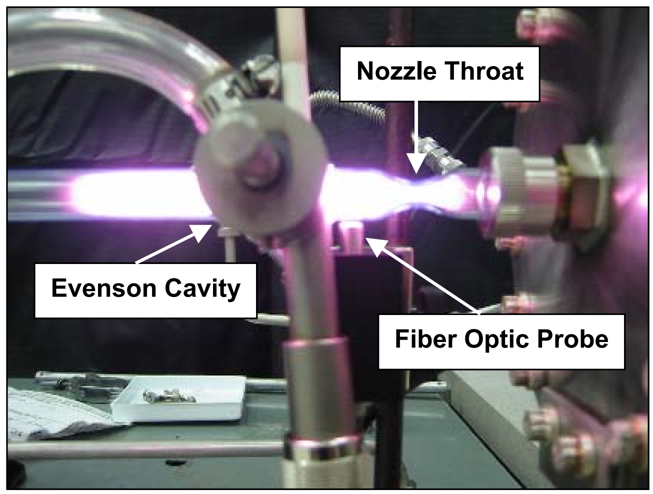
The BlackLight Rocket Engine

A Phase I Study Funded by the NIAC CP 01-02 Advanced Aeronautical/Space Concept Studies Program

Phase I Final Report



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Executive Summary

This report summarizes the final project results for the period of May 1, 2002 through November 30, 2002 for the NIAC CP 01-02 Phase I study, "The BlackLight Rocket Engine". The objective of the Phase I study was to assess the potential of low pressure, mixed gas hydrogen plasmas (i.e. the BlackLight Process) toward the development of high performance space propulsion systems.

Motivation

During the past decade, several research groups have begun to report unique spectroscopic results for mixed gas plasma systems in which one of the species present was hydrogen gas. In these experiments, researchers have reported excessive line broadening of H emission lines and peculiar non-Boltzmann population of excited states. The hydrogen line broadening in most of these studies was attributed to Doppler broadening associated with high random translational velocity of H atoms (i.e. “fast hydrogen”).

Recent data have been published by scientists at BlackLight Power reporting similar phenomena that suggests the presence of a newly identified regime of energetic mixed gas hydrogen plasma systems. Specifically, the following phenomena have been reported:

- Preferential Doppler line broadening of atomic hydrogen emission spectra,
- Inverted populations of hydrogen Balmer series in microwave hydrogen gas mixture plasmas,
- Novel vacuum ultraviolet (VUV) vibration spectra of hydrogen mixture plasmas, and
- Water bath calorimetry experiments showing increased heat generation in certain gas mixtures.

Scientists at BlackLight Power, Inc. have explained the above phenomena based on a hypothesis that, under certain conditions, hydrogen atoms can undergo transitions to energy levels corresponding to fractional principal quantum numbers. However, since the theoretical explanation of the BlackLight Process has entailed a reworking of quantum mechanics, the theory has not been readily accepted in the scientific community. Regardless of the theoretical explanation, the experimental data suggests that these plasma systems have unique characteristics that warrant further exploration for propulsion applications.

Accordingly, the objective of the present NIAC Phase I study was to assess the potential of low pressure, mixed gas hydrogen plasmas toward the development of high performance space propulsion systems. Prior to the present study, no attempt had been made to apply this type of plasma system toward the development of a rocket thruster. Preliminary calculations suggest that such a thruster could achieve performance several orders of magnitude greater than chemical rocket propulsion.

Results of the Phase I Study

During the period of May 1, 2002 to November 30, 2002, the following progress was made on the project:

- Conceptual designs for two separate proof-of-concept thrusters were completed.
- Configuration designs for thruster hardware were developed using SolidWorks 3D solids modeling.
- A BlackLight Plasma Thruster (BLPT) was fabricated.
- A BlackLight Microwave Plasma Thruster (BLMPT) was fabricated.

- An experimental vacuum test chamber apparatus was developed for testing the BLPT and BLMPT thrusters.
- A spectroscopic technique was developed for measuring thruster exhaust velocity using a Doppler shift of hydrogen emission spectra.
- A 1 kW class arcjet thruster and power supply was obtained from NASA Glenn Research Center to benchmark Doppler shift velocity measurement technique.
- Experiments on the BlackLight process were performed including:
    - Thermal characterization of a compound hollow cathode glow discharge apparatus,
    - Hydrogen line broadening measurements in low pressure microwave water plasmas,
    - Measurements of inversion of line intensities in hydrogen Balmer series,
    - Measurements of novel vacuum ultraviolet (VUV) vibration spectra of hydrogen mixture plasma, and
    - Water bath calorimetry experiments.
- The BLPT and BLMPT were installed into vacuum systems and successfully test fired.
- Preliminary experiments were performed to measure emission spectra of the exhaust gases of the BLMPT thruster.

Each of these accomplishments is described in detail in this report.

1. Objectives of the Study

The goal of the Phase 1 study was to explore the feasibility of utilizing low pressure mixed gas hydrogen plasmas (i.e. the BlackLight process) to develop a new generation of space propulsion systems that might one day power interplanetary (or perhaps even interstellar) manned spacecraft. As described in the original project proposal, preliminary calculations suggested that ultra high specific impulse rocket engines might be realized by applying the BlackLight Process toward the design of a propulsion system. If realized, the BlackLight Rocket (BLR) engine would represent a revolutionary increment in performance over today's chemical propulsion systems. Previously reported data by BlackLight Power, Inc. had reported extremely high values of energy release in dilute hydrogen gas systems. However, prior to the present study no attempt had been made to apply this new energy source toward the development of a rocket engine.

The original Phase I proposal described objectives that included development of a theoretical model, identification of potential space mission applications, and development of a bench scale BLR engine and thrust stand. Based on comments of the proposal reviewers and consultation with BlackLight Power scientists and engineers, the objectives for Phase I were refined as follows:

- Perform experiments to evaluate previously published data on energetic mixed gas H_2 plasmas.
- Develop bench scale proof-of-concept BlackLight Plasma Thruster (BLPT) and BlackLight Microwave Plasma Thruster (BLMPT) hardware.
- Develop experimental apparatus for measuring specific impulse (I_{sp}) and overall thruster efficiency (η).
- Measure specific impulse (I_{sp}) and overall thruster efficiency (η) when operating the BLPT and/or BLMPT thrusters.

The fourth objective above represents a quantitative assessment of the BlackLight Process as a power source for potential thruster applications. The first quantitative parameter of interest is *specific impulse*:

$$I_{SP} = \frac{F}{\dot{w}} \approx \frac{v_e}{g_o}$$

The specific impulse is defined as the thrust per unit propellant flow rate, which is roughly equal to the exhaust velocity, v_e , divided by the gravitational constant g_o as shown in the equation above. Since the first generation BLP thruster will require an electrical input source, a second parameter called *thruster efficiency* is also of interest. The thruster efficiency is defined as the kinetic energy of the exhaust gas per electrical energy input to the thruster according to the following equation:

$$\eta = \frac{\frac{1}{2}\dot{m}v_e^2}{\dot{W}_{elec}}$$

where $\dot{m}$ is the measured mass flow rate, v_e the exhaust velocity and $\dot{W}_{elec}$ the measured electrical input power to the device. Each of the quantitative parameters require accurate measurement of the exhaust velocity.

2. Project Personnel

A strong project team of Rowan University faculty and students was assembled during the Phase I study. The project team and their overall responsibilities are described in the following table.

Team Member	*Qualifications*	*Project Responsibility*
Anthony J. Marchese	Ph.D. Mechanical and Aerospace Engineering	Principal Investigator, theory, experiments, management of project
Peter Jansson	Ph.D. Electrical Engineering	BlackLiqht Process measurements and optimization
John L. Schmalzel	Ph.D. Electrical Engineering	Instrumentation and spectroscopic measurements of exhaust velocity
Charles Linderman	Machinist	Fabrication of BLPT hardware
Mike Resciniti, '02	B.S. Mechanical Engineering (graduate student)	Design and development of BLPT thruster hardware
Mike Muhlbaier, '04	Undergraduate, Electrical and Computer Engineering	Spectroscopic measurements and vacuum system apparatus development
Tom Smith, '03	Undergraduate, Mechanical Engineering	Design and development of BLMPT thruster hardware
Jennifer Demetrio, '04	Undergraduate, Mechanical Engineering	Design and development of BLMPT thruster hardware
Kevin Garrison, '03	Undergraduate, Electrical and Computer Engineering	Characterization of microwave Evenson cavity

Brief biographical sketches of the Principal and Co-Investigators are included below:

Anthony J. Marchese, Ph.D., Principal Investigator

Principal Investigator Anthony Marchese is an Associate Professor of Mechanical Engineering at Rowan University. He holds a Ph.D. in Mechanical and Aerospace Engineering from Princeton University and B.S. and M.S. degrees from Rensselaer Polytechnic Institute. His research areas include chemically reacting flows, chemical kinetics, microgravity experiments, rocket propulsion, spacecraft fire safety, environmental issues and refrigeration. He is currently funded by NASA to study microgravity flame spread and by NJDOT to study diesel emission reduction strategies for school buses and heavy-duty diesel vehicles. In previous work with NASA, he was a member of the science team for the Droplet Combustion Experiment (DCE) conducted aboard Space Shuttle Columbia missions STS-83 and STS-94 in 1997.

Marchese has been at Rowan since September 1996 and was promoted to the rank of Associate Professor in September 2000. At Rowan, he teaches courses in rocket propulsion, combustion, thermodynamics, fluid mechanics and product design. He has previously held positions at United Technologies Research Center in East Hartford, CT and NASA Glenn Research Center in Cleveland, OH. He is the holder of two United States Patents and is a member of Tau Beta Pi, Sigma Xi, Pi Tau Sigma, The Combustion Institute, AIAA, ASME and ASEE. In 2001 he was named a Carnegie Scholar by the Carnegie Foundation.

Peter M. Jansson, Ph.D., P.P., P.E.

Co-Investigator Peter M. Jansson, joined the College of Engineering at Rowan University in January 2001. Jansson has recently completed his Ph.D. studies at the Department of Engineering at the University of Cambridge, Cambridge, England. He received his Bachelor of Science in Civil Engineering with focus in environmental and systems engineering in 1978 from the Massachusetts Institute of Technology. Jansson has over 24-years of management and research experience in energy, engineering and consulting businesses in the United States and abroad (Conectiv, Atlantic Energy, Atlantic Energy International, Consulting Engineer Services, MIT, University of Cambridge, National Science Foundation). His master's thesis involved characterizing and measuring excess energy in catalytic hydrogen gas cell systems (Jansson, 1997) now referred to as the BlackLight Process (Mills, 2000).

