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NUMERICAL PREDICTIONS OF RAILGUN PERFORMANCE INCLUDING THE EFFECTS OF ABLATION AND ARC DRAG

N. M. Schnurr, J. F. Kerrisk, and J. V. Parker

Abstract - Thermal radiation from plasma armatures in railguns may cause vaporization and partial ionization of the rail and insulator materials. This causes an increase in mass of the arc, which has an adverse effect on projectile velocity. Viscous drag on the arc also has a deleterious effect, particularly at high velocities. These loss mechanisms are modeled in the Los Alamos Railgun Estimator code.

Simulations were performed and numerical results were compared with experimental data for a wide range of tests performed at the Los Alamos and Lawrence Livermore National Laboratories, the Ling Temco Vought Aerospace and Defense Company, and the Center for Electromechanics at the University of Texas at Austin. The effects of ablation and arc drag on railgun performance are discussed. Parametric studies illustrate the effects of some design parameters on projectile velocity and launcher efficiency. Some strategies for reducing the effects of ablation are proposed.

INTRODUCTION

The performance of railguns depends on many factors including the power supply, launcher design, and mass and injection velocity of the projectile. The Los Alamos Railgun Estimator (LARGE), a railgun system simulation code, was developed at the Los Alamos National Laboratory to predict railgun performance [1]. A typical railgun system that could be analysed by this code is shown in Fig. I. LARGE calculates rail current and projectile velocity and position as functions of time from a description of the power supply and launcher. It can model a capacitor bank, large inductances in the power supply, explosively driven magnetic-flux compression generators (MFCGs), and various railgun configurations such as square bore, round bore, staged systems, and distributed systems. This code has been used as a design tool and as an aid in interpreting experimental results [2].

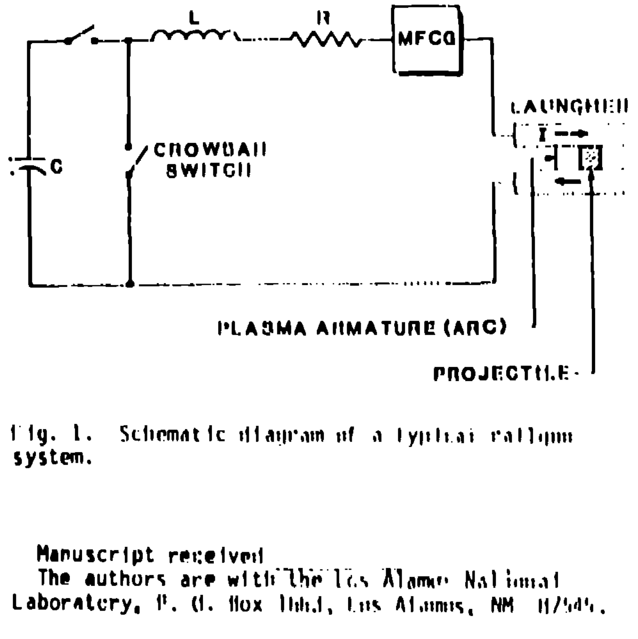

Fig. 1. Schematic diagram of a typical railgun system.

An important recent addition to LARGE is an algorithm that attempts to more accurately predict losses. Parker [3] has suggested that the most significant loss in a typical railgun shot is caused by ablation of the rails and insulator material. He postulated that the extremely large radiant fluxes from the arc cause evaporation and subsequent ionization of material, which is then added to the arc. This additional mass is also accelerated so that the final projectile velocity is lower than in a case with no ablation. In addition, a drag force is exerted on the plasma by the rails and insulator material. The magnitude of this "arc-drag" force is proportional to the arc mass and to the square of the velocity. It therefore becomes significant when ablation is large and is particularly important at high velocities.

