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REPORT TITLE: "Measurement of Radicals and Visualization of Flame Propagation in Propellant Combustion" is forwarded for your information.

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Not Applicable.

Sincerely,

Dr. Stefan T. Thynell
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The Pennsylvania State University
University Park, PA 16802

I. INTRODUCTION

This report summarizes the usage of the DoD-URIP equipment fund in establishing a molecular beam sampling capability of an existing triple-quadrupole mass spectrometer, and pictures acquired by the purchased Cordin high-speed film camera and digitized using a standard film scanner. Table 1 below lists the Manufacturer/Vendor, Name and/or Description of component, and the associated costs.

Table 1. Specification of components, which were acquired with a 35% cost sharing from Penn State University.

Manufacturer/Vendor	Name and/or Description	Cost
ABB Extrel	Cross Beam Deflector Ionizer	$9,418.57
Alexander Co.	O-rings	$31.56
Beam Dynamics	Regular and double-thick, Rhodium plated Nickel skimmers (1.0 and 1.5 mm orifice,) and sampling cones (0.1 mm orifice)	$4,270.50
DL Instruments	Lock-in amplifier (Model 3981) with PC plug-in card	$2,099.00
Electro-optical Corp.	CH 10-90 D1000 Tuning fork chopper/driver (AGC-110)	$1,159.95
Leybold Vacuum Products Inc.	Diffusion pump over-temperature protection thermal switch	$174.05
McMaster-Carr	Supplies (flow meters, fittings, hose, etc.)	$624.24
MDC Vacuum Products	Two custom-design vacuum chambers, flanges and mounting hardware, 4-inch electro-pneumatic gate valve, NW25 angle valves and NW25 butterfly valves	$9,716.18
MKS Instruments	943 Cold cathode pressure gauges and controllers	$2,411.03
Tri-State Technologies	DIP 3000 diffusion pump (3000 l/s), Baffle, and D25B backing pump	$8,769.67
Varian Vacuum Systems	VHS 4 diffusion pump (1200 l/s), Water-cooled baffle, and SD301 backing pump	$8,236.67
Technical Representatives, Inc.	NICOLET high speed data acquisition components, including 2 MultiPro 120 boards, one MultiPro 150 board, transportable mainframe, and ProView software	$41,143.72
NECX	Computer components (motherboard, case, hard drive, memory, floppy drive, CD-ROM, keyboard, ZIP drive	$1,242.55
The Chip Merchant	Matrox Millenium G 400 Graphics card	$173.32
Cordin Company	High-speed film camera model 350 with drum control, carrying case for film camera, cassette for 35 mm film, electronic control unit for film camera	$38,537.00
Insight Corporation	Nikon 35 mm film scanner with SCSI communication	$1,711.99
	Total expenditure:	**$129,720.00**

II. SUMMARY OF RESEARCH PROJECT WHICH UTILIZED THE MOLECULAR BEAM SAMPLING SYSTEM, HIGH-SPEED FILM CAMERA, AND DATA ACQUISITION SYSTEM

II.1 Title: Experimental Study of Plasma/Propellant Interactions

DoD Organization: Army Research Office

Grant Number: DAAG55-98-1-0519

Principal Investigators: Stefan T. Thynell and Thomas A. Litzinger

II.1a Background

The potential use of electro-thermal-chemical plasmas as an ignition source, e.g., in large-caliber guns, has revealed several important benefits over conventional ignitor systems. These include, among others, a shorter ignition delay, a reduced temperature sensitivity of the propellant, and a reduced susceptibility to anomalous ignition transients. To effectively design the plasma ignitor system, to optimize the charge configuration and to select a most suitable propellant, it is desirable to increase our understanding at both the practical and fundamental levels of the interaction between the plasma and propellant. The objective of the ongoing experimental work is to improve our understanding of such an interaction by systematically and parametrically studying the propellant's response to a single plasma jet.

The ongoing experimental effort is conducted in advanced diagnostic facilities at Penn State University. The primary instrument for acquiring species data is a triple-quadrupole mass spectrometer. It provides data on both compositions of stable species from the plasma near the sample surface, as well as species produced during the interaction between the plasma and the propellant. A high-powered CO_2 laser is also used to provide high heat fluxes in efforts to acquire experimental data for comparison purposes and to learn how a propellant responds to nonconvective heating conditions. Sampling of gases with high temporal (<1ms) and spatial resolution (<100μm) are achieved by using a microprobe, whose intake port will sample gases evolved from the near-surface region. Fine-wire thermocouple techniques are also employed to determine spatial and temporal variations of the temperature at and near the surface of the propellant. To establish the location of ignition, a high-speed film and CCD cameras as well as an array of mid-IR detectors are utilized to record the location of gas-phase ignition. Pressure variations along the surface are also recorded.

