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Ceramic Particle Armor

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ABSTRACT

One of the deadliest threats that ground combat vehicles regularly encounter is the Explosively Formed Penetrator (EFP). The extremely high impact velocities that are typical of EFPs necessitate extremely heavy armor, which is often impractical due to the corresponding compromise in mobility and reliability. One possible solution to this threat is to use granular ceramics as an alternative to current armor solutions. An evaluation of high-speed impacts into granular ceramics and extensive testing across a wide range of parameters provides data to support this proposal. These results demonstrate an impressive potential for granular ceramics in EFP protection kits with a substantial reduction in both cost and weight to achieve the same level of protection as plate or sheet materials.

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1. Introduction

In the constant battle to protect the crews of combat vehicles, one of the common threats that is exceedingly difficult to protect against is the Explosively Formed Penetrator (EFP). An EFP generally consists of a shallow bowl-shaped copper disc that is packed into a tube with explosive material behind it. When the explosive is detonated the copper disc is formed into a long slug and accelerated to a velocity well in excess of any rifle bullet. The effectiveness of an EFP comes from the fact that traditional armor, such as steel and composites, become less effective as impact velocity increases. At strain rates typical of bullet impacts, the tensile strength of the armor has a huge impact on its effectiveness [1]. An EFP can have an impact velocity greater than 3000 m/s [2], which is more than three times as fast as a typical rifle round. At these velocities, traditional armor has proved impractical for all but the heaviest vehicles. This

situation has led to the need to find a more effective form of armor to counter the EFP threat.

Ceramic plates are one effective form of protection against EFPs, but the cost of ceramic plates is extremely high, and the brittleness of ceramics results in extremely poor durability and multi-hit capability. Experimental research indicates that a possible solution to this dilemma is to utilize ceramics in granular form. While ceramic plate is very expensive and brittle, granular ceramics such as SiO₂ (common sand) and SiC are very cheap and durable. Sand is used extensively due to its availability on and around military bases. Sand is used to protect buildings and fortified locations from a variety of threats and it has long been known that its effectiveness increases with higher velocity impacts. According to the US Army Field Manual FM90-10-1 [3], a bullet from a 7.62 X 51mm rifle can penetrate 4.5 inches of sand after traveling 100 meters, and 7 inches of sand after

traveling 200 meters. This may seem counterintuitive, as the bullet has a higher impact velocity at the shorter distance, but nevertheless, for reasons discussed in this paper the impact depth is substantially lower at the higher impact velocity.

When it comes to stopping bullets, even high-performance ceramic particle armor (CPA) like Silicon Carbide (SiC) cannot match the light weight protection offered by high strength steel or composite armor. EFPs, however, are another matter. CPA can be utilized to counter EFPs while substantially reducing weight, decreasing cost, and providing multi-hit capability. Armor utilizing granular materials would generally be bulkier than plate materials, but in most vehicle applications the critical performance criteria is weight and not volume. CPA has the potential to revolutionize EFP protection and save lives in applications where the weight of EFP armor has been previously considered impractical. An excellent example of this is the up armored HMMWV pictured below.



Figure 1: M1151 HMMWV with EFP (Frag 6) armor

Vehicle armor is ideally designed to keep vehicle occupants from serious harm against the most powerful penetrators that they are likely to encounter. The trouble with this is that it often requires very heavy armor. Vehicle payload capacity is quickly used up and durability quickly diminishes. The EFP armor for the M1151 HMMWV protects only the lower half of each

door. Despite this the doors still weighed up to 1100 lbs. With these heavy doors and other armor, the vehicle curb weight exceeds its gross vehicle weight rating by over 2000 lbs.

Vehicle armor is primarily concerned with two velocity ranges. The two velocity ranges may be referred to as high velocity and hyper velocity. High velocity impacts are impacts that range from about 250 to 1150 m/s and are highly dependent on the strength of the armor, the areal density, velocity, and strength of the penetrator. Hyper velocity impacts are those that exceed 1150 m/s, and the mechanism of penetration is primarily hydrodynamic penetration for the most common types of armor. Table 1 indicates the velocities for typical ballistic threats from high speed bullet impacts to hyper velocity EFP impacts.

Table 1: Typical Impact Velocities

Threat	High Impact Velocity (m/s)	Low Impact Velocity (m/s)
AK47 (7.62X39)	725.4 (124gr FMJ @ Muzzle) [4]	371.3 (124gr FMJ @ 400m)
M16 (5.56X45)	987.8 (55gr FMJ @ Muzzle)	344.2(55gr FMJ @ 550m)
IED Fragment	1500 (830gr Frag @ 1m, Comp B) [4]	640(44gr Frag @ 20m, TNT) [4]
EFP	3509 (L5A1 "BALDRICK) [2]	1256 (60 mm EFP @ at 43.5m) [5]

All these threats are common on the battlefield. Hyper velocity threats are far more challenging to protect against, which means that if complete protection is required, the most efficient solution for hyper velocity threats is the most efficient solution over all.

