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Transition Armature Study Progress Report No. 4

R. S. Hawke

February 1 - March 31, 1992

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ARDEC
Transition Armature Study
Progress Report No. 4 ††
May 18, 1992
Covering the Period February 1 to March 31, 1992 †
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Executive Summary

This forth report covers the period February 1 to March 31, 1992. During this period we: 1) performed numerical simulations of plasma brush formation and evolution with a 1D MHD code, 2) commenced testing hybrid armature brushes with a test fixture for studying hybrid armature brush behavior, 3) acquired 7m of the LTS railgun containment structure for a 3 year loan, 4) began evaluation of 3D Electro-Magnetic codes and their suitability to be interfaced to existing 3D stress/strain and thermal codes and 5) conducted a program review at LLNL.

A 1D MHD code (CONFUSE) has been used to numerically simulate the evolution and formation of a plasma brush from a metal foil as it is heated through the solid, liquid, vapor and plasma phases. The simulations predict a plasma brush can be magnetically contained provided the containment chamber is longer than the quiescent brush length. The simulations predict the brush length will increase with the mass of the brush and decrease with magnetic pressure. These predictions are under investigation in the tests described below.

Assembly of a plasma brush test fixture for studying the formation, evolution and stability of plasma brushes was completed and placed in operation. The first test was performed on February 4, 1992. Thirty-six tests had been completed at the end of this report period. Hybrid armature design has evolved in order to shape the magnetic fields and successfully provide magnetic confinement of the plasma brushes. The test results have confirmed that a stable plasma brush can be formed. A parametric study of the effects of 1) brush gap, 2) transverse current gradient (magnetic pressure) and 3) initial foil mass on the brush length and voltage is in progress.

Seven meters of the LTS railgun were borrowed and transported to LLNL. It is capable of serving as a test bed for solid and hybrid armature design tests.

The design of solid armatures would be facilitated by a 3D electromagnetic code which can be interfaced to 3D stress/strain and thermal diffusion codes. We have come to the preliminary conclusion that MEGA is the most suitable EM code provided it can be interfaced to existing mechanical and thermal codes such as DYNA, NIKE, and TOPAZ.

A full day briefing on the Transition Armature Study (TAS) and potential LLNL assistance in the ARDEC Focused Technology Program, was presented to ARDEC program leaders at LLNL on March 19, 1992. The full breath of the TAS was reviewed and discussed. A visit to the railgun armature and fiber composites laboratories was included.

† A break in reporting covering the period December 1, 1991 to January 31, 1992 occurred due to a break in funding and subsequent project inactivity.

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Detailed Report

Introduction

The first Progress Report [1] included a detailed introduction of the Transition Armature Study Project. Briefly the goal of the project is to develop an understanding of the physics and engineering limits and design requirements which will lead to high performance solid and hybrid armatures, and their use in worn barrels. The reader is referred to the 1st report for a broader description of the project goals and detailed test plan. This report provides an update of the progress achieved from February 1 to March 31, 1992.

Originally the project consisted of 4 tasks: Task 1) Design and scaling of high performance hybrid armature/projectile for the 1-4 km/s range, Task 2) Determine maximum velocity achievable with solid armature/rail interface, Task 3) Develop armatures capable of high performance throughout life of barrel and Task 4) Evaluate advanced launcher concepts. During the project briefing held at LLNL on March 19, 1992 it was decided to drop Task 4 from the study.

During the start-up phase of the project a plan to study armatures and advanced launcher concepts was developed. Initially the project was principally based on numerical simulations. Powerful numerical simulation codes (2D boundary layer, 1D and 2D MHD, and 2D electromagnetic field and current coupled to stress strain) have been adapted and employed to provide direction to the experimental effort which is now underway. The experimental effort is supported by the use of several LLNL assets (2 capacitor banks, EM screen room and 25 channels of digital diagnostics) and an ARDEC funded hybrid test fixture.

The armature study has provided an excellent starting point for development of a technology base for solid and hybrid armatures. An upgraded project has been proposed and would provide the Focused Technology Program with a strong armature development effort. An increased effort level would enable us to work towards a full up hybrid armature test series in a large bore railgun (i.e. 90mm), at high energy (i.e. 8MJ KE) within a two year time frame. This test series would incorporate the design concepts developed from our sub-scale tests and numerical simulations. Another two year cycle would lead to another iteration that would assist the 1996 ATD decision.

