ARMY RESEARCH LABORATORY

Ablation Loss Studies for Capillary-Sustained Plasmas

by Anthony W. Williams and Richard A. Beyer

ARL-MR-651 **November 2006**

NOTICES

Disclaimers

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ARL-MR-651 **November 2006**

Ablation Loss Studies for Capillary-Sustained Plasmas

Anthony W. Williams and Richard A. Beyer
Weapons and Materials Research Directorate, ARL

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* November 2006	**2. REPORT TYPE** Final	**3. DATES COVERED (From - To)** October 2004–May 2005
4. TITLE AND SUBTITLE Ablation Loss Studies for Capillary-Sustained Plasmas		**5a. CONTRACT NUMBER**
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Anthony W. Williams and Richard A. Beyer		**5d. PROJECT NUMBER** 611102H4311
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRD-ARL-WM-BD Aberdeen Proving Ground, MD 21005-5066		**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-MR-651
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		**10. SPONSOR/MONITOR'S ACRONYM(S)**
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT

The most common discharge geometry used for efficiently generating plasma from stored electrical energy for gun ignition utilizes a capillary tube to contain, direct, and sustain the discharge. The plasma gas composition is determined by the air in the tube before discharge begins and by materials removed from the capillary tube wall, electrodes, and exploding wire used to start the event. The conductivity of the plasma in the capillary affects the discharge and the conversion of energy. The optimized materials, properties, and geometries for these components have not been identified. A reasonable first step in understanding the capillary tube dynamics would be to model and experimentally quantify parameters of interest. In the present work, a series of parametric experiments has been conducted utilizing polyethylene and Teflon capillary-sustained plasmas in which the mass ablation for the capillary tube is measured. The capillary geometry, exploding wire geometry, and material and energy input to the plasma have been varied to provide insight into their respective effects on the ablation. A systematic study of the efficiency of stored energy deposited into the plasma will be made with capillary wall material, capillary diameter and length, and the effects of exploding wires as variables. Observations and their implication on validation of capillary tube models are discussed.

15. SUBJECT TERMS
plasma, ablation, capillary

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Anthony Williams
a. REPORT UNCLASSIFIED	**b. ABSTRACT** UNCLASSIFIED	**c. THIS PAGE** UNCLASSIFIED	UL	18	**19b. TELEPHONE NUMBER** (*Include area code*) 419-278-6122

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

1. Introduction

The electrothermal-chemical (ETC) ignition system is continually being studied by a variety of research groups, including the U.S. Army Research Laboratory. The Army's interest in the ETC ignition system has been prompted by the demonstrated improved ballistic performance in terms of reduced ignition delays with a higher degree of repeatability and a tailored system which reduces the temperature sensitivity apparent in conventional gun systems.

As a result of the enhanced performance witnessed in ETC systems, a host of studies have been conducted in an effort to understand the properties of ETC plasmas and their interaction with gun propellants. Ultimately, it has been desired that the understanding of plasma properties will contribute to the development of design criteria for improved propellants and gun systems. Initial research efforts focused on large scale applications of plasmas (*1–5*). Additionally, numerous studies have been conducted using small-scale experimental fixtures in an attempt to characterize the important properties of the plasma and its interaction with propellant (*6–8*).

Capillary-sustained plasmas have received a great deal of attention recently in an effort to identify the ideal capillary properties (geometry and material) (*9–10*). The present work is not fundamentally new. However, these experimental studies have been prompted by a specific Army Research Office funded effort to model capillary-sustained plasmas. Necessary to validate this modeling effort is a series of experiments in which the key parameters to be modeled are experimentally measured.

The present work focuses on quantifying the capillary mass loss for two different capillary materials, three different capillary length/diameter (L/D) ratios, and across a range of plasma energies. The model to be created, based on these experiments, will be used to investigate and optimize the plasma-generating hardware. Additionally, as the desirable plasma characteristics are identified it will become increasingly important to couple that understanding with the modeling effort in order to minimize the size and power consumption of plasma electrical components.

