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AUTHOR(S): N. M. Schnurr and J. F. Kerrisk

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Los Alamos Los Alamos National Laboratory
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NUMERICAL STUDIES OF ABLATION AND IONIZATION OF RAILGUN MATERIALS

N. M. Schnurr and J. F. Kerrisk
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Abstract

The intense radiation from the arc in a railgun may cause vaporization and partial ionization of rail and insulator material. The mass of material added to the arc can have a significant adverse effect on projectile velocity. A numerical model has been developed to predict the change in mass of the arc as a function of several parameters. That model has been incorporated in the Los Alamos Railgun Estimator (LARGE) code and simulations have been run to assess the accuracy of the model. Analytical predictions were found to be in good agreement with experimental data for railgun tests run at Los Alamos. Ablation appears to have a significant effect on railgun performance.

Introduction

Railguns (electromagnetic accelerators) are devices that accelerate projectiles by the interaction of an electric current and a magnetic field. A schematic diagram of a railgun is shown in Fig. 1. The basic elements include two parallel stationary conductors (rails that are bridged by a moving armature). When a voltage is applied across the rails, a current flows down one rail, through the armature, and back through the other rail. Both solid and plasma (arc) armatures have been used in railguns. This paper is concerned with a plasma armature that starts as a metal conductor (fuse); the fuse is vaporized by initial current flow and the armature is in the form of an arc throughout most of the acceleration period.

The current in the rails gives rise to a magnetic field that interacts with the plasma current to cause a $\vec{J} \times \vec{B}$ force on the arc. The arc exerts a force on the projectile causing a rapid acceleration in the positive x direction.

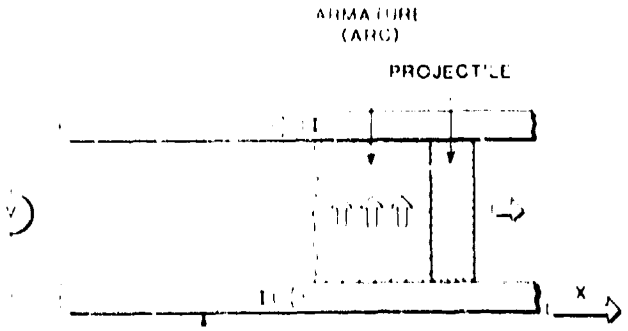

Fig. 1. Schematic diagram of an arc-driven railgun.

A prediction of the performance of a railgun, that is, the rail current and projectile velocity and position as functions of time, is a combined electrical and mechanical problem. The railgun represents an electrical load whose properties vary with projectile position. Many predictions of railgun performance have been done, ranging from simplified calculations of projectile velocity and position from a known total current to more complex calculations of rail current and projectile performance.[1] Performance models have tended to overestimate projectile velocities. This has been accounted for in the models by using effective values of the rail inductance gradient, which is used to calculate the force on the projectile from the current,[2] or by using empirical friction losses.[3] The behavior of the arc is another area in which many simplifying assumptions have been used in performance models.

The Los Alamos Railgun Estimator (LARGE) is a performance model that was written to calculate rail current and projectile velocity and position from a description of the power supply and railgun.[3] LARGE has been used to design railgun tests and analyze data taken during tests.[4] 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, or distributed systems. An attempt was made in writing LARGE to use as few empirical models or parameters as possible within the constraints of a fast-running code. To this extent, all rail inductances and resistances are calculated from a physical description of the rails. A calculated rail inductance gradient (high-frequency limit) is used to determine the force on the projectile.[5] Estimates of how current diffusion changes rail inductance and resistance with time are also included.[6] Simple, empirical models were employed in two areas: for the plasma armature and for friction between the projectile and bore walls. The arc is modeled electrically as a voltage drop that varies from a few hundred volts at low current to about 500 volts at 1 MA. This model was developed from muzzle-voltage measurements on railgun tests at Los Alamos. The electrical model of the arc in LARGE will require further work. A simplified model of friction between the projectile and bore walls was added to LARGE when it became obvious that measured projectile velocities were always less than predicted, even if the actual rail current was used. Good agreement between measured and calculated velocities was obtained by introducing a friction parameter that discarded a constant portion (normally 20-40%) of the accelerating force during the calculation. However, this model was somewhat arbitrary because no independent means of calculating friction effects was found.

Recently, Parker[7] suggested that the most significant loss in a railgun is that caused by ablation of the rails or sidewall material. He postulates 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 must also be accelerated so that the final velocity is lower than in a case with no ablation.