The development of a procedure that is capable of analyzing all of the complex processes occurring in a railgun and is computationally efficient enough to be used for parametric studies is a formidable task. It is necessary to adopt a somewhat simplified approach in some elements of the analysis, most notably in modeling the behavior of the arc. A complete description would require a three-dimensional transient solution of the conservation of mass, energy, momentum, Maxwell's equations, and several auxiliary relations. The equations are highly nonlinear because of the radiation effects and the ionization equations. McNab [4] carried out an analysis neglecting spatial variations of temperature and pressure that gave reasonable estimates of the properties of the arc. More recently, Powell and Batteh extended that analysis to include axial variations [5] and later transverse variations [6] of thermodynamic and electrical properties of the arc for a railgun of rectangular cross section. They did not consider mass changes caused by ablation and arc drag. Our approach was to neglect spatial variations of arc properties so that such values as arc temperature, degree of ionization, etc., are regarded as average values.

The effect of these simplifying assumptions on the accuracy of projectile velocity predictions is difficult to assess. Our approach was to perform simulations of a wide range of railgun experiments that were run at Los Alamos, Livermore, Ling Temco Vought, and at the University of Texas. A comparison of experimental results with numerical predictions was used to assess the accuracy of the simulations.

This paper describes the ablation and arc drag models in the LARGE code and presents an estimate of the accuracy of the code based on a comparison of the numerical results with the experimental data. The effects of these loss mechanisms on railgun performance are discussed and some measures that may alleviate the effects of these loss mechanisms are proposed.

THE LARGE CODE

Prediction of railgun performance is a combined electrical, thermal, and mechanical problem. The railgun represents an electrical load whose properties vary with projectile position. All rail inductances and resistances in LARGE are calculated from a physical

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description of the rails. A calculated rail inductance gradient (high-frequency limit) is used to determine the force of the armature on the projectile [7]. Also included are estimates of how current diffusion changes rail inductance and resistance with time [8]. A detailed calculation of the arc voltage was not attempted. Instead, an empirical model relating arc voltage to current was developed based on experimental data obtained from a variety of experiments.

The calculation of current requires the simultaneous solution of N equations of the form

$$d(LI)/dt + RI + 1/C \int_0^t I dt = E_0 \quad , \tag{1}$$

where N is the number of stages, t is time, I is current, L is the total inductance, R is total resistance (including that of the arc), C is bank capacitance, and E_0 is the initial capacitor voltage. The equations are solved numerically using Euler's method.

The current is then used in the thermal analysis of the armature (arc) and in the calculation of the accelerating force on the projectile.

CONSERVATION OF ENERGY AND MASS

The armature is initially assumed to be a solid material of specified resistance, which, for normal arc-driven projectiles, is the fuse. The flow of current through the armature causes Joule heating and a resulting increase in temperature. The armature temperature is computed at each time step, neglecting energy losses. In the case of a solid armature, the resistance is small enough to preclude melting of the armature. For cases where a plasma armature is desired, the resistance of the armature (fuse) is large enough to cause melting and vaporization, usually within a few microseconds. The resulting mass of fuse material forms the arc that is treated in subsequent calculations.

The LARGE code uses an explicit marching procedure so that parameters calculated at the end of a time step, t + Δt, are based on conditions at time t. For the arc considered as a control volume,

$$IV\Delta t + \Sigma \Delta m_i e_{v,i} = Q_R + \Sigma(m_i e_i)_{t+\Delta t} - \Sigma(m_i e_i)_t \quad , \tag{2}$$

where I and V are arc current and voltage drop, m_i and e_i are the mass and specific energy of the ith chemical species, and Q_R is the radiant energy leaving the arc in the time Δt. The radiant energy may be divided into two parts: Q_I, which represents energy conducted into the solid materials (rail and insulator) surrounding the arc; and $\Sigma \Delta m_i e_{v,i}$, the energy that goes into vaporizing mass, where $e_{v,i}$ is the specific vaporization energy and Δm_i is the mass of the ith species evaporated and added to the arc during the time Δt. Equation (2) may then be rewritten in the form

$$IV\Delta t = Q_I + \Sigma(m_i e_i)_{t+\Delta t} - \Sigma(m_i e_i)_t \quad . \tag{3}$$

Radiation flux from the surface of a semi-infinite body of high temperature gas at uniform temperature is given by

$$q = \sigma T^4 \quad , \tag{4}$$

where σ is the Stefan-Boltzmann constant and T is the plasma temperature [9]. For the range of temperatures of interest here (t > 10 000 K), the mean free path for radiation is much smaller than the characteristic cross-stream dimension of the railgun [5]. We therefore use (3) to calculate the radiant energy flux from the arc.

