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TECHNICAL REPORT ARLCD-TR-85009

EMACK RAILGUN FIRING TEST REPORT NO. 9

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18. SUPPLEMENTARY NOTES

The first five shots were performed and documented by Westinghouse R&D Center, Pittsburg, PA. Shots six through eight were performed at ARDC but have not been documented as of this publication.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Railgun	Diagnostics	Storage inductor	Lorentz force
Electromagnetic propulsion	Flash x-ray	Homopolar generator	Rail friction
	Make switches	Insertion force	Transient recorder
Armature	Soft catch	Flux density	
Interference fit	Vacuum range	Contact force	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The test firing of the EMACK railgun test bed was successfully conducted on 20 December 1983 at a peak system current of 430 kiloamperes and 1.6 megajoules stored inertially in the homopolar generator. Current was successfully commutated into the launcher in 800 microseconds. The D1.1 projectile in-flight shadowgraphs were taken with a 150 KV Hewlett Packard flash x-ray system and a motion picture of the muzzle arc was taken with a 5000 frame-per-second high speed camera. The projectile weighed 566 grams and reached a velocity of 506 m/s

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20. ABSTRACT (cont)

in the 5 meter-long barrel. The improved armature design left the barrel intact and acceptable for EMACK shot no. 10.

CONTENTS

TABLE

FIGURES

INTRODUCTION

The ninth test firing of the EMACK railgun test bed was successfully conducted on 20 December 1983 at 430 kiloamperes. This was the second test of the D1.1 armature design and the first shot of a projected series of firings using the same set of accelerator rails.

The objectives of the test firing were to:

1. Test the D1.1 projectile armature design at low launcher current

2. Establish the correlation between interference fit and insertion force on switch and projectile armatures

3. Make the first shot in a multi-shot barrel

4. Test a new flash x-ray diagnostic setup

5. Photograph muzzle blast and projectile flight with a high speed motion picture camera

6. Improve the catch tank vacuum

7. Employ a new arc stripper design

8. Test a new transient recorder trigger circuit

9. Correlate arc intensity and projectile position in the barrel

10. Recover the projectile intact in the catch tank

DISCUSSION

This low energy shot produced a launch velocity of 506 m/s that was calculated from the position-versus-time data obtained from B-dot pickup coils on the launcher barrel (fig. 1). The launch package (preshot) is shown in figure 2. Plots of projectile distance, velocity, and acceleration versus time are shown in figure 3 and the relevant shot parameters, both predicted and actual, are listed in table 1.

The muzzle voltage trace (fig. 4) indicates that the improved projectile armature design reduced rail damage. Also no arc was detected by the two pin diodes at the breech. Rail damage was minimal and restricted to the muzzle. The barrel and range were nearly free of soot and were generally cleaner than after any previous shot (figs. 5 through 7). After examination by borescope, the barrel was broached and swabbed with acetone in preparation for test 10. The broaching operation removed only a few slivers of copper.

Two of the three flash x-ray diagnostic stations succeeded in producing shadowgraphs of the projectile in flight. The foil triggering system after the test is illustrated in figures 7 and 8. One of the two shadowgraphs (fig. 9) illustrates the launch package's integrity during flight.

The high speed camera (5,000 frames per second) recorded the travel of an arc as the projectile left the barrel (fig. 10). The fifth frame showed debris from the foil switch being pushed downrange. The velocity of the tip of the arc is approximately 445 m/s, slightly slower than the projectile's launch velocity.

The catch tank vacuum was improved by welding all the seams and using an O-ring seal for the catch tank top. This resulted in a 35% improvement in catch tank vacuum from that obtained in shot 8.

While an attempt to soft catch the launch package failed, enough of the projectile and armature fragments were recovered to permit visual inspection (figs. 11 and 12). Examination of the armature fragments showed that there was minimal arc damage to the brushes. Melting of the copper fiber brushes was restricted to the contact surfaces (fig. 12).

The transient recorder trigger circuit (fig. 13) proved effective. The circuit divided the Rogowski coil output by 10 and then differentiated it to obtain a sharper rise time. Plots of recorded data are given in appendix B. The homopolar generator voltage data on Biomation Unit A (app A) was lost due to incorrect sensitivity settings. Preshot component inspection, switch delay tests, and homopolar generator parameters are also included in appendix A.

The effectiveness of the conical arc stripper could not be determined because of the redesigned armature and low kinetic energy; however, the stripper withstood the muzzle blast effects (fig. 14).

The actual insertion forces for the projectile and switch armature were 322 lb and 1,250 lb, respectively. The corresponding predicted values were 375 lb and 563 lb. A discussion on the calculation and correlation between the insertion force and the armature interference fit is included in appendix C.

The velocity of the rail switch armature was calculated to be 34 m/s. This calculation is as follows:

An approximation of the velocity of the railswitch armature was achieved through measurement of the volume of the displaced aluminum honeycomb material used in the switch catcher. The volume of crushed honeycomb material is proportional to the work done on it. The proportionality constant is called the resistivity

$$W = (V)\ (R)$$

The honeycomb had a nominal resistivity of 600 inch-pound per cubic inch. After the test, the displaced volume of aluminum was found to be 134.14 inch^3; therefore, the total work done on the impact-absorbing aluminum was

$$W = (134.14)\ (600) = 80{,}484.0 \text{ in.-lb}$$

$$= 6{,}707 \text{ ft-lb}$$

$$= 9{,}094.69 \text{ Joules}$$

If heat and other negligible energy losses during impact are neglected, the armature kinetic energy can be found from 1/2 MV^2

$$W = E_K = \frac{MV^2}{2}\ ;\ M = 15.19 \text{ kg}$$

$$V = \frac{2W}{M} = \sqrt{\frac{2\ (9094.69)}{15.19}}$$

$$= 34.6 \text{ m/s}$$

Methods for a continuous measurement of switch armature velocity in the severe railswitch environment are being devised for future tests.

CONCLUSIONS

Despite the discrepancies between predicted and actual values, test firing 9 produced a significant amount of data. The redesigned projectile/armature carried a maximum current of 370 kiloamperes and demonstrated how proper armature design can significantly reduce rail wear and improve launcher efficiency. The flash x-ray and high speed motion camera proved to be a useful diagnostic tool in determining projectile velocity and flight stability. The improved catch tank yielded a fragmented D1.1 projectile, yet it could still be reconstructed. Rail and insulator damage was minimal and the barrel will be used in EMACK firing 10.

RECOMMENDATIONS

1. Proceed with test firing 10 using the D1.2 projectile and the same set of rails used in test firing 9.

2. Employ improved methods for measuring the system current.

Table 1. Major parameters for EMACK test firing 9

Parameter	Predicted	Actual
HPG stored energy (kJ)	2,000	1,600
Drive motor speed (RPM)	2,200	2,017
Generator voltage (V)	35	--
Field excitation current (A)	1,300	1,324
Peak system current (kA)	750	430
Current rise time (ms)	122	119
Commutation time (us)	550	800
Switch armature velocity (m/s)	--	34
Maximum projectile velocity (m/s)	800	506
Launch package mass (g)	600	566
Launch package kinetic energy (kJ)	192	73
Peak acceleration (kG)	21.5	8.6
Charging efficiency (%)[1]	--	22
Accelerator efficiency (%)[2]	--	23.8

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1 $\eta_{charging} \triangleq \frac{E_{toroid}}{E_{HPG}}$

