HYBRID ELECTROMAGNETIC LAUNCHERS (HEML) FOR LARGE PROJECTILES: A NOVEL METHOD TO COMBINE EML AND ROCKET PROPULSION CONCEPTS

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ABSTRACT

New and novel concepts in electromagnetic launcher technology have been under continuous development at the University of Texas at Arlington Center for Accelerator Technology and Applied Sciences. Those concepts which accommodate conventional rocket propulsion along with EM propulsion were emphasized. It was found feasible to accelerate complex metallic rocket-like projectiles totally cleared of the rear area, thereby permitting the insertion of rocket boosters or to allow exit flow of propellant jets heated during EM launching. Optimum acceleration rate is possible by combining conventional rail-induced and external magnetic fields, suitably arranged in the launcher assembly, and recoil thrust from the ionized propellant exhausts. The overall acceleration concept we advanced here (use of rail-induced and external magnetic fields and jets from propellants) in the propulsion of large complex projectiles are generically called Hybrid Electromagnetic Acceleration (HEMA) and the accelerator, Hybrid Electromagnetic Launcher (HEML). HEM driven rocket-like projectiles which also contain solid propellants are called Hybrid Projectile (HP). HEML should find immediate applications in advanced ballistic missile development (BMD) and/or eventual development of zero stage rockets. Thrust analysis, torsional and compressional stress analysis, use of jets from the propellent exhaust for additional propulsion and HP projectile cooling during launch are found favorable. Temperature distributions in a HEML system, presented in a serial paper, suggest that cooling by vaporized propellants should be utilized. Some laboratory experimental work on HEML are briefly discussed.

INTRODUCTION

During the past several years there has been an increasing activity in hypervelocity research to accelerate macroscopic matter to high velocities. Initially this interest is in the prospect of impact fusion[1] and more recently in projectile launchers[2]. The motivation for the new interest comes from the expectation that multilayered armor materials, which resist shaped charges, are penetrable by hypervelocity kinetic energy projectiles. To drive projectiles to hypervelocities (> 5 - 10 km/sec), the Electromagnetic Launcher (EML) concept, which was often studied during the past fifty years, has been revived due to improvements in modern materials and pulsed power technology. Recently, proposal to use EML as a means to deliver payloads into space was also advanced[4]. However, simple projectiles launched electromagnetically to these high velocities are not necessarily useful in conventional rocket technology, as it lacks control, maneuverability and suffer severe ablation in the atmosphere. In point of fact, an intermediate launch velocity might well be better suited from the aerodynamic point of view.

Modern rocketry relies mainly on chemical propellants for boost and propulsion. Chemical rockets can reach higher velocities only by increasing the mass ratio, a method which is highly inefficient and expensive. We suggest, however, that propulsion technology can be significantly advanced by combining the advantages of mature rocket technology and electromagnetic (EM) propulsion technology. Our overall aims are to reduce launch weight, increase flight range and reduce reaction time in reaching the target.

THE BASIC CONCEPTS

The basic concepts advanced by one of us[3] (K. W. C.) since 1981 to achieve these aims were that initial booster stage of the rocket could be assisted, replaced or reduced in size by using EM propulsion at launch and that the stored propellants could be utilized for cooling and propulsion. Presently, EM launchers are either inductive magnetic accelerators[5] or the railgun. In single shot applications, due to its large acceleration rates, the railgun approach is currently in favor. Railgun designs consist of a projectile propelled from the rear by a metallic or plasma armature which is driven by the induced magnetic fields established in a pair of parallel conducting rails[6]. This arrangement is adequate to drive simple projectiles for tactical armaments. Thrust is exerted only from the rear with the result that the stress per unit area (pressure) behind the load is often extreme. Useful projectile shapes are limited and objects with some modest complexity such as rockets cannot be launched. In our approach, the larger projectile side surface areas and/or sabots are to provide the necessary thrust at lower overall pressure exerted on the projectile. By freeing the rear area of the projectile, it is also possible to install rocket boosters and to permit free flow of propellant exhausts. To accomplish this, in most our designs, external magnetic fields are incorporated in the launcher tube to reach thrust-producing surfaces where rail-induced fields are inadequate. Both conventional magnets and superconducting magnets were considered.