The objective of this paper is to highlight the potential to use granular ceramics in armor solutions designed to defeat hyper velocity impacts. The use of CPA would result in greatly reduced weight and cost versus the current armor solutions and would allow for EFP protection to be implemented on vehicles for which it has

previously been considered impractical. This has the potential to reduce wartime casualties and improve vehicle durability. The research and testing contained within this report is centered on investigating the effect of high velocity impacts into granular ceramic materials. The testing demonstrates favorable performance against very high-speed penetrators and makes progress towards validating the use of granular ceramics to protect against threats over a range of impact velocities.

2. Penetration Mechanics

Granular ceramics are bulk media, comprised of small irregular-shaped ceramic particles. Granular ceramics are very hard and abrasive due to the inherent hardness that is typical of ceramics and the sharp edges that form when the material fractures. In some ways, sand behaves like a shear thickening non-Newtonian fluid. Sand will flow much like a liquid under certain conditions but acts like a solid in other circumstances. The interaction between the individual particles is responsible for this apparent shift in state. Dry sand has much higher friction between the particles than wet sand and as such, will more readily act as a solid when subjected to high strain rates [6].

If sand is subjected to a very high strain rate, the multifaceted surfaces of the particles cause them to link together and act like a rigid solid. In this way, the sand can prove to be extremely difficult for a projectile to penetrate. In a high-speed impact, the individual grains of sand can be considered to form an air-filled matrix of solidly connected ceramic particles. This is highly beneficial for an armor application because this rigid matrix is very light but can absorb an extraordinary amount of energy through the fracture of individual particles. After the impacting object passes, the sand flows back to fill the cavity that was made by the impact. In addition, the hard, abrasive nature of the ceramics can break up, melt, and disperse a projectile to spread the energy out over a larger area, and thus limit penetration [6].

Steel and composite armors are very effective at stopping bullets from small arms threats. Typically, small arms threats do not involve impact velocities greater than 1000 m/s. For metal armor, penetration at this velocity is primarily due to plastic deformation and plugging. There are quite a few theories that have been used to describe penetration mechanics. Most of these theories pertain to perforation of a finite target. These theories along with methods that are commonly used for modeling and simulation of perforating impacts are described in detail by Deniz [1]. For penetration into a semi-infinite target, other penetration theories are more applicable. The most common solution for calculating long rod penetration into a semi-infinite target, was established independently by Alekseevskii [7] and Tate [8]. Their work was expanded on to solve for penetration by Segletes [9], and the solution is given in the following form:

$$P = \int_0^t U dt = -\frac{1}{V_0} \int_V^{V_0} \frac{L}{L_0} U dV \quad (1)$$

$V_0 = \text{Impact velocity}$

$L_0 = \text{Rod length at Impact}$

In specific cases where the target is a homogeneous metallic plate and is very similar to the penetrator, $R=Y$, which allows for the final penetration to be determined with the solution [9] that follows:

$$P_f = \frac{L_0}{\sqrt{\gamma}} \left(1 - \exp \left[\frac{-\rho_R \sqrt{\gamma}}{2Y(+\sqrt{\gamma})} V_0^2 \right] \right) \quad (2)$$

$P_f = \text{Final Penetration}$

$\gamma = \rho_T/\rho_R = \text{target to rod density ratio}$

As steel and composite armor have excellent strength, they are ideal for impacts at typical rifle velocities. However, at very high velocities penetration reaches what is referred to as the

“hydrodynamic limit”. The armor strength relative to the penetrator strength has a significant effect on pushing the hydrodynamic limit to higher velocities, but as the velocity goes to infinity the exponent of velocity goes to zero.

$$\lim_{x \rightarrow \infty} e^{-x} = 0 \quad (3)$$

This simplifies the penetration equation for very high impact velocities to the following equation:

$$P_f = \frac{L_0}{\sqrt{\gamma}} = L_0 \sqrt{\rho_r / \rho_t} \quad (4)$$

The above equation represents the penetration of a long rod into a target at or above the hydrodynamic limit. This means that at very high velocity impact the only variables for penetration of the rod are its length and the target to rod density ratio. The effect of this is that the benefit of using high strength armor to counter very high velocity threats is greatly diminished. In reality, even for very high speed impacts the penetration mechanism is a combination of plastic deformation, plugging, and hydrodynamic penetration. The exact mechanics of this is not well understood and can only be modeled for very specific scenarios where the solution has been tailored to experimental results. For armor steel and typical steel penetrators, hydrodynamic penetration begins to dominate penetration mechanics between 1 and 2 km/s and becomes more and more dominant as impact velocity increases.

The goal in the design of tactical vehicle CPA is to change the penetration mechanics and spread the impact out to a larger area of the armor. This is accomplished by breaking up and dispersing large projectiles into smaller pieces so that the areal density of the projectile is decreased. The energy from the projectile must be dissipated by fracturing and deformation of the sand and projectile. Hence, it is important that the impact be spread out to a large area to reduce the penetration depth.

