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4. TITLE AND SUBTITLE OF REPORT

Augmentation and Control of Burn Rates In Plasma Devices

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8. PERFORMING ORGANIZATION REPORT NUMBER:

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11. SUPPLEMENTARY NOTES:

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Navy position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

DTIC QUALITY INSPECTED 2

13. ABSTRACT (Maximum 200 words)

Enhanced burn rates of JA-2 solid granular propellant through plasma ignition is evident. Burn rates increased by about a factor of 3 compared to conventional ignition, when plasma is injected normal to the surface of the propellant sample. Geometrical influence on JA-2 burn rates with plasma ignition showed increased burn rate with increased angle of injection. Time-averaged plasma temperatures of 0.8 to 1.2 eV and plasma densities of 2×10^{23} to 4.5×10^{23} m^{-3} have been deduced from relative intensities and stark broadening of copper lines. Erosive burn may be affected by formation of new surface areas governed by the initial level of plasma-propellant interaction. Increased neutral constituents at the plasma-propellant interface at larger injection angles may also be responsible for the observed decrease in line intensity. The vapor shield plasma at the flame temperature has a strong effect on radiative heating, the boundary layer becomes optically thick and absorbs a large fraction of the incoming energy. Plasma boundary layer temperature is less than that of the core plasma showing an energy transmission factor of less than 10% at large inclination angles, suggesting that plasma kinetic pressure has a stronger effect on the burn rate than the plasma radiative heat flux.

14. SUBJECT TERMS

ETC, Burn Rates, Radiative Heating, Erosive Burn, Plasma Flow.

15. NUMBER OF PAGES: 9

16. PRICE CODE

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UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

End-of-the-Fiscal-Year Summary
September 30, 1996

AUGMENTATION AND CONTROL OF BURN RATE IN PLASMA-DEVICES

(Contract N00014-95-1-1221, P Number 96 pro 4536-00)
Department of the Navy, Office of Naval research

Mohamed A. Bourham and John G. Gilligan
North Carolina State University, Department of Nuclear Engineering
Raleigh, N. C. 27695-7909

Scientific/Technical Goals:

To understand the physical processes of plasma-chemical devices and the role of the boundary layer at the plasma-propellant interface, and possibly controls and enhances the burn rates of solid propellants for electrothermal-chemical launch applications. It has been shown that plasma injection into solid propellants enhances the burn rates, however, mixing processes are still not well understood. The effectiveness of electrothermal plasma injection into propellants resides, primarily, in radiative heating of the propellant from the plasma. The importance of radiative heating is to assess the burn rate process and whether plasma injection enhances the burn rate, or the burn rate will be limited by the evolving vapor plasma cloud. The scientific and technical goals of this research aiming to understand, characterize, and possibly control the plasma-chemical energy transport process by measuring the burn rate of candidate combustible materials (propellants), to explore the plasma-chemical interaction micro-processes, and the flame vapor shield mechanism.

Our approach focuses on:
i) Boundary layer physics in at the plasma-propellant interface
ii) Experiments on burn rates of various propellants
iii) Geometrical influence
iv) Role of radiative heating
v) Decoupling plasma parameters and effect of individual properties on burn rates
vi) Diagnostics development
vii) Modeling of plasma flow and flame-vapor shield (turbulent flow with radiation transport)

Significant Accomplishments:

The experiments conducted on the NCSU plasma-propellant device PIPE have showed that electrothermal plasma injection into the solid granular JA-2 propellant provided an enhancement to the burn rates. Burn rates increased by about a factor of 3 when compared to conventional ignition, when plasma is injected normal to the 7-hole surface of the propellant sample. The mass evolution rate scales with pressure, and the pressure exponent with plasma injection increases from 0.899 to 1.376, indicating higher burn rates at less surface pressure. Conventional ignition requires higher pressures for the same burn rates. Geometrical influence on JA-2 burn rates with plasma injection is clear from experiments conducted at various injection angles, showing an increased burn rate with increased angle of injection. Visible emission spectroscopy has been used to observe the interface of the electrothermal plasma with the propellant in order to monitor the effect of angle of incidence on the burn rates.

Time-averaged plasma temperatures of 8,800 to 14,000 °K and plasma densities of 2×10^{23} to 4.5×10^{23} m^{-3} have been deduced from spectroscopy measurements, showing gradual decrease in both temperature and density with increase injection angle from 0 to 45°. The increase in integrated intensity and density at 90° corresponds to a strong increase in burn rate, suggesting that plasma kinetic pressure has a stronger effect on the burn rate than the plasma radiative heat flux. This may result form the effect of vapor shield plasma at the flame temperature, where the boundary layer becomes optically thick and absorbs a large fraction of the incoming energy. Increased neutral constituents at the plasma-propellant interface, at larger injection angles, may also be responsible for the observed decrease in plasma density. However, the sudden increase in plasma density at 90° may be explained if evolution of neutral constituents becomes limited when new surface areas are formed.

