

# Electromagnetic Railgun Safety

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**The Cal Poly Electromagnetic Railgun is a system that with the proper precautions can be safely operated. Changes in plugs and boxes insure that the systems cannot be improperly wired, reducing the chances of accidental discharge. By covering exposed wires the system is safe to store as long as the voltage is checked before any maintenance is performed. Updates in procedures remove the possibility of injury to personnel and allow the railgun to be fired repeatedly under similar circumstances. Defined roles for the operators' decreases confusion and allows people to concentrate on their area during testing. As hardware changes it will be necessary for continued documentation and updating of procedures, as well as continued safety improvements to insure safe and consistent testing.**

## I. Introduction

In order to test the effect of a debris impact in space while on Earth we are required to accelerate projectiles up to orbital velocities. To produce the required velocity without a large facility a group at Cal Poly decided to build an Electromagnetic Rail Gun, or EMRG. With the capabilities to accelerate a projectile to orbital velocities Cal Poly will be capable of testing spacecraft components for survival in the space environment. Because of the high voltage and inherent danger of high speed projectiles safety is a major concern for the EMRG.

## II. Background

At the end of Spring Quarter 2011 a group of students led by Jeff Maniglia fired the first shot from the Cal Poly EMRG. Details of the EMRG can be found in "Design, Fabrication, and Testing of an Electromagnetic Rail Gun for the repeated testing and simulation of Orbital Debris Impacts" by Jeff Maniglia, Jordan Smiroldo, Alex Westafall, and Guy Zohar. The test was successful, but it became immediately apparent that changes would be required if the EMRG were to be used frequently, safely and have repeatable results. With all members of the original EMRG team besides Jeff moving onto other projects, I was brought in to help make the EMRG safe to use. As a starting point, I would be making changes based on suggestions given by Cal Poly Risk Management (see Appendix A, "Railgun Safety"). These changes would be broken into procedural changes, basically writing a procedure to be followed for each firing, thus increasing repeatability, and hardware changes, or replacing/upgrading parts of the EMRG to remove the possibility of damage to people or property. The hardware changes were again broken into two categories, the first related to the electrical energy stored in the EMRG and the second concerned with the projectile fired.

## III. Hardware Changes

The main hardware changes done to the EMRG involved the wiring and boxes to charge, fire and discharge the gun. Requirements for the wiring and boxes were to have rated wire for all components, and have the ability to discharge the EMRG with a manual command. The first step then became purchasing wire that would be usable for the EMRG. Wire was found that could hold 600V and over 15 amps, which would cover all operating conditions. (Wall power is approximately 125 volts and 15 amps). While the charging unit for the EMRG would increase the voltage to over 450V, this would also drop the current, so the wire chosen was felt to be more than sufficient. Next, new plugs were found to connect the control wires between the EMRG and the control boxes. These plugs allow for the wires to be separated from the EMRG for storage and transportation. The plugs purchased allowed for customization of shape, meaning each wire can only be plugged into one spot and have the colors lined up. For the controls for the injector and capacitor bank, which are important to always have properly plugged in the correct

way, the plugs were designed so there is only one possible means of connection. For the other systems, the polarity can be switched without affecting the experiments, but it is assumed most students can differentiate between black and red. One future change is to find a way to place the power charger in the EMRG bunker during charging. As is, the charging unit puts out over 450V while in the control room, an obvious hazard. Possible solutions are electrical or mechanical switches.

With the changes in plugs the boxes controlling the EMRG also needed to be updated. For the first quarter of my work, one of the requirements for the boxes was the ability to have a computer controlled firing. To protect against accidental discharge by the computer a physical disconnect switch was added to the system. During the second quarter of my work the control box was changed again, this time to allow for better data collection, and at the same time removed the computer firing with a physical fire button. From a safety point of view this posed no additional problems. To insure proper use of the EMRG and to reuse existing equipment the second control box was designed to interface with the existing plug systems on the EMRG. This means the control box can only be plugged in one way to the various data collection and command cables, removing the possibility of incorrect set up. For future projects the same idea of allowing only a single cable to be plugged into a single spot should be continued, as it prevents accidental charging or discharging of the system.

In the unlikely event of the electrical connections to the EMRG failing, there are also manual safety systems. The first is a bypass between the capacitors and the resistor bank using a door latch. The latch is typically down, keeping the system closed so the capacitors will discharge into the resistors. When firing is to occur, the latch is brought up and secured with a pin attached to a 550 cord. To manually safe the system, all that needs to be done is to pull the pin and gravity will cause the latch to drop. At first the latch was expected to contact two points when dropped, but this proved difficult to accomplish. Instead, the latch is hardwired to one side of the resistor bank, and when dropped will complete the circuit with the capacitors, safely discharging the capacitors. A possible upgrade is to add a spring as a backup in case of gravity failure. Another upgrade would be a lock out system to make the gun incapable of firing unless someone with the key or combination removed the lock holding the latch down. This could be done as lock out/tag out system, for more information see OSHA Standard 1910.147. This standard gave some guidance, and part of the door latch system is a "Remove Before Firing" tag attached to the latch, making it impossible to raise without first removing the tag. As a final backup discharge system a discharge stick was added to the EMRG. A long wooden pole with a conductive tip was wired to the resistor bank. When touched to a part of the EMRG, the discharge stick will cause any stored charge to flow into the resistors. This is a method of last resort, but can also be useful for removing small amounts of energy stored in the EMRG after a firing.

While not firing it is possible for the EMRG to develop a charge which is an obvious safety concern. When I arrived on the team, there was already aluminum blocks that would short the capacitors, reducing the charge build up. A quick addition of 550 cord insured these blocks would remain attached to the gun and not fall off or be misplaced. To monitor the charge on the rails, a voltage meter was attached, giving a heads up if a charge had built up. During firing the voltmeter has to be removed or it will be damaged by the discharge. To facilitate a quick change, the voltmeter is attached using the same plugs as the control cable for the EMRG, arranged in such a way so that the voltmeter could only be attached to one point in the system.