2 $\eta_{ACC} \triangleq \frac{E_{projectile}}{E_{switch\ point}}$

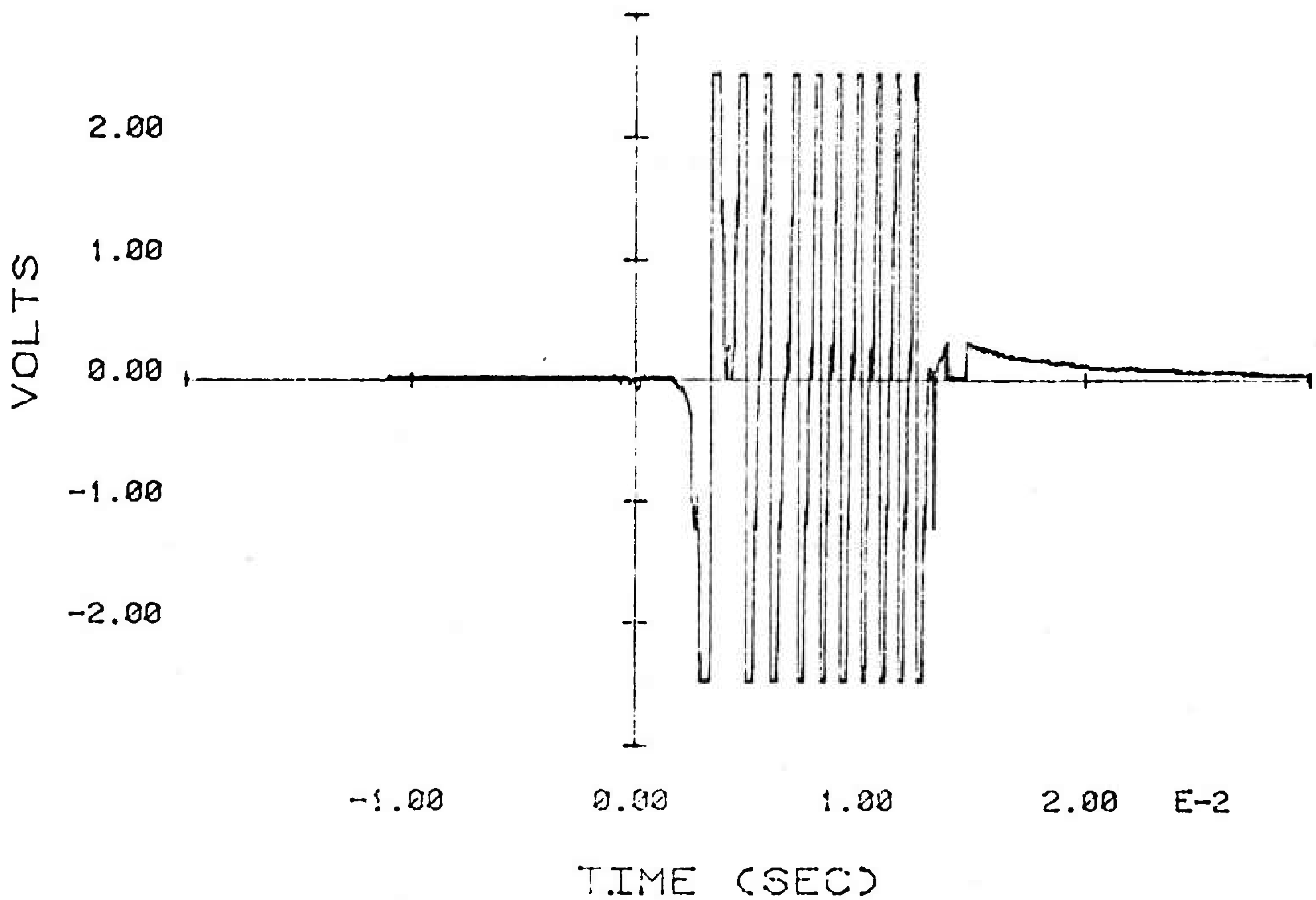

Figure 1. Launcher B dot pickup coils output versus time

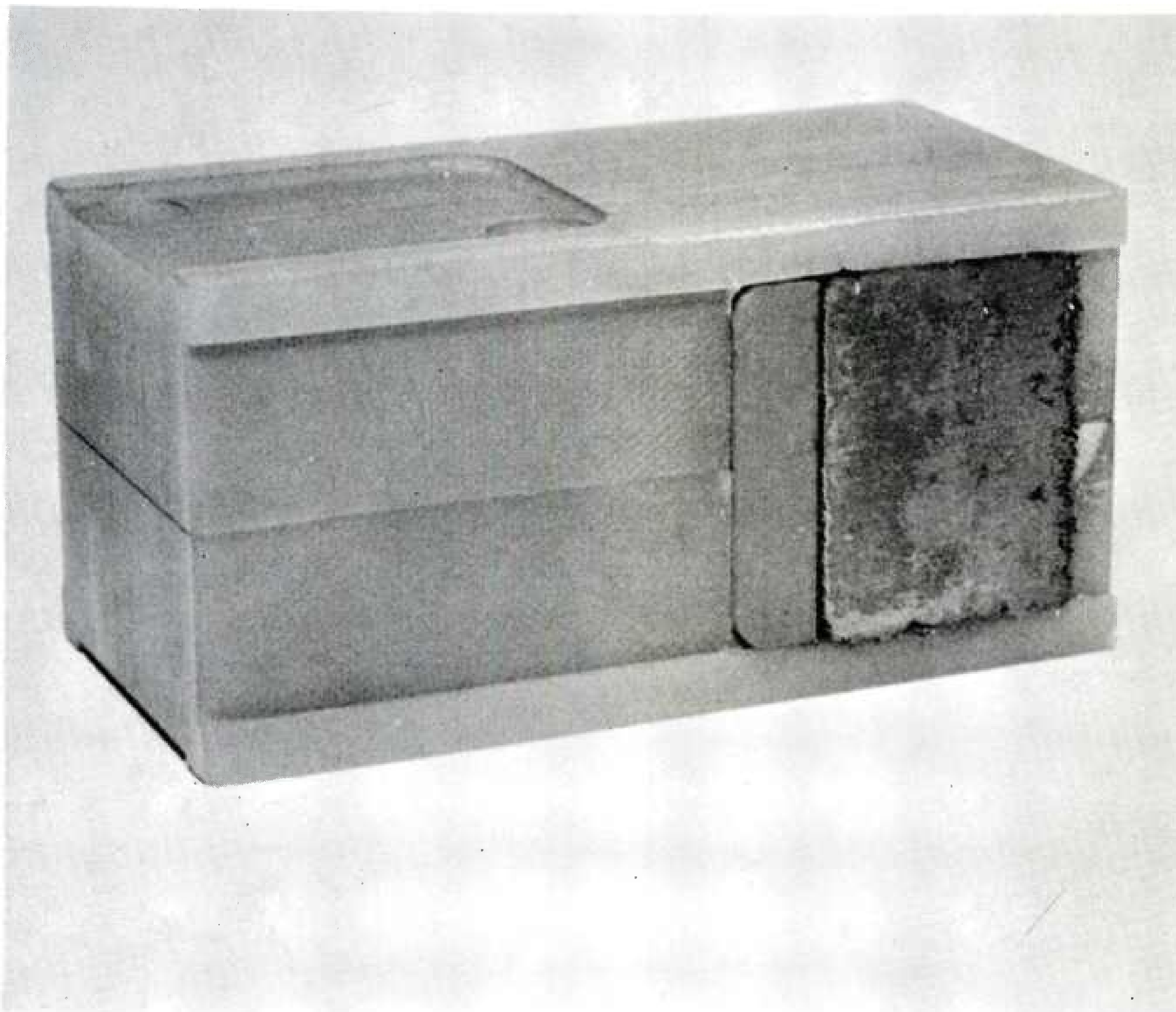

Figure 2. D1.1 before firing

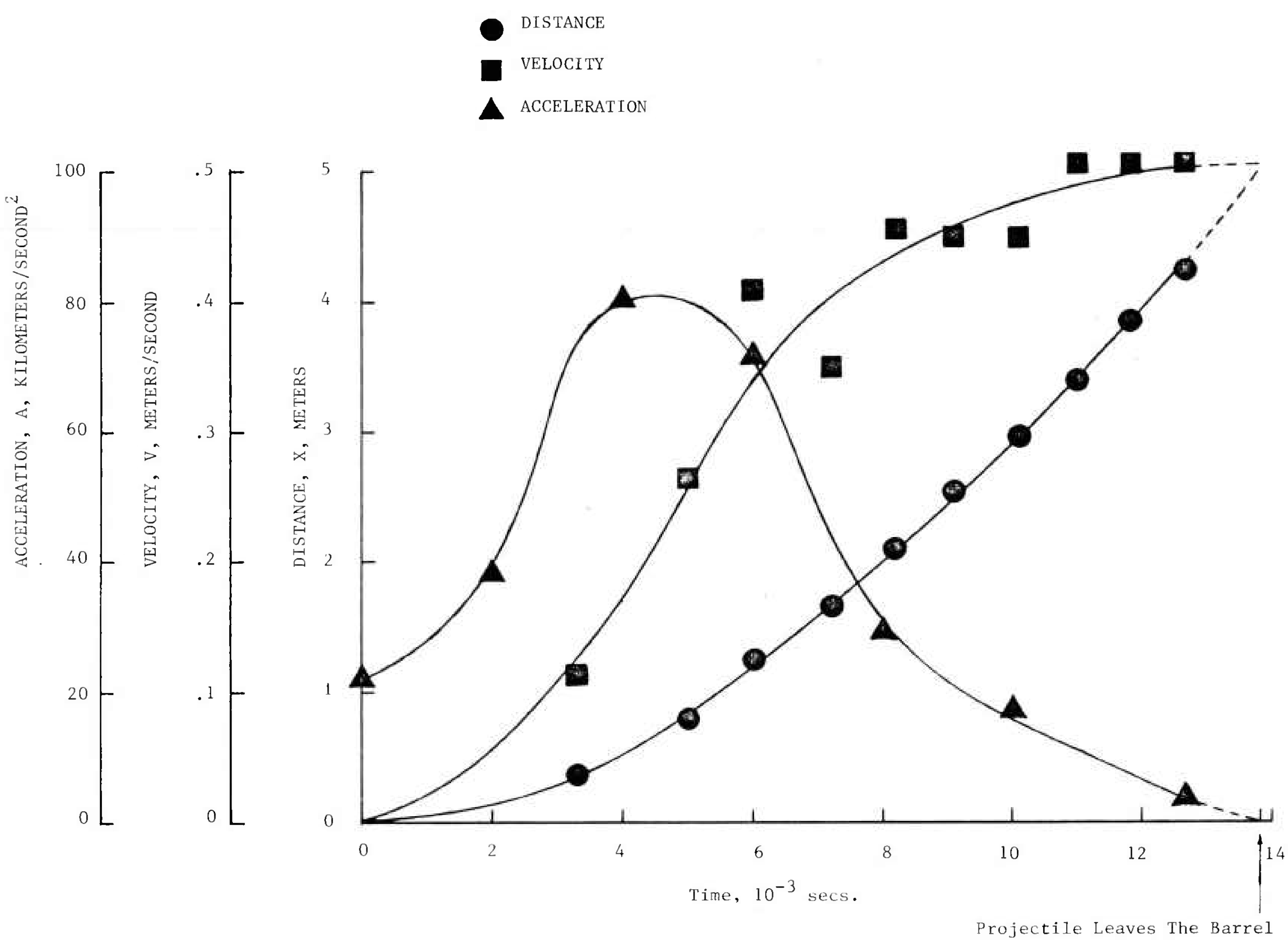

Figure 3. Projectile distance, velocity, and acceleration versus time

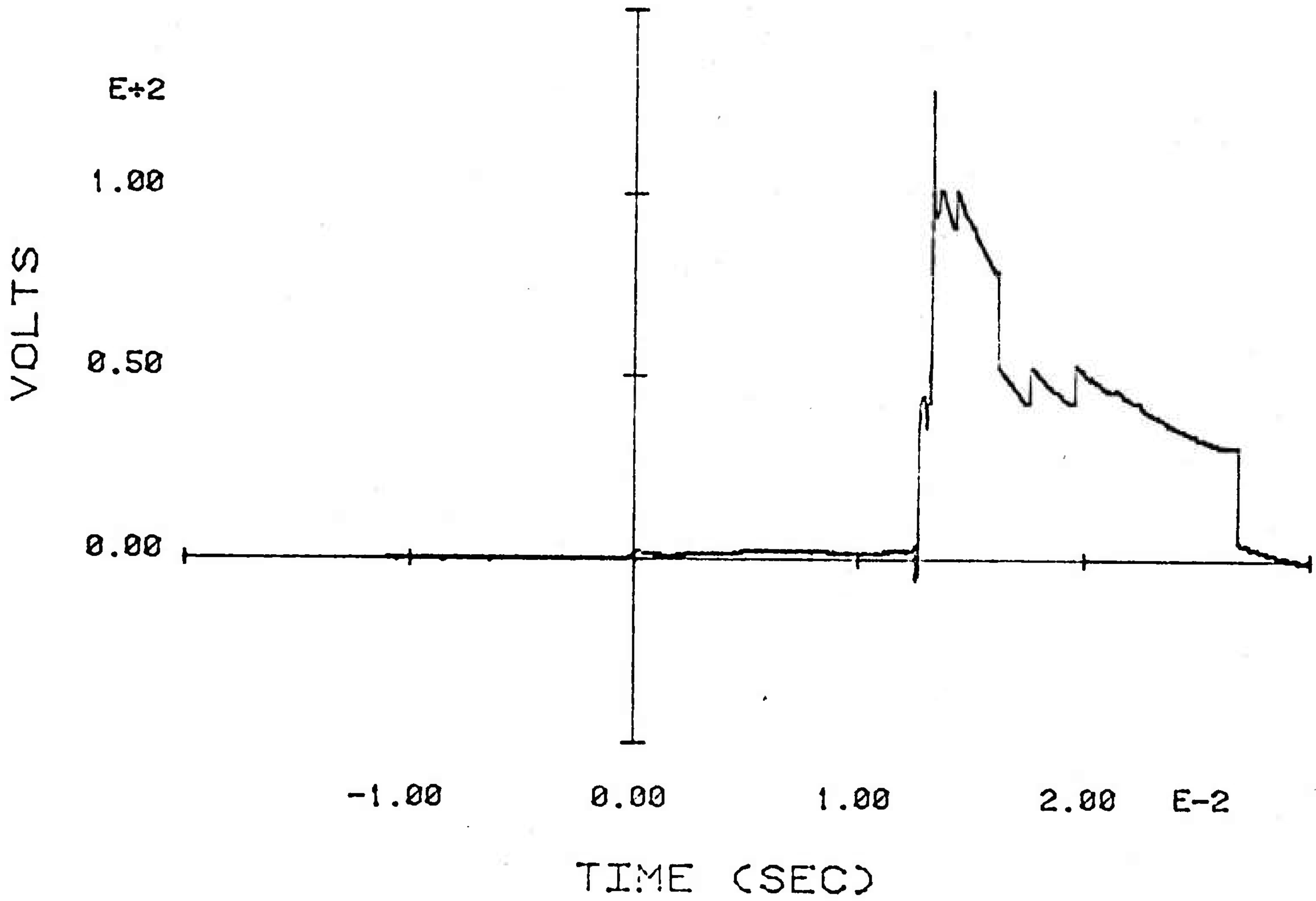

Figure 4. Barrel muzzle voltage versus time

