Marie Curie's death (17), but it remains unclear whether radium or X-rays contributed more to her ill health. Several "Radium Girls" sought reparations from the U.S. Radium Corporation for their radium poisoning, and some received payment after many months in court. Radium products fell out of favor after the discovery of the health risks. Some consumers who bought into the radium craze were fortunate enough to have purchased their medicines from fraudulent companies that claimed to use radium but did not. Others who ingested or bathed in radium in hopes of improving their health were actually depositing radioactivity in their bones. At great human cost, radium was critical to the discovery of the power and danger of radioactivity.

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Railguns:
A Revolution in Naval Warfare from the World of Science Fiction

EDWARD CHIEN '09

Imagine a cannon of extraordinary range and power, capable of hitting targets 200 nautical miles away within six minutes and striking with enough kinetic energy to penetrate 40 feet into solid ground and create a 10-foot deep, 10-foot wide crater (1). This extraordinary weapon is the railgun, and has existed in the imagination of videogame makers and science fiction screenwriters for decades, appearing in videogames such as *Quake* and *Metal Gear Solid 2* and TV series such as *Stargate SG-1*. In fact, the idea of a railgun has tantalized not only videogame makers and science fiction screenwriters, but has been on the mind of military visionaries for just as long, fueling research by academia and various militaries around the world. The United States Navy has recently joined this group of interested parties, announcing that they are developing naval railguns and hope to have them combat-ready sometime between 2020 and 2025 (2).

What is a railgun?

A railgun operates on the principles of electrodynamics and utilizes a large Lorentz force to accelerate a nonexplosive projectile from between two rails to supersonic speeds. This Lorentz force is created by a loop of current that runs up one rail, through the conductive projectile itself, and then down the other rail. The current running up and down either rail produces a magnetic field between the rails that interacts with the current running through the projectile itself to produce the Lorentz force that accelerates the projectile.

Railgun Advantages

Railguns have captivated the minds of weapons researchers and militaries around the world for many reasons. The potential power and range of the weapon easily surpass those of current naval guns. The 5-inch guns installed on U.S. Navy ships today have a muzzle energy (the kinetic energy of the projectile upon leaving the barrel) of 9 megajoules (MJ) and a range of no more than 15 nautical miles (a nautical mile is equivalent to 1.15 standard miles) (2). By comparison, naval railguns are projected to produce muzzle energies that range from 60 to 300 MJ and to have a maximum range of 200 to 250 nautical miles (1). Railguns even surpass explosive rocket-fueled shells, another long-range strike option, in terms of power and range. As an example, the Extended Range

Guided Munition (ERGM) and the Long Range Land Attack Projectile (LRLAP), both rocket-fueled explosive shells in the latter stages of development, have ranges of 43 nautical miles and 63 nautical miles and deliver 2.2 MJ and 7.8 MJ of energy upon impact, respectively. A *nonexplosive* railgun projectile that weighs 44 lbs would have at least three times the range and deliver 16.9 MJ of pure kinetic energy upon impact (1). This much kinetic energy is equivalent to that delivered by a Toyota Corolla moving at 380 mph.

Another significant advantage is the time-of-flight; a railgun projectile, due to its enormous speed, reaches the target much more quickly at any range, in addition to striking with greater force. The projectiles would be able to strike targets on the horizon in six seconds and would cover their maximum range, 200 – 250 miles, in six minutes (3). On the other hand, a Tomahawk cruise missile, a long-range strike option of comparable impact energy, covers the same range in eight minutes (2), and this excludes the extra time needed to plot an appropriate course for a Tomahawk missile.

Given the advantages in range and power, one might expect railguns to be more expensive than current technology, like most new weapons developments. However, railgun projectiles will almost certainly be much less expensive than rocket-fueled shells, missiles, and any other long-range strike options. This is perhaps the most tempting reason to develop mature railgun technology. Projectile cost estimates range from $1,000 to $10,000 per shot, a range that is still less than a third of any comparable missile (1,2).

Finally, railguns allow for more ammunition to be stored in a safer manner due to the lack of gunpowder in their operation and the use of kinetic energy projectiles. As an example, the Advanced Gun System (AGS) magazine holds 1,500 explosive rounds, while a railgun magazine of the same volume could store 10,000 nonexplosive rounds (1).