The objective of the work summarized in this paper was to develop a model that could accurately predict the change in mass of the arc and to incorporate that calculation into the LARGE code. This model will replace the empirical friction model currently in LARGE.

The Ablation Model

The physical processes occurring in the arc of a railgun are extremely complex, so some simplifications are necessary. 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[8] carried out an analysis neglecting spatial variations of pressure and temperature that gave reasonable estimates of the properties of the arc. More recently, Powell and Batteh extended that analysis to include axial variations[9] and later transverse variations[10] of thermodynamic and electrical properties of the arc for a railgun of rectangular cross section. The approach used here was to neglect spatial variations of arc properties so that values of arc temperature, degree of ionization, etc., are regarded as average values. The effect of this simplification appears to have a minor effect on the calculation of the mass of the arc. Predictions of arc length are somewhat more questionable.

The Energy Balance

The rate of Joule heating in the arc is determined at any instant of time by calculations performed in the LARGE code. LARGE uses an explicit marching procedure so that parameters calculated for the end of a time step, $t + \Delta t$, are based on conditions at time t. For the arc considered as a control volume

$$\begin{aligned} I V \Delta t &+ \Sigma \Delta m_i e_{v,i} \\ &= Q_R + \Sigma (m_i e_i)_{t+\Delta t} - \Sigma (m_i e_i)_t \quad , \qquad (1) \end{aligned}$$

where I and V are arc current and voltage drop, m_i and e_i are the mass and specific energy of the i^{th} chemical species, and Q_R is the radiant energy leaving the arc in the time Δt. The radiant energy may be divided into two portions: Q_L, which represents energy conducted into the solid materials 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 i^{th} species evaporated and added to the arc during the time Δt. Equation (1) may then be written in the form

$$I V \Delta t = Q_L + \Sigma (m_i e_i)_{t+\Delta t} - \Sigma (m_i e_i)_t \quad . \qquad (2)$$

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

$$q = \sigma T^4 \quad , \qquad (3)$$

where σ is the Stefan-Boltzmann constant and T is the plasma temperature.[11] 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.[9] We therefore use equation (3) to calculate the radiant energy flux from the arc.

Partitioning of Radiant Energy

A portion of the radiant energy striking the copper rails goes into vaporizing materials, and the remainder is absorbed by the rails. A separate analysis was performed to estimate the partitioning of radiant energy. EXPLO, a one-dimensional conduction code developed by D. L. Jaeger,[12] was used for these calculations. Initial calculations indicated that for the magnitude of heat fluxes of interest here, the surface temperature of the copper reached the vaporization temperature in a time much shorter than the flux residence time. We therefore neglected that initial phase of the conduction process and solved the problem shown schematically in Fig. 2. We assume that the material is uniformly at the vaporization temperature at some depth. Then we compute Q_L, the quantity of energy transferred into the liquid and solid material as a function of time. The remaining energy, $Q_R - Q_L$ vaporizes a mass of material

$$\Delta m = (Q_R - Q_L)/e_v \quad . \qquad (4)$$

If melting is neglected, the conduction problem may be solved in closed form.[13] The result is

$$Q_L' = K(T_V - T_I)/(\pi \alpha t)^{1/2} \quad , \qquad (5)$$

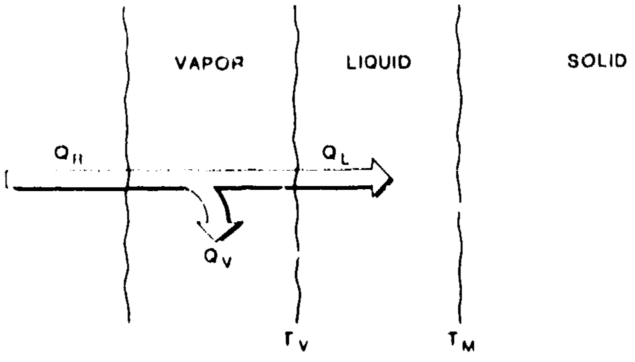

Fig. 2. Model for ablation analysis.

where K and α are the thermal conductivity and diffusivity, respectively, T_I is the initial temperature of the material, and t is the residence time of the arc. The shape of the Q_L vs t curve, which was obtained by applying the EXPLO code to the problem, including melting, was nearly identical to equation (5). The results of the analysis for copper may be expressed as

$$Q_L' = 0.95\ Q_L \quad . \tag{5}$$

The other materials surrounding the arc are insulating materials that have thermal conductivities two orders of magnitude lower than that of copper. We assume that all radiation absorbed by those materials goes into ablation. The radiant energy exchange between the arc and a surrounding surface is given by

$$Q_{R,j} = \sigma A\ F_{A,j}(T^4 - T_{V,j}^4)\Delta t \ , \tag{7}$$

where A is the effective surface area of the arc and $T_{V,j}$ is the vaporization temperature for surface j. This assumes all surfaces are radiatively black.

