Technical Progress Report

Contract: DE-FC26-01NT41059

Reduced Energy Consumption Through Projectile Based Excavation

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APTI

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COR: Mr. Mike Mosser

1. Progress to date.

During the third quarter of this effort, several activities continued from last quarter and new tasks have begun. They include the following.

1.1. Equipment acquisition.

1.1.1. The 60 mm gun cartridge cases (25 each) have been ordered from IMI and should be shipped during the coming quarter. Events of September 11 have slowed action on this task and several others. We expect, however, that the cartridge cases will be received as promised by IMI.

1.1.2. Until the electric launch system is developed in Phase II, APTI will operate the 60 mm gun using conventional propellant and primers. Mark 42 primers for the IMI shell casings have been located in US Navy stocks. These primers are no longer used by the Navy, but are the ones specified for the IMI 60 mm cartridge cases. APTI is working with the Navy personnel at the Navy Ammunition Logistics Center, Crane, IN in an attempt to get 100 of these primers released. (POCs: Mr. Tom Olsen, NALC, Mechanicsburg, PA, 717-605-3424 and Mr. Henry Wong, Crane NWSC, 812-854-5243).

1.1.3. Lubricants for the 60 mm have been identified and are on hand or in the process of being special ordered.

1.2. Scaled experiments to determine the relative effectiveness of different projectile designs have continued using a 21 mm gun on hand at APTI. These experiments include the use of three different cement/concrete mixes with several different metal additives.

Experimental Apparatus – A 21 mm smooth bore gun is being used for the scaled experiments. The gun is mounted vertically and fired downward at the target. The muzzle is approximately 6” from the target face. This apparatus, shown in last quarter’s report, is able to achieve a muzzle velocity of approximately 2800 fps for projectiles that weigh ~ 55 grams.

Targets being used are primarily Indiana limestone cubes (estimated strength of 8,000 psi unconfined compressive strength) that measure approximately 18" on a side. The targets are set in a target box consisting of a steel shell lined with plywood to reduce fly rock. Two shots have also been taken into Frederick limestone (estimated strength of 20,000 psi unconfined compressive strength) to measure relative effectiveness.

Projectiles fabricated of different combinations of grout/cement and concrete with different arrangements of steel fiber, synthetic fiber and small steel spheres are being tested. Some projectiles have been tipped with a **solid**, mild steel nose cone, while others have been tipped with a **hollow** mild steel nose cone. Typical projectile specifications are given in Table 1-1. A comparison of the projectiles with and without conical steel nose can be seen in Figure 1.1. The difference in length accounts for the density difference between steel and concrete while keeping the total projectile weight unchanged.

Table 1-1. Typical Scaled Experiment Test Projectile Specifications

Length	~ 8.3 cm
Diameter	~ 2.1 cm
Weight (total)	~ 56 gm
Weight (sabot)	~ 12 gm
Weight (projectile)	~ 44 gm
Sabot thickness	~ 0.2 cm (PVC)
Steel fiber (when used)	~ 1.4 gm (15 fibers)
Grout	6,000 – 8,000 psi unconfined compressive strength
Concrete	4,000 psi unconfined compressive strength

It is envisioned that hard aggregate (e.g. taconite) will be used in the nose of the full size projectiles. Because of the smaller diameter of the scaled experiments, steel BBs have been used in the place of the hard stone. Mild steel has a yield strength of ~ 40ksi, approximately equal to the unconfined compressive strength of taconite.

The different projectile architectures are as described in Table 1-2 below.

Table 1-2. Projectile reinforcement architectures.