Technical Obstacles and Progress

While the advantages of railgun technology are clear, there are still significant technical obstacles to overcome in developing the device. The most significant obstacle faced by the Navy and previous groups that have researched railgun technology is rail damage. Due to the nature of the device, strong magnetic forces act to pry the rails apart and the rails must be extremely resilient in the face of intense friction and heat, in addition to being strong conductors. After multiple firings, the rails may be quickly damaged by vaporization due to arcing or gouging due to the projectile (4). Furthermore, a proper projectile must be developed. In operation at maximum range, the projectile will actually exit the atmosphere and will be subject to tremendous initial acceleration. The
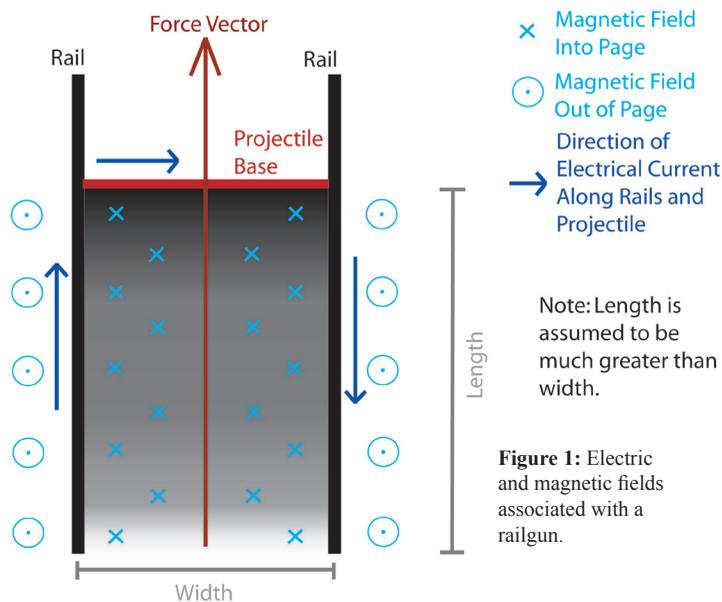

Figure 1: Electric and magnetic fields associated with a railgun.

projectile will need to integrate hardened electronics that can survive this acceleration, the ability to survive reentry into the atmosphere, and a reliable guidance system (1). Finally, the operation of a railgun requires a source of power capable of providing a very large current for a short duration of time. This need will probably be satisfied by compulsators, which store energy in mechanical flywheels (1). Fortunately, much of the research risk has been reduced in light of the extensive research already conducted by other military and academic groups. In fact, research conducted by the Army has already significantly improved our military's understanding of power source, rail design, and projectile design (1).

For an initial goal, the Navy has set its sights on demonstrating a 32 MJ (muzzle velocity) lab gun by the year 2011 to help determine the ultimate feasibility of a railgun. As mentioned previously, the main technical obstacle thus far has been survival of the rails, so the railgun will need to survive 100 shots before requiring replacement of parts due to metal fatigue. Given a success there, the Navy will aim to demonstrate a full-scale 64 MJ railgun by 2015 and attain operational readiness sometime between 2020 and 2025 (3).

Since announcing their goals in July 2006, rapid progress has already been made. The Office of Naval Research has awarded a $14.7 million dollar contract to BAE Systems to design the 32 MJ railgun (3). An 8 MJ prototype was successfully fired in October 2006 at the Naval Surface Warfare Center in Dahlgren, VA, and the same prototype was demonstrated to upper-level Navy officers in January 2007. A 32 MJ lab gun is to be delivered this upcoming June to Dahlgren (2).

A Simplified Physical Model

Much of the important behavior of railguns can be demonstrated with a simplified physical model

developed with basic electrodynamics. As mentioned before, a railgun utilizes a large Lorentz force to propel the ammunition. Lorentz forces are those that act upon a moving charge Q with velocity **v** in local electric and magnetic fields **E** and **B**, respectively, where the bold-faced variables are vector quantities. The equation for the Lorentz force is:

$$[1] \quad \mathbf{F} = Q[\mathbf{E} + (\mathbf{v} \times \mathbf{B})]$$

where the "×" represents a cross-product (5). Recall also that the local magnetic field B at the projectile is produced by the current running up and down either rail. The equation for the magnetic field **B** produced at a point **r** by a current-carrying segment of current I is known as the Biot-Savart Law:

$$[2] \quad \mathbf{B(r)} = \frac{\mu_o I}{4\pi} \int \frac{\mathbf{dl} \times [(\mathbf{r} - \mathbf{r'})/|\mathbf{r} - \mathbf{r'}|]}{|\mathbf{r} - \mathbf{r'}|^2}$$

where a line integral is performed over the path of the segment with **dl** being the differential length vector and **r'** being the position of the differential length (5). A simplified model is shown in figure 1.

There is no significant electric field present anywhere because there is no significant accumulation of charge anywhere. In any volume, the amount of negative charge is roughly balanced by the amount of positive charge. The magnetic field around the projectile is created by the current in the two rails at the projectile's position. This field can be found with the Biot-Savart Law, [2]. Since L >> w, we can assume that our rail extends out to infinity on one side of the projectile and it is approximated with an infinite line of current stretching away in one direction. With an infinite line of current I, the following expression gives the magnetic field **B** a distance *s* away from the wire:

Since $\sin(\theta_1) = \sin(\theta_2)$, therefore $d\mathbf{B}_1 = d\mathbf{B}_2$.

Figure 2: Differential current segments in a infinite line of current.

$$[3] \quad \mathbf{B}(s) = \frac{\mu_o I}{2\pi s} \hat{\varphi} \tag{5}$$

If we examine the infinite line of current, we see that a differential segment of current contributes an equal amount to the magnetic field as the differential segment that is an equal distance away on the other side of the point at which the magnetic field is desired, as can be seen in figure 2.