Thermal disintegration of the projectiles is a serious problem at high driving currents. Two additional advantages present themselves in HEML. We show that vaporized propellants possess both significant cooling capacity (to avoid melting or ablation) and additional recoil when ionized and propelled by the electromagnetic fields in the launcher.

MODEL FOR A TYPICAL HYBRID LAUNCHER AND PROJECTILE

A conventional modular railgun launcher facility shown in Figure 1 has been in operation for some time at this Center. Concurrently a variety of advanced hybrid launcher concepts is under active study. One of these advanced hybrid concepts is presented here in some detail. Fig. 2. shows a scaled HEML model (#1) with a representative eight-fin structure attached to a hollow conducting cylinder. The shaft shown in the figure is for support of the model and is normally clear of obstructions in a vertical launch. The interior portion of the cylindrical structure is hollow and is to be used to store propellants or electronics. The fin structure is to provide thrust for propulsion and can subsequently be ablated or discarded when leaving the launcher. In the launcher assembly are located matching conducting rails which supply the electric current. The projectile is made out of conducting aluminum or titanium alloys. Additionally, the launcher is instrumented with a dc external mag-

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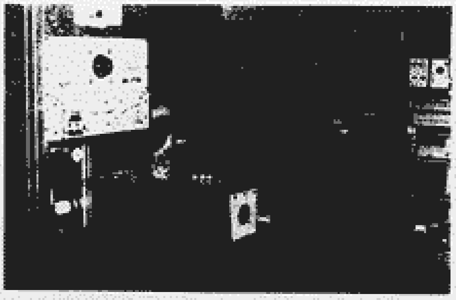

Fig. 1. Modular railgun and its associated equipment currently under operation at the Center for Accelerator Technology.

netic fields directed perpendicular to the fin surfaces. During launch, the HP projectile experiences thrusts from both the rail-induced and the external magnetic fields. If superconducting magnets are used, the F_{ext} becomes greater than rail-induced fields for much of the current levels we have examined. The fins can be increased from a value of 2 up to about 8. The optimum is of the order of 6 by our design of magnets, so that the flux return are confined with sufficient iron material to avoid severe core saturation to occur.

THRUST SIMULATION ANALYSIS OF HEML DESIGN #1

To evaluate the thrust experienced in #1 design, the rail-fin-shell configuration shown in Figure 3 was used. The projectile assumes has a 10-cm radius with fins 10 cm wide. External magnetic field is directed vertical. The rail-fin and projectile-fin interface are parametrized so as to accomodate the expected current flow of Hughes and Young[7]. Figure 4 shows thrust contributions from the rail-induced and external magnetic fields as a function of driving current for a six (6)-fin structure. Note that for a 6 T external magnetic field, F_{ext} is greater than F_{rail} below 1.6 MA. As current rises, the contribution from the external magnetic fields tend to decrease, as F_{rail} increases rapidly. At low currents F_{ext} dominates, and at higher currents F_{rail} dominates. The total thrust at 2×10^6 A is about 10 MN, sufficient to drive a 50 kg projectile to an acceleration of 2×10^4 m/sec^2. For an instrumented launcher 10 m in length, we find the final velocity to reach 2 km/sec. In Figure 5 we show the same thrust analysis except that a two-(2) fin structure are used. The resultant thrust is about a factor of three lower when compared to that in Figure 3. The total thrust as a function of current for a variety of fin structures ranging from 1 to 6 is shown in Figure 6. The percentage thrust from rail and external magnetic fields to F_{tot} for various values of B is shown in Figure 7. The crossover indicates the current at which the the percentage are equal. It should be noted that for larger rockets, say 1,000 kg or more, the fins radius will be scaled up and rail-induced fields decreases (as 1/r) so that the crossover points on Figure 3 move toward higher values of currents.