The time, t, for use in equation (5) is the residence time for the arc. This is computed on the basis of the length and velocity of the arc at a given time.

Ionization and Specific Energy Calculations

A detailed analysis of the behavior of a plastic (Lexan, for example) as it is heated would be quite complex. We are able to bypass part of this problem, however, because the temperature in the arc is so high that the matter contained in the arc may be assumed dissociated into elemental chemical species. It is then possible to determine the specific energy that must be added to a plastic of known composition to produce a gas consisting of elemental atoms. We use this approach to calculate a "vaporization" energy for the insulating side walls. It is then necessary to perform an ionization analysis to determine the degree of ionization and resulting specific energy for each constituent at higher temperatures.

We assume that atoms in the arc may be, at most, doubly ionized. Preliminary calculations have shown that for temperatures up to 40 000K, the number of triply ionized particles will be quite small. The degree of ionization is computed for each chemical species from the simultaneous solution of the following set of equations.

$$\frac{n_1^2}{n_n} = 4.8274 \times 10^{-15}\ G_1\ T^{3/2}\ e^{-\epsilon_1/kT} \quad , \tag{8}$$

$$\frac{n_2^2}{n_1} = 4.8274 \times 10^{-15}\ G_2\ T^{3/2}\ e^{-\epsilon_2/kT} \quad , \tag{9}$$

$$n = n_1 + n_2 + n_n \quad , \text{ and} \tag{10}$$

$$n_e = n_1 + 2n_2 \quad , \tag{11}$$

where n represents a number density (per cubic meter) and ϵ is an ionization potential. The subscripts 1 and 2 refer to single and double ionization and the subscripts n and e refer to neutral atoms and electrons, respectively. The statistical weight, G_i, is the ratio of the partition functions P_i/P_{i-1}, where i refers to the level of ionization. The symbol k represents Boltzmann's constant. The values of n and T are assumed known. Simultaneous solution of equations (8)-(11) leads to a fourth order polynomial that is solved by an iterative procedure to determine n_1, n_2, n_e, and n_n.

The method of calculating the degree of ionization and specific energy for each constituent is based on the principle of partial volumes. The total number of particles of each constituent is computed from

$$N_i = \frac{m_i A}{M_i} \quad , \tag{12}$$

where m_i and M_i are the mass and molecular weight, respectively, and A is Avagadro's number. Partial volumes are computed from

$$V_i = V' N_i / \Sigma N_i \quad , \tag{13}$$

where V' is the arc volume. Then

$$n_i = N_i / V_i \tag{14}$$

is used to compute the number density of atoms for use in equation (10).

The specific energy for each constituent is computed from

$$e_i = [\epsilon_1(n_1 + n_2) + \epsilon_2(n_2)]_i V_i / m_i$$
$$+ e_{v,i} + c_{v,i}(T - T_{v,i}) \quad , \tag{15}$$

where $e_{v,i}$ is the specific heat and $T_{v,i}$ is the vaporization temperature. Values of ionization potential and statistical weights were obtained from Refs. 14 and 15. Thermophysical property data were taken from Ref. 16.

The pressure in the arc varies from a high value at the projectile surface to essentially zero at the free surface of the arc. The pressure at the projectile is determined by a magnetic force calculation in LARCE. Detailed calculations of the axial variation of pressure performed by Powell and Batteh[9] indicate that the pressure varies approximately linearly in the axial direction. We therefore select one-half the pressure at the projectile surface as the average arc pressure, P. This is used with the equation of state

$$PV' = N_T kT \tag{16}$$

to calculate the arc volume V'. The symbol N_T represents the total number of particles in the arc. An estimate of the arc length is obtained by dividing V' by the cross-sectional area of the railgun bore.

Subroutine ARCMASS and Modifications to LARGE

A subroutine that performs the calculations discussed above was developed for incorporation in the LARGE code. Initial data required in ARCMASS include the mass of the fuse (initial arc mass) and radiation view factors, ionization data, and thermophysical property data for all materials. Subroutine ARCMASS is called once for each timestep. Inputs from the LARGE code to ARCMASS include values of current arc, voltage drop, projectile velocity and acceleration, magnetic force, and length of the time step.

