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Constructing and Testing a Permanent-Magnet Railgun

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Constructing and testing a permanent-magnet railgun

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Abstract

A modified magnetic railgun has been built and investigated. Permanent magnets were used to supply the magnetic field and a car battery was used to provide the current. The projectile has been successfully shot out. Alternative way to create magnetic field is running a large current through the rails. Preliminary calculations revealed that the current will need to be enormous in order to provide a satisfactory magnetic field. For such a large current a huge capacitor pool would be necessary. Strong permanent magnets are available and allow us to bypass the difficulties of simply using the current in the rails.

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I. Introduction and Overview

A railgun is an electromagnetic powered object accelerator; it uses basic electromagnetic laws to launch a projectile with a high speed.

The first railgun idea dates back to 1918 when the French inventor, Louis Ostave Fauchon-Villepee [1], designed an electric cannon, which is the earliest form of railgun. The first railgun application attempt was during WWII, when German commander Luftusaffe issued a specification for a railgun based anti-aircraft gun. The gun was to be built with a muzzle velocity of 2,000 m/s and a projectile containing 0.5 kg of explosive material. However, it was never built because the post-war report indicated that even though it was theoretically feasible, the power needed for each gun could illuminate half of Chicago [2]. The first railgun was tested in early 1970's at the Australian National University. This test drew public's eyes due to its potential military use in the 1980's. More researchers in the United States investigated the railgun. They aimed to use the railgun as a defensive system, located in orbit and nicknamed "Star Wars". It would be used to knock out the enemy's missiles from outer space [3]. The U.S government heavily funded this project and many contractors started working on building different kinds of railguns. However, the degrees of success varied dramatically. Proposed applications of railguns today are not limited to military uses, but are also been considered launching satellites and for other commercial uses.

Among all applications for railguns, launching rockets into space is one of the most exciting projects. In 2003, Ian Nab made a plan to build a system to launch supplies (such as food, water or fuel) into space. Based on cost, this method would be highly superior to using the space shuttle; the ideal railgun system would cost only $528/kg, compared of $20000/kg with the traditional method [3]. The railgun system was to be made to launch over 500 tons every year with the frequency of 2000 launches per year. The results have yet to be seen.

Proposals for using railguns as weapons include projecting heavy non-explosive missiles at speeds up to 5000miles per hour. The energy outmatches that of an explosive shell [4]. The high speed is easy to attain since the force on the projectile is proportional to the current applied.

The disadvantages of railguns are pronounced too; due to the high current required to launch the projectile, a huge amount of heat is produced at the contact between the rails and the projectile. This heat corrodes the electrical contact surface of the projectile, and also increases friction by making the surface rough, which reduce the efficiency tremendously.

II. Theory

A. Conventional railgun

The components of a conventional railgun are shown in Figure 2.1. They consist of two parallel conducting rails connected to an electrical power supply, typically a capacitor pool. Between the rails, a conducting projectile will be placed to be fired along the rails.

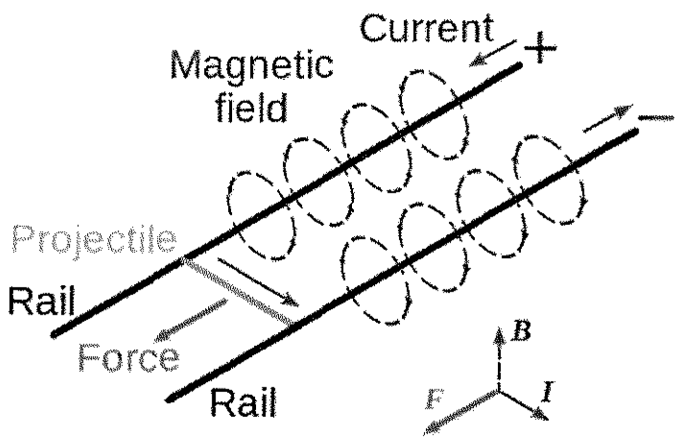


Figure 2.1 Railgun magnetic field effect [5]

The current flows from the power supply's positive terminal along one rail. Then the current runs through the conducting projectile and goes back up the second rail to the negative terminal. Rails are spaced apart by width of the projectile. Sometimes a groove is made down between the rails so that the projectile will run along smoothly.

