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"A Novel High Energy-Density Electrical Storage Device for Electric Weapons"

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Three different energy storage variants were developed and tested during Phase I. Each was based on the close-coupled, thermopile storage principle. First, direct current was stored in a thermopile ring, which was open-switched into a dummy load to measure the energy release. In the second variant, alternating magnetic energy was stored in a split ring. Energy storage was caused by pumping alternating current in the thermopile circuit, connected as an LC oscillator. Both methods were found to store energy and each delivered pulse power, resulting in a twenty-to-one pulse-power advantage between energy released from the store and energy available from the power supply at the input. Power was drawn from these systems in a millisecond, making use of a specially developed, sequentially opening switch that takes full advantage of the MOSFET's nanosecond hyper-operating speed, the intermediate switching speed of a silicon controlled rectifier (SCR), and a slower speed electro-mechanical switch. Further work with modifications of these two storage methods led then to the development of an inductor-to-inductor (L^2) electromagnetic storage system. This new type storage device seems to out perform the first two methods by roughly two orders of magnitude in storage capacity. During flux pump experiments, we also found that the L^2 prototype system could be tuned to operate efficiently at certain particular frequencies depending on the value of capacitor chosen, placed across the two conductors, to tune in steps between 50 Hz and 50 MHz, possibly operating efficiently in the GHz range.

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I. Task Objectives

The primary object of the Phase I effort was to design a Million Ampere, energy-storage device, using a novel, close-coupled thermopile concept. Ring thermopiles have been found to produce a base current of a thousand amperes when the thermally induced junctions are closely coupled. Million ampere currents can be flux pumped into this ring environment. This little known phenomena makes thermopile rings a prime candidate for high-energy electromagnetic storage for both Defense and Industrial applications. Energy can be extracted from such a system by simply interrupting the current circulation by open-switching the ring. This causes a collapse of the magnetic field, which drives current at the voltage needed to power a variety of electric weapons such railguns, coilguns, and directed energy devices.

Three different energy storage variants were developed and tested during Phase I. Each was based on the close-coupled, thermopile storage principle. First, direct current was stored in a thermopile ring, which was open-switched into a dummy load to measure the energy release, as in figure 1. In the second variant, alternating magnetic energy was stored in a split ring. Energy storage was causec' by pumping alternating current in the thermopile circuit, connected as an LC oscillator as shown in figure 2. Both methods described in figure 1 and figure 2

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were found to store energy and each delivered pulse power, resulting in a twenty-to-one pulse-power advantage between energy released from the store and energy available from the power supply at the input. Power was drawn from these systems in a millisecond, making use of a specially developed, sequentially opening switch that takes full advantage of the MOSFET's nanosecond hyper-operating speed, the intermediate switching speed of a silicon controlled rectifier (SCR), and a slower speed electro-mechanical switch. Further work with modifications of these two storage methods led then to the development of an inductor-to-inductor (L^2) electromagnetic storage system described in figure 3. This new type storage device seems to out perform the first two methods by roughly two orders of magnitude in storage capacity. During flux pump experiments, we also found that the L^2 prototype system could be tuned to operate efficiently at certain particular frequencies depending on the value of capacitor chosen, placed across the two conductors, to tune in steps between 50 Hz and 50 MHz, possibly operating efficiently in the GHz range.

Fig. 1 Magnetic Storage for Pulse Power

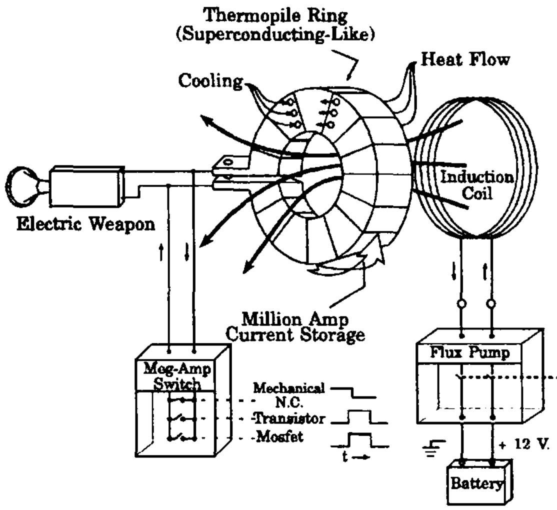


Fig. 2 Inductor-Capacitor Magnetic Storage (AC Mode)

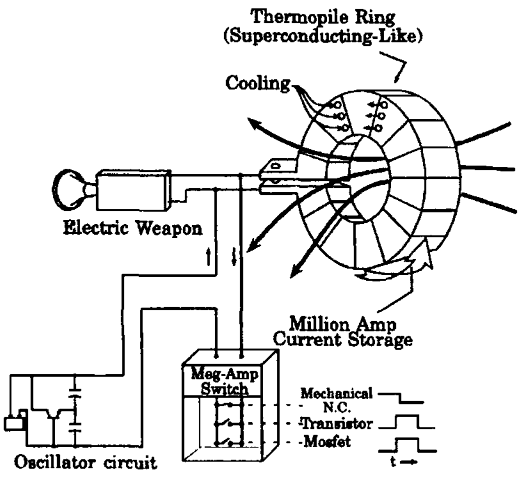
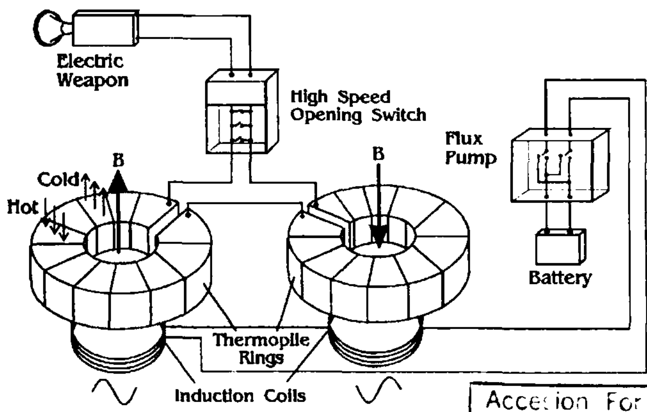