John L. Schmalzel, Ph. D., P.E., Co-Principal Investigator

Co-Principal Investigator John L. Schmalzel received the B.S.E.E. ('73), M.S.E.E. ('77), and Ph.D. ('80) from Kansas State University. He served with the US Army as a Clinical Automation Officer ('80-'84) before joining The University of Texas at San Antonio ('84-'95) as an Assistant Professor. In 1995, he moved to Rowan University as the founding chair of the Electrical and Computer Engineering program. His research interests involve instrumentation development spanning biomedical devices to nondestructive evaluation and aerospace technology. He has served on the editorial boards of IEEE Trans on I&M, and of the IEEE I&M and IEEE Micro Magazines and as the chair of the Automated Instruments Users Group ('88-'90). He writes a quarterly column, A Measured Look, for the I&M Magazine. He was named a NASA Summer Faculty Fellow for three consecutive years ('98-'00). In this capacity, he was a resident at NASA Stennis Space Center where he developed a low-cost three-axis accelerometer system.

Fall 2002 Undergraduate Research Team

During the fall of 2002, a team of 4 senior-level undergraduate students worked closely with the the investigators to develop the experimental apparatus and assist in data acquisition. The undergraduate team performed their work (approximately 40 person-hours/week) within the innovative Rowan Engineering Clinic. The Engineering Clinic is a course that is taken each semester by every engineering student at Rowan University. In the Engineering Clinic, which is based on the medical school model, students and faculty from all four engineering departments work side-by-side on laboratory experiments, design projects, applied research and product development (Marchese, *et al.*, 2002).

Brief Description of the Institution

The College of Engineering at Rowan University was created from a 1992 gift of $100 million from industrialist Henry M. Rowan. The College is composed of four departments: Chemical Engineering (ChE); Civil and Environmental Engineering (CEE); Electrical and Computer Engineering (ECE); and Mechanical Engineering (ME). Each of the four undergraduate programs received full accreditation from ABET in June 2001. With the allure of starting up a new engineering program, the College has attracted a world-class faculty with Ph.D. degrees from institutions such as Princeton, Stanford, M.I.T., Cambridge, Cornell, etc. The College is housed within the 95,000 SF, $28 million Henry M. Rowan Hall, which was completed in 1998.

3. Background

3.1 Expected Significance

During the 40 plus year history of modern space flight, the overwhelming majority of both manned and unmanned spacecraft have relied on chemical energy for their main propulsion requirements. Chemical rocket propulsion systems are simple and offer a high thrust to weight ratio and have thus been reasonably effective in delivering payload from earth to low earth orbit (LEO). Chemical rocket propulsion has also been effective in delivering human space travelers from LEO to lunar orbit. Unfortunately, the performance of a chemical rocket propulsion system is inherently limited by chemical thermodynamics and even the most exotic of stable chemical propellant combinations will yield performance only slightly higher than today's H_2/O_2 rocket engines (Zurawski, 1986; Stwalley, *et al*., 1991). The low performance of chemical propulsion systems make them extremely unattractive as candidates for the long term manned exploration of the solar system and beyond.

A manned Mars mission represents a typical example of the limitations of chemical rocket propulsion. Indeed, one of the chief hurdles that has prevented a manned Mars mission is the excessive amount of propellant mass that must be launched into LEO to assemble a Mars-bound spacecraft. For example, a high-energy "sprint" (400 day round-trip) mission using H_2/O_2 would require 1,760,000 kg to be launched into LEO. Based on the launch capability of the current Space Shuttle fleet, assembling such a spacecraft in LEO would require 70 to150 Space Shuttle launches (Palaszewski, 1990). Moreover, rocket propellants account for 75% of the total mass requirements. By incorporating In-Situ Resource Utilization (ISRU), wherein propellants are manufactured from the raw materials available on Mars, it is possible to decrease the total amount of mass required for delivery to LEO (Zubrin, *et al*., 1994; Kaplan, 1996). However, this ad hoc approach, while feasible for a manned Mars mission, will not sustain the use of low performance chemical rocket propulsion as a feasible solution for long term manned space flight.

Conversely, higher performing engines are generally limited to very low thrust (electromagnetic or electrostatic engines), low thrust to weight ratio (nuclear propulsion) or political/safety concerns (nuclear engines). While low thrust, high performance engines are attractive for unmanned cargo missions (Galecki, 1987) or deep space probes (.e.g. Deep Space 1), they are not attractive for manned space travel where trip times must be minimized. Accordingly, any long term plans for manned exploration of the solar system (and beyond) will ultimately require the development of *high thrust, high performance* propulsion systems. As described below, the BlackLight Rocket (BLR) engine offers both high performance and high thrust.

3.2 Relation to the Present State of Knowledge

For space-based rocket propulsion systems, specific impulse (I_{sp}) is the primary measure of performance. Specific impulse is defined as follows:

(1)
$$I_{SP} = \frac{F}{\dot{m} g_o} = \frac{v_e}{g_o}$$

where $\dot{m}$ is the mass flow rate [kg/s], F the thrust [N], g_o the gravitational constant [9.8 m/s^2] and v_e the effective exhaust velocity [m/s]. For a single-stage rocket propelled space vehicle (in the absence of atmospheric drag or gravity) the achievable velocity increment of the vehicle (Δv) is directly proportional to the specific impulse as shown in the following relationship:

(2)
$$\Delta v = g_o I_{SP}\, ln\left(\frac{m_o}{m_f}\right)$$

where m_o is the initial mass of the vehicle and m_f the final vehicle mass after all propellant has been expended. Equation (2) suggests that space vehicles with high I_{sp} propulsion systems are required for higher Δv missions, such as interplanetary or interstellar manned space travel.

Because they rely on the chemical energy stored in the propellants themselves, even the most exotic chemical rocket propulsion systems are limited to specific impulse of less than approximately 500 s (for stable chemical combinations). By contrast, if an external energy source is used to supply energy to accelerate the rocket propellant, it is possible to achieve a much higher specific impulse. Such energy sources include nuclear energy, electrical energy or electrostatic charge. Table 1 shows typical values for specific impulse for each of these engines. As shown in Table 1, however, typically those engines with higher I_{sp} can only achieve very low thrust. One possible exception is the nuclear rocket engine, which can achieve high thrust and relatively high I_{sp}.

Table 1. Comparison of specific impulse, thrust and effective exhaust velocity for a variety of rocket engine types (Humble, *et al*., 1995; Sutton, 1992).

Rocket Type	I_{sp} (s)	Max F (N)	v_e (m/s)
Chemical	250 to 500	12,000,000	2500 to 5000
Solid Core Nuclear	1000	12,000,000	10,000
Electromagnetic	1000 to 7000	20	10,000 to 70,000
Electrostatic	2000 to 10,000	10	20,000 to 100,000

Clearly then, development of a high thrust, high I_{sp} propulsion system would represent a revolutionary step in the long term plans for manned exploration of the solar system and beyond. Returning to a manned Mars mission as a baseline to compare various propulsion systems, consider the Δv requirements for a fast 40-day transfer from LEO to Mars. Such a "sprint" mission would require a Δv of approximately 85,000 m/s. Figure 1 is a plot of the ratio of propellant mass to total vehicle mass as a function of I_{sp} for various Δv missions as calculated from equation (2). The figure clearly shows that propulsion systems with I_{sp} on the order of 1000 seconds would require virtually the entire spacecraft mass to be dedicated to propellant for high Δv missions such as a Mars sprint mission. For high Δv missions such as a Mars sprint mission, rocket engines with I_{sp} on the order of 10,000 seconds must be developed.

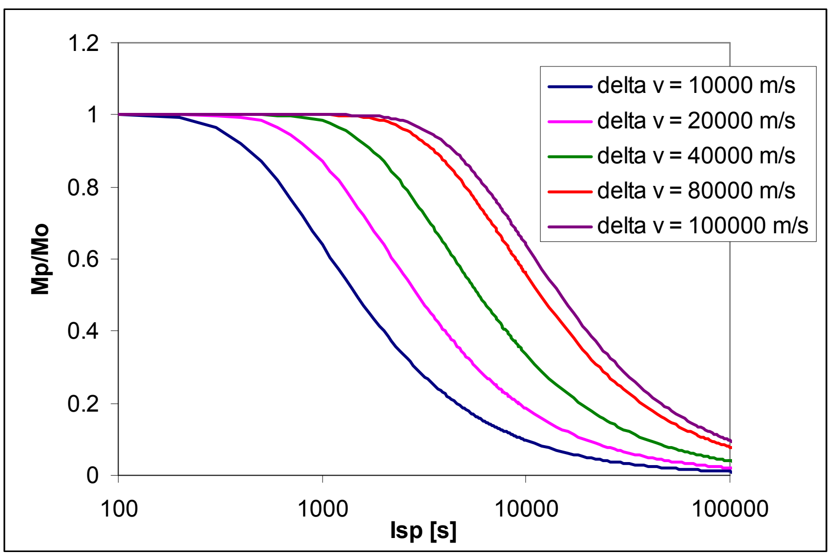


Figure 1. Ratio of propellant mass to total vehicle mass as a function of propulsion system specific impulse for various mission Δv.

The development of an ultra high specific impulse (I_{sp} < 10,000 s) rocket engine that can be scaled to produce any desired level of thrust would constitute a revolutionary step forward in mankind's ability to explore the solar system. The Phase I study represented an attempt to harness the BlackLight Process as a power source to develop such a rocket engine.

3.3 Relation to Previous Work Done on the Subject

During the past decade, several research groups have begun to report unique spectroscopic results for mixed gas plasma systems in which one of the species present was hydrogen gas.

To date, these plasmas have been generated using a variety of techniques, including:

- Glow discharge systems (Kuraica and Konjevic, 1992; Videnovic, *et al.,* 1996),
- RF discharge systems (Djurovic and Roberts, 1993; Radovanov, *et al.,* 1995), and
- Microwave systems (Hollander and Wertheimer, 1994; Mills, *et al*., 2002).

