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An Investigation of Electromagnetic Launcher Repeatability

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Electromagnetic launcher (EML) performance repeatability has been identified as a potential development issue for several years. Investigation of this isue has been difficult because an EML that is powered on a relatively continuous basis to provide long duration operation has not been available. A battery charged capacitor power system has enabled long duration, 6 to 7 seconds, EML experiments. This paper provides a summary of an experiment to investigate EML launch to launch performance consistency. A series of 8 ten-shot bursts, each separated by 15 to 30 minutes, performed in a single day using a single set of bore materials is the subject of this paper.

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PREFACE

This report documents research conducted using a battery charged capacitor power supply to produce long duration power pulses for rapid fire Electromagnetic Launcher (EML) burst fire experiments. Specifically, this paper discusses an 80-shot experiment that was conducted in one day using the same set of bore materials. This technical report was presented at the 6th Electromagnetic Launcher Conference in Austin, TX 28 April to 1 May 1992.

This work was funded by the Electromagnetic Launcher Technology Branch (WL/MNSH) of the Analysis and Strategic Defense Division of Wright Laboratory, Armament Directorate at Eglin AFB, FL under the Kinetic Energy Weapons program of the Strategic Defense Initiative. Mr. James B. Cornette and Mr. Mark W. Heyse from WL/MNSH and personnel from Science Applications International Corporation (SAIC) in Shalimar, FL performed the work during the period March 1991 to April 1992 at Eglin AFB FL 32542-5000.

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Abstract - Electromagnetic launcher (EML) performance repeatability has been identified as a potential development issue for several years. Investigation of this issue has been difficult since an EML that is powered on a relatively continuous basis to provide long duration operation has not been available. A battery charged capacitor power system has enabled long duration, six to seven seconds, EML experiments. This paper provides a summary of an experiment to investigate EML launch-to-launch performance consistency. A series of 8 ten shot bursts each separated by 15 to 30 minutes was performed in one day using a single set of bore materials. The experiment set-up is described, the experimental results discussed, and key parameters which could affect performance repeatability are identified,.

I. INTRODUCTION

EML performance repeatability is of interest for a variety of reasons. Depending on ones point of view, launch-to-launch consistency could define the fire control constraints for a given EML system or the EML electrical control requirements for a given fire control constraint. In either case, quantification of EML repeatability and establishing the principle dependencies and relationships that define it are important. As a first step, the experiment described in this paper examines the quantification of and dependencies for launch repeatability.

Speculation concerning EML repeatability over the past few years has generally been negative. The popular perception seems to be that EML performance is less consistent than conventional chemical launcher performance. While there is a relatively large data base of EML performance data available today, most of this data is derived from single shot experiments. Further, a wide variety of separate EML components were used in developing this data base. Many distinctly different barrel designs, armature types, and power supplies have been employed to conduct experiments. Experiment objectives and approaches, including instrumentation / diagnostic techniques, used have been equally varied. Thus, drawing conclusions concerning EML performance repeatability from most of the data available today is difficult at best.

Preliminary review of data from experiments previously conducted with the same hardware used for the experiment reported here seemed to indicate that EML performance decreased at an exponential rate within the first 2 to 3 shots of a 30 shot burst and then remained relatively constant until the last few shots. In addition, several shorter duration bursts, typically 5 shots, had been performed using a single set of bore materials in the EML. The objective of many of these short bursts was to provide characterization information for various component parts of the power supply, controller, or preaccelerator during development. Consequently, the EML was viewed primarily as a load ,thus, performance variation from burst to burst was not examined. However, in reviewing electrical data from many of these experiments it seemed that the early exponential decay followed by relatively constant performance trend held even when the same bore materials were used for multiple bursts.

The objective of the experiment reported in this paper was to begin investigation of the shot-to-shot and burst-to-burst performance consistency. Specifically, quantification of performance variance relative to the trends identified above. The experiment consisted of eight separate 10 shot bursts conducted in one day. The launch interval within the bursts was 200 milliseconds (ms) with each burst separated by at least 15 min.

