Modeling of the Plasma-Propellant Interaction

Andrew J. Porwitzky, Michael Keidar, and Iain D. Boyd

Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI 48109 USA

Plasma-propellant interaction for application to an electrothermal gun is studied theoretically. Electrothermal-chemical (ETC) guns are used for enhancement of the ignition and combustion of the energetic propellant. A detailed understanding of the dynamics of the plasma-propellant interaction is considered one of the key elements to the future success of practical ETC gun implementation. A model of the propellant ablation under plasma effect is developed based on the kinetic theory of ablation. The ablation model is coupled with a model of the plasma generation in the capillary discharge that allows calculation of the effective heat flux from the plasma. Calculations are performed for specific experimental conditions in which ablated mass of a double-base and a nitramine composite propellant are studied. An ablation model is used to predict the ablation rate of the propellant for different bulk plasma densities. An effective heat flux from the plasma is found which yields the experimentally determined ablated mass. One representative solution reproduces the experimentally determined ablated mass for the double-base propellant of 5.3 mg via an effective heat flux on the order of 4×10^8 J/m^{2}s. The effective heat flux that corresponds to the experimentally measured ablated mass is determined for different propellants. Differences in the calculated effective heat flux between different propellants indicate that although heat convection from the plasma is the dominant source of energy, plasma radiation, and the optical properties of the propellants themselves cannot be ignored. The difference in plasma heat flux between propellants can readily be explained by partial absorption of plasma radiation consistent with the optical properties of the propellants.

Index Terms—**Electrothermal chemical (ETC), heat flux, modeling, plasma, propellant.**

I. Introduction

THERE IS much interest in the design and implementation of electrothermal-chemical (ETC) guns. ETC guns use a capillary discharge plasma to ignite the solid propellant providing explosive force to a projectile. This ignition method leads to an enhancement of the ignition and combustion of the energetic propellant. Among these enhancements is the fact that measured ETC ignition time is on the order of one-third the ignition time of conventional chemical igniters, reducing ignition time to the order of 1–2 ms [10]. Previous modeling has not fully taken into account the dynamics of the plasma-propellant interaction, nor the properties of the capillary plasma source [11], [12]. A detailed understanding of the dynamics of the plasma-propellant interaction is considered one of the key elements to the future success of practical ETC gun implementation. The optimum plasma/propellant pair for most efficient ETC gun design is not currently known. In this paper, we model the plasma-propellant interaction for two solid gun propellants currently under consideration for future ETC gun implementation. The two propellants considered are a double-base propellant JA2 and a nitramine composite propellant XM39. Experimental data is available to determine the ablated mass of each propellant [1]. This information is incorporated into the model to find the affective heat flux from the plasma reaching the propellant surface during the plasma pulse and the resulting surface temperature. Differences in the optical properties of JA2 and XM39 lead to differences in radiative heat fluxes consistent with the model results. Results for plasma heat flux are also within the operational range of the capillary discharge device. The model developed is based on the kinetic theory of ablation. The ablation model is coupled with a model of the plasma generation in the capillary discharge and a thermal model for the propellant sample that allows calculation of the effective heat flux from the plasma. Calculations are performed for a range of possible bulk plasma densities, as the experimental value is unknown. The acceptable range of bulk plasma densities n_o based on the capillary discharge device and the experimental setup [1], is believed to be in the range of 10^{21}–10^{24} m^{-3}. During the experiment, propellants were exposed to the plasma in an open chamber to avoid pressure build up, thus preventing propellant ignition. All propellant mass loss can, therefore, be attributed to interaction with the plasma alone, and not due to burning [1].

II. Model Description

The kinetic theory of the ablation model is adapted from previous work by Keidar *et al.* [2]. To model the propellants, vapor pressure and enthalpies of sublimation are calculated via an averaging technique based on their percent composition of constituent compounds obtained from Miller [3], as no experimental data is available. Vapor pressure of constituent compounds were taken from experimental data or modeled via the Clausius–Clapeyron equation using the enthalpy of sublimation and performing a fit to one or more known data points for vapor pressure when experimental data was unavailable. These compound vapor pressures are then averaged via percent composition to yield an estimate of the vapor pressure of the propellant (Fig. 1). The calculated vapor pressure versus surface temperature equations for JA2 and XM39 are given as (1) and (2), respectively, where P is in Pascals and T_s is in Kelvin. Similarly, values for enthalpy of sublimation of the propellants was estimated yielding 4.41×10^5 J/kg for JA2 and 5.47×10^5 J/kg for XM39. The thermal model required additional parameters shown in Table I. The limits of current