Radiation exchanges between the arc and other materials are computed using equation (7). Equations (5) and (6) are used to find the energy absorbed by the rails. Mass additions are calculated from equation (4) for copper and from a similar equation (with $Q_L = 0$) for the insulators. Finally, a new arc temperature is calculated by a trial and error procedure. A new temperature is assumed and the ionization equations (8)-(11) are solved to determine the degree of ionization of each material. The specific energy of each constituent and total arc energy at the end of the time step is found from equation (15). The arc temperature is adjusted and this process is repeated until the energy balance, equation (2), is satisfied.

As originally written LARGE did not account for variations in the mass accelerated. A simplified version of Newton's law

$$F = ma = m(dv/dt) \tag{17}$$

could be used, where F is force, m is the mass accelerated, a is acceleration, v is velocity, and t is time.[3] However, if the mass accelerated can vary, the correct formulation is

$$F = d(mv)/dt = m(dv/dt) + v(dm/dt) \quad . \tag{18}$$

By rewriting equation (18) in the form

$$dv/dt = [F - v(dm/dt)]/m \quad , \tag{19}$$

we can see how ablation (dm/dt > 0) affects projectile velocity. In particular, if the product of velocity and ablation rate is larger than the accelerating force, velocity can decrease. The calculation of the velocity of the projectile plus arc mass in LARGE has been modified to conform with equation (19).

Results

LARGE, with the arc-ablation model, was used to calculate the performance of a number of Los Alamos railgun tests where sufficient diagnostic data were available to allow comparison between calculation and experiment. In a test on October 26, 1982, a 1.13-m-long, square-bore (12.7 x 12.7 mm) railgun was used to accelerate a 4.2-g projectile from an initial zero velocity.[3] A capacitor bank charged to 0.2 MJ and a 3-m-long MFCG (76.2-mm-wide plates with 76.2-mm separation) were used to power the railgun. Two calculations of rail current and projectile velocity and position as functions of time were done for this test. In the first calculation, the mass of the projectile plus fuse was assumed to be constant; this calculation was called ideal because no friction or other loss mechanism was accounted for. In the second calculation, the arc-ablation model described in this paper was employed. Figure 3 shows a plot of calculated and measured rail current for this test. The calculated current labeled ideal is well below the measured current in the 400-600 μs time range. This occurs because in the ideal calculation the projectile velocity is larger than the measured velocity; the projectile is further down the gun at a given time resulting in more total inductance from the rails and a lower current. The calculated current labeled arc-ablation model shows much better agreement with the observed current. Figure 4 shows a plot of the projectile position as a function of time. The individual points show positions measured by magnetic probes placed along the axis of the rails. The agreement between the calculated position using the arc-ablation model and the measured position is quite good. The final velocity calculated using the ideal assumption is 5.6 km/s compared with 4.2 km/s using the

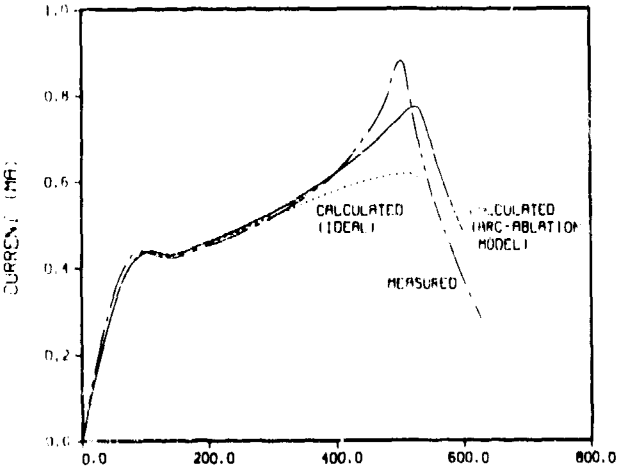

Fig. 3. Current vs time for October 26, 1982 test.

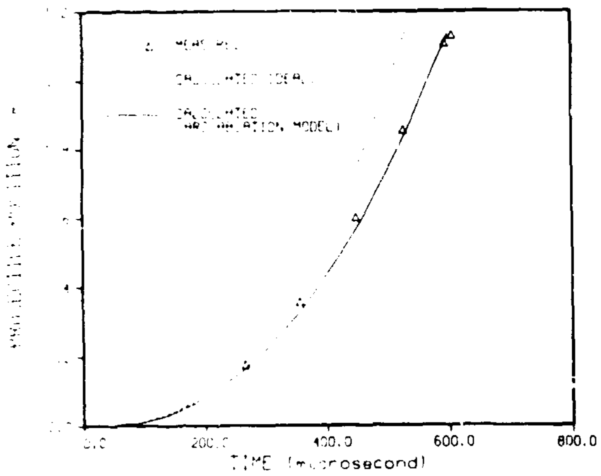

Fig. 4. Projectile position vs time for October 26, 1982 test.

