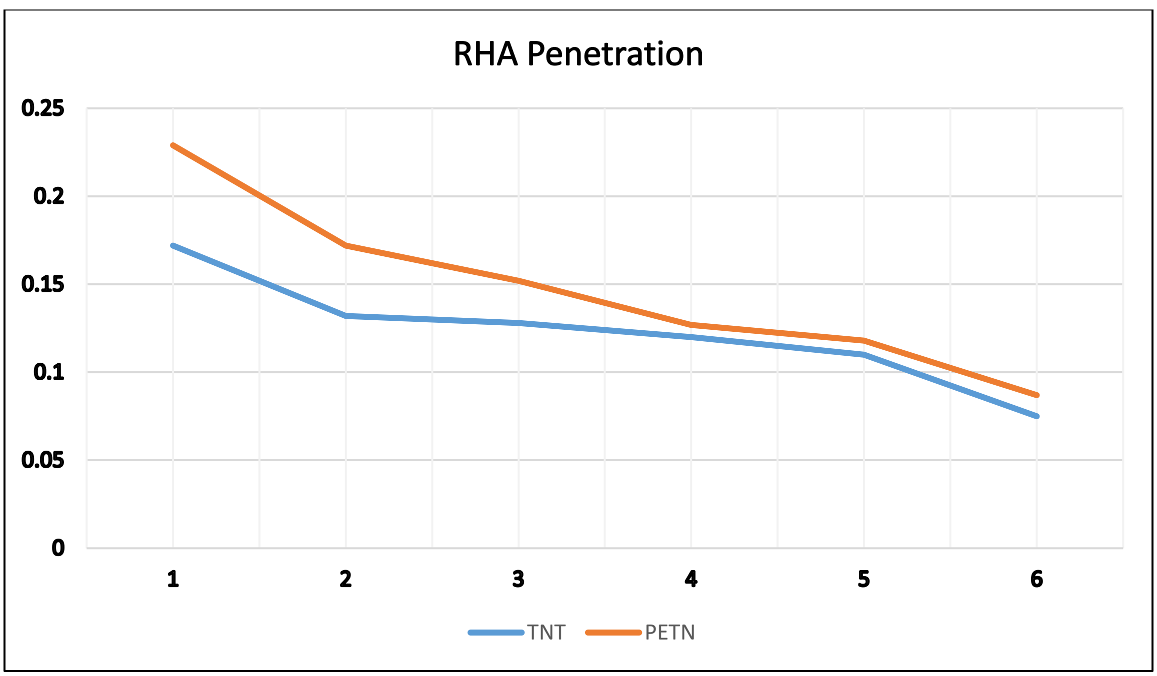

Figure 8: RHA penetration comparison – TNT and PETN

Results from all the simulation responses are shown in table 6. $V^2.d$ is one of the NATO STANAG [9] defined link between different shaped charges. In this research only one shaped charged is used, value of *d* and *v* remains the same irrespective of SODD. Diameter *d* of the shaped charge is not constant but varies throughout the SCJ length. STANAG defined $V^2.d$ for copper jet is 430,000. Calculated values of $V^2.d$ from the simulation are shown in table 6. Diameter *d,* used in the table is measured at 200 m from the initial position.

Table 6: Simulation responses from different SODD

	Stand of Distance	**Jet Diameter**	**Velocity**	**Velocity @ impact**	**v2.d**	**Penetration**
Simulation	**(meters)**	**(meters)**	**m/sec**	**m/sec**	**m*3/sec*2**	**(meters)**
1	0.001	0.00533	5224	655	145456	0.229
2	0.302	0.00533	5224	653	145456	0.172
3	0.604	0.00533	5224	184	145456	0.152
4	0.906	0.00533	5224	181	145456	0.127
5	1.524	0.00533	5224	167	145456	0.118
6	2.133	0.00533	5224	148	145456	0.087

Figure 9, 10 and 11 shows the initial pre-launch state of RPG and animated snapshots at different time stamps of the shape charge jet formation and its impact positions on RHA.