Strengthening Agent	Layout 1	2	3
Synthetic fiber	Even distribution	-	-
Steel fiber	Even distribution	Front heavy	Rear heavy
Steel BBs	Grouped, front	Single center line	Axially distributed groups
Steel nose cone	Solid	Hollow	-

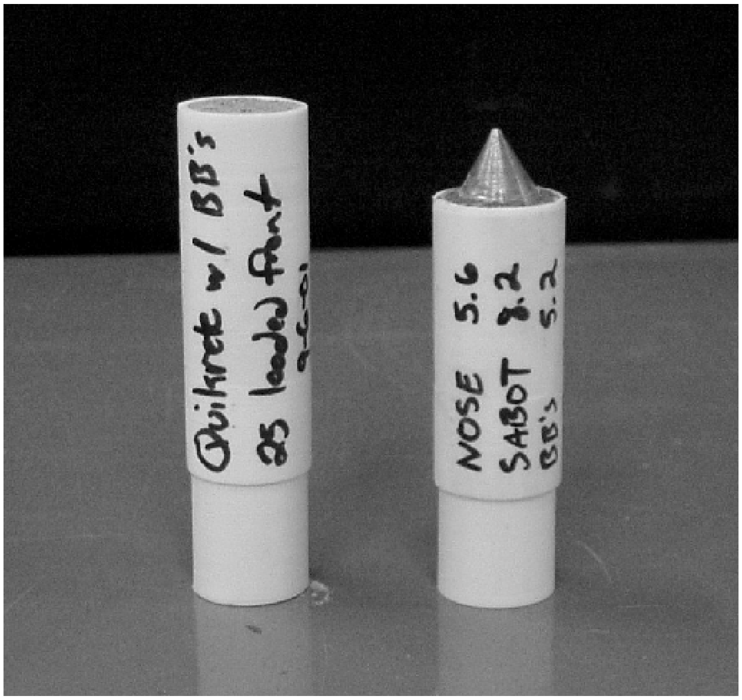

Figure 1.1. Typical reinforced grout projectiles showing PVC sabots and adjustment in length made to compensate for weight of steel cone tip of projectile on right.

Experimental Data – A total of 53 experimental shots have been taken to date. Of these, 51 have been taken in Indiana Limestone (~ 8 ksi uniaxial unconfined compressive strength) and 2 into Frederick limestone (~20 ksi uniaxial unconfined compressive strength). The results of these experiments are summarized in Table 1-3 below.

The cells in Table 1-3 marked with "XXXX" are architecture/matrix combinations not yet fired. In cases where experiments show that a particular component is non-competitive, to save resources, further shots with that component may not be taken. An example of this is the GEMITE projectile matrix. Experiments to date suggest that it is not competitive with the Non-shrink Precision Grout or the Quickrete Fiber Reinforced Concrete, therefore, depending on target availability, a full matrix using GEMITE may not be fired.

Projectiles were prepared with no reinforcement, that is, grout or concrete only and with reinforcement. Reinforcement consisted of NOVOCON Steel Fiber, a cold drawn wire flared at both ends, commonly used in the construction industry, steel BBs and mild steel nose cones. The synthetic reinforcement present on some of the Quikrete products was not considered to have any positive effect and was therefore ignored in the analysis.

It was intended to use small size, strong aggregate such as taconite gravel to improve the performance of the concrete, or grout projectiles. These aggregate are found to have a uniaxial unconfined compressive strength in the neighborhood of 40,000 psi. Mild steel has a yield strength of approximately 40,000 psi. It was felt, therefore, that due to the smaller diameter of the scaled experiment projectiles, the higher density (and therefore smaller diameter) steel BBs could be used to project the relative performance of an aggregate filled projectile design. It appears, however, the mild steel reinforcement may be used to improve performance as well as strong crushed rock.

While the synthetic and steel fiber, used for concrete reinforcement in the construction industry, improve compressive strength, they do not appear to have a positive effect in this application. Following the shots, the steel fiber is difficult to find, except by use of a magnet. The fiber fails with the concrete and grout into small fragments and does not appear to contribute to the performance of the projectiles.

In the case of projectiles reinforced with BBs and nose cones, the steel, with the exception of the solid nose cones, also fragments into small pieces. Many of the BBs survive, but many are deformed or crushed into unrecognizable steel fragments. The hollow steel nose cones were also fragmented into such small pieces as to be unrecognizable and found only with the assistance of a magnet. Figure 1.2 shows a hollow nose cone before a shot and the remains after a shot into the 20,000 psi limestone target.