In this configuration, the rails are to be approximated by a line that extends out to infinity on only one side. So with only half an infinite line the magnetic field **B** a distance s away is half that of an infinite line of current:

$$[4] \quad \mathbf{B}(s) = \frac{\mu_o I}{4\pi s} \hat{\varphi} \tag{4}$$

Even if the rail is only three times the distance to the point at which the magnetic field is desired (s, in the equations), the field will still be 95% that of an ideal infinite rail (4). With this equation in hand, we may now approximate how the magnetic field direction and intensity act along the projectile by summing the contribution of each rail:

$$[5] \quad \mathbf{B}(s) = \left(\frac{\mu_o I}{4\pi s} + \frac{\mu_o I}{4\pi (w - s)} \right) \hat{\varphi} \tag{4}$$

We must also take into account the fact that the rails have a nonzero radius, unlike the infinite wire approximation. This must be done to obtain plausible results, as the magnetic field intensity becomes infinite where the projectile meets the rails in [5]. So, if we assume the rails have a radius R, then:

$$[6] \quad \mathbf{B}(s) = \left(\frac{\mu_o I}{4\pi (R + s)} + \frac{\mu_o I}{4\pi (R + w - s)} \right) \hat{\varphi} \tag{4}$$

Now with the field intensity and direction along the projectile, the Lorentz force on the projectile can be found with the Lorentz force law, [1]. From this equation, one can derive the equation for the magnetic force **F** on a current-carrying segment with current I, in a local magnetic field **B**:

$$[7] \quad \mathbf{F} = \int I(\mathbf{dl} \times \mathbf{B})$$

where a line integral is performed over the path of the segment, with **dl** being the differential length vector (5). Notice that in our simplified model, **dl** will always be perpendicular to **B**, allowing us to make the cross product into a standard product, as long as we note the direction of the force as found by the right-hand rule. Now, we can calculate the differential force **dF**:

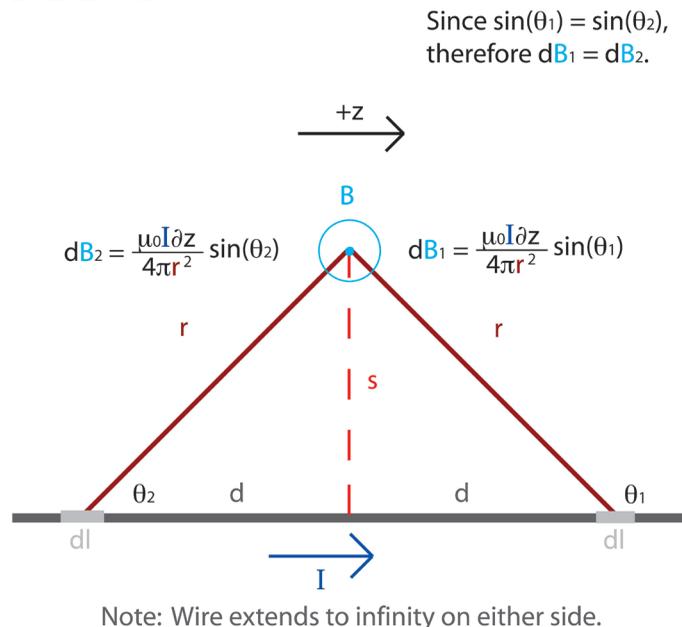$$[8] \quad \mathbf{dF} = I \left(\frac{\mu_o I}{4\pi (R + s)} + \frac{\mu_o I}{4\pi (R + w - s)} \right) dl\hat{\mathbf{z}} \tag{4}$$

If we integrate over the whole gap, we obtain an expression for the total force on the projectile:

$$[9] \quad \mathbf{F} = \int_0^w \frac{\mu_o I^2}{4\pi} \left(\frac{1}{(R+s)} + \frac{1}{(R+w-s)} \right) ds\hat{\mathbf{z}}$$

$$= \frac{\mu_o I^2}{2\pi} \ln\left(\frac{R+w}{R} \right)\hat{\mathbf{z}} \qquad (4)$$

This equation gives us an estimate for the current needed to generate a particular force on the projectile. When combined with a function describing the current over time, the end velocity and energy of the projectile can also be approximated. In this model, we can also see how the rails are forced apart in a railgun. The magnetic field created by one rail along the other rail is oriented such that the other rail is forced away according to the right-hand rule and the Lorentz force law.

Many assumptions were made in the development of this model. With respect to the rails, we assumed that they were very long with respect to the rail separation and that they were thin and round with a radius of R. With respect to the projectile, it was assumed that the projectile is round and that its radius is small compared to its length. An actual railgun would likely only satisfy the first assumption: that the rails are long with respect to the separation distance. More complicated models can be developed but require much more complicated integrals and numerical solutions (4).

In Conclusion

The concept of a tactically useful railgun may soon cross the threshold from science-fiction into modern naval warfare if the US Navy succeeds. Success would give our Navy an extremely cost-effective weapon with much greater power and range than traditional gas-expansion guns and rocket-propelled shells. The increased long-range strike capability will result in a significant increase in the ability to support inland ground troops and participate in engagements at a distance. With the arrival of the railgun as envisioned by the Navy, the tactics of twenty-first century warfare will be transformed drastically both on the ground and at sea.

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