Reduced Energy Consumption Through Projectile Based Excavation

Final Technical Progress Report

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Abstract.

The Projectile Based Excavation (ProjEX) program has as its goal, the reduction of energy required for production mining and secondary breakage through the use of a projectile based excavation system. It depends on the development of a low cost family of projectiles that will penetrate and break up different types of ore/rock and a low cost electric launch system. The electric launch system will eliminate the need for high cost propellant considered for similar concepts in the past. This document reports on the program findings through the first two phases. It presents projectile design and experiment data and the preliminary design for electric launch system. Advanced Power Technologies, Inc., now BAE SYSTEMS Advanced Technologies, Inc., was forced to withdraw from the program with the loss of one of our principal mining partners, however, the experiments conducted suggest that the approach is feasible and can be made cost effective.

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<u>**Technical Progress Report**</u>

Contract: DE-FC26-01NT41059

**Reduced Energy Consumption Through
Projectile Based Excavation**

COR: Mr. Mike Mosser

1. Progress to Date - Executive Summary

The ProjEX program was designed to take advantage of advances in materials science and combine new, low cost projectiles with a low cost electric launch system to improve the efficiency and safety of mining operations. It can improve efficiency by reducing the amount of energy expended per ton of ore. It improves safety by eliminating the explosives, currently used for drill and blast operations, from the mine.

While experimental equipment for field experiments was acquired, preparatory laboratory experiments were conducted. These experiments investigated low cost projectile designs and means to reduce the acoustic signature of the launcher to conform with MSHA standards. Team partners, Lafarge Corporation and Baker Hughes were to provide support for the field experiments and consultation during the experiment program and cost analyses respectively. The Lafarge team performed perfectly, however, the withdrawal of Baker Hughes after a management change is the cause of the program cessation.

At the conclusion of the program, a low cost projectile design has been developed and tested. The electric launch concept had matured through preliminary design that included modeling and scaling of component requirements.

2. Experimental Apparatus.

Laboratory Experiments.

Scaled laboratory experiments were conducted while field experiment equipment was assembled. These scaled experiments served as the basis for larger projectile designs tested in the field experiment campaigns.

Experimental Apparatus.

A 21 mm Remington Kiln gun is being used for the scaled experiments. Projectiles containing different combinations of grout/cement and concrete with different arrangements of steel fiber, synthetic fiber, aggregate and two different type nose cones were tested (Figure 2.1). Targets were mostly Indiana limestone cubes that measure approximately 18” on a side. The muzzle was placed approximately 6” from the target face. The apparatus is able to achieve a muzzle velocity of approximately 2800 fps for projectiles that weigh ~ 55 grams.

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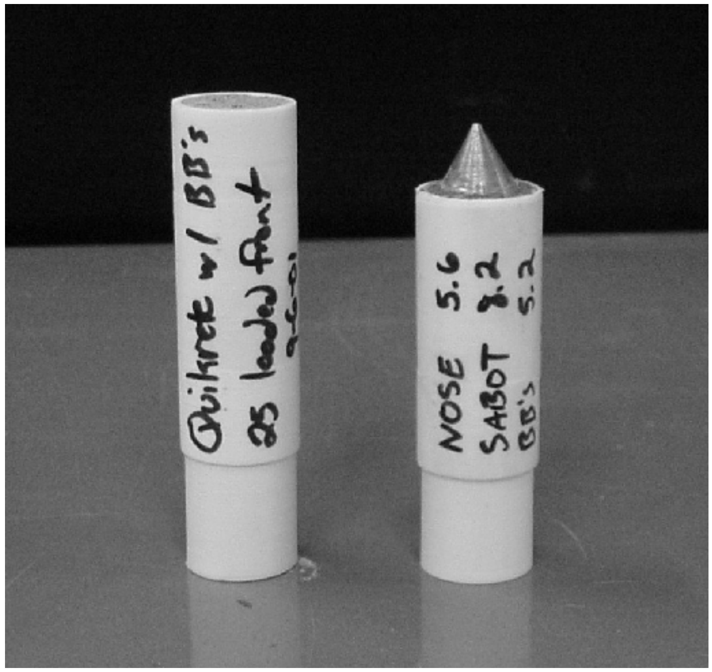

Figure 2.1. Typical scaled projectiles used in laboratory experiments

A review of the shot matrix suggests that the Quikrete Fiber Reinforced concrete (4,000 psi unconfined uniaxial compressive strength) yields the best performance when the projectiles are tipped with a steel nose cone, especially a solid steel nose cone. We attribute this to the aggregate in the concrete. That is, the steel noses probably produce the same penetration with the Quickrete and the Non-Shrink Precision (NSP) Grout; however, as the projectile penetrates into the target it also begins to fail. It is here that we believe that the aggregate in the Quickrete provides the greater work on, and therefore greater excavation of, the target than the NSP Grout projectiles reinforced with BBs alone. The NSP Grout projectiles essentially turn to dust when the projectile fails following impact and the initial penetration.

Field Experiments

Field experiments were commenced as soon as all required equipment was on hand. They were conducted in the Lafarge Frederick Quarry, an open pit limestone mine. They included the testing of projectiles constructed of concrete and grout with several different architectures similar to the scaled projectiles tested in the laboratory experiments.

Experimental Apparatus.

The projectiles tested weighed from 1.3 kg to 2 kg. They were launched using a 60 mm IMI antitank gun fired from a range of ~ 5 m from the mine face. Figure 2.1 shows the field test setup. Pressure probe readings were used to determine chamber pressure and projectile velocity. A Lica Total Station, TCR 703, was used during most of the field experiment campaign to measure productivity of the different projectile designs.

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Field experiments were conducted using a 60mm launcher obtained through Army Research Laboratory. Initial firing showed that a muffler was required to bring the acoustic signature to within the MSHA limit. Two different mufflers were fabricated. While both brought the system into compliance with MSHA requirements, the overpressure of the muzzle blast caused failure of the tire design and necessitated the fabrication of the drum design shown in Figure 2.1.

Figure 2.1. A 60 mm launcher was used for the Field Experiments with a drum muffler, shown here, following the failure of the tire muffler.

The 60 mm launcher was modified from it's Electrothermal configuration to a Powder Gun configuration by fabricating the necessary breech components as shown in Figure 2.2. Figure 2.3 shows the IMI shell casings that were used to hold the propellant charge and the US Navy primer used to initiate the propellant.