Task 1 - Hybrid Armature

The goal of Task 1 is to design a high performance hybrid armature and develop scaling relations for bore size, projectile mass and launch velocity.

Numerical Simulation of Hybrid Plasma Brush Characteristics

A four phase equation-of-state (EOS) code (CONFUSE) has been used to predict the characteristics of a quasi steady state, stationary brush. This code provides a

precise estimate of the brush evolution because it has a well refined EOS capability.

The simulations of plasma brush development in a chamber are based on the geometry shown in Fig. 1. The chamber is formed by a rail, solid metal portion of the hybrid, and sabot Magnetic pressure is used to contain the plasma brush. The barrel insulators also play a role by confining the sides of the brush but are not included in this simulation. Initially the current flows on the inside surface of the rail, through the metal fuse and returns along the adjacent surface of the hybrid link. The thin fuse is heated through its four phases ending in the expanded plasma phase with current flow distributed through its length, l_p . This configuration will generate a magnetic field and Lorentz forces on the plasma. Equilibrium will occur when the hydrodynamic pressure of the plasma is equal to the magnetic pressure generated by the current.

Fig. 2 shows an example of the simulated evolution of a plasma brush as a function of time starting with the current which is input as a step function. Results are shown for two initial thicknesses of Al fuse, 25 and 50 μ m. The linear current concentration (current per unit rail width) is 33kA/mm. The fuse is heated to the vaporization temperature at 100 and 350 ns for the 25 and 50 μ m fuses respectively and begins to rapidly expand. It reaches an equilibrium length of about 10 and 16mm in about 1.5 and 2.5 μ s respectively. A current concentration of 33kA/mm corresponds to a magnetic pressure of nearly 700MPa in a chamber with a 1mm gap.

The electrical conductivity of plasmas near their critical point is difficult to precisely determine, hence several variations have been put forward and applied to a variety of situations [2]. Fig. 3 is a composite plot of the electrical resistivity vs. internal energy density for five EOS models [2-4] for aluminum. The effect of this variation is seen in Fig. 4 where the expansion and equilibrium length of the brush is plotted for each of the five models. The range of brush lengths vary from 3.8 to 10.5mm.

Numerical simulations were performed for different; 1) brush gaps, 2) linear current concentrations and 3) initial fuse thicknesses. The simulations indicated the plasma brush length was not dependent on the chamber gap however the voltage developed across the brush increased nearly linearly with the gap. As Fig. 5 indicates, the plasma brush length, l_p varies as the square root of the initial foil thickness, t_f . The corresponding brush voltage decreases roughly as the fourth root of t_f . Fig. 6 indicates the effect of varying the current concentration. Since the confining magnetic field intensity is proportional to the current concentration, the magnetic pressure should increase as the square of the current concentration. All other parameters held constant, the brush length should decrease in proportion to the magnetic pressure or the square of the current concentration. The simulations indicate the dependence is not quite this strong but only varies as the 3/2 power. The voltage increases linearly with the current

concentration. These parametric variations provide a guide for choosing the armature chamber length and indicate the impact of varying the gap size, initial fuse thickness and current concentration.

A paper entitled "Numerical Simulations of Plasma Brush Behavior in Hybrid Armatures" was prepared for presentation at the 6th Symposium on Electromagnetic Launch Technology held April 28-30, 1992 Austin, TX [5].

Hybrid Armature Brush Tests

A. Test Fixture

The hybrid brush test fixture is shown in Fig. 7. The fixture uses a railgun geometry with an armature link locked in place. The link, along with the rails, provide chambers for the plasma brushes. Thin foils are used to establish the initial current path and supply metal vapor from which the brush can develop. The magnetic field generated by the current flow in the rail and armature link exerts a magnetic pressure on the plasma brush thereby restricting its expansion.

B. Power Supply

Fig. 8 is an equivalent circuit diagram of the energy storage capacitor bank, test fixture and pulse shaping capacitor. The 168 μ f capacitor bank stores 140kJ at 40kV and can provide peak currents greater than 1MA. A 14 μ f pulse shaping capacitor is used to modify a sine wave into a flat-top pulse as shown in Fig. 9. This provides a quasi constant current pulse for about 10 μ s during which time the plasma brushes can stabilize.

C. Diagnostics

With an armature locked in place, it is possible to measure the voltage of each plasma brush as well as the length of each brush along with the input current. The brush length is determined with the use of several B-dot probes located adjacent to the sides of the rails and by inspection of the aluminum hybrid link which is renewed with each test. The response of the probes were calibrated with current pulses through a moveable armature using a thick non-vaporizing foil in place of a fuse.