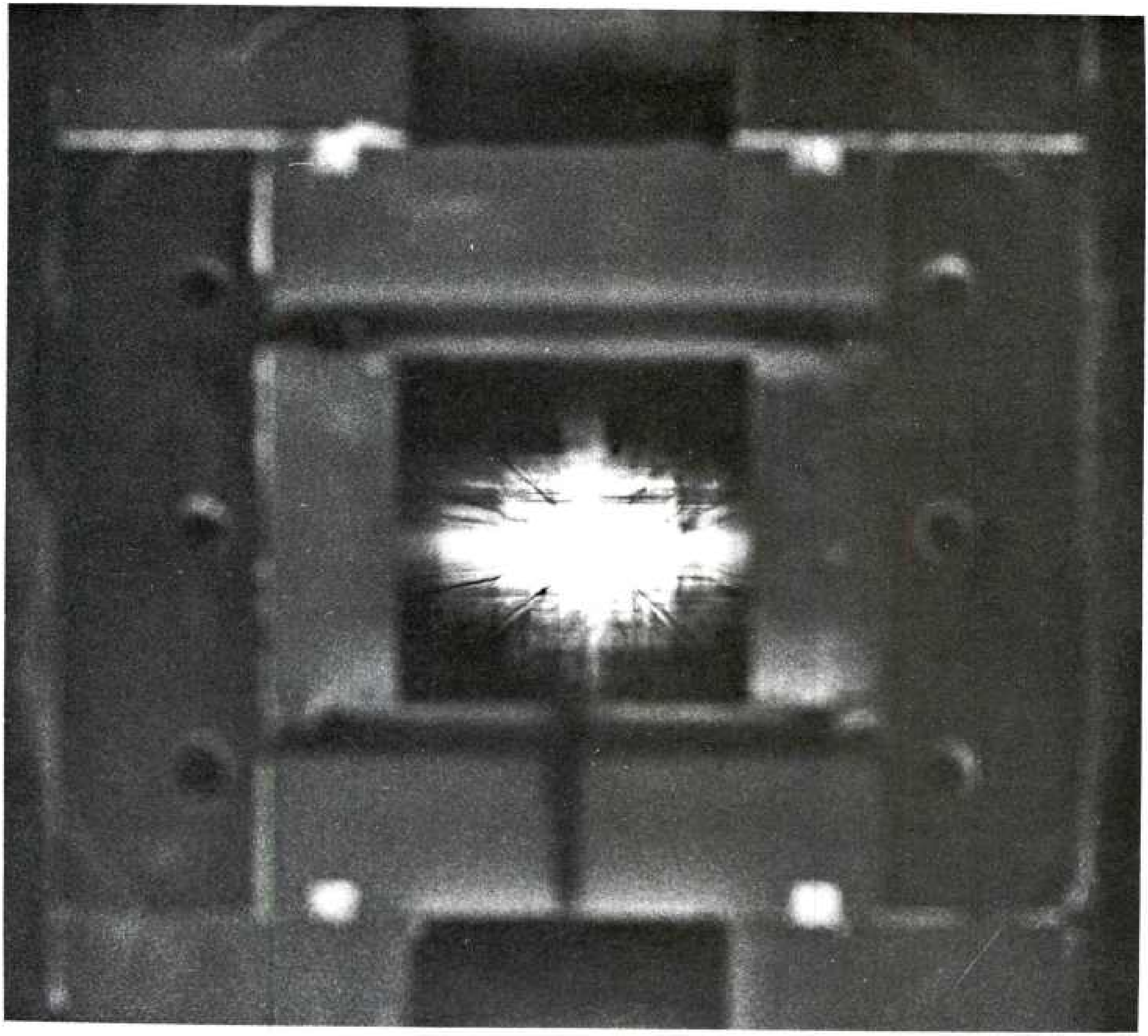

Figure 5. View down barrel from muzzle

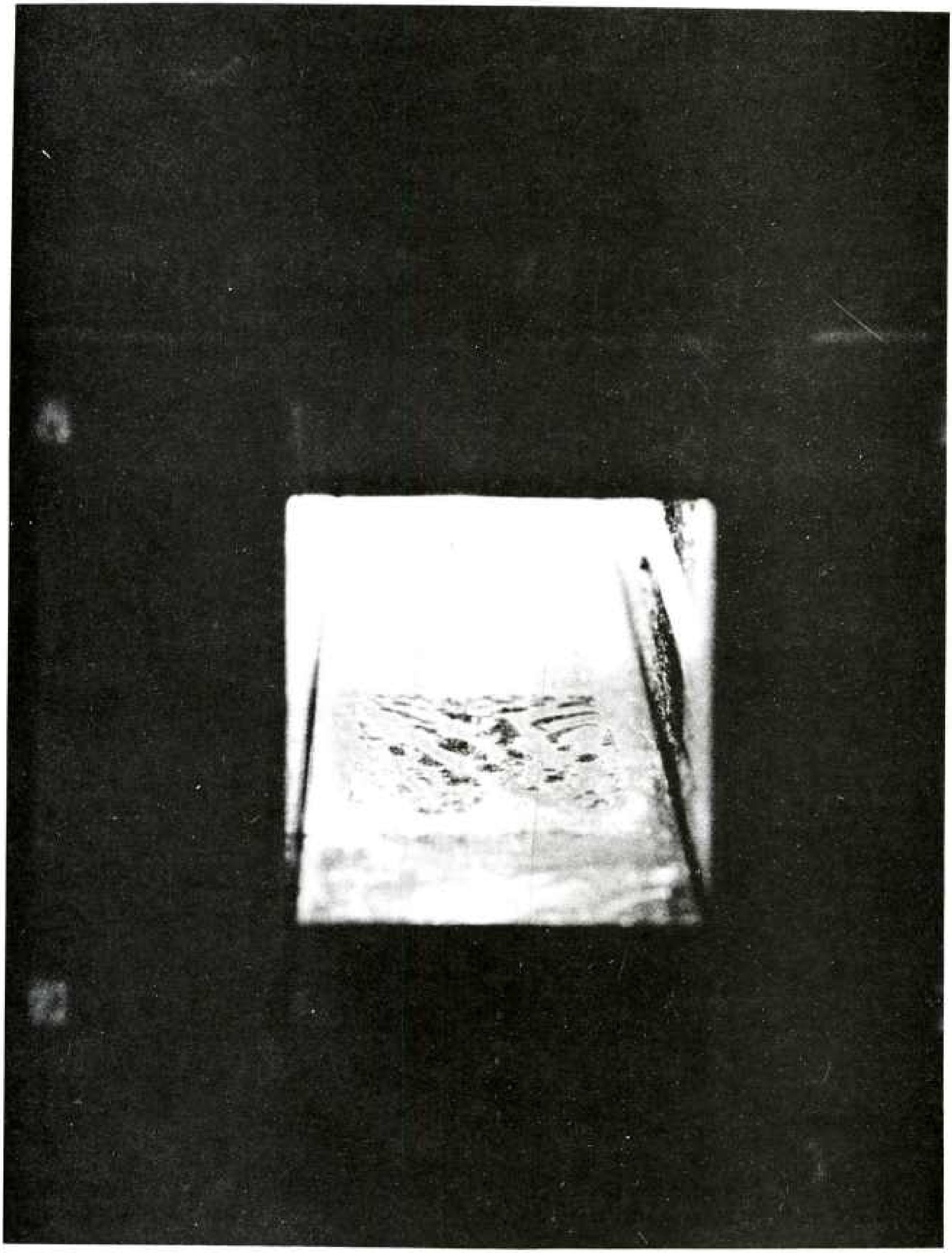

Figure 6. Arc damage at muzzle

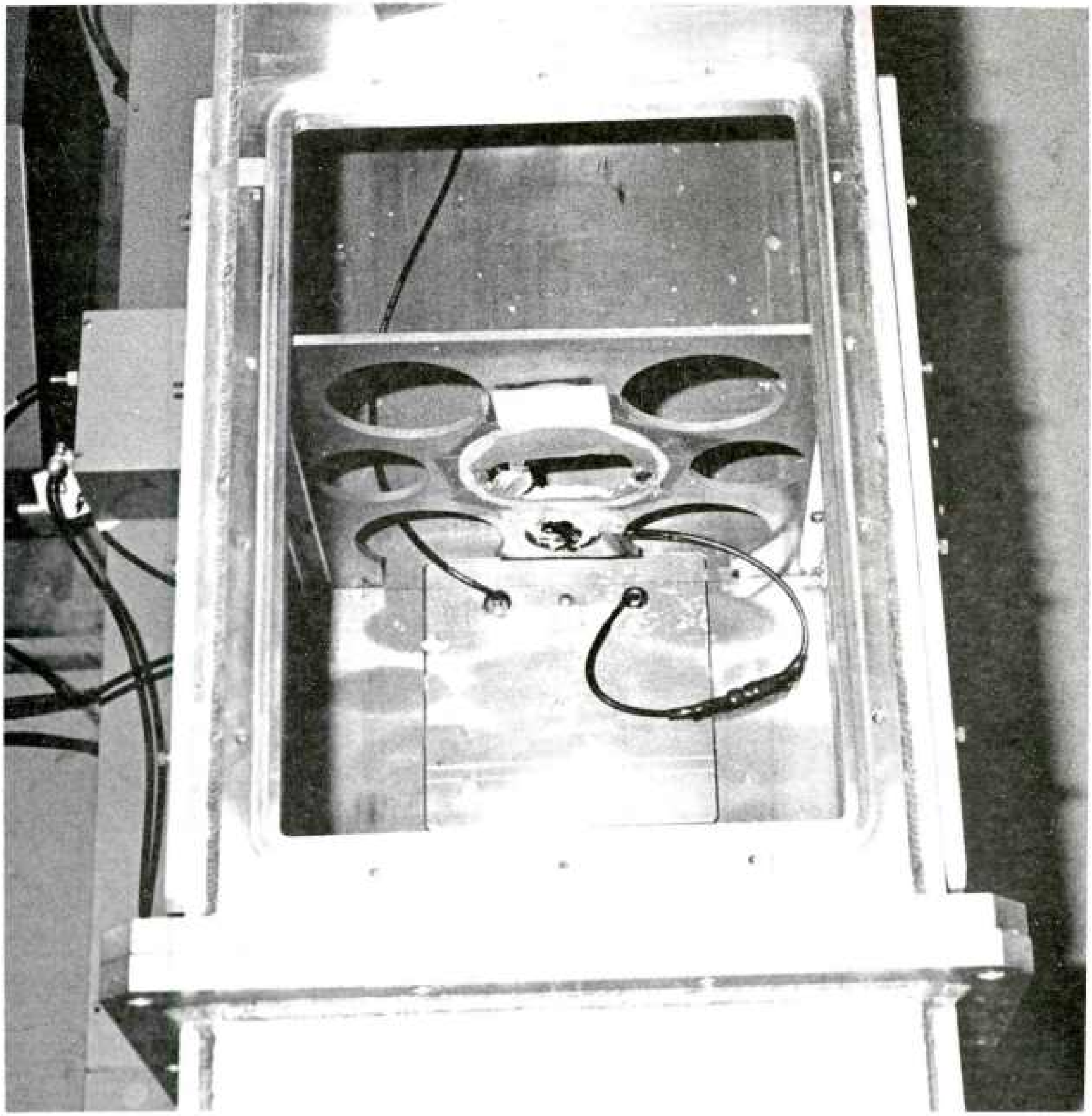

Figure 7. Range section and make switch (post shot)

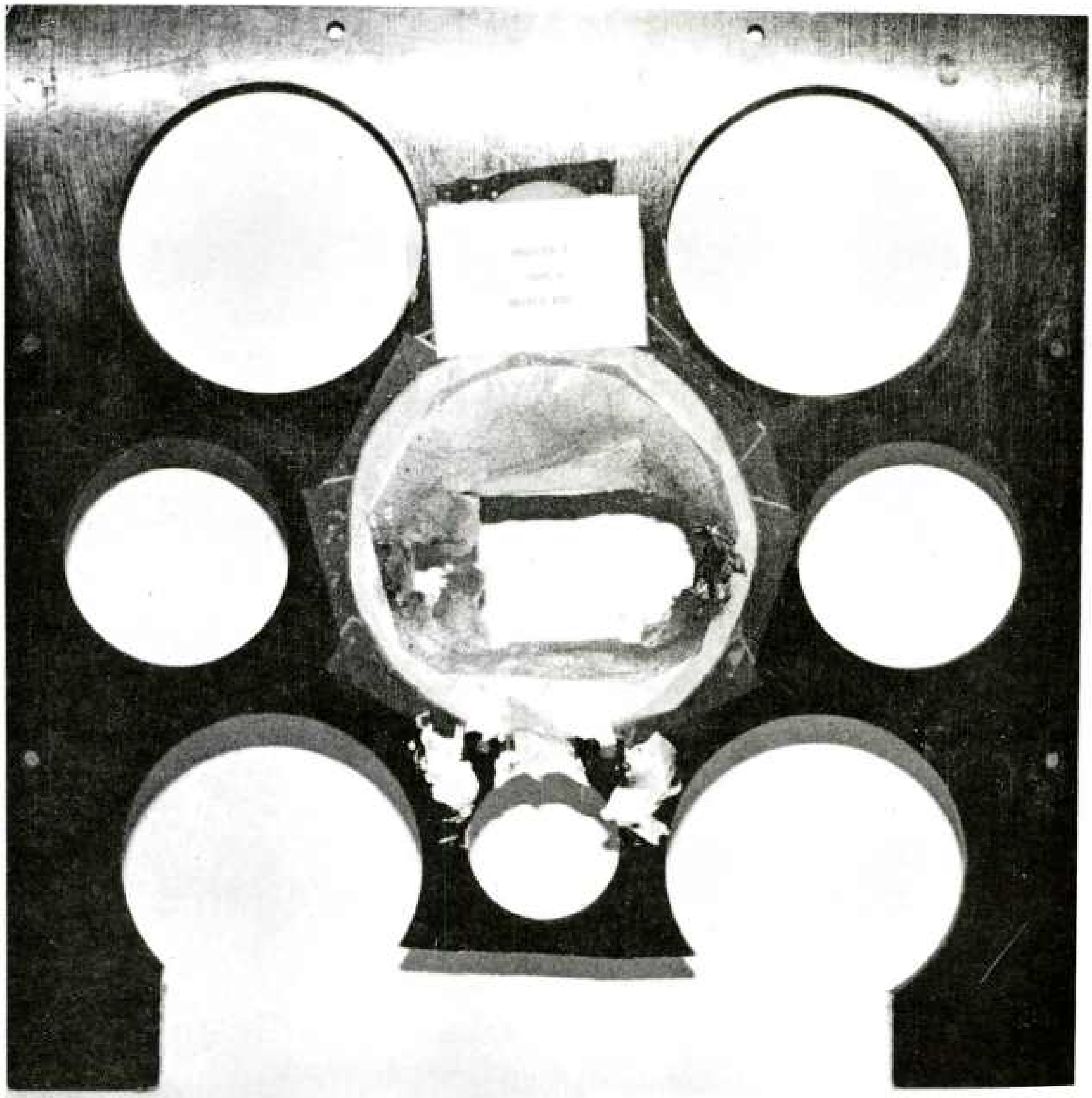

Figure 8. Make switch used for triggering flash x-ray (brown coloration on face of switch is copper deposited by passing projectile)