Pressure data from the launcher chamber has been measured using PCB Piezotronics model 109A02 pressure probes with PCB Piezotronics model 480C02 Pressure Probe Power Supplies. The pressure probes are placed forward of the chambrage and ~ 5" apart and record the pressure as the projectile travels past them. Knowing the characteristics of the propellant being used (New River Energetics, 7 perf, M14 propellant with 1 mm web), these pressure readings have been used to verify the ballistics model being used to characterize the launcher operation. The velocity measurements taken with the velocimeter have been compared with the velocities predicted by the model and found to be in good agreement. For example, Shot 4/19/02/01 had a predicted velocity of 1054 m/s. The measured velocity was 870 m/s. Shot 6/4/02/01 had a predicted velocity of 1327 m/s and a measured velocity of 1294 m/s.

Projectiles for the early 60 mm experiments were fabricated using PVC sabots. Some were designed without metallic nose cone, while others included hollow 1/8" and ¼" thick nose cones (Figure 2.4). No solid nose cones were made for the 60 mm projectiles. They were fabricated with and without hard (Taconite) aggregate to enhance penetration.

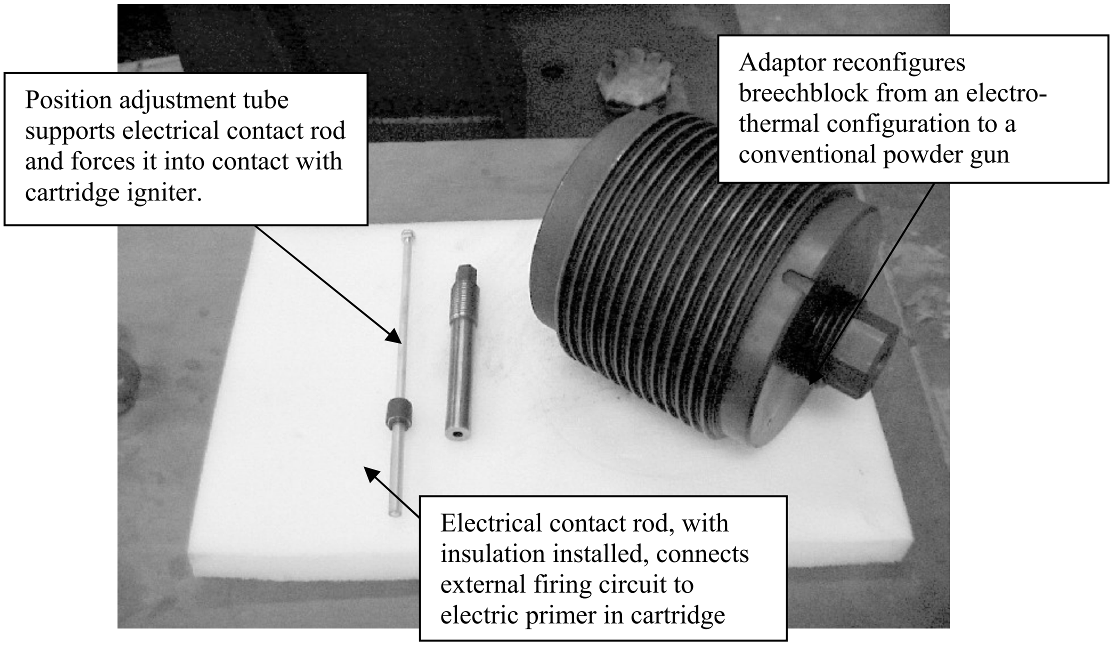

Figure 2.2. Modification of 60 mm launcher breech was necessary to convert it from an electrothermal gun to a conventional powder gun.

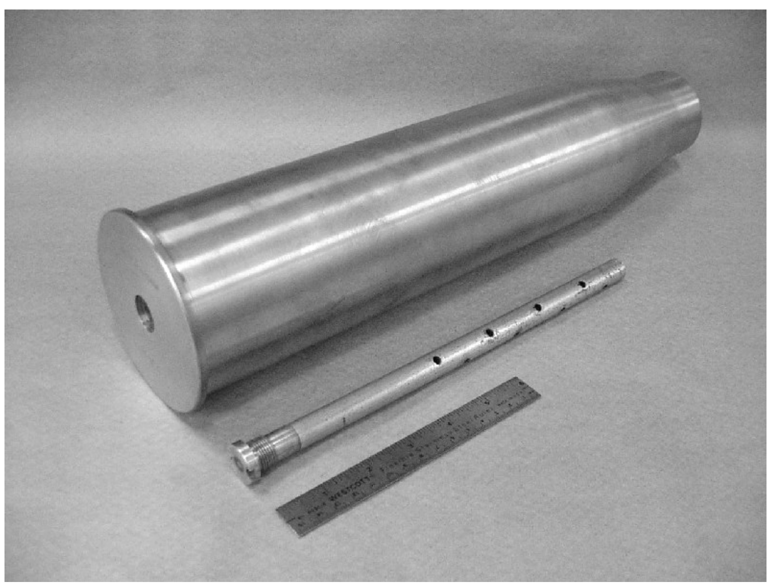

Figure 2.3. 60 mm cartridge case was acquired from IMI, while the Mark 42-2 primer was acquired from the US Navy. APTI fabricated a brass adaptor to make them compatible.

It was determined that these projectiles failed during launch as the velocity of the projectiles was increased above 1000 m/sec. Therefore, the design was modified to encase the concrete/grout within thin mild steel cases (Figure 2.5). These cases were designed to bear the load applied