Fig. 3 Inductor-to-Inductor Electromagnetic Energy Store



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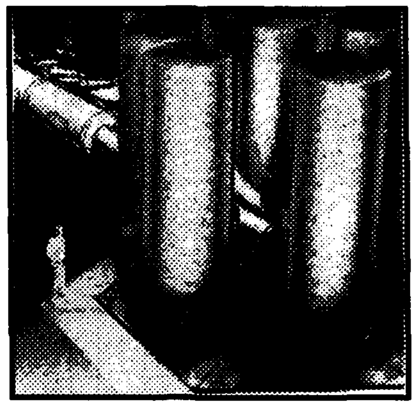
II. Technical Problems

Each of the three energy storage methods were based on a slow energy build-up into close-coupled, thermopile ring store from a modest power source releasing this energy into a load in a millisecond time frame. The first two methods pale by comparison to L^2 performance. L^2 is easy to pump, can be pumped with modest voltages and can store energy many times higher than the prototype DC storage ring and also by the split ring AC means that requires capacitors. The problem we found with the DC storage ring method was with the performance and ability of our flux pump to continue to build the energy store beyond a certain voltage limitation. Capacitor voltage is believed to be the limiting factor for energy storage in the oscillating LC circuit variant. The only limits that we can perceive for our L^2-thermopile storage system are in the strength of materials that make up the inductive, double ring circuit. Tremendous repulsion forces are exerted on the rings when the current circulation reaches Meg-Amp current levels. One of the Kevlar reinforced thermopile rings on the prototype model did in fact separate during an energy storage test. This rupture happened when current approached 1 Meg-Amp. A much higher prestress of the Kevlar reinforcement will be necessary in future experiments. Performance extrapolations from Phase I data suggest the design and construction of a 70 MJ store, with an energy-density of 10 kJ/kg. Such a system would weigh in at around 7000 kg. A Phase II development of this L^2 technology is recommended because this concept is believed to be mature enough to warrant a Phase II decision for the development and test of a full-scale power supply demonstrator at this time.

Fig. 4 Inductor for Homopolar



A new inductor-to-inductor (L^2) energy storage and fast discharge means was discovered and developed during the Phase I program. Traditional pulse-power, energy storage applications have made use of capacitors in the past. Flux compressors, chemical batteries, and rotating machinery such as homopolar generators, and compulsators have also been used. While each of these supplies satisfy the pulse-power requirement for energetic electromagnetic launch systems in the laboratory, no such system has been reduced to a field-portable unit at this time.[1] This is primarily because of the size, mass, fragility, and the ancillary requirements for these power supplies. Figure 4 depicts the magnitude of the problem.

The L^2 energy storage system, discovered and developed during Phase I, is a variation of an inductive-capacitive storage system that stores energy in an oscillating (ringing) circuit. This circuit operates as an inductor-capacitance (L-C) electrical tank circuit, only without the use of a capacitor. Trymer recently developed a ten meter section of a coilgun that made use of many L-C, triggered, ringing tank circuits to provide a pre-charged energy store, tuned upwardly toward the muzzle, to accelerate a projectile. This machine launched six inch diameter, 4.5

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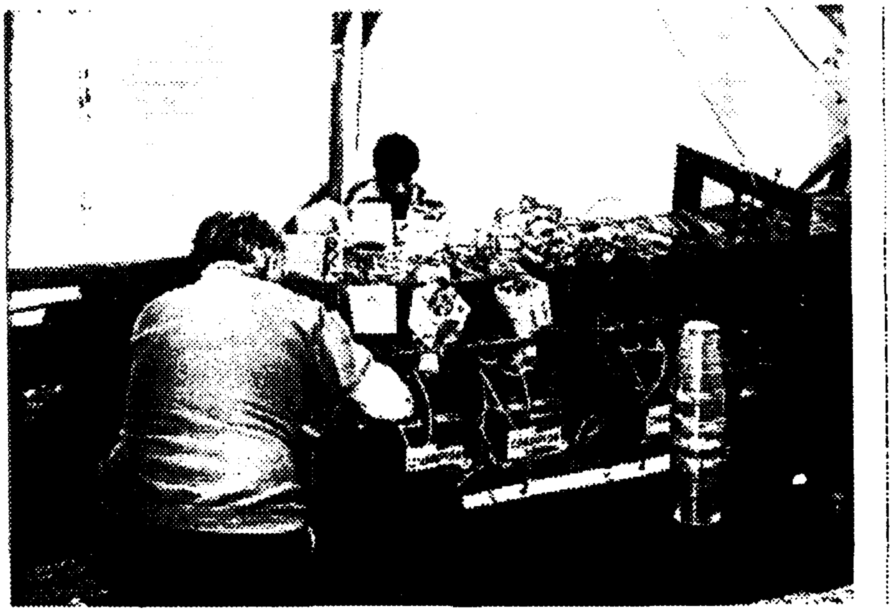
kg projectiles to a velocity of 1.33 Km/s, using only car batteries for a power supply. A section of the gun is shown in figure 5. The success ingredient for this coilgun is in the way current is pre-stored in both the bore and the special armature. Meg-Amp armature currents are stored in four close-coupled, thermopile rings prior to launch. Stored armature currents last the duration of a launch and provides the Meg-Amp-turns on which the gun operates. It is this same current storage concept and the associated magnetic field that we build on in Phase I to develop an electromagnetic energy store to pulse-power a railgun.

Fig. 5 Trymer's Six Inch Gun



III. General Methodology

The development of the armature current storage concept was proposed as a magnetic energy storage system. This Phase I effort allowed the Trymer Company to develop the rings into a novel energy storage concept capable of storing the energy required to power a rail gun. This storage concept is based on the energy in an inductor-to-inductor L^2-thermopile electro-mechanical system. Flux pumping methods were improved to first learn how to inject energy into a thermally induced thermopile ring for storage in the DC mode. This concept is described in figure 1. The significance of this configuration was; proof was obtained that energy could be stored in the magnetic field of a ring, which could later be released as an electrical pulse. Table 1 describes the transfer characteristics of this concept.

