ASSAULT CLIMBING CHALLENGE

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ABSTRACT

The kinetic energy penetrator system consists of three components that were designed, manufactured, and integrated to accomplish the task of scaling a large vertical obstacle. The first design component was pneumatic cannon that modeled the M203 grenade launcher. This system was made necessary due to Army restrictions, and designed to impart the same muzzle energy that is provided to the white star cluster round of the M203. The second component was the anchor projectile. Consisting of tungsten and steel components encased in a plastic sheath, this projectile weighed approximately a quarter of a pound and traveled at 390 feet per second from the pneumatic cannon. It was proven to successfully embed itself into multiple surfaces including plywood and concrete with a cable from the rear of the projectile attached to a lead line. The third system component established the actual climbing rope that allowed ascension. The operator pulled the lead line, which was attached to the climbing rope with an adapter to allow a smooth transition through the cable loop. A stop knot at the end of the rope secured it in the projectile loop, allowing it to be climbed by any commercial ascender or rope climbing technique.

The projectile can be made from low cost materials, and due to the simplicity of the device, does not require estensive manufacturing processes. The cost of production for the prototype was 5688.75 dollars, but unit cost of further production would be most nearly 125 dollars.

1. INTRODUCTION

The purpose of this paper is to provide an overview of the kinetic energy penetration system that was designed to satisfy the operation need of soldiers and rescue teams to climb large vertical and near vertical obstacles in order to accomplish their mission. These obstacles vary in location, accessibility, hardness, height, and a host of other attributes. Currently soldiers are equipped with climbing equipment, but are limited by the ability of a lead climber or the successful deployment of a grapple. To solve this problem a device had to be designed that would enable soldiers to face these varied conditions while being fast, light, effective, tactical, and practical.

1.1 Problem Statement

In the current operating environment the warfighter may have to rapidly and tactically ascend a variety of surfaces in both assault and rescue operations. Currently no design exists that can provide the warfighter the versatility to conquer these obstacles. The mission of our design team was to create a system that allows troops, with their equipment, to scale buildings or mountain faces under a variety of conditions, efficiently and effectively. This system is constrained both by time and resources, with a competition date of 16 April and an allocation of thirty thousand dollars from the Air Force Research Labs.

The customer for this design is the typical American soldier. While the main intent is for this type of device to be used by special operations personnel, the design is planned for the lowest common denominator. The American soldier is generally between the ages of eighteen and twenty-three with a high school diploma and some college, though not a degree. He is physically fit, and disciplined enough to be entrusted with fighting the nation’s wars. The American Soldier is also well trained in basic soldier tasks and those tasks that apply to his specific method of service.

In both mountainous and urban terrain there may exist an operational need to scale vertical obstacles in a manner which grappling or other line-over devices are not effective and which lead climbers cannot succeed. A tall concrete structure with a flat roof and no ledge is such a surface. What the soldier needs is a system that is light and small so that it can be carried into combat situations without adding a large burden to his already large combat load. Additionally the system must be durable so that it is not damaged by the realities of combat and the habits of those who will operate in such and environment. The device must also be stealthful so that it does not alert any enemy to the presence of the Soldier. Lastly, the device must be effective, allowing the Soldier to successfully accomplish his mission.

Two constraints limited our design once we had elected to use a system that focused on a high speed kinetic device. We chose to design our system after the M203 grenade launcher, but were unable to actually modify this army system due to restrictive regulations.

This necessitated the design and construction of the pneumatic cannon. A second restriction was one that we imposed upon ourselves. In order to realistically model the system, we limited ourselves to the muzzle energy that could be achieved by the M203.

1.2 Recommended Design

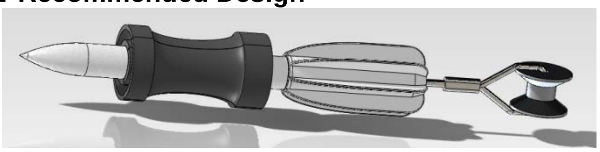

Figure 1. Prototype Photograph

The intent behind this design was to engineer a device that is functionally and operationally focused and provides for the vertical ascension of a squad sized military element in a tactical environment. We developed a system that sets an anchor point in a vertical obstacle and allows a soldier (or other trained operator) to easily connect a climbing rope to that anchor. The picture above shows the projectile design that is fired directly into the vertical obstacle in order to establish an anchor point anywhere the operator desires.

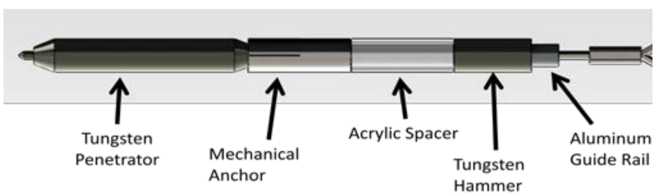

Figure 2. Prototype Photograph

The design shown above is a CAD model of the internal components of the projectile. The design is based around a 2.5 inch penetrator made of a heavy tungsten alloy. This material will provide the mass, toughness, and hardness necessary to penetrate the objective surface. The penetrator will have a diameter of 3/8th of an inch, and will have fins attached in order to stabilize the penetrator during flight. The sabot surrounding the penetrator will be used to carry and seal the projectile as it travels down the barrel of a launching device. This sabot will fall away from the projectile as it leaves the barrel. The sabot is currently designed in the range of 1 inch, but can be modified to fit nearly any barrel size for multiple weapons systems.

Behind the penetrator is a mechanical anchor that will help lodge the penetrator into the wall. A tungsten hammer behind the penetrator and anchor will smash the rear end of the anchor in order to expand the flanges and lock the system in place once inside the wall. The acrylic spacer provides time for the penetrator to enter the wall surface before there is impact from the hammer; the spacer, as well as the launch package, sheath, and fins are all disposable components and are destroyed upon impact.

An important design component to the projectile is the connector at the rear on which the climbing rope can be attached. A cable attached to the rear of the penetrator will have an eyelet attached away from the body of the projectile. The general concept behind the projectile is that it will fly to the wall surface, lodge itself with its own momentum into the vertical objective, and provide an anchor to which a trailing rope will be attached; this rope can then be climbed using a variety of methods.

Table 1. Design Specification List

Engineering Characteristic	**Priority**	**Target**	**Actual**
Size	1	1ft x 1ft x1ft	0.5ft x 0.1ft x 0.1ft
Weight	2	5 lbs	0.25 lbs
# of Climbers	3	4	1.5
Distance Traveled	4	90 ft	90 ft
Ease of Use	1	GO	GO
Stealth	2	GO	GO
Innovation	3	GO	GO
Cost	4	GO	GO

We managed to meet or exceed nearly all of our target design objectives, with the exception of # of Climbers. Our we focused extensively on trying to make our design a reality for soldiers in the field, and we wanted to make it practical, so we were able to devise a design that could meet our goals.

2. BUSINESS CASE

The Kinetic Penetrator fills a necessary void in the often difficult task of vertical ascension. Many devices currently on the market are too expensive, slow, or not adequate for the job description. When a device is required to help troops ascend a vertical obstacle rapidly and stealthily, the Kinetic Penetrator is the best solution.

The cost of the device is very competitive. The crucial components of the projective are made of tungsten metal, the only expensive material in the design. The rest of the parts are very inexpensive and readily available.

The capability of the system is unparalleled. Current systems on the market general rely on line over devices. Our system however, provides a versatile approach to approach an obstacle at any height. An operator intending to only ascend partially up a building and enter at a given level is now able to do so. The lift capacity and anchor strength, both shown in Table 1, speak to the capability of our system. Once embedded in the wall or obstacle, the limiting factor at this point now lies in the mechanical ascension device.

Further credit to our design is the ability to easily manufacture and stow the Kinetic Penetrator device. With the design finalized, the tungsten penetrator piece can be easily manufactured on a compatible lathe. For the war fighter, the device is less than 0.5 pounds and is small enough to be stowed in existing gear. This is the greatest benefit of the device since the soldier or operator needs minimal additional training and incurs no significant additional load or limitation. The device is light enough to be carried my any solider, and it is intended to be fired from existing weapons systems.

3. BACKGROUND RESEARCH

Spike

A fair amount of research was conducted in regards to penetration of rigid projectiles into various materials such as concrete and various types of rock such as granite and limestone. There is much information and data available from the study of concrete penetration, and it is an important aspect that the military likes to analyze when it comes to bullets, missiles, and kinetic energy penetrators. Correlations, equations, and concepts were gathered from the research in order to approximate the necessary engineering components needed to design a penetrator that we could use as a fixed anchor point on the top of a climbing objective.

From the research, knowledge of the stages of penetration was gathered, such as the crater region upon initial entry, and the tunneling region after initial penetration. From this, we could determine the velocities and masses needed in order to achieve an ideal penetration depth, along with the diameter of the penetrator that would best suit our needs. In addition, the nose geometry of the penetrator became an important study for normal and oblique penetration of the projectile. The amount of energy needed to accelerate the projectile was also determined through the use of the background research, and this will be crucial when developing a launching system.

Since we not only need to penetrate the wall surface, but we need to stay anchored in it, much research was conducted in order to approximate pullout strengths and various geometries needed to develop a strong anchor. Hilti, a driving and fastening company, was contacted in order to gain information on approximate pullout strengths of the design, and from this we could gain an idea of the depth of penetration needed, as well as the diameter of the penetrator. A concept involving a projectile with changing geometry upon impact was also delved into, and different mechanical anchoring systems were researched in order to try to create more dependable pullout strengths for the penetrator.

Glue

In order to deal with the possibility of a variety of surfaces, the concept of a glue based design was considered. The glue would be able to adhere to numerous different surfaces whether that be a rock face, glass window, or a wood or synthetic climbing wall. After conducting research on a variety of glues, it was determined that a super glue with an accelerant was the best possible option to work with. One potential super glue has a shear strength of at least 700 psi, but increases depending on the different types of surfaces.[1] This would be able to support the climber. This strength would also increase if a greater surface area of glue could come in contact with the wall.

After researching the glue concept further, the problem of set time became evident. The super glue researched sets in about 5 min but it not at full strength for a few hours. To combat this, an accelerant would be used. The accelerant allows for an instantaneous set time and a usable anchor point within 5 minutes.[2] The accelerant reduces the shear strength but not significant enough to rule out this option. This glue and accelerant could then be partnered with additional anchor point methods to increase the chance of a successful bond to the wall.

AIR CANNON

To simulate the round that will be modified, a pneumatic cannon will be used. There are three main sections to such a cannon: the pressure source, the chamber, and the barrel. In between the pressure source and the chamber is a regulator to control flow from the source into the chamber. Between the chamber and the barrel is a valve which allows for quick release of pressurized air into the barrel, where the projectile sits waiting to be fired. [6]

The pressure rating of all components is crucial to the design. The limiting factor is the component with the lowest pressure rating. For this cannon to successfully simulate a military round, the chamber pressure will need to be at least 300 psi. The weakest component in the system is typically the valve between the chamber and the barrel. This is because this valve needs to be quick release—it needs to open in less than 500 milliseconds to allow rapid acceleration of the projectile. Steel pipe that can withstand well over 500 psi is fairly easy to find, and the same goes for regulators and pressure sources (i.e., argon gas tank). A quick release valve, on the other hand, contains a number of moving parts, delicate seals, and electric components that make it more difficult to manufacture to high pressure tolerances.

There were three alternatives that were investigated for this important system component, which are shown in Appendix A, attached. The most suitable alternative was the Solenoid-Triggered Pneumatically Actuated Poppet valve, made by Festo Corporation in Canada. This valve can withstand 500 psi.

However, the Festo Corporation manufactures its products in Germany, and as such as very long and uncertain waiting periods on its valves. The wait time was so uncertain that valve quality had to be sacrificed for ease of ordering and scheduling.

Significant research was also done into sealing techniques. There are many ways to seal one piece of steel pipe to another, namely welding, threading, and Swage locking. The most time, experience, and cost effective technique is threading. This process allows the male and female components of the system to be threaded together to a national standard, with a taper that causes the threads to tighten as they are turned.

There are significant communication issues to be overcome in determining that all dimensions and sizings are correct for all components prior to ordering, but the concept and parts list has been researched extensively.

3.1 Social Considerations

This produce has application in both among the military and civilian contexts. At this time, the main theater of operations for combat forces is Afghanistan, which has a large area of mountainous terrain. This product has the potential to increase the mobility of NATO and US forces operating in Afghanistan as well as other countries.

While this product is being designed to be fired from military firearms. A modified version of the system may be desired by civilians for use in mountaineering, spelunking, or other outdoor activities that involve traversing tall vertical obstacles. The system could be modified for use in a flare gun or similar system that could be carried by adventurers and could provide an additional method of safety and versatility that grappling and lead climbing do not possess. Other possibilities also exist, such as use in rescue operations by firefighters, climbing by lumberjacks, or anchoring while boating.

3.2 Technological Considerations

The current devices that exist to scale vertical obstacles are all dependent on lead climbers and grapple devices, or are so large and heavy that they are impractical for the warfighter. The kinetic penetrator addresses this technology gap by providing an anchor point that can be established at challenging heights and with a direct line of sight to the anchor.

Due to the nature of our air cannon powered design there were certain challenges that we did not contend with. The greatest of these is the adaptation of the projectile to a powder combustion powered system. A powder system will introduce high temperatures that will be damaging to the lead line, and a new material will have to be chosen that can withstand such heat. Additionally, the sabot fins will have to be adapted to the new barrel of the weapon and engineered to capture the pressure released from combustion. Lastly, the rear of the projectile will have to be reshaped to fit with a powder charge, allowing it to burn and fit within the chamber of the weapon.

