ARMY RESEARCH LABORATORY

Analyses of High Energy Plasma Capillaries for Use in Electrothermal-Chemical Launch

Gary L. Katulka

ARL-TR-1069

MARCH 1996

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1996	Final

4. TITLE AND SUBTITLE

Analyses of High Energy Plasma Capillaries for Use in Electrothermal-Chemical Launch

5. FUNDING NUMBERS

PR: 1L1622618AH75

6. AUTHOR(S)

Katulka, G.L.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
Weapons Technology Directorate
Aberdeen Proving Ground, MD 21010-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
Weapons Technology Directorate
Aberdeen Proving Ground, MD 21010-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

ARL-TR-1069

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Theoretical calculations are performed with a one-dimensional, steady state, isothermal plasma code from the U.S. Army Research Laboratory for the purpose of defining plasma output parameters based on input electrical energies having relevance to the electrothermal-chemical (ETC) propulsion concept (Powell & Zielinski 1992). Input variables adjusted include capillary diameter, over a range of 1.92 mm to 7.00 mm, and input current amplitude over a range of 30 kA to 350 kA. The capillary length is fixed at 11.84 cm. Plasmas are classified according to their total power and energy level (based on a 3-ms power pulse width) and compared in terms of resistance, exit pressure, and core temperature. Plasma power levels range from 0.17 to 1.89 GW, while the plasma energy level varies from 0.52 to 5.70 MJ, which is considered adequate coverage for ETC ignition through ETC propulsion enhancement concepts. The study reveals that the range of resistance, pressure, and temperature is 12.8 to 195 mΩ, 19.8 to 2000 MPa, and 2.9 to 13.5 eV, respectively, for the capillary matrix being investigated. Flow conditions for plasma calculations include choked (no pressure boundary) and unchoked (450 MPa pressure boundary condition). Results from theoretical plasma calculations and interpretations from the perspective of capillary implementation into ETC propulsion concepts are also included.

14. SUBJECT TERMS

capillary	ETC	plasma
electrothermal-chemical	interior ballistics	propulsion

15. NUMBER OF PAGES: 30

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

Mr. William Oberle and Dr. John Powell of the U.S. Army Research Laboratory are acknowledged for their efforts in reviewing the work reported here.

INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

INTENTIONALLY LEFT BLANK

LIST OF FIGURES

INTENTIONALLY LEFT BLANK

LIST OF TABLES

INTENTIONALLY LEFT BLANK

1. INTRODUCTION

High energy electrical plasmas are of interest to the U.S. Army for application to the electrothermal-chemical (ETC) propulsion concept where their use can potentially increase the muzzle kinetic energy beyond that of a conventional gun, or it can provide a rapid and repeatable ignition source for conventional gun munitions. Much research has been reported over the years in the areas of ETC propulsion and the physics relating to plasmas that are characteristic of ETC guns.[2-4] This report provides information from a recent study of ETC type plasma devices, in the form of theoretical calculations of plasma behavior during various operating conditions. The ETC plasma study includes the following:

a. Analyses and interpretation of plasma properties including steady state resistance, exit pressure, and core temperature of the ETC plasma. Plasmas are assumed to be operating during freely expanding "choked flow" as well as "unchoked flow" conditions. The unchoked condition arises for some plasmas where a 450-megapascal (MPa) pressure boundary assumption is made;

b. Plasma calculations are performed for three capillary geometries having various radii, and based on the results of the calculations, conclusions are drawn regarding the applicability of the different capillary dimensions for the various ETC propulsion concepts.

2. PLASMA MODEL ASSUMPTIONS

The plasma calculations undertaken here are performed with the steady state plasma model of John Powell from the U.S. Army Research Laboratory, the details of which have been reported previously in several technical publications (see References 1, 4). The code is used here with the following assumptions. First, the liner material of the plasma capillary is considered to be polyethylene. Although other materials can be used for capillary liners (e.g., peek glass, polycarbonate, etc.), polyethylene is considered a standard material whose behavior as a plasma-generating device is similar (with respect to plasma power dissipation, conductivity, and temperature) to that of devices constructed from other materials.[5] In addition, the conductivity model implemented by the model is that of Kurilenkov-Valuev. The use of this conductivity model results in a modification of the Spitzer conductivity model used in the plasma code, by adjusting the collision frequency between electrons and ions at lower plasma temperatures. Although the use of the model is less frequent in recent plasma modeling work,[6] the model has demonstrated good agreement with recent experimental plasma data.[7] Finally, the calculated plasma temperatures are for the core or bulk plasma. The bulk temperatures predicted here take into account a plasma surface temperature assumption which is known to cause somewhat higher bulk plasma temperatures and resistances with lower plasma exit pressures, compared to calculations being performed that assume a completely isothermal assumption. However, the plasma output parameters as a function of power and energy will generally behave the same. This can easily be verified by exercising the code during both conditions and comparing the output parameters.

2.1 Plasma Capillary Assumptions

For comparing plasma parameters such as resistance, pressure, and temperature, it was decided to examine plasma behavior at equivalent power and energy levels as opposed to electrical current level. This approach is desirable since two capillaries with different geometries, which are operating at identical input current, can produce plasmas that exhibit widely differing powers and total energies. Of course, because of the differences in capillary dimensions, the output parameters of interest (resistance, pressure, and temperature) will also exhibit great variation, regardless of an identical input current. As a result, it was decided to classify plasmas by power and energy level (based on an assumption of a 3-ms constant current input pulse) as opposed to the current level itself. An analysis can now be performed on plasmas (capillaries) having similar power and energy characteristics, which in general, are important criteria for determining the applicability to a given ETC concept.

For a given ETC concept, however, a range of input electrical energies will be required for proper implementation, depending upon which ETC approach is selected. The source of this electrical energy is, of course, the high energy electrical plasma. For example, for an ETC igniter, it is believed that less than 1 megajoule (MJ) of electrical energy over a period of several milliseconds will be required to properly ignite a 120-mm conventional propellant charge. This is based on simplified assumptions of energy content and discharge characteristics of standard benite primers presently used to ignite large caliber (120-mm) gun systems. On the other hand, for electrical enhancement of propellant burn rates or temperature compensation of conventional propellants, both of which could possibly result in enhanced gun performance, it is believed that a minimum of about 1 MJ of electrical plasma energy will be required for proper ETC gun operation.[3]

Three power levels, which are believed to be appropriate representatives of the requirements of the ETC concepts just described, were selected for this task. These include approximately 180 MW, 700 MW, and 1.8 gigawatts (GW). Given a time constant of 3 ms, which should be a good representation of the electrical application time required for each of the ETC concepts considered, three energy levels of approximately 500 kJ, 2 MJ, and 5 MJ result, all of which fall within the range of energies that might be required for the ETC concepts just discussed.