2. Experimental Setup

Figures 1 and 2 illustrate the experimental fixture utilized in the present work. A 25.4-mm (1-in) diameter outer insulator contained a 6.3-mm (1/4-in) hole which housed a variable length capillary tube and an inner insulator. Both 23 and 38-mm long capillary tubes were investigated. The capillary tube outer diameters (ODs) were fixed at 6.2 mm; however, two different inner diameters (IDs) (3.2 and 4.1 mm) were considered. The two different capillary tube lengths were

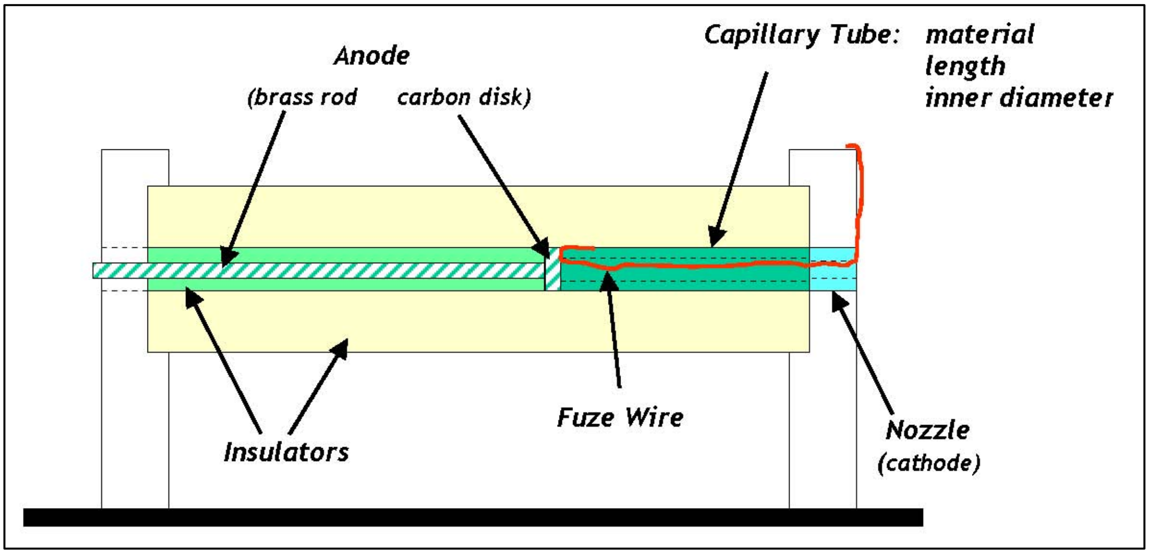

Figure 1. Schematic of experimental setup.