3.3 Economic Considerations

Currently, the nationally economy is experiencing a prolonged recession and the military is being forced through extreme budget cuts. Any new technology is forced to deal with these reduced funding constraints where fewer resources are available for research and development and the government is less likely to purchase a new product, especially if it does not greatly surpass the current solution. The device must be constructed in a cost efficient way and engineered so that training and retooling costs are offset by the gain provided by the device.

In order to be practical in the civilian world the device must also be affordable. The demand is likely lower in the civilian sector because they do not engage in similar high risk and time sensitive situations, but there is certainly a market. To remain practical a civilian version of the penetrator system would have to be able to integrate with existing delivery systems such as flare guns and produced cheaply so that each shot does not also blow a hole in the climbers pocketbook.

3.4 Political Considerations

Political considerations for this device are intertwined with the social and economic considerations. The nature of the contracting economy force politicians to look for ways to save money, necessitating that the device provides a benefit to the military that is greater than its cost.

Additionally, because of the potential for rescue operations and cooperation with foreign militaries this device has the potential to improve relations with allies through proper deployment.

3.5 Applicable Standards/Regulations

AFRL mandated multiple regulatory procedures for the use of the pneumatic cannon. Firstly, in a teleconference communication, they dictated that the cannon would need to be hydrostatically tested to a pressure of at least 1.5 times the maximum competition pressure. This was done to 800 psi, 1.6 times the max operating pressure of 500 psi.

In addition, the competition's safeties mandated that the cannon have a relief valve. This was to ensure that, in the event a projectile was loaded and the chamber pressurized, the cannon could be depressurized without actually firing the cannon. This was added to the cannon by simply putting a small ball valve upstream of and connected to the chamber.

4. RESULTS

The design process consists of conceptual design, embodiment design, and detailed design. Development of the prototype included construction and assembly of components, risk management, and testing.

4.1 Conceptual Design

Customer Requirements were supplied by the Air Force research labs in their problem statement. It was specified that the competing systems would be graded objectively on the size, weight, speed of ascent, number of climbers that reached the top of the obstacle and subjectively based on the ease of operation, innovation and stealth. The objective criteria were weighted twice as heavily as the subjective criteria, causing them to be twice as important in the later calculations of the design process. In order to distinguish between objectives that were given the same value in the grading criteria we gave our own subjective measures to the value of each attribute, based on the operational effects that we saw as most important.

With the raw criteria and weighted objectives, a Pareto chart could be constructed (appendix B-1) that shows each attribute with a graphical representation of the importance and a cumulative percentage of the attributes as they move from most important to least important. Using the Pareto; functionality, usability, speed, size and weight were determined to be the critical attributes along with a few others that constitute the first eighty percent of the cumulative percentage.

Due to the small and specified nature of the design attributes, a design tree was not necessary for completion of the design phase. All attributes could be compared and evaluated in later steps without placing an undue burden on the engineers.

Next, using the custom requirement attributes determined by the objective tree, a pairwise comparison (appendix B-3) was conducted. By battling each attribute head to head with the other attributes and summing the number of wins and losses a weight was given to each attribute. This allowed the final attributes to be ranked with functionality being the most important, followed by usability, then speed, size and weight. Stealth and elegance were considered to be the least important attributes, though again, their inclusion in further design steps did not create an undue burden.

Using the ranked attributes from pairwise comparison the Quality Function Deployment (QFD) can be constructed. As seen in appendix C, this tool compares customer requirements and the different engineering characteristics that are involved in the construction of the device. No devices currently exist that can accomplish these tasks in a tactical environment, so although they were considered in the brainstorming stages, competitor designs were not considered for the QFD. The relationships are then analyzed to rank each engineering characteristic based on the importance and correlation to the customer requirements. A comparison of the characteristics of current products allows one to determine the target values for the new product. The final product produced by the QFD is each engineering characteristic ranked in order of relative importance and a target value to achieve design success. Control of the device and the ability to penetrate multiple surfaces were the two attributes determined to be most important characteristics, followed by ascension power and weight of the system. Much of these design characteristics dealt with the ascension piece of the design problem, not the anchoring system. With the decision that was made later to make a system adaptable for a number of pwered and manual ascenders our design would focus almost entirely on the design of the anchoring system. For that purpose our most important attributes would be surface penetrations, weight, size, and simplicity.

A Functional Decomposition is the next stage in the product development process. Unlike previous steps, this stage is not dependent on previous statistical conjectures but rather on brainstorming techniques. Through the functional decomposition different levels of interaction are determined and functions that the design should accomplish are built into each level to ensure customer satisfaction. Appendix D shows the full development of the main areas that the assault climbing device needs to succeed in, broken down into three sections: interaction with the user, the target surface, and the weapon system.

Using the characteristics determined by the functional decomposition, a morphological chart can be constructed. This tool takes the functions from the previous step and brainstorms different means for accomplishing each function, and also provides a brief explanation of the underlying physics of each mean. For example, in order to accomplish the task of anchoring into the target surface, one alternative was using a high speed kinetic metal spike design; another option was a low speed glue capsule that would adhere an anchoring platform to the wall. The dilemma between these two alternatives would prove to be the challenge of our design process as we chose to deal with commercial ascension systems and were forced to use a pneumatic cannon for the delivery system.

From the morphological chart different design alternatives were developed. The design alternatives focused on the anchoring system, again due to choices made previously, either because of restrictions or availability of current solutions. The two competing anchoring designs were a high energy spike that would be delivered at high speed, penetrating into the wall like a nail to create the anchor. The second system was a glue capsule that would be fired in a parabolic path at a low speed and use the chemical reaction between high strength glue, accelerant and the air to create an anchor point for an associated pad.

In order to decide between these two alternatives, a decision matrix was used to compare all the characteristics of competing designs. The matrix makes use of QFD by comparing the different criteria and the goals presented in each to the characteristics of the different alternatives. Eventually, the decision matrix was proven useless. Technological difficulties including rapid evaporation, ineffective bonding to unclean surfaces, the high reaction temperature, and impractical delivery system made the kinetic penetrator the only viable option.

4.2 Embodiment Design

The basic design determined was the kinetic energy penetrator. The cannon was necissary to construct only in that it was our method of delivery for the projectile. The ascension components did not involve any engineering, only the application of already existing systems. For those reasons the embodiment design will focus solely on the design and production of the penetrator itself and its components.

The components of the projectile were designed to fit into multiple weapons systems through the alteration of the sabot and tail fins and also be able to penetrate into multiple surfaces through adjusting the pressure that was powering the projectile. The main component of the projectile was the tungsten head. This design featured a small point at the front of the penetrator, followed by a small shaft, and then a blunt surface that transitioned into a slope. This particular nose geometry took advantage of the different requirements of penetration determined through in the background research and input by ARL. The initial point of the tungsten piece breaks the surface tension of the target, a characteristic that is particularly important for concrete applications. Also important for concrete applications is the need to minimize the cratering region before deep penetration can be achieved, a goal which is accomplished by the blunt portion of the geometry. The slope on the rest of the projectile allows the projectile to take advantage of the penetrating power, forcing the target surface apart so that the rest of the tungsten head and the following components can enter the region created. Tungsten is chosen for this component because it is incredibly hard and dense.

The following components create the hammer system. The consist of a mechanical anchor, acrylic spacer, and tungsten hammer, all riding on an aluminum spine. The mechanical anchor is a commercially available product that was altered for this design. The back of the tungsten penetrator is also sloped, and when the anchor is forced against this slope it is forced to expand due to the force applied to the back. This force is supplied by the tungsten hammer. In flight the hammer is kept separate from the anchor by the acrylic spacer, but when impact is made the momentum hammer shatters the spacer, slides along the aluminum spine and impacts the anchor. The spine keeps all components aligned in flight and encases the cable, protecting it from damage.

The cable, loop and rear spacer create the end of the projectile. The cable extends the length of the projectile, passing through the aluminum spine and adhered to the tungsten projectile by a high strength metal bonder. At the opposite end of the cable is a loop for the lead line to pass through and wide enough for the eleven millimeter climbing rope as well. The rear spacer is an aluminum device with a larger diameter on the two outer ends than in the middle that increases the distance over which the rope has to bend when it is being pulled through the loop. This device was determined essential after failed attempts to pass the rope through the loop due to the great tension needed to bend the rope over the very small pressure point.

All of these components are held in a plastic sheath that provides alignment and protection for all components both in the barrel of the delivery system and while in flight. This sheath has a pointed nose geometry to make it aerodynamically stable and ridges on the front half of the shaft that are used to grip the sabot petals. The sabot petals are also mad of ABS plastic and are designed to fit snuggly inside the barrel. There are three sabots in each projectile that are taped together once assembled. They have cavities in the front and rear that are used to catch the air pressure inside the barrel to propel the device forward, and also to catch the air outside the barrel so that they properly deploy and do not interfere with the stable flight. The final outer component is the tail fin. This piece holds all the inner components inside the jacket while exiting the barrel and provides aerodynamic stability, preventing any rolling of the projectile as it travels. Additionally, the expanded fins create a low pressure cone behind the projectile that minimizes the effect of the protruding cable and rear spacer on the flight of the projectile.

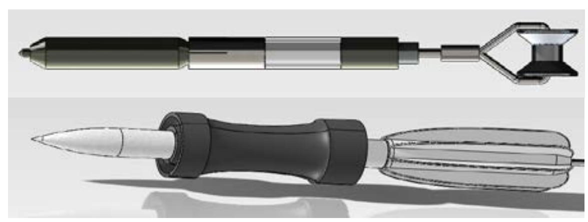

Figure 3. CAD Drawing of Prototype

4.3 Detail Design

The engineering drawings presented in Appendix I are “AS-BUILT” schematics that show the size and tolerances that each part was constructed to. Due to the radial nature of the device, only the front and side views are shown.

The Bill of Materials, which can be found in Appendix J, shows the materials purchased and the manufacturing processes done to design and build the cannon, penetrators, and molds for testing. The Bill of Materials also tells the dates delivered and required. As well as who had the responsibility for a certain material or process.

The largest monetary value was spent designing and building the air cannon. This, along with the price and time spent making molds, made testing the most expensive part of the project.

The penetrators, both steel and tungsten, were not significantly expensive. Looking at the prices involved in creating one full tungsten penetrator, the price of the system would be about $85.

In the manufacturing, many of the pieces had many processes that had to be completed. The number of processes would drive the time spent on labor, which determines the labor costs. With the number of process that had to be completed, it is safe to assume that the labor involved in producing the system would be a large cost.

4.4 Analysis

PROJECTILE

Penetration depth predictions

Once we settled on going forward with the penetrator design and background research was conducted, a projectile penetration depth prediction model was used in order to determine a benchmark for our design. Projectile penetration of concrete can be analyzed by examining the regions of penetration, the depth classification of penetration, and the obliquity of the penetration angle to the surface of the target.

There are three regions of penetration, the cratering region, the tunneling region, and the shear plugging region. The cratering region is greatly affected by nose geometry, and is the initial stage of penetration marked by surface spalling in all three depth cases. Tunneling is independent of nose geometry, has little spalling, and is only apparent in medium and deep penetration. Shear plugging is also independent of nose geometry, and is the result of spalling of the back side of the concrete target with the exit of the projectile. All three have differing importance on the modeling of penetration depending on the classification of the depth of penetration.

In general, shallow penetration occurs when only cratering is present after impact. Medium penetration occurs when there is both cratering and tunneling, yet both may be under developed regions. Deep penetration occurs when cratering is fully developed, and tunneling is the most significant region within the concrete target. Deep penetration is what we were most concerned with for our design

Oblique penetration is another important case of projectile penetration, and is defined by the angle of the velocity vector with respect to the surface normal. Oblique penetration is very similar to normal penetration, and can be modeled similarly. This aspect of penetration would be critical to us as we would be firing our design at about 30 degrees from the horizontal.

Nose Geometry determination

The nose geometry of the projectile has significant importance in the cratering region of concrete penetration, yet is not associated with the tunneling or shear plugging regions. The nose geometry has little effect on tunneling or shear plugging because these processes are a result of shear force imparted on the concrete as the projectile travels through the medium, and the shape of the front of the projectile has little implication on the shear force that travels parallel to the velocity vector of the projectile.

The cratering region is very dependent on the nose geometry of the projectile, and this is important to us as this affects the effective penetration of the projectile. We wanted as much of the penetrator within the tunneling region so as to have frictional contact with the wall and the penetrator.

Computational fluid dynamics analysis

Since we were firing a projectile that would fly through the air, we conducted a significant amount of Computational fluid dynamics analysis to design an effective system. We used the FlowWorks add on in Solid works in order to run an external CFD model on our design. This allowed us to create a flow path over the projectile that we could analyze in order to see the forces acting upon it and if it was stable. By looking at the constant pressure lines that flow over the projectile, we can see that there are very few high pressure areas and that the contours are very symmetric around the projectile's body. This indicates that there is a small drag coefficient on the projectile, and the design should be stable in flight because of its symmetry. From this software, we were also able to extract data on velocities of flow and frictional effects on the projectile. This was very useful to us in determining energy losses due to drag forces and flight through the air.

We also got much aid from Army Research Labs in validating our design and its predicted flight. They ran a more sophisticated projectile path simulation and they were able to derive similar data on the flight characteristics of the projectile. It was determined that the projectile was aerodynamically stable, and there would be no roll, pitch, or yaw during flight. This was due to the appropriate number of fins that were added to the projectile in order to move the center of pressure behind the center of gravity. Graphs depicting the projectile flight paths were also included in the analysis, and we could use this information to generate a good idea of how the design would act when fired from various velocities.