The anticipated results from this study are expected to be particularly useful in ARL's efforts of optimizing the design of the plasma ignitor system. From a practical point of view, anticipated information gleaned from this study include (a) knowledge about the location of ignition for different propellants in terms of plasma strength and proximity to the plasma exit port, (b) role of radicals in the ignition event through data reduction support analysis, and (c) the variation in the heat flux along the surface. Anticipated fundamental results include (a) knowledge about the effect of heating rate of the plasma on the propellant's decomposition and ignition behavior, (b) a detailed understanding of the role of the temporal species evolution and its linkage to the propellant's temperature sensitivity, and (c) the relative roles of the reactive plasma species versus the convective and radiative heat transfer during the inert heating and subsequent pyrolysis event.

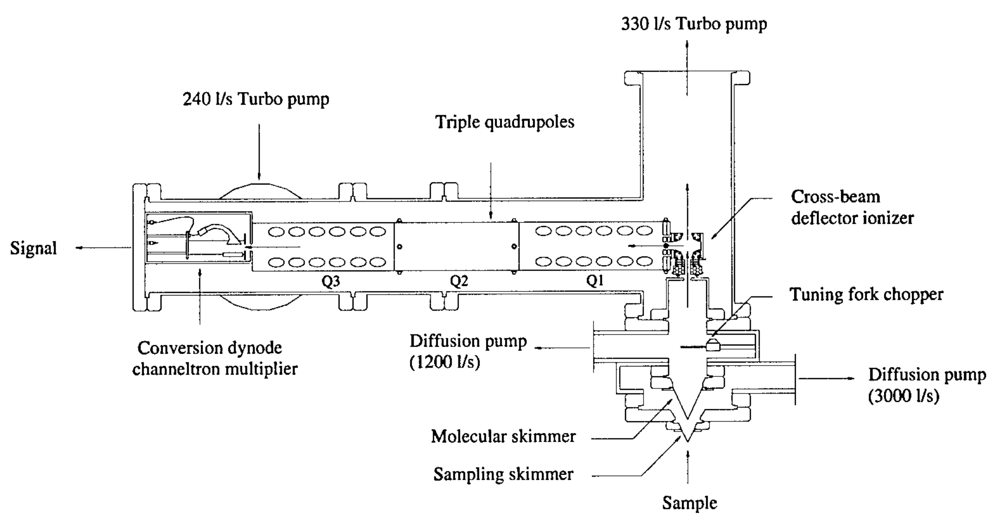
II.1b Brief Discussion of Results from using Molecular Beam Sampling System

A major reconfiguration of a existing mass spectrometer system was undertaken to allow the system to accommodate both molecular beam and microprobe sampling. The use of both sampling approaches will maximize the use of the triple quadrupole mass spectrometer for several projects related to propellant combustion. For the highly transient, plasma propellant experiments the molecular beam sampling provides two significant advantages: a much faster sampling response time and the ability to detect highly reactive species in the plasma.

As sketched in Figure 3, the plasma jet is sampled through a 0.1mm diameter orifice at the apex of a 20mm high conical skimmer and supersonically expanded into the first stage vacuum chamber pumped down to less than 10^{-3} torr by a DIP3000 diffusion pump (3000 l/s) with a D25B rotary vane backing pump (25.7 m^3/h). The core of the expanding gases is then collimated and skimmed by a second 1.5mm diameter and 50mm high skimmer to form a molecular beam entering the second stage vacuum chamber (10^{-5} torr), which is evacuated by another diffusion pump (Varian VHS4, 1200 l/s) with a SD301 mechanical backing pump (15m^3/h). Water-cooled baffles are used for both diffusion pumps to prevent back streaming. Both skimmers are made of nickel with rhodium plating for better protection from gas corrosion. The interior included angles at orifice for the first and second skimmers are 50° and 55°, respectively, and the exterior included angles are 5° larger than interior angles for each one. This selection of skimmer angles represents a trade-off between a small exterior angle to avoid detached shocks upstream of the skimmer, and a large interior angle to reduce collisions inside the skimmer and allow a rapid rarefaction of the extracted beam. Spacers are used to adjust the distance between the two skimmers from 10 to 30mm.