In these experiments, researchers have reported excessive line broadening of H emission lines and peculiar non-Boltzmann population of excited states. In argon/hydrogen systems, for example, hydrogen emission lines have been shown to be significantly broader than any argon line. And, in several of these plasma systems, both the Lyman and Balmer α lines have been shown to be overpopulated.

The hydrogen line broadening in most of these studies was attributed to Doppler broadening associated with ultra high random translational velocity of H atoms (i.e. "fast hydrogen") caused by an artifact of the experimental configuration. Specifically, theories have been presented that attribute the Doppler line broadening to acceleration of hydrogen ions in the vicinity of the cathode and subsequent emission as the hydrogen ion picks up an electron near the cathode.

More recently, data have been published by scientists at BlackLight Power reporting similar phenomena (in different experimental configurations) that suggests the presence of a newly identified regime of energetic mixed gas hydrogen plasma systems. Specifically, the following phenomena have been reported:

- Preferential Doppler line broadening of atomic hydrogen emission spectra (Mills and Ray, 2002a).
- Inverted populations of hydrogen Balmer series in microwave hydrogen gas mixture plasmas (Mills, Ray and Mayo, 2002c).
- Novel vacuum ultraviolet (VUV) vibration spectra of hydrogen mixture plasmas (Mills, He, *et al*., 2002b).
- Water bath calorimetry experiments interpreted by the authors as showing increased heat generation in certain gas mixtures (Mills, Ray, *et al*., 2002e).

Each of the above phenomena was observed in low-pressure mixed gas hydrogen plasmas generated using an Evenson microwave discharge cavity (Fehsenfeld, *et al.* 1964). As described below, each of the above experiments were reproduced as part of the Phase I study.

Scientists at BlackLight Power, Inc. have explained the above phenomena based on a hypothesis that, under certain conditions, hydrogen atoms can undergo transitions to energy levels corresponding to fractional principal quantum numbers (Mills, 2000). Since the theoretical explanation of the BlackLight Process has entailed a reworking of quantum mechanics, the theory has not been readily accepted in the scientific community. However, regardless of the theoretical explanation, the experimental data suggest that these plasma systems have unique characteristics that warrant further exploration for propulsion applications.

In the following sections, an explanation of the Mills theory (i.e. the BlackLight Process) will be presented along with the results of earlier experiments aimed at quantifying excess energy production in low-pressure hydrogen gas systems (Mills, *et al*., 2001). Next, preliminary calculations for a BlackLight Rocket (BLR) engine will be presented. These calculations will show that the BLR rocket engine has the potential to achieve high performance.

BlackLight Process Theory

The foundations of quantum theory are built upon observations of electromagnetic emission from atomic hydrogen at discrete spectral lines. The measured spectral lines are associated with the transition of an electron from a higher to lower energy state. Bohr (1913) and later Schrödinger (1927) developed theories that predict the energy levels of the electron in a hydrogen atom according to the following equation (which agreed with an earlier empirical formulation of Rydberg):

(3)
$$E_n = -\frac{e^2}{n^2 8\pi\varepsilon_o a_o} = -\frac{13.598\text{eV}}{n^2}$$
$$n = 1,2,3,4,...$$

where a_o is the ground state radius of the hydrogen atom, ε_o the permittivity constant and n the principal quantum number (Beiser, 1987).

Mills (2000) has presented an alternative solution of Schrödinger equation that predicts the presence of fractional principal quantum numbers. Specifically, Mills predicts that, in the presence of certain catalysts, hydrogen atoms can collapse into increased binding energy states. These collapsed hydrogen atoms (called hydrinos) as postulated by Mills, have binding energies of:

(4)
$$E_B = \frac{13.6\text{eV}}{n^2}$$
$$n = \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, ..., \frac{1}{p}$$

where p is an integer greater than 1. Hydrinos are predicted to form by reacting an ordinary hydrogen atom with a catalyst having a net enthalpy of reaction of approximately:

(5)
$$E_R = m \cdot (27.2\text{eV})$$

where m is an integer. Each catalysis interaction of this type liberates energy from the hydrogen atom as it collapses into a hydrino. For example, the catalysis of a ground state hydrogen atom (n=1) into an n=1/2 hydrino atom releases 40.8 *eV* as the atomic radius decreases accordingly from a_o to $a_o/2$.

Several observations support the theory that atomic hydrogen can exist in fractional quantum states at lower energies than the traditional n=1 ground state. For example, extreme ultraviolet background emission from interstellar space (Labov and Bowyer, 1991) has been attributed to the presence of hydrinos (Mills, 2000) as a constituent of interstellar dark matter. A second experimental observation is the measurement of extremely high-energy heat release in low-pressure hydrogen gas/catalyst systems. The high-energy heat release associated with catalytic hydrogen collapse forms the basis of the BLR rocket engine proposed herein. First generation BLR rockets would use stored hydrogen as a propellant and would serve as main propulsion systems for interplanetary travel. In the longer term (and perhaps even more excitingly), if hydrinos do in fact exist as dark interstellar matter, a "dark-matter breathing" interstellar ramjet (Bussard, 1960) might one day be realized and form the basis of manned interstellar space flight.

Previously Reported Data: BlackLight Process Excess Energy Measurements

A variety of experimental configurations have been employed to measure excess energy in low-pressure hydrogen gas/catalyst systems (Phillips, *et al*. 1996; Jansson, 1997; Mills, 2001). One of the recent experiments (Mills, 2001) will be described briefly here since the authors reported extremely high heat release (orders of magnitude greater than H_2/O_2 combustion) and the reported figures were used in preliminary calculations of BlackLight Rocket performance. A schematic diagram of the experiment presented by Mills and coworkers (2001) is shown in Fig. 2.

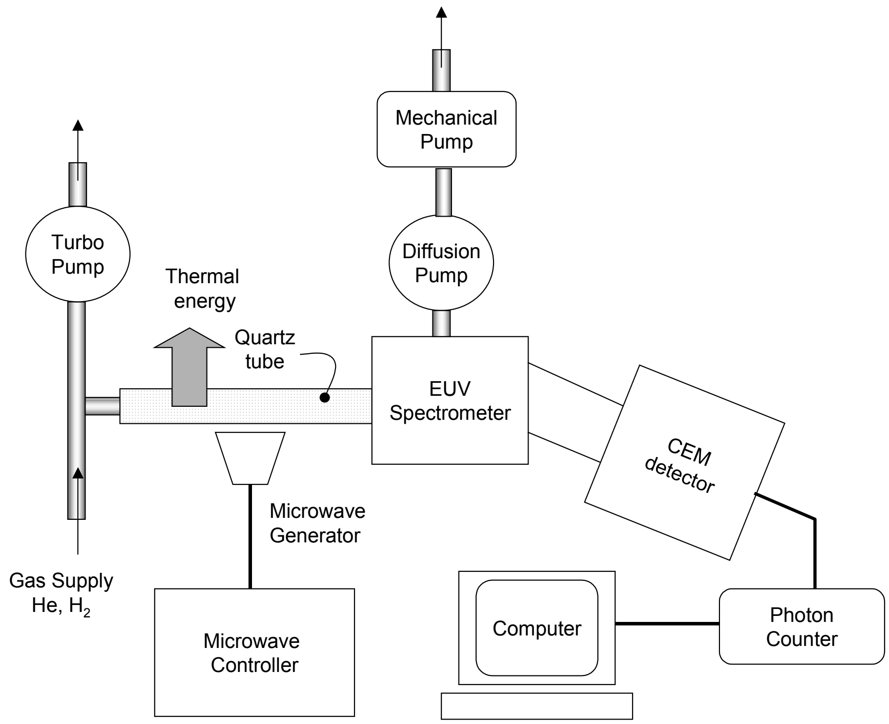


Figure 2. Microwave discharge gas cell experiment to measure excess thermal energy and VUV spectra from He/H_2 gas (Mills, *et al.,* 2001).

The theory described above (Mills, 2000), suggests that Helium ions might be an effective catalyst because the second ionization energy of helium is 54.471 *eV*, which is equivalent to m=2 in equation (5). In this case, the catalysis reaction is:

(6 and 7)
$$54.417\text{eV} + \text{He}^{+} + \text{H}[a_o] \rightarrow \text{He}^{2+} + e^{-} + \text{H}\left[\frac{a_o}{3}\right] + 108.8\text{eV} \; .$$
$$\text{He}^{2+} + e^{-} \rightarrow \text{He}^{+} + 54.417\text{eV}$$

The overall result from reactions (6) and (7) is that the presence of the catalytic helium ion causes a hydrogen atom to collapse into a (p=3) hydrino, with energy release of 108.8 *eV*:

(8)
$$\text{H}[a_o] \rightarrow \text{H}\left[\frac{a_o}{3}\right] + 108.8\text{eV} \; .$$

To capitalize on the potential of He^+ as a candidate catalyst, Mills and coworkers (2001) have built the microwave discharge gas cell apparatus shown in Figure 2. In the experimental set up H_2/He gas mixtures flow through a quartz tube maintained at a given pressure. The tube is fitted with an 2450 MHz Evenson microwave cavity, which is used to generate the helium ions necessary for catalysis. VUV spectroscopy is recorded using a monochromator capable of measuring emission from 5 to 560 nm.

For the power balance experiments, the gas pressure inside the cell was maintained at 300 mtorr. Helium flow rate was maintained at 1.639×10^{-7} kg/s and Hydrogen flow rate was maintained at 1.975×10^{-8} kg/s. In this configuration, Mills and coworkers (2001) reported experiments using heat loss calorimetry that resulted in an output power of 300 W for a measured input power of 30 W. Mills and coworkers (2001) reported that this power output is equivalent to -4×10^5 kJ/mole H_2. The enthalpy of combustion of H_2/O_2, by comparison is –241.8 kJ/mole H_2.

4. The BlackLight Rocket (BLR): Theoretical Description

The high-energy heat release reported by MIlls and coworkers (2001) formed the basis of the BLR rocket engine originally proposed for the Phase I study. As described in this section, preliminary calculations suggest that a BLR rocket engine can achieve performance several orders of magnitude greater than chemical rocket propulsion (e.g. I_{sp} > 10,000 s) and, unlike other high I_{sp} engines, the BLR engine is not limited to low thrust.