AIR CANNON

There were many analytical steps taken in the construction of the pneumatic cannon. The first step in the process was laying out a rough outline of what the cannon would look like in its final form, so that all system components could be accounted for. This can be seen in FIGURE 4, below.

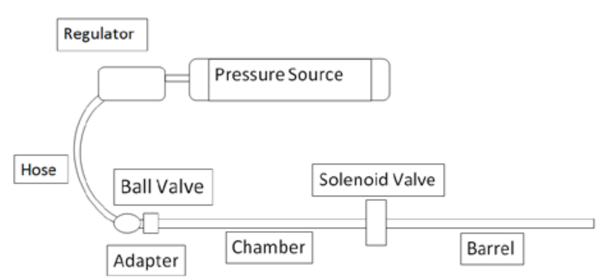

Figure 4. Rough Sketch of Pneumatic Cannon

The next step involved determining exactly how much pressure would be needed to propel the projectile to the appropriate energies. To do this, Microsoft excel, as well as Newton's Second Law, proved to be useful tools. An excel spreadsheet was constructed that used available pressures to determine the energy accumulation of the projectile as it accelerated from zero. A copy of this spreadsheet and the resulting data are available in Appendix O.

The results of this analysis indicated that a minimum of 300 psi would be needed to even remotely replicate the energies present in an M203 round, but the more pressure available, the better.

Therefore, a determination of which system component would be the limiting factor in the cannon's pressure envelope had to be made. Extensive research was conducted of various system components, and the limiting factor was determined to be either the solenoid valve or the welding regulator used in the design. Either way, the limiting pressure was going to be 500 psi.

Upon realizing the limits of the system, the remainder of the cannon was built with this limitation, as well as a factor of safety of at least two, in mind. All other system components, other than the regulator and solenoid valve, were rated to well over 1000 psi.

The remainder of the analysis done in the completion of this design involved taking the rough sketch shown above and turning it into a specific system that would fit together snugly. As discussed above, the methods used to make this happen, the sealing techniques, were extensively researched as well. Stress in a pressurized pipe is a function of not only the pressure in the pipe, but the dimensions of the pipe as well. A larger pipe with equivalent pressures as a smaller one will have higher stresses. The easiest way to determine if a certain sealing technique would be effective was to calculate the longitudinal stress (i.e., the stress put on the end fittings and threads) and determine if it was tolerable. The longitudinal stress equation is

$$\sigma_{long} = \frac{Pressure * Radius}{2 * t}$$

Where t is the thickness of the pipe's wall. The results of this analysis showed that the pressures in this system could be adequately handled by threaded connections, which made for simple construction as well.

4.5 Construction/Assembly

The construction and assembly of the Kinetic Penetrator was very much an iterative approach. We quickly determined that the necessary penetration depth would only be achieved with a large amount of momentum, which lead to the decision to use tungsten metal for the penetrator. Tungsten is readily available and able to be formed to the design that we needed.

The key changes to the projectile design came with each stage of testing that we preformed. Through our testing, some key changes were made. Penetrator tip geometry was a key design parameter for the surface and conditions we would operate in. Research in this area lead us to the combination or a sharp point for initial penetration and angled shots in combination with a secondary blunt section of the tip to provide for penetration without a large crater forming.

Furthermore, as we continued the testing process and integration, we added a posterior loop in order to connect the penetrator device to our lead line, which would further allow for attachment to the actual climbing device. One major takeaway was the importance of iteration and testing in order to improve and adapt our design to be most effective.

AIR CANNON

With all parts confirmed correct and on hand, actual construction of the cannon was relatively easy. Teflon tape or machined flanges on the fittings were used to strengthen the seal of the stainless steel threads, and all components simply screwed together.

The more complicated part of the construction process involved the triggering system. The solenoid valve that was purchased uses a standard 110 AC power source to open the pilot valve. The competition also mandated that the cannon be able to be fired from a minimum standoff distance of 50 ft. This meant wiring a switch box into a power cord that was 50 ft long. Although easy enough, small errors can be made in circuitry that are difficult to troubleshoot. Thankfully, none were made, and the electrical triggering system functioned flawlessly. The air cannon was now completely ready for testing.

4.6 Final Cost

Table 2 lays out the costs associated with developing and manufacturing the prototype. The largest costs came from the air cannon. This machine was used in testing, which means that the largest costs can be associated with the testing of prototypes. The second largest cost was the labor aspect. As is described in section 4.5, many of the parts needed to be individually machined, which takes time. At a wage of $10/hours, the labor costs add the largest amount to the development.

The costs of the extras and the trip costs were not considered as part of the developing and manufacturing of the prototype. The extras are the costs associated with materials bought in support of the competition. These include the harnesses, a hands-free video camera, climbing rope, etc. The trip costs are the hotel costs, the vehicle rentals, and the per diem given to group members.

The costs directly associated with the prototype add up to be less than $500. The actual penetrator system is not overly expensive. The price for one individual penetrator comes to be about $85.

The individual expenditures can be found in Appendix K.

Table 2. Cost Breakdown

Item	**Cost**
Molds	**$355.35**
Air Cannon	**$2104.45**
Penetrators	**$124.68**
Extras	**$3118.87**
Trip Costs	**$2504.26**
Labor Costs	**$1000**
Total Cost	**$9207.61**

4.7 Risk Management

Due to the hazardous nature of our system, safety considerations had to be taken into account. The largest risks came during testing, which involved shooting projectiles at concrete or wooden blocks.

To ensure the safety of group members during testing, firing commands were implemented. During firing, the area near the cannon and target were clear of personnel. Avenues of approach had a posted guard to ensure no pedestrians walked into the testing site. All group members wore eye protection and were behind cover during the cannon's operation. In Appendix L, risk assessment sheets can be found for testing which involved firing the cannon.

The air cannon itself is a dangerous piece of equipment, if used incorrectly. Safety features were installed. As the cannon is bore-loaded, there is a risk involved in firing while loading. Before loading the cannon, the pressure in the chamber was verified as zero, any pressure was released. To allow the release of extra or unwanted pressure, a release valve was installed into the cannon. This was a necessary addition because firing the projectile did not release all of the pressure from the chamber. The chamber had to be drained after each shot.

4.8 Testing

The first testing that was conducted was hydrostatic testing of the cannon and all of its components. Using a hydraulic pump, the ends of the cannon were sealed, the cannon filled with fluid, and the pressure of the fluid increased to 800 psi. The cannon was left like this for 15 minutes and no leaks or other issues occurred. This test proved that the cannon was structurally safe and would be able to deal with the 500 psi pressure that would be used in the firing of the projectiles.

The second level of test that were conducted was the firing of plastic test plugs at gradually increasing pressures. The first shot was conducted at 150 psi, and the pressure was gradually raised to the full test pressure of 500 psi with successive shots. This test was conducted in order to test the functioning of the solenoid valve in the cannon and proper travel down the barrel, as well as our aiming system and the effect of reaction forces on the cannon. Through these tests it was determined that the cannon was functioning exactly as desired, with no problems when the projectile traveled down the barrel and no adverse effects of the reaction forces.

Following that were the tests of steel projectiles that lacked the internal components of the tungsten pieces, but had similar masses. The penetrators were inserted down the barrel, which was positioned approximately twenty feet from the concrete blocks that served as targets. The cannon chamber was pressurized after a safe standoff distance had been taken by all observers. The projectile was fired, and then the process repeated for further shots with high speed recording equipment moved to different locations to determine different aspects of flight.

Many results were determined from the analysis of the high speed video and the examination of the target after impact. First, it was possible to determine the exit velocity of the projectile. Using a paneled backstop and the high speed camera it was possible to capture the projectile at two points in time, and then compare the distance traveled to the change in time in order to determine the velocity. Secondly it was determined that there was an undesirable amount of pressure loss because the barrel was not long enough for the projectile to effectively capture all of the potential energy from the expanding gas. This realization drove the purchase and use of a longer barrel in later firing. The high speed video did show that the sabot fins functioned as desired, shedding without interfering with the path of the projectile. Additionally, the high speed video showed that flight was incredibly stable, with no roll, pitch or yaw evident in the entire travel of the projectile. Lastly the shots were very accurate and precise, traveling and impacting in exactly the same spot multiple times. Unfortunately the steel prototypes did not achieve the desired penetration into the concrete.

The next portion of testing was conducted by Doctors Krauthauser and Klusewitz at Army Research Labs. Due to the nature of our pneumatic cannon and the limited speed of expanding gas in a chamber, we were unable to achieve the high velocities necessary for penetration into reinforced concrete. ARL was able to use their high caliber powder guns to launch our projectiles. Using our tungsten pieces and sabots that they designed to fit their guns, they fired the penetrators into 18 inch reinforced concrete to determine the penetration depth at different velocities. From their testing we determined that in order to achieve the desired six inches of penetration into reinforced concrete, a worst-case scenario, we would need to fire at 1200 feet per second, three times faster than our cannon was capable of.

The final portion of testing was testing for proper deployment of the entire system with cable, rear spacer and lead line. It was set-up and conducted in the same manner as the steel prototype tests. This test proved the validity of our spooling system and the success of rear components upon impact with a solid surface.

5. PROJECT MANAGEMENT

Project management was focused around the different tasks that need to be completed in order to be successful, split into two phases; construction and testing. The construction phase drove the testing phase, requiring completion before the testing stages could be conducted. Afterward, the results of the testing drove limited redesign of the project in an iterative design process

The first of the many tasks completed was construction of the pneumatic cannon, led by Cadet Walter. Concurrently, construction of the projectile was led by Cadet Freitag. All of the management portions of the project to include scheduling, planning and report requirements were handled by Cadet Coe. Cadets Martin and Knittle were focused on the system integration components and on the construction of testing moulds that would be necessary for the later steps. Additionally, Cadet Lucas was responsible for finances and material resources.

When many of the components neared completion and the project transferred to a testing phase. Cadet Coe was the lead for this portion, organizing and planning the test events. Cadet Walter focused his efforts on measuring and achieving the accuracy and precision of the projectile firing, Cadet Freitag was in charge of measuring the impact of the projectile and working to achieve the best possible penetration. Cadets Knittle and Martin were in charge of setup and documentation of the tests and Cadet Lucas will be the safety officer.

The Gantt chart in Appendix N sets out a timetable for each task of the main projects, cannon construction, projectile construction, testing, and report requirements. Much of the project was frontloaded into the months of January and February, requiring a push from the beginning, and providing a small amount of room for error and unexpected issues. As expected, there were unforeseen issues that bogged down the project and slowed construction or limited testing. Even with these challenges we were able to complete multiple redesigns of the projectile and prepare ourselves for the competition.

The critical path of this project was the construction, testing, and redesign of the projectile. As the key component of our design it received the main focus of our attention and drove all of the other requirements.

The division of labor and specialization into certain areas of expertise allowed the group to make the most of its time, with each individual becoming a subject matter expert on their components.

4. LESSONS LEARNED

Over the course of the entire project there were many lessons learned. One of the first lessons learned was during the first semester when the group was getting to know each other while simultaneously having to get started on creating our preliminary designs. It was actually beneficial for us to not know each other as we could bring different ideas to the table. We had not been forced into a group think mentality. Because of this we developed numerous initial ideas and were able to continue on with one that proved to be successful. The lesson learned was even though the group is still new, good work can get done and the beginnings of the design phase should not wait until the team is necessarily comfortable with one another.

The next lesson learned involved the design process. After agreeing on the design we wanted, we iterated through numerous variations of all the aspects of our design, continually modifying it to better the results. We learned that adequate time needs to be set aside to design and designing early is key. Going along with this idea, we learned the importance of also setting aside time to test. Testing for us was the most valuable aspect of our design process. Based on the advice from our advisor we gave ourselves plenty of time to physically test our designs. These tests led to changes in the design that we would not have known to do because in the conceptual world, the design worked. It was not until we took it out into the field and tested it did we find the problems. We gave ourselves that extra time and that allowed us to fix the problems and come out with a better design. At the competition it was evident who had learned that lesson and who had not as both Air Force and Navy brought design they had not real world tested, only lab tested, and their designs failed.

Luckily for our group we did not have to learn many hard lessons about working as a team. Our group worked well together and we were able to depend on one another to get assigned tasks completed. In this we learned the value of having a good team and understanding each others' strengths and weaknesses. We were able to match people up with their skills. This made wanting to complete the tasks given fun and efficient. If possible the lesson learned from this is to surround oneself with people that are diverse in skill sets and work well together.

As a group we learned an important lesson in manufacturing. All of us experienced at least one instance in which a purchased or personally manufactured part did not fit like it was supposed when it fit perfectly in the design on paper. We had to learn about tolerances and the disconnect between creating something on paper and physically building it. Some of these lessons were easy fixes while others required the purchasing of completely new parts or time wasted reconstructing components. In any case, this lesson was one that we all experienced and one that will not be easily forgotten.

The final important lesson we learned was in terms of project management. As described before we had a stellar team that was able to have tasks delegated to it by our group leader and have the tasks completed. However, there were times in which we would not meet deadlines or fail to complete certain tasks. We had been doing well but during the middle of the second semester we relaxed and our project management slipped. We learned a couple of things from this. The first was we would stick together and allow no one person to take the blame for any one mistake. The second was we needed to be diligent throughout the project and continue to focus and meet our deadlines. Although some tasks seemed trivial, they helped to keep the group focusing on the important parts of the project. Project management, while difficult, is actually beneficial and can help keep projects moving even in “slow” times.

All in all as a group we learned many valuable lessons in both engineering and team work. Many of the lessons can be transferred to the Army during our time as platoon leader. It may be a few years before any of us utilize the design process but having a good understand of it and having been through it once and learning the potential pitfalls will definitely be useful in the future.