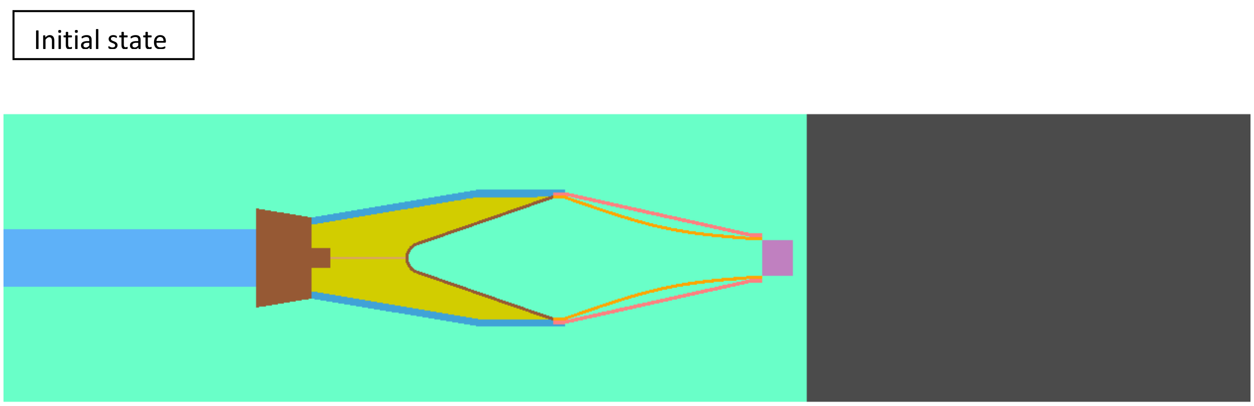

Figure 9. Pre-launch state of RPG and RHA

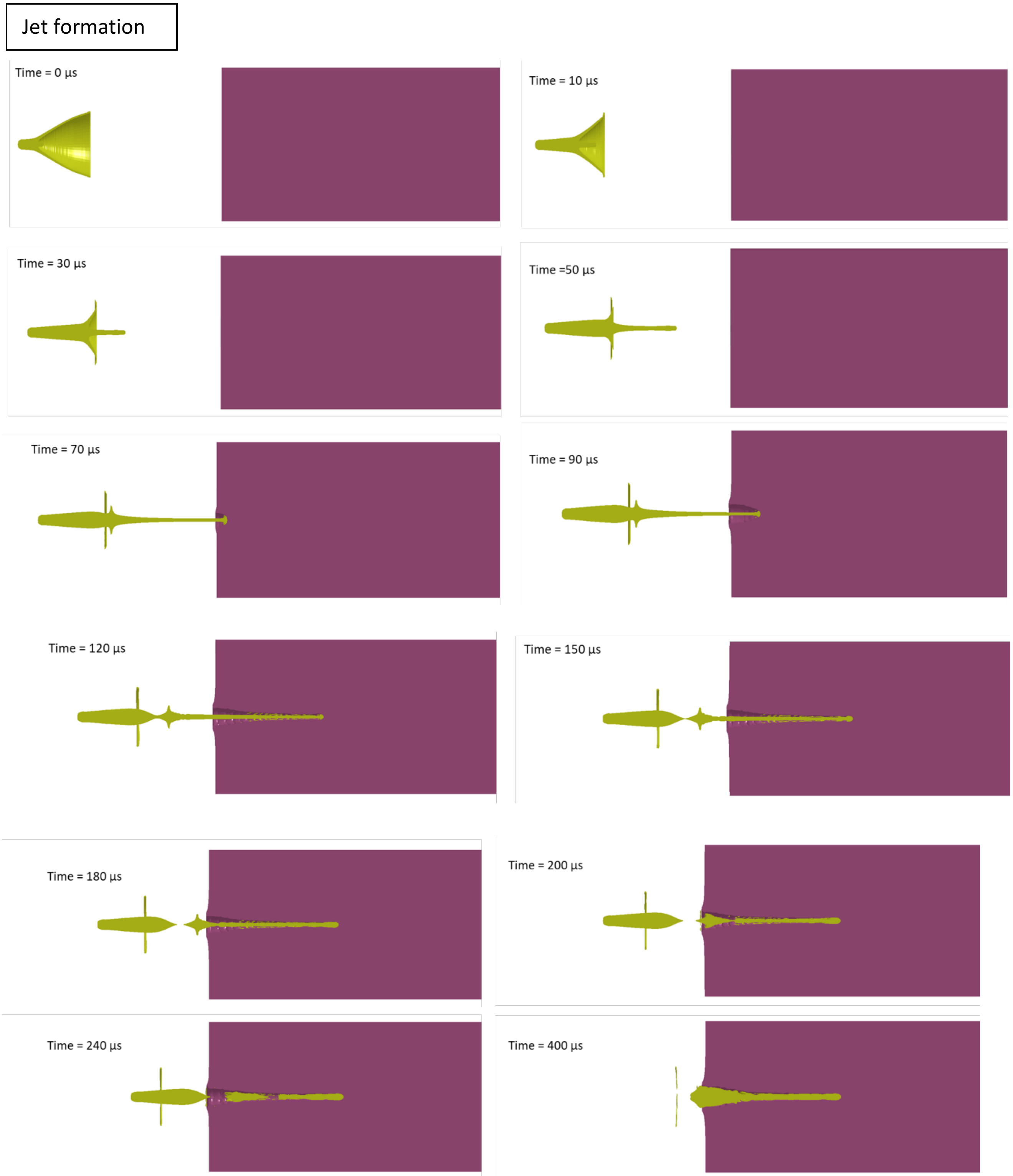

Figure 10. animated snampshots of RPG impact on RHA armor

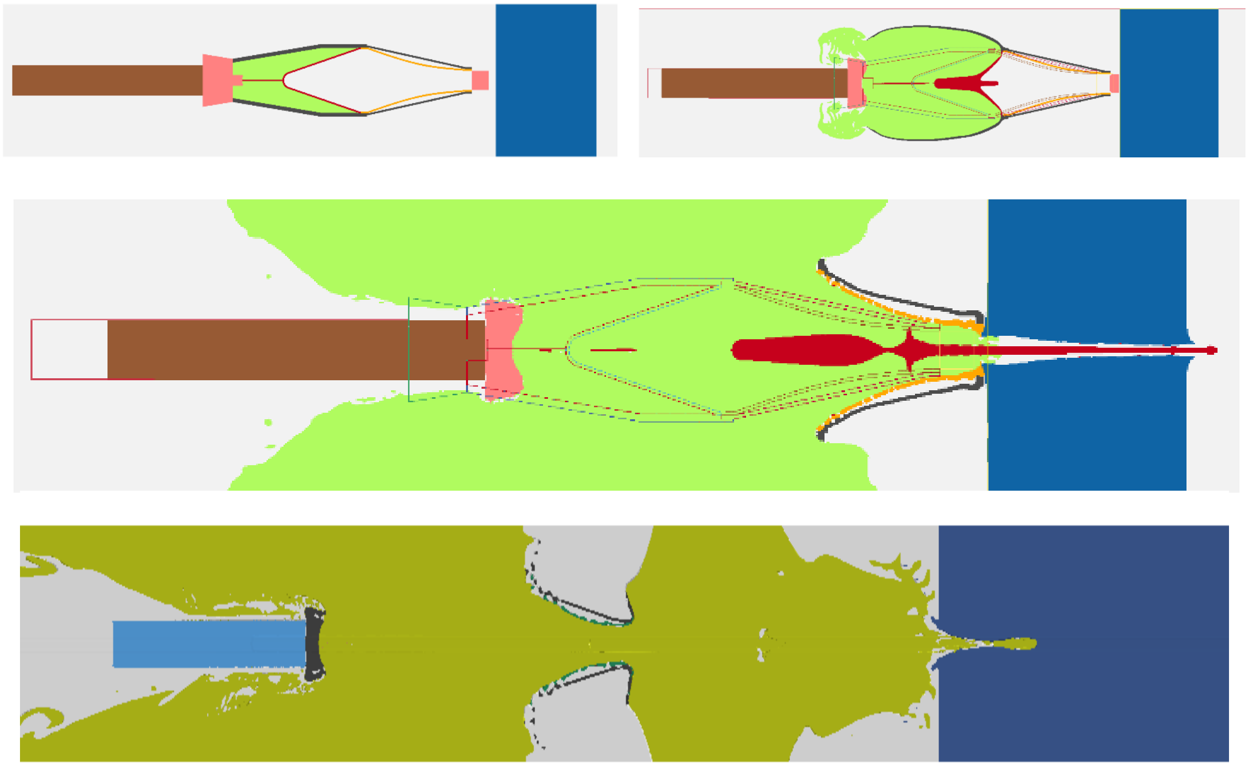

Figure 11. Complete view of RPG impact on RHA armor at SODD zero and 3 meters

Jet tip velocity over time is plotted in figure 12**.** Detonation velocity of jet tip peaks immediately after the detonation and gradually slows down as the jet progresses forward. Closer the target, higher the impact velocity and more the damage.