As discussed in the original Phase I proposal, the experimental configuration described above and shown in Fig. 2 could be modified into a bench scale, low thrust BLR rocket engine thrust stand. Accordingly, calculations presented here are based on the flow rates, pressures and heat release figures described above and reported in Mills and co-workers (2001). It should be noted that the extremely high levels of heat release reported in the previous study result in extremely elevated temperatures. Thus, the calculations presented in this section are estimates of theoretical maximum performance. Actual achievable performance might be limited by engineering considerations such as material properties of the engine. Indeed, it should be noted that a major effort of the future studies will entail developing a more accurate theoretical model of a BLR rocket.

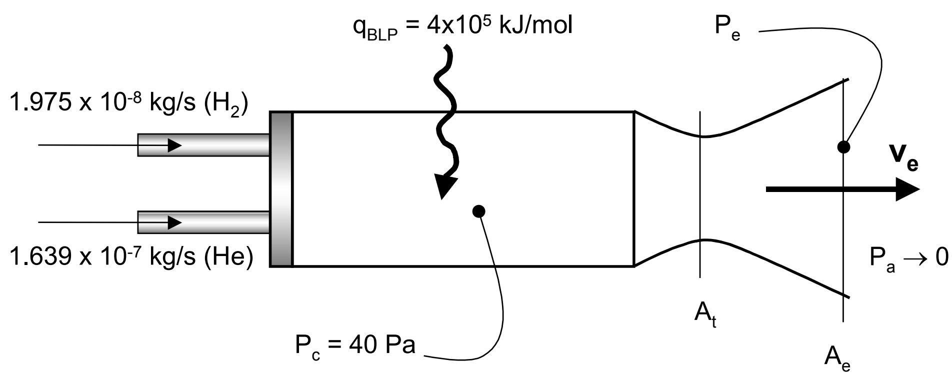


Figure 3. Schematic diagram of a prototypical bench scale BLR rocket engine.

Figure 3 shows a schematic diagram of a bench scale BLR rocket engine operating under the same flow and pressure conditions as reported in Mills and co-workers (2001). For simplicity, the heat release associated with the catalytic hydrogen collapse from $H[a_o]$ to $H[a_o/3]$ is modeled as an external heat addition of 4x10^5 kJ/mol-H_2. Since the proposed BLR rocket engine is being designed for space applications, an ambient vacuum pressure is assumed. Indeed, the low chamber pressures required for the BlackLight Process (P_c = 40 N/m^2 based on the reported results) will most likely limit of the use of this technology to space applications, particularly if traditional supersonic nozzles are to be used to accelerate the high-temperature working fluid. The First Law of Thermodynamics yields the following open system energy balance on the above rocket engine:

$$(9) \qquad \left(\dot{m}_{He}h_{He} + \dot{m}_{H2}h_{H2}\right)_{inlet} + \dot{Q}_{BLP} = \dot{m}\left(h + \frac{v^2}{2}\right)_{exit}$$

where h is the enthalpy in J/kg, $\dot{m}$ the mass flow rate in kg/s, Q_{BLP} is the heat generation from the BlackLight Process in J/s and v the exit velocity of the gas mixture in m/s. The maximum theoretical performance of rocket engine occurs if the exit gas is allowed to expand down to zero K such that $h_{exit} \to 0$. Note that this cannot be achieved in the laboratory since the exit pressure will be maintained at a finite positive value and the length of the nozzle is always finite.

Solving (9) for the exit velocity with $h_{exit} \to 0$ yields the maximum theoretical exhaust velocity:

(10) $$v_e = \sqrt{2\frac{\left(\dot{m}_{He}h_{He} + \dot{m}_{H2}h_{H2}\right)_{inlet} + \dot{Q}_{BLP}}{\dot{m}_{He} + \dot{m}_{H2}}}$$

Noting that the inlet enthalpy terms are in the numerator of equation (10) are much less than the heat release term, the above equation can be solved using the operating conditions shown in figure 3 to yield a maximum theoretical exhaust velocity of 207,000 m/s. This value can be compared to approximately 5000 m/s as the maximum theoretical exhaust velocity for an H_2/O_2 chemical rocket. The conservation of momentum for the rocket engine in Fig. 3 yields the thrust for the conditions given:

(11) $$F \approx \dot{m}v_e = 0.04\text{N}.$$

By contrast, an H_2/O_2 chemical rocket engine with the same flow rate would yield a total thrust of only 0.0009 N. Finally, equation (1) allows us to calculate the maximum theoretical specific impulse (I_{sp}) given the exhaust velocity calculated above. For the BLR Rocket engine, a maximum theoretical I_{sp} of 21,000 seconds is predicted as compared to approximately 500 seconds for an H_2/O_2 chemical rocket. It should be noted that the calculations presented above are theoretical maximums. However, assuming that the heat release levels reported in Mills and co-workers (2001) are reproducible, it is quite reasonable to expect that a BLR rocket engine with a finite length nozzle can readily be designed to obtain an I_{sp} well over 10,000 seconds. A shown in Fig. 1, at such a high specific impulse, high Δv mission spacecraft can be developed.

5. Conceptual Design of a BlackLight Thruster

The BlackLight Process is said to occur when hydrogen atoms are mixed with catalyst ions at low pressures (approx. 1 torr). A review of the propulsion literature along with a series of conceptual design meetings with Rowan and BlackLight scientists and engineers yielded several candidate concepts for a first generation BLP thruster. The candidate thruster concepts were evaluated based on the following criteria:

- Potential for increased specific impulse (I_{sp})
- Potential for increased thruster efficiency (η)
- Hardware development requirements, and
- Adaptability to the current knowledge of the BlackLight Process.

A review of the electric propulsion literature suggests that there are several available electric propulsion systems that could be readily adapted to operate under conditions at which the BlackLight Process is said to operate (See Fig. 4). For example, a BLP thermal propellant jet (similar to a resistojet) could be designed within which heat is transferred from a BlackLight gas cell to an external working fluid which is then exhausted through a supersonic nozzle to generate thrust. This device could potentially result in higher thruster efficiency than the current state-of-the-art in resistojets, if excess energy is realized from the BlackLight process. Unfortunately, such a device does not have a high potential for increased I_{sp}, since material design considerations would likely limit the temperature of the working fluid to temperatures similar to today's resistojets.

ArcJets offer increased I_{sp} with respect to resistojets since it is possible to locally heat a portion of the working fluid in and around the electrical arc to temperatures that are much higher than that which could be achieved in a resistojet (Curran, 1988). In principal, an ArcJet Derivative BL thruster could be designed to operate under conditions at which the BlackLight Process is said to occur. In this case, the hydrogen/catalyst gas itself would be the propellant. In theory, if the BL process were to occur in and around the electrical arc, it should be possible to elevate temperatures of the propellant gas even higher than a typical ArcJet, resulting in the potential for increased Isp and increased thruster efficiency. The ArcJet derivative was therefore judged as a possible future thruster design. However, given the time constraints of a six-month Phase I study, it was decided that this concept not be pursued at this point since it would require significant study and optimization of the BlackLight Process itself since the process has not been examined under conditions that would be found in the ArcJet.

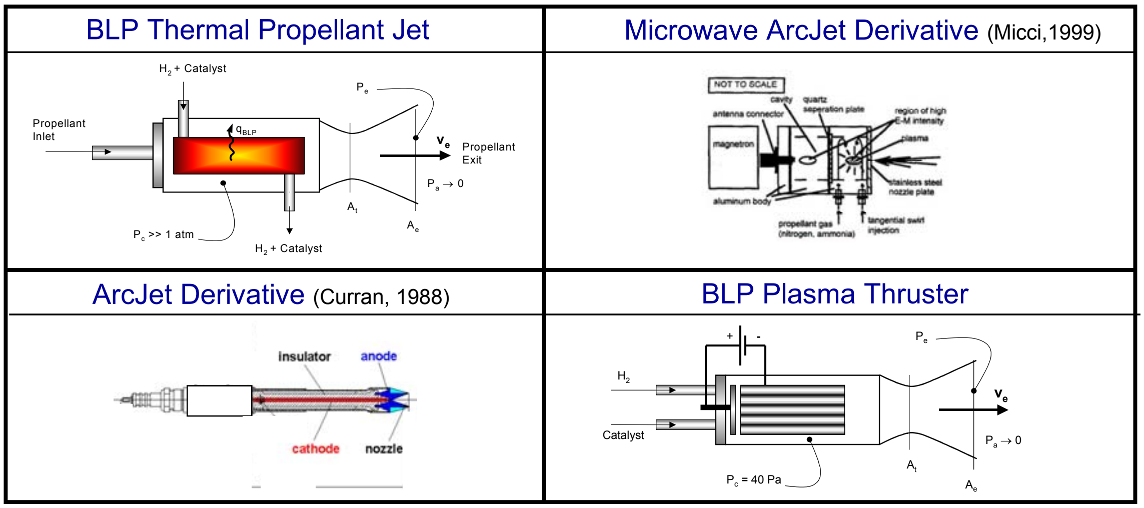


Figure 4. Conceptual designs for the first generation BLP thruster.

Micci and co-workers (1999) have recently developed a Microwave ArcJet, which uses a microwave source to locally raise propellant temperatures. Accordingly, a Microwave ArcJet Derivative BLP thruster was also considered as a candidate thruster. Once again, the hydrogen/catalyst gas itself would be the propellant. In this configuration, if the BL process were to occur in the microwave cavity, it should be possible to elevate temperatures of the propellant gas even higher than the current Microwave ArcJet, resulting in the potential for increased I_{sp} and increased thruster efficiency. Moreover, since BlackLight Power is currently conducting experiments by exciting H_2/He plasmas with a microwave source, it was decided that development of a BlackLight Microwave Thruster (BLMPT) be given a top priority for the Phase I study.

Since BlackLight Power scientists had recent success with a H_2/Ne plasma discharge cell in the months prior to the beginning of the Phase I study, it was decided that adapting this system into a BLP Plasma Thruster represented the highest potential for successful demonstration of a first generation BLP thruster. This design used the H_2/Ne gas as the propellant. In principal, such a device should exhibit increased specific impulse and increased thruster efficiency if operated under conditions in which the BlackLight Process is said to occur. Since the thrust chamber can be designed to be virtually identical to existing BlackLight Power glow discharge test cells, very little optimization of the process was anticipated.