The fixture is configured as a 30mm square bore and has provision for smaller bores, round or square. The diagnostics are closely spaced B-dot probes (2mm diameter by 6mm long, 30 turn coils) used to measure the plasma brush lengths. Peak current is about 1MA which will generate an average magnetic pressure of about 170MPa (25ksi) on the hybrid armature and up to 700MPa (100ksi) on the plasma brush. Results of these tests will be included in the next report (No. 5).

A paper entitled "Measurements of Experimental Plasma Brush Behavior in Hybrid Armatures" was prepared for presentation at the 6th Symposium on Electromagnetic Launch Technology held April 28-30, 1992 Austin, TX [6].

Task 2 - Solid Armature

The goal of task 2 is to determine 1) the physics limits to solid armature function and 2) the optimum engineering parameters that can achieve the maximum velocity. A solid armature is inherently more electrically efficient than a hybrid which has a relatively large voltage drop across the brushes. It is also more difficult to maintain solid electrical contact between the armature and the rails, especially at velocities above 1 km/s.

Numerical Simulation of Solid-Rail Interface

Motion of the solid armature results in frictional heating of the armature and to a lesser extent of the rails. This frictional heating results in surface melting and vaporization. TKBLIMP has been used to simulate this interface and estimate the velocity at which melting and vaporization will occur. TKBLIMP combines the effects of elastic material response, surface contact friction, and surface energy balance to estimate the melting and vaporization transitions as functions of velocity, interface pressure and armature/barrel materials.

There are three stages in which the interface can operate. The first stage is a sliding contact between two solid surfaces. The heat generated at the surfaces is proportional to the shear work which is the product of a shear drag coefficient and the normal interface pressure integrated over the interface surface. Initially the friction coefficient is the result of interference between the interlocking ridges and valleys of the surfaces (see Fig.10) As the friction heats the surface, incipient melting of the ridges occurs and results in a dynamic friction coefficient which is lower than static value. The second stage of interface interaction has a thin molten layer. Friction and heating are computed from shear stress and heat transfer in a thin coquette flow model. The third stage of interaction occurs when a vapor layer is formed. Friction and heating are computed from shear stress and heat transfer established by thin coquette flow, multicomponent, and if necessary, reactive constituent gas phase and gas/surface kinetics.

Fig. 11 illustrates the simulated interface temperature vs velocity for an aluminum armature sliding on a copper rail. Three curves for three interface pressures and accelerations are shown. The melt layer stage is reached at 250m/s or less. The vapor layer develops at 850m/s for interface pressures of 240 and 115MPa while about 1600m/s is achieved at a pressure of 60MPa.

Fig. 12 illustrates the simulated interface temperature vs velocity for copper armature sliding on a copper rail. Three curves for three interface pressures and accelerations are shown. The melt layer stage is reached at 600m/s or less. The

vapor layer develops at 1000 and 1400m/s for interface pressures of 140 and 65MPa respectively while about 2100m/s is achieved at a pressure of 250MPa.

The results for aluminum and copper armatures indicate that the highest velocity is not achieved at the same pressure. Furthermore, the simulations are the result of simultaneously convoluting the effects of interface pressure and duration of contact (a result of different accelerations). Further simulations will separate these and other variables.

Dimensional analysis can be applied to the results of systematically varied numerical simulations to yield useful information on: (a) functional dependence and relative importance of the influential physical processes; and (b) generalization of the information in an easy-to-apply form for optimization, materials selection, launch condition control analysis, experimental and design analysis. Here the approach is applied to the search for and establishment of a limit to the launch speed for solid armatures, U_{lim} .

It is expected that our results will fit the expression:

$$U^*_{lim} = C_0 \cdot (p^*)^{-j} \cdot (g^*)^k \cdot (\alpha^*)^l \cdot (H_m^*)^{-m} \cdot (H_v^*)^n \cdot (\rho^*)^r$$

Where the superscript (*) designates a dimensionless quantity, C_0 is the scale constant of order unity, p is the system controllable negative influence of increasing interface pressure, g is the partially positive system controllable influence of increasing acceleration (reduction in time), α is the positive material influence of high thermal diffusivity, H_m is the positive material influence of a low effective melt energy (sensible plus latent enthalpy), H_v is the positive material influence of high effective vaporization energy (enthalpy), and ρ is the positive material influence of high material mass density (thermal capacity). Additional simulations will provide the magnitude of the exponents and reported at a later time. At this time it is expected that in general, higher solid armature velocities will be achieved with higher: (1) acceleration or reduced acceleration duration, (2) thermal diffusivity, (3) vaporization enthalpy and (4) mass density of the armature material and lower: (1) interface pressure and (2) melting enthalpy of the armature material. There is an expected limit on the minimum required interface pressure to overcome magnetic repulsion.