5. SUMMARY

The endstate of our design was a multi-stage system composed of an anchor and ascension system. The anchor’s main feature was its tungsten penetrator that not only created the hole but also held majority of the climber’s weight. The anchor had a loop at the end allowing for a line to be run through providing the rope necessary to climb. The ascension system used was a commercially bought device that we utilized to successfully ascend the rope. Our design met all of the given competition objectives of size, weight, stealth, ease of use, and innovation with the exception of only marginally meeting the number of climbers category as the provided ascension system failed.

It is also pertinent to note that we successfully designed and manufactured our own firing device that modeled the muzzle energy of the M203, the weapon system we designed our device to be fired from. This was not initially a competition requirement but became one when we could not modify existing Army munitions in the given time frame of the competition.

6. CONCLUSIONS

In all, this capstone project was a very positive experience that tied together our mechanical engineering knowledge and challenged us to meet deadlines and objectives. The project spanned almost the entire year, but we realized that even that was not a lot of time for the amount of work we wanted and needed to do. The entire team was eager to work on a real world problem facing the military and we focused our efforts on actually contributing something useful to that effort rather than orienting our approach towards simply winning a competition with ambitious ideas that did not come to fruition.

Looking forward, we hope to make our system readily available to the war fighter. We have demonstrated proof of concept with the air cannon, still the device needs to be packaged into a projectile that can be fired from an existing Army weapon system. Once this is complete, the ground soldier can begin to carry our device as another piece of gear, allowing him more versatility and maneuverability.

7. ACKNOWLEDGMENTS

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Mr. Rob Lee
Mr. Rod Wilson
Dr. Christopher Conley
Mr. Michael Boss
Mr. Don Hoffman

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APPENDICES

APPENDIX A

LITERATURE REVIEW

1. Hilti Corporation, < http://www.hilti.com/holcom/ >

Hilti Corporation was contacted in order to discuss some of their products and how the products worked. Specifically we wanted to understand how they determine the pull out strength of their concrete nails. We had a lengthy discussion on some of the characteristics of how a nail would get set into the wall and how the material reacts to being fired into.

2. Permabond Engineering Adhesives, “Permabon 2011 Cyanoacrylate Technical Datasheet” <http://www.permabondllc.com/TDS/2011_TDS.pdf>

This website was used to research adhesives and their affects on potential materials that our project could be tested on. It provided a variety of adhesive types, ranging in strengths and bondable materials. From this site we were able to determine the best adhesive for our design.

From this site we also were able to research and choose an accelerant. The setting time for most of the adhesives was longer than we had available during the competition. From this website we determined the available accelerants that would speed up the setting time. With the provided accelerant the adhesive can set in a matter of seconds.

3. Ryan Bavetta, *Big Steel Air Cannon* <http://supersoda.com/detail.php?id=000000 00143>

This website article was written by a private engineer, and describes the construction and testing process for two pneumatic cannons that he built. The first was a smaller-scale project involving lower pressures, and the other was a large cannon that fired at higher pressures (relatively). The article discusses construction of both cannons, as well as pertinent safety steps that need to be taken. The large cannon managed to fire a potato at 250 mph and over 600 feet in range.

This article helped largely in conceptually determining which components I would need for my cannon, and what specific type of components I would need. This article drove me to use a solenoid poppet valve, due to its rapid opening time and high operating pressure. I also used this website to confirm the need for a hydro-static pressure stress test (called a hydro test in the article) before putting air to high pressures inside the cannon.

4. McMaster-Carr <www.mcmaster.com>

This is the website for McMaster-Carr, the industrial supply company. They have hundreds of thousands of products for sale, as well as thousands of pages of information regarding the sizing and selection processes behind these components.

This website and company was an immense help in learning about the fittings and sizing that was needed for the pneumatic cannon’s components, as well as information about the stress and pressure capabilities of these components. Finally, many parts were ordered from this site.

5. Robert S. Bernard, *EMPIRICAL ANALYSIS OF PROJECTILE 0F PENETRATION IN ROCK*, Miscellaneous Paper S-77-16, Soils and Pavements Laboratory, U.S. Army Engineer Waterways Experiment Station.

This is a source used in order to derive useful information regarding projectile penetration in rock for a given nose projectiles. From this source, we were able to obtain an empirically derived formula for predicting depth of penetration into rock based on mass and speed of the projectile. This also broadened our knowledge of how surfaces and projectiles behave when they come in contact with one another.

This article directly pertains to our project because we are launching a projectile into a surface of some kind, and it may possibly be made of rock or stone. Since we are trying to design a projectile that is able to penetrate multiple surfaces, we had to look into materials such as natural stone. This article was also very useful because it gave us a method to determine benchmarks we need to design towards in regards to projectile velocity and mass.

6. SwageLok <www.swagelok.com>

Like McMaster-Carr, SwageLok provides fittings and components for systems in heavy duty industrial applications. They also have immense literature on system components, fitting specifications, and tolerances for machined pneumatic components.

This website and company was very useful in providing information about fittings and the various types that are available for pneumatic systems, as well as providing a secondary source for components to McMaster-Carr.

7. Q.M. Li and X.W. Chen, *Dimensionless formulae for penetration depth of concrete target impacted by a non-deformable projectile*, School of Civil and Environmental Engineering, Protective Technology Research Centre, Nanyang Technological University, Singapore.

This reference was the main source in which the research of the background was conducted. It references nose shape factors, correlations of penetration in concrete, the two regions of penetration in a material, and prediction and models for non-deformable projectiles. The biggest information that was gathered from this article was the knowledge of the different impact deformation geometries. From this source, we learned about the crater and tunneling region, and the theory behind their formations. We also learned about how different nose shape factors could affect the penetration of our projectile.

This source was extremely useful to us in helping determine what kind of designs we should consider for the projectile alternative. From this, we can test different nose geometries, as well as see their effects on the geometry of the deformation of the impact surface. The impact surface is critical to our design because we need the projectile to stay lodged inside of the surface, and we need to consider the extent of destruction that could be caused by a rapidly moving projectile.

8. X.W. Chena, S.C. Fana, and Q.M. Lib, *Oblique and normal perforation of concrete targets by a rigid projectile*, Protective Technology Research Center, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore, and Department of Mechanical, Aerospace and Manufacturing Engineering, Manchester, UK.

This resource was very useful in order to obtain information regarding oblique penetration of projectiles. This is very pertinent to our project since the angle of impact is most likely not going to be normal to the surface, and we are going to be shooting up at an angle. One important fact that was learned is that when a projectile enters a surface at an oblique angle, it tends to begin positioning itself parallel to the surface as it enters the material. This is a serious design point because we would like the projectile to enter at as normal an angle as possible.

The information is critical to our design because of the nature of the competition. We need to launch the projectile up a tall objective, so naturally it will enter the surface at an angle. This is a design consideration that is very important to consider, and it must be dealt with accordingly through the design process

APPENDIX B
CUSTOMER REQUIREMENTS

1. Ability to accommodate troops and their gear, approximately 300lbs

2. Capability to climb rock faces and concrete/adobe walls of 90ft or taller, that are vertical or near vertical – this may be replicated by typical gym climbing walls and firefighter training towers.

3. The ability to provide climbing assistance without the need to grapple over the top edge of the structure is desired. These faces may have some structure (fissures, ledges, windows, etc), but the ability to accommodate a variety of conditions is desired.

4. Anchor points are possible either by placing "friends" or pitons. Permanent holes in the wall faces are allowed.

5. The ability for the device to permit multiple pitches during the climb or to allow use by multiple troops is desired (reusability).

6. Rate of climb should be faster than what is done today, or less strenuous than current operations at comparable speeds.

7. Minimize the weight of the system that needs to be carried by the operator (s).

8. Device/system should be easily carried by a single troop, ideally fitting in an assault/tactical backpack with volume of roughly 20”x10”x8”, or attaching to a backpack in a way that allows soldier mobility, or fitting in a larger rucksack with dimensions of approximately 24”x14”x10”.

9. It is desirable that the system allows the operator to do other tasks while climbing, including holding and using his weapon, radio or other equipment.

APPENDIX C
QUALITY FUNCTION DEPLOYMENT

Problem Statement: The mission of our design team is to create a system that allows troops, with their equipment, to scale buildings or mountain faces under a variety of conditions, efficiently and effectively. This system is constrained both by time and resources, with a competition date of 16 April and an allocation of thirty thousand dollars from the Air Force.

		Engineering Characteristics											
Improvement Direction		↓	↓	↑	↑	↑	↑	↑	↑	↓		↓	↑
Units		lb	ft^3		watts	ft-lb	#	ft	degrees	#	Competitor Rankings		1
Customer Requirements	Importance Weight Factor	Weight	Volume	Control System	Battery Power	Motor Power	Surface Options	durability	innovation	number of parts	A	B	
Functionality	0.2222			9	9	9	9			3			
Usability	0.1944	3	3	9			9		3	3			
Speed	0.1667	3			9	9	3						
Ease of Operation	0.1389			9					9	3			
Size	0.0833	9	9		3	3	3	9		3			
Weight	0.0833	9	9		3	3	3	9		3			
# of Climbers	0.0833			3			3						
Innovation/elegance	0.0278						9		9	3			
Stealth	0.0000	3	3		9	9	3						
Raw Score		2.58	2.08	5.25	4.00	4.00	5.25	1.50	2.08	2.25			
Relative Importance		0.089	0.072	0.181	0.138	0.138	0.181	0.052	0.072	0.078			
Rank Order		4	3	2	5	1	9	7	7	6			
Technical Assessment													
Target Values		>3	1	simple	?	500	3	100	3	100			
Units		lb	ft^3		watts	ft-lb	#	ft	degrees	#			

Design Specification List

Engineering Characteristics	Relative Importance	Target (with units)
Surface Options	0.181	3 (#)
Control System	0.181	simple
Motor Power	0.138	? (watts)
Battery Power	0.138	500 (ft-lb)
weight	0.089	3 (lb)
number of parts	0.078	100 (#)
volume	0.072	1 (ft^3)
simplicity	0.072	3 (degrees)
durability	0.052	100 (ft)

APPENDIX D
FUNCTIONAL DECOMPOSITION

Ascend Vertical/Near Vertical Obstacle

1.0 Interact with User
- 1.1 Allow Lifting of user
  - 1.1.1 Needs to come with harness
  - 1.1.2 Harness needs to be compatible with user's gear
  - 1.1.3 Needs to come with ascension assisting device
- 1.2 Allow Controllability
  - 1.2.1 Input Ascent
  - 1.2.2 Input Descent
  - 1.2.3 Allow for low hassle control of both
    - 1.2.3.1 Ergonomically built into design (on the weapon, perhaps)
    - 1.2.3.2 Easy to make input (not hard to press/switch)
    - 1.2.3.3 Easy to do without looking at controls
      - 1.2.3.3.1 Need to be able to feel controls
    - 1.2.3.4 Should not be too easy to input, to avoid misfires
- 1.3 Allow for safe use
  - 1.3.1 Avoid Sharp Edges/Points
  - 1.3.2 Avoid Exposing Chemicals
  - 1.3.3 Prevent premature combustion of propellant
  - 1.3.4 Prevent exposure to high velocity components
    - 1.3.4.1 Prevent exposure to the line
    - 1.3.4.2 Prevent exposure to backblast
    - 1.3.4.3 Prevent exposure to the projectile
  - 1.3.5 Make strong enough to hold user's weight (300 lbs)

2.0 Interact with Harness
- 2.1 Connect to harness
  - 2.1.1 Multiple attachment points to harness
  - 2.1.2 Multiple types of line/d-rings can be attached

3.0 Interact with Wall
- 3.1 Secure lead line to wall

4.0 Interact with Weapon System
- 4.1 Fits M203/AT4/LAW chambering
- 4.2 Allows for weapon functionality during/post use
- 4.3 Compatible with existing trigger mechanisms

5.0 Interact with Environment
- 5.1 Survive Impact
  - 5.1.1 Store sensitive components within structure
    - 5.1.1.1 Allow attachment points to remain connected

5.1.1.2 Prevent damage to lead line

5.1.1.3 Don’t make things so structurally sound that chemical capsules can’t break.

5.2 Survive Dust

5.2.1 Keep dust/debris out of chemicals

5.3 Survive Storage

5.3.1 Repel Rust

5.3.2 Survive transportation in combat

5.3.3 Repel Water

5.3.4 Prevent premature mixing of chemical components

APPENDIX E
MORPHOLOGICAL CHART AND DESIGN ALTERNATIVES

Functions		Means	
		Glue	Penetrator
1	Interact with User		
1.1	Allow lifting of user		
1.1.1	Needs to come with harness	N/A	N/A
1.1.2	Harness needs to be compatible with user's gear	Hard point attachment and D-link	Hard point attachment and D-link
1.1.3	Needs to come with ascension assistance device	Ascension device attaches to static rope	Ascension device attaches to static rope
1.2	Allow controllability		
1.2.1	Input ascent	Buttons on ascension device	Buttons on ascension device
	(Underlying Physics)	electronic signals sent from connecting electrodes	electronic signals sent from connecting electrodes
1.2.2	Input descent	Buttons on ascension device	Buttons on ascension device
	(Underlying Physics)	electronic signals sent from connecting electrodes	electronic signals sent from connecting electrodes
1.2.3	Allow for low hassle control of ascent/descent		
1.2.3.1	Ergonomically built into design (on weapon perhaps)	Cable from ascension device to weapon system	Cable from ascension device to weapon system
	(Underlying Physics)	conductive materials used to pass signals	conductive materials used to pass signals
1.2.3.2	Easy to make input, not hard to press/switch	Well constructed buttons on ascension device	Well constructed buttons on ascension device
	(Underlying Physics)	small force required to depress buttons	small force required to depress buttons
1.2.3.3	Easy to do without looking at controls		
1.2.3.3.1	Need to be able to feel controls	elevated buttons	elevated buttons