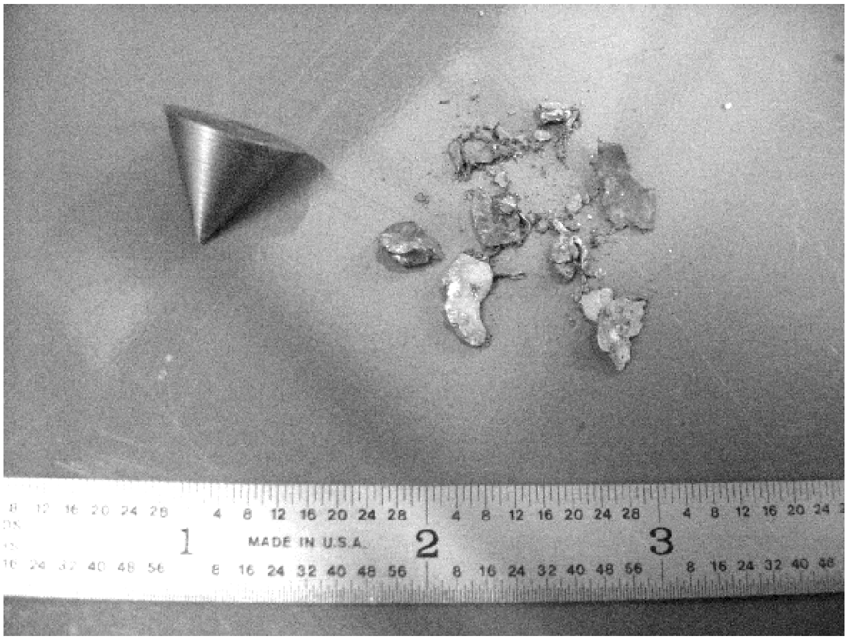

Figure 1.2. Hollow, mild steel nose cones break apart into small fragments when used to engage hard rock.

Solid, mild steel nose cones survived shots into 8,000 psi Indiana Limestone, but were crushed on impact into the harder Frederick Limestone (20,000 psi). Past experience with steel projectiles tells us, however, that with proper heat treatment, the nose cones would also survive impact into the harder limestone.

For mining purposes, it would seem that the ideal reinforcement would be one that fragments into small pieces during the engagement. Such reinforcement would not pose a problem for later crushing steps and probably not in any further processing of the ore. If necessary, they could also be removed by magnets along the ore processing path.

Table 1-3. Different projectile architectures yield different performance. Figures indicate average nominal crater volume, in cubic inches, for all shots taken for a given architecture.

Projectile Architecture	**Non-shrink Precision Grout**	**GEMITE**	**QUIKRETE Fiber Reinforced Concrete**
No reinforcement	2.4347	1.1451	3.4168
15 Steel Fibers, even distribution	1.6905	2.1906	2.0375
15 Steel Fibers loaded heavier in front, 2/3-1/3	2.7684	0.4712	3.085
30 Steel Fibers even distribution	XXXX	XXXX	2.7732
15 Steel Fibers, loaded front only	2.0445	XXXX	XXXX
17 BBs in straight line (Lexan tube)	8.103	XXXX	3.2981
25 BBs clustered in front	4.1971	XXXX	1.7936
25 BBs clustered in 5 equal segments	XXXX	XXXX	5.6985
Solid steel nose cone w/ 15 BBs behind it	46.2762	XXXX	XXXX
Hollow steel nose cone w/ 15 steel BBs	10.2934	XXXX	xxxx

In Figure 1.3, one can see the effect of a cluster of 25 BBs at the front of a concrete projectile. While the shots were placed a little closer together than desired, their effects were measurable. The craters caused by these shots were not as large as those produced by other architectures, however, they did achieve significant cracking and the target broke in half when an attempt was made to move it. This is significant and shows that crater size is not necessarily the most important result. If the energy applied to the target is used in cracking, the result may be more valuable than large amounts of surface spall.