Digital Object Identifier 10.1109/TMAG.2006.887674

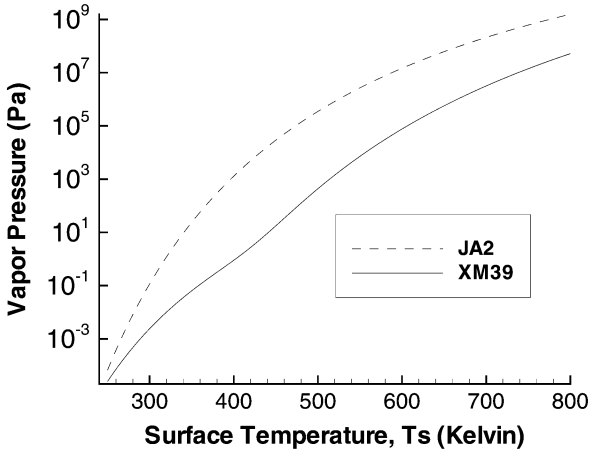


Fig. 1. Calculated vapor pressure for each propellant.

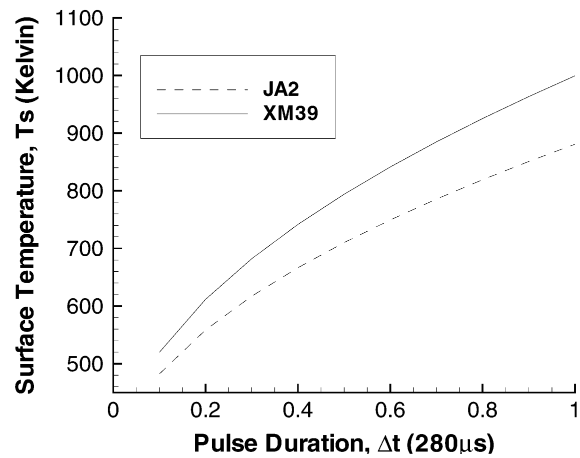


Fig. 2. Representative surface temperature versus increments of plasma pulse duration for each propellant that matches their respective experimental ablated masses at $n_o = 1 \times 10^{21}$ m^{-3}. Effective heat fluxes are 4.1×10^{8} W/m^2 and 2.75×10^{8} W/m^2 for JA2 and XM39, respectively.

TABLE I
THERMOPHYSICAL PROPERTIES TAKEN FROM [3]

	$C_p\ (J/kgK)$	$\lambda\ (W/Km)$	$\alpha\ (m^2/s)$
JA2	$1520.45, 75°C$	$0.280, 49°C$	$1.30 \times 10^7, 49°C$
XM39	$1296.35, 75°C$	$0.246, 48°C$	$1.21 \times 10^7, 48°C$

experimental data made it necessary to use low temperature values and assume them as constant for the simulation. Shown are the values used throughout this paper as well as the temperature that the data were taken from [3].

Where C_p is the specific heat at constant pressure, and λ and α are the thermal conductivity and diffusivity of the propellant, respectively.

$$P_{\mathrm{JA2}}(T_s) = 0.2518\exp(36.5447 - 11222/T_s) + 0.1579\exp(32.9496 - 10715.4/T_s) + 0.0074\exp(17.2491 - 8005.77/T_s) \quad (1)$$

$$P_{\mathrm{XM39}}(T_s) = 0.76\exp(37.5986 - 15648.3/T_s) + 0.076\exp(19.3853 - 6849.89/T_s) + 0.004\exp(18.1824 - 7541.5/T_s). \quad (2)$$

The ablation model is coupled with a one-dimensional (1-D) thermal model to predict the surface heat flux q incident on the propellant. Preliminary studies show that over the duration of the brief plasma pulse, roughly $\Delta t = 280\ \mu$s, the propellant surface temperature T_s rises very slowly and does not reach a steady state value (Fig. 2). The T_s profile is, thus, numerically integrated for a certain q, n_o pair to determine the total ablated mass. It is assumed that the propellant surface is exposed to the uniform bulk plasma for the duration $0 \leq t \leq \Delta t$, after which time the plasma dissipates fully. The surface temperature after the plasma pulse is modeled empirically as $T = T_s(\Delta t/t)^{1/2}$ [4]. For cooling, there will be no ablation after the vapor pressure of the propellant reaches atmospheric pressure, so this gives an upper bound on t. There are a number of reasons to expect the propellant to cool rapidly after the pulse. During the experiment [1], the sample was held in place by an object of significantly larger thermal mass, which would act as a sink for cooling. Room temperature air would be pushed out of the experimental chamber by the plasma wave, with cool air rushing back into the chamber after the pulse, dropping the ambient temperature. Perhaps, most importantly, the thermal model indicates that at the end of the pulse the temperature gradient is contained within 1% of the surface, an effect that will lead to more rapid surface cooling. In addition, with 99% of the sample still at room temperature, there is much room within the homogeneous propellant for the heat to dissipate.