	(Underlying Physics)	unique texture from surrounding area	unique texture from surrounding area
1.2.3.4	Should not be too easy to input, to avoid misfires	stiff buttons	stiff buttons
	(Underlying Physics)	Force great enough to resist easy depression	Force great enough to resist easy depression
1.3	Allow for safe use		
1.3.1	Avoid sharp edges/points	Encase all components	Sand/finish/cover all sharp components
	(Underlying Physics)	Construct shell using brittle material to surround components	Using a strong material to remove the sharp excess material
1.3.2	Avoid exposing chemicals	Ensure all chemicals are properly encapsulated	n/a
	(Underlying Physics)	Material encapsulating chemicals is resistant to chemical properties	n/a
1.3.3	Prevent premature combustion of propellant	Design to prevent combustion until firing pin strikes primer	Design to prevent combustion until firing pin strikes primer
	(Underlying Physics)	Primer material resistant to combustion	Primer material resistant to combustion
1.3.4	Prevent exposure to high velocity components		
1.3.4.1	Prevent exposure to the line	Encase the line	Encase the line
1.3.4.2	Prevent exposure to back blast	Educate user on safety area	Educate user on safety area
	(Underlying Physics)	Rapid expansion of gases can cause death or serious injury	Rapid expansion of gases can cause death or serious injury
1.3.4.3	Prevent exposure to projectile	Educate user on safety area	Educate user on safety area
	(Underlying Physics)	Fast moving projectiles can cause death or serious injury	Fast moving projectiles can cause death or serious injury
1.3.5	Make strong enough to hold user's weight (300 lbs)	Glue is strong enough to hold weight	Spike is large enough to hold weight
	(Underlying Physics)	Glue properties are strong enough to withstand shear stress	Bending moment of weight is not larger than the strength of material

2	Interact with harness		
2.1	Connect harness		
2.1.1	Multiple attachment points to harness	Multiple nylon loops in harness	Multiple nylon loops in harness
2.1.2	Multiple types of lines/D-rings can be attached	Make attachments points universal	Make attachments points universal
	(Underlying Physics)	The attachment hole is large enough to accept multiple size attachments	The attachment hole is large enough to accept multiple size attachments
3	Interact with Wall		
3.1	Secure lead line to wall	Eyelet glued to rock	Spike penetrate rock
	(Underlying Physics)	Friction of glue keeps attached to wall	Friction on spike keeps it in wall
4	Interact with Weapon System		
4.1	Fit M203/AT4/Law chambering	Design round size to fit caliber	Design round size to fit caliber
	(Underlying Physics)	Machine proper size to correct tolerances	Machine proper size to correct tolerances
4.2	Allows for weapon functionality during/post use	Design to allow for firing of weapon during use	Design to allow for firing of weapon during use
4.3	Compatible with existing trigger mechanisms	Design round to match existing rounds of same caliber	Design round to match existing rounds of same caliber
	(Underlying Physics)	Machine round to proper dimensions	Machine round to proper dimensions
5	Interact with Environment		
5.1	Survive Impact		
5.1.1	Store sensitive components within structure		
5.1.1.1	Allow attachment points to remain connected	Design to allow lead line to stay connected to eyelet	Design to allow lead line to stay connected to eyelet
	(Underlying Physics)	strength of line and eyelet stronger than impact force	strength of line and eyelet stronger than impact force
5.1.1.2	Prevent damage to lead line	Membrane separating lead line from glue	Make lead line strong enough to handle impact forces

	(Underlying Physics)	Design membrane that can withstand impact	Line strength stronger then impact force
5.1.1.3	Don't make things so structurally sound that chemical capsules don't break	Design capsules to withstand firing but brittle	n/a
	(Underlying Physics)	Material tough but brittle	n/a
5.2	Survive dust		
5.2.1	Keep dust/debris out of chemicals	Design capsule to prevent materials from entering chemicals	n/a
	(Underlying Physics)	encapsulate materials in lab prior to leaving sterile environment	n/a
5.3	Survive storage		
5.3.1	Repel rust	Use non corrosive materials	Use non corrosive materials
	(Underlying Physics)	Non-corrosive materials cannot oxidize, preventing rust	Non-corrosive materials cannot oxidize, preventing rust
5.3.2	Survive transportation in combat	Design to be shock resistant	Design to be shock resistant
	(Underlying Physics)	encapsulating material stronger than average shock round will experience	encapsulating material stronger than average shock round will experience
5.3.3	Repel water	seal round	seal round
	(Underlying Physics)	water molecules are larger than porosity of material	water molecules are larger than porosity of material
5.3.4	Prevent premature mixing of chemical components	Separate the chemical components	Separate the chemical components
	(Underlying Physics)	two separate casings prevent molecules from mixing	two separate casings prevent molecules from mixing

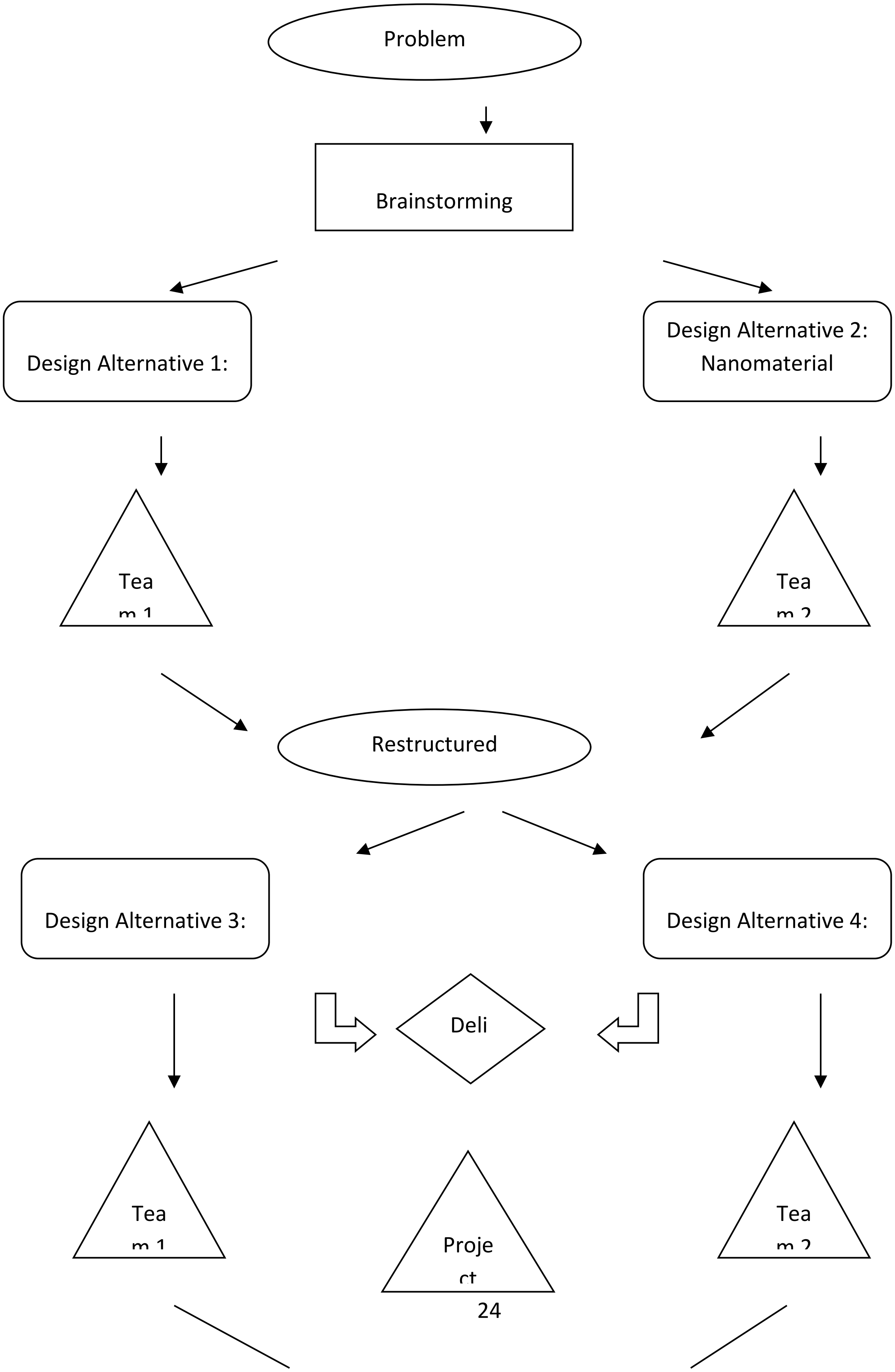
APPENDIX G
DECISION MATRIX

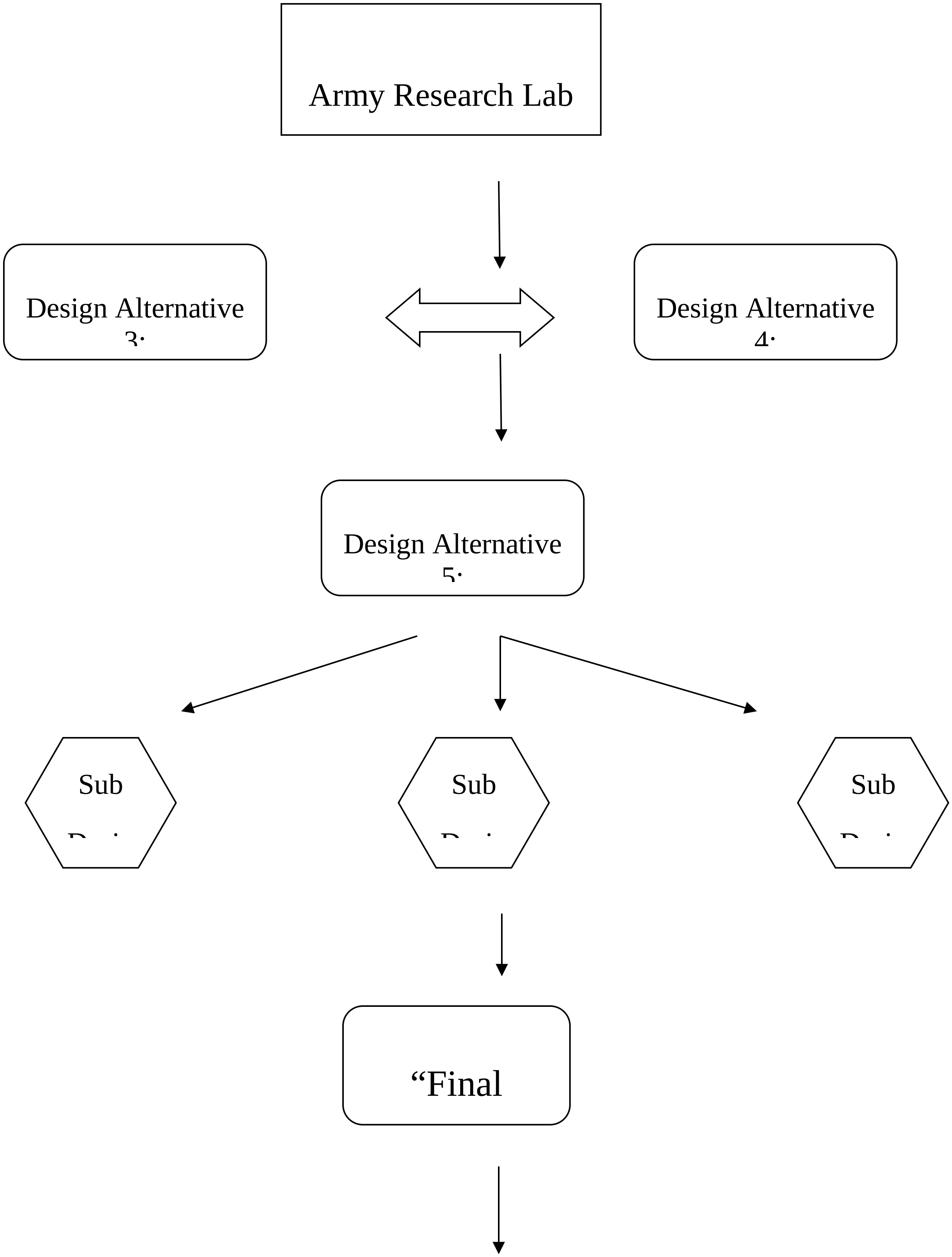
Alternative 1: Penetrator puts anchor into vertical obstacle surface

Alternative 2: Glue Capsule sticks anchor onto vertical obstacle surface

			Alternative 1			Alternative 2		
Design Criterion	Weight Factor	Units	Magnitude	Score	Rating	Magnitude	Score	Rating
Surface Options	0.181	#	10	8	1.45	10	8	1.45
Weight	0.089	lb	0.5	10	1.81	1	8	1.45
Number of Parts	0.078	#	4	10	1.81	4	10	1.81
Volume	0.072	ft^3	0.003472222	10	1.81	0.0138889	9	1.63
Simplicity	0.072	deg	3	10	1.81	5	8	1.45
				Total Rating	8.69		Total Rating	7.78