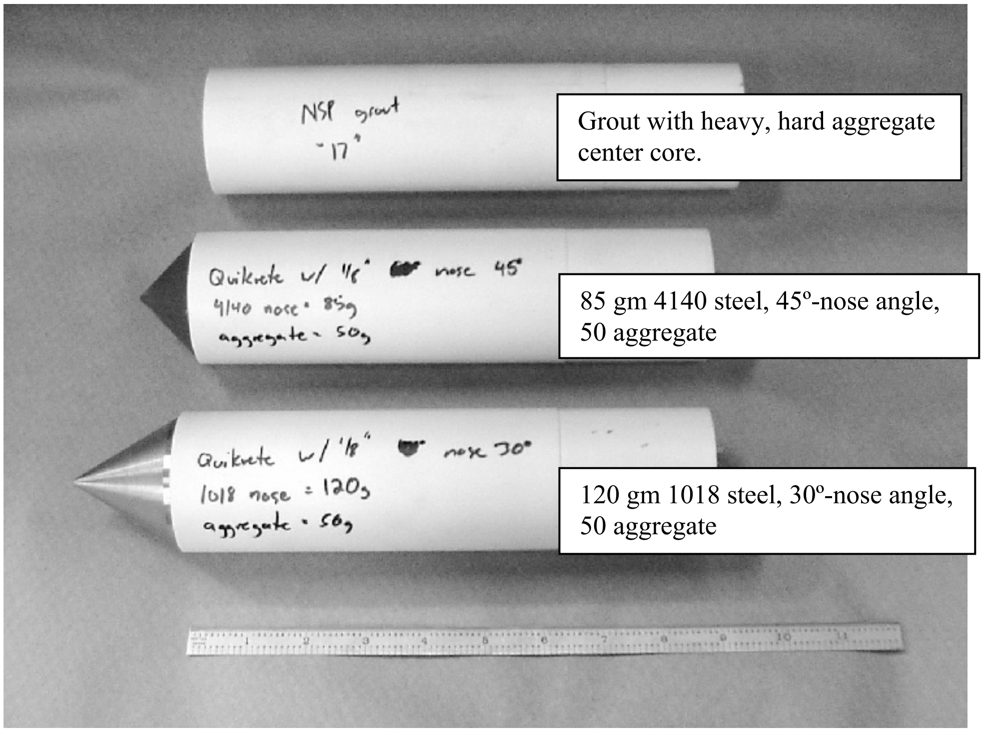

Figure 2.4. Three different 60 mm projectiles. At the top is an NSP grout projectile with <u>no</u> metallic nose cone. In the center is a Quickrete projectile with a 45º half-angle nose cone of 4140 steel, heat-treated to RC 42. At the bottom is a Quickrete projectile with a 30º half angle nose cone of 1016 steel. (all ~ 1400 gm)

during acceleration, but to fragment into small pieces during impact and penetration. In Figure 2.5, sketches of the projectiles tested appear on the left, while a photo of a fully assembled round appears on the right. These rounds proved robust enough to survive the launch to a velocity of ~ 1.4 km/sec and are designed in a way that will allow low cost manufacturing.

While craters developed in laboratory experiments in homogenous rock were essentially regular and symmetric, those created in the field are anything but regular. This is due to the irregular faults that occur in the natural rock (Figure 2.6). Therefore, craters created during field testing were measured using a Lica Total Station which was provided In-Kind by the University of Utah. It is shown in Figure 2.7 with an APTI laptop that was used for data recording and analysis.

3. Experimental and Operating Data.

Laboratory Experiment Program. Table 3.1 presents a compilation of the date collected from a total of 93 laboratory shots. It presents the mean nominal cone volume produced by the several different projectile designs. Where early tests showed that the material or design was not competitive, the tests were suspended in the interest of saving resources and the appropriate box shows, “XXXX”.

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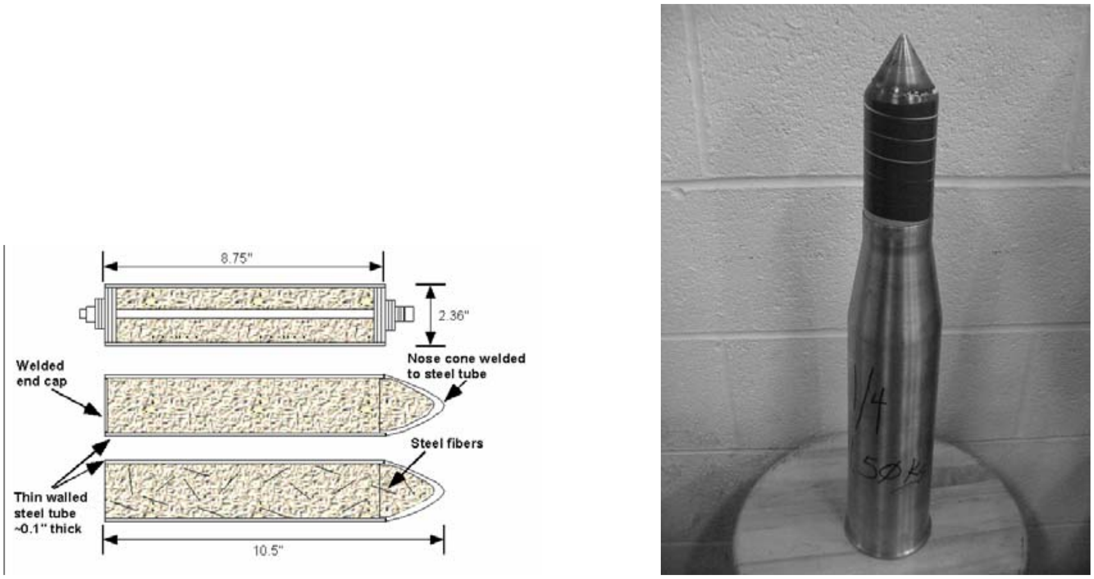

Figure 2.5. Steel encased rounds survived high acceleration forces during launch. Sketches of the rounds tested appear on the left, while a fully assembled 60 mm round, ready to fire, is shown on the right.

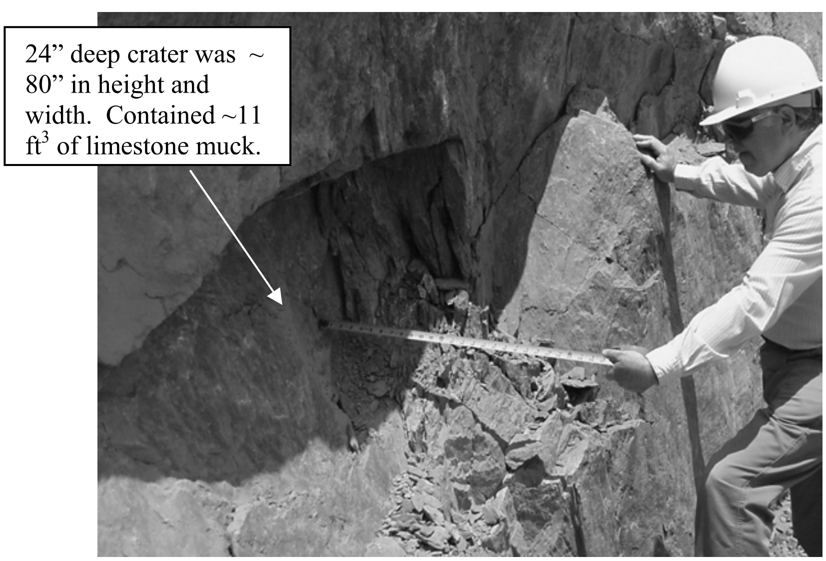

Figure 2.6. Shot # 7 from 6/20/02 campaign, ~ 11 cubic foot crater. Achieved with concrete projectile traveling at ~ 1.3 km/s, even though projectile broke apart before impact.