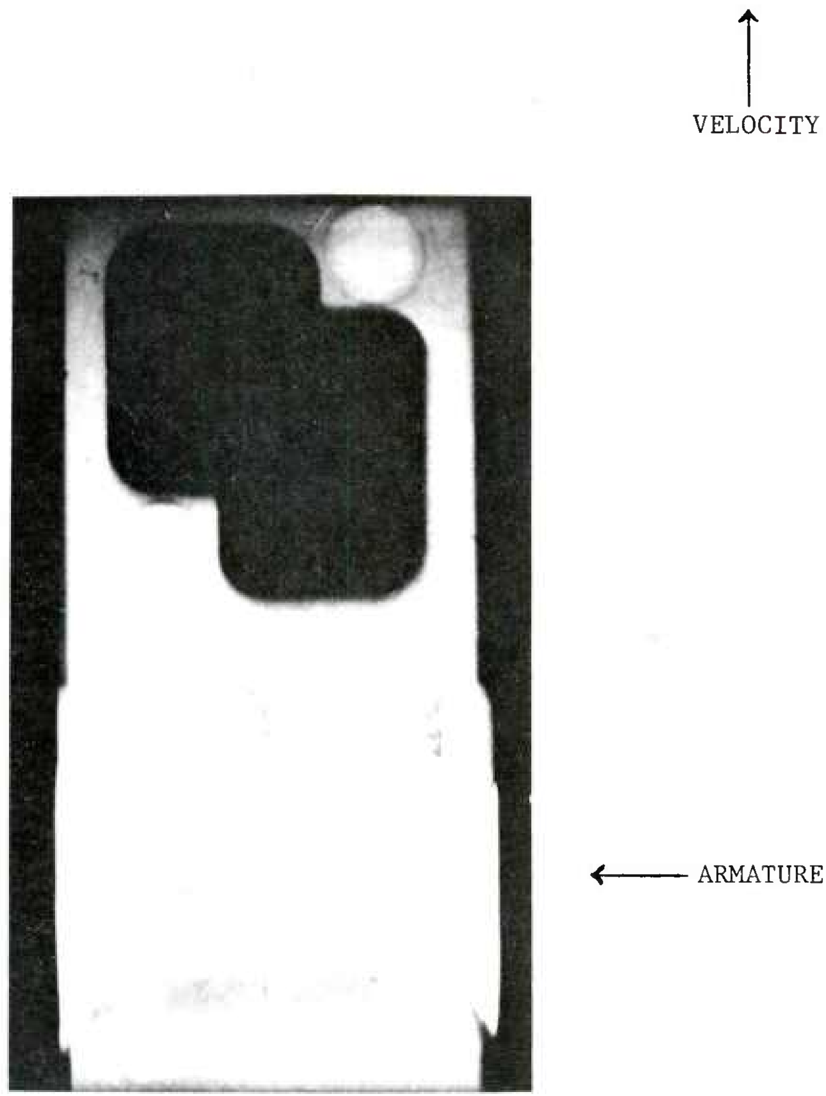

Figure 9. Flash x-ray photograph of projectile in flight

Figure 10. High-speed photograph of muzzle flash

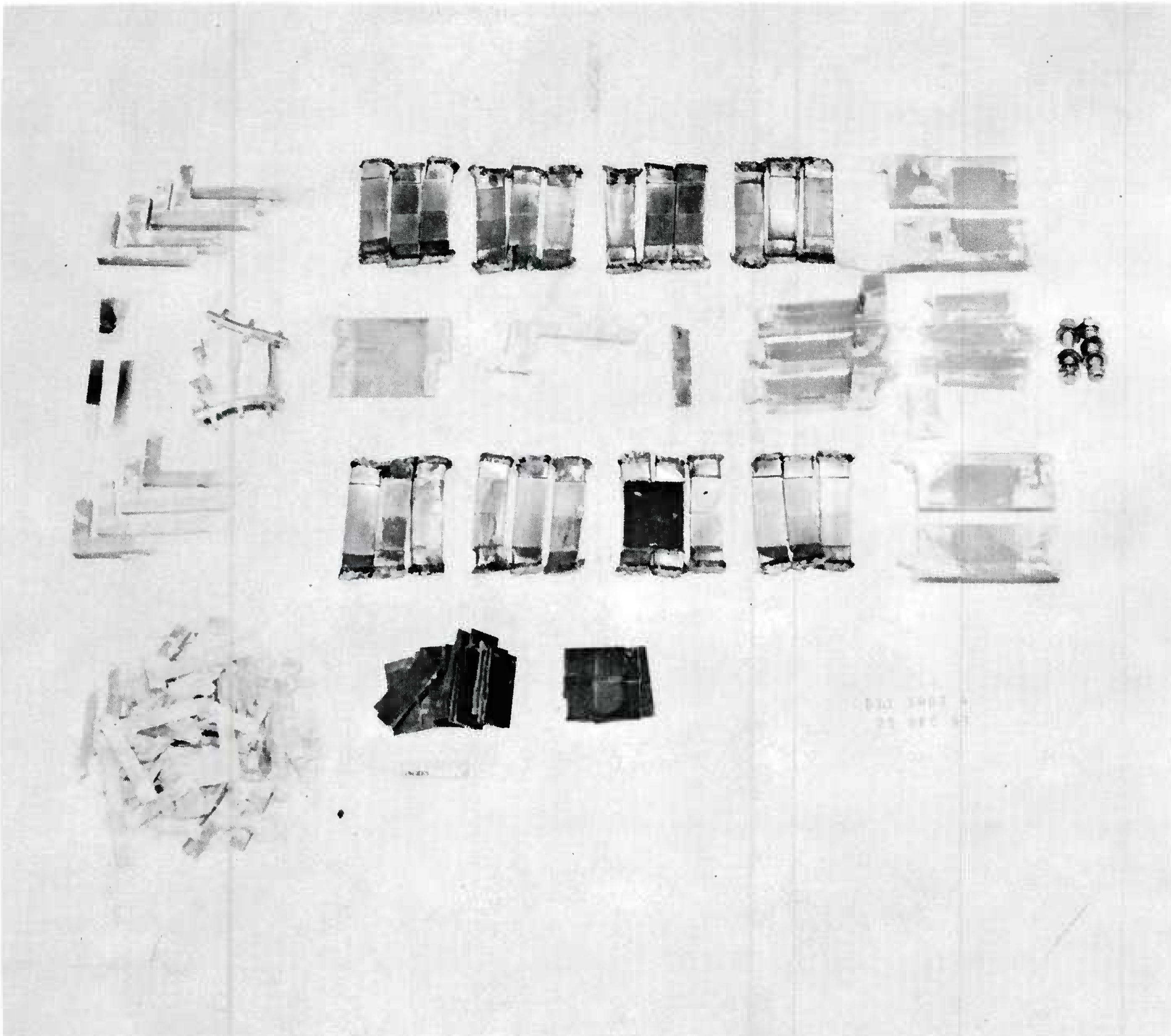

Figure 11. Pieces of D1.1 recovered from catch tank

Figure 12. Post shot reconstruction of projectile armature

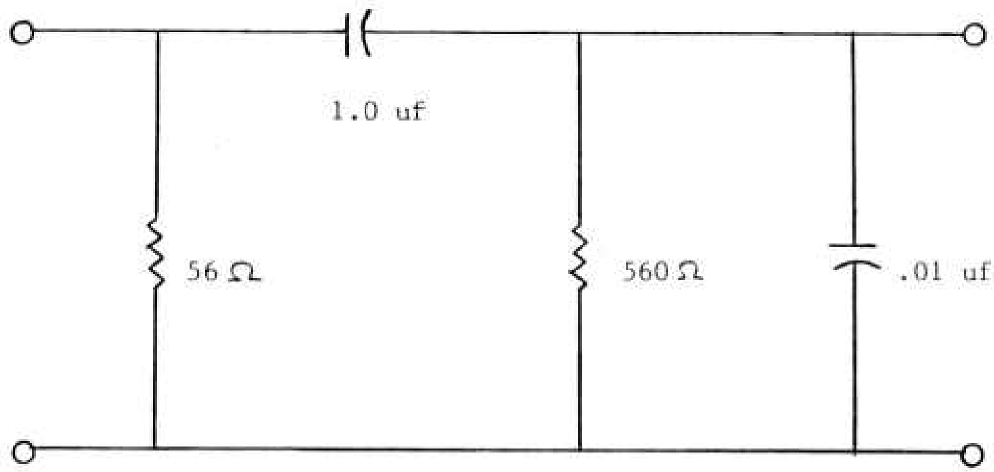

Figure 13. Transient recorder trigger circuit

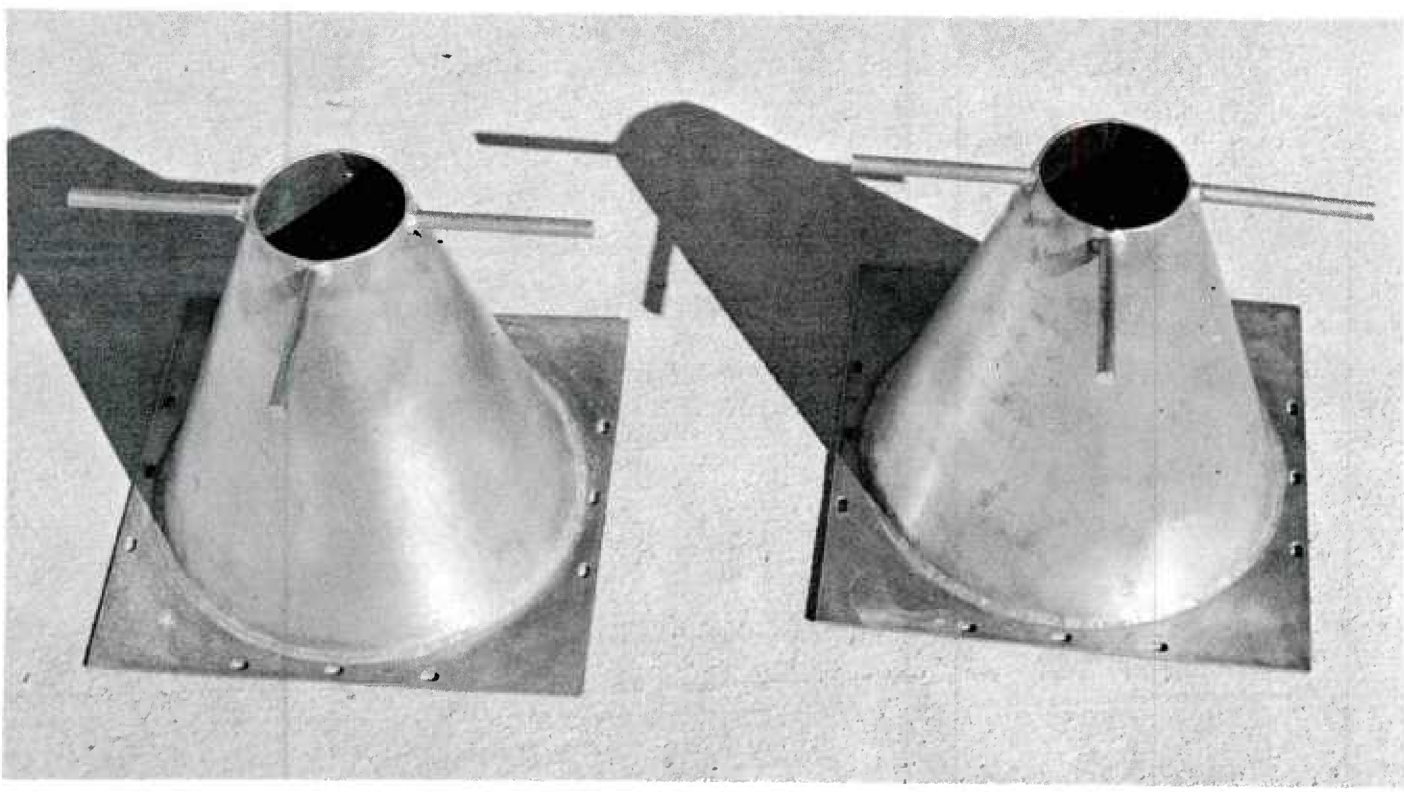

Figure 14. Range arc strippers (post shot)