Launcher Test Bed

A power supply and railgun launcher are needed for verification and development tests of both hybrid and solid armatures. An LLNL capacitor bank has been loaned to the ARDEC Transition Armature Study. The 5kV, 50mf, 600kJ bank is capable of operating at currents up to 1MA. The bank has been moved to a new facility where the 40kV, 140kJ bank is located. Both banks will share a screen room containing 25 channels of digitizer and a data reduction system. An assessment of the most appropriate path concluded the LTS railgun would be the best choice.

The LTS railgun has been moved to LLNL for a three year loan. It has been stored outside in Albuquerque for several years and is in need of refurbishment and modification to meet the needs of the project. Further evaluation is in progress.

Task 3 - Worn Barrel Armatures

The goal of this task is to develop both solid and hybrid armatures which will provide high performance over the lifetime of a barrel which experiences wear and erosion. This task is an extension of work described in Tasks 1 and 2 and has not yet begun.

Task 4 - Advanced Launcher Concepts

The goal of this task was to generate and evaluate non-conventional railguns. Initially the focus was on multi-rail geometry's. It was decided at the March 19, 1992 project review that this task should be suspended. Analytical tools are on hand for a future restart if appropriate.

Summary

During this reporting period we began testing with a hybrid test fixture. The railgun test laboratory includes a 140kJ, 1MA capacitor bank, 25 channels of digitizers and a data reduction system. A 600kJ, 1MA capacitor bank will be part of the facility. A Railgun test bed has been borrowed.

References

- [1] R. S. Hawke, ARDEC Transition Armature Technology Project, Progress Report No. 1. [Dec. 12, 1991]
- [2] Y. T. Lee & R. M. More, *Phys. Fluids*. 27, 1273 (1984).
- [3] Group T-4, *Los Alamos National Laboratory Report No. LALP-83-4* (1984).
- [4] N.F. Roderick, B.J. Kohn, W.F. McCullough, C.W. Beasor, J.A. Lupo and J.D. Letterio, *Laser and Particle Beams* I, 181 (1983).
- [5] R. S. Hawke and P. A. Pincosy, "Numerical Simulations of Plasma Brush Behavior in Hybrid Armatures" *6th Symposium on Electromagnetic Launch Technology*.
- [6] R. S. Hawke, J. J. Morrison and A. R. Susoeff, "Measurements of Plasma Brush Behavior in Hybrid Armatures", *6th Symposium on Electromagnetic Launch Technology*.

Prior Reports

- R. S. Hawke, ARDEC Transition Armature Technology Project, Progress Report No. 2. [Feb. 21, 1992]
R. S. Hawke, ARDEC Transition Armature Technology Project, Progress Report No. 3. [May 13, 1992]

Fig. 1. Plasma Brush Chamber Portion of Hybrid Armature. Fig.1A Shows the chamber with a metal foil at the forward position of the chamber. The metal foil is used to provide an initial current path and after vaporization, material to form a plasma brush. Fig.1B Shows the chamber with a plasma brush commutating current from the rail to the solid metal armature link. The chamber is bounded by a rail, sabot and solid armature link surface. Magnetic pressure generated by Lorentz forces acts on the plasma to confine the brush. The length of the chamber must be designed to always be longer than the brush in order to maintain a hybrid armature and prevent transitioning to a pure plasma armature. The sides of the chamber (not shown) are formed by the barrel insulator or non-conducting projectile/sabot material.

Fig. 2. Evolution of a Plasma in a Hybrid Armature Brush Chamber. The metal foil used to provide the initial current path is rapidly heated and will vaporize thereby providing material from which a plasma can form. Upon reaching the vaporization temperature, the foil begins to rapidly expand. The expansion continues until the hydrodynamic pressure is balanced by the magnetic pressure generated by the Lorentz force of the rail and hybrid magnetic fields interacting with the brush current (very similar to a conventional plasma armature railgun). This simulation used a current concentration of 33kA/mm and the original More-Lee EOS discussed in a following section. Two fuse thicknesses were simulated, 25 and 50μm and reached equilibrium at 11 and 16mm respectively.