For the remainder of the report, plasma properties are plotted with respect to total plasma energy, based on the approach just described. For each of the plots in Figures 1 through 6 of the following section, dividing the energy by the constant of 3 ms yields the plasma power amplitude for the calculation.

In addition, for the calculations performed here, the capillary lengths were fixed at 11.84 cm, which could realistically be used in a 120-mm tank cannon application. In addition, for simplicity, it was decided to investigate only three capillary radii. Again, the radii are selected for application to a 120-mm gun chamber and were chosen at 1.92 mm, 4.75 mm, and 7.0 mm. For the remainder of the report, the convention in referring to the capillaries is as follows: Capillary 1, 7.0-mm radius x 11.84-cm length; Capillary 2, 4.75-mm rad. x 11.84-cm length; and Capillary 3, 1.92-mm rad. x 1.84-cm length.

In the following section, calculations with the model are performed to detemine the resistance, pressure, and temperature behavior of plasmas from three different capillaries, at each of the power and energy levels being considered. The first set of calculations has no boundary pressure, while the latter are performed with a 450-MPa boundary pressure. The convention in referring to the nominal plasma energy level assumed in the calculations is as follows: low, 0.5 MJ; medium, 2 MJ; and high energy level, 5 MJ.

2.2 Plasma Calculations

The steady state resistance, exit pressure, and plasma core temperature were selected as parameters of interest and included in the investigation. For each of the capillaries (1 through 3), an input current was chosen to give the approximate power and energy level required by the study. The choice of input current is the result of a somewhat arbitrary process in which the plasma code is exercised in an iterative manner, until the input current and plasma resistance values are such that the plasma power and energy levels are close enough to the preselected target values of power and energy. For this process, the steady state plasma power is determined from the product of the calculated plasma voltage drop (depending on the conductivity characteristics of the plasma) and the test current, at the given current level. The current is adjusted, either increased or decreased, until the target power and energy levels are reasonably matched. For this study, reasonable agreement was considered agreement within about 18% of target values, although much better agreement could easily be obtained through further iteration with the code.

Since the plasma resistance plays a role in the transfer of electrical energy from a power supply to the plasma, the behavior of plasma resistance as a function of energy is investigated. For these calculations, unchoked flow is assumed by the model. The results are given in Figure 1, for each of the three capillaries at the given energy levels (low, medium, high), where the plasma resistance varies from about 13 milliohms (mΩ) (Capillary 1 at high energy) to as much as 195 mΩ (Capillary 3 at low energy). Figure 1 demonstrates rather strong relationships among plasma resistance, operating energy, and capillary radius.

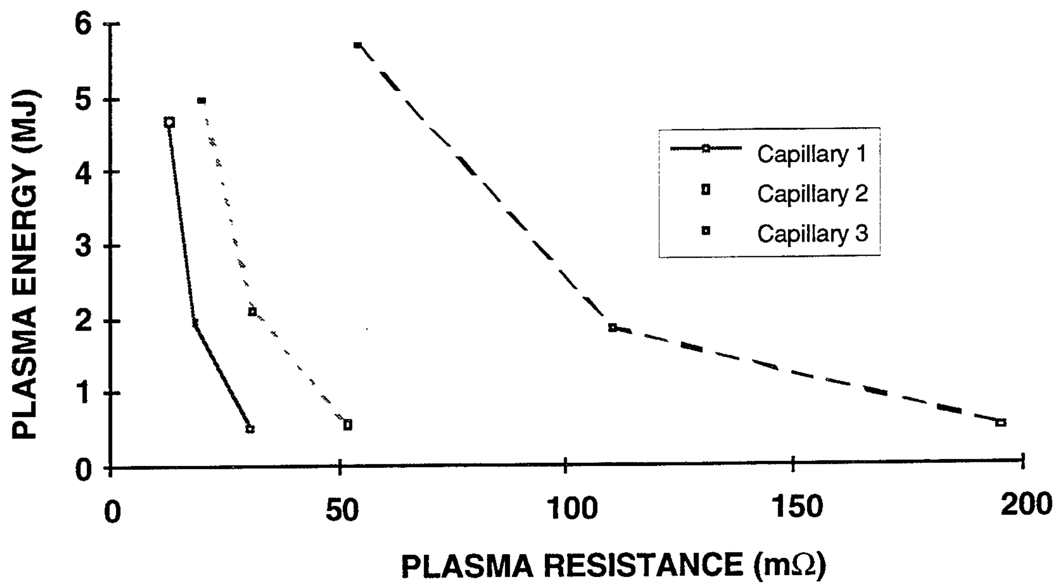

Figure 1. Plasma Energy Versus Resistance for Capillaries 1 Through 3, Having Radii as Depicted: 7.0, 4.75, and 1.92 mm, and Choked Flow Condition.

It is noticed how a very large dynamic range results for Capillary 3 (smallest diameter) resistance, over the given energy range, while the converse is true as the capillary radius is systematically increased.

Figures 2 and 3 are plots of plasma energy versus plasma exit pressure and plasma temperature, respectively. The exit pressure is the pressure at the open end of the capillary where plasma gases initially appear as the plasma flows from the capillary, while the plasma temperature is that experienced in the core of the plasma. Once again, it is noted how Capillary 3 has a wide (dynamic) range of exit pressures and core temperatures compared to Capillaries 1 and 2.