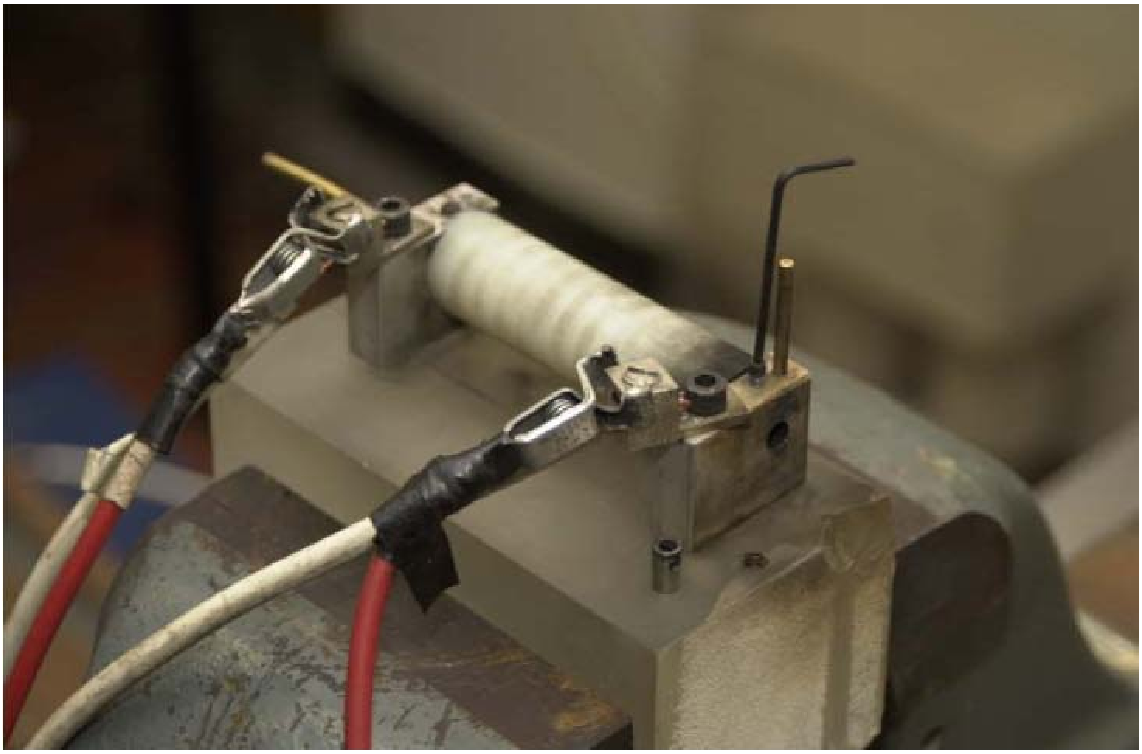

Figure 2. Photograph of experimental setup.

accommodated by adjusting the total length of the anode (brass rod + carbon disk) and the supporting inner insulator (see figure 1). The capillary nozzle (mild steel, length = 11 mm, OD = 6.1 mm, and ID = 3.1 mm) served as the cathode which was electrically connected to the anode by a 0.10-mm (0.004-in) diameter aluminum fuse wire. The mass of the aluminum fuse wire was 0.6 and 1.0 mg for the 23- and 38-mm capillary tubes, respectively.

The capillary-sustained plasma characteristics observed were produced by an electrical discharge directed across the aluminum fuse wire. The system, which delivers the current across the fuse wire, includes a standard pulse-forming network (PFN) power supply. The PFN power supply is used to charge a 1700-μF capacitor. The system-charging voltage ranged from 680 to 1210 V with corresponding stored energies of 350 to 650 J in the experiments discussed here. The current is delivered across the fuse wire producing the electrically-charged plasma. From this system the resulting plasma pulse width was typically around 375 μs. The discharge current is measured by integrating the output of a Rigowski coil, and high voltage probes are used to measure the voltage across the electrodes. The carbon disk portion of the anode was introduced specifically because it has been shown to have minimal erosion (compared to other materials) characteristics in the plasma environment. Thus, the carbon disk has minimal contribution to the nearby capillary-sustained plasma.

Once the plasma is formed inside the capillary tube, the local pressure begins to rise and the plasma vents through the nozzle into open air. The plasma is temporarily sustained and enhanced by ablating material from the capillary wall. Two different materials (polyethylene [PE] and Teflon[*]) were used in the present experiments.

Given that the mild-steel nozzle was subjected to the fast moving plasma, the nozzle mass was also recorded before and after each experiment.

3. Experimental Results and Discussion

A series of experiments was conducted in which the system voltage was varied and thus the energy input to the plasma. In addition, the capillary material, length, and ID were varied. Table 1 summarizes the experimental results, noting the voltage, peak current through the electrical circuit, calculated peak energy and power, and the capillary mass loss details. The "area" noted in the table refers to the inside surface of the capillary tube which is exposed to the plasma.

Typical electrical measurements for the long (38 mm) and short (23 mm) capillary are shown in figure 3. The 38-mm capillary electrical characteristics were similar for both the Teflon and PE capillary tubes. As seen in the figure, only the voltage plot appears noticeably different. It appears that the shorter capillary is not able to maintain the voltage in the same manner as seen in the longer capillary experiments.

---

[*] Teflon is a registered trademark of Dupont (Wilmington, DE).

Table 1. Experimental capillary mass loss.

Capillary Material	ID (mm)	L (mm)	Voltage (kV)	Current (kA)	Power (MW)	Energy (kJ)	ΔMass (mg)	Area (mm^2)	Δ/Area (mg/cm^2)
PE	3.2	38	1.21	2.40	2.96	0.63	4.5	382	1.18
PE	3.2	38	1.13	2.09	2.49	0.53	3.5	382	0.92
PE	3.2	38	0.97	1.47	1.51	0.34	2.5	382	0.65
PE	4.1	38	0.93	2.47	2.25	0.51	3.5	490	0.72
PE	4.1	38	Lost	Lost	Lost	Lost	4.1	490	0.84
PE	4.1	38	1.01	2.99	3.00	0.65	4.4	490	0.90
Teflon	3.2	38	1.07	2.65	2.82	0.65	15.5	382	4.01
Teflon	3.2	38	0.91	1.70	1.55	0.36	9.0	382	2.36
PE	3.2	23	0.76	3.26	2.69	0.60	3.0	231	1.30
PE	3.2	23	0.68	2.33	1.59	0.35	1.5	231	0.65
PE	3.2	23	0.72	2.81	2.20	0.48	2.1	231	0.91