II. EXPERIMENT DESCRIPTION

Overall, the approach employed was to use existing hardware without special modifications specifically designed for this experiment. The hardware used was designed for proof-of-concept purposes and not to perform rigorous repeatability investigations. Never the less, initial repeatability information was obtained. The hardware consisted of a 15mm, plasma armature EML driven by a battery charged capacitor power

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supply. The EML used was a four rail bore configuration with the rails electrically connected as a quadripole. One set of copper rails and G-9 insulators was used for the entire experiment. Plasma armatures were initiated with an aluminum mesh fuse attached to the rear of each projectile. These 5 gm projectiles were preaccelerated with high pressure helium prior to injection into the EML. Armature initiation was timed to occur 0.14 meters into the 0.61 meter long launcher. Active cooling of the bore materials during burst operation was not used, however, compressed air was blown through the EML bore between bursts in order to return the bore materials to room temperature.

Experiment power was supplied by a 336 millifarad (mF) capacitor bank. Switching between the capacitor bank and the EML was accomplished with silicon controlled rectifiers. The capacitor bank was charged to approximately 500 volts for each launch by a series connected string of standard automotive batteries which were switched into the capacitor bank using mechanical relays.

Data collection was accomplished using an integrated waveform digitizer system [1]. Signals monitored include; breech current, breech voltage, armature voltages, capacitor bank voltage, and experiment control signals.

Unresolved engineering issues still existed with the hardware used at the time of this experiment. The most significant of these issues relative to repeatability was armature initiation timing. More reliable armature initiation techniques have been developed and employed successfully on larger bore EMLs. Since the technique used here was known to periodically fail and emphasis was placed on using the hardware without modification, it was decided to exclude attempted shots that failed to produce an active armature in the final analysis.

III. EXPERIMENT RESULTS

Of the 80 shots attempted during the experiment 65 were successful. That is, there were 65 shots were current flow through the EML was observed. During the first shot of the second burst a lens from one of the light gates, used to sense projectile position in the preaccelerator, shattered. Since proper projectile position was not sensed for the remaining shots in burst 2, the experiment controller entered a default mode on each shot attempt. This default mode prohibited capacitor bank discharge and resulted in preacceleration only (air-shot). Random armature fuse failure resulted in 6 additional air-shots throughout the experiment. The specific shot attempts which resulted in air-shots are; 9,10,12-20,29,37,45, and 53.

Insulator flash-over began to occur in front of the projectile, on an intermittent basis, early in the fifth burst. It is believed that this was a result of soot buildup caused primarily by insulator erosion [2]. This internal shorting resulted in an additional 7 shots being degraded substantially below average performance (peak current < 200 kA). These shots were not included in the analysis performed here since this phenomena appears random and could be controlled by using an insulator material with higher heat capacity.

The total data base resulting from the 58 successful shots was reviewed. Hardware performance was consistent with previously conducted experiments of smaller scope. Fig 1. shows the electrical data for shot 7 which is representative of the data for all shots.

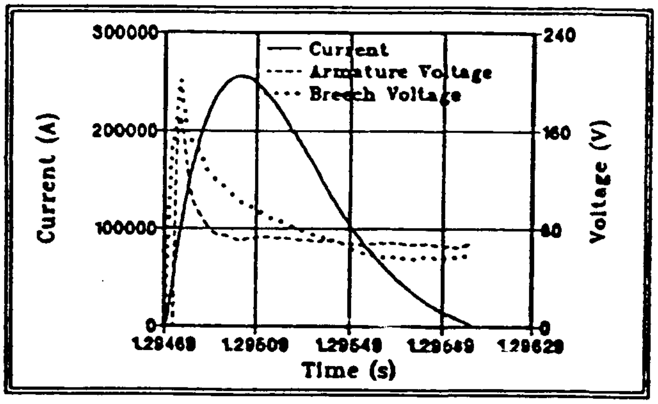

Fig 1. Shot 7 Electrical Data

Average values for the entire experiment of key electrical parameters are as follows; capacitor bank voltage = 497.6 volts (V), breech current = 251.2 kiloamperes (kA), breech voltage = 111.8 volts, armature voltage = 81.7 volts, and breech action = 3×10^7amperes squared seconds. The average injection velocity was 303 meters per second (m/s). Breech current data from each shot was numerically integrated and the muzzle velocity calculated using previously established physical characteristics of the hardware and the following relationships:

$$F = Ma = \tfrac{1}{2} L' I^2 \tag{1}$$

$$v = (L'/2M)\,\Sigma\, I^2 \text{ Delta t} \tag{2}$$

where F is the accelerating force [3], M is the projectile mass (5 gm), a is acceleration, L' is the inductance gradient (.15 μH/m), I is the electrical current entering the EML breech,and Delta t is the time step used by the data acquisition system (7μsec). The calculation was performed over the acceleration period. Resulting calaulated velocities were averaged to yield 753 m/s overall. The average launch time was 875 microseconds.

To keep data presentation within a manageable scope for this paper, only the data from a subset of the total number of shots is considered. Data for shots 1,3,7, & 10 from bursts 1,3,5, & 8 are used. This four by four matrix of shots crosses the complete experiment and is representative of the overall results from the analysis of the 58 fully successful shots . The specific shots used are indicated in Table I. A total of 15 shots are represented by this matrix since shot 10 was an air shot.

TABLE I.
SHOTS USED IN ANALYSIS

Burst	Shot Number			
1	1	3	7	-
3	21	23	27	30
5	41	43	47	50
8	71	73	77	80

IV. LAUNCH REPEATABILITY

Average values for each parameter were calculated from the matrix of data represented in Table I. The resulting averages are shown in Table II.

TABLE II.
AVERAGE VALUES OF KEY PARAMETERS

Parameter	Burst 1	Burst 3	Burst 5	Burst 8
Capacitor Voltage (V)	502	497	496	496
Injection Velocity (m/s)	316	297	301	300
Breech Current (A)	265	262	250	225
Armature Voltage (V)	79	80	83	84
Breech Voltage (V)	105	101	99	132
Breech Action (MA^2s)	32.4	32	28.8	27.5
Muzzle Velocity (m/s)	801	778	733	711
Launch Time (s)	784	852	926	959

Parameters considered include; capacitor bank charge voltage (Vc), armature voltage (Va),, breech current (I), launch time (t), calculated muzzle velocity (v), electrical action (Action), and injection velocity (vi), breech voltage (Vb). The amount of variation for key parameters was calculated based on percent difference basis. Equation (3) shows the formula used for these calculations with peak current as an example. The consolidated results are shown in Fig 2.

$$\%Diff = 100\,(Ipeak - Ipeak_{avg})/Ipeak_{avg} \qquad (3)$$

The mean variation, as computed with this data, is not intended to represent an absolute measure of repeatability. For the purpose of this preliminary analysis, it serves as a basis for relative comparison of the selected parameters. Velocity is usually the parameter of greatest interest when discussing EML performance repeatability. For that reason the other parameters were evaluated for their contribution to the variation in calculated velocity.

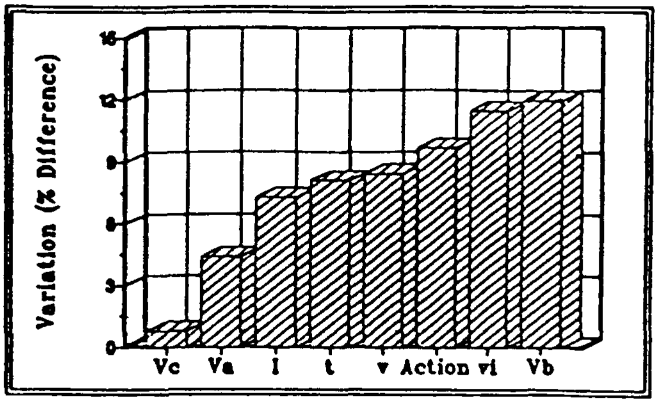

Fig 2. Average Variation in Key Parameters

Capacitor bank charge voltage was extremely consistent varying less than 1% across the complete experiment. Some variation was expected here due to the changes in the state of charge (SOC) and internal resistance of the batteries [4]. The relatively high consistency demonstrated by the power supply indicates that it is not a major contributor to the overall EML repeatability. Therefore, power supply performance is excluded from further consideration here.