Table 1 Shorted Ring Storage

Type	Input	Frequency	As Stored	Pulse-Power Out (1ms)
DC	12VDC, 7A	(DC System)	8V, 170A, 1360 Watts	9 Mega-Watt

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The energy per unit volume, or energy density for this system can be calculated as:

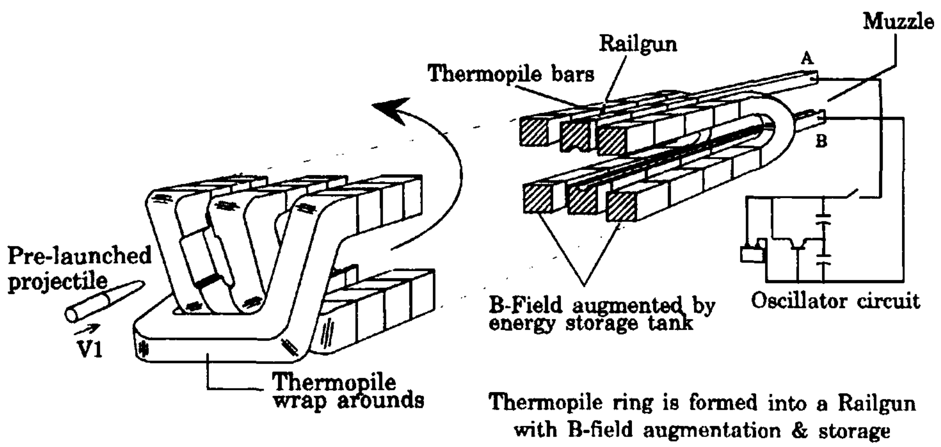
$$U = \text{energy density} = \frac{1}{2}\frac{B^2}{\mu_o}$$

During the test of this model we noticed a puzzling phenomenon. Upon opening the ring circuit, with a high speed MOSFET switch module, we observed a hesitation in current reversal. Perhaps this is because the quench load is wired in parallel with the opening switch, or perhaps it is caused by the speed of the opening (15 ns). What we found was; the energy release time cannot be predicted within the time frame required to operate a railgun. We were embarrassed by this finding. We realized however, that there may be other ways to store and recover energy from a thermopile ring storage system that might behave more predictably. An inductor-capacitor circuit was constructed from this variant and tests were conducted. Inductive-capacitor oscillators are known to store energy and have predictable, harmonic oscillation that can be counted on during an energy release. We found that successful energy storage could be obtained in the AC mode. Figure 2 illustrates this concept. Magnetic energy is stored as an oscillating field which can possibly be integrated into the augmentation coils of a railgun. Figure 6 shows how this might be accomplished. Energy is stored periodically in the capacitor C for this system when the potential difference across the coil is:

$$U = \frac{1}{2}CV^2$$

Just as an inductor can be used to store energy in its magnetic field, energy can also be stored in the capacitor as mentioned at the beginning of this section. Energy resides in the electric field between capacitor plates during half cycles of operation. In an LC circuit, energy is handed back and forth between elements to realize maximum energy storage when the magnetic field is at a maximum or the charge on the capacitor is at a maximum.

Fig. 6 Railgun With Field Augmentation



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To analyze energy in an LC circuit, the energy stored in the electric field of the capacitor at any time t is given by:

$$U_E = \frac{1}{2}\frac{Q^2}{C} = \frac{Q_o^2}{2C}\cos^2(\omega t + \phi)$$

whereas the energy stored in the magnetic field of the inductor at the same time instant is given by:

$$U_B = \frac{1}{2}LI^2 = \frac{L\omega^2 Q_o^2}{2}\sin^2(\omega t + \phi) = \frac{Q_o^2}{2C}\sin^2(\omega t + \phi)$$

Recognize that at t = T/2, 3T/2, and so on, $U_E = 0$ and $U_B = Q_o^2/2C$. All of the energy at this time is stored in the magnetic field of the inductor. The advantage of using this type system is in the multiplication of drive voltage that can be obtained when using a Colpitts oscillator to build-up the energy store. It was found that much more energy could be stored over a period of time with the LC circuit as opposed to the L only, DC storage system. This is probably because we did not know exactly how at this time to optimize the design of our flux pump. There is yet another advantage; we can accurately predict current reversals and plan for an energy discharge. This is the real advantage visualized for the LC storage system. We have wasted a great deal of time in the past trying to understand why current can flow in both directions in the thermopile ring when urged by an oscillating magnetic field. Because we do not want to get off track again studying the storage phenomenon, we simply used the AC method to get around the non-predictability of the DC storage system's discharge. In the LC system we have an opportunity to use peak voltage sensing circuitry to cause the operation of the opening switch. Table 2 illustrates the advantage of AC magnetic storage over DC storage for a modification of the same working model.

Table 2 Ring Storage Performance

Type	Input	Frequency	As Stored	Pulse-Power Out (1ms)
DC	12VDC, 7A	(DC System)	8V, 170A 1360 Watts	9 Mega-Watt
L-C	24VDC, 22A	3,500 Hz	50V, 150A 5250 Watts	37 Mega-Watt

To further explain the AC, L-C energy storage concept, a child's swing, as in figure 7, comes to mind. The Colpitts oscillator that we refer to frequently, is simply one of many classic oscillator circuits that we can use to pump energy into the LC storage system. The Colpitts simply adds voltage to the capacitor when it has the least, to increase the effective charge and thus causes the magnetic energy in the inductor to gain additionally with each cycle

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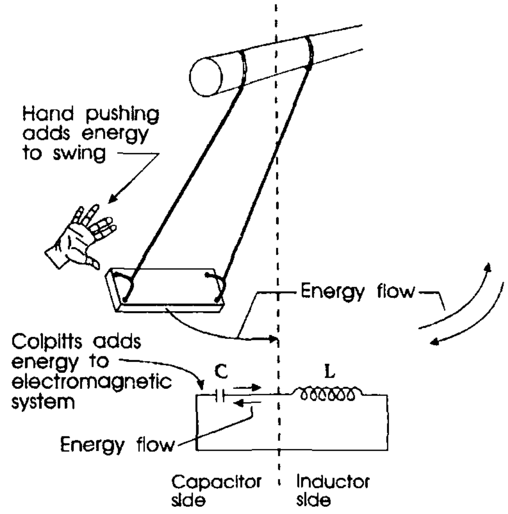
from modest addition of energy. The child's swing benefits from continuous, gentle pushes at just the right time to increase the overall magnitude of the swing. Should the person pushing the swing walk into the swing's path just as it nears the ground (highest velocity), pulse power can be extracted that is many times the force of a single gentle push. The kinetic energy of the swing is imparted to the person impeding swing travel. Using this analogy, a thermopile-ring inductor, swapping energy between an inductive ring and the capacitor, has the ability to release energy in the form of voltage driven current during magnetic field decay and this can be used to power a railgun. The LC circuit is, however, limited in storage capacity by the voltage a capacitor can withstand without rupture. Recognizing this as a weak point and the fact that inductors operate at very low voltage, but at high current, we chose to replace the capacitor with another inductor to allow the system to oscillate L-to-L, tolerating much higher voltages.

