

Experimental Characterization of Plasma Effects on Energetic Materials for Electrothermal-Chemical Launch Applications

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ABSTRACT—Energetic electrical plasmas play a fundamental role in the electrothermal-chemical (ETC) propulsion concept, where they are used to provide energy conversion from an electrical power source to the combustion chamber of an ETC launcher. Recent research in the areas of large-caliber ETC gun experiments as well as small-scale plasma experiments have demonstrated the ability to alter the propellant combustion process and the chemical or physical properties of propellant samples exposed to energetic electrical plasmas. Such results have warranted continued investigations into the underlying processes involved in propellant and plasma interactions, specifically in the behavior of exposed propellant samples to plasmas operating at varying degrees of electrical power.

Experimental characterization has been performed with various samples of energetic materials including JA2, CL20, RDX, M9, M30, M43, HELP, and BAMO-AMMO (BA), which were allowed to interact with plasmas having different electrical power levels. The plasma power level ranged from 60 MW to a maximum of 264 MW, and total energy transferred to the plasma capillary ranged from 17 to 70 kJ. Propellant samples were analyzed using a Fourier transform infrared spectroscopy (FTIR) technique, which was used to determine the effects of plasma exposure on the energetic materials.

Preliminary results from the experiments indicate that some propellant formulations are easily altered (either chemically or physically) or ignited by a plasma while others are less sensitive to the plasma exposure. In addition, the effects of the plasma are found to be minimized with the introduction of protective films even for plasmas of high power and energy levels.

Index Terms—electrothermal/electrothermal-chemical launchers.

I. INTRODUCTION

The electrothermal-chemical (ETC) gun concept is an advanced propulsion concept that incorporates a highly energetic electrical plasma for ignition and potentially combustion control mechanisms for improving the ballistic performance beyond that obtainable with conventional chemical gun propulsion. Recent research in the area of large-caliber ETC gun firing experiments ignited by plasma generators as well as small-scale plasma-propellant experiments have demonstrated significantly different behavior compared to conventionally ignited combustion events. Specifically, it has recently been demonstrated both within the government and private industry that increases to projectile muzzle velocity and propellant burn rates, and improvements in gun ignition reproducibility, can be obtained with the use of electrical

plasma energy [1]–[3]. Also, it has been demonstrated previously that the plasma properties of kinetic pressure, core temperature, and conductivity are easily modulated by the operating power level of the plasma [4]. Resulting effects of plasma power modulation include altering the spectral content of the plasma source. For example, plasmas at higher power levels generally exhibit a larger percentage of shorter wavelength energy compared to those of lower power due to the increased ohmic heating of the higher power plasma. Other investigations of propellant properties used for ETC launchers have shown large differences in the optical characteristics of sample propellants, which may be important for radiation transport into the surface of propellant samples. It is believed that the ability to optimize the energy transfer from the plasma to the propellant could have a large impact on the overall performance of ETC launchers, and, therefore, specific requirements and an understanding of the physical behavior of both the plasma and candidate propellants will be necessary prior to ETC weapon optimization. The objective of the experiments detailed in this report is to perform a preliminary assessment of the physical and chemical effects induced in candidate energetic materials exposed to a highly energetic plasma having varied pulsed power amplitudes.

II. EXPERIMENTAL PROCEDURE

A 100-kJ capacitor-based pulsed-power supply (PPS) was designed, assembled, and tested for generating high-energy plasma sources for the experiments performed. In addition, theoretical calculations were performed with electronic circuit analysis software and a steady-state, one-dimensional (1-D) plasma code [5] for the purpose of predicting the required PPS electrical configuration, the operating voltage, input plasma generator current, plasma generator dimensions, and resultant plasma temperature. The power supply consists of two 11-kV, 800- μ F capacitors interconnected with a 10- μ H inductor and an ignitron switch as indicated in the diagram of the experimental set-up in Fig. 1. The plasma generator has an inner diameter of 0.635 cm and an overall length of about 10.16 cm. A number of experiments were conducted using a set of energetic samples that were (1) exposed directly to the freely propagating electrical plasma, or (2) exposed to the plasma through a protective film of Mylar (polyethylene terephthalate), or (3) exposed to the plasma through a protective film of aluminum. It is believed that although the plasma discharge is fairly repeatable at a given power and energy level with respect to plasma structure and the expansion process, the array of energetic samples and the degree to which the samples are exposed will likely vary in a given test due to nonuniformity in the spacial characteristics of the freely expanding plasma.