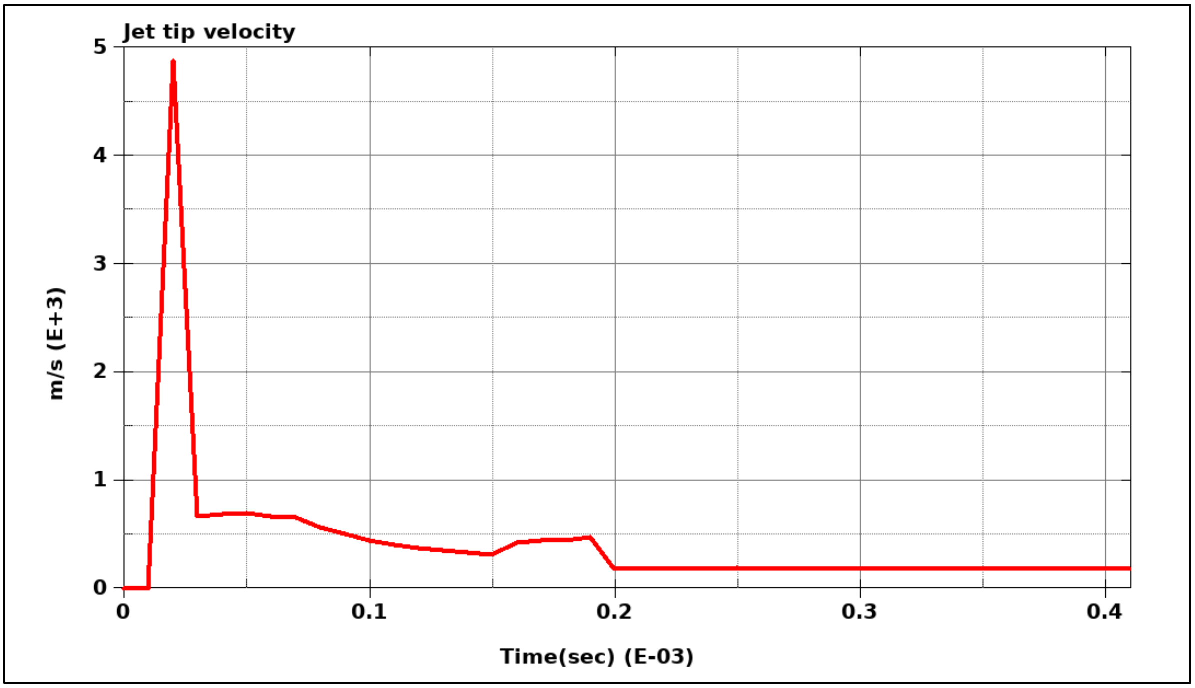

Figure 12. Jet tip velocity Vs time

6.2 ALE with adaptive SPH simulation

In this adaptive SPH simulation, RPG cover, nose cones, fuse, sustainer motor are modeled as Lagrange elements. Fragmenting materials from material failure can be captured by Lagrangian method. One of the drawbacks in Lagrangian method is, once the element is failed it will be deleted from further simulation for numerical stability. This results in significant loss of failed elements and mass associated with it. Alternatively SPH or other meshless methods are well suited for such cases. Another hybrid approach is to use adaptive SPH method, purpose of this is to adaptively transform a Lagrangian solid part or part set to SPH particles, when the Lagrangian solid elements comprising those parts fail. One or more SPH particles will be generated for each failed solid element and these SPH particles will inherit all the Lagrangian properties and conservation of mass, momentum and energy will be maintained throughout the simulation.

Target plate RHA armor is modeled with *MAT_JOHNSON_COOK using Johnson Cook strength and failure models [10]. Material properties of RHA used in this research is shown in table 7.

<u>TABLE 7: Mechanical Properties of RHA</u>

Property	**Value**	**Damage Parameters**
Density (kg/m3)	7,822	D1 = -0.80
Modulus of elasticity (Pa)	210E09	D2 = 2.10
Shear modulus (Pa)	77E09	D3 = 0.50
Poisson's ratio	0.30	D4 = 0.002
A (Pa)	7.92E08	D5 = 0.61
B (Pa)	5.22E08	
N	0 26	
C	0.014	
M	1.030	
Cp (J/kg-k)	478.0	

RPG penetration into RHA armor is shown in figure 13 for adaptive SPH method. Fragmented casing elements are shown as adaptive SPH particles in figure 14. Both ALE and adaptive SPH methods show similar jet tip velocities however adaptive SPH method shows slightly higher depth of penetration. This could be due to the effect of fragmented elements not completely eliminated in the computation due to erosion. Computationally adaptive SPH method is 20% faster than that of ALE simulation.