Fig. 7 Electromagnetic Swing Analogy



This would allow a thermopile inductor to store large currents at very low voltage. An inductor-to-inductor energy storage variant (L^2) was attempted. Nowhere in the literature could we find where an inductor was used to replace a capacitor in an LC circuit. When this was tried, it resulted in the highest level of energy-density storage that we had obtained with variations of the working model. This system had the potential to yield the greatest pulse-power release. Such a system, driven by the highest output voltage, would require little or no power conditioning to operate a railgun. Figure 8 describes this concept and table 3 describes the prototype's performance compared to previous storage concepts. Based on actual performance, extrapolations were then made from the Phase I prototype model and this allowed a conclusion that we have a very good chance of successfully building a workable pulse-power supply on the order of 70 MJ, to power a railgun. Such a device would be a solid-state machine, with no moving parts, and would have a mass and volume of 700 kg for about 1 m^3. This concept is believed mature enough to develop a full scale version of this power supply. The proposed pulse-power supply will be capable of storing 70 MJ for a mass budget of 7,000 kg (15,400 lbs), or about 10 kJ/kg. Aluminum-nickel construction will reduce the system weight, substituting for the denser copper-nickel.

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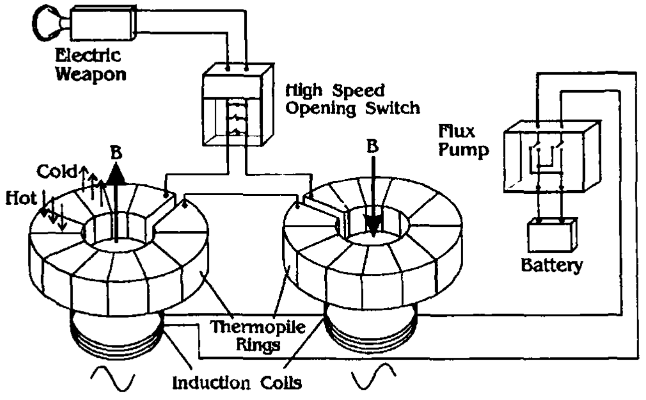
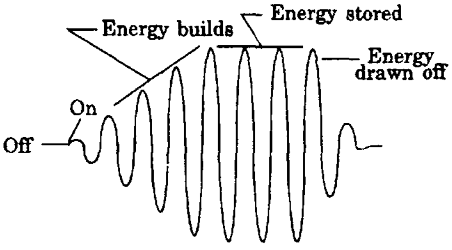
Fig. 8 Operation of L^2 Electromagnetic Energy Storage System





Stored Energy in Oscillator

Table 3

Type	Input	Frequency	As Stored	Pulse-Power Out (1ms)
DC	12VDC, 7A	(DC System)	8V, 170A, 1360 Watts	9 Mega-Watt
L-C	24VDC, 22A	3,500 Hz	50V, 150A, 5250 Watts	37 Mega-Watt
L^2	120V, 25A	4,000 Hz	105 KW	100 MW*

* Potential for the bench model (Not actually measured)

Experiments and modeling were performed during Phase I which proved energy could be pumped slowly into an L^2 circuit made only of copper, then recovered on a pulse basis in an instant of time (no thermopile). This allowed us to measure L^2 inductive storage with and without thermopile enhancement.

To analyze energy in an L^2 circuit, the energy stored in the electric field of the capacitor at any time t is given by:

$$U_E = \frac{1}{2}\frac{Q^2}{C} = \frac{Q_o^2}{2C}\cos^2(\omega t + \phi)$$

whereas the energy stored in the magnetic field of the inductor at the same time instant is given by:

$$U_B = \frac{1}{2}LI^2 = \frac{L\omega^2 Q_o^2}{2}\sin^2(\omega t + \phi) = \frac{Q_o^2}{2C}\sin^2(\omega t + \phi)$$

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Recognize that at t = T/2, 3T/2, and so on, $U_E = 0$ and $U_B = Q_Q^2/2C$. All of the energy at this time is stored in the magnetic field of the inductor. By replacing U_E with another U_B we have a system where:

$$U_B = \frac{1}{2} LI^2 = \frac{L\omega^2 Q_Q^2}{2} \sin^2(\omega t + \phi) = \frac{Q_Q^2}{2C} \sin^2(\omega t + \phi)$$

$$\frac{Q_Q^2}{2C} \sin^2(\omega t + \phi) \text{ of one coil} = \frac{Q_Q^2}{2C} \sin^2(\omega t + \phi) \text{ of the other coil}$$

The only difference is, theta for one side is 180° out of phase with the other.

Figure 9 illustrates this electromagnetic pulse power concept, using an air compressor analogy, slowly building up air pressure for a later, rapid air blast release. This could be compared to the slow electromagnetic energy build up with a flux pump, storing magnetic energy for a pulse release of magnetic to electrical energy which is the form needed to operate a Railgun. Figure 8 shows how electromagnetic energy can be stored in the L^2 system until such a time as it is released into a Railgun with a rapid burst of electrical current. Current is forced by a voltage that is caused by the collapse of the magnetic field.