A partitioning of arc radiation into energy absorbed by the copper rails and into energy that vaporizes rail material was estimated by applying a one-dimensional transient code that included the effects of phase change. The partitioning is a function of the surface heat flux (arc temperature), and the resident time of the arc computed from the arc length and velocity. Results of the analysis were curve-fitted and incorporated in the LARGE code. These analyses indicate that there is some threshold velocity, typically on the order of 5 km/s, above which ablation of the copper ceases. Insulator materials typically have thermal conductivities two orders of magnitude lower than those of copper. All radiant energy absorbed by those materials is assumed to cause ablation.

The specific energy of the arc is computed as a function of temperature and pressure, assuming that all chemical species are completely dissociated and that the atoms are, at most, doubly ionized. The degree of ionization for each constituent is computed using Saha's equations for both single and double ionization based on the arc temperature and the partial pressure of that constituent. Additional details for this procedure are given in ref. [10].

The arc temperature at each time step is calculated by a trial and error procedure. The radiation from the arc is estimated based on the temperature at the previous time step, and the energy partitioning algorithm is used to calculate the mass of vaporized rail and insulator material. A new arc temperature is assumed and the specific energies of all arc constituents are computed using specific heats and ionization levels calculated from Saha's equations. Additional iterations are performed until (3) is satisfied.

CONSERVATION OF MOMENTUM

The conservation of momentum, including the effects of ablation and arc drag, takes the form

$$1/2\, L'I^2 - F_d = m(dU/dt) + U(dm/dt) \quad . \tag{5}$$

where L' is the inductance gradient of the rails, F_d is the drag force on the arc, U is the projectile velocity, and $m = m_p + m_a$ is the combined mass of the projectile and arc. The drag force is computed from

$$F_d = f(m_a/2D_H)U^2 \quad , \tag{6}$$

where D_H is the hydraulic diameter of the barrel and the friction factor is computed from

$$f = 0.184/Re^{0.2} \quad . \tag{7}$$

The Reynolds number, Re, is based on the barrel's hydraulic diameter and estimated values of plasma properties at the arc temperature. It should be noted that for any given current and projectile mass, there will be some velocity at which the effect of ablation (U dm/dt) and arc drag, F_d, will be equal and opposite to the propulsive force. This represents the maximum velocity condition. Ablation occurring after this condition has been reached will cause the projectile to separate from the arc.

STRESS CALCULATIONS

Railgun performance is frequently limited by structural considerations. Structural calculations are performed at Los Alamos using NIKE2D [11]. The loading functions used as input to that code are calculated using LARGE. The rail force (per unit length) tending to force the rails apart is

$$F_R = 1/2(dL'/dS)I^2 \quad , \tag{8}$$

where S is the spacing between the rails. The derivative of the inductance gradient with respect to spacing is calculated by a separate analysis using a variation of the code described in ref. [7]. An additional force on the rails and on the insulator material is caused by the arc pressure. This pressure is most easily computed by applying Newton's law to the projectile to determine the pressure at the arc/projectile interface.

COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

Experimental data have been obtained from several sources covering a wide range of conditions. Specifications for these tests are given in Table I. The values of rail inductance gradient were computed using the field and current calculation methods of ref. [7] for cases where those data were not available.

Results of the numerical simulations are given in Table II. The parameters U_e and U_N represent the experimentally measured and numerically calculated projectile exit velocities. Simulations were also performed for each case with the ablation and arc drag calculations suppressed. These ideal velocities, U_I, are also given in Table II.