Investigation into the vapor shield effect has been conducted by comparing the plasma temperature at the boundary to that extracted from the ODIN (1-D, time dependent) code. The ODIN code predicts the core plasma temperature, which the plasma boundary temperature is that evaluated from optical emission spectroscopy. Considering a blackbody plasma, the ratio between the plasma boundary temperature to that of the core has been calculated over a wide range of inclination angle. The energy transmission factor through the vapor shield plasma showed to be 30% at 0° and decreases with increased inclination angle to approach 8% at 30°, and continues to drop to 5% at 90°. This is in good agreement with predictions and previous estimates of the energy transmission factor for most material surfaces exposed to similar plasma parameters and heat fluxes. As the plasma boundary layer temperature is less than that of the core plasma, showing an energy transmission factor of less than 10% at large inclination angles, then it is suggestive that plasma kinetic pressure has a stronger effect on the burn rate than the plasma radiative heat flux.

An additional investigation compares the results and observations to the US Army Research Laboratory experiment for similar capillary, where it has been shown that the blackbody radiation is partitioned as 97.8% in the ultraviolet, 2.1% in the visible, and 0.1% in the infrared regions. Additionally, sub-surface reactions of melting and possibly chemical reactions were observed, which are similar to the NCSU observations. A rapid change in the optical transmission properties of the JA-2 propellant, as observed in the ARL experiment correlates well to the obtained energy transmission factor in the NCSU experiment. In-depth UV penetration into the propellant is not well understood and requires additional experiments and theoretical work.

Development in the detailed 2-D boundary layer model with turbulent/radiation transfer to predict mass evolution rates at the plasma-chemical (combustible) interfaces is ongoing. The code will allow the determination of the relative importance of energy transport to the propellant via radiation and turbulent convection. The system has been modeled using fluid boundary layer equations, including a two equation (k-ω) model for turbulence, coupled with multigroup thermal radiation transport. The set of governing equations is solved numerically using finite difference methods. Code results for both laminar and turbulent flows match analytical predictions and the published results of others. Since the focus of the study is on energy transport rather than the dynamics of the combustion process, a simple one-species model is used. The plasma-propellant interaction will be modeled using mass and energy source terms in the fluid equations. Testing of the code is being conducted, and the radiation transport and propellant mass/energy addition models are being added.

Accomplishments Impact on ETC Research:

Results obtained from the NCSU experiment on the burn rates of solid propellant JA-2 will help in assessing the ETC field test experiment. Geometrical influence of burn rates should be considered in the design of ETC charges to allow the plasma to expand into the charge with maximum momentum transfer. A factor of 3 higher burn rates could be obtained with plasma impact normal to the grains of the propellant. The role of vapor shield plasma is becoming obvious in assessing the role of radiative heating showing that plasma kinetic pressure has a stronger effect versus radiation flux. Continuous investigation into UV spectra may reveal additional information on the in-depth heating and sub-surface processes. Modeling will allow for better evaluation of plasma turbulent flow from the plasma source into the surface of the propellant, with radiation transport added to predict the mass evolution rate at the plasma-propellant boundary.

Plans for Next Year:

- Conduct experiments on other candidate solid propellants to evaluate burn rates under various plasma parameters.

- Conduct experiments on plasma flow through the propellant and compare to plasma impact results.

- Develop new diagnostics methods to evaluate radiative heating, additional to a full diagnostic of the plasma parameters.

- Study the effect of electrode erosion and metallic impurities on burn rates.

- Investigate the role of plasma pressure versus temperature and predict the chamber temperature for a given geometry and plasma cartridge parameters.

- Continue modeling efforts and predict the mass evolution rate and the flame vapor shield.