The key characteristics that CPA must demonstrate to be effective at defeating very high velocity threats are summarized below:

1. Intergranular friction, which results in rigid behavior at high strain rates
2. High hardness and abrasiveness to effectively break up large penetrators
3. High friction so that projectile fragments melt above a certain critical velocity [10]
4. Irregular grain shape to cause rapid dispersion of projectile fragments
5. Compressive failure stress increases at high strain rates [11]
6. High fracture area compensates for low fracture toughness and quickly dissipates kinetic energy [12]
7. Fluid like properties of granular ceramics provides some degree of self-healing

If the characteristics listed above prove to be adequately effective, then CPA will be an excellent choice for vehicles that require a protection level for threats greater than high power armor piercing rifle rounds.

As previously mentioned, granular ceramics are not especially effective at stopping small arms threats when compared to steel and composite armors. However, at higher velocities the extreme hardness of ceramics causes the penetrator to erode and breakup into smaller pieces that have much smaller areal density than the original penetrator. In addition, these smaller pieces tend to spread out, further reducing their penetration potential. The results of this project indicate that penetration into granular ceramics decreases above a certain velocity until a stable penetration depth is reached. This phenomenon was studied in detail by Savvateev et al. [10], where he postulated that the velocity where the penetration depth begins to decrease is equivalent to the velocity corresponding to a kinetic energy equal to two times the penetrator’s specific heat capacity.

3. Testing

To validate the proposal that CPA is more effective at stopping very high velocity impacts, it was necessary to perform ballistic tests using variations to the CPA, the projectile, and the impact velocity. These results then needed to be compared to existing penetration data for conventional armor. The testing was broken up into Small Arms Testing and Fragmentation/EGFP testing with each of these categories intended to prove different aspects of the hypothesis

3.1 Small Arms

The small arms testing is intended to measure how various types of CPA perform in stopping small arms weapons that are shot directly at a target. This would include bullets from various rifle and pistol rounds. The small arms testing is intended to validate the assertion for CPA that above a certain critical velocity, an increase in impact velocity will result in a decrease in penetration depth. Because small arms testing is relatively inexpensive, this phase of testing was used to test how variation in the media, such as grit size and moisture content, will impact the effectiveness of CPA.

Test Equipment

To allow for a high number of iterations in this test, the test materials used were various grades of silica sand (SiO_2). The SiO_2 was loosely placed in a wood test box with a 19 mm thick rigid polystyrene foam insert in the front of the box to hold the sand in while not significantly impeding the projectile

The interior dimensions of the box were 368 mm wide X 368 mm high X 551 mm deep. The test box is shown in Fig. 2.



Figure 2: Test box filled with landscape sand (lid removed)

After the second round of testing, it was determined that paper witness panels should be inserted to assist in locating the projectile fragments and ensuring that the penetration depth was not affected by the projectile shifting, as the test media was removed to find it. The first witness panel was 150 mm behind the back of the polystyrene panel. Subsequent witness panels were spaced at 50 mm intervals. The witness panels are shown in Fig. 3.



Figure 3: Test box with paper witness panels

The small arms testing utilized a bullet similar to the 7.62X51 M80 cartridge. The bullets used were 150 grain (9.72 gram) Full Metal Jacket (FMJ), which is 3 grains (0.194 grams) heavier than the FMJ bullet used in the M80 cartridge. FMJ bullets have a soft lead core jacketed in copper. The small arms projectile is shown in Fig. 4.

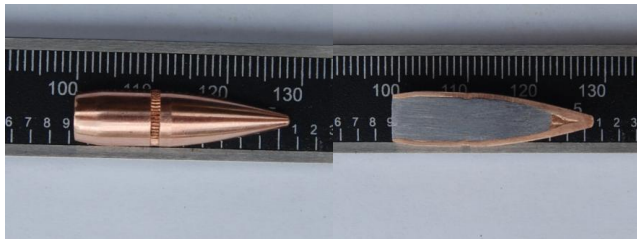


Figure 4: Small arms projectile (cut in half lengthwise)

The test rifle was a K31 bolt action rifle. The rifle was situated approximately 5 yards from the CPA test box and the powder charge was varied to achieve the range of desired impact velocities. The impact velocity of each shot was measured using an optical chronograph. A schematic representation of the test setup is pictured in fig. 5.

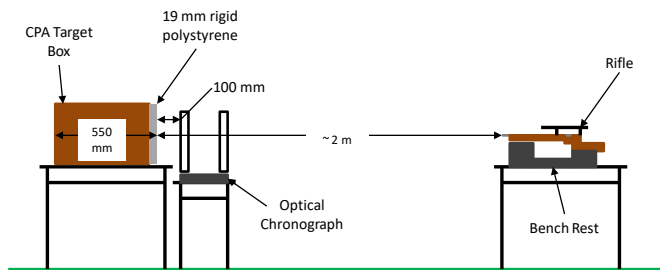


Figure 5: Small arms test setup diagram

Test Media

The first CPA used was coarse landscape sand. It is primarily silica sand, but the content and grain size were varied and not precisely controlled. This media can be described as generic sand. It is typical of the type of material that is often used to fill sand

bags. The coarse landscape sand is pictured in Fig. 6.



Figure 6: Coarse landscape sand

The second test media used was wet landscape sand. The wet sand was made by mixing landscape sand and water and using a soil moisture meter to measure the relative change in moisture and provide consistency between tests. The moisture meter provides a general gauge for how moist one target media is relative to another. The terms wet and dry are being used generically and there was no attempt to correlate them to precise moisture percentages.