6. Experimental Approach

Accurate determination of specific impulse and thruster efficiency requires accurate measurement of exhaust velocity or thrust. After a review of the literature it was decided that exhaust velocity measurement is would be more easily realized than developing a milli-Newton thrust stand given the time constraints associated with the Phase 1 study. The technique chose for exhaust velocity measurements was a Doppler shift technique developed by Micci and co-workers (1999). Using this technique, emission spectra of the hydrogen/catalyst exhaust plume is measured and the Doppler shift of a specific peak is used measure the exhaust velocity from the following equation:

(12) $$v_e = c\frac{\Delta\nu}{\nu}$$

To develop such a system, Micci and coworkers used of a high-spectral resolution Burliegh TL-15 Fabry-Perot interferometer along with a SPEX 1870, 0.5 meter spectrometer. Without the use of the interferometer, Micci's 0.5 meter spectrometer had a resolution of approximately 0.020 nm. With the interferometer system in place, a wavelength resolution of 0.002 nm was possible. Assuming that the 656.3 nm H_2 Balmer line will be used to measure the Doppler shift, equation (12) suggests that a velocity resolution of approximately 900 m/s is possible using Micci's system. In August, the Rowan project team made a trip to Penn State University to visit Professor Micci's laboratory and consult with him on the development of such a system.

At BlackLight Power a JY Horiba 1250M, 1.25 meter spectrometer was available for use in the Phase I study, which resulted in a wavelength resolution of 0.006 nm without the use of the interferometer. The system at BlackLight Power, which was used for this study at no cost to the project, results in a velocity resolution of approximately 2700 m/s without the use of the interferometer system. Based on time and cost constraints (the Fabry-Perot system costs approximately $15,000) associated with the Phase I study, it was decided that the JY Horiba 1250 spectrometer would be used without an interferometer for the Doppler shift experiments. Based on preliminary calculations of thruster performance it was believed that a resolution of 2700 m/s would be sufficient.

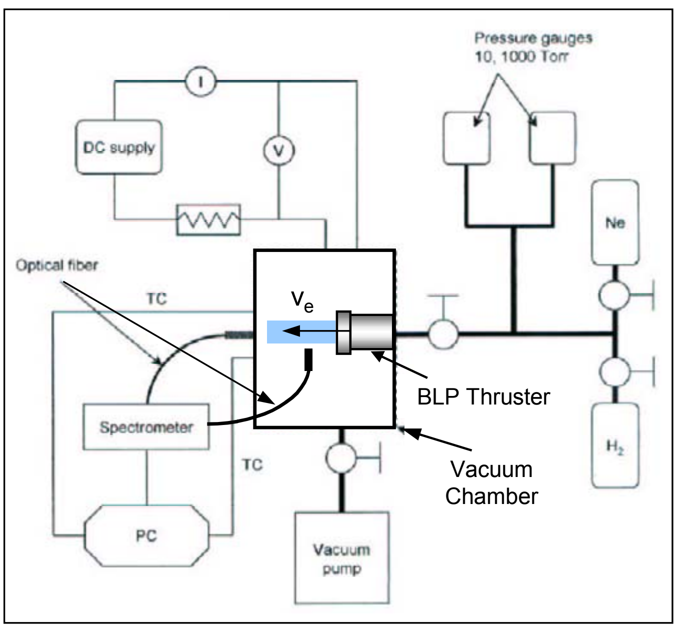


Figure 5. Schematic diagram of experimental apparatus for measuring BLP thruster performance.

Figure 5 shows a schematic diagram of the fuel/catalyst feed system, vacuum system and exhaust plume spectroscopy system that was developed to perform the spectroscopic measurements of exhaust velocity. As shown in the figure, in order to accurately measure the Doppler shift, emission spectra must be acquired both perpendicular and parallel to the exhaust stream. As shown in Fig. 6, a vacuum chamber was purchased and, as will be discussed in the following section, BLP Thruster hardware was designed to integrate with the vacuum chamber. The vacuum chamber was manufactured by MDC and is fitted with a CryoTorr 8 cryopump that can achieve vacuum levels of 1.0 e-7 Torr. The experimental setup will be described in greater detail below.

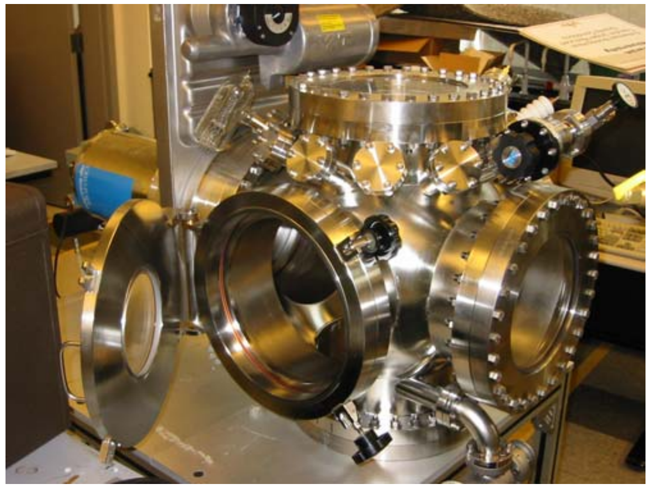


Figure 6. Vacuum system for thruster performance testing.

NASA 1 kW Class ArcJet Hardware

To benchmark our spectroscopic Doppler shift measurement technique, a system capable of producing a plasma with a known and repeatable velocity was required. Accordingly, arrangements were made with engineers at the On-Board Propulsion Branch at NASA Glenn Research Center for an equipment loan of a 1kW Class Hydrogen ArcJet and power supply. The NASA Lewis 1 kW class ArcJet (Curran, *et al.,* 1990), which can achieve an exhaust velocity of approximately 10,000 m/s, will be used to validate Doppler shift technique.

7. Hardware Development: BlackLight Plasma Thruster (BLPT)

During the first two months of the project, it was decided that adapting a BlackLight Power H_2/Ne plasma discharge cell system into a BlackLight Plasma Thruster (BLPT) represented the highest potential for successful demonstration of a first generation BLP thruster. In this configuration, since the thrust chamber could be designed to be virtually identical to an existing BlackLight Power test cell, very little optimization of the process itself was anticipated. Such a device should exhibit increased specific impulse and increased thruster efficiency if operated under conditions in which the BlackLight Process is said to occur.

Having selected the H_2/Ne BLPT as the conceptual design of choice, an existing BLP glow discharge gas cell was redesigned into a BLP thruster. The first phase hardware was designed and built to have as few discrepancies as possible from Black Light Power's plasma cell. Figure 6 shows a disassembled H_2/Ne BlackLight Process gas cell. To redesign the gas cell into a BLP thruster, the system was reproduced and adapted using SolidWorks 3D solids modeling software. The redesigned BLP thruster is shown in Fig. 7b.

Figure 7. a) Disassembled H_2/Ne compound hollow cathode gas cell used to generate the BlackLight process (Mills, *et al.*, 2002) and **b**) SolidWorks 3D assembly drawing of BLP thruster design.

As shown in Figs. 7a and 7b, the proof-of-concept BlackLight Plasma Thruster (BLPT) design is very similar to BlackLight Power's compound hollow cathode gas cell. The major differences between the BLP gas cell and the thruster are associated with the propellant inlet and exit. In terms of the propellant exit, the thruster contains an interchangeable supersonic nozzle assembly shown at the bottom of Fig. 8.

The propellant inlet was also redesigned to direct the gas directly through the anode, into the compound hollow cathode assembly and into the nozzle. The BLP gas cell design uses a side feedthrough for the gas inlet. In this design, after the gas enters the chamber, it diffuses into the tube bundle via holes in the bundle casing. In the thruster design, the gas inlet is directed concentrically through the anode electrode. Therefore, all of the gas must pass directly through tube bundle. In addition, in the thruster design, the tube bundle is welded directly to the casing at the inlet to the supersonic nozzle. The redesigned anode/gas inlet system is shown in Fig. 8.

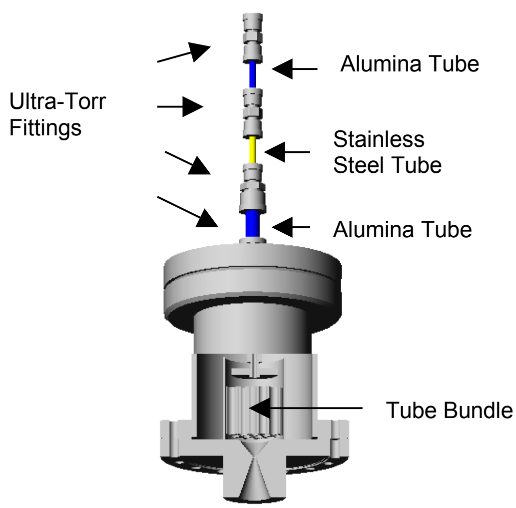


Figure 8. Cutaway view of BLPT showing redesigned anode/gas inlet system.

Calculations were performed to determine nozzle design parameters such as throat diameter and area ratio. Since the equilibrium temperature of the gas plasma inside the BLPT was not fully characterized experimentally, the plasma temperature was used as a design variable in the calculations. For a given plasma temperature, chemical equilibrium calculations were performed using the NASA CEC (Gordon and McBride, 1973) code to determine the thermodynamic properties of the gas upstream of the supersonic nozzle. Figure 9 is a plot of the required nozzle diameter as a function of the effective plasma temperature inside the cell for a cell pressure of 1 Torr at various Neon flow rates. Based on these calculations, a throat diameter of 0.100 inches was chosen as a first design iteration

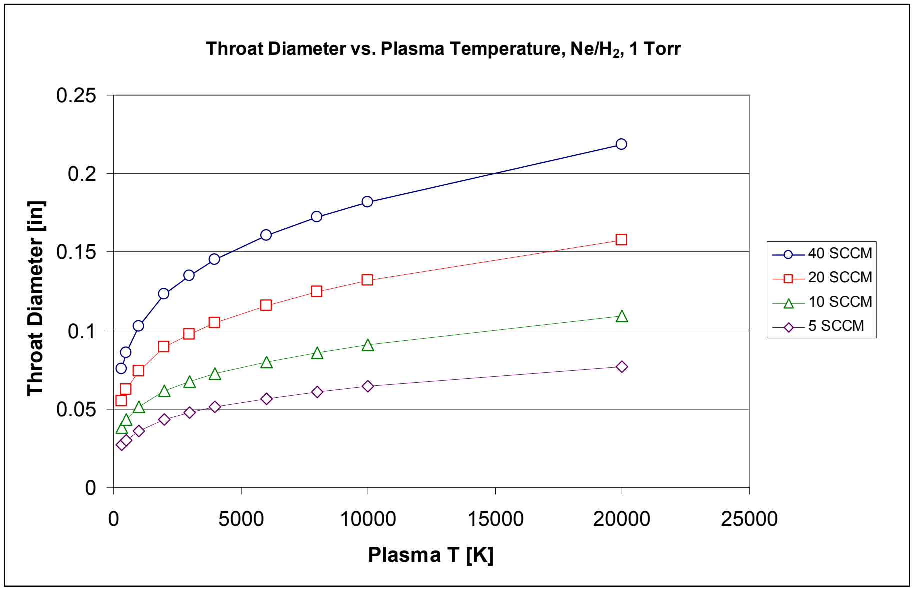


Figure 9. Required nozzle throat diameter as a function of plasma temperature for cell pressure of 1 Torr and Ne flow rate of 5, 10, 20 and 40 SCCM.