APPENDIX A

SYSTEM COMPONENT PRE-SHOT INSPECTION

List of Measured Parameters

Rotor speed
Homopolar generator field current
Homopolar generator voltage
Switch breech voltage
Barrel breech voltage
Barrel muzzle voltage
Storage inductor I dot
Barrel I dot
Projectile position in barrel
Light intensity of projectile arc
Vacuum system pressure
Homopolar generator lubrication system and gas system pressures
Homopolar generator drive system, excitation ring coolant system and lubrication system temperatures
Homopolar rotor vibration

Transient Recorder Setup

Biomation A:

CHA1 - Inductor I dot
Sensitivity: 10-V full scale
CHA2 - Homopolar generator voltage
Sensitivity: 2-V full scale

Biomation B:

CHA1 - Barrel I dot
Sensitivity: 20-V full scale
CHA2 - Switch breech voltage
CHA3 - Barrel breech voltage
CHA3 - Barrel muzzle voltage
CHA4 - Barrel muzzle voltage
CHA5 - Position coil
CHA6 - Position coil

Vacuum System Pressures

Barrel and range (in. Hg)	27.5
Catch tank (in. Hg)	29.0

Homopolar Generator Gas System Pressures

	Before	After
Seal gas (psi)	4.0	--
Cover gas (psi)	1.0	--
Flow to brushes (cfm)	10	--
Bubbler gas (psi)	8	--
Accumulator (psi)	105	35
Bottle (psi)	2,000	--

Homopolar Generator Lubrication System Pressures

Oil inlet (psi)	15
Pump (psi)	29

Homopolar Generator Drive System Temperatures

	Fore	Aft
Journal bearings (°C)	41	41
Thrust bearings (°C)	44	34

Homopolar Generator Excitation Ring Coolant Temperatures

	Fore	Aft
Water (°C)	20	22

Homopolar Generator Lubrication System Temperatures

Inlet (°C)	30
Ambient (°C)	27

Homopolar Generator Rotor Vibration

Fore (in.)	0.16E-3
Aft (in.)	0.04E-3

Switch Armature Mechanical Inspection

Length (in.)	20.125
Mass (lb)	32.5
Contact bending angle (deg.)	37.5
Insertion force (lb)	1,250
Contact thickness (in.)	
Top front	2.018
Top center	2.02
Top rear	2.023
Bottom front	2.016
Bottom center	2.019
Bottom rear	2.022

The positive contact side of the armature showed little or no wear from the previous shot. The negative contact side showed some arc damage on the forward half of the armature. The rearward half was clean.

Delrin sheets were used on the arc chamber as an ablative material.

Switch Armature Electrical Inspection

500 volts were applied across the contact surface and the tailpiece. No current leakage was observed.

Switch Mechanical Inspection

Ablative material in switch - GP03
Age of ablative material - 4 shots
Age of switch rails - 4 shots
Condition of switch rails - minor pitting was observed, otherwise the rails were in good condition.

Projectile

Type	D1.1
Mass of projectile	566 g
Mass of armature	
Copper fiber	259 g
Stainless steel	47 g
Initial position (measured from breech to rear of projectile)	6.375 in.

Barrel Mechanical Inspection

Terminal contact condition	
Positive upper	Good, no change from previous shot
Positive lower	
Negative upper	
Negative lower	

Contact condition of jumpers	
Positive (steel) upper:	Good, no change from previous shot.
Barrel contact	
Switch contact	
Positive (steel) lower:	
Barrel contact	
Switch contact	
Negative (copper) upper:	
Barrel contact	
Switch contact	
Negative (copper) lower:	
Barrel contact	
Switch contact	

Rail condition - new
Clamp bolt condition - good, none damaged

Barrel Electrical Inspection

	Negative bus	Positive
Applied voltage (V)	500	500
Leaking current (A)	140E-6	155E-6
Resistance to ground (ohms)	3.58E6	3.23E6

Switch Honeycomb Volume

	No. of pieces	Dimensions of each piece (in.)
End of catcher	7	5 X 10 X 3
Middle of catcher	2	4.25 X 8 X 3
Next to switch muzzle	3	6 X 9.75 X 3

Switch Electrical Inspection

	Negative rail	Positive rail
Applied voltage (V)	100	100
Current leakage (A)	0.2E-6	0.2E-6
Resistance to ground (ohms)	500E6	500E6

Switch Delay Tests

Test	Switch delay time (ms)
1	51.2
2	29.8
3	34.8
4	59.4
5	58.9
6	59.2
7	58.5
8	61.0
9	59.1
10	61.7
11	85.8*
12	83.1*
13	83.4*
14	85.1*

Charge pressure: 300 psi
Wet bulb temperature: 62 °F
Dry bulb temperature: 68 °F

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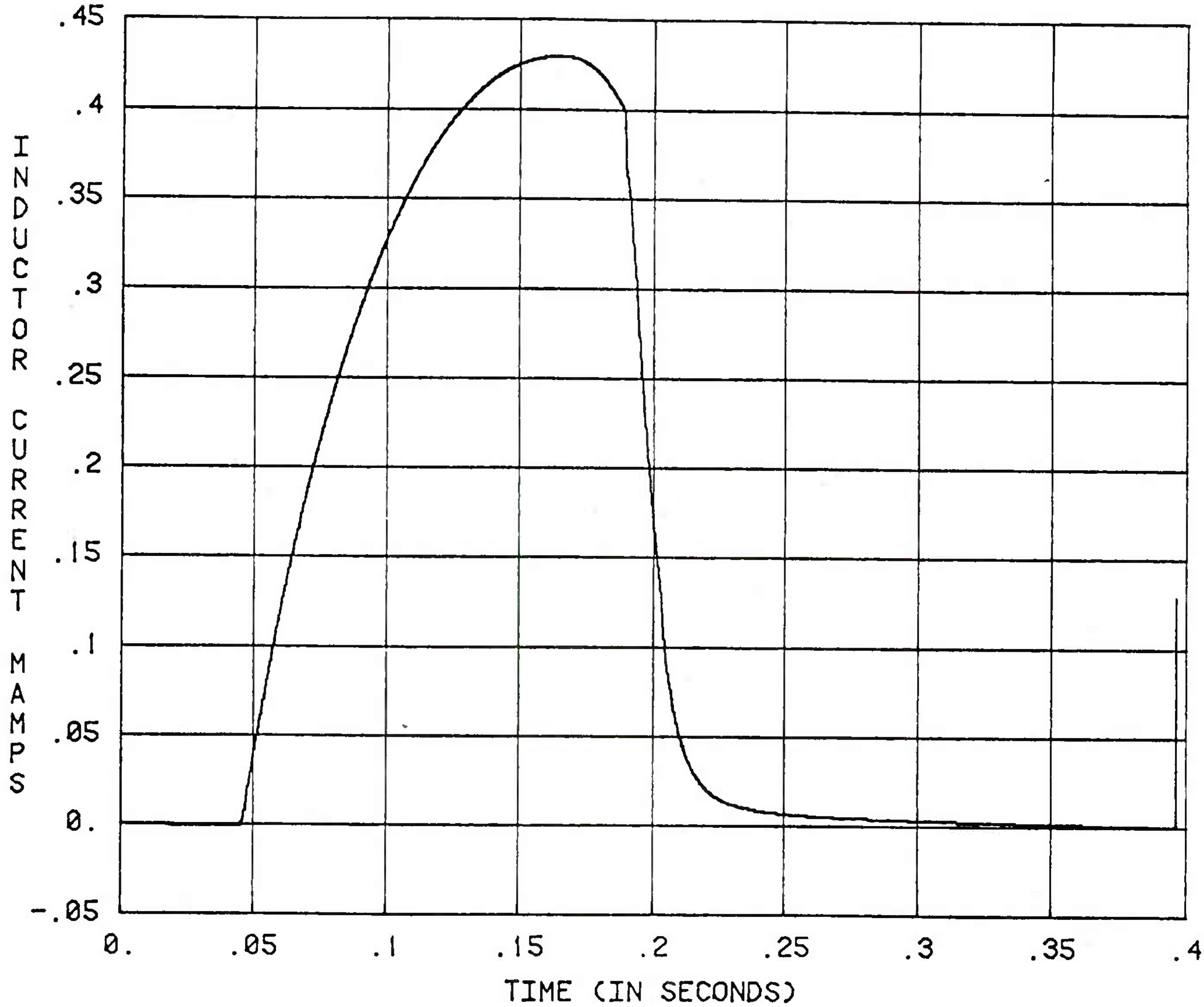
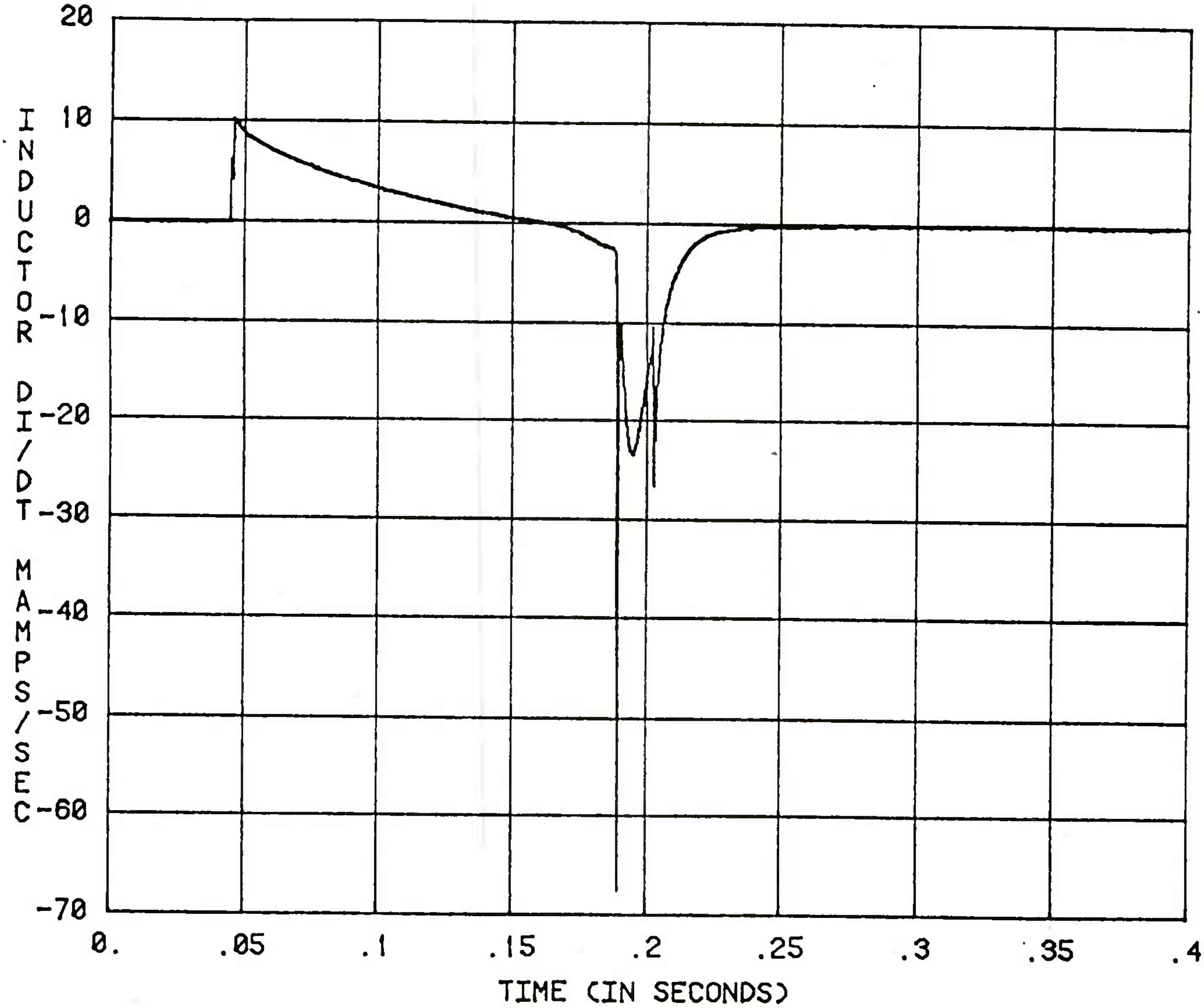
* Tests immediately prior to shot used to determine switch control system trigger time.