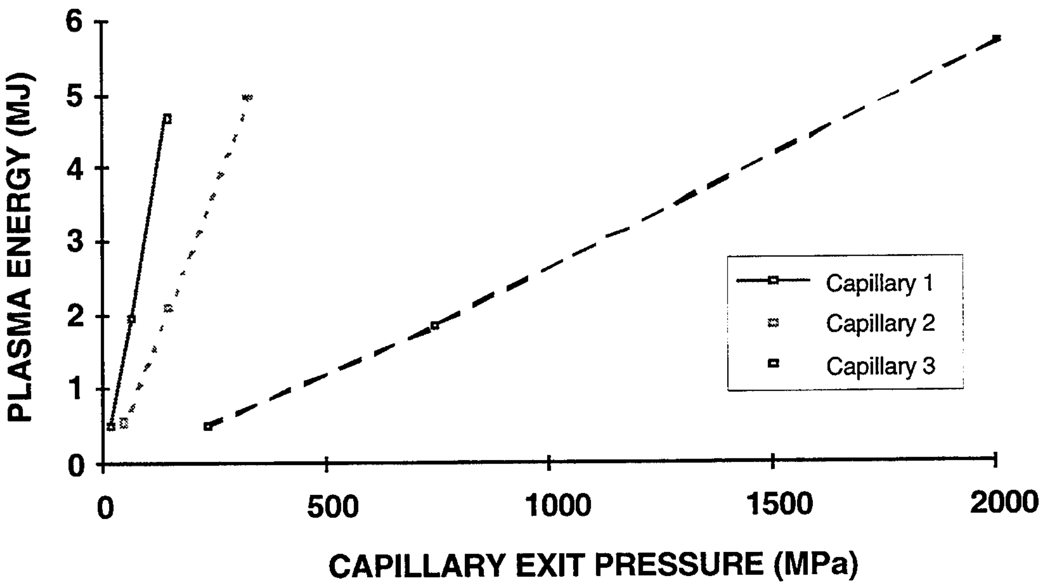

Figure 2. Plasma Energy Versus Exit Pressure for Capillaries 1 Through 3 Having Radii as Depicted, 7.0, 4.75, and 1.92 mm, and Choked Flow Condition.

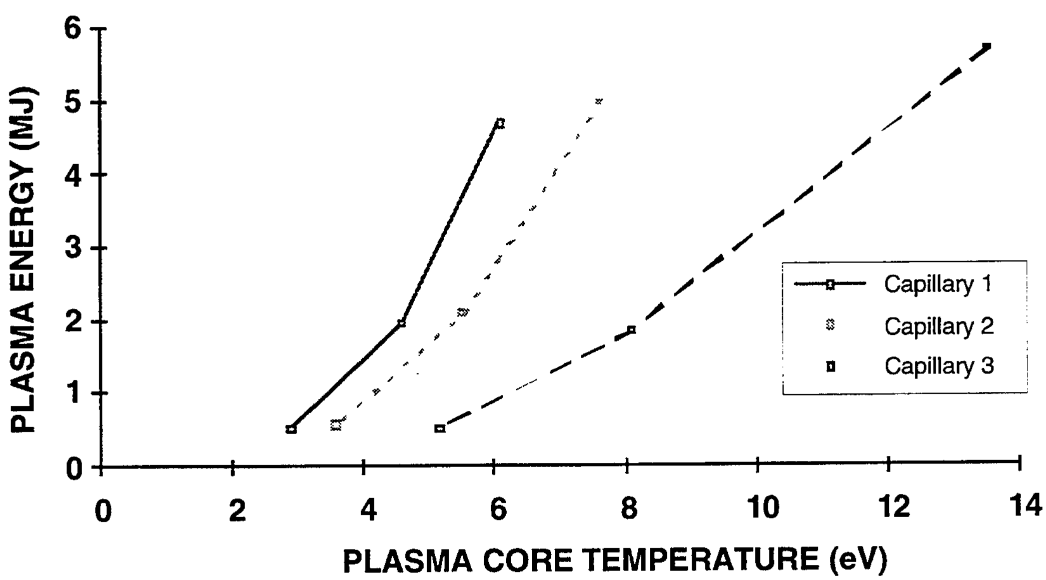

Figure 3. Plasma Energy Versus Core Temperature for Capillaries 1 Through 3 Having Radii as Depicted, 7.0, 4.75, and 1.92 mm, and Choked Flow Condition.

Figures 4 through 6 are the results of plasma calculations with the additional assumption of a pressure boundary condition at the plasma exiting plane. For this set of calculations, the boundary pressure is set at 450 MPa. The calculations are now performed only for Capillaries 2 and 3 with all previous calculation assumptions remaining unchanged. The results with the pressure boundary condition are plotted in Figures 4 through 6 (broken lines) together with the results from the previous calculations, which did not have the externally applied 450-MPa pressure boundary (solid lines). Figure 4 contains the plasma resistance relationships; Figure 5 contains the exit pressure relationships; and Figure 6 shows the core temperature relationships.

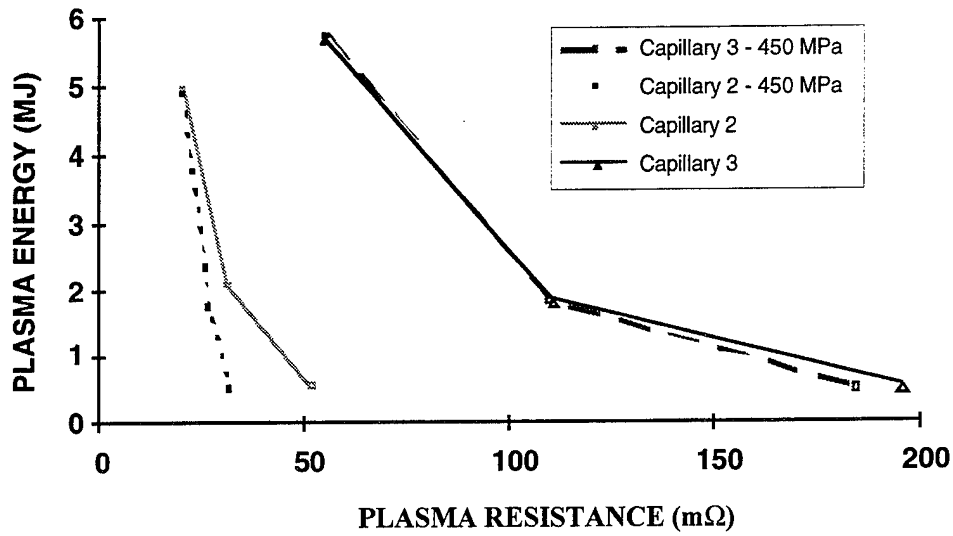

Figure 4. Plasma Energy Versus Resistance for Capillaries 2 and 3 Having Radii as Depicted, 7.0, 4.75, and 1.92 mm, and 450-MPa Pressure Boundary Condition.