Fig. 7 Air Compressor and Magnetic Compressor for Pulse-Power

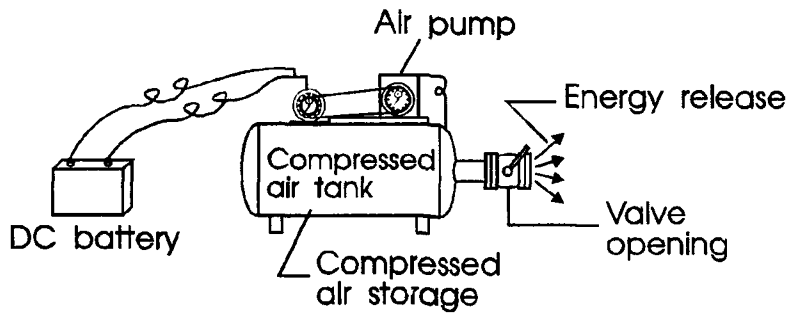
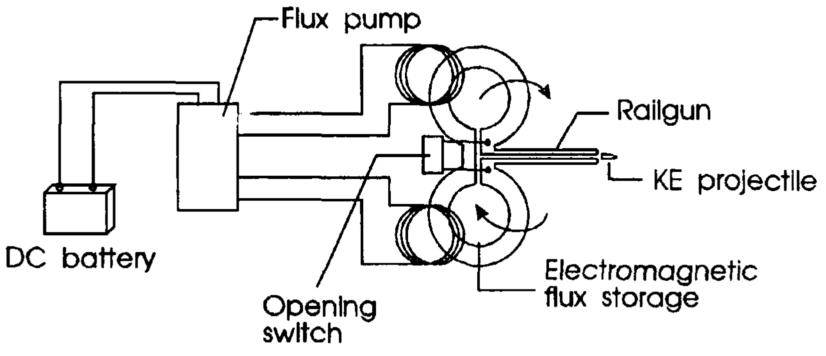


Fig. 10 L^2 Electromagnetic Energy Buildup to Power a Railgun



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IV. Technical Results

The most significant feature of L^2 storage is believed to be in the ability of this system to deliver conditioned electrical energy to a railgun without a need for pulse transformers, switches, and the ancillary equipment normally associated with laboratory guns. The basic problem with other options is actually one of power conditioning. Power conditioning technology is required for most burst power supplies to condition the prime power generated into a form unique to the particular electric weapon. Power conditioning sub-systems for all but the compulsator are much larger and more massive that the prime power system itsel' as illustrated in figure 4.

This is not the case with L^2 energy storage technology. Power conditioning is a natural phenomenon of magnetic field collapse within an inductive circuit, so it is already built into the L^2 supply. The L^2 program will culminate in first-of-a-kind unit that will undergo extensive testing and evaluation during the Phase II time frame. This power supply will be lightweight compared to counter parts, with no moving or gyroscopic effects as with a compulsator's rotating armature. The focus of Phase II should be on a new, lightweight design, the construction, and testing of a pulse-power supply, capable of powering a railgun that is capable of launching a 5 kg projectile to a velocity of 4 km/s or 70 MJ at 30% efficiency. The L^2 supply is expected to weigh in right at 7,000 kg so that it can be easily transported, along with the railgun, acquisition system, and crew, in a single load for a C-130 aircraft. Current power supply options, such as ultra-lightweight power generation components that use technologies such as pulse-alternators, fuel cells, magnetohydrodynamics (MHD), and even chemical storage batteries are considered to be too massive and out-sized for this mission.

This new L^2 technology has dual-usage in Defense and Commerce. An L^2 can be configured as a lightweight RF source locked at a particular frequency by a tuning capacitor. This was discovered during Phase I much to our surprise. This technology can possibly find applications, not only in electric defense weapons, but in Radar, Broadcast Television, Microwave, Energy Beaming, and X-Ray, all of which are important in Defense mission. The greater uses, however, will be found in the Commercial sector. All of the potential applications can benefit from a compact, energy efficient power supply that operates off a combination of waste exhaust heat, and freon refrigeration. Energy can be stored from any type electrical source, from photovoltaic panels, to portable generators, even off the utility grid. Other applications that make use of pulse-power properties of the L^2 system are; welding, directed energy, emergency utility grid hold-up, energy transmission, NMR, Tomography, remote sub-sea sensing and imaging, naming just a few. For Phase III, a successful Phase II will result in a solid-state, railgun power supply, that will replace a battery-transformer supply of marginal reliability, that drives Trymer's "Earth Drill". Trymer uses a railgun to make shot-holes in our commercial quarry drilling service. Trymer is believed to be the World's largest commercial user of railgun technology and the proposed L^2 development will greatly expand the commercial uses of railgun technology.

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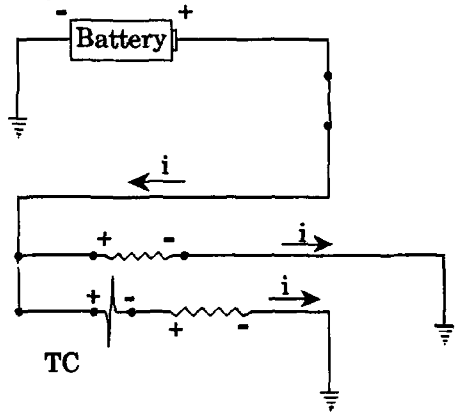
V. Important Findings and Conclusions

We are currently at a loss as to how and why the thermopile ring storage system actually works. During the development of the Navy's Earth-to-Orbit coilgun, we used to be ever so careful in assembling thermopile rings on the projectile so that the current produced by the thermally induced thermopiles would add with the current added by the flux pump to increase the current in each ring. Also, we thought that this was necessary so that the magnetic polarity of each ring on the projectile would match the accelerating magnetic wave in the gun. What we found out, by making mistakes in assembly, was that it didn't matter which way you installed the thermopile rings. It mattered little which way the current in the thermopile rings flowed originally. The current could be pumped into these rings in either direction, forcing the magnetic polarity to mate with the gun, regardless of the polarity or preferred current direction of the thermopile rings. We found that we could always switch the polarity of the pump coil wires to fix internal problems in the assembled projectile. We wasted a lot of time trying to figure this out. Then, a very simple experiment was developed to illustrate how forced current in the thermopile system actually works. This experiment suggests how close-coupled thermocouple-ring systems operate, but it falls short in explaining thermopile junction phenomenon.