Once the throat diameter was chosen, an interchangeable nozzle was designed so that a variety of area ratios could be tested. A converging only nozzle, a 20:1 area ratio nozzle and a 100:1 area ratio nozzle have been designed and built. The throat diameter of the three nozzles is 0.100". Each nozzle has a 32° converging half angle and a 15° diverging half angle. Since the spectroscopy system must be accurately aligned at the outlet of the nozzle, all of the nozzle exits are designed to be in the same axial position. An example of one of the nozzle designs (100:1 area ratio) is shown in Fig. 10.

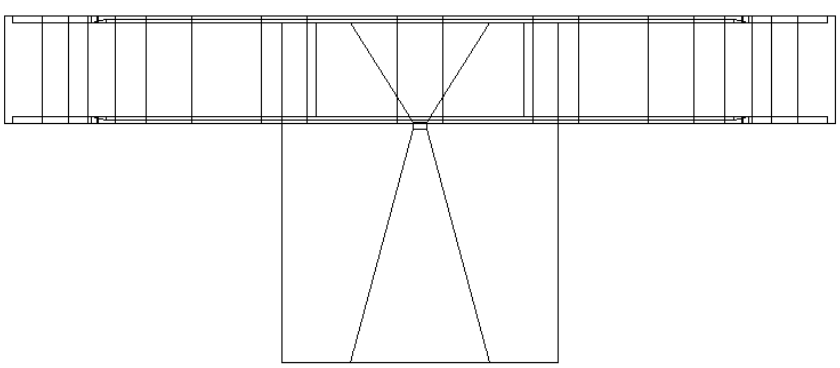


Figure 10. Nozzle design for BLP thruster with throat diameter of 0.100 inches and 100:1 area ratio.

The BLP thruster hardware shown in the figures above was designed using SolidWorks 3D solids modeling software. The 3D solid models were imported into MasterCam manufacturing software and then manufactured in-house using a CNC turning center and CNC milling center. The diverging section of the 20:1 and 100:1 nozzles were machined using a wire EDM. Figures

11a and 11b show the nozzle during machining on the CNC turning center and the center spool piece during machining on the CNC milling center.

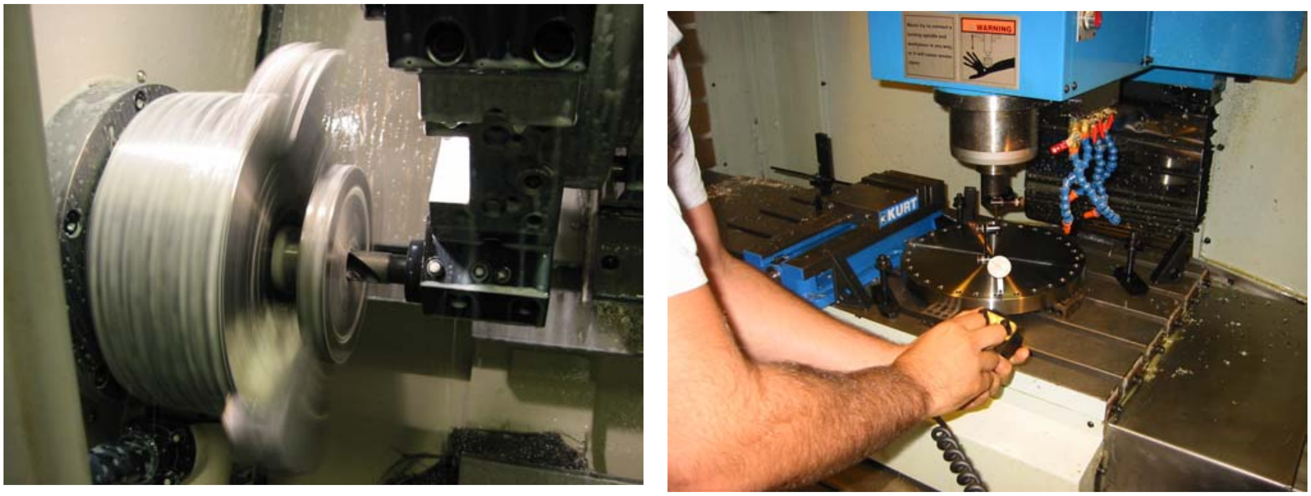


Figure 11. a) Nozzle machining on CNC turning center and b) center spool piece machining on CNC milling center.

As will be mentioned above, a new vacuum chamber was purchased that will better facilitate spectroscopic measurement of the thruster exhaust (See Fig. 6). To adapt the BLPT to the new vacuum chamber, a 13.25" blank CF flange was purchased and modified to accommodate the center thruster spool piece which was welded in place as shown in Figs. 12a and 12b. The welded flange and thruster spool piece was attached to the vacuum chamber as shown in Fig. 13. As will be discussed below, the thruster was mounted in the vacuum chamber so that the exhaust emission spectra can be measured both parallel and perpendicular to the flow stream.

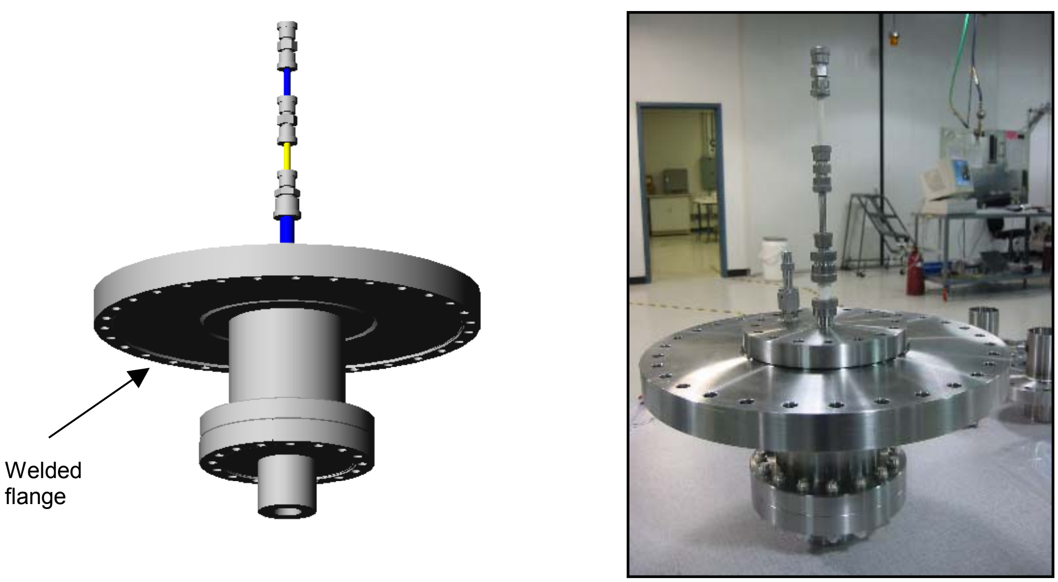


Figure 12. a) Drawing and b) photograph of vacuum chamber adapter and BLPT.

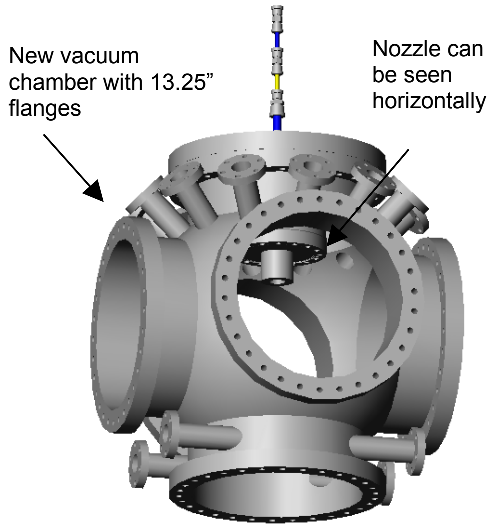
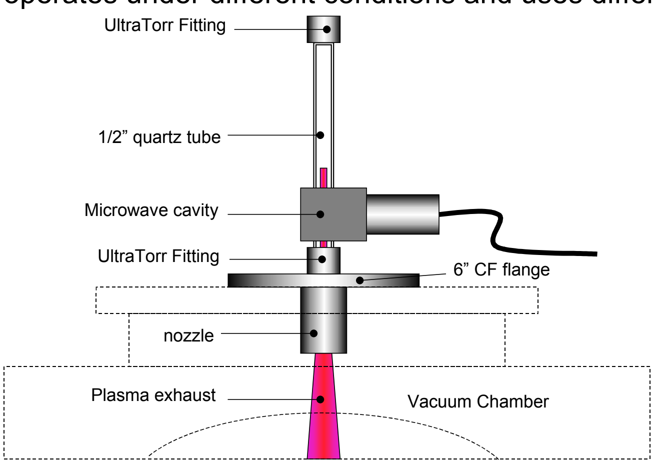


Figure 13. Assembly drawing of BLPT in test configuration integrated with vacuum chamber.