A final measure of protection for the rail gun is covering exposed circuits with insulating material. For the capacitor bank a simple plywood cover is used. While the wood appears to be a poor decision for protection, it is actually a good choice of material. Wood is a good insulator, is cheap to manufacture, and will not be damaged by the electromagnetic pulse caused by the EMRG firing. For other wires, PVC pipe was used to provide insulation. Like the wood, the PVC is inexpensive and easy to work with while still providing protection. The PVC can be easily removed from the EMRG as it is attached with reusable zip-ties. This allows access to the EMRG wires to be worked on when the EMRG is in a safe configuration.

Besides the high electrical charge stored in the EMRG there is also a risk from the projectiles fired. Current firings use a half inch of steel to stop the projectiles, assuming they are able to penetrate a test object. As the EMRG was unable to penetrate 1/16" of aluminum it is unlikely to penetrate the steel. However, the next generation railgun is designed to fire a larger projectile at a higher velocity, which will require more thought put into a ballistic trap. Some preliminary research is detailed in Appendix B, "Steel Ballistic Trap for EMRG", which

shows that over one inch of steel will be necessary to stop the higher velocity projectiles. Another problem is the fragmentation of the EMRG projectile, but for the current system this is a minor issue. Due to the relatively low speeds of the projectiles they are mostly intact after impact, although the high-speed camera used in the firing bunker is protected by a thick piece of Plexiglas. For the second EMRG the issues of fragmentation will likely become larger.

More so than debris, the ElectroMagnetic Pulse (EMP) generated by the EMRG would be the most likely cause of property damage. To mitigate this all electronic components are to be removed a safe distance from the EMRG or be properly shielded. As of now this is simple enough to do, but if the EMRG were to increase in power discharge the distance required to move objects might become larger than viable, requiring increased shielding and more knowledge of the effects of an EMP.

Also present during any EMRG firing is a large amount of plasma which has the potential to interfere with data collection, mainly by overexposing the camera and completing an electrical circuit in break screens used for velocity calculations. To try and counter act the effects of the plasma a Kevlar plasma shield was installed during the third firing (March 2, 2012) which was able to reduce the amount of plasma seen by the camera, but let enough through to interfere with the break screens. To further reduce the effects of plasma, aluminum foil was placed over the Kevlar and a wire attached from the foil to the resistor bank. This will cause the plasma to charge the foil which will dissipate into the resistor bank. By doing this, the plasma should collect at the aluminum foil instead of passing through, which should reduce the interference with the camera and the break screens. However, it is unlikely to stop all of the plasma, so further augmentation may be required.

#### **IV. Procedural Changes**

There were two main procedural changes that needed to be made for the EMRG. The first was to define roles for members and a firing. The second was to formalize the procedure for firing to improve the repeatability of the experiments. The first procedural change is important because it gives defined roles and a defined command structure to the EMRG tests. Due to the danger of the EMRG and the possibility that quick decisions may need to be made, it is necessary that those at a test know what they are doing and that there is ultimately one person responsible for firing the EMRG. Details of the team members can be found in Appendix C, "Responsibilities of Rail Gun Team". For each test, there are four primary positions, the Firing Director, the Safety Officer, the Data Recorder and the Operations Overseer. The Firing Director is responsible for the overall firing and has final say in any decisions. The Safety Officer is responsible for a safe testing environment and keeping personnel up to date with safety concerns. The Data Recorder is responsible for the data collection systems attached to the EMRG. Finally, the Operations Overseer is responsible for reading the procedure and recording any changes to the procedure during testing.

The second main change is creating a usable procedure. The original procedure form was quickly written and had some issues. An updated form was used for the second firing (first one I was at), but as I had no firsthand experience with the EMRG this new procedure had some issues. After the second firing, a more updated procedure was written out and updated more at the third firing. The procedure used for the second firing had been broken into sections for different people, but this was more confusing than helpful. At this point, the procedure is done as a checklist, with who does what task to be decided by the EMRG team before a firing. The current procedure, as of time of writing can be found in Appendix D, "Firing Procedure V3.3". The procedure is designed in such a way that no one is near the EMRG when it becomes dangerous. This is accomplished by leaving control and power cables disconnected from their boxes until the all personnel are out of the firing bunker. As hardware changes the procedure will also need to be updated, something which should be done with input from multiple team members.

Another aspect of my work as Safety Officer was creating documents for recording the results of tests and also creating schedules for each testing session. The document recording the results of each test can be found in Appendix E, "EMRG Test Objectives and Results". By documenting each test, there is a paper trail for who is responsible and also a means to record changes to the procedure. Due to the large number of changes during the first few firings the change log is incomplete, but as the procedure is refined it should become possible to document each change as it occurs. This will help to determine the cause of any accidents or failures. For the testing days the

use of a schedule is important, especially when industry representatives are present, as it keeps the testing on track and also allows people to arrive when the main firing is occurring without having to wait. When forming a schedule time needs to be allotted to fix any problems that arise from a non-nominal firing. Examples of schedules used can be found in Appendix F, "Schedules". As hardware is improved the time required for charging will decrease, meaning the schedules shown might not be usable for future test. They do however give a good baseline for future schedules. When hardware and procedures are closer to being finalized a general schedule for each day of testing should be made.

## **V. Safety Philosophy**

Overall my look at safety for the EMRG was similar to any other firearm. When in storage, the EMRG should be separated from ammunition and the control cables and the shorting capacitors shorted out, removing the possibility of accidental discharge. When working around the EMRG the injector system, or breach, should be opened so a person can see down the barrel, confirming there is no projectile. Once the breach is closed no one is allowed in front of the EMRG as the final preparations are made. Due to the large amount of electricity involved with discharging the EMRG it is necessary to have more safety concerns than a conventional firearm. This involves removing everyone from the area around the EMRG during charging and insuring that the EMRG cannot accidentally gain a charge.