Consider the following experiment:

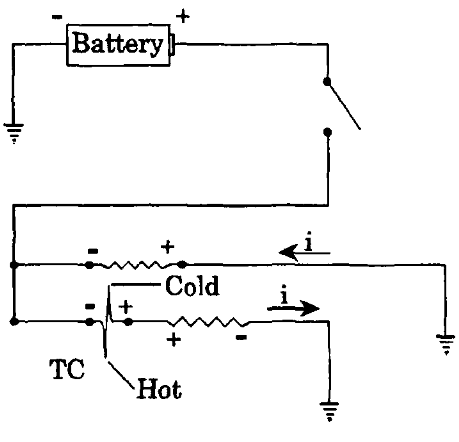
Fig. 11



Starting with all elements of the circuit in figure 11 at room temperature, the switch is closed allowing current to flow through each element and the room temperature thermocouple to ground.

Notice the polarity of both the thermocouple (TC) and the test resistors. The polarity of all elements except the battery are represented as voltage drops.

Fig. 12



Now, the TC junctions are heated and cooled as in figure 12.

Notice that millivolt gains appear across the TC junctions. Check the polarity of the thermopile with respect to the resistors. The TC is a voltage producer while the resistors drop voltage. An oscilloscope can be used to accurately measure these low DC voltages. Notice also that these voltages appear across the end terminals of the TC.

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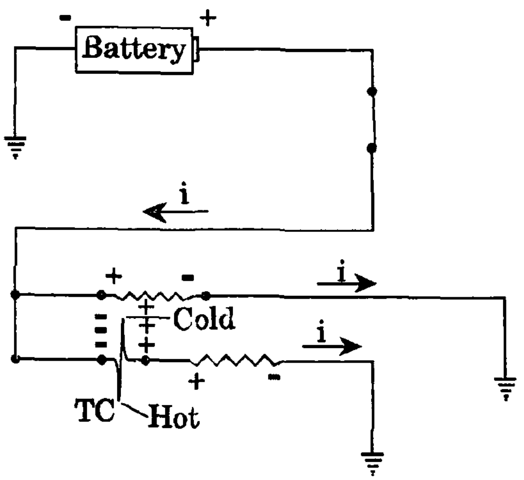
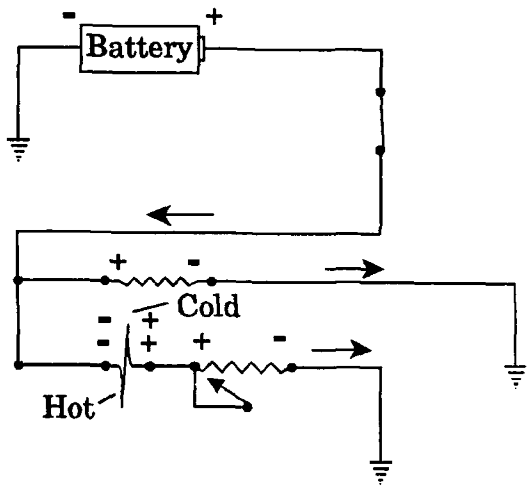
With the TC heated and cooled and the switch closed, in figure 13, this forces current in both legs of the circuit to ground. The voltage gain across the TC actually increases as shown in figure 13. Normal reasoning says that the voltage across the TC should drop when the switch is closed and forcing current. The TC should assume exactly the same polarity as the above resistor .... but it doesn't.. We do not know why.

Fig. 13



The polarity of the TC in figure 13, when it is thermally induced and current forced, is the same as the battery. There is actually a voltage gain across the ending terminals which is much larger than that produced by the TC itself. This larger voltage ''gain'' is due to the forced current supplied by the battery, or, in the case of a closed loop, by the flux pump.

Fig. 14a



In figure 14a, the switch is closed, forcing current through both thermocouple and resistors. Both resistors are connected to ground. Notice the polarity of each component. There is something very strange about the polarity and the magnitude of the voltage produced by the thermocouple that is being forced by the battery.

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In figure 14b, the variable resistor is shorted to reduce the resistance in the thermocouple leg. Notice that the voltage again rises and the polarity remains as if it were a battery, not a resistor.

The voltage rises across the thermocouple to accept the additional current. **We would expect a voltage drop when current is forced through the TC.**

Fig. 14b

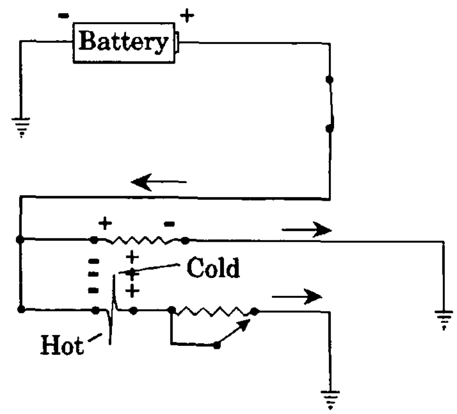
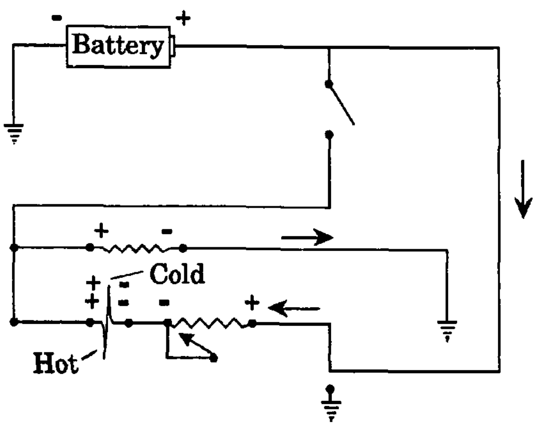


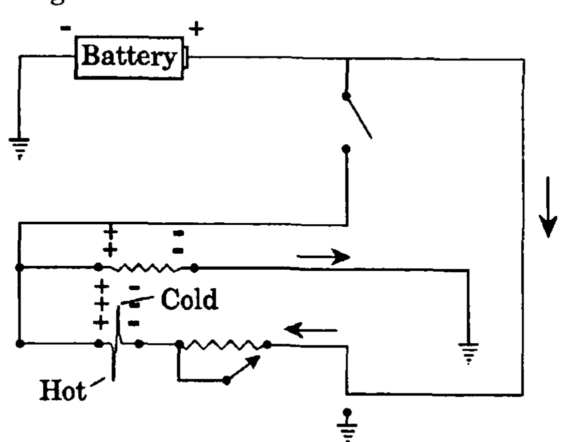
Fig. 15a



In figure 15a, a jumper lead has been attached from the battery to the point where the ground lead was connected below the thermocouple. Current is forced backwards through the thermocouple. Current travels through the top resistor and back to ground. Notice that the signs on the resistor in the thermocouple leg reverses. The thermocouple polarity reverses. **This should not happen.**