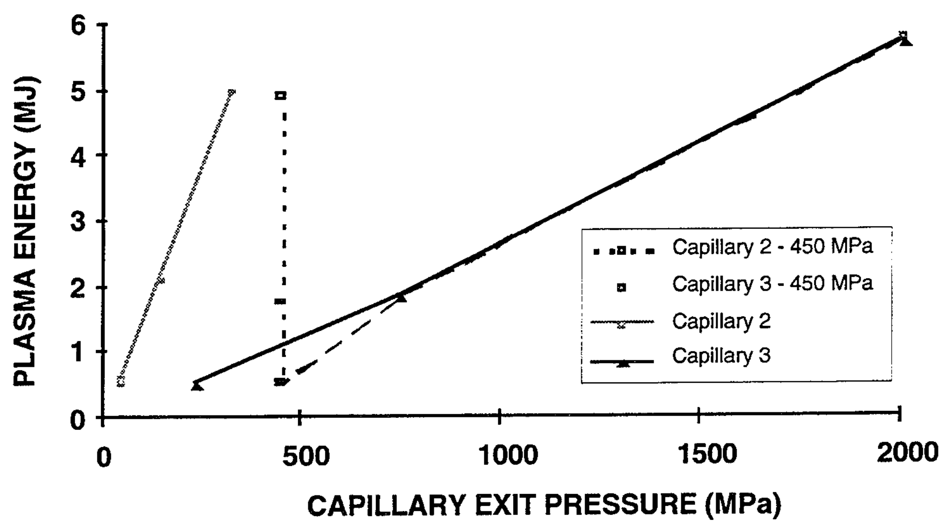

Figure 5. Plasma Energy Versus Pressure for Capillaries 2 and 3 Having Radii as Depicted, 7.0, 4.75, and 1.92 mm, and 450-MPa Pressure Boundary Condition.

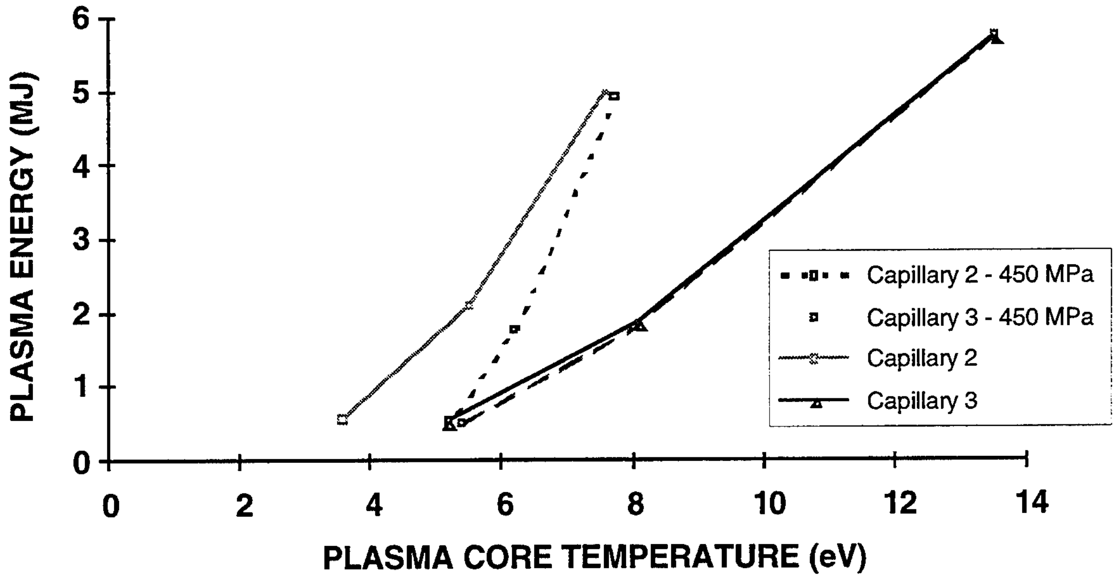

Figure 6. Plasma Energy Versus Temperature for Capillaries 2 and 3 Having Radii as Depicted, 7.0, 4.75, and 1.92 mm, with 450-MPa Pressure Boundary Condition.

3. DISCUSSION

The data for the calculations performed here are arranged in Tables 1 and 2. Table 1 gives the input parameters for the choked flow calculations along with the outputs for each capillary at the given energy and power levels. Table 2 shows the results for the calculation having the 450-MPa boundary condition for Capillaries 2 and 3 at each of the three energies and powers. Note that the numbers in Table 2 under the heading of percent difference represent the difference between choked and pressure boundary values, as a percentage. Percent difference as calculated here represents the absolute value of the choked value minus the pressure boundary value divided by the choked value.

For Capillary 2, the exit pressure is obviously dominated by the boundary pressure of 450 MPa, with increases of 406 (918%), 304 (208%), and 125 (39%) MPa for the low, medium, and high energies, respectively. The resulting temperatures are 5.2, 6.2, and 7.7 electron volts (eV), respectively, for the low, medium, and high energy levels. This represents an increase in temperature of 1.63 (44%), 0.7 (13%), and 0.13 (1.3%) eV, compared to the previous calculations without the 450-MPa boundary condition. The resistance of the Capillary 2 plasma is also sensitive to the pressure boundary, with decreases in resistance ranging from 20.4 mΩ (39%) to 0.3 mΩ (1.5%) over the range of energies investigated.

Table 1. Plasma Calculation Results for Capillaries 1 Through 3 During the Choked Flow Condition at Low, Medium, and High Energy and Power Levels

Capillary Dimensions (number)	Input Current (kA)	Plasma Resistance (mΩ)	Input Power (GW)	Input Energy (MJ)	Plasma Exit Pressure (MPa)	Plasma Core Temp (eV)
7.0 mm (1)	75	30.5	0.17	0.52	19.8	2.9
	187	18.6	0.65	1.96	64.0	4.6
	350	12.8	1.57	4.70	145.0	6.1
4.75 mm(2)	60	51.7	0.19	0.56	44.2	3.6
	150	31.2	0.70	2.10	146.0	5.5
	287	20.2	1.67	4.98	325.0	7.6
1.92 mm(3)	30	195.0	0.18	0.53	235.0	5.2
	75	110.0	0.62	1.86	744.0	8.1
	187	54.9	1.89	5.70	2000.0	13.5

Table 2. Plasma Calculation Results for Capillaries 2 and 3 During 450-MPa Pressure Boundary Condition at Low, Medium, and High Energy and Power Levels

Capillary Dimensions (number)	Input Current (kA)	Plasma Resistance (mΩ) Percent Δ		Input Power (GW)	Input Energy (MJ)	Plasma Exit Pressure (MPa) Percent Δ		Plasma Core Temp (eV) Percent Δ	
4.75 mm(2)	75	31.3	39.5	0.18	0.53	450	918	5.2	44.4
	150	26.3	16	0.59	1.78	450	208	6.2	13
	287	19.9	1.5	1.64	4.92	450	39	7.7	1.3
1.92 mm(3)	30	184	5.6	0.17	0.49	450	92	5.4	3.8
	75	110	0	0.62	1.85	744	0	8.1	0
	187	54.9	0	1.92	5.80	2000	0	13.5	0