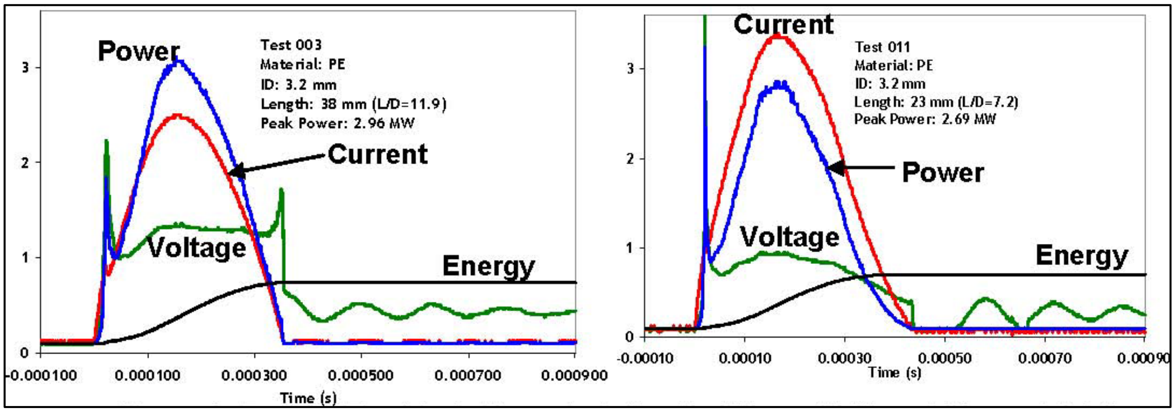

Figure 3. Typical electrical characteristics for 38- (left) and 23-mm (right) capillary-sustained plasmas.

The mass loss data from table 1 is plotted in figure 4. It is observed that the capillary tube ablates fairly consistently for PE. There appears to be no noticeable dependence between capillary length and ID (or L/D) on mass loss for the power levels considered. Less data are presently available on the Teflon capillary. However, given the limited data, it appears the Teflon is more sensitive to changes in the plasma power when compared to the same sensitivity of PE. A greater mass loss is clearly evident at similar plasma power levels for the Teflon vs. PE capillary.

Table 2 lists and figure 5 plots the nozzle mass losses recorded for the present experiments. From the plot, it is observed that the ablating material (Teflon vs. PE) does not affect the nozzle erosion significantly. It is also seen that erosion is greater for the larger ID capillary (4.1 vs. 3.2 mm diameter). Similarly, the nozzle erosion appears greater for the shorter capillary (23 vs. 38 mm).