As the circuit is connected, the current will go through the rails, generating a magnetic field between the rails that is proportional to the current and inversely proportional to the distance from the wire in accordance with the Biot-Savart Law:

$$\vec{B} = \frac{\mu_0}{4\pi} \oint \frac{I d\vec{l} \times \vec{r}}{r^3}, \tag{1}$$

where $\vec{B}$ is the resultant magnetic field [6]. Figure 2.2 shows the relationship between the components in equation (1). The angle between the magnetic field and the central axis is 90 degrees and the direction of the vector can be determined by the right-hand rule. In the same equation above, μ_0 represents the magnetic permittivity constant, I stands for the transient current, $\vec{r}$ is the full displacement vector from the wire element to the point at which the field is being computed.

In this experiment, the rails are made of two pieces copper with a dimension of $6'' \times 2'' \times 0.3''$ copper bars. In order to estimate the magnetic field between the bars, the magnetic field caused by a wire segment was calculated. The field of this straight segment of wire, in terms of initial angle ϕ_1 and final angle ϕ_2 are given by

$$\mathbf{B} = \frac{\mu_0 \mathbf{I}}{4\pi s}(\sin \phi_2 - \sin \phi_1) \qquad (2)$$

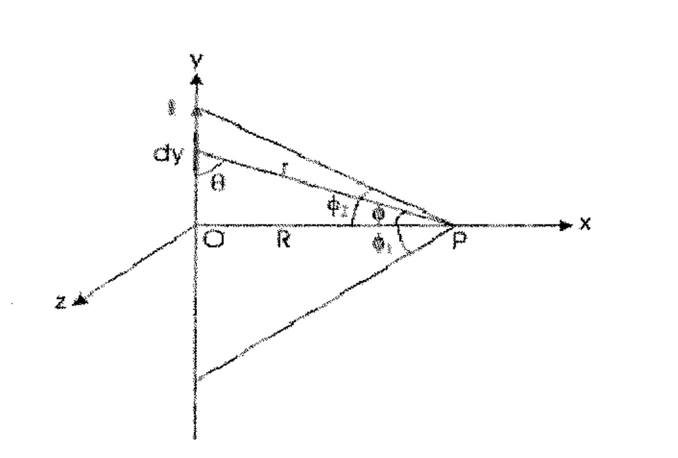


Figure 2.2 Magnetic field at a point created by a wire segment

Since $\mu_0 = 4\pi \times 10^{-7} \frac{N}{A^2}$, the magnetic field created by one wire carrying for daily activity tends to be small.

If an object carrying a current is placed in a magnetic field, the object will experience a force, which can be calculated as:

$$\vec{F} = I\vec{L} \times \vec{B}, \tag{3}$$

where $\vec{F}$ indicates the force on the projectile, $\vec{B}$ is the magnetic field vector, and $\vec{L}$ is the width of the wire projectile with the direction of the current, I is the magnitude of current.

The current through the wire is producing the magnetic field described above. Thus, combining the equation for Lorentz force, we come to a conclusion that the force is proportional to I^2. Even though the force increases as I^2, the force will still be very small because of the magnitude of μ_0 unless the current is extremely large.

The ideal projectile weights 10 g. In order to accelerate it up to a desired speed as 10m/s, the average force exerted on the projectile can be found by the conservation of energy :

$$\bar{F}S = \frac{1}{2}mv^2 \tag{4}$$

where $\bar{F}$ is the average accelerating force, S is the rail length, 16 inches in the experiment. This force was found to be $\bar{F} = 16.7\text{N}$. In accordance with the formula (2) and (3), the average magnetic field needed is 0.7 Tesla.

We refer the Equation (2) to estimate the current needed to produce this required field. For the apparatus used here, the width between the rails is approximately 2.5 cm, and the angle $\theta_1 = 60° and \theta_2 = -60°$ and two rails are involved in producing the field along the center. Thus the magnetic field is approximately given by

$$B = \frac{\mu_0 \sqrt{3} I}{2\pi S} \ . \tag{5}$$

This determines that the current needed to produce the required field of 0.7 Tesla is roughly 25,000 A. Firstly, this enormous amount of current can hardly be created in a fund-limited project. To supply such power, we need 10 capacitors, each rated at 6300uF and 400V. Secondly, High current will create huge amount of heat, this heat will increase friction and can be destructive because of the electrical actions between the sliding contacts. This result forces us to use permanent magnets to provide the magnetic field.