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Figure 2.7. A Leica Total Station TCR 703, shown on tripod with APTI laptop computer connected for data download, was used to record the size of craters generated during field experiments.

Table 3-1. Average cone crater volume resulting from different projectile designs/materials

AVERAGE CRATER CONE VOLUME FOR EACH DESIGN

	NON-SHRINK PRECION GROUT (6-8,000 psi)	GEMITE	QUIKRETE FIBER REINFORCED CONCRETE (4,000 psi)
NO FIBER 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 BB'S IN STRAIGHT LINE WITH LEXAN	8.103	XXXX	3.2981
25 BB'S CLUSTERED IN FRONT	4.1971	XXXX	1.7936
25 BB'S CLUSTERED IN 5 EQUAL SEGMENTS	2.7423	XXXX	5.6985
SOLID STEEL NOSE CONE W/ 15 BB'S BEHIND IT	46.2762	XXXX	XXXX
HOLLOW STEEL NOSE CONE W/ 15 STEEL BB'S	10.2934	XXXX	xxxx

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MARBLE TARGET

SOLID STEEL NOSE CONE W/15 BB'S BEHIND IT	4.3243	XXXX	5.4486
HOLLOW STEEL NOSE CONE W/ 15 STEEL BB'S	2.7892	XXXX	2.8511

GRANITE TARGET

SOLID STEEL NOSE CONE W/15 BB'S BEHIND IT	2.7756	XXXX	3.2935
HOLLOW STEEL NOSE CONE W/ 15 STEEL BB'S	0.7958	XXXX	0.7089
17 BB'S IN STRAIGHT LINE WITH LEXAN	0.0335	XXXX	0.0619
25 BB'S CLUSTERED IN FRONT	0.5234	XXXX	0.1587
25 BB'S CLUSTERED IN 5 EQUAL SEGMENTS	0.1105	XXXX	0.0687

Field Experiment Program. Twelve field experiments were conducted during the period April 2002 through December 2002. They were organized in four experiment campaigns which produced mixed results. Presented in Table 3-2 is a compilation of the field experiment data. The 60mm projectile performance indicates that an encased round performs to a level that suggests commercial exploitation is feasible, provided the electric launch system can be made robust enough to provide for approximately 2000 shots between component replacement and maintenance (6 shots/minute for 6 hours).

The field test program was conducted in the Lafarge Frederick Quarry. Projectile weights tested ranged from 1.3 kg to 2 kg. Velocities varied from 870 m/s to 1440 m/s and chamber pressures varied from 17,000 psi during system checkout to ~ 50,000 psi. It was determined that as velocity increased, it became more difficult to maintain the integrity of the projectile. At muzzle velocities approaching 1.3 km/s, it was determined that the projectile concrete was being crushed by the forces exerted on it during acceleration. It was necessary, therefore, to encase the concrete projectiles in a thin mild steel case. This modification produced successful launches at velocities of ~1400 m/s. Volumetric data for muck produced is presented only for Shots 9 – 12 in Table 3-2. The reason for this is that in the high velocity shots that preceded Shot 9, the projectile failed during launch. These shots produced spoil, as shown in Figure 2.6, but are not considered to be reliable data points because of the projectile failure.

The information contained in Table 3-2 is the basis for confidence that a cost effective projectile can be developed that will produce commercially interesting quantities of ore. In this short program, we were able to achieve nearly half of the 1 m^3 per shot goal. Clearly, this amount could be improved with continued research and experimentation.

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Table 3-2. Field Experiment Data FOR 60mm Launcher.

QUARRY SHOT RECORD

	Projectile Weight	Powder Charge	Projected Velocity/Actual	Projected Pressure/Actual	Production
SHOT 1	1.4Kg	1.0Kg	1054m/s - 870m/s	17,300 psi - UNK	
SHOT 2	1.4Kg	1.2Kg	1167m/s - UNK	22,700psi - UNK	
SHOT 3	1308.9g	1.2K	1167m/s - UNK	22,700psi - UNK	
SHOT 4	1394.2g	1.3K	1222m/s - UNK	25,500psi - UNK	
SHOT 5	1.4Kg	1.5Kg	1327m/s - 1294m/s	31,500psi - 31,586psi	
SHOT 6	1.4Kg	1.6Kg	1305m/s - UNK	34,900psi - 37,500psi	
SHOT 7	1910.1g	1.5Kg	1327m/s - UNK	39,218psi - 42,204psi	
SHOT 8	1900.4g	1.6Kg	1305m/s - UNK	43,620psi - 49,193psi	
SHOT 9	1885.1g	1.6Kg	1305m/s - UNK	43,620psi - UNK	
SHOT 10	2.010kg	1.5 kg	1298 m/s - 1222 m/s	45,820psi -- UNK	1.9m3
SHOT 11	1.620 kg	1.65kg	1439m/s - UNK	46,313psi - UNK	2.9m3
SHOT 12	1.818kg	1.60kg	1380m/s - UNK	47,560psi - UNK	2.4m3

Electrical Launch System Design

ATI conducted the necessary analyses to perform a preliminary design of the electric launch system. The withdrawal of one of the principle mining partners, however, prevented the planned fabrication of the prototype electric power system for the launcher.