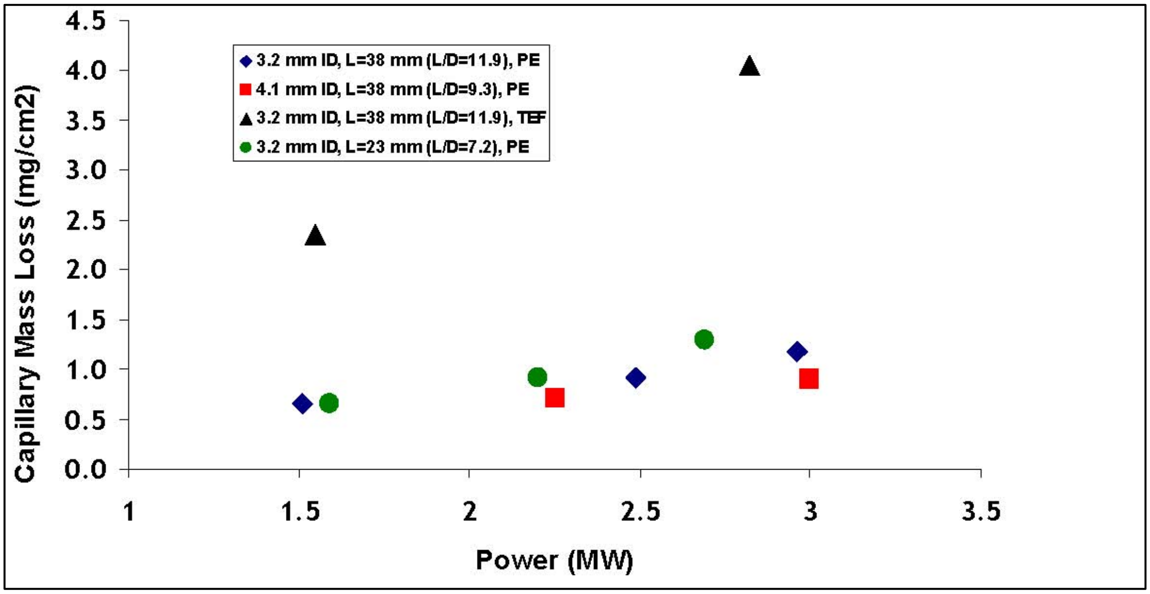

Figure 4. Capillary mass loss vs. power input to plasma.

Table 2. Experimental nozzle mass loss.

Capillary Material	ID (mm)	L (mm)	Voltage (kV)	Current (kA)	Power (MW)	Energy (kJ)	ΔMass (mg)
PE	3.2	38	1.21	2.40	2.96	0.63	Not recorded
PE	3.2	38	1.13	2.09	2.49	0.53	13.0
PE	3.2	38	0.97	1.47	1.51	0.34	4.3
PE	4.1	38	0.93	2.47	2.25	0.51	20.1
PE	4.1	38	Lost	Lost	Lost	Lost	28.4
PE	4.1	38	1.01	2.99	3.00	0.65	25.1
Teflon	3.2	38	1.07	2.65	2.82	0.65	18.4
Teflon	3.2	38	0.91	1.70	1.55	0.36	1.1
PE	3.2	23	0.76	3.26	2.69	0.60	22.3
PE	3.2	23	0.68	2.33	1.59	0.35	10.8
PE	3.2	23	0.72	2.81	2.20	0.48	21.2

4. Summary and Future Work

Presented here are initial results from an ongoing parametric study of the ablation losses for capillary-sustained plasmas. Initial observations indicate the capillary mass losses correlate with the power and energy input to the system. Further, the Teflon capillary ablates 4–5× more material per surface area than does the PE capillary.

The mild-steel nozzle demonstrated higher erosion losses for capillary having the larger ID and also the shorter length. High-speed video of the plasma exiting the capillary may add insight on differences (mach disk strength, speed of precursor shock, etc.) in the plasma for these cases.