Shots 40 and 41, shown in Figure 1.4 demonstrate the performance of the same number of BBs as were used in shots 49 and 50, but when placed in a configuration where 5 clumps of 5 BBs each were arranged axially up the center of the projectile. Notice that the crater size increased significantly, suggesting the effect similar to segmented impactors. This same arrangement will be fired in the Non-Shrink Precision Grout to see if the higher grout strength produces better performance with this configuration as it did when the BBs were clustered up front.

Another configuration that shows great promise is a column of 17 BBs held in a line down the center of the projectile by a thin Lexan tube. Figure 1.5 shows the results of such an arrangement (Shots 46, 47 and 48). This configuration produced better performance than the other BB alone configurations in both grout and concrete. Performance was especially good in the grout, suggesting that the strength of the grout adds to the penetration of the steel reinforcement even though the grout alone does not perform particularly well.

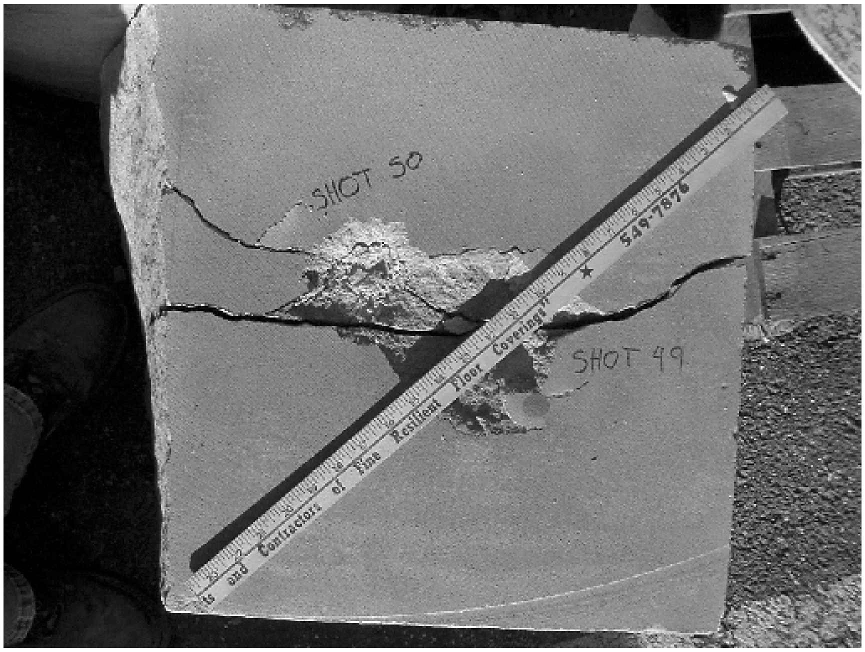

Figure 1.3. Shots 49 and 50 show effect of 25 BBs (~9 gm) clustered at front of a Quikrete Fiber Reinforced concrete projectile. Target broke in half when moved.