B. Permanent magnet railgun

By using permanent magnetics, we can provide a much larger magnetic field than the current can. As the calculation has shown, in order to produce a magnitude of 1.0 Tesla magnetic field, an instantaneous current of roughly 25,000 Amperes is needed. In our case, we implemented pairs of permanent magnets obtaining magnetic field of 1.5 Tesla.

The power supply is a 12-V battery, the resistance along the rails is approximate 0.1Ω, so the current is 120 A. According to equation (3) and (4), theoretically, the final velocity out of the gun is 7.5m/s. (Assuming no friction)

The most prominent advantage of this model compared with the conventional railgun is that the battery can accelerate the projectile for a long period of time compared to using capacitors. It is a better choice for the space shuttle application, which was mentioned earlier.

III. Experiment: Railgun with permanent magnets

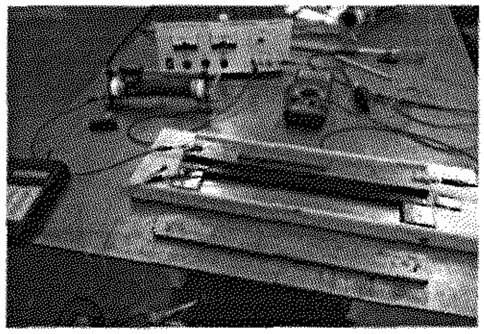


Figure 3.1 measuring the resistance of the system

The railgun designed in this project consists of three parts, as shown in Figure 3.1. The 12-V car battery provides the current, the copper rail bars that the projectile and the copper projectile.

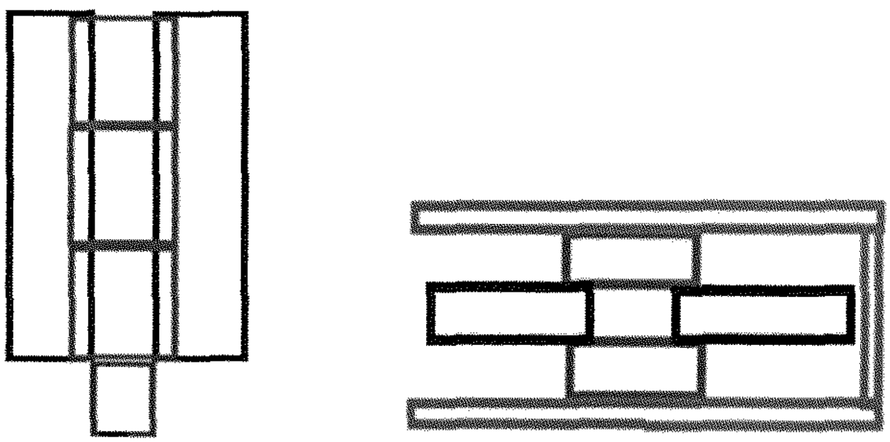
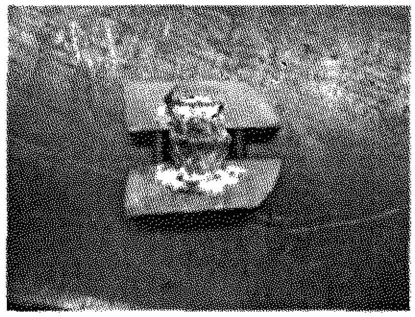


Figure 3.2 Simplified model of the raigun main body

Figure 3.2 shows two different views to setup the railgun, the black bars are made of copper, and they are seven inches long and 2.5cm away from each other. Copper was chosen for conducting rails because it has high heat conductance and copper is not magnetic. As shown in Figure 3.2, seven pairs of permanent magnets are put above and below the gap between the copper bars to provide magnetic field needed to accelerate the projectile. The blue pieces are iron sheets, they were made to balance the whole apparatus and the magnetic flux can flow through the iron sheets, which creates a magnetic circuit. This magnetic circuit will increase the magnitude of the magnetic field. The permanent magnets we chose are rare earth magnets, they are $1' \times 0.5' \times 0.3'$. Each pair creates a magnetic field with the magnitude of 1.5 Tesla.