Figure 13: RPG penetration into Lagrangian RHA armor

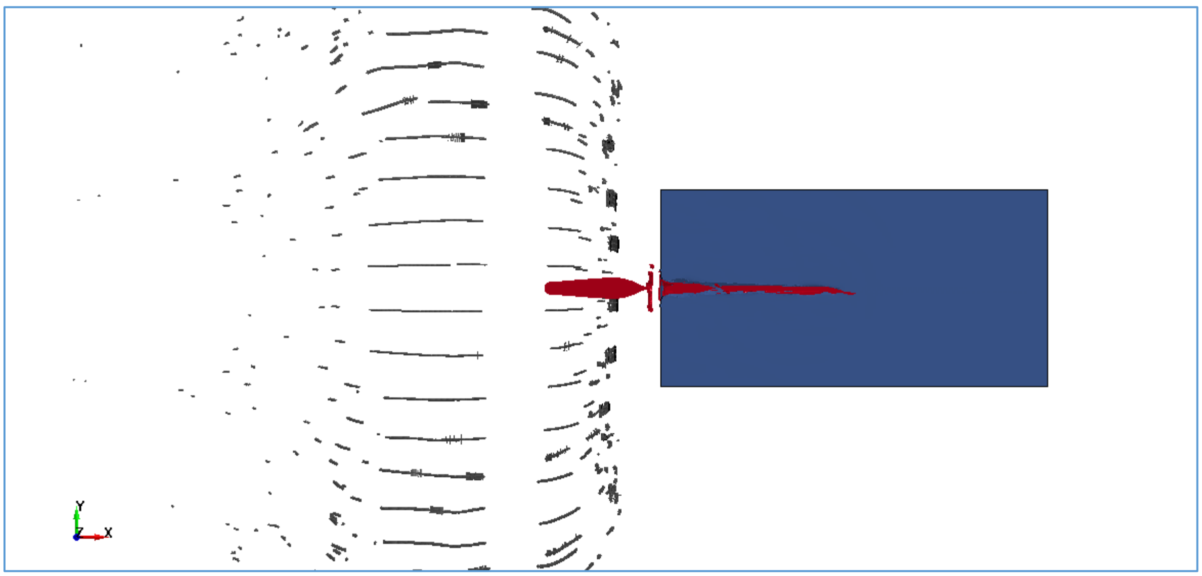

Figure 14: Fragmented elements as adaptive SPH particles

Internal energies of copper liner in both ALE and adaptive SPH methods are identical as shown in figure 15. However, rise of IE in RHA from ALE method steadily increases from the time of impact, whereas IE of adaptive SPH remains near constant after the initial rise as shown in figure 16. Ideally rise of IE between ALE and adaptive SPH for RHA should be very similar if not identical. Keep in mind that RHA in adaptive SPH is modeled as Lagrangian formulation whereas in ALE it is modeled as an Eulerian formulation. IE response of RHA in Eulerian formulation seems to show high stiffness and in adaptive SPH formulation shows softer. This explains why the depth of penetrations are different between ALE and adaptive SPH methods.