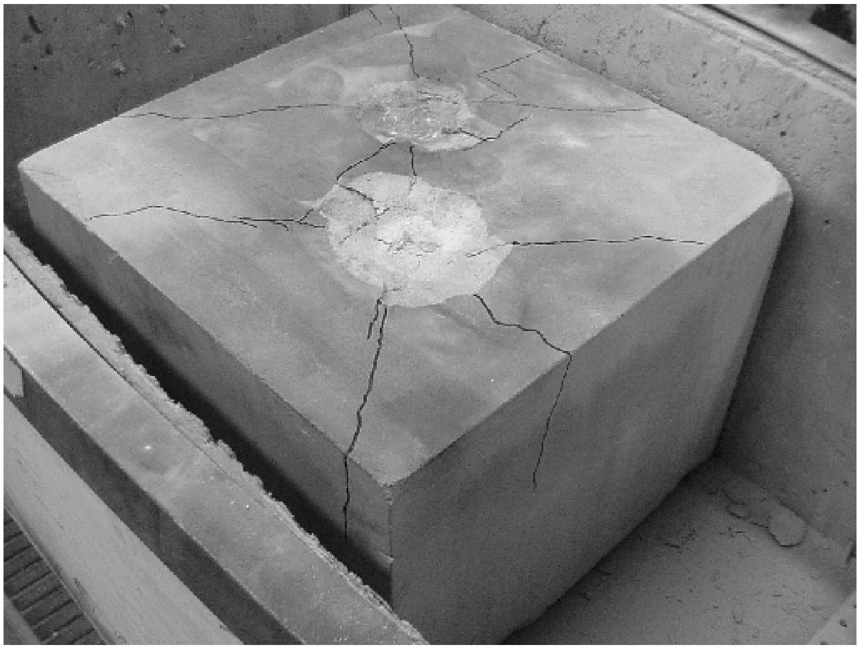

Figure 1.4. Shots 40 and 41 show the effect of 25 BBs (~9 gm) arranged in 5 clusters distributed axially within Quikrete Fiber Reinforced concrete projectile

Figure 1.5 Shots 46 and 47 show the effect of a column of 17 BBs (~6gm) aligned axially down the center of the Quikrete Fiber Reinforced concrete projectile. BBs are kept aligned by a thin Lexan sleeve.

The addition of mild steel nose cones have another step improvement in performance. Two types of nose cones were tested, solid noses, weighing approximately 10 gm, and hollow nose cones weighing approximately 5 gm. In both cases, the nose cones were backed by a cluster of 15 BBs (approximately 5.5 gm). The length of the projectiles was adjusted downward to compensate for the heavier steel (so that the total round weight would not exceed our gun limit of ~ 55 gm).

Figure 1.6 shows the results of two hollow nose shots (Shots 50 and 51. More significant than the craters formed by the shots is the extensive cracking of the target. This target fell apart after these two shots when an attempt was made to move it. In both cases, the nose cone was completely fragmented by the interaction with the rock. This suggests that such an approach (hollow, mild steel nose) could be used without concern for crushing equipment down stream in the ore processing.

Figure 1.7 gives the results of one of the solid nose cone shots, Shot 38. In this case the nose cone was backed by 15 BBs (5.5 gm) and the nose cone weighed 10 gm. Three of these shots were taken. In the cases where Indiana Limestone (8,000 psi) targets were engaged, the 16 inch cube target was destroyed with a single shot. In both of these shots, the nose cone survived with little noticeable damage – indicating that there is potential to reuse the nose cones if recovered by magnet somewhere in the ore processing chain. In the case of the third shot, the target selected was a Frederick Limestone rock from a local quarry (16” x 25” x 9”). The shot created a small crater, but significant cracking. In this case, the solid nose cone survived, but was smashed flat and could not be reused.

Figure 1.6. Shots 51 and 52 show effect of placing a 5 gm hollow steel cone at nose of Non-Shrink Grout projectile with 15 BBs (5.5 gm) behind nose cone.