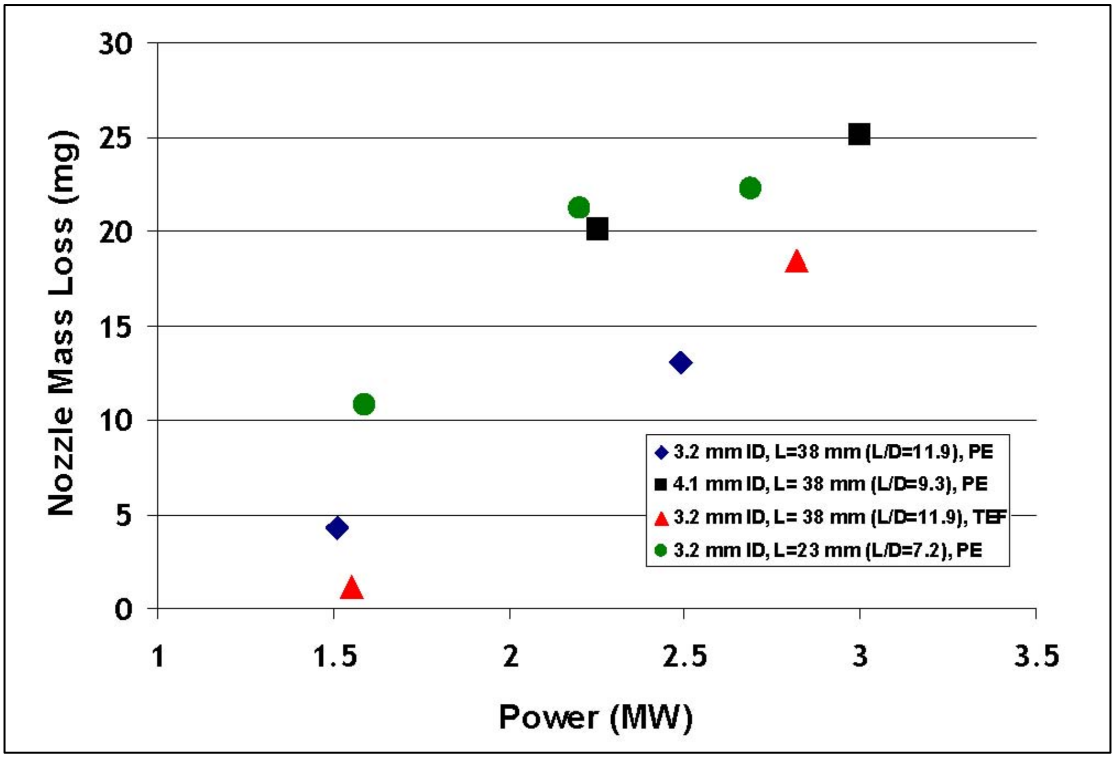

Figure 5. Nozzle mass loss vs. power input to plasma.

Future experiments will be conducted in which other fuse wire materials (nickel, etc.) are considered. Also, experiments are planned in which longer plasma pulse width plasmas (present pulse width about 375 μs) are planned to determine possible effects this may have on the capillary mass loss. High-speed video will also be utilized to qualify the plasma flow as it exits the capillary.

5. References

1. Katulka, G.; Dyvik, J. A. Experimental Results of Electrical Plasma Ignition in 120-mm Solid Propellant Tank Gun Firings. *Proceedings of the 33rd JANNAF Combustion Meeting*, CPIA Publication 653, **1996**, *3*, 103.
2. White, K. J.; Katulka, G. L.; Driesen, S. Electro-Thermal-Chemical Plasma Interaction with Propellants. *Proceedings of the 32nd JANNAF Combustion Subcommittee Meeting*, CPIA Publication 631, **1995**, 113.
3. White, K. J.; Katulka, G. L.; Khong, T.; Nekula, K. *Plasma Characterization for Electrothermal-Chemical (ETC) Gun Applications*; ARL-TR-1491; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 1997.
4. White, K. J.; Katulka, G. L.; Driesen, S. Electro-Thermal-Chemical Plasma Interaction with Propellants. *Proceedings of the 32nd JANNAF Combustion Subcommittee Meeting*, CPIA Publication 631, **1995**, 113.
5. Del Guercio, M. A. *Electrothermal-Chemical (ETC) Closed Chamber Study of Plasma Capillary Materials*; ARL-TR-2268; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2000.
6. Beyer, R. A. Small Scale Experiments in Plasma Propellant Interactions. *Proceedings of the 37th JANNAF Combustion Subcommittee Meeting*, CPIA Publication 701, **2000**, *1*, 137.
7. Taylor, M. J. Measurement of the Properties of Plasma from ETC Capillary Plasma Generators, *IEEE Transactions on Magnetics* **2001**, *37* (1), 194.
8. Williams, A. W.; White, K. J. Plasma-Propellant Interaction Studies: Measurements of In-Depth Heating by Plasma Radiation: Investigation of Possible Plasma-Induced Propellant Erosion. *Proceedings of the 36th JANNAF Combustion Meeting*, CPIA Publication 691, **1999**, *2*, 67.
9. Thynell, S. T.; Das, M.; Li, J.; Litzinger, T. A. Transient Radiative Heat Transfer From a Plasma Produced by a Capillary Discharge. Presented at the *40th JANNAF Combustion Subcommittee Meeting*, Charleston Area Convention Center, Charleston, SC, 13–16 June 2005.
10. Shafir, N.; Zoler, D.; Wald, S.; Shapira, M. Reliable, Highly Reproducible Plasma Injectors for Electrothermal and Electrothermal-Chemical Launchers. *IEEE Transactions on Magnetics* **2005**, *41*, (1).