The comparison between numerical predictions and experimental results is generally quite good. It should be noted, however, that for cases where the losses in the launcher are small, a numerical model using some type of projectile friction loss mechanism, rather than the ablation and arc-drag model, would give equally good agreement. We therefore selected a few specific experiments that give some insight into the ablation and arc drag mechanisms for a more detailed examination.

TABLE I SPECIFICATIONS OF EXPERIMENTAL SYSTEMS

Test No.	Location/Year	Barrel Length (m)	Bore Round/Square (mm)	Projectile Mass (g)	Injection Velocity (km/s)	Maximum Current (MA)	Inductance Gradient of Rails (μH/m)
1	Los Alamos/81[a]	[illegible]	[illegible]	[illegible]	0.0	[illegible]	[illegible]
2	Ling Temco/81	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	Los Alamos/82	[illegible]	[illegible]	[illegible]	0.0	[illegible]	[illegible]
4	Livermore/84[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	Livermore/84[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	Livermore/84[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7	Livermore/84[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	Livermore/84[b]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9	Los Alamos/84	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	U. of Texas/81	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
11	Los Alamos/81	[illegible]	[illegible]	[illegible]	0.0	[illegible]	[illegible]
12	Los Alamos/81[c]	[illegible]	[illegible]	[illegible][f]	[illegible]	[illegible]	[illegible]
13	Los Alamos/85[d]	[illegible]	[illegible]	[illegible][f]	0	[illegible]	[illegible]
14	Los Alamos/85[e]	[illegible]	[illegible]	[illegible][f]	[illegible]	[illegible]	[illegible]

[a] See ref. [11]

[b] See ref. [11]

[c] G-10 Insulator

[d] Lexan Insulator

[e] High density polyethylene insulator

[f] Equivalent mass based on 10 [illegible] in launcher

TABLE II

COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS

Test No.	U_e (km/s)[a]	U_N (km/s)[b]	U_I (km/s)[c]	$\frac{U_N-U_e}{U_e}$
1	(1133)[d]	(1190)[d]	(943)[d]	-0.07
2	4.3	4.8	5.7	0.12
3	3.5	4.2	5.6	0.20
4	4.1	4.0	5.4	-0.02
5	5.1	4.1	5.8	-0.23
6	5.2	4.0	5.8	-0.23
7	5.9	5.1	8.6	-0.08
8	6.6	6.8	11.1	0.03
9	2.9	3.2	4.5	0.10
10	5.1	4.8	5.9	-0.06
11	1.0	0.9	N/A[e]	-0.10
12	8.2	8.4	40.3	0.02
13	8.9	9.3	40.3	0.04
14	11.1	10.9	40.3	-0.02

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[a] U_e = experimental measured velocity

[b] U_N = numerically calculated velocity

[c] U_I = ideal velocity

[d] Time to reach x-ray camera location

[e] Confined system, plug at breech

In Test No. 9 the losses were relatively large. The diagnostics for this test were extensive so that detailed comparisons of numerical predictions with experimental data are possible. Magnetic probes were used at nine locations along the barrel to measure currents and determine projectile position as a function of time. A wire switch was used to measure the exit velocity.

Measured and predicted current profiles are shown in Fig. 2. The current measured at the breech reaches a peak of slightly more than 200 kA and then decreases slowly. The current measured at x = 0.76 m reaches a similar level but drops off more sharply. At x = 1.17 m, the measured current is significantly lower than the corresponding breech current indicating that a restrike arc has formed behind the plasma armature. At x = 1.[illegible] m, only a small portion of the current measured at the breech remains in the plasma armature and is effective in accelerating the projectile. Also shown in Fig. 2 is the current profile predicted by the LARGE code based on specifications of the capacitances, inductances, and resistances of the power supplies and the location and timing of the stages.