TORSIONAL AND COMPRESSIONAL STRESS ANALYSIS

Using the #1 model shown in Figure 3, torsional and compressional stress distributions were evaluated at fixed $B_{ext} = 2$ T. Figure 8 shows these stress distributions along the rail-fin interface for a sample input current of 10^6 A. The compression is uniform across the interface while torsional stress changes from 0.9 kpsi to - 0.97 kpsi. The total stress varies from -11.3 kpsi at A to -13.1 kpsi at point B. For example, hot roll steel alloy G 43440, the safety factor is 5.25 and for casting aluminum

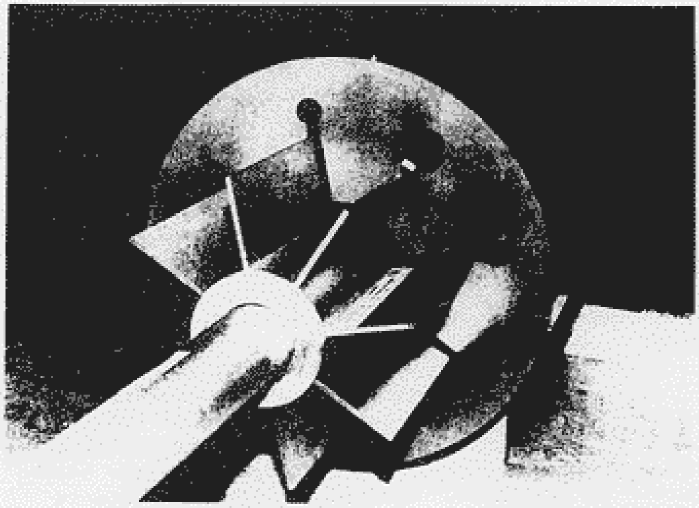

Fig. 2. HEML Model for UTA design #1 discussed in text. The 8 fin structure has a hollow interior. The shaft is for support only.

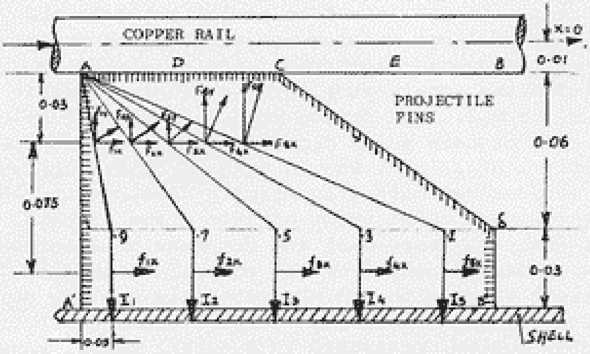

Fig. 3. Optimized launcher and projectile configuration for HEML #1 used in thrust and stress analyses. The current distributions of Hughes and Young were used.

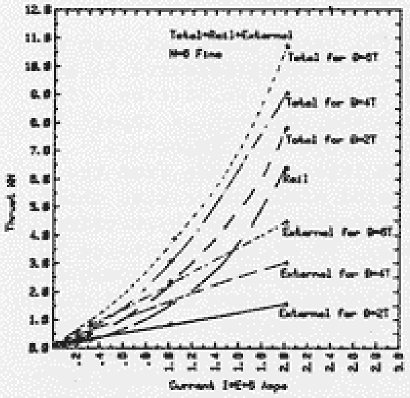

Fig. 4. Thrust generated by rail-induced and several values of permanent magnetic fields for a 6-fin HEML. The total thrust are plotted for B_{ext} = 2, 4, and 6 T. The rail-induced field rises as i^2. The total thrust exceeds 10 MN for a 10 cm fin structure.

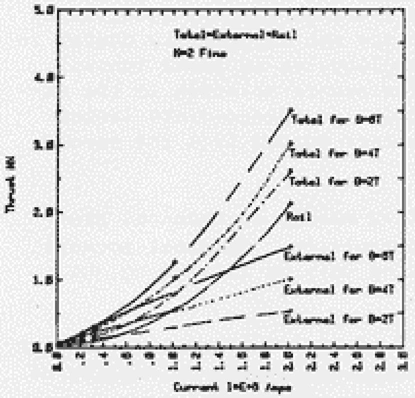

Fig. 5. Same as Fig. 4. except that results are for a 2-fin HEML.