General observations for Capillaries 1 and 2 (larger diameters) include

a. Plasma output parameters of resistance, pressure, and temperature are less sensitive to the input energy level assumed in the calculations, compared to Capillary 3 (smallest diameter).

b. Pressure boundary conditions have a strong influence over all plasma parameters considered in the study, at nearly every energy level. Resistance tends to drop, exit pressure increases, and core temperature increases for the plasmas of these capillaries, as the pressure boundary is applied to the calculation.

c. Lower exit pressures are experienced in nearly all calculations with these capillary dimensions (19.8 to 325 MPa). As a result, the ability for Capillaries 1 and 2 to inject plasma material into a pressurized gun chamber remains in question at the relatively low plasma pressures calculated. Larger capillaries might therefore be best used purely as an ignition source when plasma injection late in the ballistic cycle is not a requirement and when plasma output parameters with respect to input energy level are more stable.

The relationships for Capillary 3 are nearly unchanged by the added 450-MPa pressure boundary condition, regardless of energy level. In fact, for Capillary 3, the plasma resistance is identical for medium and high energies, while it is only decreased by 11 mΩ (5.6% difference) for the low energy case. The pressure and temperature of the plasma from Capillary 3 is increased by 215 MPa (91%) and 0.22 eV (3.8%), respectively, at low energy, and it remains completely unchanged in exit pressure and core temperature for medium and high energies. The output parameters of Capillary 3 are obviously dominated by the self-generated capillary pressure at all energies considered, especially medium and high, regardless of the 450-MPa pressure boundary condition. Based on these results, it seems reasonable that such a capillary would be appropriate for ETC propulsion concepts requiring continued plasma flow from the capillary into the gun chamber, during the ballistic cycle.

The summary of observations for Capillary 3 (small diameter) calculations includes the following:

a. Exit pressures and core temperatures increase more rapidly, compared to the other capillaries examined, as input energy is increased. The plasma resistance decreases more rapidly as input energy is increased.

b. The small diameter capillary is much less sensitive to pressure boundary conditions at the exit plane of the capillary, with respect to resistance, exit pressure, and core temperature, in comparison with other capillaries in the study. In fact, in some calculations, the output is completely unchanged by the pressure boundary, which indicates that the self-pressure of the plasma is dominant.

c. Exit pressures and core temperatures achieved extreme levels (2000 MPa, 13.5 eV) as the energy approached 5 MJ.

In summarizing this set of calculations, capillaries having diameters similar to those of Capillary 3 appear to be best for injection of plasma material into a pressurized gun chamber, perhaps late in the ballistic cycle. Of course, this may come at the expense of a very high core temperature and a somewhat higher plasma resistance and pressure. The use of smaller (diameter) capillaries for ETC performance augmentation will then require the ability to employ higher temperature plasmas as well as employ pulsed power supplies of higher impedances, although the latter of these should not be difficult. In addition, the ability to use plasmas with widely fluctuating output parameters must be considered, if a variety of energy levels is needed for proper ETC operation. This is because of the large dynamic range observed for each of the plasma output parameters (resistance, pressure, temperature) as a function of input energy.

The large dynamic range observed in Capillary 3 may have practical limitations if relied upon in an ETC application. For example, it has been shown in previous investigations that the electrical transfer efficiency of a fixed impedance pulsed power supply will exhibit a poor (approximately 40%) electrical transfer efficiency for capillaries having a resistance unmatched to that of the power supply.[7] As a result, one might expect that a fixed impedance power supply will have a large variation in transfer efficiency with small diameter capillaries, over a given range of input power and energy levels. Large capillary plasmas could therefore be described as more stable in terms of their impedance behavior and transfer efficiencies with respect to power and energy input levels. One technical method of overcoming variations in transfer efficiency is to allow the impedance of the power supply to fluctuate with the plasma resistance. This, of course, could translate into a more complex power supply in terms of the additional switching and control components that are necessary to achieve the more dynamic power supply.

Additional computations and experiments for the purpose of further defining the behavior of plasmas at energy levels and of dimensions appropriate for ETC applications should be pursued aggressively before final conclusions are drawn with regard to optimal ETC plasma capillaries. The calculations in this report are performed with potentially severely limiting assumptions (e.g., one-dimensionality, isothermal effects, exclusion of hydrodynamics effects). As a result, it is highly advisable to continue theoretical and experimental exercises in the areas of ETC plasma investigations, with increasing levels of complexity before making any serious or profound conclusions with regard to ETC plasma capillary selection.

4. SUMMARY AND CONCLUSIONS

Theoretical calculations have been performed with a one-dimensional, steady state, isothermal plasma model with the objective of defining high energy plasma output parameters of interest to the electrothermal propulsion concept. Capillary radii were varied over a range of 1.92 to 7.00 mm, while the input current level was modulated between 30 kA and 350 kA for capillaries having a fixed length of 11.84 cm. The range of plasma powers and energies investigated include 0.17 to 1.89 GW and 0.52 to 5.70 MJ, respectively. The plasma output parameters of resistance, exit pressure, and core temperature fluctuated greatly over the range of energy and capillary diameters used. The range of resistance, pressure, and temperature is 12.8 to 195 mΩ, 19.8 to 2000 MPa, and 2.9 to 13.5 eV, respectively. The effect of a 450-MPa external pressure boundary condition was noticed to have a more significant impact on the plasma output parameters for large diameter capillaries and little or no impact on small diameter capillaries.

Large diameter capillaries studied here (Capillaries 1 and 2) showed a reduced sensitivity to the plasma energy level with respect to output parameters (resistance, pressure, temperature). An externally applied pressure boundary condition (450 MPa) had a strong influence on plasma output parameters, and the self-generated plasma pressures experience were generally much less than those of the small capillary (Capillary 3). Based on these observations, it appeared that a larger capillary might best be used in the application of an ETC igniter.

The small diameter capillary (3) was observed to have output parameters that were much more sensitive to the plasma energy level used; it was much less sensitive to the externally applied (450-MPa) pressure boundary condition, and it produced very large exit pressures and core temperatures. As a result, it might appear that a smaller diameter capillary would be best for applications when injection of electrical plasma energy into a gun chamber for a longer period in the ballistic cycle, such as ETC performance augmentation, is a requirement.