In figure 15b, the variable resistor in the thermocouple leg is adjusted so as to force more current through the thermocouple. The voltage across the TC increases to aid the flow of current. **This definitely shouldn't happen.** There should be the millivolt contribution from the thermocouple that would act like a very small resistor, subtracting voltage. But why does a large voltage gain in the direction of the current flow appear? This might explain why we are able to pump current both ways through a close-coupled thermopile in the AC mode with a Colpitts oscillator. It might also explain why we can make the L^2, inductor-to-inductor thermopile oscillator operate and store energy in the AC mode.

Fig. 15b



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What this tells us is: 1) Large currents can be built up to circulate in a closed ring of thermally induced thermocouples, driven in either direction; 2) The voltage across each of the TC junctions rise to support the current in the ring. This tends to make the resistance in all parts of the circuit cancel out or disappear. This sounds crazy. It all began with our attempt to reduce the resistance in a ring to store current for a longer lifetime in a projectile. This storage system does not store indefinitely, at least this is our experience. Energy must be continually added but does allow a build up much greater than the input energy.

It bothers us that such a thing can happen, but allows us to treat thermocouple rings as LC, L^2 energy storage tanks and to operate in an alternating current mode.

High Current Opening Switch for L^2 Storage

In the above tests, we talk about million ampere opening switches. This is a hypothetical solution to the switching problem that we have yet to fully try. A million amp, very fast switch will be needed to off-load power from the inductive energy store. The following represents what we know about this problem:

We know that a mechanical switch (solenoid) can be built to carry high current, perhaps a million ampere, for a short period of time, then open. The problem with using such a switch to remove power is in the slow opening speed. Energy will be dissipated in the arc. We also know that diesel-electric locomotives switch heavy currents with paralleled SCRs. While SCRs are much faster than mechanical switches, they are still too slow to commutate Meg-Amp currents. We discovered through experience with paralleled MOSFETs that they have the switch speed (10 to 50 nanoseconds) and can carry super currents, but only when pre-chilled, and only for an instant, less than a millisecond. They heat up fast and this heat destroys these devices. By making use of the best of all three types of switches and operating speeds, we think this might be one way (not the only way) to open-switch a million amps to extract power from the L^2 storage ring. Another way to help the problem is by opening the switch as the projectile is injected between the rails. In this way, the projectile maintains the voltage low in the early portion of the launch. Also, a large capacitor placed across the switch will act as a snubber for the switch.

The success ingredient for our thousand amp switch, used on the coilgun, is in the matching of individual MOSFET components, so that they "electrically" open at the same voltage, all at once when operated by the single triggering voltage ramp.

Semiconductor Theory Might Explain the Operation of Thermopiles

Current flow in a thermocouple is due in part to electrons in one material occupying lower energy states than the other, so electrons flow across the junction when heated. This leaves one metal slightly more positive than the other, so a contact potential exists between them. If two junctions are at the same temperature, the same potential exists in each; they balance

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each other, and no current will flow. However, when one junction is at a higher temperature, the energy states are altered and the contact potential will be different. In this case there will be a net emf and a current will flow. But this does not explain how current can flow in either direction as is possible with L^2 inductive storage.

Semiconductor behavior on the other hand, is explained at the atomic level using the so-called electron band theory of solids, which is based on quantum mechanics. Electrons in a single atom can occupy only certain energy levels. The lowest possible energy level is called the ground state and higher ones are called excited states. In a solid, these energy levels spread out into wide "bands" because of the interaction among the atoms. The outer electrons can be considered to be in either of two bands: the lower valence band, which corresponds to the ground state; or the upper conduction band. No electron can have an energy in the "forbidden" energy gap between the two bands. Normally the electrons reside in the valence band where they are held rather tightly to individual atoms. But when electrons in a material are excited, say by heating, they jump to higher energy levels, leaving electron holes behind. In materials with a direct band gap, the recombination of a decaying electron drops down to another energy state with a hole and this usually results in the emission of a photon. Silicon has an indirect band gap, so decaying electrons do not drop immediately into a lower energy state unless the silicon is specially etched into a lattice of filaments. Speculation is that the porous silicon confines electrons in these filaments, somehow causing silicon to act as if it were a direct band-gap material.

In metal conductors, such as the copper and nickel used in the thermopile, there is no gap. The two bands may overlap, or there is simply one band that is not filled and the electrons are free to move easily to other states; they can thus move about freely and carry an electric current. In a pure (or intrinsic) semiconductor, such as germanium or silicon, the forbidden energy gap between valence and conduction bands is very small. Only a small percentage of electrons can have enough energy to jump the gap, so there will be a very slight amount of conduction. (At room temperature, the average KE of electrons is on the order of $kT = 1/40$ eV). However, if the temperature is raised, more electrons will have enough energy to jump the gap; this effect can often more than offset the effects of reduced mean free path due to increased disorder at increased temperature, and this is why the resistivity of semiconductors decreases with temperature.