ATI proposed the use of a classical electrothermal gun layout (Figure 3.1) to demonstrate one means of launching projectiles at low cost. In this layout, an enlarged diameter, water filled gun chamber couples to a barrel containing the projectile. An electrically insulating, small diameter tube couples to the breech end of the chamber. A plug electrode (high voltage insulated) blocks the outer end of the tube and a ring electrode (grounded) encircles the entrance of the tube into the chamber. The entire electrode/tube structure is typically referred to as a capillary. Since it must contain high pressures, a capillary is typically constructed by inserting a polycarbonate liner in an alloy steel tube and using epoxy glass laminates to support and insulate the plug electrode. A capacitor discharge circuit connects to the electrodes.

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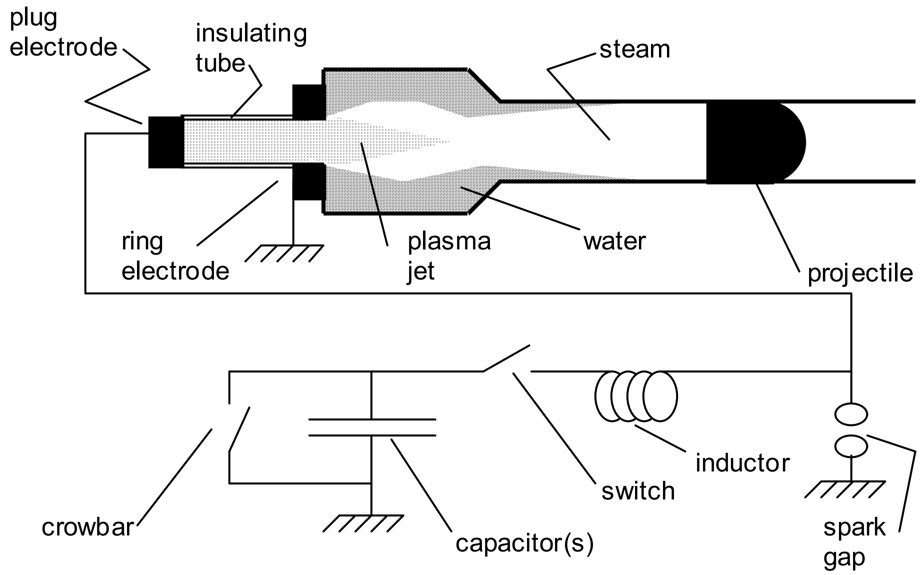

Figure 3.1. Electric launch architecture shows simplicity of design prodending low operating/maintenance costs.

When ready to fire, the capacitor is charged to high voltage, storing all the energy needed to propel the projectile. The projectile is positioned at the chamber end of the barrel. Water fills (or mostly fills) the chamber. The capillary is empty except for a metal fuse connecting the plug and ring electrodes. Closing the switch causes the fuse to explode, starting an electrical arc between the two electrodes (the electrodes are typically too far apart for an arc to start without a fuse).

The radiative and convective heating of the insulating tube by the arc ablates the insulating tube. Ablated material is incorporated into the arc, heated, and expelled through the ring electrode as a plasma. While it carries away the dissipated electrical energy, the plasma is typically much too hot (10,000 to 20,000º K) to use as the working fluid in a gun. However, as the plasma enters the gun chamber, it mixes with the water to produce steam at a lesser temperature. The plasma and steam pressurize the gun chamber and start the projectile moving.

The amount of water mixing with the plasma determines the temperature and density of the steam. As the projectile moves, the water forms an annulus in the chamber (and in the barrel to some degree, depending on the chamber diameter). As the plasma flows inside this annulus, the instability of the water/plasma interface (Kelvin-Helmholtz instability) promotes good mixing. It is possible to produce steam that is cool enough to not erode the barrel (≤ 3000 ºK).

The rate of energy deposition within the gun controls the ballistic process, determining parameters such as peak pressure and muzzle velocity. An inductor controls the discharge rate of the capacitor. The inductor must therefore be sized appropriately. While ATI proposes to use a simple LC discharge circuit in the interests of cost and time, more sophisticated pulse forming circuits can be used to optimize ballistic performance.

Energy storage capacitors typically do not tolerate rapid voltage reversals. Closing a "crowbar" switch at the appropriate time clamps the capacitor voltage at zero. Diodes represent a high cost option to using a switch.

If chamber pressure extinguishes the capillary discharge, very high voltages may appear at the gun terminals. A spark gap protects the system insulation.

Each firing destroys a fuse and an insulating liner. APTI envisions a fielded system using disposable cartridges, each containing a new fuse and liner. The cartridges, when loaded into the capillary, would keep out water. The projectiles, when loaded into the barrel would seal the barrel entrance. Thus, the chamber could be reloaded with water through high pressure poppet valves, such as those used in liquid propellant guns. If the symmetry of the water charge within the chamber proved important, the water could be spun into the chamber to form an annulus.

Electrode erosion is normally controlled through the use of refractory metals (typically Tungsten alloys). It might be possible, however, to include sacrificial electrode covers within the disposable cartridges. Via reduced area support, the pressure generated within the capillary would keep the covers in intimate contact with the permanent electrodes to prevent welding-in-place of the covers. Mechanical preload would handle the pre-fuseblow period and allow pressurized contact to develop.

Electric Launch System Modeling

In order to parameterize our demonstration system, ATI has modified a one-dimensional (1-D) gun code to include a steady state capillary model and a model of the capacitor discharge circuit shown in Figure 3.1. We use a co-volume equation of state for steam, with parameters evaluated by comparison to SESAME[1] data.

The plasma/water mixing process that occurs with the geometry shown in Figure 3.1 is very complex. To simplify the modeling, we assume that the rate at which water is introduced into the system is proportional to the rate at which energy is added to the system. (In effect, we specify the temperature of the steam entering the system. This temperature is analogous to the isobaric flame temperature of a chemical propellant.) The simplified geometry shown in Figure 3.2 is then appropriate for modeling the flow. Water held within a gun chamber is converted to steam at its forward surface by the addition of electrical energy. The surface of the water erodes at a rate corresponding to the specified energy/mass ratio.