INTENTIONALLY LEFT BLANK

REFERENCES

1. Powell, J. D., and Zielinski, A. E., "Theory and Experiment for an Ablating-Capillary Discharge and Application to Electrothermal-Chemical Guns," BRL-TR-3355, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1992.

2. Oberle, W., Stobie, I., DelGuercio, M., White, K., Bourham, M., Gilligan, J., "Summary of Experimental Efforts to Determine Plasma-Augmented Burn Rates for Solid Propellants," U.S. Army Research Laboratory and North Carolina State University, ARL-TR-782, Aberdeen Proving Ground, MD, June 1995.

3. White, K. J., Oberle, W. F., Juhasz, A. A., Stobie, I. C., Nekula, K., Katulka, G. L., Driesen, S., "Electrothermal-Chemical Propulsion with High Loading Density Charges," U.S. Army Research Laboratory Technical Report, ARL-TR-845, Aberdeen Proving Ground, MD, August 1995.

4. Powell, J. D., "Analysis of Piccolo-Type Injectors for Electrothermal-Chemical Launch," U.S. Army Research Laboratory Technical Report, ARL-TR-952, Aberdeen Proving Ground, MD, January 1996.

5. Batteh, J., Powell, J., Sink, D., Thornhill, L., "A Methodology for Computing Thermodynamic and Transport Properties of Plasma Mixtures in ETC Injectors," IEEE Transactions of Magnetics, Vol., 31, No. 1, January 1995.

6. Powell, J. D., Private communication, U.S. Army Research Laboratory, March 1996.

7. Princeton Combustion Research Laboratories, "Final Report: A Time Dependent, Lumped Parameter Power-Plasma-Interior-Ballistic Code (PPIB) for Electrothermal-Chemical (ETC) Gun Performance Prediction," Delivered under contract to the U.S. Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5066, June 1995.

8. Katulka, G., Oberle, W., Wren, G., Okamitsu, J., Messina, N., "Pulse-Power, Plasma, and Interior Ballistic Simulations for Application to Electrothermal-Chemical Guns," Technical Report ARL-TR-1070, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5066, March 1996.

INTENTIONALLY LEFT BLANK

NO. OF
COPIES ORGANIZATION

2 ADMINISTRATOR
DEFENSE TECHNICAL INFO CENTER
ATTN DTIC DDA
8725 JOHN J KINGMAN RD STE 0944
FT BELVOIR VA 22060-6218

1 COMMANDER
US ARMY MATERIEL COMMAND
ATTN AMCAM
5001 EISENHOWER AVE
ALEXANDRIA VA 22333-0001

1 DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL OP SD TA/
RECORDS MANAGEMENT
2800 POWDER MILL RD
ADELPHI MD 20783-1197

1 DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL OP SD TL/
TECHNICAL LIBRARY
2800 POWDER MILL RD
ADELPHI MD 207830-1197

1 DIRECTOR
US ARMY RESEARCH LABORATORY
ATTN AMSRL OP SD TP/
TECH PUBLISHING BRANCH
2800 POWDER MILL RD
ADELPHI MD 20783-1197

1 COMMANDER
USA ARDEC
ATTN SMCAR WAH T J DOMEN
BLDG 62 NORTH
PCTNY ARSNL NJ 07806-5000

1 COMMANDER
USA ARDEC
ATTN SMCAR AEE BR K KLINGAMAN
BLDG 1501
PCTNY ARSNL NJ 07806-5000

1 DIRECTOR
USA BMD
ADV TECH CTR
PO BOX 1500
HUNTSVILLE AL 35807

NO. OF
COPIES ORGANIZATION

1 CHAIRMAN
DOD EXP SAFETY BD
RM 856 C HOFFMAN BLDG 1
2461 EISENHOWER AVE
ALEXANDRIA VA 22331-0600

1 DA OFC OF PM
155MM HWTZR M109A6 PALADIN
ATTN SFAE AR HIP IP
R DE KLEINE
PCTNY ARSNL NJ 07806-5000

1 COMMANDER
USA ARDEC
ATTN AMSMC PBM E L LAIBSON
PCTNY ARSNL NJ 07806-5000

3 PEO ARMAMENTS PM TMAS
ATTN AMCPM TMA K RUSSELL
AMCPM TMA 105
AMCPM TMA 120
PCTNY ARSNL NJ 07805-5000

2 DIRECTOR
BENET LAB USA WATERVLIET ARNSL
ATTN SARWV RD G CARAFANO
R HASOENBEIN
WATERVLIET NY 12189

2 DIRECTOR
BENET LAB USA WATERVLIET ARNSL
ATTN SARWV RD P VOTIS
M CIPOLLO
WATERVLIET NY 12189

1 COMMANDER
USA AMCCOM
ATTN AMSMC IRC G COWAN
SMCAR ESM R W FORTUNE
R ZASTROW
ROCK ISLAND IL 61299-7300

2 COMMANDER
USA AMCCOM
ATTN SMCAR ESM R W FORTUNE
R ZASTROW
ROCK ISLAND IL 61299-7300

1 COMMANDER
USA CECOM
ATTN ASQNC ELC ISL R
R&D TECH LIB MYER CTR
FT MONMOUTH NJ 07703-5301

NO. OF COPIES	ORGANIZATION
1	COMMANDANT USA AS ATTN AVIATION AGENCY FT RUCKER AL 36360
1	DIRECTOR HQ TRAC RPD ATTN ATCD MA MAJ WILLIAMS FT MONROE VA 23651-5143
1	HQ USAMC ATTN AMCICP AD M F FISETTE 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
2	COMMANDER USA ARDEC ATTN SMCAR CCD D SPRING SMCAR CCS PCTNY ARSNL NJ 07806-5000
2	COMMANDER USA ARDEC ATTN SMCAR CCH T L ROSENDORG SMCAR CCH V E FENNELL PCTNY ARSNL NJ 07806-5000
2	COMMANDER USA ARDEC ATTN SMCAR AEE B D DOWNS P CHIU PCTNY ARNSL NJ 07806-5000
2	COMMANDER USA ARDEC ATTN SMCAR AEE J LANNON SMCAR AED S KAPLOWITZ PCTNY ARSNL NJ 07806-5000
2	COMMANDER USA ARDEC ATTN SMCAR FSA T M SALSBURY T GORA PCTNY ARSNL NJ 07806-5000
2	COMMANDER USA ARDEC ATTN SMCAR B KNUTELSKY A GRAF PCTNY ARSNL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	COMMANDER USA ARDEC ATTN SMCAR K CHEUNG PCTNY ARSNL NJ 07806-5000
2	COMMANDER USA ARDEC ATTN SMCAR EG G FERDINAND R ZIMANY PCTNY ARSNL NJ 07806-5000
1	US ARMY RSCH LAB ATTN AMSRL WT N J INGRAM 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	US ARMY RSCH LAB ATTNAMSRL WT NH J CORRIGAN 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	US ARMY RSCH LAB ATTN AMSRL WT NG T OLDHAM 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	US ARMY RSCH LAB ATTN AMSRL EP MC D SINGH BLDG 2707 FT MONMOUTH NJ 07703-5000
2	COMMANDER USARO ATTN TECH LIB D MANN PO BOX 12211 RSCH TRI PK NC 27709-2211
1	COMMANDER USABRDEC ATTN STRBE WC TECH LIB VAULT BLDG 315 FT BELVOIR VA 22060-5606
1	COMMANDER USA TRAC FT LEE DEFENSE LOGISTICS STUDIES FT LEE VA 23801-6140