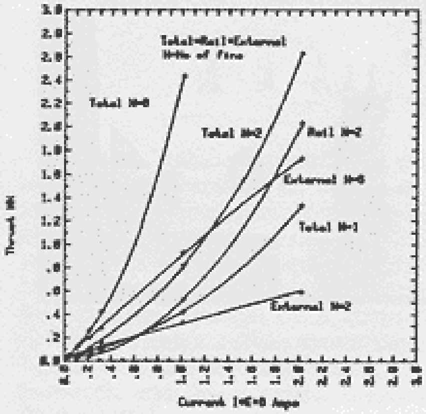

Fig. 6. Total thrust as a function of driving current for number of fins N = 1, 2, and 6. Also shown are components of the total thrust. The fins are 10 cm wide. Calculations are for UTA design #1.

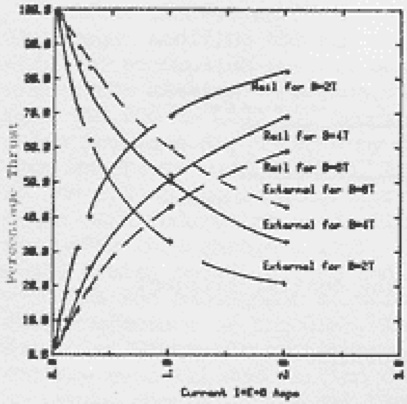

Fig. 7. Percentage thrust from rail-induced and external magnetic fields to that of the total thrust for UTA Design #1

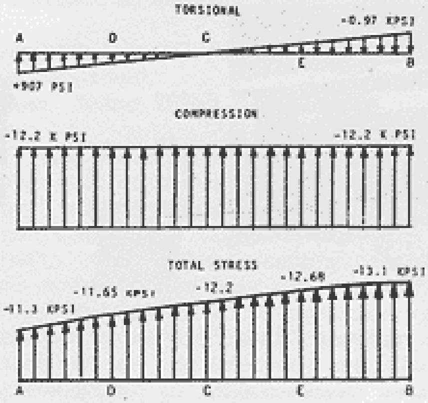

Fig. 8. Torsional and compressional stress distributions at the rail-fin interface for five locations indicated. $i = 10^6$ A.

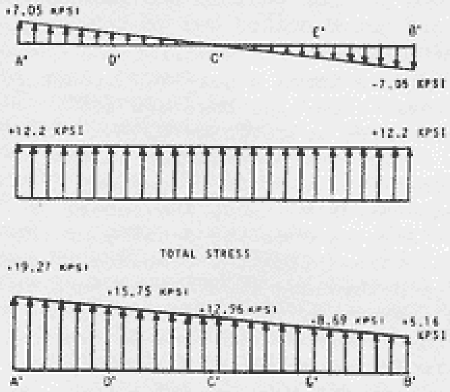

Fig. 9. Torsional and compressional stress distributions for the fin-shell interface for $i = 10^6$ A

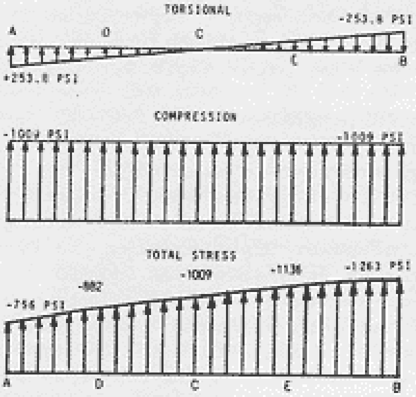

Fig. 10. Same as Fig. 8 except that $i = 10^5$ A.