APPENDIX B

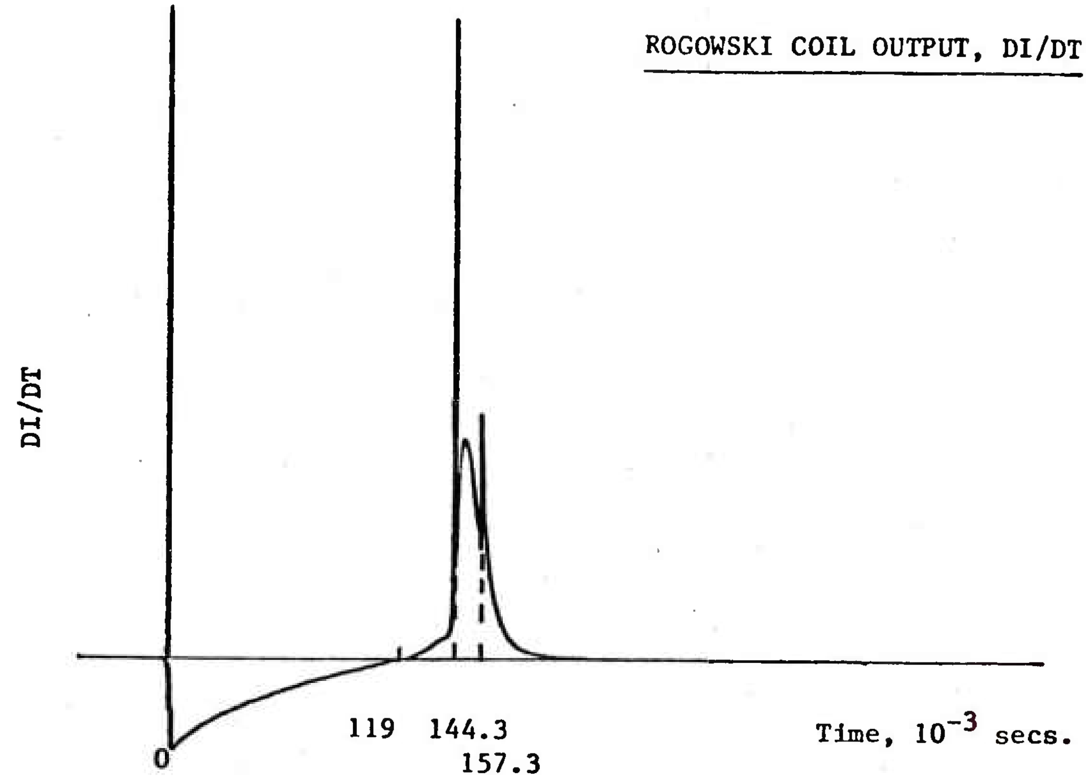
PLOTS OF RECORDED DATA



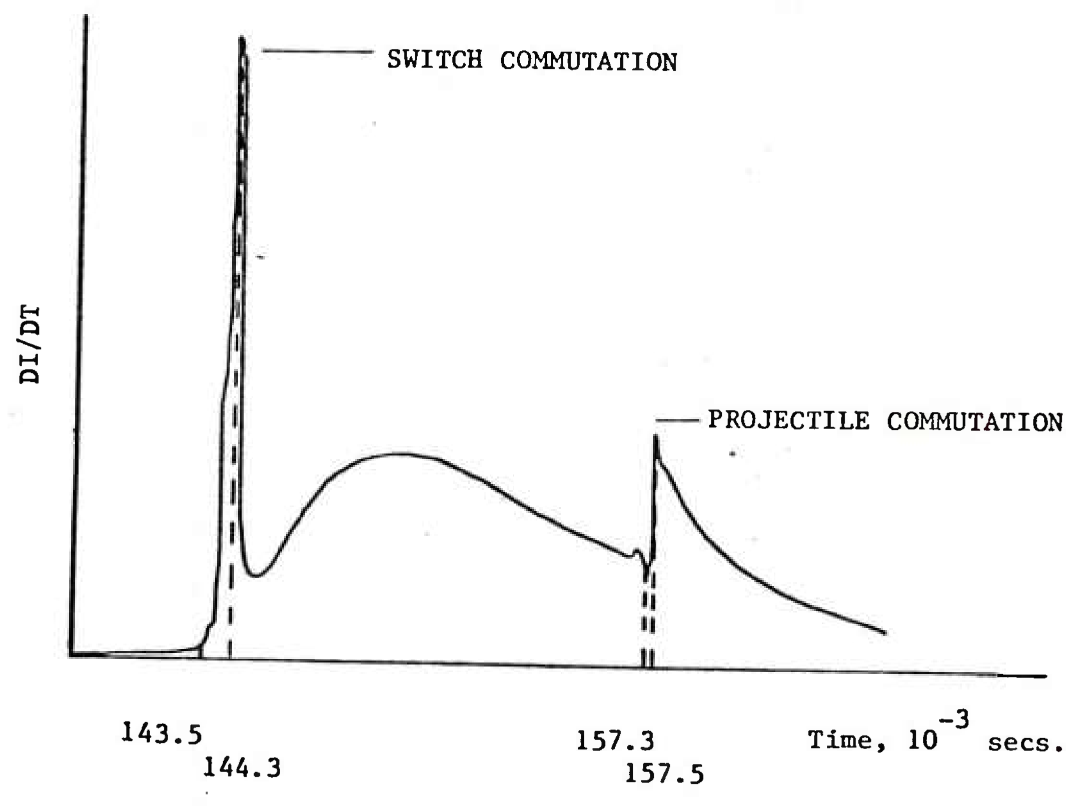
INDUCTOR CURRENT MAMPS
.45
.4
.35
.3
.25
.2
.15
.1
.05
0.
-.05
0.
.05
.1
.15
.2
.25
.3
.35
.4
TIME (IN SECONDS)

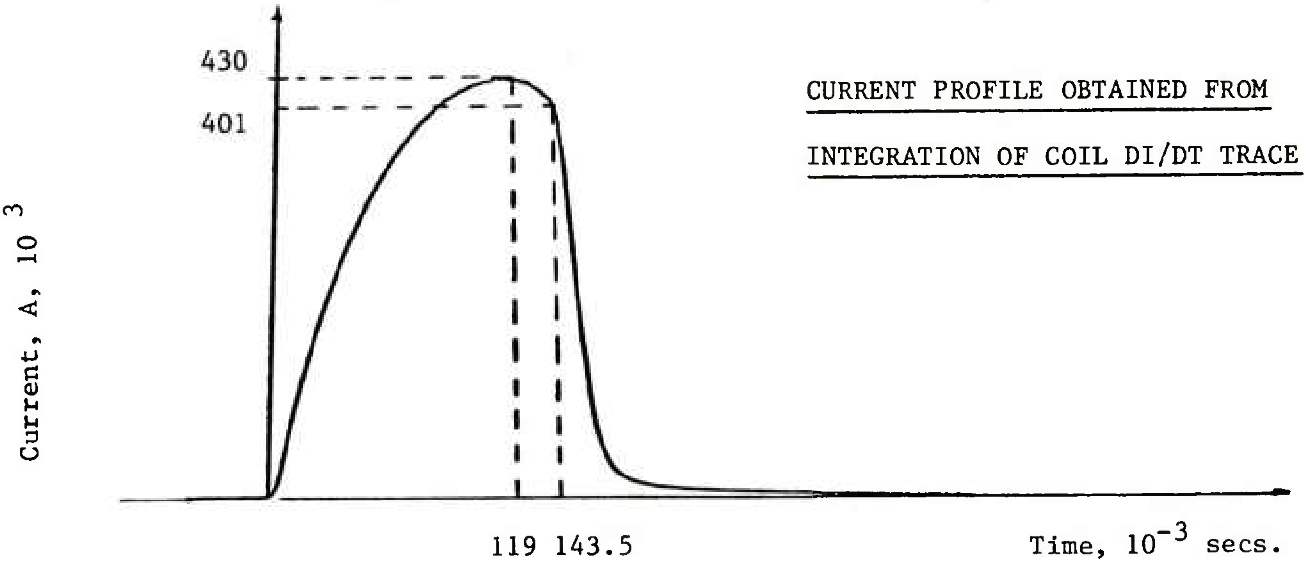


INDUCTOR DI/DT MAMPS/SEC
20
10
0
-10
-20
-30
-40
-50
-60
-70
0.
.05
.1
.15
.2
.25
.3
.35
.4
TIME (IN SECONDS)