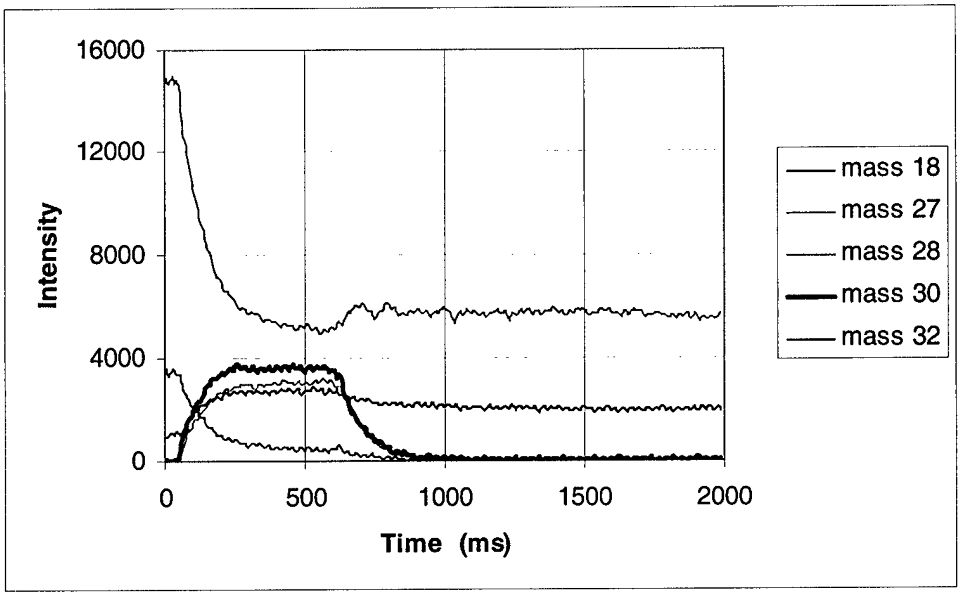
The rapid reduction in temperature and collision frequency due to supersonic expansion and the formation of molecular beam effectively quenches chemical reactions occurring in the source and inhibit condensation. Thus, all species including both positive and negative ions, neutrals, and important reaction intermediates, such as radicals, survive and remain in gas phase at temperatures far below their condensation points for a long time compared to reaction rates. The system can be used to detect plasma ions by electrically biasing either or both of the skimmers and turning off the ionizer filament to allow efficient extraction and focusing of plasma ions.

Figure 1. Schematic diagram of MBMS system



The new system has been used in testing of XM-39 gun propellant to verify that the performance delivered is as expected. The results of one of the tests are shown in Figure 2. The testing of the propellant was performed in an air environment so the initial signals at 28 and 32 are due to air. Once the propellant ignites and products are generated the nitrogen and air signals decrease and products of combustion typical of XM-39 are observed including HCN, 27 amu, N_2 and CO, 28 amu, and NO, 30 amu. The results indicate that the system is performing as expected and is providing better. Testing is currently underway with the MBMS system to prepare for sampling from the plasma.

Figure 2. Species results for XM39 with upgraded system.