8. Hardware Development: Black Light Microwave Plasma Thruster (BLMPT)

In the later stages of the Phase I study, BlackLight Power, Inc. continued to make further progress in development of their microwave plasma systems. In light of these developments, BLP scientists recommended that the concept of a BlackLight Microwave Plasma Thruster (BLMPT) be given further consideration. As discussed above, Micci and co-workers (1999) at PSU have recently developed a Microwave ArcJet, which uses a microwave source to locally raise propellant temperatures. The BLMPT configuration is similar to Micci’s device, but operates under different conditions and uses different propellants.



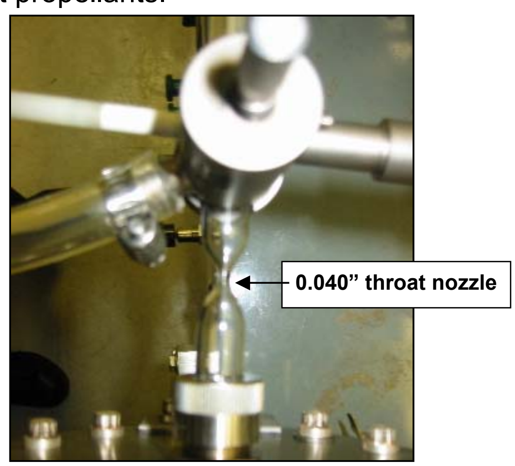


Figure 14. Schematic diagram of BLMPT currently under development for testing and
Figure 15. Supersonic quartz nozzle for BLMPT.

The BLMPT consists of a tubular quartz thrust chamber of approximately 0.500” outer diameter and 5” length. The propellant gases enter the thrust chamber through a standard UltraTorr fitting and are excited using an Opthos model B1 co-axial Evenson microwave discharge cavity (Fehsenfeld, et al. 1964). The Evenson cavity is is powered by an Opthos MPG-4M 2.45 GHz microwave power supply.

Figure 14 is a conceptual design for the BLMPT, which has recently been designed and built at Rowan. The BLMPT is virtually identical to the microwave plasma configurations currently being tested at BlackLight Power, with the exception of the nozzle section. Originally, a converging nozzle was fabricated from a 6” CF vacuum flange so that it could be mated directly with the vacuum chamber using the center flange section shown in figure 12b. However, preliminary tests showed that the plasma exhaust plume quenched when coming in contact with the large metallic flange. Since emission of the exhaust plume is integral to our plans to measure exhaust velocity, it was decided that a non-metallic nozzle needed to be designed. As shown in Figure 15, a series of supersonic converging-diverging nozzles were constructed by drawing quartz tube to specified diameters. This simple design enabled the testing of a variety of throat diameters from 0.25 inches to 0.15 inches.

9. Experimental Evaluation of BlackLight Process

Prior to testing the BLPT and BLMPT thrusters, a series of experiments were conducted to evaluate previously published experiments on the BlackLight Process. These experiments were performed to determine whether previously reported data were reproducible and to better characterize the thermal characteristics of these systems so that their performance might be optimized for propulsion applications.

In the following sections, the following experiments that were conducted as part of the present Phase I study are described:

- Thermal characterization of Ne/H_2 glow discharge gas cell,
- Unique line broadening in low pressure microwave water plasmas,
- Inversion of line intensities in hydrogen Balmer series,
- Novel VUV emission spectra in hydrogen gas mixtures, and
- Water bath calorimetry experiments on mixed gas hydrogen plasmas

9.1 Thermal Characterization of Ne/H_2 Glow Discharge Gas Cell

As described in Mills, *et al.*, (2002), experiments on the BlackLight Process have been performed using a Ne/H_2 glow discharge gas cell (See Fig. 7a). The gas cell is a 304 stainless steel cylindrical cell that is 5.70 inches in height and 3.63 inches in diameter. The top of the cell is welded to a 6.0 inch CF vacuum flange. The top flange is bolted to a blank, non-rotatable 6.0 inch CF vacuum flange. The mating flange contains a welded stainless steel thermocouple well, a high voltage vacuum feedthrough and a stainless steel reentrant tube (0.25 inches in diameter) that serves as the gas inlet. The high voltage vacuum feedthrough is used to transmit the power to a compound hollow cathode assembly inside the gas cell.

The compound hollow cathode electrode assembly consists of a bundle of 19 tubes, which are concentrically packed within a larger support tube. The smaller tubes are 0.375 inches in diameter, with a length of 2 inches and a wall thickness of 0.035 inches. The support tube has an outer diameter of 2 inches and an inner diameter of 1.889 inches. The anode is a 1.654 inch 316 stainless steel disk, which is electrically isolated from the cathode tube bundle by a 0.393 inch gap.

During experiments, the cell is maintained at a pressure of approximately 1 Torr as gas mixtures of neon and hydrogen flow through the cell at flow rates of 0 to 20 SCCM. A glow discharge is started and maintained by a DC electric field in the compound hollow cathode supplied by a DC power supply (0 to 600 V). In previous experiments performed by BlackLight Power scientists (Mills, *et al*. 2002), the heat generated inside the cell has been determined using calorimetry and compared to control experiments that use different gas mixtures or resistive heating at the same input power. In the previous experiments, BLP scientists have shown that for the same input power, a Ne/H_2 plasma cell produces a higher rate of heat rejection (as measured by the temperature difference between the cell and the ambient kiln temperature) than a similar cell fitted with a resistance heating element. As a first step in understanding the BlackLight Process, these experiments were verified by the Rowan team and shown to be repeatable.

In the prior experiments performed by BlackLight scientists, the process was optimized to yield maximum heat output in the form of heat transfer through the gas cell walls. In the case of the BLPT *thruster*, the goal is to transfer thermal energy within the cell to kinetic energy of the exhaust gases. The performance of the latter system is therefore a function not only of the plasma energetics but also a function of the cell pressure. Thus, the conditions under which the BlackLight process were previously optimized may or may not be identical to the conditions under which a BLPT will yield optimum performance.

To better understand the thermal characteristics of the BlackLight process so that it might be optimized for the BLPT, a Ne/H_2 gas cell was instrumented with 12 high temperature type K thermocouples. Table 2 is a list of thermocouple locations. Thermocouples 1 through 5 were 0.040" Type K shielded thermocouple probes, which were fed through the gas cell using an Omega MFT-040-5 multiple thermocouple feed through. Thermocouples 6 through 9 were Omega C03-K surface mount thermocouples that were mounted to the surface using stainless steel hose clamps. Thermocouples 10 and 11 were installed into thermowells in the upper flange and lower portion of the cell. The thermocouple locations are shown in Fig. 16.

Table 2. Instrumentation list for BlackLight Process thermal characterization.

Name	Instrument Type	Measurement
T1	Type K, 0.040" shielded probe	Tube bundle gas temperature, center tube, upper
T2	Type K, 0.040" shielded probe	Tube bundle gas temperature, center tube, lower
T3	Type K, 0.040" shielded probe	Gas temperature below tube bundle
T4	Type K, 0.040" shielded probe	Tube bundle gas temperature, outer tube, lower
T5	Type K, 0.040" shielded probe	Tube bundle gas temperature, outer tube, upper
T6	Type K, surface mount	Outer cell temperature, lower
T7	Type K, surface mount	Outer cell temperature, upper
T8	Type K, surface mount	Outer cell temperature, lower
T9	Type K, surface mount	Outer cell temperature, upper
T10	Type K	Upper cell flange temperature
T11	Type K	Lower cell temperature
T12	Type K, 0.040" shielded probe	Ambient furnace temperature

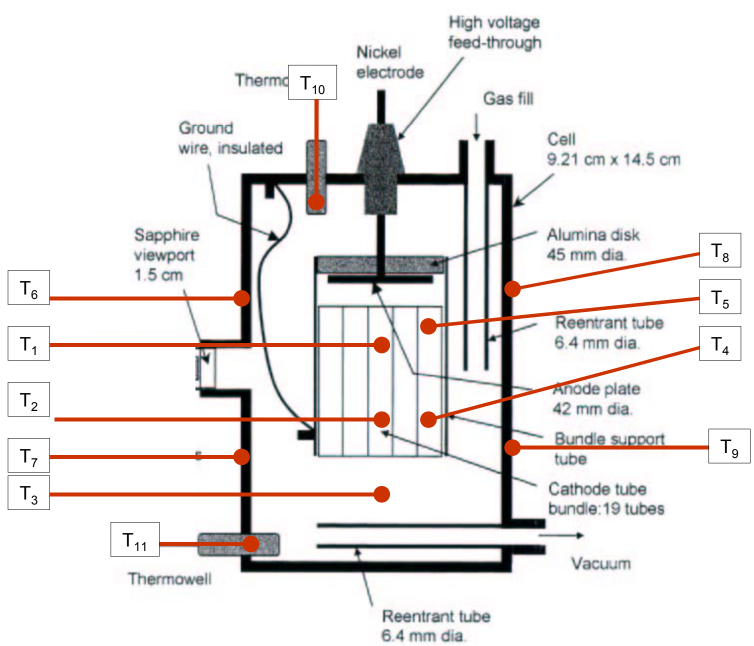


Figure 16. Schematic diagram of thermocouple locations for thermal characterization tests (Diagram of plasma cell from Mills, *et al,* 2002).

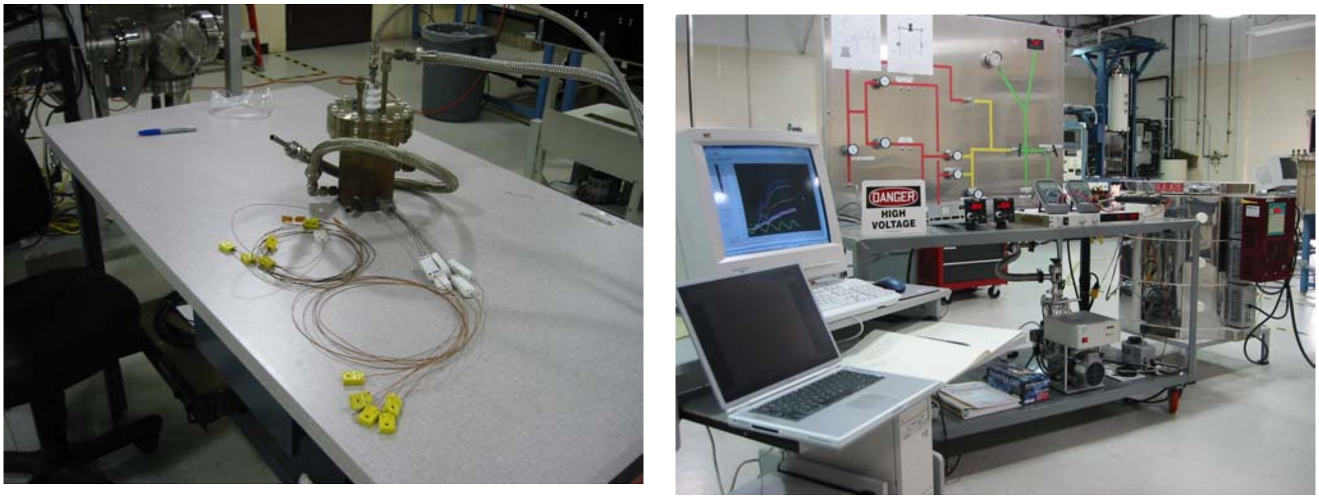


Figure 17. Instrumented Ne/H_2 gas cell and b) the experimental set up used to perform thermal characterization tests on the BlackLight Process.