Numerical predictions of the velocity profile are given in Fig. 3. The base case is the calculation using the current profile computed from the power supply data. The LARGE code also has the option of using experimentally measured current profiles to

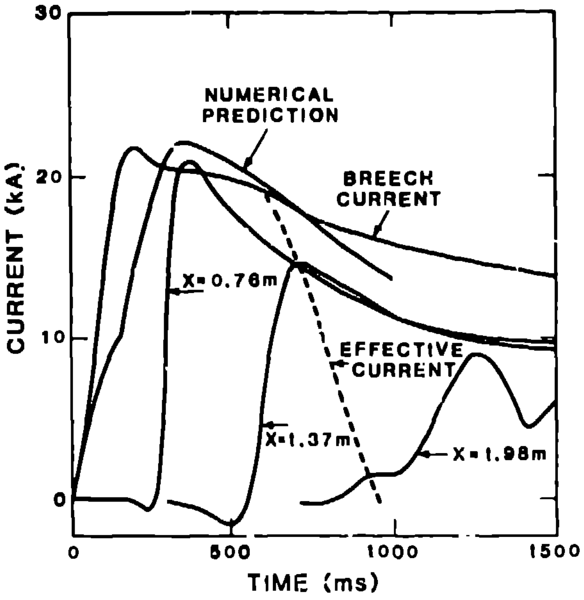

Fig. 2. Measured and calculated current profiles for Test No. 9.

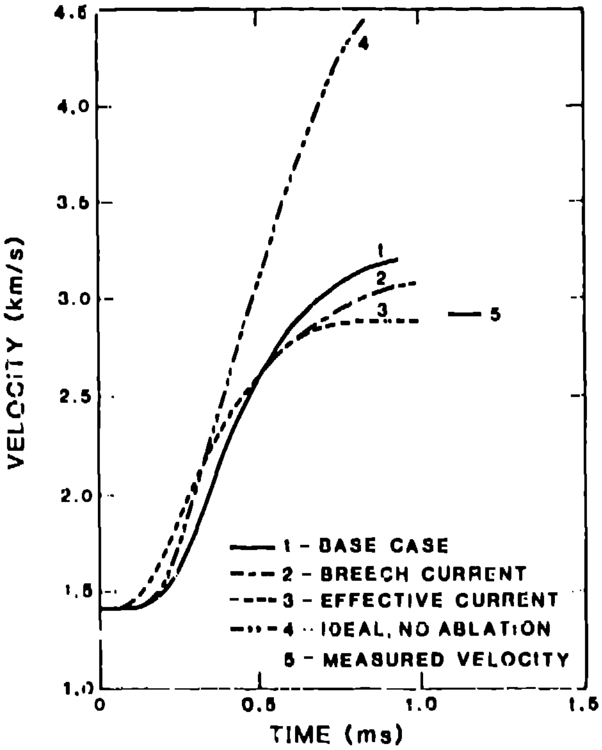

Fig. 3. Calculated velocity profiles for Test No. 9.

predict projectile velocities. The results of a simulation using the measured breech current gives a somewhat lower final velocity. If the "effective" current profile is used, agreement with the measured projectile velocity is excellent.

The restrike or arc-splitting phenomenon that occurs in some experiments is not currently predicted by the LARGE code. That condition seems to occur when the code predicts an elongated arc and arc drag forces comparable in magnitude to the accelerating force.

An additional simulation was performed that did not include the effects of ablation (Fig. 3, Curve 4). The predicted velocity for that case was more than 50% higher than the measured value. The inclusion of various types of projectile friction models in that simulation still gave velocities that were significantly higher than the measured value. These results give some confidence that the ablation and arc drag algorithms used in the LARGE code accurately represent the actual physical process.