The remaining test media used in the small arms test are commercially pure SiO₂ and are strained to produce a consistent grain size. The grain sizes used are fine (60 grit), medium (36 grit), and coarse (16 grit). It is evident from the color that the purity of the SiO₂ decreases as the grain size increases. However, the changes in purity are minimal enough that all three grit sizes can be considered commercially pure SiO₂. Fig. 7 shows all three grit sizes of SiO₂.



Figure 7: Coarse (16 grit), Medium (36 grit), Fine (60 grit) SiO₂

Small Arms Results

Each test was assigned a distinct letter. The first three tests were performed without any witness paper. The fourth test was performed to compare the difference with and without the witness paper. The witness paper was a common 20 lb office paper attached to a wood frame to hold it in place.

The penetration was measured using a tape measure from the back of the strike face to the location of the projectile within the CPA. The testing took place over several weeks with varied atmospheric conditions, but all the individual tests except test C were started and finished on the same day. The results from all the small arms tests are charted together in Fig. 8

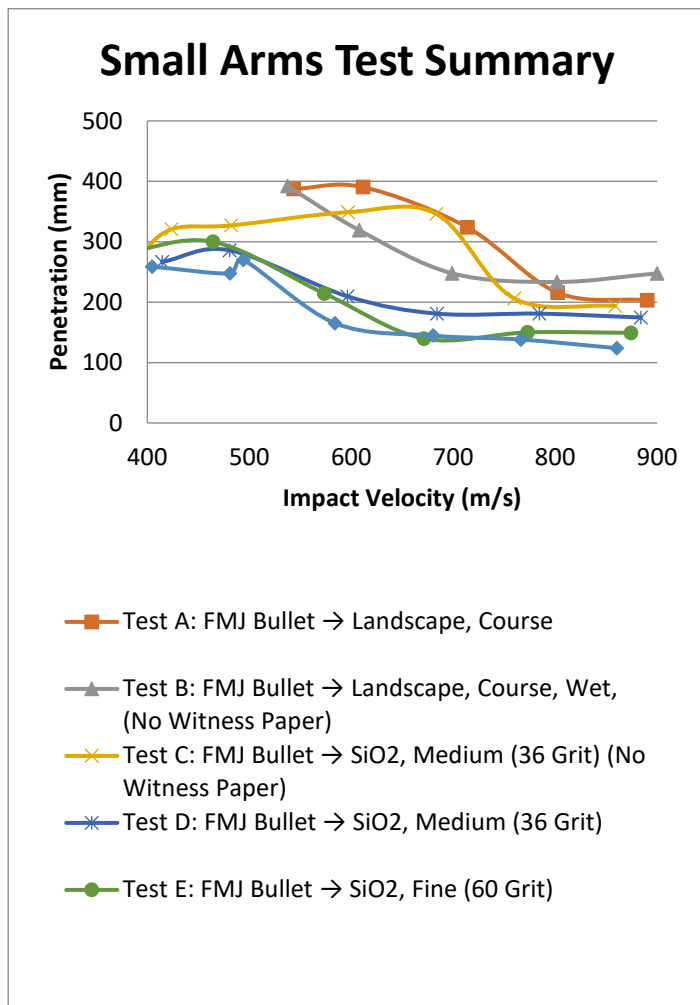


Figure 8: Small arms test results summary

The small arms testing showed several interesting trends. The dry landscape sand was less effective at the lower velocities but proved to be more effective against the higher velocity impacts. Also, the witness paper causes a surprisingly large reduction in penetration and produced more consistent curves. The course grit was chosen for subsequent tests because it had the best performance at the highest velocities and it had less of a tendency to flow through holes in the target box.

Penetrator Condition

The condition of the penetrator after impact showed a direct correlation with the depth of penetration. When the penetrator was relatively intact, it achieved much higher penetration. The greater the degree of penetrator degradation, the less penetration it achieved. Fig. 9 illustrates this relationship.

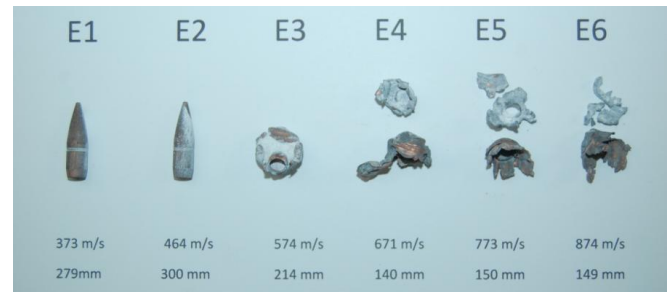


Figure 9: Test E - penetrator condition

Except for some minor abrasion, the first two projectiles were essentially undamaged. The white color is fragmented SiO₂ that has been ground into the surface of the copper. The third shot caused the projectile to mushroom, but the projectile retained nearly all its mass. When mushrooming occurred the penetration depth started to decrease. The last three shots all resulted in separation of the copper jacket from the lead core and caused increasing amounts of degradation to both the jacket and core. Once the bullet fragmented the penetration depth stabilized to a lower limit. This trend was consistent throughout the small arms testing.