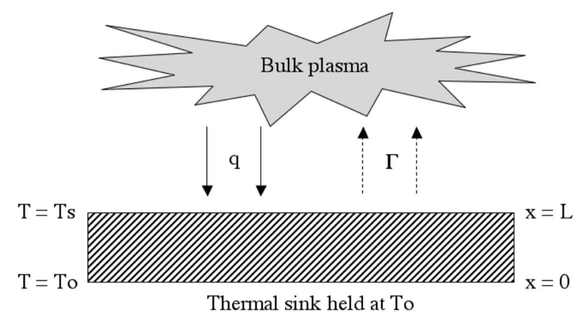


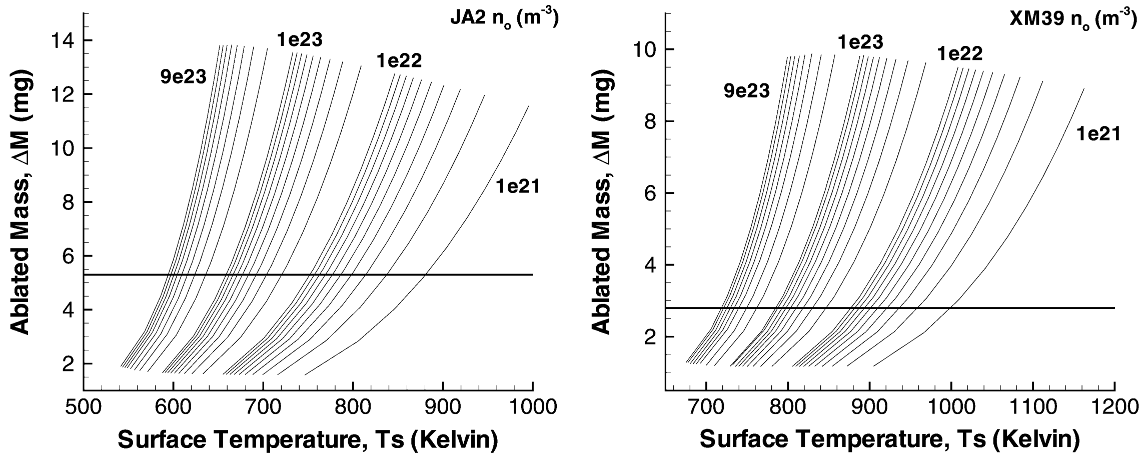
Fig. 3. Thermal model coordinate system.

The thermal model requires a solution to the 1-D heat flux equation with boundary conditions given as

$$\partial_t T(x,t) = \alpha \partial_x^2 T(x,t)$$
$$T(0,t) = T_o, T(x,0) = T_o \quad (3)$$
$$\partial_x T(L,t) = -\lambda^{-1}(q - \Delta H \Gamma - C_p(T_s - T_o)\Gamma)$$