Steam flow is modeled using a flux-corrected-transport algorithm[2]. The modeling allows for changes in cross-section between chamber and barrel (i.e. chambrage is permitted). The LCPFCT algorithm is both robust and particularly suited to modeling shocks. In our implementation, variable length cells abut the projectile base and the water surface. The remainder of the chamber and barrel are divided into fixed, standard length cells. When either variable length cell grows too long, it is shortened by one standard length and a new fixed cell is

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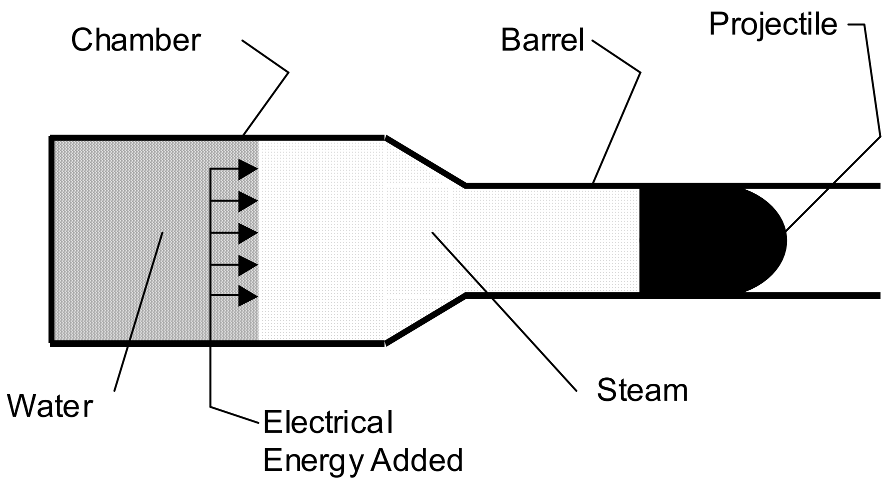

Figure 3.2. Simplified launcher architecture makes 1-D modeling useful.

added to the system. Manipulations involving the variable length cells use linear interpolation and are thus second order correct. Convective, diffusive and anti-diffusive fluxes are conserved between the fixed cells and the variable cells.

Motion of the projectile causes the steam to perform work. Erosion of the water surface is akin to a free expansion and does not involve work (the water being considered incompressible). Overall, the code conserves mass and energy to about 1 part in 5000.

Conditions within the capillary can change so rapidly, compared to conditions in the gun or the discharge circuit, that the use of a steady state model is justified. The capillary model combines the results of Tidman, Thio, Goldstein, and Spicer[3] with those of Loeb and Kaplan[4], to cover both choked and non-choked capillary flow (ejecting into a pressure assumed to be that at the water surface) and provides pressure, temperature, and electrical resistance within the capillary. Polyethylene is assumed as the ablative insulating tube material, with SESAME[2] tables providing the necessary data.

Figures 3.3 and 3.4 present an example of code output. Input parameters used in this code run, and some results, are given in Table 3-3.

Figure 3.3 presents the pressure at the water surface, the discharge current, and the electrical resistance of the capillary, all as functions of time. The wiggles in the pressure trace result from pressure waves reflecting between the water surface and the projectile. The action of the crowbar switch is seen in the rapid current rise and the subsequent slower current decay. The electrical resistance starts near zero and then jumps suddenly at ~0.1 milliseconds. A fuse model is incorporated into the code. When the fuse “blows”, the capillary model “takes over” and resistance jumps. The resistance then falls with increasing current, and finally increases with decreasing current (and also responds, to a lesser degree, to pressure changes).

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Table 3-3. Model input parameters accompanied by typical run results.

Capacitance	10 (mF)
Inductance	30 (μH)
Charging voltage	10 (KV)
Peak current	128 (KA)
Capillary diameter	0.635 (cm)
Capillary length	7.0 (cm)
Chamber diameter	4 (cm)
Chamber length	12.7 (cm)
Chambrage length	4.6 (cm)
Barrel diameter	3 (cm)
Projectile travel	1.36 (m)
Projectile mass	250 (g)
Energy deposited	497 (KJ)
Steam produced	77 (g)
Muzzle velocity	1094 (m/s)
Peak pressure	55 (Kpsi)

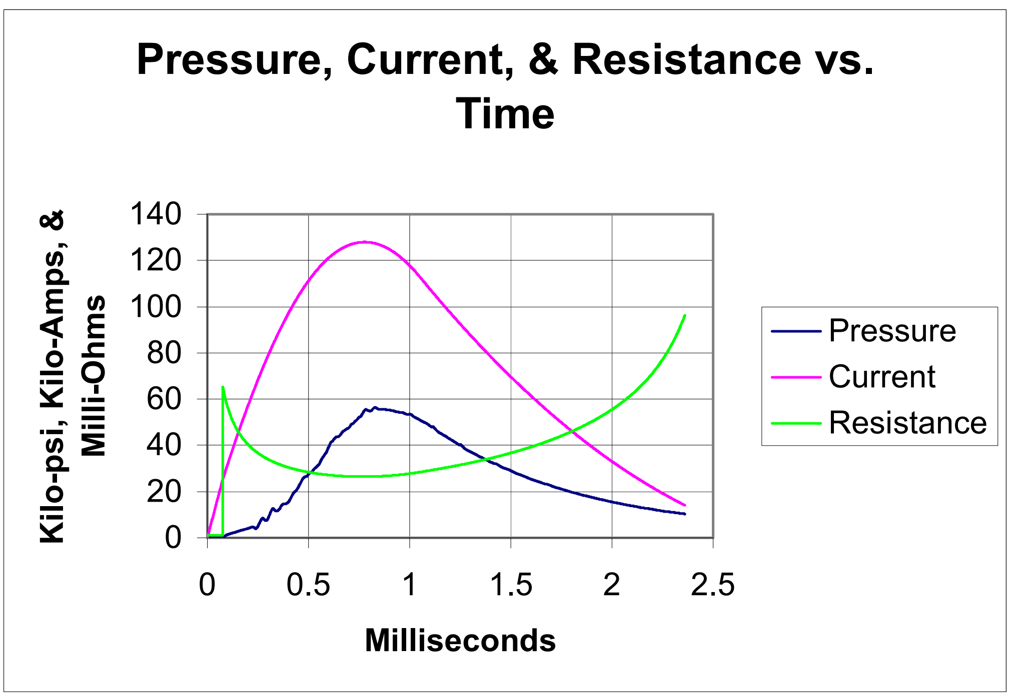

Figure 3.3. The pressure at the water surface, the discharge current, and the electrical resistance of the capillary, are shown as functions of time

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Figure 3.4 shows "snapshots" (at a time of 1.25 milliseconds) of the steam pressure and steam velocity, as functions of distance from the gun breech. The left and right ends of the traces are the locations of the water surface (0.05 meters) and the projectile (0.48 meters) respectively. Zero velocity is assumed at the water surface. The added energy causes an immediate jump in velocity, which necessitates a drop in pressure. Another large jump in velocity, and pressure drop, occur in the chambrage (0.13 meters to 0.17 meters). An approximately linear increase in velocity occurs in the barrel and a modest drop in pressure drives this expanding flow.