But remember that electrons in metals can easily acquire sufficient energy to reach the conduction band, especially when heated to a high temperature as in the hot junctions of a thermocouple. Once across the junction, an electron would not be bound to a particular atom but could move about freely in the lattice. By jumping the junction interface between di-similar metals, this creates a contact potential and thus causing current flow, or it could jump backward caused by the field and wander through the lattice of the thermopile ring in search of a hole, driven by the oscillating magnetic field of the storage system. This we believe is the donor level that supplies electrons to the conduction band of a close-coupled thermopile ring. Further study is needed to verify this. The region where the electron just left is called an acceptor level because electrons from the valence band can easily jump into it. A positive hole is left behind; and as other electrons move into this hole, the hole moves around through the conductor, in

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either direction, swept by the magnetic field, until trapped by free electrons, launched from a close coupled junction. The simple experiment described in the first part of this section concerning thermopiles was shared with a number of colleagues in an attempt to explain close-coupled thermopile activity. We are searching still for answers. Perhaps there is no reason to know exactly how or why the L^2 system works, but that it is reproducible and serves our energy storage requirement needs for portability. Semiconductor diodes and transistors are essential components of modern electronic devices. Their miniaturization is achieved by special photolithographic processes, which allows many thousands of diodes, transistors, resistors, and so on, to be formed on a single chip (integrated circuit), a centimeter or so on a side. The L^2 thermopile storage concept is probably just a useful assembly of "Old Science" and we should not be too surprised if it can be described by conventional solid state theory. What we seem to have discovered with the L^2 storage concept, is the antithesis of the integrated circuit, a gargantuan, semi-super-conducting metallic ring device, that serves our purpose as an energy storage device, running on muffler fumes and green radiator water, creating a semi-superconducting environment where we can conveniently store energy in the form of current and its associated magnetic field. On demand, such a device can deliver hundreds of Mega-Joules of pulse power. Such a device could never have evolved from semiconductor disciplines, but the technology roots trace directly back to the nanoampere, sub-micron structures of the microelectronics industry. If there is ever a search to discover the principles behind this storage behavior, it should begin with semiconductor theory.

VI. Implications for Further Research

The inductor-to-inductor (L^2) electromagnetic storage for pulse-power applications is a brand new concept. Perhaps it is not really new, but a combination of old Science, rehashed, re-exploited, and combined into a new form to satisfy the defense need for a pulse-power supply for a railgun. Trymer's staff has a long history of developing solutions for industry that are different and non-conventional. These solutions are non-obvious or follow a different path from conventional wisdom. To analyze our efforts requires time, and unorthodox treatment, and this is hard work. We of course are driven to make the L^2 power supply work for us to satisfy our own power supply needs and make our commercial earth drill program a success. We have gained enough experience during Phase I to see our way clear to develop a sizeable L^2 power supply for our commercial needs. We owe our sponsors, SDIO/IST and the U.S. Army Strategic Defense Demand, Huntsville further verification of the principles of our work. It is proposed by our Technical Point of Contact, Mr. Dimitrios Lianos, that we develop a series of working L^2 models and share these with the federal laboratories for test and evaluation prior to proceeding with the Phase II development of a 70 MJ, 7,000 Kg pulse-power supply based on L^2 technology. We at Trymer totally concur and praise Mr. Lianos for his insight, diligence, and courage. We, too, have a sincere desire to have our Science evaluated, refereed, and certified. The L^2 concept is too far off the beaten Science path to quickly evaluate, so we are desperately seeking competent evaluation. An interim development of a technology demonstrator will make the best use of shrinking R&D dollars. The Pulse Power Laboratory at Picatinny Arsenal would be the best facility to perform such tests. After thorough evaluation of the L^2 storage concept, the findings and suggestions for improvement can then be incorporated into a Phase II development to construct and test a full scale 70MJ pulse-power supply for a railgun.

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A Phase II proposal was submitted prior to this Final Report. The object of this proposal is to design, construct, and test of a 70 MJ pulse-power supply to support SDIO's anti-missile program. The supply will use a unique inductor-to-inductor, oscillating magnetic storage concept, storing energy in close-coupled thermopile, inductive ring environment. Energy will be stored electromagnetically, oscillating L-to-L (L^2) as opposed to conventional L-to-C oscillation. This "first of a kind", L^2 electromagnetic storage and discharge system will be powered by a conventional, field portable, AC generator. It will also be possible to power this unit directly off the utility grid. The prototype will provide conditioned electrical energy to launch a 5 kg projectile to a velocity of 4 km/s from a railgun, at a store-and-release rate of 1 Hz. The demonstrator is expected to have an energy-density ratio of 10 kJ/kg, which will make single load, anti-missile defense system transportation possible by C-130 transport. The new, solid-state L^2 power supply and pulse-power generator has broad application in both Defense and Industry. A remarkable feature of the L^2 technology is the ability to tune and control operating frequencies between 50 Hz and 50 MHz. L^2 operation in the GHz range may be possible and such a system can be used as an RF source, producing fantastic burst energies. Commercial applications of this technology range from welding, radio, television, radar, microwave, X-Ray, directed energy, utility grid hold-up, transmission, NMR, tomography, sub-sea sensing, imaging, to a Phase III power supply for Trymer's Commercial Earth Drill program.

VII. Significant Hardware Development

Significant hardware was developed during Phase I. This hardware was used to test the energy storage principle in the flux pump, open-ring DC mode, the AC pumped mode, and the inductor-to-inductor L^2 pumped mode. These were small bench models, worthy only of Scientific study and modification to enhance operating parameters. These models helped to direct the development effort and allowed us to select the L^2 storage concept as the most efficient for a railgun power supply. All experimental setups were video taped with audio explanations of elements and each of the tests were filmed for slow motion analysis of electromagnetic wave forms. These tapes are archived and will be used in future developments.

VIII. Special Comments

The L^2 storage concept, developed in Phase I, is a combination of ideas and expressions put forth by Scientists such as Sadedin, Marshall, Driga, Weldon, Zowarka, Lianos, Barber, Scallion, and too many others to mention. We had no intention of playing havoc with the established status quo. This Phase I effort represents our interpretation of how to use their best work. What they said and published, and how we interpreted this to result in the L^2 power supply. A black box, no moving parts, small, portable, pump the energy in slowly, build a great electrical store, and release it fast. Recycle the system and do it again and again. This is what SDIO/IST said it wanted and now we have it, at least in principle. The Trymer Company does not have to know every detail about L^2 Science to be able to make the best commercial use of it. We are poised to develop and build a number of Industries based on this technology, to bring Texas and the nation out of its doldrums. We have made good progress with this development

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program and would like to keep up the momentum and enthusiasm. We see L^2 as the solution to a practical pulse-power supply for a railgun for Defense purposes, but our's is a different quest. We would like to take advantage of this concept commercially. We thank SDIO/IST, and the U.S. Army Strategic Defense Command, Huntsville Alabama for their encouragement and support in this development.

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