NO. OF COPIES	ORGANIZATION
1 (PDF ONLY)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FORT BELVOIR VA 22060-6218
1	US ARMY RSRCH DEV & ENGRG CMD SYSTEMS OF SYSTEMS INTEGRATION AMSRD SS T 6000 6TH ST STE 100 FORT BELVOIR VA 22060-5608
1	DIRECTOR US ARMY RESEARCH LAB IMNE ALC IMS 2800 POWDER MILL RD ADELPHI MD 20783-1197
3	DIRECTOR US ARMY RESEARCH LAB AMSRD ARL CI OK TL 2800 POWDER MILL RD ADELPHI MD 20783-1197
	ABERDEEN PROVING GROUND
1	DIR USARL AMSRD ARL CI OK TP (BLDG 4600)

NO. OF COPIES	ORGANIZATION
4	PRIMEX E KIRSCHKE A GONZALEZ J DRUMMOND D WORTHINGTON PO BOX 222 ST MARKS FL 32355-0222
2	PRIMEX N HYLTON J BUZZET 10101 9TH ST N ST PETERSBURG FL 33716
1	PAUL GOUGH ASSOC INC P GOUGH 1048 SOUTH ST PORTSMOUTH NH 03801-5423
1	GEN DYN DEF SYS PCRL PRINCETON CORP PLAZA N MESSINA BLDG IV STE 119 11 DEERPARK DR MONMOUTH JUNCTION NJ 08852
1	G & A KELLER 84 W WALNUT ST 604 ASHEVILLE NC 28801-2816
3	VERITAY TECHGY INC E FISHER R SALIZONI J BARNES 4845 MILLERSPORT HWY EAST AMHERST NY 14501-0305
1	SRI INTERNATIONAL TECH LIB PROPULSION SCIENCES DIV 333 RAVENWOOD AVE MENLO PARK CA 94025-3493
1	US ARMY ARDEC AMSTA AR WE D DOWNS PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC AMSRD AAR ATD B MACHAK BLDG 1 PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC AMSRD AAR AEW F (D) R KOPMANN BLDG 62 N PICATINNY ARSENAL NJ 07806-5000
1	AUBURN UNIVERSITY DEPT OF CHEMISTRY R BLUMENTHAL 179 CHEMISTRY BLDG AUBURN AL 36849
1	UNIVERSITY OF ILLINOIS DEPT OF MECHANICS M BREWSTER URBANA IL 61801
2	UNIVERSITY OF TENNESSEE SPACE INSTITUTE D KEEFER MS24 F G CLEMENT ACADEMIC TULLAHOMA TN 37388-8897
1	UNIVERSITY OF MICHIGAN DEPT OF AEROSPACE ENGINEERING M KEIDAR 2049 FRANCOIS XAVIER BAGNOUD BLDG 1320 BEAL AVE ANN ARBOR MI 48109-2140
1	PA STATE UNIVERSITY DEPT OF MECHANICAL ENGINEERING T LITZINGER UNIVERSITY PARK PA 16802

NO. OF
COPIES ORGANIZATION

1 ARMY RESEARCH OFFICE
D MANN
PO BOX 12211
RESEARCH TRIANGLE PARK NC
27709-2211

1 ARMY RESEARCH OFFICE
CHEMICAL SCIENCE DIV
B SHAW
PO BOX 12211
RESEARCH TRIANGLE PARK NC
27709-2211

1 US ARMY TACOM ARDEC
AMSRD AAR AEE W
J O’REILLY
BLDG 382
MCS 120 MM LOS/BLOS SYS ATD
PICATINNY ARSENAL NJ 07871

1 OKLAHOMA STATE UNIVERSITY
DEPT OF CHEMISTRY
D THOMPSON
STILLWATER OK 74078

1 PA STATE UNIVERSITY
DEPT OF MECHANICAL
ENGINEERING
S THYNELL
UNIVERSITY PARK PA 16802

ABERDEEN PROVING GROUND

30 DIR USARL
AMSRD ARL WM BD
W ANDERSON
R BEYER
A BIRK
A BRANT
S BUNTE
C CHABALOWSKI
L CHANG
T COFFEE
J COLBURN
P CONROY
A ZIELINSKI
B FORCH
B HOLMAN
S HOWARD
P KASTE
A KOTLAR
C LEVERITT

NO. OF
COPIES ORGANIZATION

K MCNESBY
M MCQUAID
A MIZIOLEK
J MORRIS
J NEWBERRY
M NUSCA
R PESCE-RODRIGUEZ
G REEVES
B RICE
R SAUSA
A WILLIAMS
S PIRIANO
AMSRD ARL WM TE
J POWELL

NO. OF COPIES	ORGANIZATION
1	K KAPPEN ESTERWAGNERSTR 19A 85635 HOEHENKIRCHEN GERMANY
1	CAVENDISH LAB W PROUD MADINGLEY RD CAMBRIDGE CB3 OHE UNITED KINGDON

INTENTIONALLY LEFT BLANK.