During operations care should be taken to note any changes made to the procedure, and also to have a minimal amount of 'on the fly' decisions. To reduce confusion the entire procedure should be run thought with all team members before a firing so everyone present knows what will occur. If the procedure needs to be changed during a firing only the Firing Director should make the change.

## **VI. Future Improvements**

As stated before the procedures will be improved as more firings are completed. Ultimately the procedure should be good enough to be used consistently without change by people who have not previously used the EMRG. The bullet trap may be modified to deflect the projectile at an angle into sand or a similar substance, making it easier to find the projectile and also increasing the effective thickness of the steel. As new parts are added to the EMRG or if a new EMRG is built there will be more safety concerns, but the current system provides a good baseline for decisions.

## **VII. Conclusion**

The three main issues that I see in relation to safety are electrical shock, accidental discharge and electromagnetic pulse. To mitigate electrical shock wires have been upgraded, multiple redundancies have been installed to discharge the EMRG and procedure has been written to keep people from being near the EMRG while charged. Future modifications will separate high voltage components from people. To mitigate accidental discharge, multiple safeties are in place to prevent the EMRG from discharging. A combination of switches and a computer must all work together for a successful firing. Beyond this, procedure has been implemented to prevent people from being near the EMRG when it could possibly fire. The last issue, EMP, still needs to be looked into more in the case of a larger gun. There are mitigations available, including shielding and separating the gun from sensitive electronics, which may need to be looked into and implemented in the future. Properly handled the EMRG should be as safe if not more so than any other test carried out in the propulsion bunker.

## **Appendix A Railgun Safety**

### **Suggestions from Tim Hastings, May 31 2011**

Procedural:

1. Designate one person to be the "Firing Director". This person will direct the set-up and firing procedure.
2. Designate one person to be the "Safety Officer". This person will be

responsible for all safety related aspects of the firing.

3. Write a comprehensive procedure for the setup, firing, safeing, and emergency shutdown of the system.
4. Write position descriptions for each functional position on the team.
5. Do a hazard analysis to determine the appropriate personal protective equipment necessary for working on/around the system when firing.
  - A. Shock hazard
  - B. Arc Flash
  - C. Molten metal spray
  - D. High velocity projectile

Physical:

1. Shield all exposed conductors with a rated insulating material – not wood.
2. Any exposed conductor supports must be an insulating material – not wood.
3. Place the voltage divider network for the capacitor monitoring leads at the rail gun cart. Replace monitor lead clips with a plug/socket type connector.
4. Change the firing, discharge, charging lead connector to something that is not a power cord connection.
  - A. Ensure the wire, connectors, case, and components are all rated for their maximum working voltage/energy that may be applied.
5. Restrain or more rigidly connect all components that experience the capacitive discharge energy.
6. Bolt or clamp the rail gun to the cart top.
7. Check all connections for cold solder joints, ensure all conductors in multi-stranded wire are connected. Use mechanical connectors when appropriate.
8. Install a knife switch, or similar rated switch, to engage the discharge system in the event the relay fails.
9. Consider a second knife switch, or similar rated switch, as a direct short for the capacitor leads that bypasses the discharge resistors to hold the system in an uncharged state.
10. Install indicator lights on the cart to show the firing status. For example: Discharging, charging, and armed.
11. Build/install chocks for the wheels of the cart.
12. Install the capacitor charger on the cart and power remotely.

## Appendix B

# Steel Ballistic Trap for EMRG

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For the new 20kJ Electromagnetic Rail Gun (EMRG) it is necessary to stop the projectile at the end of its flight. Steel was chosen as the stopping material due to cost, machinability and effectiveness as armor. To figure out how much steel is required to stop the projectile three different sets of equations were looked at. The first deals with hypersonic impacts while the second and third deal with conventional firearms. The second and third equations seem more reliable for the tests to be conducted due to the relatively low velocity and high mass of the EMRG projectile. Using these two equations a shielding thickness of around 2.5 to 4 cm should be sufficient to stop a 20kJ projectile. The issues of spall and stopping the sabot still need to be looked into further.

### Nomenclature

|          |  |
|----------|--|
| $d_m$    | = diameter of projectile                             |
| $E_0$    | = material property of steel based on heat of fusion |
| $H_f$    | = heat of fusion of steel                            |
| $l$      | = length of projectile                               |
| $m$      | = mass of projectile                                 |
| $KE$     | = kinetic energy                                     |
| $t$      | = thickness of shielding material                    |
| $t_c$    | = critical thickness                                 |
| $V_c$    | = critical velocity                                  |
| $V_m$    | = velocity of projectile                             |
| $\theta$ | = impact angle                                       |
| $\rho_m$ | = density of projectile                              |

### I. Introduction

For the next step in the Cal Poly Electromagnetic Rail Gun (EMRG) project a 20kJ system will be developed which will operate in a vacuum. This system will fire an approximately 10 gram projectile consisting of a nine gram sabot and a one gram test object. The purpose of this is to test different spacecraft shielding systems against a variety of materials. During a test the EMRG will be loaded with a test object inside an electrically conductive sabot which will then be fired at a test shield. In theory, the sabot will separate from the test object and be collected in a sabot trap. The test object will then impact with the test shield, where depending on the outcome the test object will then continue to the end of the testing area.