3.2 Fragmentation/EFP

Fragmentation and simulated EFP testing were performed at Demmer Corp. in Lansing, Michigan. Demmer generously demonstrated their continued support for higher education, engineering, and the US war fighter by providing test services at no cost.

Test Equipment

A new test box was fabricated from steel to be able to withstand the tremendous energy that this phase of testing would produce. In lieu of the polystyrene strike face that was previously used the new box had a small hole covered on the inside by a sheet of office paper to retain the test media. The new test box is shown in fig. 10.



Figure 10: Steel test box (lid removed)

The test cannon was a custom-made smokeless powder test gun with a 96 inch barrel, weighing approximately 400 lbs. It fires standard alloy steel 20 mm Fragment Simulating Projectiles (FSP) at velocities that range from 800 to 1800 m/s. The test gun is shown in the Fig. 11.



Figure 11: 20 mm test cannon

The impact velocity is measured using redundant magnetic and optical chronographs. The magnetic chronograph is shown on the right and the optical chronograph is on the left in Fig. 12.



Figure 12: Optical and magnetic chronographs

There were two test projectiles used in this test. One is the standard 20mm FSP, which is 830 grains (53.8 grams), 4340H Alloy steel hardened to RC 30 \pm 2. The dimensions for the standard 20 mm FSP are described in Fig. 13.

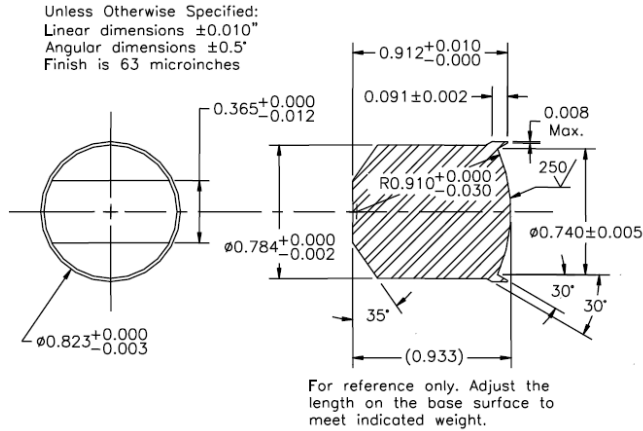


Figure 13: Standard FSP dimensions [13]

The other projectile is made of pure copper and has the same outside dimensions as the standard FSP but is bored out slightly at the base to keep the mass at 830 grains (53.8 grams). These two test projectiles are shown alongside the 7.62 mm bullet from the small arms test in Fig. 14.

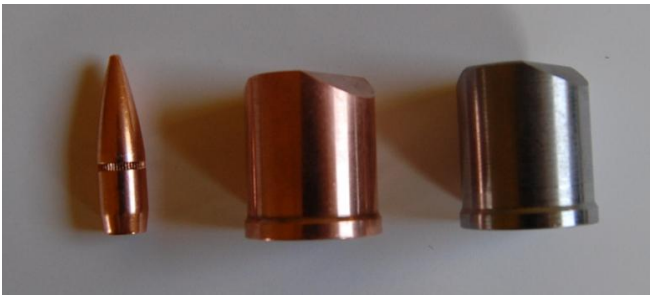


Figure 14: 7.62 mm bullet, 20mm copper FSP, and 20 mm steel FSP

Test Media

There were two different test media used in the laboratory testing. The first shots were fired into coarse (16 grit) silicon dioxide sand, which has been described in Section 3.1. The second media was coarse (16 grit) silicon carbide. SiC was selected because it has excellent hardness, fracture energy, and low density. SiC plates and discs are already used in vehicle and personnel armor but are extremely expensive and have poor multi-hit capability. The SiC used for this project was

generously donated by Detroit Abrasives Co. in Chelsea, Michigan and is pictured in Fig. 15.



Figure 15: Coarse (16 Grit) Silicon Carbide (SiC) with 20mm steel FSP

Fragmentation/EFP Test Results

Results from the 20mm steel and copper FSPs are as follows. Due to test equipment and projectile limitations it was not possible to perform all the desired tests. For the Fragmentation/EFP testing the weight of the penetrators were made to be 830 ± 0.2 grains and the retained weight of the largest portion of the projectile was weighed after the shot. The projectiles were lightly brushed to remove CPA residue, but residue that had become imbedded into the projectile was not removed.

Test I

Test I was performed on the wooden box before the steel box was constructed. The wooden box did not stay together and as a result this test was not completed.

Test J

Test J was the first test performed with the steel box. The test was performed by firing the standard 20 mm steel FSP into Coarse (16 Grit) SiC. The last shot of test J was not obtained, because the FSP was not able to be stabilized in the barrel and went off course causing extensive damage to the test

equipment. The largest piece of the penetrator missed the box entirely, so no penetration was observed.

Test K

Test K was performed by firing 20 mm copper FSPs into coarse SiC. On the 9th shot the FSP was not stabilized and it went slightly off course. A substantial piece of the penetrator still struck the box, but it hit the steel plate on the front of the box rather than going through the paper cover. The box was repaired but no further testing was performed with the copper FSPs.