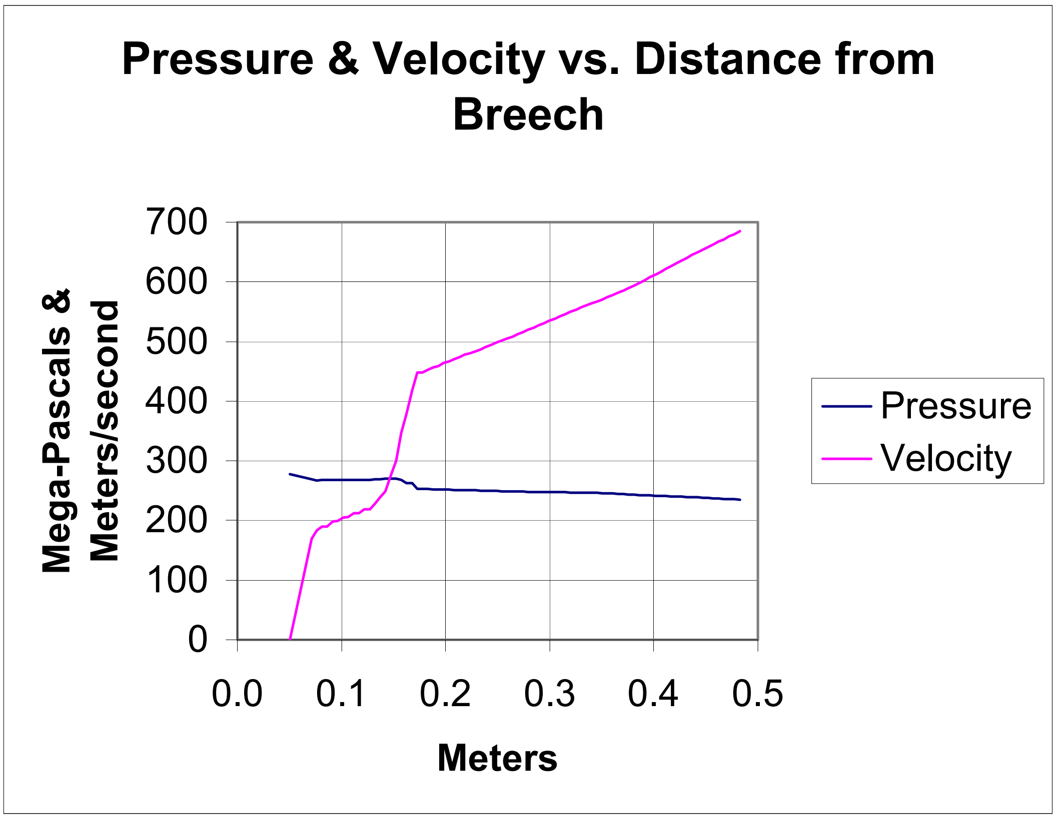

Figure 3.4. Steam pressure and steam velocity, as functions of distance from the gun breech at 1.25 milliseconds.

Electrical Launch System Status

Table 3-4 lists component requirements to demonstrate an electrothermal firing. Also listed are the items on hand within AT (at the termination of the program) and the material costs associated with some "big ticket" missing items. A high voltage option (20 KV) and a low voltage option (10 KV) are presented for the capacitor discharge circuit.

Table 3-4. Electric launcher component listing and cost estimate.

Component	Requirement	Present Holdings	Materials Cost
30mm gun barrel	1	1	$5000
Gun chamber	1	1	$5000
Capillary housing	1	1	$5000
Capillary/chamber internals	10 sets	0 sets	$1000
I-beam	1	1	$500
Barrel support clamp Trailer/Vehicle	1 1	1 0	$250 $10000
Target tank	1	1	$2000
Target holder	1	0	$1000
Target shock absorber	1	1	$1000
Targets	10	0	$500
Bus bar connections, 20+ KV, 170+ KA	1 set	0 sets	$3000
Overvoltage spark gap	1	0	$500
Capacitors, 20 KV Option, 500 KJ	2.50 mF	6.18 mF	$45000
Capacitors, 10 KV Option 500 KJ	10.0 mF	9.58 mF*	$45000
Inductors, 20 KV Option	30 mH, 170 KA**	0	$750
Inductors, 10 KV Option	30 mH, 160 KA**	0	$750
Ignitron switch, 20 KV Option	20 KV, 470 Coulombs**	20 KV, 90 Coulombs***	$ 2150
Ignitron crowbar, 20 KV Option	20 KV, 420 Coulombs**		$ 2150
Ignitron switch, 10 KV Option	10 KV, 480 Coulombs**		$ 2150
Ignitron crowbar, 10 KV Option	10 KV, 380 Coulombs**	15 KV, 480 Coulombs***	$2150

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Charging supply, 20 KV Option	20 KV, 0.4 Amps****	0	$ 13850
Charging supply, 10 KV Option	10 KV, 1.67 Amps****	10 KV, 1.8 Amps	$25000
Charge relay	1	1	$500
Dump relay	1	1	$500`
Dump resistor(s)	1	0	$ 833
System controller	1	1	$5000
Current monitor, 170+ KA	1	0	$1000
Voltage monitor, 20+ KV	1	1	$1000
Misc hardware		0	$2000

Table footnotes:

* All 20 KV capacitors, plus all 10 KV capacitors, paralleled to make 10 KV bank.
** 10 mΩ short.
*** The number given is the sum of the Coulomb capacities of the tubes owned. Per Richardson Electronics, ignitrons may be operated in parallel.
**** Two minute charge time.
***** One minute charge time.

The 20 KV option, while more attractive in terms of capacitor bank size (using the high voltage capacitors fully), requires larger investment in charging supply or ignitrons. The "big ticket" materials cost for this option totals to $23,233 (bus bar, spark gap, one coil, two ignitrons, one power supply, dump resistors).