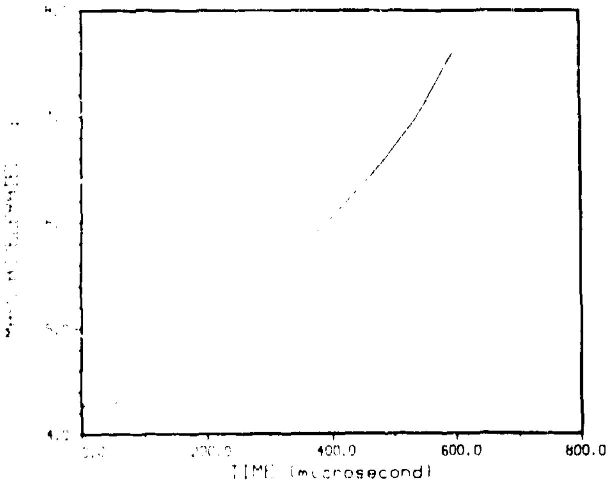

Fig. 5. Total mass accelerated vs time for October 26, 1982 test.

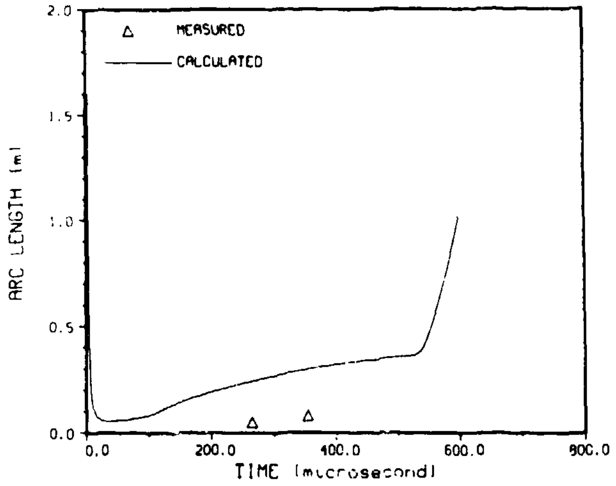

Fig. 6. Arc length vs time for October 26, 1982 test.

arc-ablation model. Figure 5 shows a plot of the total mass accelerated as calculated using the arc-ablation model. The initial mass is the 4.2-g projectile plus 0.07-g fuse. During the initial 50 μs, essentially no mass is added because the current is relatively low. The final mass accelerated is almost double the initial mass. Figure 6 shows a plot of arc length as calculated using the arc-ablation model as a function of time. Two estimates of arc length, made from magnetic probes located along the rails, are also shown. The calculated arc lengths are much greater than the measured values. This could result from an underestimation of the average pressure in the arc by the model, or it could indicate that the measurements do not sense the entire arc. The measured arc lengths are derived from magnetic field measurements made with probes that sense current flow in the arc as it passes under the probe. Thus, only those portions of the arc that carry significant amounts of current would be sensed by the probes. The sharp rise in calculated arc length, from 530-600 μs (see Fig. 6), corresponds to the time when total current is decreasing (see Fig. 3) The calculated position of the back of the arc actually moves back toward the breech during this period. Another railgun test, which was similar to the test described above, was conducted on September 23, 1982. Comparisons between calculated (using the arc-ablation model) and measured rail current and projectile position as a function of time are similar to those shown in Figs. 3 and 4.

In another test, conducted on August 5, 1982, a 0.53-m-long, round-bore (16-mm diameter) railgun was used to accelerate an 18.5-g projectile from an initial zero velocity. The capacitor bank was charged to 0.3 MJ and supplied a 3-m-long MFCG (76.2-mm-wide plates with 76.2-mm separation). Again, two calculations were done, an ideal calculation and a calculation using the arc-ablation model. Figure 7 shows a plot of projectile position as a function of time for this test. The difference between the ideal calculated position and the measured position is smaller than that seen in Fig. 4. The position calculated using the arc-ablation model is again in good agreement with the measured position. The final mass accelerated is about 30 greater than the initial mass. Although the absolute mass gain from ablation in this test (about 6 g) is greater than the gain in the October 26, 1982, test (about 4.5 g), the gain in this test is a smaller percentage of the initial mass and thus causes a smaller deviation from the ideal (no mass gain) calculation. The final velocity calculated using the ideal assumption is 3.25 km/s compared with 2.89 km/s using the arc-ablation model.