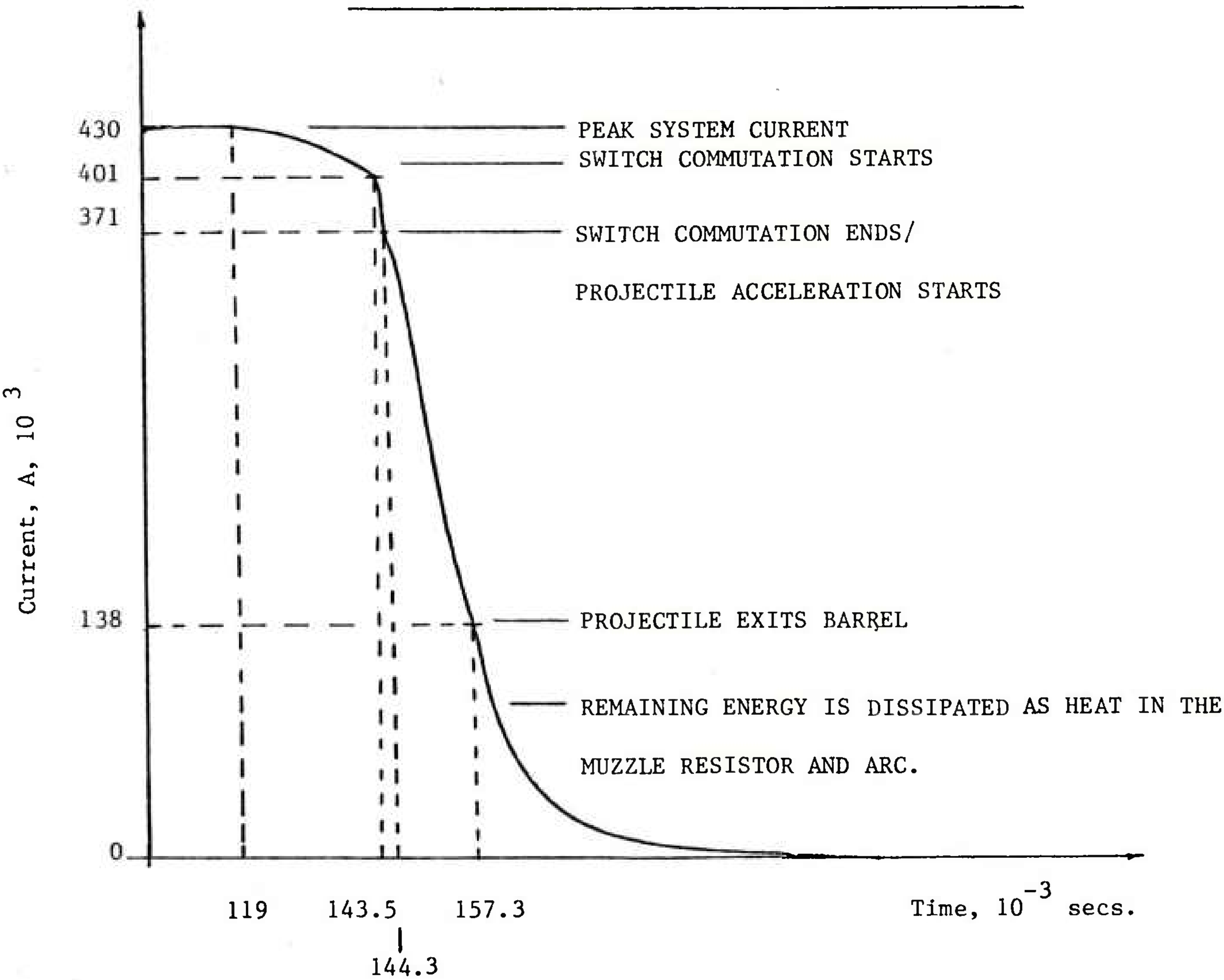


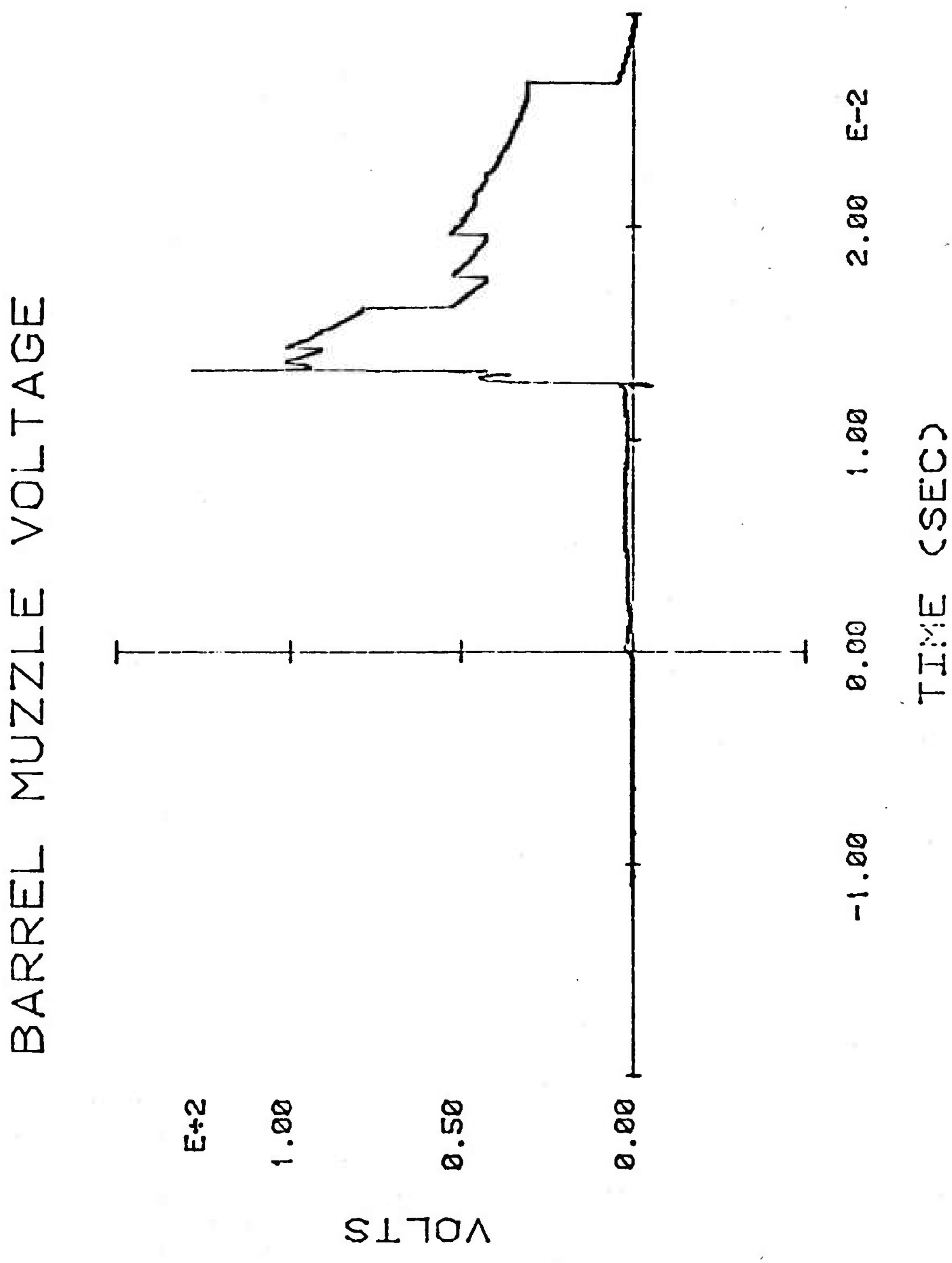
EXPANSION OF DI/DT TRACE DURING PROJECTILE ACCELERATION



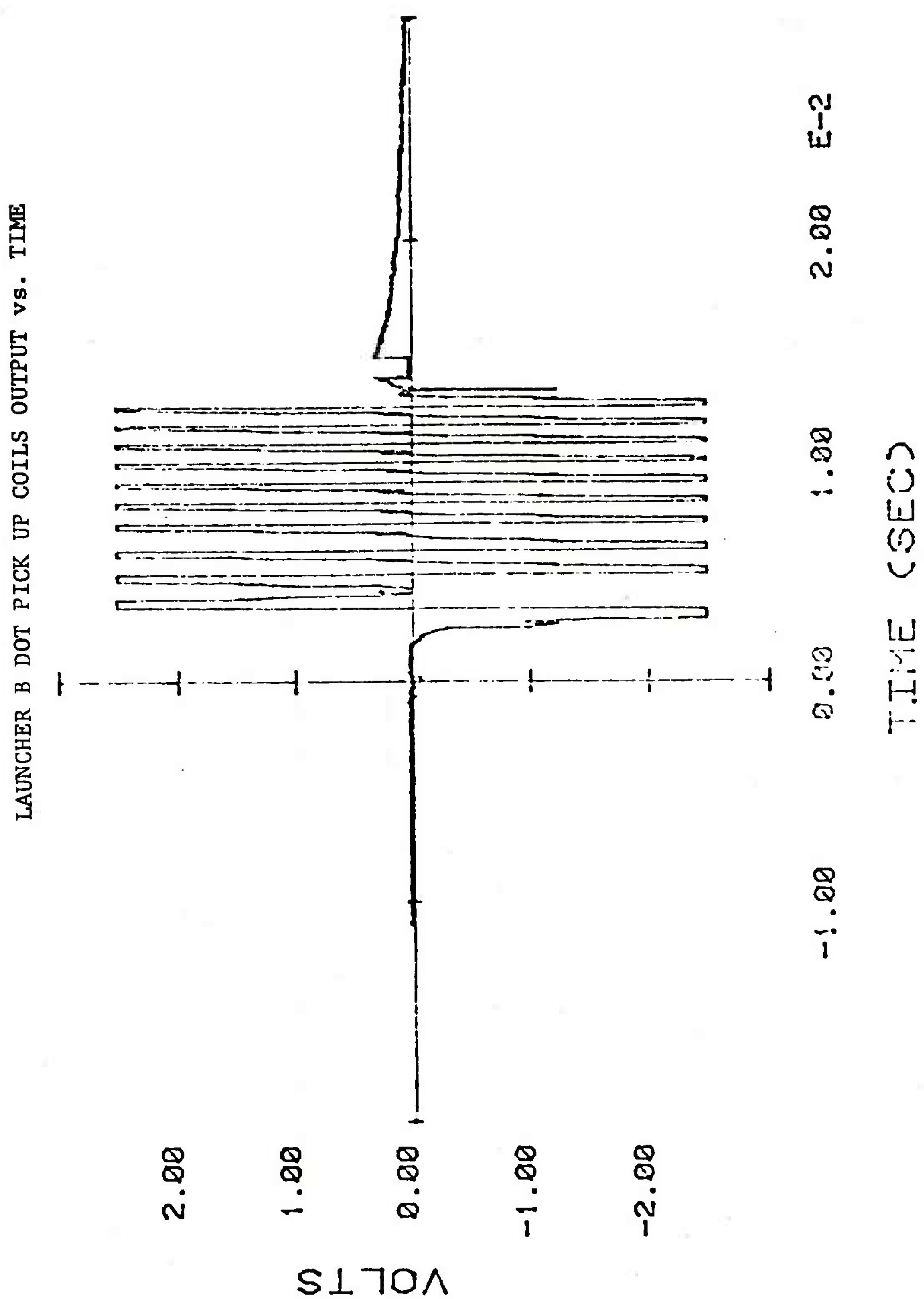


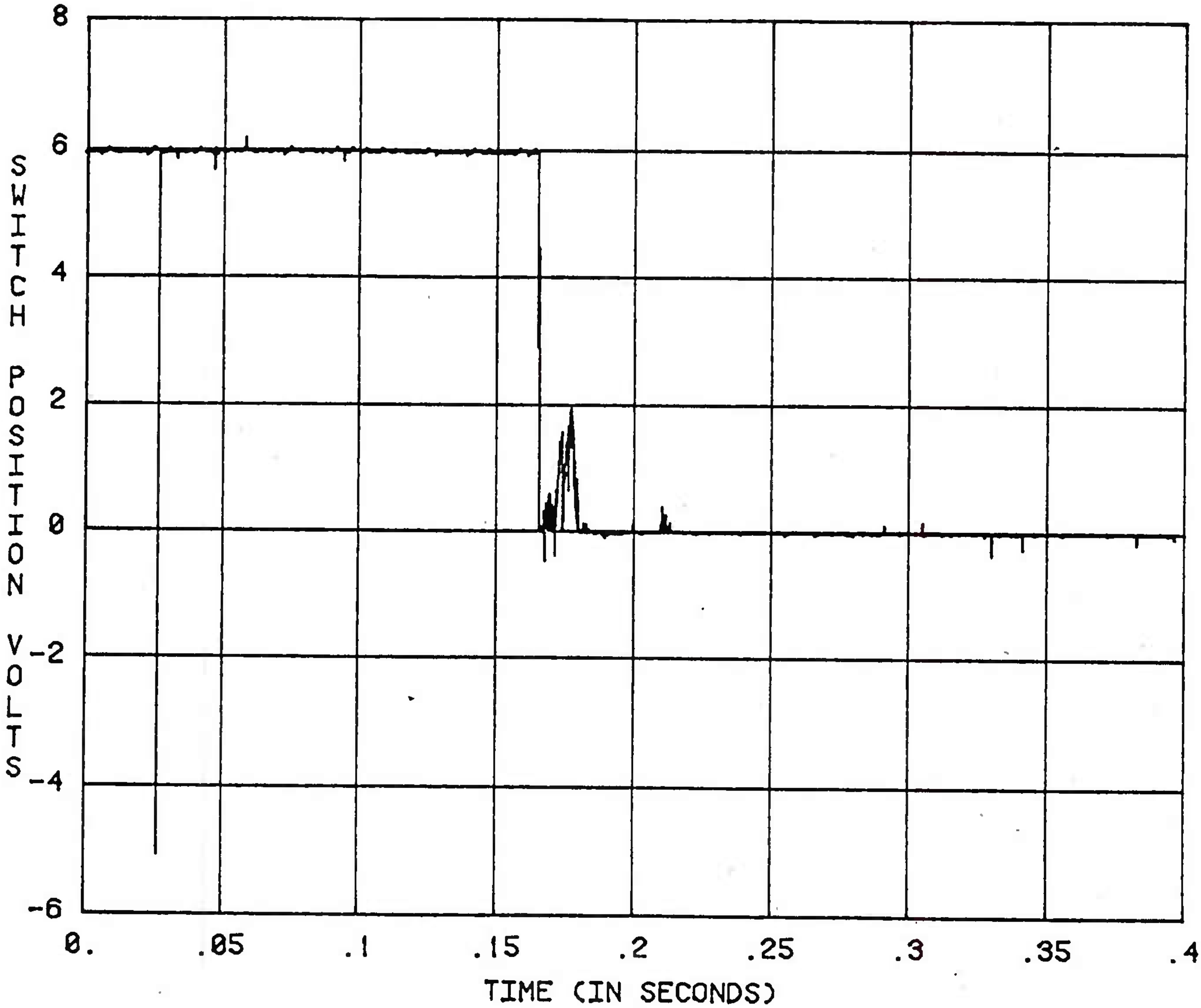
EXPANSION OF CURRENT WAVEFORM NEAR CURRENT PEAK



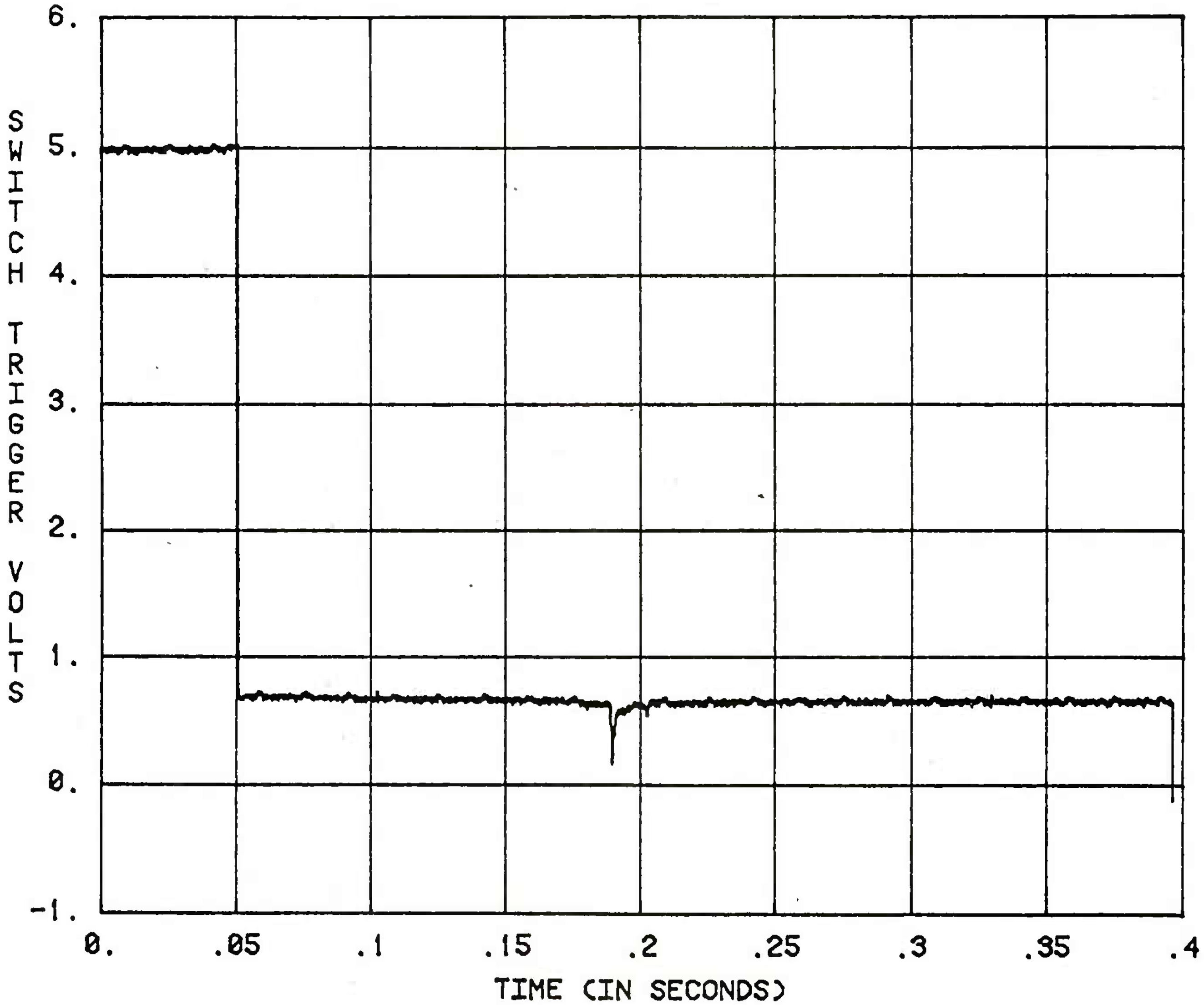


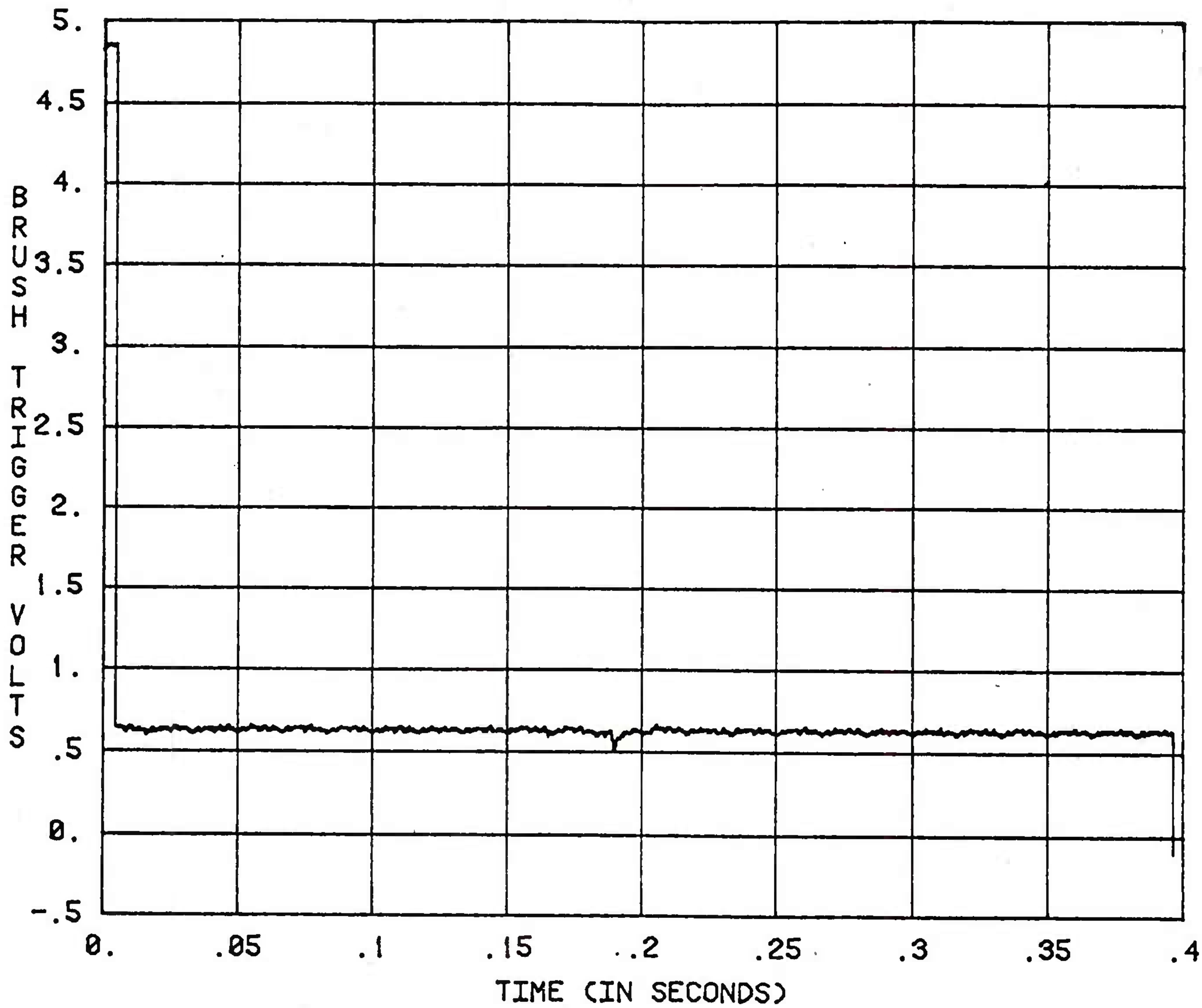
BARREL MUZZLE VOLTAGE
VOLTS
E+2
1.00
0.50
0.00
-1.00
0.00
1.00
2.00
E-2
TIME (SEC)


LAUNCHER B DOT PICK UP COILS OUTPUT vs. TIME
VOLTS
2.00
1.00
0.00
-1.00
-2.00
TIME (SEC)
-1.00
0.00
1.00
2.00
E-2



8
6
4
2
0
-2
-4
-6
SWITCH POSITION VOLTS
0.
.05
.1
.15
.2
.25
.3
.35
.4
TIME (IN SECONDS)


6.
5.
4.
3.
2.
1.
0.
-1.
SWITCH TRIGGER VOLTS
0.
.05
.1
.15
.2
.25
.3
.35
.4
TIME (IN SECONDS)



BRUSH TRIGGER VOLTS
5.
4.5
4.
3.5
3.
2.5
2.
1.5
1.
.5
0.
-.5
0.
.05
.1
.15
.2
.25
.3
.35
.4
TIME (IN SECONDS)

APPENDIX C

CALCULATION OF ARMATURE INSERTION FORCE

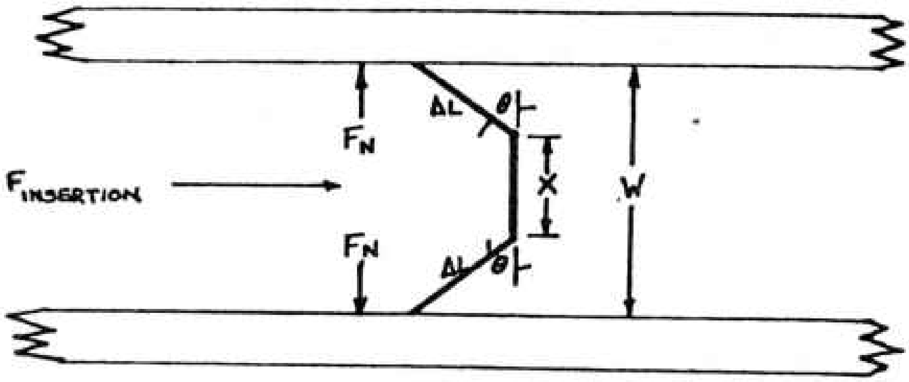


Figure C-1. Armature fiber between accelerator rails

Assuming that the magnetic field is uniform along the surface of the armature cross member, and since the magnitude of the acceleration force on the armature is known to be

$$F = \frac{L'I^2}{2} = WIB$$

an expression relating the magnetic flux density to the inductance gradient and current through the armature can be found

$$B = \frac{L'I}{2W}$$

The force normal to the rails caused by the Lorentz force on a current-carrying fiber is

$$F_N = (\Delta L \sin\Theta)\,\frac{L'I^2}{2W}$$

If the minimum contact force between armature and rail surface is 1-gram per ampere or 10^{-2} newtons per ampere, then a minimum value for $\Delta L \sin\Theta$ can be obtained