An interesting aspect of ablation is the effect of insulator material on performance. The code predicts lower ablation rates (and better railgun performance) for low molecular weight materials because they have higher specific ablation energies (J/kg). A series of tests have been performed at Los Alamos (Test Nos. 12-14) that were a direct verification of this concept. Free arcs were accelerated to very high velocities in a 1.83-m gun using identical conditions except for the insulator material. An approximate simulation of these tests was done by specifying a projectile mass equal to the mass of air initially in the launcher volume at the test condition of 10 torr. Although the extremely good agreement between numerical predictions and experimental results (Table II) may be somewhat fortuitous, the differences in velocities caused by different insulator materials is very strong evidence that ablation of insulator materials is a significant factor. The relative values of velocity for the three materials are in excellent agreement with numerical predictions. A simulation of this test, neglecting ablation, gave a predicted velocity of 40 km/s.

The effects of ablation and arc drag on railgun performance at extremely high velocities are of particular interest. The arc drag increases as the square of the velocity and may dictate the maximum achievable velocity for a given current. Unfortunately, very little data are available above 6 km/s. The highest velocity results available are from Test No. 1. This test, performed at Los Alamos in 1981, used an explosively driven magnetic flux compression generator to produce currents of nearly 1 MA. Unfortunately, the only diagnostics that produced usable results were a magnetic probe that measured the breech voltage and an x-ray camera 4 m downstream from the muzzle that yielded a time for the projectile to reach that location. The numerical prediction shown in Table I was based on a model of the power supply and the magnetic flux compression generator. It gave a slightly higher current vs time curve than was obtained from the experimental values. An additional simulation, using the experimental values of current vs time, predicted that it would take 1350 μs for the projectile to reach the x-ray camera, a value 20% higher than the measured value. This indicates that the effects of ablation, and particularly arc drag, may be overpredicted for high-velocity cases. More high velocity experimental data are needed before a more definite conclusion can be reached.

PARAMETRIC STUDIES

The large number of design variables that affect railgun performance preclude a comprehensive parametric study. Some limited studies have been carried ut, however, to illustrate the effects of a few arameters on performance. The effect of insulator aterial is illustrated by the results of the calcuations simulating Test Nos. 12-14 in Table I. A eries of runs was also made to assess the effects f some power supply parameters on projectile velocity and launcher efficiency (the ratio of projectile kinetic energy to energy delivered to the rails). These calculations were performed for a -cm-square-bore launcher with Lexan insulators, a .5-g projectile injected at 1 km/s, and a single-stage, 50-mF capacitor bank. The length of the rails for all cases is the length at which maximum projectile velocity is attained.

The effect of rise time of the current is shown n Fig. 4. The resistance of the power supply is ssumed negligible, and the inductance and initial apacitor voltage are adjusted to give the desired alues of rise time and maximum current. Note that n optimum occurs for a rise time of about 200 μs. maller values cause too rapid a drop-off after the eak. Larger values allow too much time for ablation efore the maximum acceleration is reached.

The effect of maximum current is shown in Fig. 5. . rise time of 200 μs is selected and the initial capacitor bank voltage is adjusted to provide the desired peak current. The effects of ablation and arc drag are clearly illustrated in a comparison of the results computed with and without these effects ncluded. Although projectile velocity continues to ncrease with increasing peak current, the launcher efficiency reaches a maximum at about 300 kA. A launcher designed to maximize projectile velocity would use the highest possible peak current consistent with the structural limitations of the launcher.