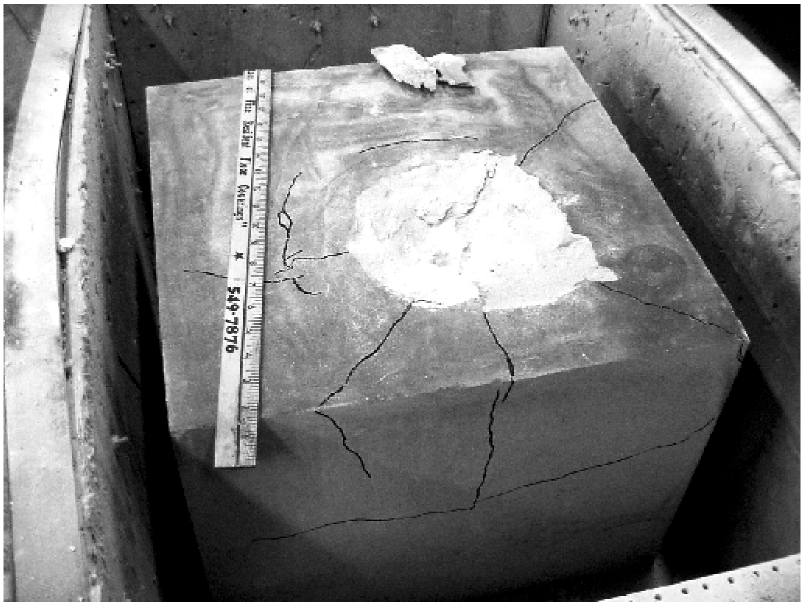

Figure 1.7. Shot 38 shows effect of 10 gm solid steel nose cone backed by 15 BBs (5.5 gm).

A second shot was taken into the Frederick Limestone target using a **hollow** nosed projectile. The results are shown in Figure 1.8 below. It can be seen that the rock was broken and severely cracked by the two shots. These results suggest that the addition of only a few grams of steel or other strong reinforcement can make concrete, or grout projectiles effective against even some of the hardest ores.

Additional experiments using mild steel nose cones are planned. The projectiles to be used will be made of the Quikrete Fiber Reinforced Concrete to compare the performance of the concrete with that of similar projectiles made of grout. Because of a shortage of Indiana Limestone targets, marble targets, roughly comparable to the Frederick Limestone in strength, will be used.

Figure 1.8. Shot 53, 25" x 17" Frederick Limestone (~20 kpsi) following two shots with steel nose cone projectiles, first with solid nose cone, second with hollow nose cone, both backed with 15 BBs.

Data Reduction – This series of scaled experiments continues to reveal potential projectile designs that promise to be cost effective. Although the experiment series is not yet complete, a review of the shot matrix presented in Table 1-3 shows that the Quikrete Fiber Reinforced concrete (4,000 psi unconfined compressive strength) yields better performance when used as manufactured. The steel fiber does not appear to add to the performance of the grout or concrete when shock loaded, probably because of its light weight and tendency to fail upon impact, allowing the concrete to fragment as if there were no reinforcement.

When other reinforcement such as steel BBs or mild steel nose cones are applied, however, we see that the Non-Shrink Precision Grout (6,888 – 8,000 psi unconfined compressive strength) yields better performance. This is attributed to the stronger grout holding together longer after impact, producing better penetration by the steel reinforcement at the nose of the projectile. Further testing will be conducted to see if this suggestion holds true.

Hypothesis and Conclusions – The hypothesis to be tested is that the addition of steel or other synthetic fiber and/or high strength, low cost aggregate to strong grouts or concrete will result in a projectile of sufficient strength to produce cracking and spall enough to make its use cost effective for mining.

Based on experiments conducted to date, no conclusions can yet be reached. Results of the experiments conducted suggest that reinforcement of a concrete projectile can yield performance that portends cost effective projectile based excavation. It is recognized that the projectile is but one component of the matrix. The electric launch system to be developed in the next phase of the program is the other factor that weighs heavily in the cost effectiveness equation. At this point, however, emerging low cost options for the projectile are very promising.

2. Problems encountered. The current world situation in view of the September 11 attacks appears to have slowed progress in the acquisition of the cartridge cases and primers for the 60 mm gun. It is hoped that these items will arrive in time for experiments in the coming quarter.

3. Plans for next reporting period. During the coming report period, plans call for the following.

- Renovation of the 60 mm gun system and conversion to a powder gun configuration.
- Acquisition of 60 mm cartridge cases from IMI.
- Acquisition of the Mark 42 primers for the 60 mm cartridges.
- Design of firing mechanism for the powder version of the 60 mm gun system.
- Continued exploration of candidate projectile designs and candidate projectile materials using scaled experiments within APTI’s Alexandria, VA laboratory.

4. Prospects for future progress. It is anticipated that program momentum will pick up in the coming report period with the arrival of the needed 60 mm gun system equipment. It will continue to build with the quarry experiments. At this point, prospects for future progress are excellent.