### II. Ballistic Challenge

The main issues with the new EMRG set up are going to be separating the sabot from the test object and stopping the test object and possibly the sabot at the end of the test area in a safe manner. By surrounding the test object in a sabot it is possible to test nonconductive materials, but also means the sabot must be stopped before the test shield. Stopping nine grams of metal traveling at two kilometers a second is not small challenge. This is about the same mass as a 7.62X51mm NATO rifle round at over double the velocity. From the point of view of kinetic energy, this is similar to stopping a .50 BMG rifle round. There is also the possibility that the sabot does not separate from the test object, and the whole 10 g mass continues to the end of the test chamber. This will be considered the worst case

scenario, and will be used as the base line for later calculations. To stop the projectile a ballistic trap needs to be constructed. This trap needs to be able to withstand multiple impacts as well as prevent spall damage. Also needed is a sabot separator which will stop the sabot but allow the test object to carry on unhindered. Like the ballistic trap, the sabot separator must be able to withstand multiple impacts and prevent spall damage.

Steel was chosen to be the bullet trap material because it is cheap and easy to work with. There is also data available for ballistic impacts against steel, although with research the same could be said for most other metals and even some ceramics. Aluminum could also be used for the shield, although it is unlikely to be as resistant. Because mass is not a driving factor in the design of the ballistic trap and sabot stopping mechanism steel is used here as a baseline.

### III. Analysis

One of the issues associated with creating a ballistic trap is the small amount of knowledge for projectiles with the properties being studied. For spacecraft impacts projectiles are expected to be traveling at orbital velocities (~7km/s), and this is where most of the NASA research has taken place with their Light Gas Gun. Objects in these tests are small, as anything above 2g is considered too big to effectively defend against<sup>1</sup>. However, for the test we are conducting the projectiles will be traveling only 2km/s, and could be up to 10g. When traveling in the hypersonic region, so a space debris impact, the materials involved will likely melt, causing different effects than projectiles traveling below hypersonic velocities. For larger, slower moving objects there is plenty of data available from the military and similar groups for bullets. However, most bullets travel around 1km/s at best, but they do have masses around 10g. This leads to a gap in knowledge between hypersonic, low mass objects and slower, heavier objects. Another approach to this problem is to study the kinetic energy produced by the impacting projectile. This ignores the properties of the projectile, a dubious assumption, but can allow for comparisons between known ballistic tests and the tests the EMRG will be performing.

The first equation used to calculate the necessary amount of material to stop the 20kJ projectile is the Swift/Bamford/Chen equation found on page 255 in the book Spacecraft-Environment Interactions

$$t_c = \left(\frac{3d_m}{4}\right) [\rho_m V_m^2 / (2E_0)]^{1/3} \quad (1)$$

Where  $t_c$  is the critical thickness in cm, or thickness needed for the projectile to not penetrate the material.  $\rho_m$  is the density of the projectile in g/cm<sup>3</sup>,  $V_m$  is the velocity of the projectile in m/s and  $E_0$  is a material property based on the heat of fusion

$$E_0 = H_f / 2 \quad (2)$$

Where  $H_f$  is the heat of fusion, adjusted for area, of the target material. For steel  $E_0$  ends up being about 9.7E8 J/m<sup>3</sup>. Equation 1 assumes a spherical object traveling at hypersonic velocities. The object's shape to be used in the EMRG experiment still needs to be determined, but will most likely be square. To approximate the diameter the total mass was taken and using the density of aluminum, the current material used for the EMRG, the area could be found, which translated into the diameter.

The second equation used to determine the necessary shielding to stop the projectile is Lambert Equation for Projectile Penetration taken from a report created by the Explosives Applications Department, 5122 Sandia National Laboratories

$$V_c = \left(\frac{l}{d_m}\right)^{0.15} (4000) \sqrt{\left(\frac{d_m^3}{m}\right) \left( \left(\frac{t}{d_m}\right) \sec^{0.75} \theta + e^{-\left(\frac{t}{d_m} \sec^{0.75} \theta\right)} - 1 \right)} \quad (3)$$

Where  $V_c$  is the critical velocity in m/s, or the velocity where 50% of the projectiles are stopped.  $l$  is the length of the projectile in cm. Because this was not known, the length was assumed to be the cube root of the area.  $m$  is the mass of the projectile in grams,  $t$  is the thickness of the shield in cm and  $\theta$  is the impact angle, with zero being an impact at a right angle to the shield, and 90 being a shot that passes parallel to the shield. This equation is supposed to be

used for a rifle bullet hitting steel, so should provide a good baseline for our tests, although it does not take into account all the material properties of the projectile.

The last source of information for stopping the projectile came from MIL-DTL-12560J, the specifications for steel armor plating in American combat vehicles. Based on the tables provided in the manual it was possible to create a correlation between the kinetic energy of a projectile and the amount of steel needed to stop that projectile. For the specification the projectile is a .50 cal M2 AP bullet with a mass of 45.8 grams. Data is available for testing between approximately 580 and 950 m/s. Using data from the tables provided in the specification a high and low end kinetic energy rating could be found by fitting a second degree polynomial to eleven data points. The data points are for 0.55 inches of armor and then every 0.5 inches up to 1.0, where the last data point is 1.2 inches, the highest available rating. The more conservative or higher armor equation

$$t_c = -9E - 11 * KE^2 + 0.0002 * KE + 0.2292 \quad (4)$$

Where KE is the kinetic energy of the projectile. Because the military data gave a high and low velocity value for their tests, the results when using the higher velocity ratings, or for this report the lower armor rating was