Electrical action was computed from the data and is given by,

$$\text{Action} = \Sigma\, I^2\, \text{Delta } t \qquad (4)$$

the sum was computed over the acceleration time interval. Since variation in action reflects both the current and acceleration time they too will be excluded from further discussion.

Focusing attention on the remaining parameters, armature voltage, action, breech voltage, injection velocity and calculated velocity, Fig 3. shows their variation by burst. Fig 2 and 3 together suggest that contributions to the velocity variation made by action, breech voltage, and injection velocity are likely to be more significant than that made by armature voltage. However, armature voltage is a component of breech voltage so, that conclusion may be premature. Breech voltage may be expressed as,

$$Vb = V_c + V_r + V_{br} + V_s + V_a \qquad (5)$$

where V_c is the connection voltage due to the power feed connection resistance at the breech, V_r is the rail resistance voltage, V_{lr} is the rail inductive voltage, and V_s is the speed voltage. To further isolate the voltage contribution, the quantity Vb-Va was determined and the mean variation calculated. This variation was found to be over 48 % across the complete experiment. Fig 4 compares the variation of Va to Vb-Va broken down by burst.

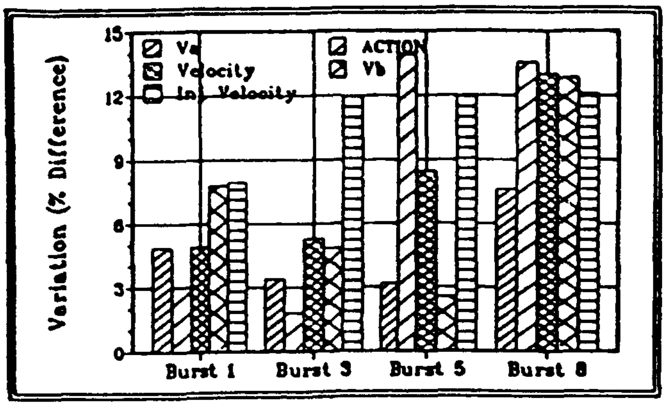

Fig 3. Variation By Burst

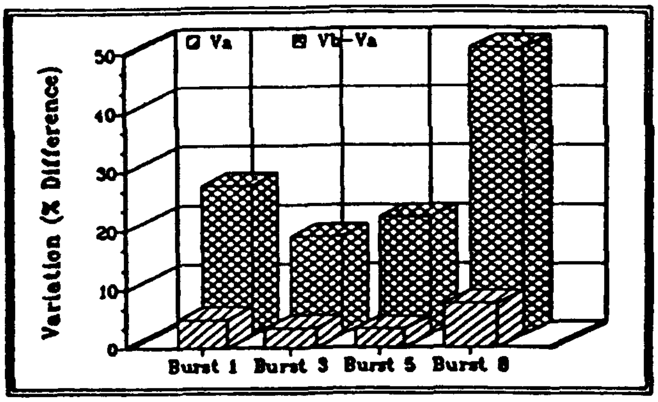

Fig 4. Va Compared to Vb-Va

Armature voltage for this particular EML bore configuration is surprisingly consistent. In fact the variation as presented so far is somewhat skewed upward by a few shots where armature initiation was delayed by approximately 100 μsec. When this occurs, the voltage across the rails approaches the capacitor bank charge voltage and the average value calculated from the data is increased. This is illustrated in Fig 5. where the armature voltages from the third shot of bursts 1,3, and 5 in the study matrix are compared. All beginning times were referenced to zero for direct comparison. Armature initiation for shot 43, the third shot of burst 5, is delayed by approximately 91 μsec. The resulting average calculated for shot 43 is off-set by 10-15 volts however, it is clear from the figure that the actual armature voltage, once fully initiated, is approximately 80 volts which is consistent with the other shots. This observation implies that armature voltage is relatively insensitive to bore condition. In the later bursts, the rails and insulators had been noticeably eroded and, as previously noted, covered with soot. Yet armature voltage did not change appreciability.