Fragmentation/EFP Test Results Summary

The results from tests J and K are charted together in Fig. 16.

hardness of the steel projectile or the higher latent heat of fusion.

Penetrator Condition

As was the case with the small arms penetrators, there was a correlation between the penetration depth and the condition of the penetrators. The solid FSPs degraded more gradually than the jacketed bullets. The condition of the steel FSP is shown in Fig. 17 and the condition of the copper FSP is shown in Fig. 18. As was the case with the small arms projectile the FSPs started to mushroom, and then proceeded to fragment as velocity increased. This trend was more gradual in the FSPs since they were solid and there was no jacket to become separated. The copper FSPs decreased in penetration depth as mushrooming increased. Once the copper FSPs became fragmented the penetration depth leveled off at a lower limit. The Steel FSPs appeared to show a similar trend, but the differences in penetration depth were much smaller. The combination of small variations in velocity and a small sample size made it more difficult to determine a definite trend for the steel FSPs. None of the projectiles showed obvious signs of extreme heat such as discoloration or melting. Abrasion was evident on all the FSPs, and the copper FSPs showed substantial pitting on the front face of the projectiles.

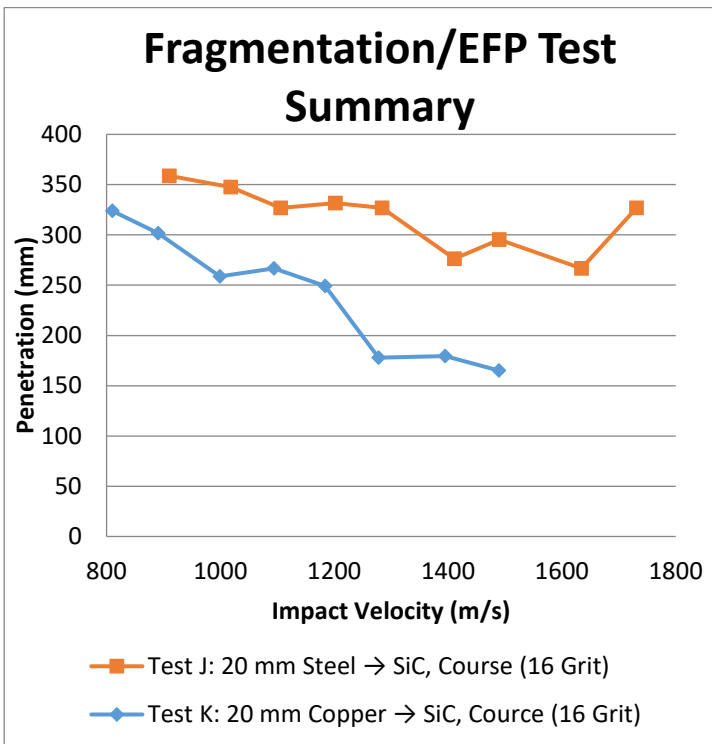


Figure 16: Fragmentation/EFP test results summary

Fig. 16 clearly shows how big a difference the penetrator material makes. Despite being the same shape and mass the copper FSPs produced substantially less penetration than the steel FSPs. It is unknown whether this is due to the higher



Figure 17: Test J – Steel penetrator condition

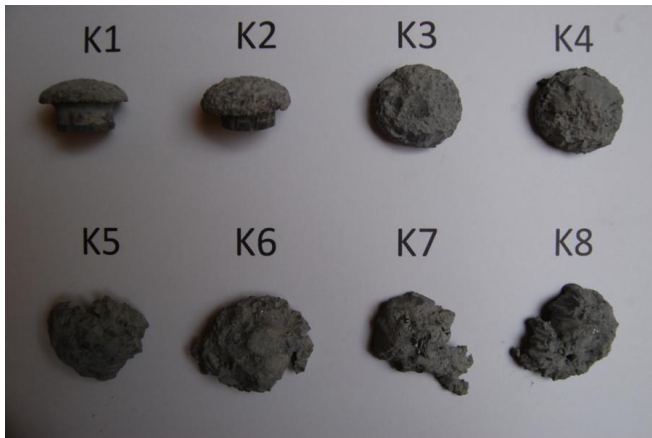


Figure 18: Test K – Copper penetrator condition

3.3 Test Summary

The testing confirmed the core concept of the hypothesis by consistently demonstrating that, for high speed impacts into granular ceramics, the penetration depth will decrease after the critical velocity is reached. The results of this project indicate that the critical velocity is reached when the penetrator begins deforming. Furthermore, once the penetrator is substantially fragmented the penetration depth levels off to the Fragmented Projectile Penetration Limit (FPPL). The critical velocity and FPPL are dependent on both the CPA and projectile composition. The testing showed that this effect is much more dramatic with copper and lead as opposed to steel.

Due to test equipment limitations, extremely high velocity shots were unobtainable. This information would have been very beneficial in defining the critical velocity and FPPL and making correlations between these factors and the material of the penetrator and CPA. The testing also demonstrated that, even though most of the energy is absorbed by heat and plastic deformation, there is still a substantial shock force that can act on the CPA enclosure. Despite the test limitations, the testing was sufficient to validate the hypothesis of this project and to justify further testing.