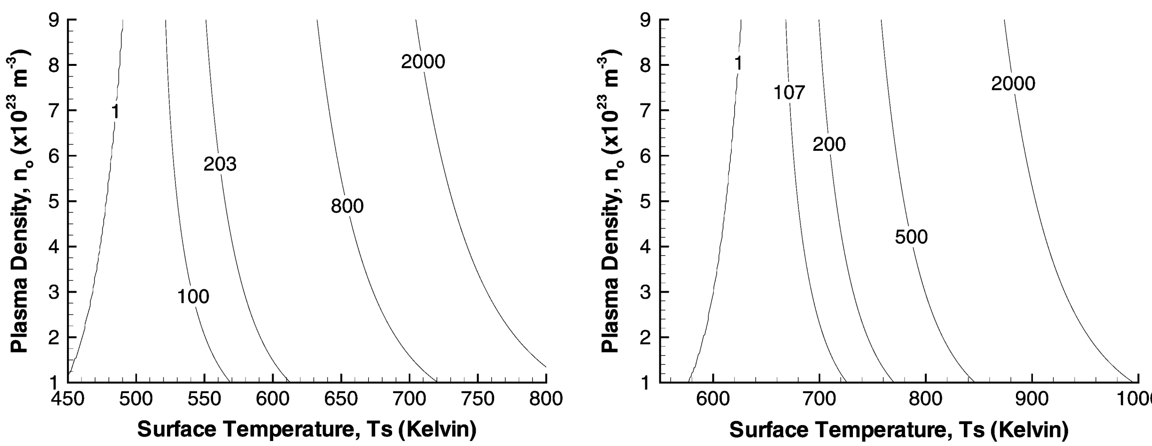
where Γ is the ablation rate, ΔH is the enthalpy of sublimation of the propellant, $L = 4$ mm is the propellant thickness, T_o is the initial propellant temperature taken to be 298 K, and q is the heat flux from the plasma to the propellant surface, assumed to be constant. The coordinate system used can be seen in Fig. 3. The appropriate plasma temperature according to the capillary model is $T_e = 1.5$ eV [7].

The effective heat flux can be modeled as $q = q_{\mathrm{conv}} + q_{\mathrm{rad}}$, the sum of the convective (particle flux) and radiation heat fluxes, respectively. The particle heat flux to the surface can be modeled as follows: $q_{\mathrm{conv}} = n_o v_B (3T_e + \Delta\phi)$, where $v_B = \sqrt{T_e/m_i}$ is



(a) (b)

Fig. 4. Simulation results for ablated mass versus propellant surface temperature. (a) JA2. (b) XM39.



(a) (b)

Fig. 5. Ablation rate contours for each propellant. (a) JA2. (b) XM39.

the ion Bohm velocity, m_i is the average ion mass taken here to be 8 amu, and $\Delta\phi = 0.5T_e \ln m_i/(2\pi m_e)$ is the potential drop due to charge buildup on the propellant surface. The radiation flux is, thus, the difference of q and q_{conv}.

Heat flux q and plasma density n_o, are used as parameters in the thermal model. Plasma density appears in the model for Γ [2]. Once the surface temperature profile during the pulse is determined, it is combined with the estimate for surface temperature after the pulse and numerically integrated to yield a total ablated mass for some q, n_o pair. In order to find the heat flux that exactly matches the experimental results [1], a polynomial fit of ablated mass as a function of heat flux for a given plasma density is performed and numerically solved for the experimental ablated mass.

III. Results

Coupling the ablation model and thermal model of the propellant make it possible to calculate the ablated mass of the propellant exposed to the capillary plasma. In this calculation, the geometry of [1] is adopted. To match experimental results, a total ablated mass is needed for JA2 of 5.3 mg and for XM39 of 2.8 mg [1], shown as horizontal lines on Fig. 4. In the experiment, the distance between the capillary exit and the sample was 25 mm, with a capillary charging voltage of 4 kV. The curves presented are for different bulk plasma densities. T_s is the propellant surface temperature at $t = \Delta t$ and the ablated mass ΔM is in milligrams.

Fig. 5 contains contour plots of Γ in T_s, n_o space for each propellant. Assuming a constant ablation rate in the experiment yields ablation rates for JA2 and XM39 of 203 and 107 kg/m^{2}s, respectively [1]. These plots suggest that the same ablated mass can be achieved with various combinations of plasma density and propellant surface temperature. For the calculation of heat flux, T_s was eliminated as a free parameter by the thermal model results such as those shown in Fig. 2.

IV. Discussion

It is assumed that for both propellant samples, the capillary generates a plasma with identical properties. Thus, any differences in the incident heat fluxes are due to differences in the propellants themselves. The model predicts that JA2 will consistently have a higher effective heat flux than XM39 (Fig. 6), and that XM39 will have a higher surface temperature (Fig. 4). As

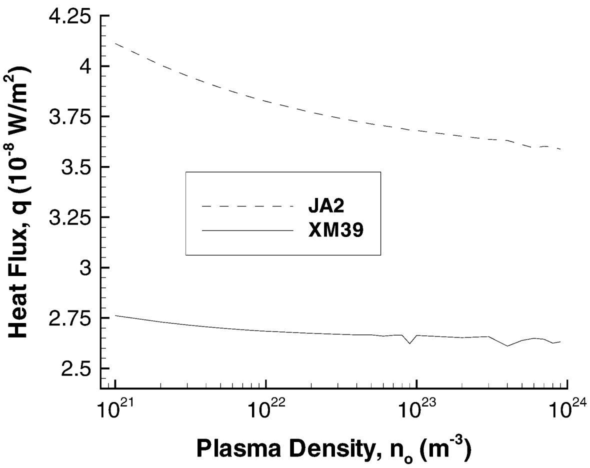


Fig. 6. Effective plasma heat flux to each propellant predicted by model, where the ablated mass equals the experimental value.