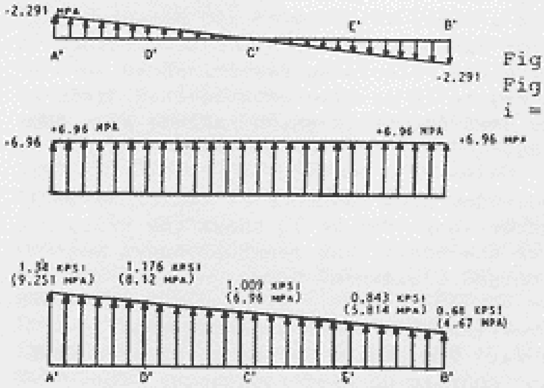

Fig.11. Same as Fig.9 except that $i = 10^5$ A.

alloy, the safety factor is only 1.5. Using higher stress resistant materials, it is relatively safe at even higher current levels. For the fin-shell interface, similar stress distributions were obtained. The total stress varies from 19.3 kpsi to 5.2 kpsi which are again tolerable, as shown in Figure 9. For the lower input current of 10^5 A, we show in Figure 10 and 11 the stress distributions along the rail-fin and fin-shell interfaces. As expected the stress is reduced compared to the case with 10^6 A.

COOLING AND RECOIL EFFECTS WITH PROPELLENTS IN HP

Severe joule heating of the HP projectile occurs during launch. As shown in the accompanying paper [8], at a current level of 5.7 MA melting should occur in copper rails or projectiles. Conventional cooling methods are found to be inadequate. We note, however, a convective cooling method inherent in HEML might provide a solution: The heat generated is sufficient intense to vaporize solid (such as solid nitrogen or hydrogen) propellent stored in the hybrid projectile. Once vaporized, the heated propellent exits through the rear thereby rapidly removing heat from the projectile. The thusly produced exhaust gases can also be ionized (heated to a very high temperature) by the high magnetic field intensity in the launcher tube. The ionized plasma subsequently interacts with the magnetic field resulting in a recoil force which adds to the thrust. The thrust is instantaneous and tend to reduce the current flow through the projectile itself (hence lower joule heating) while maintaining the same acceleration rate.

Detailed calculations of the convective cooling are described elsewhere. Briefly, consider the cooling effects as follows. The heating rate dQ/dt of the propellant with density ρ is given by $C_p v_o T_o/d$ where T_o is the vaporization temperature, v_o is the velocity of evaporation, c_p is the specific heat and d is the characteristic heat diffusion length. The propellent is therefore an effective heat sink, removing heat from the projectile by evaporation in the form of a jet. From continuity, $\rho v = \rho_o v_o$. The velocity of the jet stream depends on the conductivity of the projectile, density of the propellent and the projectile velocity. Thus the quantity of heat that can be removed depends on the total mass stored and conduction of heat into the propellant. To be most effective, the conducting projectile should be maintained at cryogenic conditions to maximize the thermal conductivity. Cooling effects under launch conditions are found favorable.

The vaporized propellent, when exited from the HP projectile, encounters a strong electromagnetic field and will be ionized[9]. The plasma experiences a strong

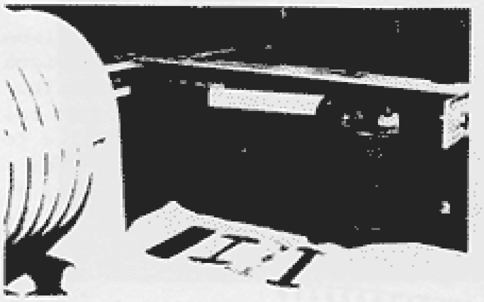

Fig. 12. Laboratory apparatus showing the dc electromagnet, parallel rails and projectiles successfully driven.

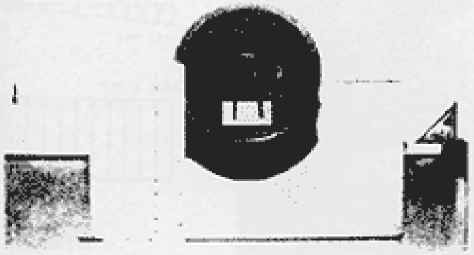

Fig. 13. Small Dedicated HEML showning a two-pole configuration. The driving coils are not shown. The N = 2 projectile is located in the gaps.