$$(\Delta L \sin\Theta)_{min} = \frac{(F_{Nmin})\,(2W)}{(L'I)}$$

The normal Lorentz force combined with the mechanical force at loading must be greater or equal to the desired minimum; therefore

$$F_N = K_1 I^2 + F_{preload} > K_2 I$$

where

$$K_1 = \frac{(\Delta L \sin\Theta)\,L'}{2W} \qquad \text{(newtons per ampere}^2\text{)}$$

and

$$K_2 = 10^{-2} \qquad \text{(newtons per ampere)}$$

In order to select a preload force to satisfy this condition, the critical current at which the greatest shortfall occurs must be found for the Lorentz normal force with respect to the required normal force. Therefore

$$\frac{dF_{N,JxB}}{dI} = \frac{dF_{N,reference}}{dI}$$

$$2K_1 I_{crit} = K_2$$

$$I_{crit} = \frac{(10^{-2})\ W}{(\Delta L \sin\Theta)\ L'}$$

and

$$F_{preload} = K_1 I^2_{crit} = \frac{(10^{-4})\ W}{2(\Delta L \sin\Theta)\ L'}$$

The normal force required for a two-sided brush is

$$F_N = \frac{(10^{-4})\ W}{(\Delta L \sin\Theta)\ L'}$$

and the force required to insert the projectile into the barrel is

$$F_{insert} = (F_N)\ (u) \qquad \text{(newtons)}$$

It is significant to note that the armature insertion force is not dependent upon the brush contact area but upon the inductance gradient alone. Having developed the necessary equations, a solution can be found for the relevant parameters for both the switch and projectile armatures (table C-1).

Table C-1. Armature preload calculation parameters

Parameter	Switch armature	Projectile armature
L' (μH/m)	0.2	0.45
W (mm)	50	50
$(\Delta L \sin\Theta)_{min}$ (mm)	2.5	1.11
$(\Delta L \sin\Theta)$ actual (mm)	3.0	2.0
I_{crit} (kA)	833.3	555.5
F_{insert} (lbf)	563	375

Note: I_{max} = 2 MA

μ_s = 0.3

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