Fig. 3. Resistivity Ratio vs Internal Energy for Five Aluminum Models. Several models of resistivity dependence on internal energy (deposited by Joule heating) have been developed for various applications of the CONFUSE code. In all cases, aluminum transitions from a liquid to vapor at about 10MJ/kg. As the internal energy increases the resistivity increases to a maximum and then decreases becoming a plasma at about 40-45MJ/kg. The equilibrium plasma brush length occurs when the internal energy is about 100MJ/kg or more, hence the diverse relationships in the vapor phase have minimal effect on the equilibrium brush length in the plasma phase. Generally, the modified More-Lee model is the most suitable for high temperature, high energy density plasmas.

Fig. 4. Plasma Brush Evolution vs Time for Five Aluminum Resistivity Models. Plasma brush length evolution is shown as a function of time for the five EOS models shown in Fig. 3. The most appropriate EOS for a plasma brush is probably the modified More-Lee model. Experiments will be used to determine which model will be most appropriate for hybrid design.

Fig. 5. Plasma Brush Length and Voltage vs Initial Foil Thickness. The simulations indicate the equilibrium plasma brush length increases with the initial foil thickness while the brush voltage decreases approximately with the inverse fourth root of the foil thickness. These simulations used the modified More-Lee EOS for aluminum. The current concentration used was 33kA/mm. These simulations indicate that a lower voltage, hence higher electrical efficiency can be obtained with a thicker fuse (or more brush mass by whatever means). However the brush length will be longer and require a longer chamber to contain it.

Fig. 6. Plasma Brush Length and Voltage vs Current Concentration. The equilibrium plasma brush length decreases with the $3/2$ power of the current concentration while the brush voltage increases linearly with the current concentration. These simulations indicate a lower voltage and higher efficiency could be obtained but would require a longer brush chamber. Often other factors dictate the current concentration. The simulations are for a $25\mu\text{m}$ initial foil thickness.

Fig. 7. Hybrid Armature Brush Test Fixture. This is a side section view. Initially the current flows through the rail, foil and metal link. After the current vaporizes the metal foil, a plasma brush is formed. The brush expands until the hydrodynamic pressure is in equilibrium with the magnetic pressure generated by the Lorentz forces from the rail and hybrid current generated magnetic field interacting with the brush current. The present configuration is a 30mm square bore. B-dot probes are located adjacent to the 4 sides of the 2 rails at 1cm intervals. The 1mm gap brush chamber is 45mm long and 30mm wide.

Fig. 8. Equivalent Circuit Used to Power Hybrid Brush Test Fixture. A 168 μ f, 40kV capacitor bank is capable of providing currents up to 1MA. An opening fuse switch is used to open the circuit after the first one-half cycle in order to prevent reverse charging of the bank and limit each test to a single brush formation cycle. A pulse shaping capacitor is used to provide a 10 μ s flat-top pulse instead of the standard sine wave.

Fig. 9. Modified Flat-Top Current Pulse Shape. The 14 μ f pulse shaping capacitor provides a 10 μ s flat-top current pulse at about 80% of the unmodified sine wave peak current. The pulses were generated with a bank charge voltage of 13kV and a stored energy of 14kJ.

[A] interlocking ridges

[B] incipient ridge melting

[C] liquid melt layer forms

[D] vapor layer

Fig. 10. Illustration of Three Stages of Armature and Rail Interface. Fig. 10A represents the interface between two solid materials with interfering ridges. This condition is typical for initial static and slow moving conditions. Fig. 10B indicates the onset of ridge melting due to frictional heating. Fig. 10C illustrates a full melt layer at the interface. Fig. 10D represents a fully developed vapor layer between the armature and rail.

Al/Cu: Armature temp. limited launch speed
Influence of peak normal surface stress and acceleration

Fig. 11. Interface Temperature vs Velocity for an Aluminum Armature on a Copper Rail. Three temperature profiles are plotted for three acceleration and interface pressure combinations. Aluminum melting and vaporization temperatures are shown. The velocities at which the melt and vapor layers form are shown for the best case.

**Cu/Cu: Armature temp. limited launch speed
Influence of peak normal surface stress and acceleration**

Fig. 12 Interface Temperature vs Velocity for a Copper Armature on a Copper Rail. Three temperature profiles are plotted for three acceleration and interface pressure combinations. Copper melting and vaporization temperatures are shown. The velocities at which the melt and vapor layers form are shown for the best case.

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