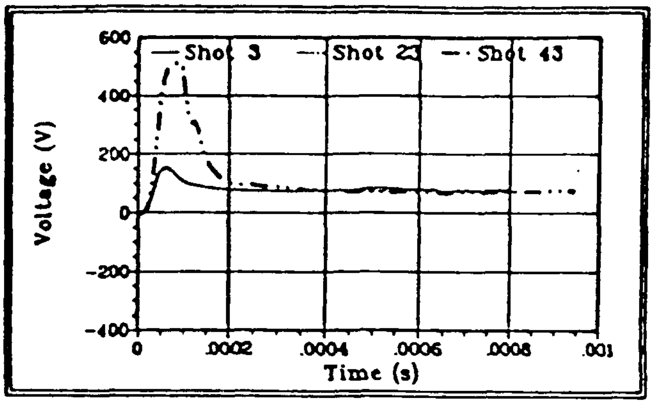

Fig 5. Armature Voltage For Shot 3 of Each Burst

The remaining terms in (5) were analyzed to determine which was the main contributor to the large variation noted. Equations (6)-(9) express the other contributing terms in more detail.

$$V_c = IR_c + L_c \, dI/dt \qquad (6)$$

$$V_r = IR_r = I \int \frac{2v}{\sigma h \delta} \, dt \qquad (7)$$

$$V_{lr} = L'x \frac{dI}{dt} \qquad (8)$$

$$V_s = IL'v \qquad (9)$$

where R_c is the connection resistance, L_c is the connection inductance, σ is the conductivity of the rail material, h is the rail height, δ is the electrical skin depth [3], and L' is the inductance gradient.

Within a given burst, the degradation in velocity performance appears to follow an exponential trend as illustrated in Fig. 6 for the first burst. For direct comparison, the time base was adjusted to zero for each velocity in Fig 6. This exponential performance decay could be characteristic of a thermally affected increase in material resistivity, however, the decay in injection velocity is also somewhat exponential which is also illustrated in Fig. 6.

To investigate this further, simulations were run to match the data. First, the simulation was anchored against shot 1. The resulting match is shown in Fig 7. Next, variations in selected parameters were introduced, one at a time, and the resulting impact on breech voltage and velocity determined using shot 1 parameters as a baseline for comparison. The breech voltage components are clearly coupled as equations (6)-(9)

indicate. Each component's percentage of the total was observed to change each time one of the variations discussed was introduced into the simulation. The varation which resulted in the gratest change is identified in the paragraphs that follow along with the corresponding change in Vb and v.