PUBLICATIONS/PATENTS/PRESENTATIONS REPORT
01 October 1995 through 30 September 1996

P Number:	**96 pro 4536-00**
Contract/Grant :	**N00014-95-1-1221**
Program Officer:	**Drs. Richard Miller**
Principal Investigator:	**Dr. Mohamed Bourham**
Mailing Address:	**North Carolina State University Department of Nuclear Engineering Raleigh, NC 27695-7909**
Phone Number:	**(919) 515-7662**
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E-Mail Address:	**Bourham@ncsu.edu**

a. Number of Papers Submitted to Refereed Journal but not yet published(*):	2
b. Number of Papers Published in Refereed Journals: (List Attached):	None
c. Number of Books or Chapters Submitted but not yet Published:	None
d. Number of Books or Chapters Published (List Attached):	None
e. Number of Printed Technical Reports & Non-Refereed Papers (List Attached):	3
f. Number of Patents Filed:	None
g. Number of Patents Granted (List Attached):	None
h. Number of Invited Presentations at Workshops or Professional Society Meeting (List Attached):	None

i. Number of Presentations at Workshops or Professional Society Meetings (List Attached): 1

j. Providing the following information will assist with statistical purposes.

PI/CO-PI:	TOTAL	2	
	Female	None	
	Minority**	None	
Grad Students:***	TOTAL	5	
	Female	1	
	Minority**	None	
Post Doc:***	TOTAL	1	
	Female	None	
	Minority**	None	

k. Degrees Granted (list follows): None

* In case of classified publication(s), communicate as appropriate.

** Under-represented or minority groups include Blacks, Hispanics, and Native Americans. Asians are not considered an Under-represented or minority group in science and engineering.

*** Supported at least 25~ this year on contract/grant.

Enclosure (1)

TECHNOLOGY TRANSFER

Technology transfer is an important measure of the relevance of scientific & technical endeavors. ONR Program Officers need to be aware of any such transfer, and they will use it to the benefit of their programs. Please describe any recent (approximately last two years) direct or indirect interactions you had with Navy, other DoD, or industrial scientists and engineers; describe only those interactions that resulted in their use of methodology, data, software, or other developments Produced or directly derived from you ONR grant/contract/work request. Also describe similar technology transfer, if any, that resulted without any such interactions.

- Program under this contract investigates plasma-propellant interface for ETC guns. Interaction and technology transfer are provided via other DoD agencies, which include:
  - The US Army Ballistic Missiles Defense Organization.
  - The US Army Research Laboratory.
  - The US Army Research Office.
  - Collaboration with the Naval Surface Warfare Command, Indiana Head Division, White Oak, Silver Spring, MD, Detonation Physics.

- Technology transfer includes:
  - Data base on plasma-materials interaction and erosion behavior.
  - Data obtained on plasma-propellant interactions for JA-2 solid propellant and role of radiative heating and geometry.
  - Methodology of plasma-propellants experiments to characterize burn rates and pressure-temperature effects.
  - Diagnostics development for plasma-propellant interface physics.
  - Theory and modeling of the boundary-layer physics, radiation transport and turbulent flow of electrothermal plasmas with ETC applications.

Enclosure (2)

LIST OF PUBLICATIONS/REPORTS/PATENTS/GRADUATES *

1. Papers Published in Referred Journals:

   Accepted:
   "Analysis of Solid Propellant Combustion Behavior Under Electrothermal Plasma Injection for ETC Launchers", M.A. Bourham and J.G. Gilligan (NCSU), and W.F. Oberle (ARL), IEEE Trans. Magnetics, January 1997.

   "Observation of Visible Light Emission From Interactions Between an Electrothermal Plasma and a Propellant", O.E. Hankins and M.A. Bourham (NCSU), and D. Mann (ARO), IEEE Trans. Magnetics, January 1997.

2. Books (and sections thereof) Published:

   None

3. Technical Reports, Non-Refereed Papers:
   "Investigation of Geometrical Influence on Plasma-Augmented Burn Rates of JA-2 Solid Propellant for ETC Guns", M.A. Bourham, J.G. Gilligan, O.E. Hankins, R.M. Mayo, M.L. Nahm, J.P. Sharpe and C.D. Buchanan, Proc. 32nd JANNAF Combustion Meeting, NASA Marshall Space Flight Center, Huntsville, AL, CPIA Publications 631, vol.1, pp.103-112, October 1995.

   "Effect of Electrothermal Plasma Parameters on the Burn Rates of JA-2 Solid Propellant for ETC Guns", M.A. Bourham, J.G. Gilligan and C.D. Buchanan, Accepted for the 33rd JANNAF Combustion Meeting, Naval Postgraduate School, Monterey, CA, 4-8 November 1996.

   "Simulation of Plasma-Propellant Energy Transport in ETC Launchers", E.C. Tucker, N.P. Orton, J.G. Gilligan and M.A. Bourham, Accepted for the 33rd JANNAF Combustion Meeting, Naval Postgraduate School, Monterey, CA, 4-8 November 1996.