APPENDIX H
PROJECT ARCHITECTURE




Army Research Lab
Design Alternative 3:
Design Alternative 4:
Design Alternative 5:
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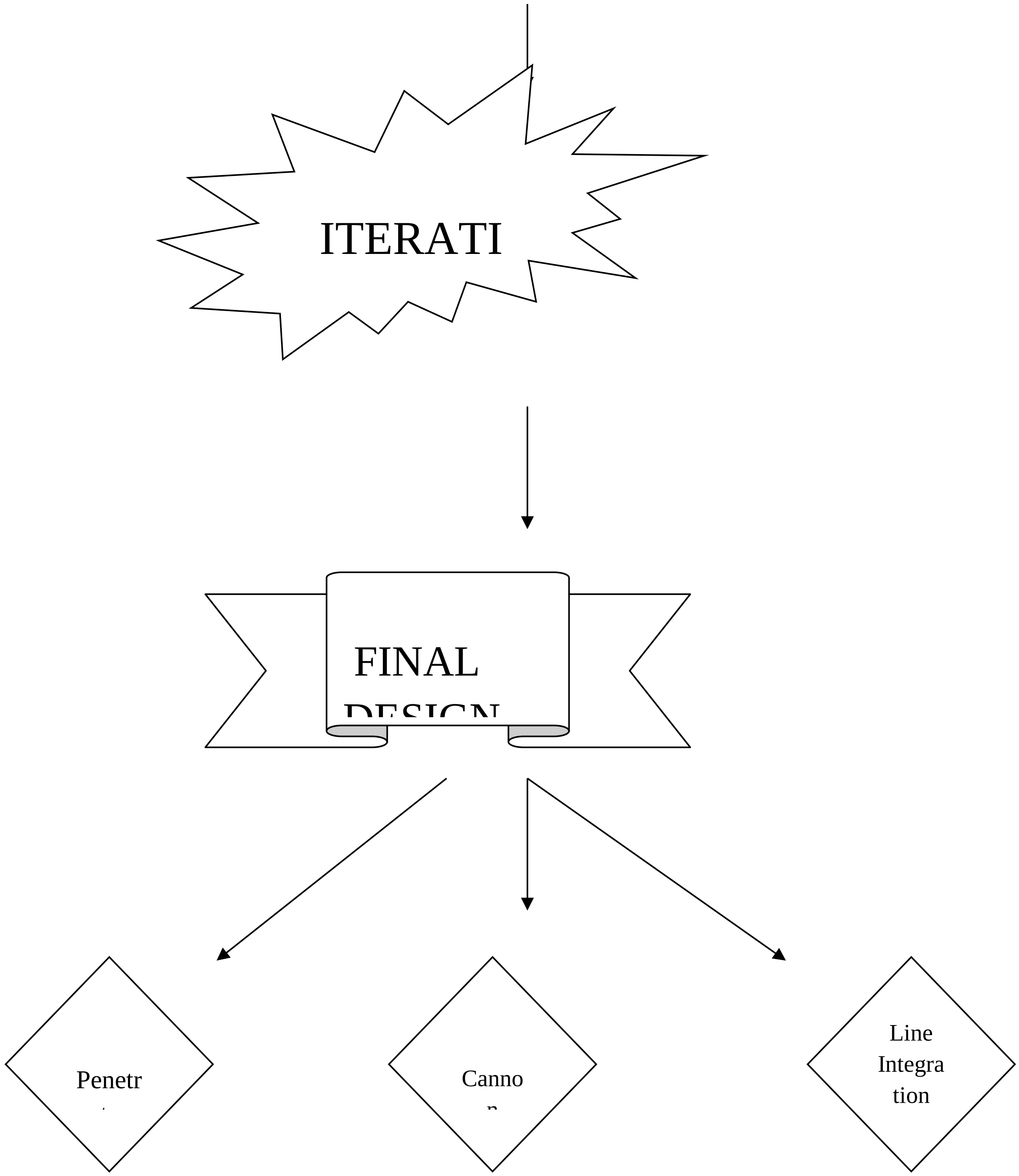
“Final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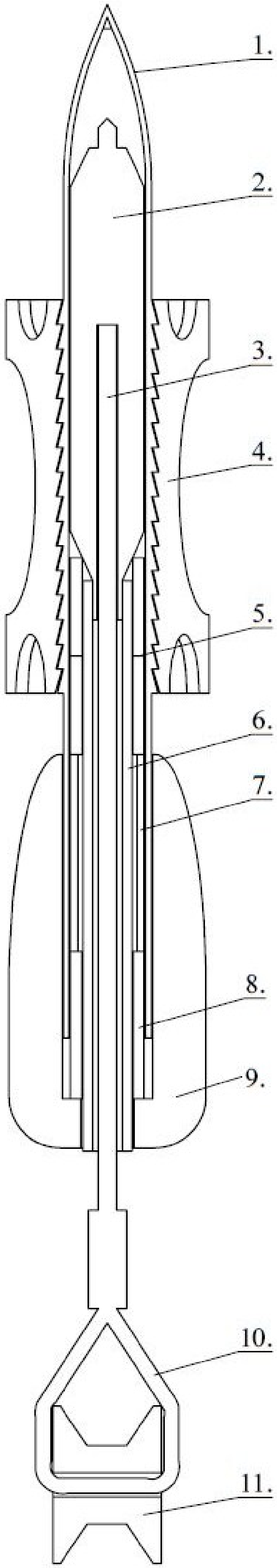
APPENDIX I
ENGINEERING DRAWINGS



1. Sheath
2. Penetrator
3. Cable
4. Sabot
5. Expandable Anchor
6. Spine
7. Guide Rail
8. Hammer
9. Fins
10. Cable Loop
11. Lead Line Wheel

PPENDIX J

Bill of Materials

urchase

ty	Part/Material Description	Part Number	Unit Cost	Total Cost	Source	Delivery Date	Date Required	Responsibility
	Acrylic Rod	23736	5.45	13.21	Tap Plastics	Mid JAN	Mid JAN	CDT Walter
0	80 Lbs Quikrete	10385	37.2	37.2	Lowes	Mid JAN	Mid JAN	CDT Lucas
0	1x6x8 Lumber	30906	48.7	48.7	Lowes	Mid JAN	Mid JAN	CDT Lucas
	60" CR Steel	-	25.05	37.87	The Metal Store	Mid JAN	Mid JAN	CDT Freitag
0	Int. Thr. Anchor	97083A290	9.83	9.83	Mcmaster-Carr	Mid JAN	Mid JAN	CDT Freitag
0	High Str. Anchor	97073A720	25.18	25.18	Mcmaster-Carr	Mid JAN	Mid JAN	CDT Freitag
0	Zinc Drive Anchor	97090A106	10.45	10.45	Mcmaster-Carr	Mid JAN	Mid JAN	CDT Freitag
0	Zinc Drive Anchor	97090A110	9.23	9.23	Mcmaster-Carr	Mid JAN	Mid JAN	CDT Freitag
	Threaded Pipe	4813K64	199.18	218.2	Mcmaster-Carr	Mid JAN	Mid JAN	CDT Walter
	Plywood	12244	22.98	22.98	Lowes	Mid JAN	Mid JAN	CDT Lucas
	316 St. Stl. Valve	46495K18	30.83	30.83	McMaster-Carr	Mid JAN	Mid JAN	CDT Walter
	High Pr. Hose	5355K112	48.69	57.69	McMaster-Carr	Mid JAN	Mid JAN	CDT Walter
00	Wood Screws	90031A257	18.94	24.07	Mcmaster-Carr	Late JAN	Late JAN	CDT Lucas
	Parker Expander	1x1/4 FG-SS	62.99	62.99	RG Group	Late JAN	Late JAN	CDT Walter
	Mcmaster_Carr 4	multiple	61.5	61.5	McMaster-Carr	FEB	FEB	CDT Lucas
	Mcmaster-Carr 5	multiple	26.25	26.25	McMaster-Carr	FEB	FEB	CDT Lucas
	Mcmaster-Carr 6	multiple	220.17	237.93	Mcmaster-Carr	FEB	FEB	CDT Lucas
	Mcmaster-Carr 7	multiple	52.89	57.87	McMaster-Carr	FEB	FEB	CDT Lucas
	Mcmaster-Carr 8	multiple	8.92	8.92	McMaster-Carr	FEB	FEB	CDT Lucas
	Mcmaster-Carr 9	multiple	141.92	160.69	Mcmaster-Carr	FEB	FEB	CDT Lucas
	Permabond 910FS Adhesive	910FS 1OZ BOTTLE	40.6	73.6	Ellsworth Adhesives	FEB	FEB	CDT Lucas
	Argon Gas, size 80 cylinder	-		99.4	Air Gas	FEB	FEB	CDT Walter
	Valve Unit	8223G005 120/60,110/50	628.54	628.54	ASCO	FEB	FEB	CDT Walter
	2x6x16 Lumber	-	150.12	150.12	Lowes	FEB	FEB	CDT Lucas
	Harris Single Stage Regulator	3000606	114.99	126.63	Harris	FEB	FEB	CDT Walter

APPENDIX J

1	SS Swagelok Tube Fitting	SS-400-6-4AN	9.41	9.41	Swagelok			CDT Walter
1	10 ft pipe		148.87	148.87	Mcmaster-Carr	MAR	MAR	CDT Walter
1	Fishing line		174.99	214.94	Cabelas	MAR	MAR	CDT Lucas
1	Plywood	12229	65.2	65.2	Lowes	MAR	MAR	CDT Lucas
100	Plain Steel Nails	97801A505	2.6	7.08	Mcmaster-Carr	MAR	MAR	CDT Lucas
	Mcmaster-Carr 11		168.73	168.73	Mcmaster-Carr	APR	APR	CDT Walter
1	HD HERO2		299.99	318.94	GoPro	APR	APR	CDT Lucas
1	STERLING black rope	SSS10X	373.9	373.9	Rock-n-rescue	APR	APR	CDT Lucas
6	Petzl Harnesses	14381	750	757.95	Moosejaw	APR	APR	CDT Lucas
1	Fiberglass Rod	854K322	8.45	8.45	Mcmaster-Carr	APR	APR	CDT Walter
2	ABS	#340-21203 and #340-21202	1350	1375	Allegheny	-	Late APR	CDT Freitag
			Total:	5688.35				

Manufacturing

Qty	Part Description	Material	Process	Machine	Date Required	Responsibility
5	Steel Penetrators	Steel	Cut, turn, chamfer, drill	Lathe	Early FEB	CDT Freitag
5	Steel Hammers	Steel	Cut, turn, bore	Lathe	Early FEB	CDT Freitag
15	Aluminum Spine	Aluminum	Cut, bore	Bandsaw, Lathe	Early FEB	CDT Freitag
10	Expanding Anchors	Aluminum	Drill	Lathe	Early FEB	CDT Freitag
1	PVC joiner for electrical circuit	PVC	Bore	Mill	Early FEB	CDT Walter
15	ABS Sheath	ABS	Print	3D Printer	FEB	CDT Freitag thru Mr. Wilson
15	Sabot Petals	ABS	Print	3D Printer	FEB	CDT Freitag thru Mr. Wilson
15	Fin Stabilizers	ABS	Print	3D Printer	FEB	CDT Freitag thru Mr. Wilson
15	Acrylic Spacers	Acrylic	Cut	Hacksaw	FEB	CDT Knittle and CDT Martin
10	Aluminum Spacer	Aluminum	Turn, chamfer, drill	Lathe	Early APR	CDT Freitag
1	Barrel End Cap	Aluminum	Cut, bore, drill, tap, Chamfer	Lathe	Early APR	CDT Walter
1	Tooling Mount for Adapter	Aluminum	Turn, chamfer, Press	Lathe, Mill	Early APR	CDT Walter
5	Tungsten Penetrators	Tungsten	-	-	Early APR	Picatinny Arsenal
5	Tungsten Hammers	Tungsten	-	-	Early APR	Picatinny Arsenal
1	Plastic Adapter	ABS	Cut, turn, bore	Lathe	Mid APR	CDT Walter
1	Bore Sight Adapter	Aluminum	Bore, turn, chamfer	Lathe	Mid APR	CDT Walter