NO. OF COPIES	ORGANIZATION
1	PRESIDENT USA ARTILLERY BD FT SILL OK 73503
1	COMMANDANT USACGSC FT LVNWORTH KS 66027-5200
1	COMMANDANT USASWS ATN REV & TNG LIT DIV FT BRAGG NC 28307
1	COMMANDER RADFORD ARMY AMMO PLANT ATTN SMCRA QA HI LIBRARY RADFORD VA 24141
1	COMMANDANT USAFAS ATTN STSF TSM CN FT SILL OK 73505-5600
1	DEP CDR SDC ATN SFAE SD HVL D LIANOS PO BOX 1500 HUNTSVILLE AL 35887-8801
3	COMMANDER USA FSTC ATTN AMSCT MC 3 S LEBEAU C BEITER 220 SEVENTH ST NE CHARLOTTESVILLE VA 22901
1	COMMANDANT USA FACS ATTN ATSF CO MW B WILLIS FT SILL OK 73503
1	OFC NAVAL RSCH ATTN CODE 473 R S MILLER 800 N QUINCY ST ARLINGTON VA 22217
2	COMMANDER NSSC ATTN SEA 62R SEA 64 WASHINGTON DC 20362-5101

NO. OF COPIES	ORGANIZATION
1	COMMANDER NASC ATTN AIR 954 TECH LIB WASHINGTON DC 20360
1	NAVAL RSCH LAB TECH LIB WASHINGTON DC 20375
2	COMMANDER HSWC ATTN J P CONSAGA C GOTZMER SLVR SPRNG MD 20902-5000
2	COMMANDER NSWC ATTN CODE R13 K KIM CODE R13 R BERNECKER SLVR SPRNG MD 20902-5000
3	CDR NSWC INDIAN HEAD DIV ATTN 6210 C SMITH 6210J K RICE 6210C S PETERS INDIAN HEAD MD 20640-5035
3	CDR NSWC DAHLGREN DIV ATTN CODE G33 T DORAN J COPLEY CODE G30 G&M DIV DAHLGREN VA 2448-5000
3	CDR NSWC DAHLGREN DIV ATTN CODE G301 D WILSON CODE G32 GUNS SYSTEMS DIV CODE E23 TECH LIB DAHLGREN VA 2448-5000
1	CDR NSWC CRANE DIV ATTN CODE 4052 S BACKER BLDG 108 CRANE IN 47522-5000
2	CDR NUSC ENG CONV DEPT ATTN CODE 5B331 R S LAZAR TECH LIB NEWPORT RI 02840
1	CDR NSWC INDIAN HD DIV ATTN CODE 270P1 MR E CHAN 101 STRAUS AVE INDIAN HEAD MD 20640

NO. OF COPIES	ORGANIZATION
1	CDR NSWC INDIAN HD DIV ATTN CODE 3120 MR R RAST 101 STRAUS AVE INDIAN HEAD MD 20640
1	CDR NSWC INDIAN HD DIV ATTN CODE 210P1 R SIMMONS 101 STRAUS AVE INDIAN HEAD MD 20640
2	CDR NSWC INDIAN HD DIV ATTN CODE 6210 S BOYLES N ALMEYDA 101 STRAUS AVE INDIAN HEAD MD 20640
1	CCDR NAWC ATTN CODE 3891 A ATWOOD CHINA LAKE CA 93555
1	CDR USAARDEC ATTN SMCAR CCH J HEDDERICH BLDG 1 PCTNY ARNSL NJ 07806-5000
1	OLAC PL TSTL ATTN D SHIPLETT EDWARD AFB CA 93523-5000
10	CIA OFC OF CENTRAL REFERENCE DISSEMINATION BRANCH RM GE47 HQS WASHINGTON DC 20502
1	CIA ATTN J E BACKOFEN HQ RM 5F22 WASHINGTON DC 20505
3	DIRECTOR LANL ATTN B KASWHIA H DAVIS E526 W REASS LOS ALAMOS NM 87545
1	DIRE LLNL ATTN MS L355 A BUCKINGHAM PO BOX 808 LIVERMORE CA 94550

NO. OF COPIES	ORGANIZATION
1	DIR SANDIA NAT LAB COMBUSTION RSCH FACILITY ATTN R ARMSTRONG DIV 8357 LIVERMORE CA 94551-0469
1	DIR SANDIA NAT LAB COMBUSTION RSCH FACILITY ATTNS VOSEN DIV 8357 LIVEMORE CA 94551-0469
1	UNIVERSITY OF ILLINOIS DEPT OF MECH INDUST ENGR ATTN PROF H KRIER 144 MEB 1206 N GREEN ST URBANA IL 61801
1	JHU CPIA ATTN T CHRISTIAN 10630 LTLE PATUXENT PKWY STE 202 COLUMBIA MD 21044-3200
2	PENN STATE UNIV DEPT OF MECHANICAL ENGR ATTN J BROWN 312 MECHANICAL ENGR BLDG UNIVERSITY PK PA 16802
1	NCSU ATTN J G GILLIGAN BOX 7909 1110 BURLINGTON ENGR LABS RALEIGH NC 27695-7909
1	NCSU ATTN M BOURHAM BOX 7909 1110 BURLINGTON ENGR LABS RALEIGH NC 27695-7909
2	INST FOR ADV TECH ATTN DR H FAIR P SULLIVAN 4030 2 W BAKER LANE AUSTIN TX 78759-5329
1	INST FOR ADV TECH ATTN DR I MCNAB 4030 2 W BAKER LANE AUSTIN TX 78759-5329