$$t_c = 7E - 11 * KE^2 + 0.0001 * KE + 0.1454 \quad (5)$$

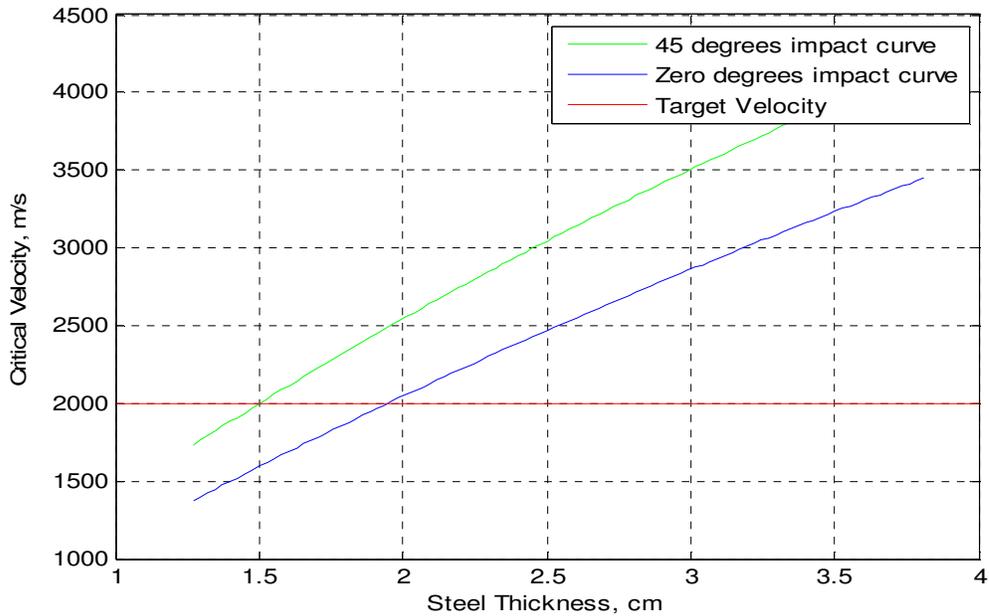
This is not a perfect solution as the shape, density and other mechanical properties of the projectile will change the effects on a ballistic trap, but this does give another method of comparison. These equations are also likely to be the most conservative, as this is for an armored vehicle that needs to be able to survive multiple impacts without damage to people or equipment.

As for looking into the issue of spall this has not yet been covered. It is likely that a 20kJ impact into steel will cause fragments to fly off the back which could still damage people or equipment. Equations are likely available, but likely are estimates due to the numerous factors at play. Spall can be counteracted by having multiple levels of armor, like a Whipple shield, or by installing a Kevlar blanked behind the steel as is done on some armored vehicles. Another solution would be to use sand, rubber or some other substance to absorb fragmentation.

#### IV. Results

MATLAB was used to run all equations, while Excel was used to determine equations 4 and 5. For all cases it was assumed that the projectile had an approximate mass of 10 grams, a velocity of 2km/s and was made of aluminum with a density of 2.7 g/cm<sup>3</sup>. For the equation using a hypervelocity impact the thickness of steel needed to stop the projectile was 0.26 cm. This seemed like an unlikely amount of material, which is probably due to the equation not being well suited to the scenario. Where the projectile smaller and the velocity higher, the hypervelocity impact equation would be the one to use.

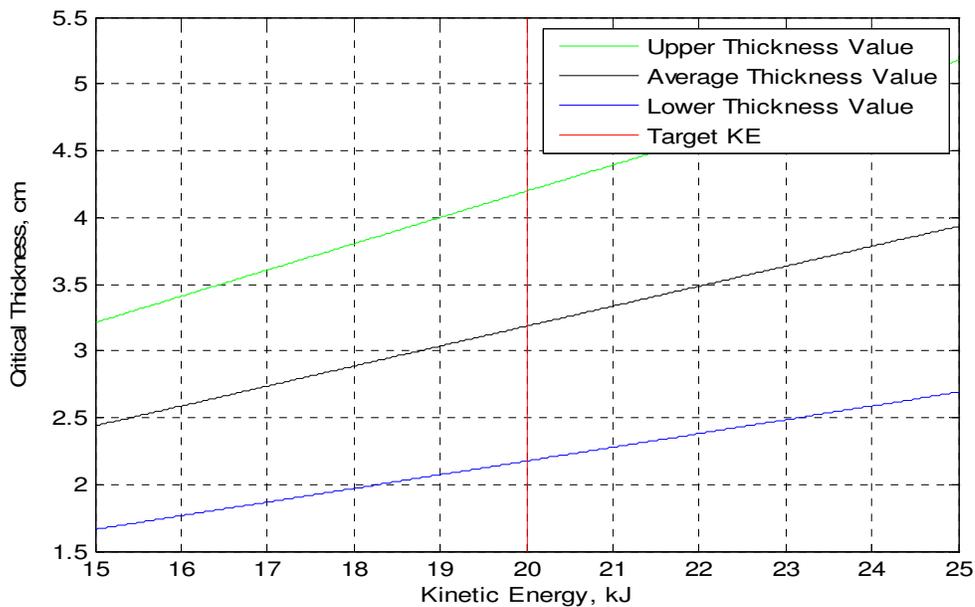
The Lambert equation, or equation 3, was run over a range of shield thicknesses. The equation was used for both a straight on hit, with theta equal to zero, and for theta equal to 45 degrees to show the effects of angling on the effectiveness of the shield. The results are shown below in Fig. 1.



**Figure 1. Comparison of shielding thickness to critical velocity for a 10g projectile at zero and 45 degrees impact angle.**

Figure 1 shows that for a direct strike a thickness of about 2cm would stop a little over half of all impacting projectiles. To insure that all projectiles are stopped the thickness would need to be increased, but not doubled. By about 2.5cm the steel should be capable of stopping all the projectiles to be used.

The last means of determining the amount of shielding material needed is the kinetic energy model, the results of which are shown in Fig 2.



**Figure 2. Comparison of kinetic energy in kJ to critical thickness in cm for a 10g projectile impacting the shield at an angle of zero degrees.**

The kinetic energy model has three lines, the upper thickness, using slower velocities, the lower thickness using higher velocities and the average of the two. The lower velocities require more material to stop as it assumes the same amount of steel can be penetrated by less kinetic energy. When looking at the lower value the critical thickness is similar to the results from the Lamberts equation. However, when looking at the average and the higher thickness values it seems necessary to add additional thickness to the shield.