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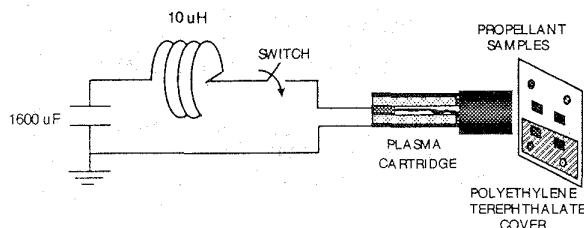


Fig. 1. Diagram of PPS, plasma generator, and propellant sample holder for plasma-propellant interaction studies.

The power level of the plasma was fixed at 60, 125, and 264 MW of peak power, and post-testing analysis was performed on the samples. The test matrix along with the test conditions, percentage of constituent materials (in parentheses), and the experimental results are summarized in the data provided in Tables 1-4. Typical dimensions measured for the energetic samples characterized ranged from 0.5 to 1 cm long and approximately 1 to 2 mm thick. Energetic samples were arranged on the sample holder in an arbitrary fashion with sample centers spaced approximately 2 cm from adjacent energetic samples.

The results from the experiments indicated the 60-MW plasma produced structural and possibly chemical changes to the samples but not ignition. It was determined from the experiments conducted that a thin sheet of Mylar film was very effective in shielding the plasma from the samples and keeping propellant ignition from occurring even at the 125-MW power level. Also, mechanical fracturing of propellant occurred, providing information on the pressure produced by the plasma near the surface of the samples. The experimental matrix included tests where samples were exposed directly to the plasma while other tests consisted of energetic samples protected from the plasma source with thin layers of Mylar or aluminum foil. The Mylar film was used to filter plasma convective energy and ultraviolet radiation while the aluminum film was to filter plasma radiative energy. The test conditions were arranged such that all samples were firmly fixed approximately 30.48 cm in front of the plasma output nozzle. The direction of propagation of the plasma was normal to the surface of the samples. Based upon computer simulations of the plasma at the 125-MW power level, it is estimated that the core plasma temperature reached about 30,000 K.

III. DISCUSSION AND CONCLUSIONS

The following observations were made as a result of the plasma and propellant interaction experiments that were completed in the six sets of tests performed.

1. *Energetic material (JA2 propellant) exposed directly to the 60-MW plasma in experiment T1 did not result in propellant ignition; however, surface modifications to the samples were identified.* The modifications included surface color changes and surface charring of the material. The results from T2 indicated that all of the JA2 samples of propellant were ignited by the direct exposure to the 264-MW plasma, regardless of the presence or type of protective film used. In T3, the JA2

TABLE I
EXPERIMENTAL RESULTS FROM PLASMA-PROPELLANT INTERACTIONS STUDIES
OF TESTS 1-3

Test I.D. #	Peak Power (MW)	Propellant Tested	Covering Used	Experiment Results
T1	60	JA2		No ignition, surface changes from green to white
		JA2	Mylar	No ignition, surface changes from green to white
		JA2	A1 foil	No ignition, surface changes from green to white
T2	264	JA2		Sample ignited
		JA2	Mylar	Sample ignited
		JA2	A1 foil	Sample ignited
T3	60	JA2		Partial ignition, probably from CL20
		JA2		Partial ignition, probably from CL20
		JA2		Partial ignition, probably from CL20
		CL20		Sample ignited

samples appeared to have some signs of partial ignition; however, the ignition appeared to have been caused by the vigorous ignition and combustion products from the nearby CL20 sample in that test. It was noted that CL20 samples were more sensitive (compared to JA2) to the plasma having been ignited by the 60-MW plasma. In experiment T4, all ten

TABLE II
EXPERIMENTAL RESULTS FROM PLASMA-PROPELLANT INTERACTIONS
STUDIES OF TEST 4 AT 125 MW (ALL SAMPLES DID NOT HAVE A PROTECTIVE
COVERING)

Test I.D. #	Peak Power (MW)	Propellant Tested	Experiment Results
T4	125	JA2	Sample ignited
		M30	Sample ignited
		M10	Sample ignited
		RDX-NQ-BA (52-24-24)	Sample ignited
		CL20-BA (70-30)	Sample ignited
		M43	Sample ignited
		RDX-BA (73-27)	Sample ignited
		RDX-NQ-BA (58-18-24)	Sample ignited
		CL20-NQ-BA (52-24-24)	Sample ignited
		M9	Sample ignited

TABLE III
EXPERIMENTAL RESULTS FROM PLASMA-PROPELLANT INTERACTIONS STUDIES
OF TEST FIVE AT 125 MW WITH AND WITHOUT MYLAR COVERING