The current can be created in various ways. Most people use a bank of capacitors to provide the transient large current. The advantages of using bank of capacitors are it is relatively easily to discharge and the instant current amount can go up to 20,000 amperes. However, using such high current can produce a tremendous amount of heat, which can damage the system. For instance, a student project railgun power supply consists of eight large 350V, 1.8mF capacitors in parallel to feed the firing current. The total amount of heat created is 7056 joules, this amount of heat can easily destroy the experimental set-up by melting the projectile or adhering the projectile with the rails it runs on. On the other hand, the conventional railgun needs a high enough current to induce the magnetic field along the accelerating path, therefore, the discharging time has to be very small(in terms of milliseconds) to make the current high enough, meaning the process of acceleration is as short as several milliseconds. Obviously, it is not applicable for a railgun with heavy loads like the space shuttle application mentioned in the introduction.

The power supply used is a 12-V automotive battery. As the magnetic field is fully provided by the permanent magnets, the current needed in this design is much smaller than that used in this railgun that depend on current to generate the magnetic field. The working circuit is mainly made of copper, so the resistance of the system is 0.1 Ω. By connecting the circuit, the car battery can create 120 amperes current. This current will also generate magnetic fields along the rails. However, as we have calculated, the magnitude of the magnetic fields created is so small that it can be ignored.



3.3 Modified projectile for the third round

For the projectile used in this experiment, a lead ball was first used as projectile in this experiment. However, contacting area between the lead ball and sliding rails is small.

$$R = \rho \frac{l}{A} \tag{6}$$

where R is the resistance of a conductor, ρ is the resistivity, l is the length of the conductor and A represents the cross-section area of the conductor. For a conducting ball, the conducting area is very small, so the resistance is becoming relatively large, as a result, the final current will not be as large as conductors with a bigger conducting areas.

The next projectile tried was a pure copper strip with 1 inch long. However, since the copper bars and strip are uneven, the projectile and the copper bars do not contact well consistently.

The third one tested was composed of non-uniform shaped copper piece. Two tungsten springs were used to provide the tension in between. This arrangement will give a good electrical contact between the rails and projectile. A piece of coaxial wire shielding was used to provide current path. The benefit of using this kind of shield is it is flexible. It can carry relative large current. The projectile with the spring is 1.10 inch wide, which is slightly wider than the gap between the rails. It ensures the projectile is well electrically conductive with the rails.

According to calculation presented as Equation (3), the force is big enough to accelerate the projectile to a final velocity as 7.5m/s, but the resistance between the projectile and the rails is not taken into consideration. Conducting grease is dusted evenly on the rails for two purposes. One, it can reduce the resistance between the projectile and the sliding rails. Two, it cools the contacts, avoiding the high temperature.

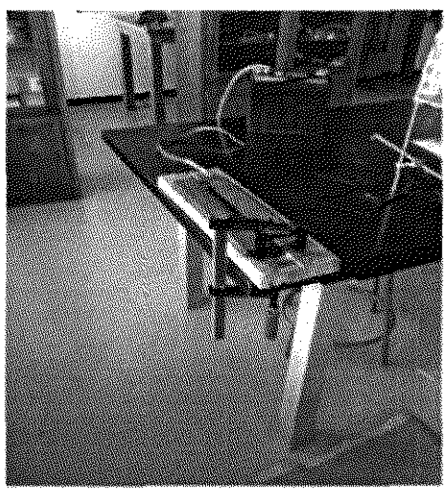


Figure 3.4 Railgun system with a motion sensor at the exit

IV. Tests and Results

Three rounds of tests have been tried over the whole process. This experiment set-up has been tried for several times. The first time we used a whole copper piece shown on the right in Figure 4.1. It never worked because two rails can hardly set preciously parallel therefore the contact between rails and the projectile because a serious problem. In the second round of tests, two pieces of copper were attached with two springs, and a thick piece of copper shield was attached onto the projectile. This is shown at the left in Figure 4.1. The railgun did function, the armature exploded inside the barrel, creating a blast and a shower of fragments from the muzzle. The projectile moved along the path for 5 inches on the averge after the switch was closed. However, it stopped at the near end of the barrel every time. The copper-made projectile was modified with a copper wire soldered at front for the third trial as shown in Figure 4.2.