Because the two sets of equations related to bullets give similar answers, and more conservative answers, they seem the ones to follow. The consequences of too much material are small, while the consequences for not enough could be deadly. However, all of these examples have major flaws, and further research should be done. There is also little information on how many strikes the shielding can withstand. If the shield becomes heavily deformed after a single strike there is a chance that a second impact could penetrate the shield and cause damage.

## V. Conclusion

Stopping the 20kJ projectile can be accomplished using around 2.5 to 4cm of steel. However, the damage caused to the shielding could be extensive, meaning an increase in thickness or some sort of backing material. Any calculations will involve a large amount of guess work do to the nature of ballistic impacts. While the end of the test chamber should be easy to protect, as most of the kinetic energy of the projectile will be lost in the sabot and the experiment, the system to stop the sabot will suffer some punishment. More time needs to be taken to investigate other shielding methods, the effects of spall and the amount of damage the shield will sustain. If possible a small scale model of the ballistic trap and sabot blocker could be built and tested on the existing EMRG. This would also give the opportunity to evaluate the effectiveness of the assumptions made in this report.

## References

“Armor Plate, Steel, Wrought, Homogeneous (For use in Combat-Vehicles and for Ammunition Testing)”, MIL-DTL-12560J, 24 July 2009.

<sup>1</sup>Hastings, D. and Garrett, H., *Spacecraft-Environment Interactions*, Cambridge University Press, UK, 1996.

Preece, D.S., Berg, V.S., Payne, L.R., “Bullet Impact on Steel and Kevlar/Steel Armor-Experimental Data and Hydrocode Modeling with Eulerian and Lagrangian Methods”, *Explosives Applications Department, 5122 Sandia National Laboratories*, <http://www.dtic.mil/ndia/22ndISB2005/tuesday/preece.pdf>. [Cited 19 January 2012]

## Appendix C

# Responsibilities of Rail Gun Team

*Note: All members of the team present at a firing have the ability and responsibility to call a cease fire at any time.*

### I. Positions

While many people can be present during the firing of the rail gun, there should as a minimum be two people, one designated the Firing Director and the other the Safety Officer. These two positions are to be appointed prior to the firing of the rail gun. The Firing Director is responsible for the set-up and firing of the rail gun, while the Safety Officer is responsible for the safety of the firing. In the likely event that more than two people are present at a firing, more positions are available. The specifics of each position are detailed below.

### II. Firing Director

The Firing Director (FD) is ultimately in charge of the rail gun firing. More specifically, the FD is responsible for the set up of the rail gun, including but not limited to the aiming, the wiring, the gas injection system and anything else that is necessary for the rail gun to fire. In the event that only two people are present to fire the rail gun, the FD is also responsible for data collection. The FD is responsible for firing the rail gun, so has final say in who gets to fire the system. The FD is also the leader of the team during firing, so is able to give any directions necessary for the proper firing of the rail gun as long as these directions do not impose a safety hazard. As part of this, the FD can assign new positions as needed. The FD is also the only person who can make changes to the firing procedure during a firing and the only person who can give orders during a firing besides safety issues. If there is confusion about the order of events during a firing, the FD's word overrides both the procedure and other members present. At any point, the FD can call a cease fire.

### III. Safety Officer

The Safety Officer (SO) is responsible for the safety aspect of the firing. This includes but is not limited to properly announcing a rail gun firing; insuring all safety equipment (ear and eye protection) is worn during the firing, and deciding if the rail gun is safe to be worked on. The SO is also responsible for stopping any firing if a cease fire is called for. The FD and SO must both agree for the rail gun to be fired for it to be possible to fire. The SO must agree with the FD before allowing anyone to approach the rail gun at any point during a firing. If status lights are used, the SO is responsible for changing the status. At any point, the SO can call a cease fire.

### IV. Data Recorder

If more than two people are at a firing, a third position, Data Recorder (DR) is available. The DR is responsible for connecting the data recording equipment and recording data during the firing of the rail gun. During the firing the DR runs the computer, cameras and other systems that record data. This essentially breaks the firing into three sets of responsibilities: The FD controls the actual rail gun, the SO regulates the movements of people around the rail gun and the DR is responsible for the instruments monitoring the rail gun. If only two people are at a firing, the responsibility of the DR is passed to the FD, who can then delegate responsibilities to the SO as needed. At any point, the DR can call a cease fire.

### V. Operations Overseer

Like the DR, the Operations Overseer (OO) is a position that can be filled if extra people are present at a firing. The OO is responsible for reading the checklist and insuring it is followed. The OO is also responsible for making necessary changes to the procedure and noting any deviations from the firing procedure. If only two people are present the responsibilities of the OO are passed to the FD, who can delegate to the SO as he or she sees fit. At any point, the OO can call a cease fire.

### VI. Other Members

Beyond three people, any additional personnel will be assigned jobs at the discretion of the FD as needed. Any duty performed by any member of the firing team needs to be approved by the FD and SO, and in the case of data collection also needs to be approved by the DR, if applicable. At any point, any member of the firing team can call a cease fire.

## Appendix D

# Firing Procedure V3.3 (valid until 03/08/2012)

*Note: All members of the team present at a firing have the ability and responsibility to call a cease fire at any time.*

### I. Procedural Notes

For this document, it is assumed that a minimum of two people are present at the firing, the Firing Director (FD) and the Safety Officer (SO). However, it is suggested that an Operations Overseer (OO) and Data Recorder (DR) be present to help with the firing. For more on the positions, see “Responsibilities of Rail Gun Team”.