These comparisons indicate that the arc-ablation model provides an excellent replacement for the empirical friction model that had been used in LARGE. The arc-ablation model has the

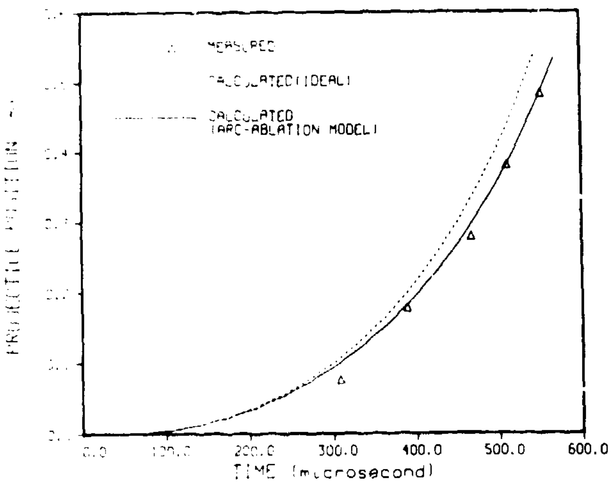

Fig. 7. Projectile position vs time for August 25, 1982 test.

advantage of providing a physically realistic mechanism for the lower observed velocities that can be tested and used to predict the effect of this mechanism in future systems.

A series of calculations was done to show the effect of arc ablation on the final velocity of projectiles of various masses. For the calculations, a high-inductance power supply (about 20 µH) was used to power a 10-m-long railgun with 0.35-µH/m inductance gradient. For these conditions, the effect of projectile velocity on the rail current is small so that all the calculations have a similar current profile, a peak current of about 975 kA at 300 µs decaying to about 600 kA at 4000 µs. The projectile was assumed to have an initial velocity of 1 km/s. Figure 8 shows a plot of the ratio of the final velocity calculated using the arc-ablation model (v) to the ideal (no mass gain) velocity (v_i). The effect of ablation is greater on projectiles of smaller mass; in this case a 5-g projectile attains only about half of its ideal final velocity. Because of the relatively long acceleration times (1300 µs for a 5-g projectile to 4400 µs for a 160-g projectile) and high currents, the mass ablated is large (from about 8 g for a 5-g projectile to about 45 g for a 160-g projectile) compared with the tests described above. The results presented in Fig. 8 depend strongly on the assumptions about railgun length, rail current, acceleration time, and initial projectile velocity. Although they are not universally applicable, they do show the trend of increasing effect of ablation as the initial projectile mass decreases.

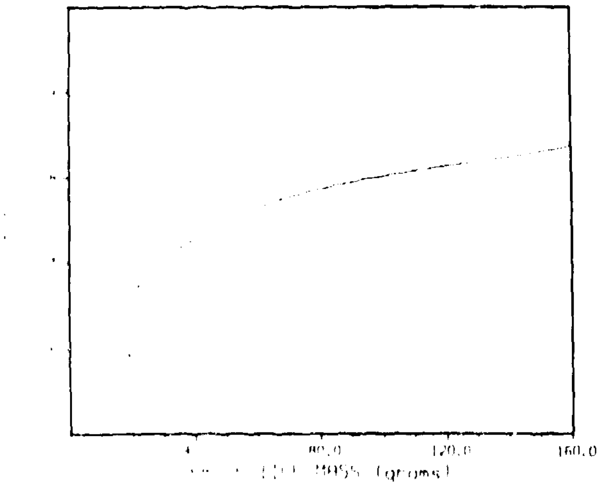

Fig. 8. Effect of arc ablation on projectile velocity for various mass projectiles.

Conclusions

A model has been developed to predict the rate of ablation and increase in mass of the arc for an arc-driven railgun. This model has been incorporated in the LARGE code that is used to predict the performance of various types of railguns. Analytical predictions are found to be in good agreement with experimental results for railgun tests conducted at Los Alamos.

The results obtained here indicate that the ablation of rail and insulator material can have a significant adverse effect on railgun performance. The effect is greater for small masses accelerated to very high velocities than for large masses accelerated to moderate velocities.

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