4. Presentations at technical/professional meetings:
   (do not report briefs to Navy managers here).

   Listing under item 1 has been presented in the 8th EML Symposium on Electromagnetic Launch Technology, Baltimore, MD, April 21-24, 1996.
   Listing under item 3 has been presented in the JANNAF Combustion Sub-Committee Meetings as indicated above.

   "Radiative Heating and Erosive Burn of a Solid Propellant Subject to Electrothermal Plasma", M.A. Bourham and J.G. Gilligan, Presented in the 23rd IEEE ICOPS, Boston, MA, paper 3G01, p.201, IEEE Cat.# 96CH35939, June 3-5, 1996.

   "Plasma Parameters and Radiative Heating Effects on Solid Propellant Burn Rates for ETC Launchers", M.A. Bourham, J.G. Gilligan, C.D. Buchanan and C.J. Boyer, accepted for presentation in the 14th Annual Meeting of the Electric Launcher Association (ELA), Maxwell Laboratories, San Diego, CA, 9 - 11 October 1996

5. Patents Granted:

   None

6. Degrees Granted (name, date, degree):

   None

* List only those funded directly from your ONR grant/contract/work request. Use additional pages, if necessary.

Enclosure (3)

LIST OF AWARDS/HONORS/PRIZES

Name of Person Receiving Award	Recipient's Institution	Name of Award	Sponsor of Award
None			

PI INVOLVEMENT WITH OTHER SPONSORED RESEARCH & DEVELOPMENT

(Include title, sponsors's name, dollar amount and start and end dates for the award)

The following are current contracts:

(1) *In-Bore Diagnostics of Heat Flux, Plasma Resistivity and Drag Forces in Electromagnetic and Electrothermal launchers*, Contract DAAL03-92-G-005
Principal Investigator: Mohamed Bourham, Grant Period: 05/01/92 to 04/30/96
Granting Agency: US Army Research Office Amount of Grant: $ 78,234

(2) *Plasma Surface Interaction and Boundary Layer Phenomena in Electromagnetic and Electrothermal Launchers*, Contract DASG60-93-C-0029
Principal Investigator: John Gilligan & Mohamed Bourham, Grant Period: 03/16/93 to 09/30/96
Granting Agency: US Army Ballistic Missile Defense Amount of Grant: $ 622,360

(3) *Aerosol Behavior and Plasma-Facing Components Safety During Hard Disruptions and Accidental Energy Release in Fusion Reactors: Phase I*, Contract C87-101407-007 (LKK24-95)
Principal Investigator: Mohamed Bourham & John Gilligan, Grant Period: 02/03/95 to 01/31/96
Granting Agency: Lockheed Idaho Technologies (INEL) Amount of Grant: $ 42,389

(4) *Plasma-Bore Interface and Boundary Layer Physics in Electric Launchers*, Contract DAAH04-95-1-0214
Principal Investigator: Mohamed Bourham, Grant Period: 01/01/95 to 04/30/98
Granting Agency: US Army Research Office Amount of Grant: $ 119,838

(5) *Aerosol Behavior and Plasma-Facing Components Safety During Hard Disruptions and Accidental Energy Release in Fusion Reactors: Phase II*, Contract 101128330
Principal Investigator: Mohamed Bourham & John Gilligan, Grant Period: 12/01/95 to 12/31/96
Granting Agency: University of California San Diego Amount of Grant: $ 38,164

(6) *A Laboratory Plasma Source as an MHD Model for Astrophysical Jets*, Contract NAGW-4869
Principal Investigator: Robert Mayo and Mohamed Bourham, Grant Period: 01/01/96 to 12/31/96
Granting Agency: NASA Amount of Grant: $ 60,000

(7) *Safety of Plasma-Facing Components and Aerosol Transport During Hard Disruptions and Accidental Energy Release in Fusion Reactors: Phase II*, Contract DE-FG02-96ER54363
Principal Investigator: Mohamed Bourham & John Gilligan, Grant Period: 07/01/96 to 12/31/97
Granting Agency: US Department of Energy, Amount of Grant: $ 120,756

FUNDING BALANCE

An issue at ONR is expenditure rates. Not meeting Navy required expenditure rates may result in redirection of FY97 resources within ONR. I would like to enlist your help in preventing this from occurring. If your expenditure rate is below that required by your contractual arrangement with ONR, we will be forced to delay funding increments in your contract/grant, even if the delay is due to slow billing from your business office. If the problem is at your business office, please take action to correct it.

Report the remaining ONR resources you have in your institution for this effort, as of 30 SEP 96:

$ 28,500 Balance is on open commitments for students support "salaries"; equipment purchase orders (in process); and travel commitments to the Electric Launchers Association and JANNAF Combustion Subcommittee Meetings.

Enclosure (4)