### II. Preparation

1. Walk through firing procedure with all team members. FD will assign job positions as needed and any questions about the procedure will be dealt with and recorded by the OO. SO will go over any important safety issues for the day.
2. Place voltmeter on EMRG and turn on. If voltage above 5V stop working on EMRG and use discharge stick to drop voltage below 5V
3. System Check
  - a. Check to see that there are no obstructions down the rails
  - b. Ensure bleed resistors are functioning properly and are connected to the rails
    - i. Check that resistance across each resistor is around 100 ohm and visually inspect that the resistors are attached to the EMRG
  - c. Engage braking mechanisms on wheels and place chocks behind wheels
4. Remove jet fuel and other flammable materials from area around the EMRG
5. Align barrel with target
  - a. Ramrod can be used to show approximate travel of projectile
6. Bolt target lead onto frame at the appropriate length from the muzzle of the EMRG
7. Place experiments
  - a. Place break screen and attach leads. Check leads using a multimeter
  - b. Place experimental target
8. Check EMRG
  - a. Torque on all bolts along rail to be 30 **foot-pounds**, start from the air-injector end and work from top to bottom back to front in a zig zag pattern
  - b. Insure grease is on all connections
  - c. Connect main power cables to rails
9. Place PVC covers over main rail power connections
10. Assemble injector fittings and tubes. **DO NOT attach injector to rails**
11. Place full nitrogen injector tank into cradle and latch down with chain
12. Turn on LabView and load the \_\_\_\_\_ file that contains the firing/data acquisition logic
13. Set the High Speed Camera Shield Box (HSCSB) in view of barrel profile.
  - a. **The camera must be AT LEAST 1.5 meters from the rails.**
  - b. Plug power and Ethernet cables through hole in back of the high Speed Camera Shield and place.
  - c. Open top of HSCSB to avoid overheating the camera.
  - d. Turn on camera lights if needed (note: lights are not used for full voltage firings)
14. Prepare High Speed Camera
  - a. Open Phantom Camera Control
  - b. Plug extension cord powering lights and high speed camera into wall.
  - c. When the camera is accessible by the computer open the camera pool window and check that the camera is accessible

### III. Pre-Firing

1. Prepare Boxes and Safeties
  - a. Attach 5 point control wire to EMRG
  - b. Attach 25 pin data wire to diagnostic box
  - c. Attach 9 pin data wire to diagnostic box
  - d. Attach BNC power cable to diagnostic box
  - e. Attach 2 point charging cable to EMRG
  - f. Take wires and manual discharge pin string back to control bunker
2. Remove shorting blocks from the resistor bank.
3. Raise manual discharge plate and place manual discharge pin.
4. Close lid of HSCSB to protect the camera.
5. Box Set up
  - a. Connect 5 point control cable to control box
  - b. Connect 25 pin data cable to the control box
  - c. Connect 9 pin data cable to control box
  - d. Connect 2 point charging cable to charging box.
  - e. Connect power supply to control box. **DO NOT turn on power supply**
  - f. **DO NOT Plug in Control or Charging box to Wall Power**
6. In LabView test the measurements and make sure the connections to the physical data acquisition system are correct and functional
7. Load projectile into EMRG
  - a. Insert projectile from breach (end opposite of target), pointed end first
  - b. Gently push projectile until fins are completely within the rails. Use ramrod as needed
  - c. Remove ramrod. Place ramrod in a visible location in the firing room.
8. Bolt injector to EMRG
9. Turn off voltage meter and remove from EMRG
10. Pressurize piping. This is the last action before clearing the firing chamber. Check with other team member(s) to insure completion of their tasks before performing this step.
  - a. Slowly open the pressure valve until the pressure gauge reads the desired pressure.
  - b. **Caution: A choking hazard now exists due to possible high concentrations of nitrogen in the area around the EMRG**
  - c. **Caution: EMRG is now capable of launching a projectile. DO NOT stand down range of the EMRG without first stopping the gas flow, removing the injector system and removing the projectile**
11. Have Safety Officer bring Fire extinguisher into control bunker for a test including a charging of the EMRG
12. Insure all personnel are out of the firing area once the nitrogen is attached and open. Have SO and FD sign place initials on "EMRG Test Objectives and Results" to confirm bunker is clear
13. Close door to EMRG
14. Activate Red Safety Light on door to EMRG
15. Plug control box into wall power
  - a. For a nitrogen only test, skip to Step 25 in Section III Pre-Firing
16. Plug charging box into wall power
17. Turn resistor bank to OFF
18. Turn charging box to ON
19. Charge EMRG to appropriate voltage (450V for full firing)
20. **WARNING: EMRG is now extremely dangerous. DO NOT enter the firing bunker without completing the entire discharge procedure.**
21. Pass out and put on ear and eye protection

22. Turn charging box OFF.
23. Disconnect charging box from wall
24. Disconnect charging cable from charging box. DO NOT reconnect the cable until a discharge has occurred.
25. Turn power supply connected to control box on. Turn voltage and current to zero, then raise voltage to 5V
26. Attach control box to computer and load Arduino data as needed

#### **IV. Firing**

1. Flip injector ARM switch on control box to allow EMRG to be fired
2. Begin countdown from 5
3. On fire press FIRE button on control box
4. After firing IMMEDIATELY end the camera's cycle to acquire footage of the firing
5. Immediately after firing switch the resistor bank to ON and turn off firing switch
6. Allow four (4) minutes for capacitors to fully discharge
7. Pull pin for manual discharge release
8. Disconnect 5 point control cable from EMRG
9. Turn Red Safety Light off

#### **V. Post Firing**

1. Insure the EMRG is completely discharged. **DO NOT APPROACH UNTIL SYSTEM VOLTAGE BELOW 5V.** Have SO and FD sign place initials on "EMRG Test Objectives and Results" to confirm voltage is below 5V
2. Attach voltmeter to EMRG and turn voltmeter on
3. Use discharge stick to remove any remaining voltage from EMRG
4. Turn off nitrogen supply and release excess pressure as needed.
5. Safe the system
  - a. Remove injector assembly.
  - b. Replace aluminum shorts on the capacitors.
6. Disconnect cables.
  - a. Disconnect 25 pin data cable from EMRG
  - b. Disconnect 5 point control cable from EMRG
  - c. Disconnect 2 point power cable from EMRG
  - d. Disconnect BNC power cable from diagnostic box
  - e. If no more firings for the day disconnect 9 pin data cable and all remaining cables from the control box
7. Turn off HSC lights
8. Open lid of HSCSB
  - a. If done firing for the day, turn off HSCSB and pack up the camera