For the 10 KV option it was planned to use AT's high and low voltage capacitors together (64 total capacitors), sixteen of AT's small ignitrons in parallel to handle the coulomb transfer of the crowbar switch, and six of AT's power supplies in parallel to provide the charging current. The "big ticket" materials cost for this option totals $7,233 (bus bar, spark gap, one coil, one ignitron, dump resistors).

When minor hardware item costs, the manpower for design manufacture and assembly of the new system are considered, it is estimated that a 20 kV system will cost approximately $ 109,000 for materials and $102,000 for fabrication/integration manpower for a total of $211,000. A 10 kV system will cost approximately $121,000 for materials and require the same manpower effort for a total cost of approximately of $223,000. The unexpected relative cost of the 10 kV and 20 kV systems is attributable to the cost of commercial power supplies that are available. That required for the 10 kV system had a slightly faster recharge capability and therefore, is more expensive.

As an alternative, for a proof of principle demonstration, time may be rented at an existing gun firing facility. With an estimate of one week of setup and one week of firing, the cost for use of such a facility (80 hours lab use time, 100 hours of facility support labor time) should total approximately $14,000.

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4. Results, Discussion, and Data Reduction

Projectile Design. A review of the laboratory test shot matrix presented in Table 3-1 suggests that the Quikrete Fiber Reinforced concrete (4,000 psi unconfined uniaxial compressive strength) yields the best performance when the projectiles are tipped with a steel nose cone, especially a solid steel nose cone. We attribute this to the aggregate in the concrete. That is, as the projectile penetrates into the target the concrete also begins to fail. It is here that we believe that the aggregate in the Quickrete provides the greater work on, and therefore greater excavation of, the target than the NSP Grout projectiles reinforced with BBs alone. The NSP Grout projectiles essentially turn to dust when the projectile fails following impact and the initial penetration.

The field test program, it was determined that as velocity increases above 1 km/second, the acceleration in the projectile exerts high compressive pressure forces on the projectile causing the concrete to fail. Therefore, to obtain the advantage of a low cost mass, the concrete must be contained within a thin metal shell, eliminating the possibility of using an extremely low cost nonmetallic sabot/case. However, a low cost projectile that is effective in excavating ore below 20,000 psi unconfined uniaxial compressive strength is still possible.

It was found that encasing the concrete within a thin steel shell provides the strength needed to maintain projectile integrity during launch (Figure 4.1). Upon impact, the thin walled case fragments into small, thin metal pieces that are acceptable to the miner. They are small and thin enough that they will not obstruct the down stream crushing steps and may also be removed by a magnet during transport. The disintegration of the thin metal shell also permits the aggregate within the concrete center to work on the target, causing surface spall and some penetration and cracking.

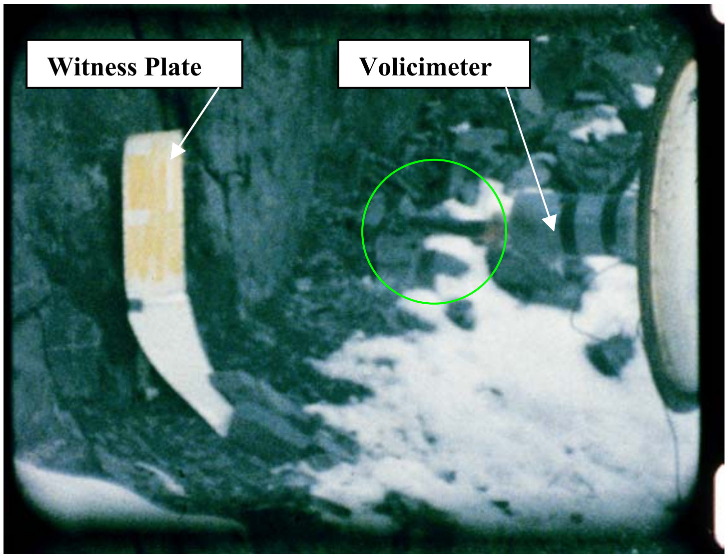
These preliminary tests were able to achieve 0.4 m^3 in a single shot. This is nearly half the stated goal of 1 m^3 per shot in order to achieve a system that is economically interesting. It is reasonable to believe, therefore, that with a continued development effort, the goal of $1m^3$ should be attainable.

The considerable modeling and design work completed on the electric steam launcher system suggests that such a 20 kV system can be fabricated in 6 months for a cost of approximately $211 k. The driving issue in the lifecycle cost of the launcher system is component longevity. Once fabricated, the electric system will require testing to determine expected life of some of the critical components. This life expectancy will determine, to large measure the operating cost of such a system. The goal is to design a system where components are either changed with each shot as part of a cartridge arrangement, or at the end of each shift, meaning that the components must have a lifetime of several thousand shots.

5. Findings and Conclusions

Laboratory Experiments.

Data collected during the laboratory experimentation campaign confirm the hypothesis that reinforcement of a strong concrete with a strong aggregate and a steel (or other hard material) nose cone may result in a cost effective projectile-based excavation.



Frame a.

Frame b.

Figure 4.1. Two frame sequence from high speed camera catches steel encased concrete projectile leaving velocimeter (Frame a.) and penetrating wall, having passed through witness plate (Frame b).

Field Experiments.

The field experiments confirmed the hypothesis that the laboratory experiments could be scaled from 21 mm to 60 mm launcher bore size. They also showed that concretes and grout mixtures are not sufficiently strong to survive the high compressive forces applied during acceleration to high velocities, i.e. above 1 km/s.

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They did demonstrated, however, that a projectile capable of producing 1 m^3 of muck per shot, while not achieved, is a reasonable expectation. Once a design was found that could survive high velocity launch, nearly ½ a cubic meter was achieved, even though only a few experiments could be run with the resources available. It is believed that with further experimentation, the goal of 1 cubic meter per shot would not be an unreasonable goal.

Electric Launch Design

The laboratory design of the electric launcher suggests that a production electric launch system could be developed that will have a capital cost far less than $200 k, considering that a prototype can be fabricated for ~ $211 k. The life cycle cost effectiveness cannot yet be determined, however, since it is dependent on the life expectancy of certain system components that will have to be replaced periodically. The component replacement cost ant the replacement period will drive the total system life cycle cost, or cost per ton of ore produced, since the known cost of electricity per shot is very low and it appears that an effective projectile can be manufactured in volume at low cost.

6. References

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