CAPSTONE FINANCES							
	Item	Part #	Supplier	Order Form	Cost	S/H	Total Cost
1	Acrylic Rods	23736	Tap Plastics	acrylic rods	5.45	7.76	13.21
2	80 Lbs Quikrete	10385	Lowes	Concrete and Lumber	37.2	-	37.2
3	2x6x8 Lumber	30906	Lowes	Concrete and Lumber	48.7		48.7
4	60" CR Steel	-	The Metal Store	Steel	25.05	12.82	37.87
5	Int. Thr. Anchor	97083A290	Mcmaster-Carr	Mcmaster-Carr 1	9.83	-	9.83
6	High Str. Anchor	97073A720	Mcmaster-Carr	Mcmaster-Carr 1	25.18	-	25.18
7	Zinc Drive Anchor	97090A106	Mcmaster-Carr	Mcmaster-Carr 1	10.45	-	10.45
8	Zinc Drive Anchor	97090A110	Mcmaster-Carr	Mcmaster-Carr 1	9.23	-	9.23
9	Threaded Pipe	4813K64	Mcmaster-Carr	Mcmaster-Carr 1	199.18	19.02	218.2
11	Plywood	12244	Lowes	Plywood	22.98	0	22.98
12	316 St. Stl. Valve	46495K18	McMaster-Carr	Mcmaster-Carr 3	30.83	-	30.83
13	High Pr. Hose	5355K112	McMaster-Carr	Mcmaster-Carr 3	48.69	9	57.69
14	Wood Screws	90031A257	Mcmaster-Carr	Mcmaster-Carr 2	18.94	5.13	24.07
15	Parker Expander	1x1/4 FG-SS	RG Group	Reducing-Adapter	62.99	-	62.99
16	Staff and faculty expense	-	-	-	6000	-	6000
17				Mcmaster-Carr 4	61.5	-	61.5
18				Mcmaster-Carr 5	26.25	-	26.25
19				Mcmaster-Carr 6	220.17	17.76	237.93
20				Mcmaster-Carr 7	52.89	4.98	57.87
21				Mcmaster-Carr 8	8.92	-	8.92
22				Mcmaster-Carr 9	141.92	18.77	160.69
23	Permabond 910FS Adhesive	910FS 1OZ BOTTLE	Ellsworth Adhesives	Glue	40.6	33	73.6
24	Argon Gas, size 80 cylinder		Air Gas	Argon Cylinder			99.4
25	Valve Unit	8223G005 120/60,110/50	ASCO	Valve 2	628.54	-	628.54
26			Lowes	Molds 2	150.12		150.12
27	Harris Single Stage Regulator	3000606	Harris	Regulator	114.99	11.64	126.63
28	SS Swagelok Tube Fitting	SS-400-6-4AN	Swagelok	Tube Fitting	9.41	-	9.41
29	10 ft pipe		Mcmaster-Carr	pipe2	148.87		148.87
30	Fishing line		Cabelas	fishing line	174.99	39.95	214.94
31	Return Shipping		UPS	return shipping	15	-	15
32	Plywood	12229	Lowes	Plywood2	65.2	-	65.2
33	Plain Steel Nails	97801A505	Mcmaster-Carr	Mcmaster-Carr 10	2.6	4.48	7.08
34	Mcmaster-Carr 11		Mcmaster-Carr	Mcmaster-Carr 11	168.73		168.73
35	HD HERO2		GoPro	Go-Pro Camera	299.99	18.95	318.94
36	STERLING black rope	SSS10X	Rock-n-rescue	ropes	373.9		373.9
37	Petzl Harnesses	14381	Moosejaw	harnesses	750	7.95	757.95
38	Fiberglass Rod	854K322	Mcmaster-Carr	Push rod	8.45	-	8.45
39	ABS	#340-21203 and #340-21202	Allegheny	ABS	1350	25	1375
Total							11703.35

ARL Trip Costs							
1	CDT Freitag	1st Trip- ARL	Per Diem		84	-	84
2	CDT Knittle	1st Trip	Per Diem+ Vehicle		402	-	402
3	CDT Lucas	1st Trip	Per Diem		84	-	84
4	CDT Coe	2nd Trip -ARL	Per Diem+ Vehicle + Gas		301.26	-	301.26
5	CDT Walter	2nd Trip	Per Diem + Gas		139	-	139
6	CDT Freitag	2nd Trip	Per Diem		84	-	84
7	CDT Coe	Competition	Per Diem + Rooms + Gas		282	-	282
8	CDT Freitag	Competition	Per Diem + Rooms + Gas		282	-	282
9	CDT Knittle	Competition	Per Diem + Rooms + Gas		282	-	282
10	CDT Walter	Competition	Per Diem + Vehicle + Gas		282	-	282
11	CDT Martin	Competition	Per Diem + Gas		282	-	282
12	CDT Lucas	Competition	Per Diem		2332	-	2332
Total							2504.26

Allotted Amount	30000
Amount Spent	14207.61
Amount Remaining	15792.39

Molds	355.35
Air Cannon	2104.45
Trip Costs	2504.26
Penetrators	124.68
Staff	6000
Extras	3118.87

APPENDIX L

Risk Management Work Sheet

A. Mission or Task: Capstone Testing	**B. Date/Time Group:** 221000FEB12	**C. Date Prepared:** 23 FEB 2012

D. Prepared By: CDT Lucas, Safety Officer

E. Task	F. Identify Hazards	G. Assess Hazards	H. Develop Controls	I. Determine Residual Risk	J. Implement controls
1. Loading Projectile	1. Premature launch	1. If the chamber is filled, the projectile may launch. (L)	1. Firing Procedure	1. Moderate/ High	1. Verbal commands
2. Launching Projectile	1. Person in flight path 2. Shrapnel 3. Ricochet	1. Projectile hits person 2. Shrapnel hits person 3. Projectile misses target 4. Projectile ricochets off target 5.	1. Firing Procedure 2. Firing area visibly marked 3. Guards (personnel) posted on any paths 4. Firing area clear of all non-essential personnel 5. Guards (material) built around molds	1. High	1. Verbal commands 2. Written SOP 3. Guards (material) constructed out of metal or plexiglass

K. Determine overall mission/task risk level after controls are implemented : Low(L)

APPENDIX M
TEST PLAN

Nose Geometry Test Plan

Test Title: Nose Geometry Test	**Date Test Conducted**: 22 FEB 2012
Description: Test the three different nose geometries in a high pressure firing to determine which has most potential	**Conditions**: • Location: River Courts • Weather: Partly Cloudy, High of 53 • Time required to conduct test: 120 min.
Test Director: Patrick Coe	

Resources Required

Personnel:	**Supplies/Equipment**:	**Facilities**:
• Test Director (Coe) • Safety Officer (Lucas) • Cannon Officer (Walter) • Projectile Officer (Freitag) • Observers: Knittle, Martin	• High Speed Camera • Test Blocks • Test Plugs • Steel Projectiles • Air Cannon • Safety Equipment • Digital camera	• River Courts • Boat House

Prior to Start of Test	**Build-up Strategy**
• Cordon off test area • Set up recording equipment • Anchor down cannon • Conduct inspection of equipment	• Low Pressure Test Plug • Full Pressure Test Plug • Full Pressure Different Geometries

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if It Occurs	**Mitigation Measures**
Projectile Ricochet – Medium Risk	• Place all personnel inside boat house • Work at all times with eye-pro and ACH
Cannon Failure – Medium Risk	• Place all personnel inside boat house • Work at all times with eye-pro and ACH
Unauthorized persons in testing area – Low Risk	• Set up cordon at top of Jurassic Park stairs and Boat House parking lot • Conduct Testing at low traffic time of day
Unstable firing platform – Medium Risk	• Use Concrete blocks to stabilize cannon • Constrict all lateral and vertical barrel movement

Test Tasks

Description (with standards if applicable)	**Results**
Cannon completes multiple full pressure tests	
Hit concrete block with all projectiles	
Measure penetration depth of all nose geometries	
Obtain high speed footage of projectile launch and impact	
Determine best nose geometry for further testing	

Horizontal Shot Test Plan

Test Title: Horizontal Tungsten Test	**Date Test Conducted**: XX MAR 2012
Description: Test the tungsten projectiles as a metric for comparison with previous penetration and future oblique testing **Test Director**: Patrick Coe	**Conditions**: • Location: River Courts • Weather: XXX • Time required to conduct test: 120 min.

Resources Required

Personnel:	**Supplies/Equipment**:	**Facilities**:
• Test Director (Coe) • Safety Officer (Lucas) • Cannon Officer (Walter) • Projectile Officer (Freitag) • Observers: Knittle, Martin	• High Speed Camera • Test Blocks • Tungsten Projectiles • Air Cannon • Safety Equipment • Digital camera	• River Courts • Boat House

Prior to Start of Test	**Build-up Strategy**
• Cordon off test area • Set up recording equipment • Anchor down cannon • Conduct inspection of equipment	• Low Pressure Test Plug • Full Pressure Test Plug • Full Pressure Tungsten (multiple shots)

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if It Occurs	**Mitigation Measures**
Projectile Ricochet – Medium Risk	• Place all personnel inside boat house • Work at all times with eye-pro and ACH
Cannon Failure – Medium Risk	• Place all personnel inside boat house • Work at all times with eye-pro and ACH
Unauthorized persons in testing area – Low Risk	• Set up cordon at top of Jurassic Park stairs and Boat House parking lot • Conduct Testing at low traffic time of day
Unstable firing platform – Medium Risk	• Use Concrete blocks to stabilize cannon • Constrict all lateral and vertical barrel movement

Test Tasks

Description (with standards if applicable)	**Results**
Cannon completes multiple full pressure shots	
Hit concrete block with all projectiles	
Measure penetration depth of tungsten samples	
Obtain high speed footage of projectile launch and impact	
Achieve repeatable results for tungsten projectile	

Oblique Shot Test Plan

Test Title: Oblique Tungsten Test	**Date Test Conducted**: XX MAR 2012
Description: Test the tungsten projectiles in a close approximation of the competition to determine performance. **Test Director**: Patrick Coe	**Conditions**: • Location: River Courts • Weather: XXX • Time required to conduct test: 120 min.

Resources Required

Personnel:	**Supplies/Equipment**:	**Facilities**:
• Test Director (Coe) • Safety Officer (Lucas) • Cannon Officer (Walter) • Projectile Officer (Freitag) • Observers: Knittle, Martin	• High Speed Camera • Test Blocks • Tungsten Projectiles • Air Cannon • Safety Equipment • Digital camera	• River Courts • Boat House

Prior to Start of Test	**Build-up Strategy**
• Cordon off test area • Set up recording equipment • Anchor down cannon • Conduct inspection of equipment	• Low Pressure Test Plug • Full Pressure Test Plug • Full Pressure Tungsten at steadily steeper angles

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if It Occurs	**Mitigation Measures**
Projectile Ricochet – Medium Risk	• Place all personnel inside boat house • Work at all times with eye-pro and ACH
Cannon Failure – Medium Risk	• Place all personnel inside boat house • Work at all times with eye-pro and ACH
Unauthorized persons in testing area – Low Risk	• Set up cordon at top of Jurassic Park stairs and Boat House parking lot • Conduct Testing at low traffic time of day
Unstable firing platform – Medium Risk	• Use Concrete blocks to stabilize cannon • Constrict all lateral and vertical barrel movement

Test Tasks

Description (with standards if applicable)	**Results**
Cannon completes multiple full pressure shots	
Hit concrete block with all projectiles	
Measure penetration depth of tungsten samples	
Obtain high speed footage of projectile launch and impact	
Achieve repeatable results for tungsten projectile at oblique angle	

Pullout Strength Test Plan

Test Title: Pullout Strength Tests	**Date Test Conducted**: XX MAR 2012
Description: Test force required to remove embedded projectile from concrete test samples	**Conditions**: • Location: Mahan Hall • Weather: N/A • Time required to conduct test: 30 Min
Test Director: Patrick Coe	

Resources Required

Personnel:	**Supplies/Equipment**:	**Facilities**:
• Test Director (Coe) • Safety Officer (Lucas) • Projectile Officer (Freitag) • Lab Technician (Mr. Wilson)	• Instron Machine • Test projectile and sample embedded in concrete • Digital camera • Laptop Computer	• Mahan hall B19

Prior to Start of Test	**Build-up Strategy**
• Successfully embed projectile in concrete sample • Coordinate with Laboratory Technicians • Transport sample to B19	• N/A

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if It Occurs	**Mitigation Measures**
Flying concrete/metal splinters - Low	• Wear proper eye protection

Test Tasks

Description (with standards if applicable)	**Results**
Determine Pullout Strength of projectiles (>300 lbs)	
Achieve consistent results for like samples	
Mimic competition conditions as closely as possible	

Accuracy Test Plan

Test Title: Accuracy Test	**Date Test Conducted**: XX MAR 2012
Description: Determine accuracy of air cannon system and implement changes to have accurate, precise, repeatable results **Test Director**: Patrick Coe	**Conditions**: • Location: River Courts • Weather: XXX • Time required to conduct test: 120 min.

Resources Required

Personnel:	**Supplies/Equipment**:	**Facilities**:
• Test Director (Coe) • Safety Officer (Lucas) • Cannon Officer (Walter) • Projectile Officer (Freitag) • Observers: Knittle, Martin	• High Speed Camera • Test Blocks • Tungsten Projectiles • Air Cannon • Safety Equipment • Digital camera	• River Courts • Boat House

Prior to Start of Test	**Build-up Strategy**
• Cordon off test area • Set up recording equipment • Anchor down cannon • Conduct inspection of equipment	• Low Pressure Test Plug • Multiple Full Pressure Test Plugs • Full Pressure Tungsten (multiple shots)