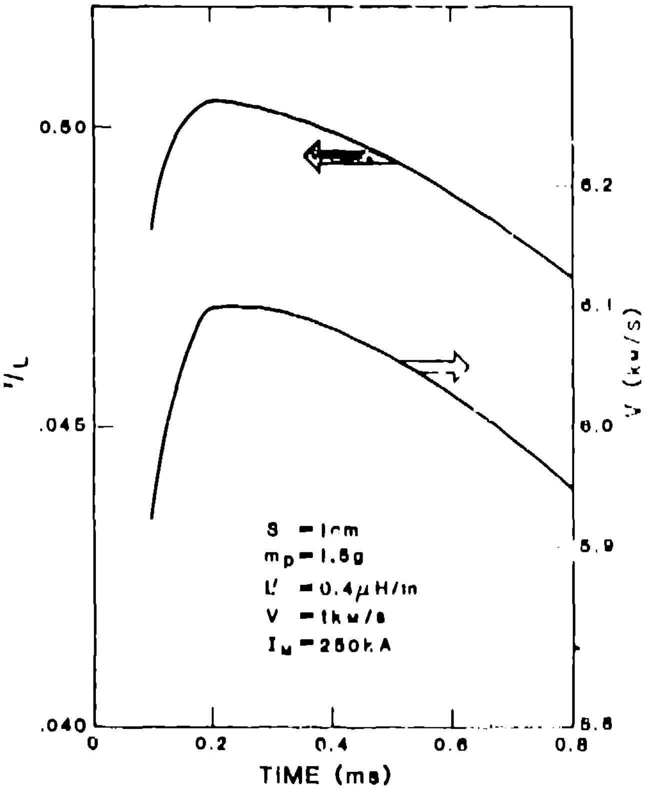

Fig. 4. The effect of rise time on railgun performance.

It should be emphasized that the results shown in Figs. 4 and 5 are for one specific set of design conditions. They are presented only as an illustration of the effects of some specific design parameters and are not intended for general use in designing railgun systems.

CONCLUSIONS AND RECOMMENDATIONS

A series of simulations were performed and the results were compared to experimental data as a test of the accuracy of the LARGE code. The results indicate that the code is relatively accurate and that effects of ablation and arc drag may be significant and even dominant for some railguns. There is some indication that the effects of arc drag may be overpredicted at very high velocities. The assumption used in the code, that all ablated material will be ionized and entrained in the arc, may be overly conservative. Nevertheless, there is little doubt that ablation is an important loss mechanism in arc-driven railguns.

Several design strategies are available that may significantly reduce the effects of ablation. The most obvious is the selection of insulator material. Low-molecular-weight materials are preferable. If these materials lack the desired structural properties, they may be used as a coating on stronger materials. Accelerating the projectile at the maximum possible rate, consistent with structural constraints, is also beneficial. The higher radiant flux from the arc caused by higher currents is more than offset by the shorter residence time. Injecting at high velocities reduces (or in some cases eliminates) ablation from the rail but has a much smaller effect on ablation of the insulator material. Some technique may be possible for venting a portion of the arc, increasing its conductivity (hence reducing Joule heating) by seeding with some material, or reducing ionized arc mass by adding a material that quenches ionization. Such techniques are still in the speculative stage.

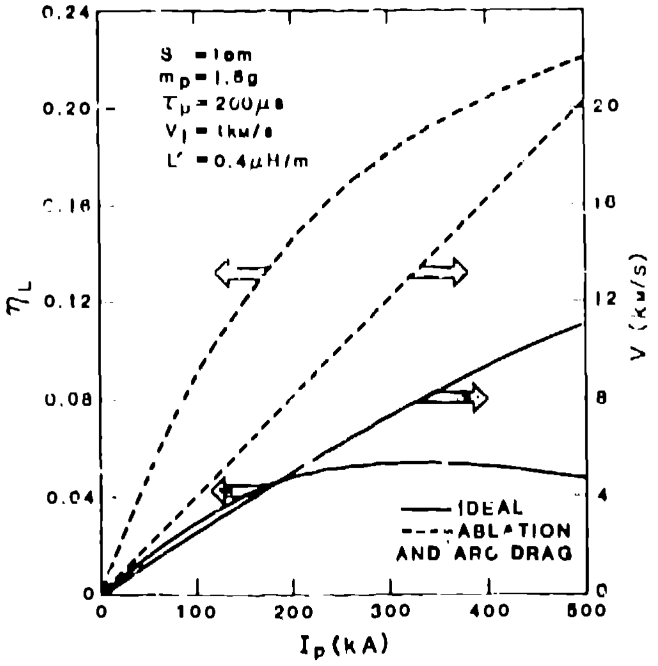

Fig. 5. The effect of maximum current on railgun performance.

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