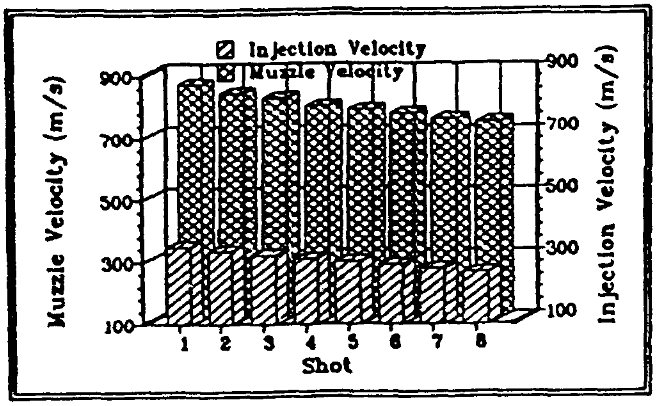

Fig 6. Burst 1 Injection and Calculated Muzzle Velocity For Each Shot

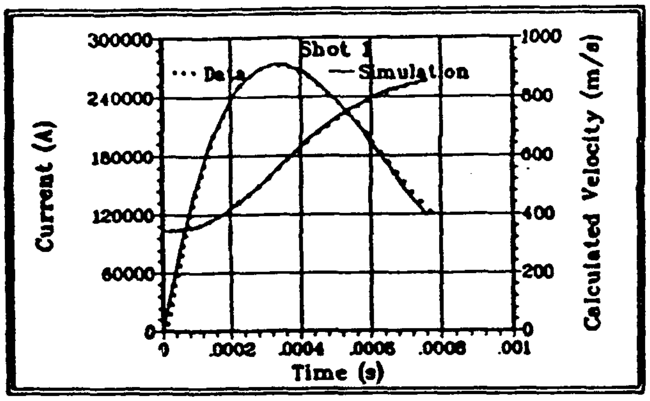

Fig 7. Shot 1 Simulation & Data Match

Both V_e and V_r are most directly affected by changes in the rail resistivity which are brought about by the increasing rail temperature. Equation (10) has been shown to provide a good approximation of temperature changes for fully diffused current conductors [5],

$$\text{Delta T} = \left(\int I^2\, dt \right) / \sigma \Gamma C_p A^2 \qquad (10)$$

where, Delta T is the change in temperature, Γ is material mass density, C_p is the specific heat, and A is the cross-sectional area. Equations (11) and (12) were derived using reference table values for resistivity and specific heat at room tempreature and 100 °C. Equations (10), (11), and (12) were iteratively solved using the calculated action values from the data to approximate the temperature rise experienced in the EML rails.

$$1/\sigma = 2.0\text{x}10^{8}(1+3.9\text{x}10^{-3}\ \text{Delta T})\ \Omega\text{m} \qquad (9)$$

$$C_p = 384.9(1\text{-}4.49\text{x}10^{-3}\ \text{Delta T})\ \text{J/kg °C} \qquad (10)$$

The results of these calculations, for the first burst, are presented in Table III. Total temperature rise predicted for the 8 successful shots in burst 1 is approximately 55 °C which, agrees quite well with temperature measurements taken during previous experiments fro the rear rail surface. Resistivity was found to increase by approximately 34% over a ten shot burst. A median resistivity increase of 17% was introduced into the simulation. The resulting change in breech voltage was approximately 1% and the muzzle velocity variation was 0.4%.

TABLE III.

TEMPERATURE RISE DURING BURST 1

Shot	Action (MA^2s)	$1/\sigma$ ($\Omega m \cdot 10^{-8}$)	C_p (J/kg °C)	Delta T (°C)
1	33.8	2.05	374.6	6.0
2	32.6	2.10	364.3	6.09
3	32.4	2.15	353.9	6.36
4	31.5	2.20	343.5	6.52
5	31.5	2.26	332.9	6.89
6	31.3	2.32	322.1	7.25
7	30.9	2.39	311.0	7.62
8	31.0	2.47	299.6	8.15

Fig. 8 provides a comparison of the current data and calculated velocity to the simulation results for the seventh shot in bursts 1, 3, and 5. The measured values of capacitor bank charge voltage and muzzle voltage were used for each shot simulation. Rail resistivity was increased to account for the increased rail temperature and the same value used for each shot.

V_b is most strongly influenced by changes in injection velocity and armature initiation position. The median change in vi during the experiment was approximately 14%. When introducted into the simulation, the corresponding change in V_L was 42% which resulted in a 4% change in breech voltage and a 4% change in muzzle vleocity. As previously discussed, armature initiation delays of upto 100 μsec were observed during the experiment. Assuming the average injection vleocity, a 100 μsec delay results in a 14% change in armature initiation position. This change in starting position resulted in a 39% change in V_L, a 2% change in breech voltage, and a 0.9% change in muzzle velocity.

Variation in injection velocity also impact speed voltage. The 14% variation in vi used above reslulted in an 8% change in V_e. Again, the corresponding change in breech voltage was 4% and the resulting muzzle velocity change was also 4%.