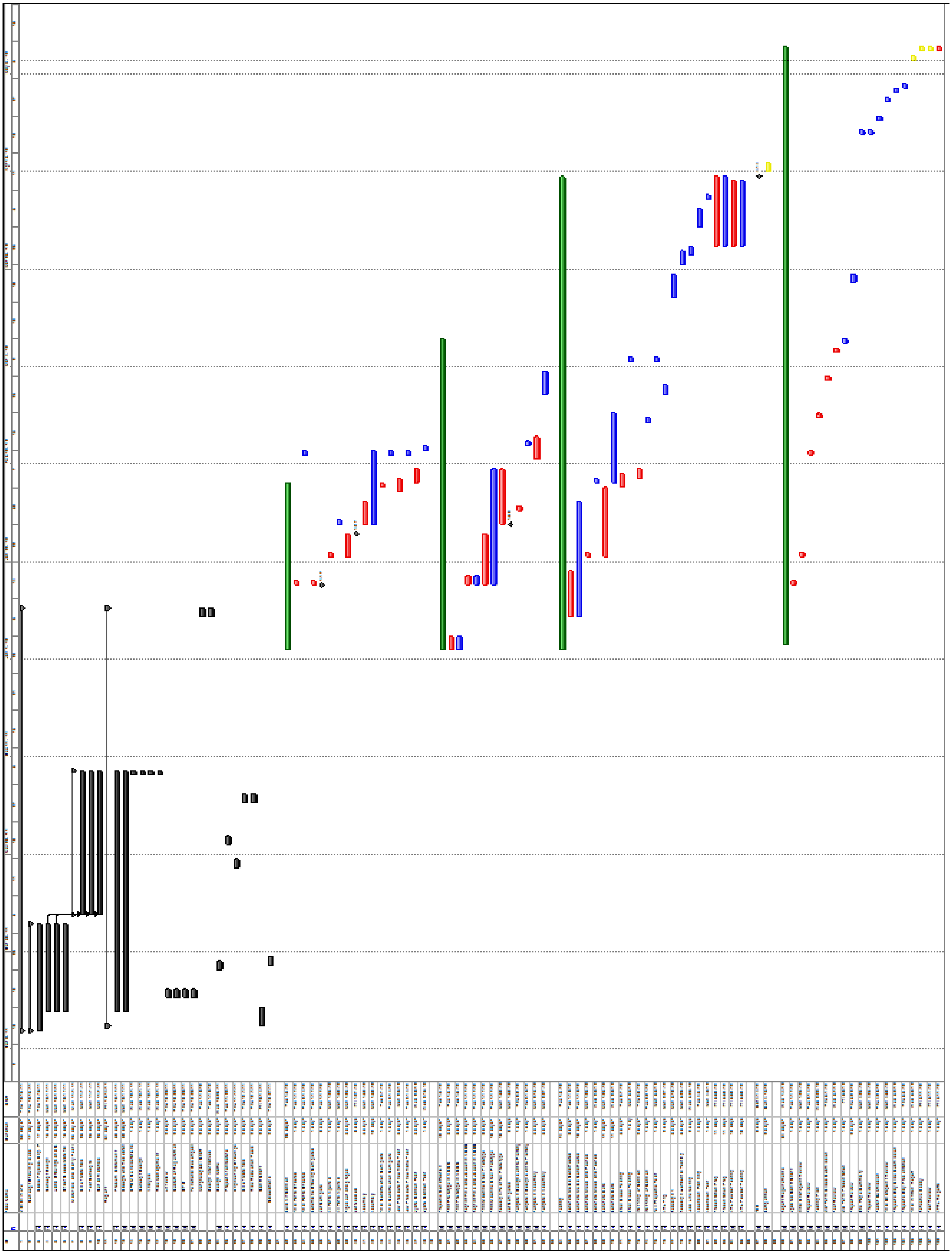
Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if It Occurs	**Mitigation Measures**
Projectile Ricochet – Medium Risk	• Place all personnel inside boat house • Work at all times with eye-pro and ACH
Cannon Failure – Medium Risk	• Place all personnel inside boat house • Work at all times with eye-pro and ACH
Unauthorized persons in testing area – Low Risk	• Set up cordon at top of Jurassic Park stairs and Boat House parking lot • Conduct Testing at low traffic time of day
Unstable firing platform – Medium Risk	• Use Concrete blocks to stabilize cannon • Constrict all lateral and vertical barrel movement

Test Tasks

Description (with standards if applicable)	**Results**
Cannon completes multiple full pressure shots	
Hit concrete block with all projectiles	
Determine precision of cannon with multiple 90 foot shots	
Determine accuracy and aiming offset for 90 foot oblique angle shots	
Correct for deviations to make results repeatable	

APPENDIX N
TEST PLAN



APPENDIX O
SUPPORTING CALCULATIONS

1. Chamber Stress

Hoop

$$\sigma_{hoop} = \frac{pressure * radius}{thickness}$$

Longitudinal

$$\sigma_{long} = \frac{pressure * radius}{2 * thickness}$$

2. Barrel Length Optimization/Projectile Energy Summation

Ideal Gas Law

$$Pressure * Volume = \bar{R} * Temperature$$

Chamber Volume

$$V_{chamber} = length * (\pi * radius^2)$$

System Volume

$$V_{system} = V_{chamber} + x * (\pi * radius^2)$$

Where *x* = position of projectile in barrel

System Pressure

$$\sigma_{hoop} = \frac{initial\ pressure * V_{chamber}}{V_{system}}$$

Viscous Fluid Drag

$$F_{d,viscous} = \frac{1}{2}\rho_{air}\vec{V}^2 * \pi * radius^2$$

Force on Projectile

$$F_{net} = Pressure * \pi * radius^2 - F_{d,viscous} - F_{d,kinetic}$$

Acceleration of Projectile

$$\vec{A} = \frac{F_{net}}{projectile\ mass}$$

3. Number of Shots Per Tank

Chamber Volume (see above)

Shots Per Tank

$$Number\ of\ Shots = \frac{tank\ volume}{chamber\ volume} * \frac{tank\ pressure}{chamber\ pressure} - \frac{tank\ volume}{chamber\ volume}$$

PENETRATOR

A area
X penetration depth
x depth of crater region
I impact function
M projectile mass
f concrete unconfined compressive strength
d diameter
ρ density
V_0 initial velocity of projectile
α shear plugging cone angle
k dimensionless crater depth variable
N nose geometry factor
ρ density of concrete target
H projectile nose height
β obliquity angle
δ angle of directional change

depth of the crater region is the product of *d* and *k*, calculated as

$$x = kd \tag{1}$$

.
The nose geometry factor is a variable that describes the sharpness of the point at the end of the projectile. *N* can be calculated for pointy and conical nose shapes by

$$N = \frac{M}{\rho d^3 \left(1 - \frac{d^2}{(8)H^2}\right)} \tag{2}$$

The impact factor is a function of the velocity of the projectile (*V_0*), the mass of the projectile (*M*), the diameter of the projectile (*d*), and the unconfined compressive strength of the concrete target (*f*).

$$I = \frac{(0.0121)MV_0^2}{d^3 f^{0.456}} \tag{3}$$

Equations (4a) and (4b) are used to find penetration depth, depending on the significance of the crater depth factor (*k*).

When
$$\frac{X}{d} < k$$

$$X = d\sqrt{\frac{(4)kI}{\pi\left(1 + \frac{I}{N}\right)}} \tag{4a}$$

and when
$$\frac{X}{d} \geq k$$

$$X = \frac{2}{\pi} N \ln\left(1 + \frac{I}{N}\right) + \frac{k}{2} \tag{4b}$$

Deep penetration occurs when the ratio of total penetration depth (*X*) and projectile diameter (*d*) is greater than or equal to 5.

$$X/d \geq 5 \tag{7}$$

For deep penetration, the nose geometry has little affect on the total penetration, and it is sufficient to find the dimensionless crater depth using [1]

$$k = 1.5 - 2.5d \quad (8)$$

Table 1. *k* values for various nose-geometries [1]

Nose-Geometry	***K***
Flat nose	0.707
Hemi-spherical nose	1.207
Ogive nose with a caliber radius head of 3	2.367
Ogive nose with a caliber radius head of 4.5	2.77

a. Oblique Penetration Depth

The equations to predict oblique penetration depths are very similar to those of normal concrete penetration, however they are significantly influenced by a function of angle of impact (*β*) and the angle of directional change (δ).

When

$$\frac{X}{d} > k$$

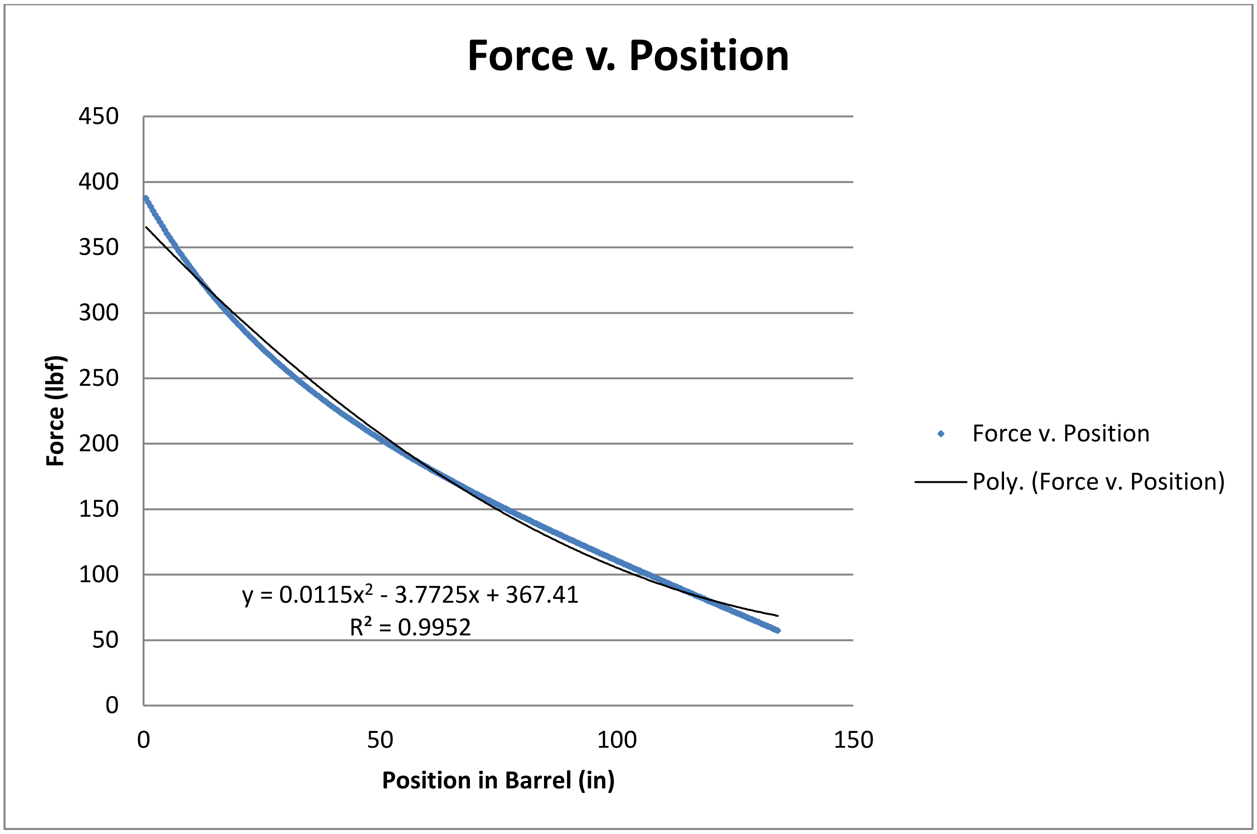
$$X = \frac{2}{\pi} Id(\cos\delta)^2 + \frac{k}{2} \quad (12a)$$

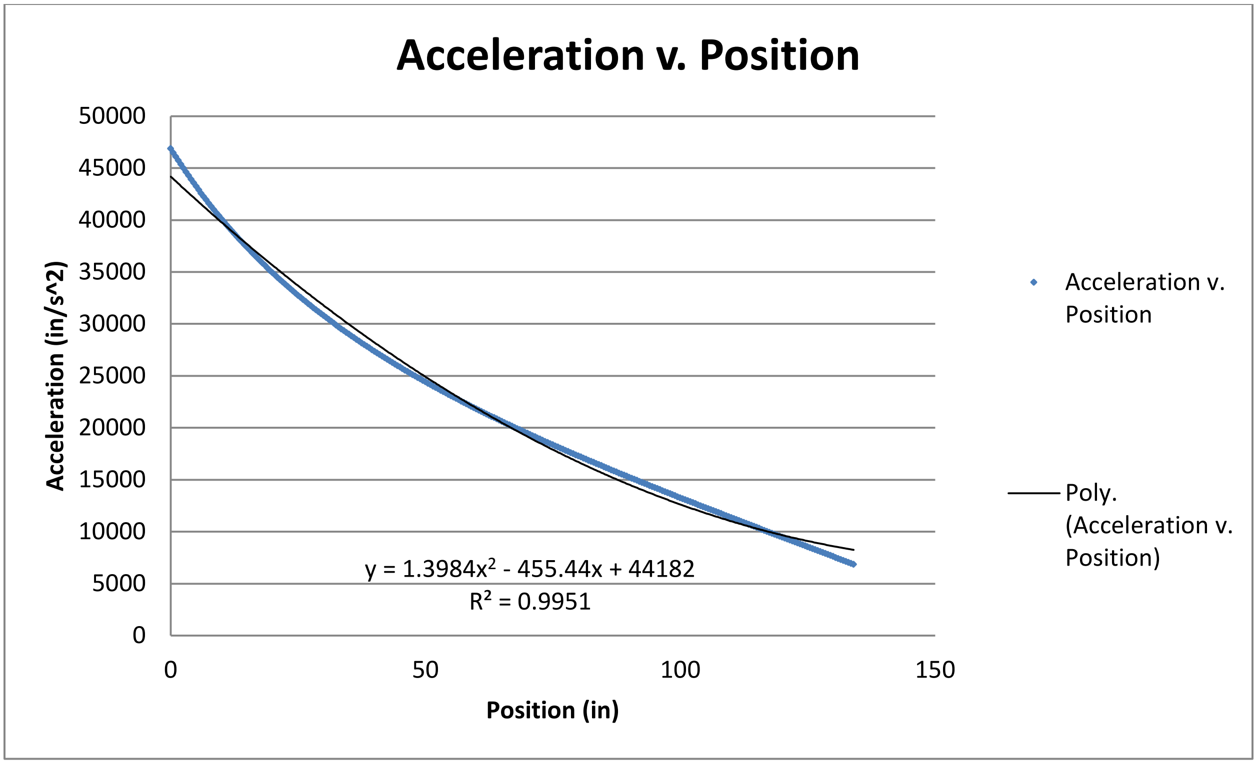
and when

$$\frac{X}{d} \leq k$$

$$X = d\sqrt{\frac{4}{\pi} kI(\cos\delta)^2} \quad (12b)$$

APPENDIX P
PROJECTILE ANALYSIS




Acceleration v. Position
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Acceleration (in/s^2)
0
50
100
150
Position (in)
y = 1.3984x² - 455.44x + 44182
R² = 0.9951
Acceleration v. Position
Poly. (Acceleration v. Position)