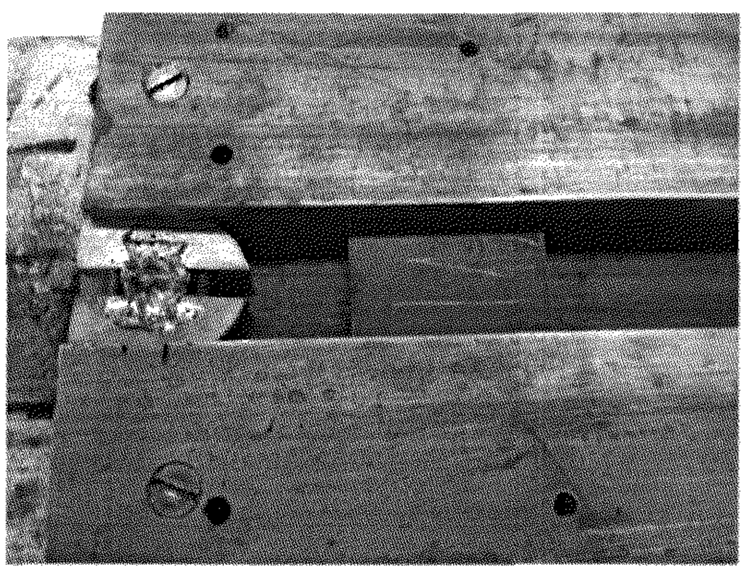


Figure 4.1 The second version projectile (left) and the first version projectile (right)

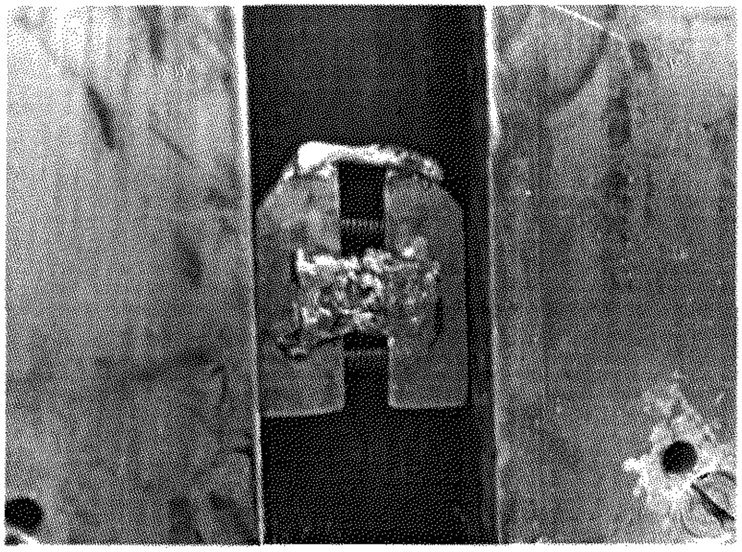


Figure 4.2 Final version projectile

After closing the switch, the projectile fired to a distance roughly 10 meters away from a 1-meter high table shown in Figure 4.3. Ohm's law was used to predict the peak current to be in the neighborhood of 120 amps. Neglecting the imperfections of the device, the current should be producing a total force of 16.7 Newton. (The magnitude of the magnetic field created by the permanent magnet is 1.5 Tesla). The railgun functioned very well this time, accompanied by flashes which were reminiscent of arc welding. For the first time of the third round, the railgun top part was removed so that we could observe the acceleration.