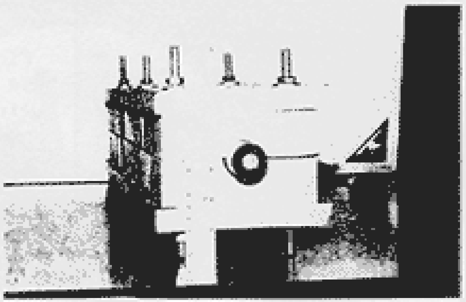

Fig. 14. A novel laboratory coaxial railgun under study.

Lorenz force which in turn exerts a recoil force on the projectile. The plasma forms a jet-like structure which is easily confined, much like the "arc-jet" thrusters. The recoil force is given by $F_r = - v\ dm/dt$ where m is the propellent mass stored in the projectile and v is the instantaneous propellent exhaust velocity. Since $dm/dt = - A\rho v$, the recoil force is equal to $A\rho v^2$, where ρ is the density of the propellent. The total thrust from the combined EM and chemical thrust can be determined in a closed form to yield, $v/v_o = (m_o/m)^2$, where m_o is the initial propellent mass. This equation compares more favorably than the well known rocket equation without EM propulsion term added to it: $v = v_o \ln(m_o/m)$. For example, if $v_o = 0.1$ km/sec and $m_o/m = 10$, v is 10 km/sec for the HEML and for a conventional rocket v is only 0.27 km/sec, for the same path length for travel.

EXPERIMENTAL

Several laboratory experiments have been successfully carried out to study the HEML concepts. The first, and an early one, consists of constructing dc magnetic fields out of power transformers. In Figure 12 we show the UTA-CAT apparatus with hybrid components. A series of dc magnets having a peak magnetic field of 2T is aligned with two copper conducting rails. A copper clad projectile of the order of 50 g was placed at the entrance to the magnet. Successful firings have been achieved with an efficiency of 15% yield a final velocity of 150 m/sec with a launcher length of about 30 cm. The thrust obtained is consistent with the calculated results shown in Figure 5-7. In Figure 12 we also show several different projectiles used for tests which include aluminum and copper plates.

A small dedicated HEML launcher of the order of 1 m is under construction. Figure 13 shows the cross sectional view of the HEML. The launcher has a magnetic gap of 2 mm and a width of 5 cm.

Another novel launcher under investigation is shown in Figure 14. The design is not strictly a HEML since it does not contain dc electromagnets. The rails are replaced by a coaxial configuration shown in Figure 15. The launcher barrel is made out of copper with a center conducting rod serving as the current feed. The projectiles will be donut shaped with conducting or plasma armature at the rear. The launcher has a cylindrical symmetry so as to optimize the magnetic field energy delivered to the projectile. The launcher tolerance need to be precise so that friction can be maintained at a minimum. Efficiency of this launcher is expected to be optimum.

A larger HEML is currently under design. This launcher has improved interior characteristics such that it can be adopted to realistic rocket-like bodies.

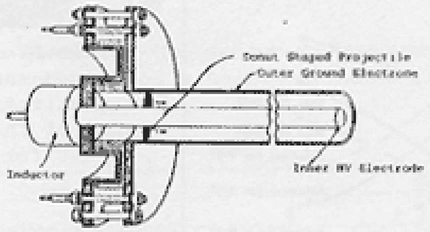

Fig. 15. Schematic of the coaxial railgun.

DISCUSSION

We have presented some active programs in HEML technology being carried out at the Center for Accelerator Technology and Applied Sciences. We have shown that the HEML concepts viable for propulsion of rocket-like projectiles. Our designs avoid the use of the rear area so as to permit ejection of propellant from it. The hybrid concepts utilizes the combined use of dc electromagnets to augment the railgun fields, which cannot by themselves drive the complex shaped projectiles efficiently. Additional cooling and recoil effects can be exploited. Temperature distribution studies indicate that the projectiles with chemical propellants in hybrid launchers has the added advantage of cooling the projectile so that the driving current can be raised substantially without the effect of melting to occur. For a given barrel length, HP projectiles can out perform conventional chemical rockets. Scaling to larger projectiles size appear feasible. These concepts could provide basis for significant advancement in conventional rocket propulsion technology in order to realize the possibility of zero stage rockets.

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