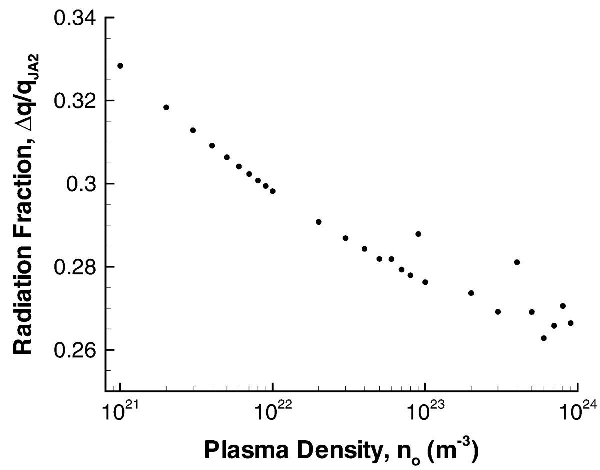


Fig. 7. $\Delta q/q_{\rm JA2}$ the dependance of the fraction of radiation flux on the plasma density in the vicinity of the propellant.

plasma density increases, heat flux (or surface temperature) will decrease, as evident in Figs. 4 and 6. This can be explained via the ablation rate contours; following a contour on Fig. 5 shows that as plasma density increases, the surface temperature will decrease. This change in ablation rate affects the heat flux through the thermal model boundary conditions.

A comparison of the optical properties of the two propellants is made. Nitramine composite propellants are opaque to most wavelengths, and studies indicate that they do not allow radiation to penetrate and effect change in-depth. It has been demonstrated that JA2 allows radiation to penetrate in-depth, with physical and chemical changes occurring up to approximately 1 mm into the propellant [5], [6]. In addition, it has been determined in experiments that XM39's reflectivity may be as high as 50% [13]. This evidence suggests that the difference between the heat flux to JA2 and XM39 is due to the optical properties of each propellant, specifically to penetrating radiation from the plasma.

Calculation of the expression for $q_{\rm conv}$ may overestimate the heat flux. Given that the plasma sheath thickness is generally several Debye lengths, calculation of the Knudsen number leads to the conclusion that the sheath is collisional and entering the continuum regime, indicating that an MHD approach to modeling the particle heat flux to the surface is most appropriate. Among the properties of a collisional plasma sheath is the effect of reducing $q_{\rm conv}$ to a level that should agree with the presented simulation results. The dynamics of a collisional plasma sheath in the continuum regime is a topic of interest in a wide range of applications from analysis of probe measurements [8] to fusion devices [9]. Common simplifications to the hydrodynamic equations exist which have the potential to yield insight into the present topic [8]. A future work will apply an MHD analysis to the present problem.

As noted earlier, the radiative heat flux for JA2 is expected to be much higher than for XM39, although XM39 should still have a small radiative flux due to surface heating. Thus, the difference between the heat flux to each propellant Δq can be roughly interpreted as the difference in penetrating radiation flux between the propellants. It should be noted that Δq represents only a small fraction of the radiative heat available in a black body plasma at $T_e = 1.5$ eV. This can be partially explained by indications that vaporized propellant can act as a plasma radiation shield, helping to block some of the radiation flux [1]. Continuing this line of reasoning, $\Delta q/q_{\rm JA2}$ can be approximated as the percent of JA2's heat flux attributable to penetrating radiation (Fig. 7), which drops from 33% at low density to 28% at high density. This indicates that penetrating radiation is responsible for between a quarter and a third of JA2's total effective heat flux.