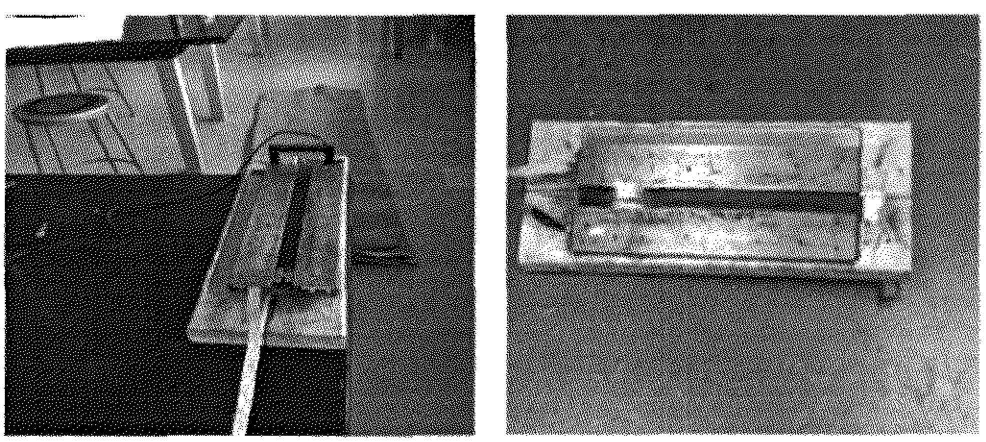


Figure 4.3 Experiment apparatus, the blur in the right shows the accelerating moment

A motion sensor gate was located at the end of the railgun. It measured the amount of time the infrared beam was blocked by the projectile, thus allowing us to calculate the velocity.

Results and Discussion

After firing the railgun, I collected the elapsed time and the resulting velocity, which is shown in Figure 4.4:

	A	B	C	D
1	Elapsed Time (s)	Length of the projectile	velocity	accelerating time
2	0.0032	0.0316	9.88	0.02
3	0.0063	0.0316	5.02	0.04
4	0.0056	0.0316	5.64	0.05
5	0.0039	0.0316	8.1	0.03
6	0.0172	0.0316	1.84	0.09

Figure 4.4 Five groups of data shows the time and velocity at the exit of the barrel

We found that the exiting speed of the railgun varied greatly among the five tests. The first velocities are between 5m/s to 10m/s. However, after the fourth test, the contacting slides were heavily burned, a layer of copper oxide was created along the rails and projectile, causing it to fracture from within. Ever since the fifth test, the efficiency of the railgun decreased markedly. The blast during accelerating process increased dramatically, and many times, the projectile stopped at the end of the railgun. A sandpaper was used to erase the oxide.

The friction of the acceleration process is 7.5 N, as the length of the barrel is 50cm long, heat created is 3.75 Joules. Take the first group velocity of 9.875m/s while the mass is 40g, the kinetic energy is 1.95 Joules. Meanwhile, we measured the accelerating time to be 0.02s,

$$E = U\frac{U}{R} \times \Delta t \qquad (6)$$

The total energy of the system is 14.4 Joules, which implies the total efficiency to be 6.60%. As we knew from research, railgun devices are usually very inefficient; rarely do railgun operates with a total efficiency over 2% [7], which marked permanent magnet railgun competitive. Nevertheless, this version for a railgun launch system is simpler, less expensive and more feasible than the conventional railgun based on instant high voltage.

IV. Conclusions and Future work

Permanent magnet railguns present a challenging design problem but are overall successful. Over the course, I designed and built a railgun. However, for as long as two months after the railgun was built, the projectile could not be shot out of the barrel. Investigations had been done to solve the problems; we spent the later month to adjust the distance between the rails in order to make it perfectly symmetric everywhere, and designed & built a new projectile.

There is plenty of future work to improve my current railgun design. The first thing is to reduce the friction during the acceleration. The modified projectile will be a plastic projectile wrapped up with copper piece, as shown in Figure 5.1. We will make a track inside the copper bar with guiding wheels. The problem we are confronting is how to avoid having the high current melt the wheels and result in adhering the parts together.

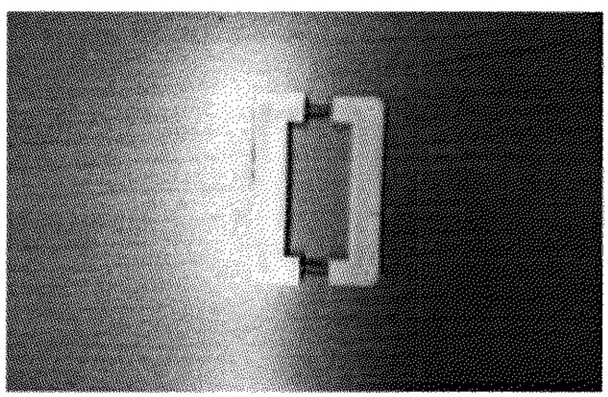


Figure 5.1 Plastic projectile

VI. Acknowledgements

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