One useful data point that was unfortunately not collected throughout testing was the average diameter of the disintegrated CPA that marked the

penetrator's path. This attribute is shown in Fig. 19. It was observed that this diameter did increase with impact velocity; but as no consistent measurements were taken, it was not possible to make any quantitative observations or conclusions.



Figure 19: Width of disintegrated CPA, J7

As was proposed in the introduction, the CPA was shown to consume the penetrator's energy through deformation of the penetrator, fragmenting of the CPA, and heat in both the penetrator and the CPA. After each shot, a large area of CPA was found to be warm to the touch, and at the higher velocity shots, the remnants of the penetrator needed time to cool before they could be safely touched. This heat was most dramatically demonstrated with the wet sand tests when a large pocket of steam was found around the penetrator.

The plastic deformation of the CPA is shown in Fig. 20.



Figure 20: Shattered and undamaged SiC, J7 – 50X

The degree to which the CPA broke down illustrates how it can absorb so much energy. In failure at high strain rates the CPA fractures across numerous fracture plains and breaks down into a fine talc-like consistency.

Witness Paper

The Witness paper provided a 3D cross-section of on the disturbances that the projectile caused along its penetration path. The first sheet of witness paper shown in Fig. 21, exhibited a very large hole with circular ridges around the hole that are believed to correspond to the shock wave that propagated through the sand along the projectiles path. The subsequent frames show less dramatic penetration holes as the shock wave decreased with the decreasing kinetic energy of the projectile.



Figure 21: 150 mm witness paper from shot E2

The witness paper that was added to the small arms testing inadvertently provided an important insight. It was initially thought that the effect of the paper would be negligible; there was however, a substantial decrease in penetration depth when witness paper was added. There were also several instances where the penetrator was found up against the witness paper indicating that the witness paper had stopped the bullet. The conclusion from this is that the CPA is most effective while the projectile is still moving above its critical velocity and that its effectiveness dramatically decreases as the penetrator is slowed. This is an important conclusion, because it means that the most effective use of CPA would be as hybrid armor with a high tensile material behind it. The best CPA armor solution would utilize CPA at the front to disintegrate and slow the penetrator and have a backing of composite armor to catch the slowed and disintegrating projectile and serve as a spall liner in the case of an overmatch. A hardened steel strike face might be included to improve durability against small arms and light fragments. This arrangement would allow for much thinner armor to be utilized then if CPA was used by itself. An example of this hybrid CPA is shown in Fig. 22.

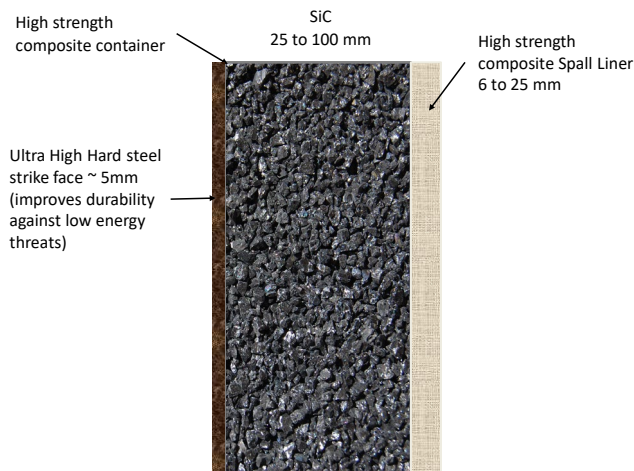


Figure 22: Hybrid CPA diagram

Effects of Other Variables

In each test, the CPA was filled to near the top of the box, but it was not compressed or restrained. In some of the setup shots for the small arms testing the top of the box was left off and there was no discernible difference noted in the penetration depth with or without the top. It is therefore believed, that restraining or compressing the CPA has no substantial effect on the penetration depth. It is further proposed that the reason for this is that the shockwave propagates through the material behind the penetrator and has no effect on impeding its penetration.

The effects of the penetrator material, CPA material, grit size, and moisture content, were all specifically investigated in this analysis. Other variables have been investigated by other authors such as penetrator shape and aspect ratio [10]. Additionally, it would be of interest to investigate the effect of changing the hardness of the penetrator while retaining the same chemistry. An analysis of the effect of penetrator hardness would shed further light on what determines a penetrator's critical velocity. Is the critical velocity solely a function of the penetrator's heat of fusion and melting

temperature, or are there other material properties that have an influence?

The test data was insufficient to confirm or reject Savvateev et. al's conclusion that the critical velocity is primarily dependent on the projectile's melting point and latent heat of fusion. The state of the recovered projectiles seems to indicate that the critical velocity has more to do with the mechanical breakdown resulting in a decrease in areal density rather than projectile melting. Further testing utilizing copper and steel alloys of various strength would be required to develop a conclusion regarding the mechanism responsible for the difference in penetration depth.

4. Comparison to Current Armor Solutions

Specific armor solutions are classified, so for this paper it is only possible to make a generic comparison of weight and cost.

EFP Protection

Despite not being able to achieve true EFP velocities, the results from test J establish the trend that demonstrates the potential of CPA for EFP protection.