NO. OF COPIES	ORGANIZATION
1	SRI INTERNATIONAL PROPULSION SCIENCE DIV ATTN TECH LIB 333 RAVENSWOOD AVE MENLO PARK CA 94025
1	SPARTA ATTN DR M HOLLAND 945 TOWNE CENTER DR SAN DIEGO CA 92121-1964
2	UNITED DEFENSE ATTN MR M SEALE DR A GIOVANETTI 4800 E RIVER RD MINNEAPOLIS MN 55421-1498
1	UNITED DEFENSE ATTN MR J DYVIK 4800 E RIVER RD MINNEAPOLIS MN 55421-1498
1	HERCULES INC RADFORD ARMY AMMO PLANT ATTN D A WORRELL PO BOX 1 RADFORD VA 24141
1	HERCULES INC RADFORD ARMY AMMO PLANT ATTN E SANFORD PO BOX 1 RADFORD VA 24141
2	GDLS ATTN MR F LUNSFORD DR M WEIDNER PO BOX 2074 WARREN MI 48090-2074
2	OLIN ORDNANCE ATTN V MCDONALD LIBRARY H MCELROY PO BOX 222 ST MARKS FL 32355
1	OLIN ORDNANCE ATTN D WORTHINGTON PO BOX 222 ST MARKS FL 32355
1	PAUL GOUGH ASSOC INC ATTN P S GOUGH 1048 SOUTH ST PORTSMOUTH NH 03801-5423

NO. OF COPIES	ORGANIZATION
1	PHYSICS INTL LIBRARY ATTN H W WAMPLER PO BOX 5010 SAN LEANDRO CA 94577-0599
1	ROCKWELL INTL ROCKETDYNE DIV ATTN BA08 J E FLANAGAN 6633 CANOGA AVE CANOGA PK CA 91304
1	ROCKWELL INTL ROCKETDYNE DIV ATTN BA08 J GRAY 6633 CANOGA AVE CANOGA PK CA 91304
1	SCIENCE APPLICATIONS INC ATTN J BATTEH 1225 JOHNSON FERRY RD STE 100 MARIETTA GA 30068
1	SCIENCE APPLICATIONS INC ATTN L THORNHILL 1225 JOHNSON FERRY RD STE 100 MARIETTA GA 30068
1	ELI FREEDMAN & ASSOC ATTN E FREEDMAN 2411 DIANA RD BALTIMORE MD 21209
1	VERITAY TECH INC ATTN MR E FISHER 4845 MILLERSPORT HWY E AMHERST NY 14051-0305
1	BATTELLE ATTN TACTEC LIB J N HUGGINS 505 KING AVE COLUMBUS OH 43201-2693
1	CA INSTITUTE OF TECH JET PROPULSION LAB ATNT L D STRAND MS125 224 4800 OAK GROVE DR PASADENA CA 91109

NO. OF COPIES	ORGANIZATION
1	CA INSTITUTE OF TECH JET PROPULSION LAB ATTN D ELLIOT 4800 OAK GROVE DR PASADENA CA 91109
1	USA BENET LAB ATTN SMCAR CCB R DR DR S SPOCK WATERVLIET NY 12189
1	MARTIN MARIETTA DEFENSE SYS ATTN DR J MANDZY MAIL DROP 42 220 100 PLASTICS AVE PITTSFIELD MA 01201
1	STATE U OF NY DEPT OF ELEC ENGR ATTN DR W J SARGEANT BONNER HALL RM 312 BUFFALO NY 14260
1	TEXAS TECH UNIVERSITY DEPT OF EE COMPUTER SCIENCE ATTN DR M KRISTIANSEN LUBBOCK TX 79409-4439
1	UNIV OF TEXAS AT ARLINGTON DEPT OF ELEC ENGR ATT DR L GORDON BOX 19016 ARLINGTON TX 76019-0016
1	WILKES UNIVERSITY DEPT OF ELEC ENGR ATTN DR A ARMAND WILKES BARRE PA 18766
2	UNIVERSITY OF DELAWARE DEPT OF ELEC ENGR ATTN DR N GALLAGHER DR J KOLODZEY NEWARK DE 19716
1	COLORADO SCHOOL OF MINES DEPT OF ENGINEERING ATTN C BRAUN GOLDEN CO 80401
1	SNL ATTN MR M GRUBELICH DIV 2515 PO BOX 5800 ALBUQUERQUE NM 87185

NO. OF COPIES	ORGANIZATION
2	LOCKHEED MARTIN DEF SYSTEMS PRINCETON COMBUSTION RSCH LABS ATTN N A MESSINA 11 DEER PARK DR BLDG IV SUITE 119 MONMOUTH JUNCTION NJ 08852
1	COMMANDER USA ARDEC ATTN SFAE ASM TMA AS R BILLINGTON PICATINNY ARSENAL NJ 07806-5000
2	RARDE GS2 DIVISION BLDG R31 ATTN DR C WOODLEY, DR G COOK FORT HALSTEAD SEVENOAKS KENT TN14 7BP ENGLAND
1	MATERIALS RESEARCH LABORATORY SALISBURY BRANCH ATTN ANNA WILDEGGER GAISSMAIER EXPLOSIVES ORDNANCE DIVISION SALISBURY SOUTH AUSTRALIA 5108
	ABERDEEN PROVING GROUND
5	DIR ARL ATTN AMSRL OP AP L (TECH LIB) BLDG 305 APG
5	CDR USAATC ATTN WALTON G RICE D LACEY C HERUD STECS DA ID L FRANCIS
36	DIR USARL ATTN AMSRL WT I MAY J ROCCHIO D ECCLESHALL AMSRL WT P A HORST E SCHMIDT P KASTE AMSRL WT PC B FORCHE R PESCE-RODRIGUEZ AMSRL WT PB P PLOSTINS D LYON A ZIELINSKI AMSRL WT PD B BURNS AMSRL WT PA T MINOR M DEL GUERCIO J DESPIRITO

NO. OF
COPIES ORGANIZATION

A JUHASZ
J KNAPTON
G KATULKA (5 CYS)
G KELLER
P CONROY
D KOOKER
W OBERLE
C RUTH
T ROSENBERGER
I STOBIE
P TRAN
K WHITE
G WREN
M MCQUAID
AMSRL WT T W MORRISON
AMSRL WT W C MURPHY
AMSRL WT WB W D'AMICO
AMSRL WT WD
A NIILER
C HOLLANDSWORTH
J POWELL