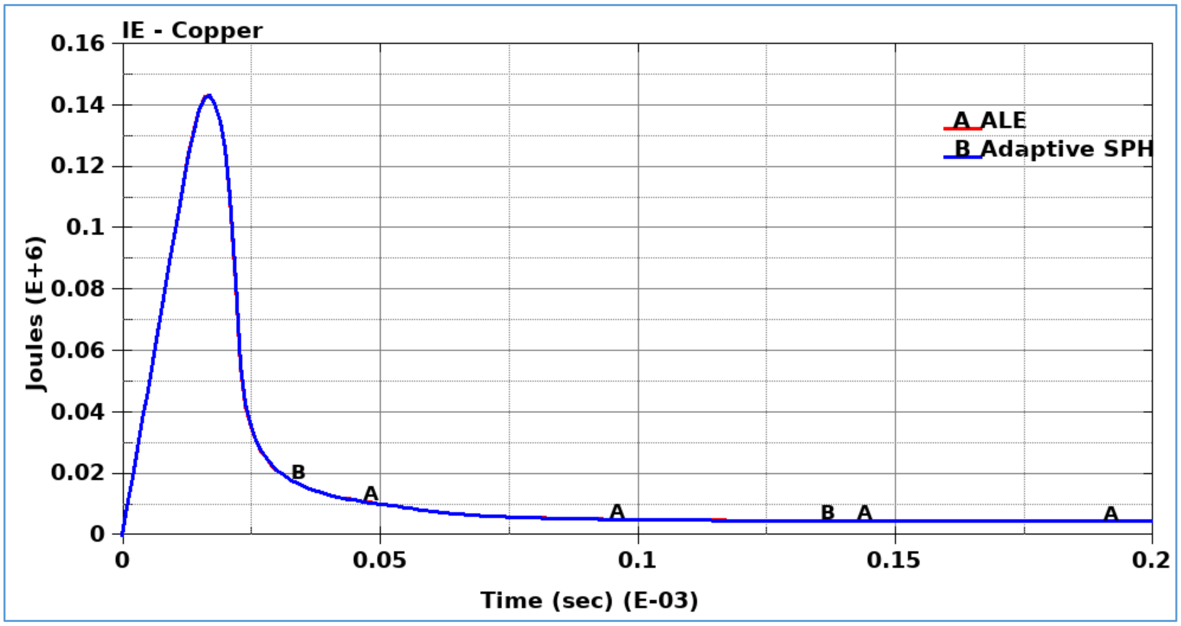

Figure 15: Internal energies of Copper liner

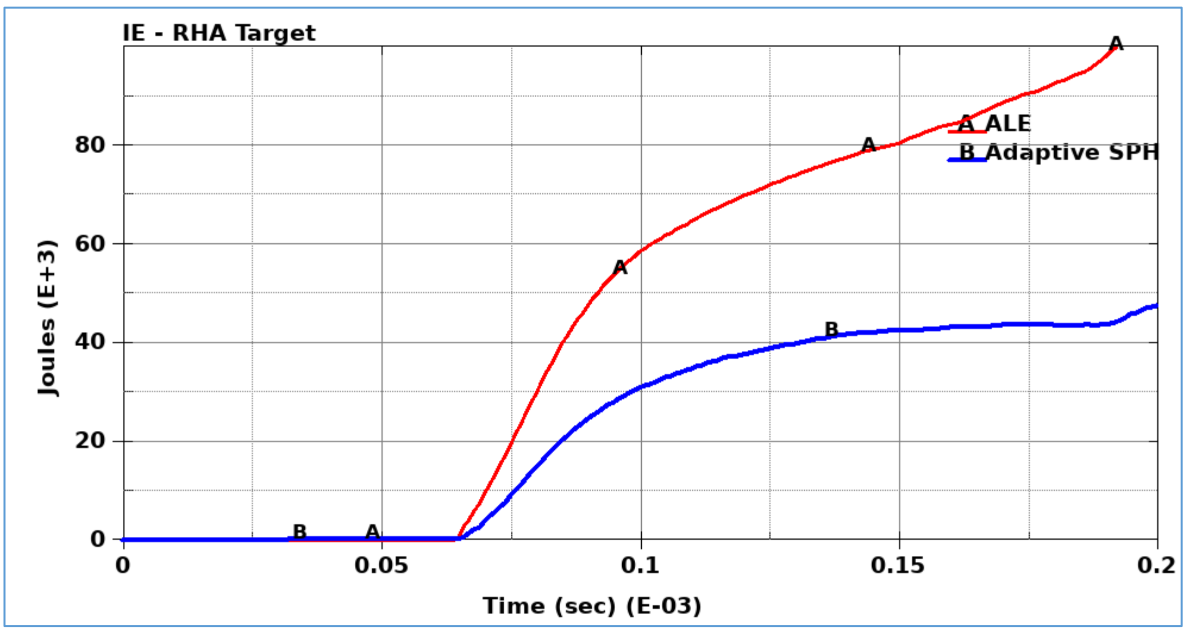

Figure 16: Internal energies of RHA armor

Conclusions

RPG engagement and impact on a 350 mm thick RHA target armor was investigated in this paper with 6 SODD's and 3 HE's, namely TNT, PBXN and PETN. Shaped charge engagement with the RHA armor was modeled using commercially available software LS-DYNA3D. From the simulated responses and from published literature, when RPG detonates near the target, jet tip velocity will be as high as 655 m/s for PETN explosive. This high impact velocity on 350 mm RHA armor penetrates 229 mm for PETN explosive and 179 mm for TNT explosive. Higher detonation velocity of PETN results in deeper shaped charge penetration compared to that of the

TNT. As the SODD increases, jet tip velocity and the penetration depth decreases. Farther the SODD, jet tip breaks into segments and travels with less mass and lower velocities. Also in ALE with adaptive SPH simulation, selected metal parts of RPG were modeled as Lagrange with adaptive SPH. Both the ALE response and the ALE with adaptive SPH response are comparable for the simulated case. ALE with adaptive SPH response show slightly higher depth of RPG penetration compared to that of the ALE. Further research is ongoing to understand the differences between ALE and adaptive SPH methods. Successful simulation of RPG engagement on RHA armor will provide opportunity to assess the different APS Hard Kill systems and modify them as needed upfront in the design and development phase. This simulation methodologies will significantly reduce and eliminate the unknowns from these APS systems and provide program managers knowledge necessary to make decisions. Further research and development is ongoing to explore different meshless methods to reduce the computation time.

Acknowledgements

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Abbreviations

ALE – Arbitrary Lagrange in Euler

APS – Active Protection Systems

CLIS – Constrained Lagrange in Solid

DEP – Discrete Element Particles

HE – High Explosive

IED – Improvised Explosive Device

JASPO – Joint Aircraft Survivability Program Office

JWL – Jones-Wilkins-Lee

NATO – North Atlantic Treaty Organization

SCJ – Shaped Charge Jet

STANAG – Standardization Agreement

SODD – Standoff Detonation Distance

SPH – Smooth Particle dynamics

TRADOC – Training and Doctrine Command

RHA – Rolled Homogeneous Armor

RPG – Rocket Propelled Grenade

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