Test I.D. #	Peak Power (MW)	Propellant Tested	Covering Used	Experiment Results
T5	125	CL20-BA (70-30)		Sample ignited
		RDX-NQ-BA (58-18-24)		Sample ignited
		CL20-BA (73-27)		Sample ignited
		RDX-BA (72-27)		No ignition
		M9		No ignition
		JA2		Sample ignited
		HELP (76 RDX, 16 CAB, 8 plasticizer)		No ignition
		CL20-BA (70-30)	Mylar	No ignition
		RDX-NQ-BA (58-18-24)	Mylar	No ignition
		CL20-BA (73-27)	Mylar	No ignition
		RDX-BA (73-27)	Mylar	No ignition
		M9	Mylar	No ignition
		JA2	Mylar	No ignition
		HELP (same as above)	Mylar	No ignition, but propellant fractured

propellant samples ignited with direct exposure to the 125-MW plasma. In T5, four out of the set of seven exposed energetic samples (including CL20-BA, RDX-NQ-BA, RDX-BA, and JA2) and all exposed samples in T6 produced strong signs of ignition upon direct interaction with a 125-MW plasma.

2. All samples (set of seven) covered with a thin Mylar film were shielded from the plasma and did not ignite when exposed to a 125-MW plasma in test T5. However, most (six of nine) samples ignited when the protective cover was changed to aluminum foil in T6, which used the same plasma power level of 125 MW. Ignited samples included RDX-NQ-BA, RDX-BA, M9, JA2, and two types of CL20-BA. It was noted that the characteristics (physical and optical properties) of the Mylar and aluminum protective films used during the experiments were much different and may play a role in determining the type and amount of reaction allowed in the propellant samples. For example, the Mylar film used in test T5 did not rupture as a result of the kinetic energy introduced by the plasma. Conversely, in T6 the aluminum foil was severely ruptured. If the aluminum foil ruptured early in the plasma exposure process of T6, then the samples would have been directly exposed to the plasma possibly for a significant length of time. It was also observed in T5 that a sample of HELP propellant covered with Mylar produced signs of fracturing

TABLE IV
EXPERIMENTAL RESULTS FROM PLASMA-PROPELLANT INTERACTIONS STUDIES
OF TEST SIX AT 125 MW WITH AND WITHOUT ALUMINUM COVERING

Test I.D. #	Peak Power (MW)	Propellant Tested	Covering Used	Experiment Results
T6	125	CL20-BA (70-30)		Sample ignited
		RDX-NQ-BA (58-18-24)		Sample ignited
		CL20-BA (73-27)		Sample ignited
		RDX-BA (73-27)		Sample ignited
		M9		Sample ignited
		JA2		Sample ignited
		HELP (76 RDX, 16 CAB, 8 plasticizer)		Sample ignited
		RDX-CL20 (50-50)		Sample ignited
		CL20-NQ-BA (52-24-24)	A1 foil	Sample ignited
		CL20-BA (70-30)	A1 foil	Sample ignited
		RDX-NQ-BA (58-18-24)	A1 foil	Sample ignited
		CL20-BA (73-27)	A1 foil	Sample ignited
		RDX-BA (73-27)	A1 foil	Sample ignited
		M9	A1 foil	Sample ignited
		JA2	A1 foil	Sample ignited
		HELP (same as above)	A1 foil	No ignition
		RDX-CL20 (50-50)	A1 foil	No ignition
		CL20-NQ-BA (52-24-24)	A1 foil	No ignition, but deformation

during exposure to the 125-MW plasma. This result indicated that the peak pressure in the vicinity of the propellant surface possibly reached as high as the fracturing threshold, estimated at between 40 and 60 MPa, for the particular formulation of the HELP propellant studied [6].

3. Fourier transform infrared spectroscopy (FTIR) analyses of propellant surfaces indicated definite chemical changes to those samples exposed directly to the plasma that did not ignite in test T5. This included (1) denitration of the nitrate ester in M9, (2) denitration of nitrocellulose in HELP, and (3) reduction of the RDX composition in the RDX-BAMO-AMMO sample. In addition, preliminary measurements using FTIR techniques also indicated possibly some chemical modification to several propellant samples exposed to the plasma through the protective Mylar film, but further testing is required to confirm these measurements.

IV. FUTURE RESEARCH

The plasma propellant interaction experiments reported here are considered as providing an initial assessment of the effects of ETC plasma generators, operating at varied power and energy levels, on the behavior of a wide variety of candidate energetic materials under the conditions of varying plasma exposure levels. Based upon the results of these experiments, it appears that there is evidence that propellant chemistry and the physical characteristics of the plasma play a role in the amount of energy deposited to samples of energetic materials. Future experiments should include analysis with spectroscopic techniques and temperature measurements of the plasma in the vicinity of the energetic sample surfaces.

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