Recent experimental work by Das *et al.* [14] indicates that the heat flux estimate presented here lies at least within an order of magnitude of reality. In the experiment, temperature sensors were placed behind an optically transparent stagnation plate which only allowed radiative heat flux to affect the sensors. When a capillary discharge plasma was directed at the plate, the surface temperature as a function of time was determined. A thermal model similar to that employed here was used to determine the radiative heat flux incident on the surface. For a capillary-sample distance of 50 mm and capillary charging voltage of 2.5 kV, a peak heat flux of 1.4×10^7 W/m^2 was found. Increasing the sample distance to 75 mm, decreased the peak heat flux to 3.8×10^6 W/m^2 [14]. In this paper, the radiative heat flux is on the order of $\Delta q = 10^8$ W/m^2. It is well within reason that a decrease in capillary-sample distance to 25 mm and an increase in charging voltage to 4 kV could readily yield a radiative heat flux on the order of Δq.

V. Conclusion

It was found that although ablation alone accounts for a majority of the heat flux from the plasma, the optical properties of the propellants can not be ignored. Effective heat flux from the propellant was found to be in the range 2.5–4.25$\times$ 10^8 W/m^2. It is estimated by comparison to XM39 that penetrating radiation accounts for between one-quarter to one-third of JA2's radiation flux. Our results agree with previous experimental work that indicates the most effective propellant choice is one that allows plasma radiation to penetrate its interior, allowing for an additional mode of heating beyond particle flux.

ACKNOWLEDGMENT

This work was supported by the Army Research Office under Grant W911NF-04-1-0251 (Dr. K. McNesby, technical monitor). The authors would like to thank Dr. R. Beyer, Dr. M. Nusca, Dr. A. Williams, and Dr. R. Pesce-Rodriguez from the Army Research Laboratory for their useful discussions and suggestions.

REFERENCES

[1] J. Li, T. A. Litzinger, and S. Thynell, "Interaction of capillary plasma with double-base and composite propellants," *J. Propulsion Power*, vol. 20, no. 4, pp. 675–683, Jul./Aug. 2004.

[2] M. Keidar, I. D. Boyd, and I. I. Beilis, "On the model of Teflon ablation in an ablation-controlled discharge," *J. Phys. D: Appl. Phys.*, vol. 34, pp. 1675–1677, 2001.

[3] M. Miller, "Thermophysical properties of six solid gun propellants," ARL-TR-1322, 1997.

[4] M. Keidar, I. D. Boyd, and I. I. Bellis, "Electrical discharge in the Teflon cavity of a coaxial pulsed plasma thruster," *IEEE Trans. Plasma Sci.*, vol. 28, no. 2, pp. 376–385, Apr. 2000.

[5] R. A. Beyer and R. A. Pesce-Rodriguez, "The response of propellants to plasma radiation," *IEEE Trans. Magn.*, vol. 41, no. 1, pp. 344–349, Jan. 2005.

[6] R. A. Pesce-Rodriguez and R. A. Beyer, "A theory of plasma-propellant interactions," ARL-TR-3286, 2004.

[7] M. Keidar and I. D. Boyd, "Ablation study in the capillary discharge of an electrothermal gun," *J. Appl. Phys.*, vol. 99, no. 053301, 2006,.

[8] M. S. Benilov, "Can the temperature of electrons in a high-pressure plasma be determined by means of an electrostatic probe?," *J. Phys. D: Appl. Phys.*, vol. 33, pp. 1683–1696, 2000.

[9] P. C. Stangeby, *The Plasma Boundary of Magnetic Fusion Devices*. Bristol, U.K.: Inst. Phys., 2000.

[10] A. Koleczko, W. Ehrhardt, S. Kelzenberg, and N. Eisenreich, "Plasma ignition and combustion," *Prop. Explos. Pyrotech*, vol. 26, pp. 75–83, 2001.

[11] J. D. Hurley, M. A. Bourham, and J. G. Gilligan, "Numerical simulation and experiment of plasma flow in the electrothermal launcher SIRENS," *IEEE Trans. Magn.*, vol. 31, no. 1, pp. 616–621, Jan. 1995.

[12] N. P. Orton and J. G. Gilligan, "Simulation of the plasma-surface interaction in electric launchers," *IEE Trans. Magn.*, vol. 31, no. 1, pp. 640–644, Jan. 1995.

[13] R. Beyer, *private communication.* Nov. 29, 2005.

[14] M. Das, S. T. Thynell, J. Li, and T. A. Litzinger, "Transient radiative heat transfer from a plasma produced by a capillary discharge," *J. Thermophys. Heat Transfer*, vol. 19, no. 4, pp. 572–580, Oct./Dec. 2005.

Manuscript received December 16, 2005 (e-mail: aporwitz@umich.edu).