Substantial armature voltage changes were observed on a few shots. As previously discussed, the cause of these changes was delayed armature initiation. The maximum variation in Va observed was approximately 10% with respect to the average value. When this variation was entered into the simulation the corresponding change in breech voltage was 6% and the resulting change in muzzle velocity was 2%.

Breech voltage and velocity sensitivity to changes power supply parameters was examined. A 2% variation in capacitor bank charge voltage was found to yield a 1.5% change in Vb and approximately 2% variation in muzzle velocity. In addition, a 15% increase in power supply resistence resulted in a 2% decrease in breech voltage and a 3% decrease in velocity. This magnitude of resistence increase is probably higher than actually experienced however, some increase in power supply resistence is expected due to increased temperature in the power supply conductors.

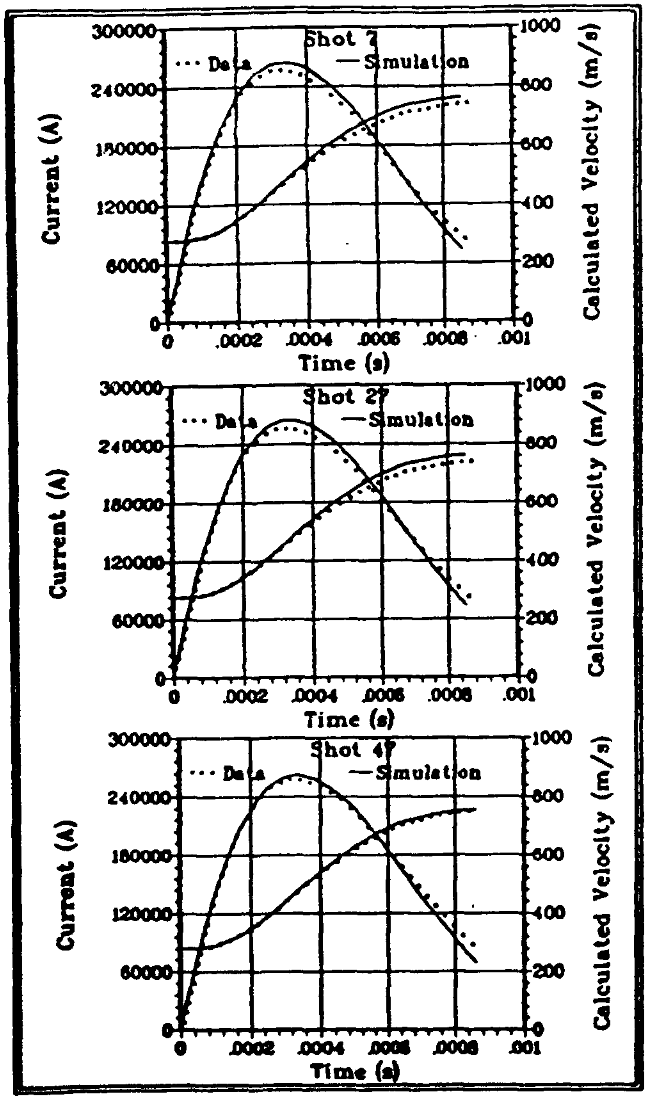

Fig 8. Data & Simulation Agreement

V. CONCLUSION

EML performance repeatability has been examined in this paper and determined to vary less than 9% with respect to an average velocity calculated for the complete experiment. While there are several factors which influence the variance observed, injection velocity decay and armature initiation delays appear to be the dominant factors. The rail resistance increase which results from the bulk heating of the rails was determined to have a relatively minor influence on performance. Armature performance for this particular EML bore configuration was shown to be surprisingly consistent and not likely to contribute significantly to the velocity variance observed. In addition, the armature voltage drop appears to be relatively insensitive to bore condition. While capacitor bank charge voltage was relatively consistent for this experiment, muzzle velocity was found to be sensitive to relative small changes. There does not appear to be a fundamental issue relative to achieving consistent performance with this EML. Tighter injection velocity control and resolution of the armature initiation timing issue should significantly reduce the variance observed.

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