From a comparison to current solutions it is expected from the test results that the use of SiC in EFP kits would result in at least a 35% weight savings vs RHA. If the SiC armor weighs 35% less than the RHA armor then the expected cost savings would be as high as 67.5%. This cost savings is substantially affected by the cost of other materials that make up the armor solution and by the fabrication techniques required. While these numbers are preliminary there is no question that the use of granular SiC in EFP armor would save substantial cost and weight vs conventional armor.

Fragmentation Protection

Steel FSPs are the standard method of evaluating armor protection capability against fragmentation. Therefore, the data exists to make a comparison between CPA and RHA. This comparison was

made using V50 ballistic limits from MIL-DTL-12560K [14] and is shown in Table 2.

Table 2: RHA equivalence for test J

Shot #	Actual Velocity (m/s)	Penetration (mm)	Density adjusted penetration (mm)	RHA equivalence
J1	910.2	359	32.9	19.4
J2	1018	348	31.9	22.1
J3	1106	327	30.0	24.3
J4	1202	332	30.5	26.7
J5	1284	327	30.0	28.8
J6	1411	276	25.1	32.0
J7	1490	295	27.0	34.0
J8	1634	267	24.5	37.6
J9	1731	327	30.0	40.0

Table 2 demonstrates that when the velocity is above 1300 m/s, the SiC CPA has an increasingly favorable performance over RHA. When the penetration is adjusted for the fact that SiC is less than one tenth the density of RHA, the density adjusted penetration of a 20 mm steel FSP at 1600 m/s is 24.5 mm versus an RHA equivalence of 37.6 mm. This corresponds to a 35% reduction in weight versus solid RHA. Table 2 does not consider the fact that with a high tensile composite liner backing the CPA, it is likely that the thickness could be dramatically reduced, which would result in an even more favorable weight reduction.

5. Practical Implementation

It was observed in the first shot from the Fragmentation/EFP testing that a great deal of energy is exerted outwards on the walls of the box. Another observation was that CPA tends to flow out of any large holes, especially if a fine grit size is used. This knowledge is critical to designing a practical armor solution. The design of the CPA box is very important to the CPAs multi hit capability.

The most basic implementation of CPA would be to attach boxes to the sides of a vehicle and fill them with SiC. This solution would lend itself well to replacement of existing kits and in many cases could be a drop-in solution that would save weight and cost. Hardened steel armor and ceramic plates have always been extremely difficult to implement around a vehicle.

This design could be improved by including a thin high strength strike face to deflect the most common small arms threats and the majority of explosive fragments. The box could be lined with rubber or even constructed from a flexible thermoplastic resin composite to reduce the size of entry holes. Further improvement in multi-hit and stopping capability could be obtained by placing the CPA within a fiber mesh to limit flow after a hit and provide additional resistance to pieces of the projectile that have already been slowed by the CPA. The final layer should be a high tensile woven composite sheet utilizing fibers with high strength and relatively low modulus. S2 glass fibers or the polyethylene fibers used in Dyneema would be ideal. This final layer serves to catch the penetrator or any remaining fragments once the CPA has disintegrated the main part of the penetrator. In the event of an overmatch, the high tensile composite layer will serve as a spall liner to catch the smaller fragments and limit the damage that would be caused on the inside of the vehicle.

6. Conclusion and Recommendations

This report demonstrates the potential for Ceramic Particle Armor (CPA) to replace metal, composites, or ceramics in armor applications that are intended to protect against very high velocity impacts such as those resulting from EFPs. The benefits of CPA that have been demonstrated are its low density, low cost, and penetration mechanics that result in a reduction of penetration depth with increasing velocity. These benefits are exactly what are required to protect combat vehicles from common threats that currently cause so much damage and loss of life.

Current and Future applications

The first application of CPA should be as EFP protection on vehicles that are already in combat areas and currently carry heavier EFP solutions. Once CPA EFP solutions are developed, they can be easily substituted for the EFP solutions that are currently carried in side boxes on Mine Resistant Ambush Protected (MRAP) vehicles and other combat vehicles. The next application would be to produce CPA EFP kits for vehicles that could not previously carry EFP protection due to the weight. This would include High Mobility Multipurpose Wheeled Vehicles (HMMWV) and other light combat vehicles. CPA should also be investigated for EFP protection on the roofs of armored vehicles, such as tanks and Armored Personnel Carriers (APC). These vehicles do not have EFP protection on the roofs due to the difficulty of putting such extreme weight so high on the vehicle,

and the fact that, generally, EFPs that are a threat to the roof are only fielded by militaries with sophisticated weaponry.

Next Steps

This project demonstrated the potential of CPA but stopped short of providing a definitive quantified improvement over existing EFP solutions. What remains is to optimize CPA in an armor solution designed to stop a specific threat and to provide a design for implementation onto existing combat vehicles. Further testing using higher velocity impacts and actual EFPs, while concurrently testing existing EFP solutions, should be the next step in evaluating CPA. Once further testing has precisely established the benefit of CPA and optimized an EFP solution, the final step is to develop armor kits for specific combat vehicle.

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