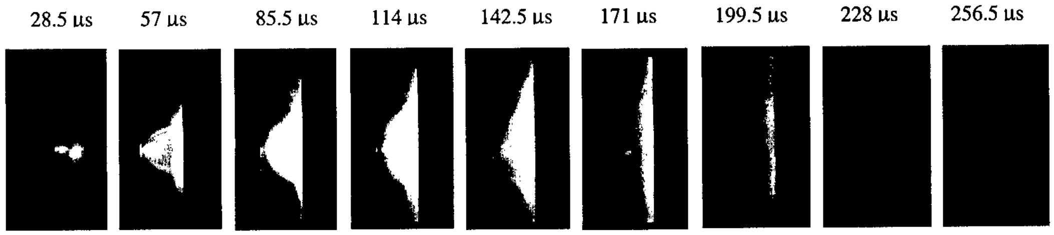


II.1c Brief Discussion of Results from using High-speed Film Camera

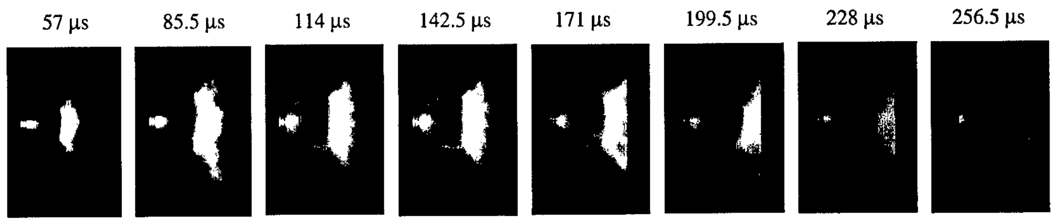
The Cordin 350 high-speed film camera with Fuji 160 color film was utilized for capturing images during the plasma evolution. This camera uses 35 mm film and is capable of acquiring up to 35,000 pictures per second with a 1.9 μs shutter speed. Each image measures 7 by 10 mm on the film, and a total of 224 images can be acquired for a film length of 867mm. The negative of the film was scanned directly into a PC using a Nikon 2000 film scanner. In order to prevent the pictures from being over-exposed due to the extremely high luminosity of the plasma, two neutral density filters producing a total attenuation of 64 with a lens aperture of f/5.6 were selected for the framing speed of 35,000 pictures per second.

Figures 3 (a) and (b) show typical evolution of the plasma for two different separation distances in the flat plate configuration of sample holder. From these images, one can see the expected gas dynamic features characteristic of a highly under-expanded supersonic jet [1]: a distinct barrel shock (oblique shock) and a strong Mach disk (normal shock). In Fig. 3(a), pictures were taken with the separation distance of 20mm, and a charging voltage at 7kV. The barrel shock is clearly visible in the image at 57 μs after triggering the ignitron, and stayed to next image at 85.5 μs. Shortly after this, the structure of the jet becomes less distinct due to diffusion and mixing within the short separation distance. Pictures in Fig. 3(b) reveal the same dynamic structure, but show a more clear evolution process because of the longer distance of separation. In terms of image luminance, apparent difference is observed between the two sets of images that were obtained at charging levels of 4kV and 7kV. In both tests, two regions of greatest luminosity were found near the exit port and on the opposing plate just downstream of the Mach disk, which may correspond to the highest temperature zones. Recent modeling work confirms these observations [2].

Figure 3. Images of plasma evolution from a 3.2mm bore PE capillary into open air with the plate held down away from the nozzle exit (for additional details, see Ref. 3).



(a) L=20mm, 7kV plasma



(b) L=38.5mm, 4kV plasma

III. REFERENCES

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2. Carling, J.C. and Hunt, B.L., "The Near Wall Jet of Normally Impinging, Uniform, Axi-Symmetric, Supersonic Jets," *Journal of Fluid Mechanics,* Vol. 66, No. 1, pp. 159-176, 1974.
3. Li, J.Q., J. Kwon, G. Kudva, S. T. Thynell and T. A. Litzinger, "Experimental Investigations of Characteristics of Electro-Thermal-Chemical Plasma, AIAA Paper 2001-3855, presented at the 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 8-11 July 2001, Salt lake City, Utah.

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13. ABSTRACT (Maximum 200 words)
This report describes instrumentation acquired as part of the DoD-DURIP program. The major pieces of equipment purchased were components that upgraded an existing triple quadrupole spectrometer to a molecular beam sampling capability, a high-speed film camera, and components for a data acquisition system. These components are now being utilized in studies on the interaction between a high-temperature, high-pressure plasma and a solid propellant. The plasma is being generated by a capacitive discharge that lasts about 300 μs, depending upon ambient pressure, capillary size, and capillary material as the temporal variation of resistance of the plasma has a controlling influence on the behavior of the *RLC* circuit. The molecular beam sampling capability allows the identification and possibly quantification of radicals present in the plasma due to decomposition of capillary material and solid propellant, as well as reactions between species present in the plasma and decomposition products of the propellant. The high-speed film camera has been used to capture the evolution of the plasma to reveal the complex structure of the underexpanded supersonic jet. A 12-channel data acquisition has been acquired and is further upgraded with additional channels and filtering capabilities in order to effectively deal with measurement of small voltages in a noisy, high-voltage environment.

14. SUBJECT TERMS
Mass spectrometer, molecular beam sampling, plasma propellant interactions, measurement of radicals and low molecular weight species, capacitive discharge, thermal decomposition, energetic materials, high speed film camera, underexpanded supersonic jet, data acquisition, LOVA and double base propellants, nitramines

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