#### **VI. Emergency Shutdown**

As noted at the top of the procedure it is the responsibility of everyone at the firing to call a stoppage for any reason. Once a cease fire is called, the EMRG is to be completely safed, and the procedure is not to continue until the cause of the stoppage is determined and solved. **If the procedure restarts, it will do so from the top.**

##### **A. Nitrogen connected, no charge on EMRG**

1. Pull manual discharge pin.
2. Turn off nitrogen.
3. Bleed off excess nitrogen.
4. Remove injector assembly.

5. Remove all connected wires from EMRG.
6. Replace aluminum shorting rods.

**B. EMRG is completely charged**

1. Turn off and unplug power supply.
2. Turn on the resistor banks.
3. Turn off injector system.
4. Wait four (4) minutes for the capacitors to discharge into the resistors.
5. Pull pin for manual discharge release.
6. Unplug all boxes and wires in the control room.
7. Follow procedure for a normal shutdown as detailed in "Post Firing".

**Appendix E**  
**EMRG Test Objectives and Results**

Date of Firing: \_\_\_\_\_ / \_\_\_\_\_ / \_\_\_\_\_

**Operators Present:** Sign and print for all that apply. Note that at least two operators must be present for any firing. For definitions of the responsibilities of the operations consult “Responsibilities of Rail Gun Team”.

*Print*

*Sign*

Firing Director: \_\_\_\_\_

\_\_\_\_\_

Safety Officer: \_\_\_\_\_

\_\_\_\_\_

Data Recorder: \_\_\_\_\_

\_\_\_\_\_

Operations Overseer: \_\_\_\_\_

\_\_\_\_\_

**Purpose of Test:** Fill out for all parts that apply as instructed by the Firing Director.

*Velocity Test:* Planned velocity: \_\_\_\_\_ Actual velocity measured at: \_\_\_\_\_

*Shielding Test:* Shield material(s): \_\_\_\_\_

Thickness of shielding: \_\_\_\_\_ Layers/spacing of Shielding: \_\_\_\_\_

Expected result: \_\_\_\_\_

Experimental result: \_\_\_\_\_

*Power Test:* Theoretical amperage: \_\_\_\_\_ Measured amperage: \_\_\_\_\_

Theoretical voltage: \_\_\_\_\_ Measured voltage: \_\_\_\_\_ Expected pulse time: \_\_\_\_\_ Measured: \_\_\_\_\_

*Projectile Mass:* Before firing: \_\_\_\_\_ After firing: \_\_\_\_\_

*Other:*

**Procedural changes:** Make a note of any changes from firing procedure. For a change report, note the section, the step number and the step letter, as applicable. For a change in location of a step, note the original location and the location of the step as performed. For all changes state the change made and the reason for the change.

**Error Report:** Note any errors that occurred during the firing that required a stop in the procedure. Note the likely cause of the error and any actions taken to correct the error. Also note the position in the procedure where the error occurred.

**Appendix F**  
**EMRG Test Schedule**

2 March 2012

**I. Preparation (0900-1100)**

0900: Arrive, initial briefing  
0915: Gather hardware  
0930: Start the procedure as outlined in Firing Procedure V3.0  
1030: Prepare for first test firing using the nitrogen injection system

**II. Nitrogen Test (1100-1130)**

1100: Pressurize EMRG and test injection system  
1100: Review of test results, make necessary changes

**III. Partial Charge Test (1130-1230)**

1130: Prepare for partial charge test  
1145: Begin charging  
1200: Discharge EMRG  
1200: Review of partial charge test, make necessary changes  
1230: Lunch

**IV. Full Test (1330-1630)**

1330: Pre-fire briefing (purpose of test)  
1345: Final setup of target  
1400: Pressurize system, begin charging  
1500: Expected end of charge time, discharge of EMRG  
1600: Charge time margin, discharge of EMRG  
1600: Safe system, begin post fire review

**V. Post Firing (1630-1800)**

1630: Target collected, EMRG wiring removed, system safe to inspect  
1700: Begin breakdown of EMRG, save digital data, box up camera, and return hardware to appropriate spots  
1800: Hardware returned to appropriate labs, testing is now over

**EMRG Test Schedule**

9 March 2012

**I. Preparation (0800-1030)**

0800: Arrive, initial briefing  
0815: Gather hardware  
0830: Assign positions and walk through procedure V3.3 and make changes as necessary  
0900: Prepare for first partial charge test

**II. Partial Charge Tests (0930-1100)**

0930: Setup for first partial charge test  
0945: Begin charging of first partial charge test  
1000: Discharge EMRG  
1030: Prepare for second partial charge test  
1045: Begin charging of second partial charge test  
1100: Discharge EMRG  
1100: Review of second partial charge test, make necessary changes

**III. First Full Charge Test (1100-1230)**

1100: Pre-fire briefing (purpose of first test)  
1115: Final setup of target  
1130: Pressurize system, begin charging  
1230: Expected end of charge time, first discharge of EMRG  
1230: Lunch

#### **IV. Second Full Charge Test (1330-1500)**

1330: Pre-fire briefing (purpose of second test)  
1345: Final setup of target  
1400: Pressurize system, begin charging  
1500: Expected end of charge time, second discharge of EMRG

#### **V. Post Firing (1500-1630)**

1500: Target collected, EMRG wiring removed, system safe to inspect  
1530: Begin breakdown of EMRG, save digital data, box up camera, and return hardware to appropriate spots  
1630: Hardware returned to appropriate labs, testing is now over