Figures 17a and 17b show the instrumented gas cell and the experimental apparatus used to perform these tests. The experimental apparatus (see Fig. 17b) used for the thermal characterization studies shown was contributed to the Phase I study by BlackLight Power at no cost to NIAC. The experimental system, which is shown schematically in Fig. 18, consists of a H_2/Ne gas feed system, vacuum pump, kiln, DC power supply and data acquisition system. The hydrogen and neon gas flow rates are controlled using MKS 0-20 and 0-100 SCCM mass flow controllers, respectively. The gas cell pressure is maintained using an Anest Iwata ISP-250B oil free scroll pump and measured using an MKS Baratronic vacuum gauge. To initiate and maintain the gas plasma, a Xantrex XFR600-2 (0-600V, 0-2A) DC power supply is used. During the experiments, the gas cell is placed within a Dynatrol kiln, which maintains the ambient air surrounding the gas cell at a fixed temperature. Data are acquired using a PC in conjunction with a National Instruments A/D card and LabView data analysis software.

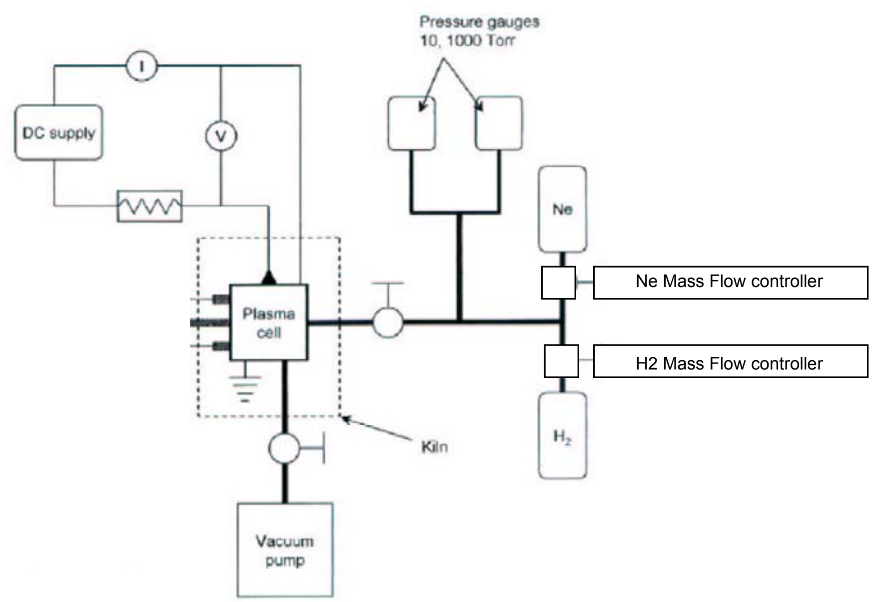


Figure 18. Schematic diagram of experimental apparatus used for thermal characterization tests.

Using the experimental apparatus shown in Figs. 16-18, experiments were conducted to determine the plasma energy as a function of mass flow rate, H_2:Ne ratio, pressure and input power. Figure 19 is a plot of several of the cell temperatures as a function of input power for a fixed flow rate, Ne/H_2 ratio, pressure and ambient kiln temperature. The temperatures plotted in Fig. 19 include the average temperature inside the hollow cathode tube bundle (T_1, T_2, T_4, T_5), the gas temperature inside the cell directly below the tube bundle (T_3), and the average cell wall temperature (T_6 – T_{12}). As would be expected, all of the temperatures increase with increasing power. Experiments were conducted to determine cell temperatures as a function of cell pressure, flow rate, and H_2:Ne ratio.

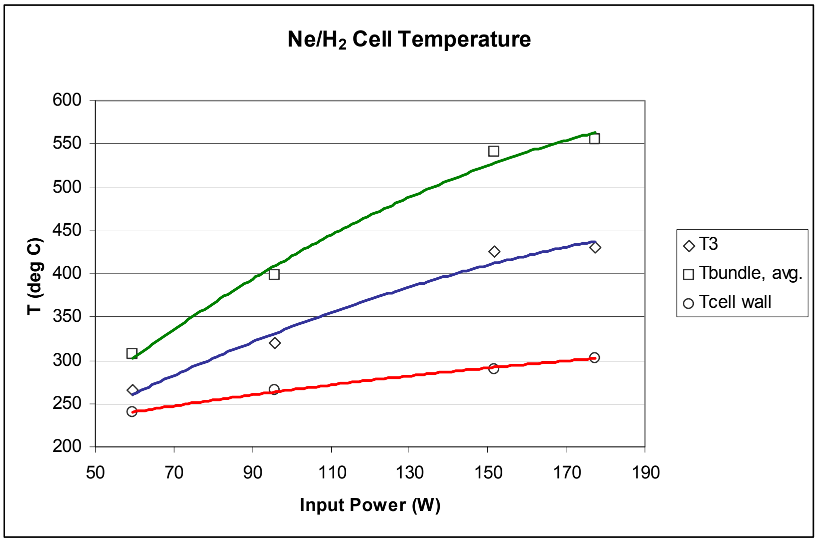


Figure 19. Gas cell temperatures as a function of input power for 2.0 SCCM total flow rate, 1 Torr and 200 °C ambient kiln temperature.

9.2 Unique Hydrogen Line Broadening in Low Pressure Microwave Water Plasmas

Mills and coworkers (2002c, 2002d) have shown that in low pressure mixed gas plasmas containing hydrogen (He/H_2, Ar/H_2, H_2O vapor), Balmer α lines broader than 2.5 Angstroms were observed. In each of these cases, only hydrogen lines showed any broadening. Moreover, in pure hydrogen plasmas and other mixed gas plasmas (H_2/Xe, H_2/Kr), no line broadening was observed. This preferential hydrogen line broadening was attributed to Doppler broadening from high random translational velocity of hydrogen atoms (i.e. fast H).

Doppler broadening of a spectral peak is due to the random distribution of translational velocities of emitting H atoms. Doppler broadening produces a Gaussian line shape. Stark broadening is caused by interactions between electronically excited atoms and ions and free electrons in a plasma. Stark broadening produces a Lorentzian profile. Generally speaking, a plasma line shape might show both effects. In this case the line shape is called a Voigt profile (Griem, 1964). In the microwave discharge experiments reported by Mills and coworkers (2002c), a Langmuir probe was used to measure at electron density in these systems of approximately $n_e = 2 \times 10^7 cm^{-3}$. At these electron densities, calculations show that Stark broadening is insignificant. Moreover, the line shape was shown to very closely match a Gaussian profile which is another indication that the line broadening is caused by fast H.

As part of the Phase I study, experiments were performed to evaluate previously reported data by BLP scientists showing excessive hydrogen Balmer series line broadening in rarified mixed gas hydrogen plasmas generated by microwave discharge. Since at these low pressures and high temperatures the H_2O rapidly dissociates into H and O atom, the H_2O microwave plasma is also a mixed gas hydrogen plasma. The experiments were performed using a 0.500" diameter by 10" length tubular quartz reactor, which was located downstream of a de-ionized water vessel fitted with a metering needle valve. An Anest Iwata ISP-250B oil free scroll pump, which was located downstream of the quartz reactor, pumped water vapor out of the water vessel and maintained a water vapor pressure inside the cell of 0.2 Torr. Pressure inside the gas cell was measured using an MKS Baratronic vacuum gauge.

The water vapor plasmas were generated using an Opthos model B1 co-axial E-mode Evenson microwave discharge cavity (Fehsenfeld, *et al*. 1964). The Evenson cavity was powered by an Opthos MPG-4M 2.45 GHz microwave power supply, which measured the microwave input power and reflected power. For the experiments reported here, input power was maintained at approximately 90 W and reflected power was maintained at approximately 5 W.

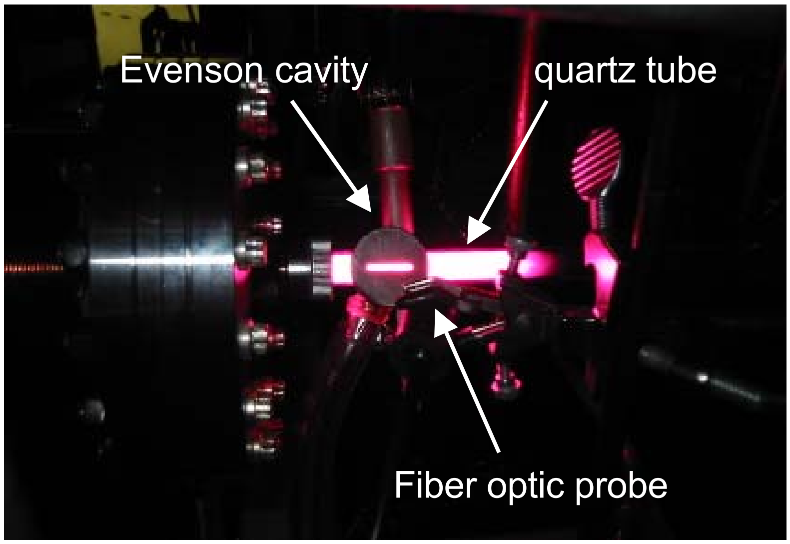


Figure 20. Microwave generated water plasma experimental set up.

Spectroscopic data were obtained using a Jobin Yvon Horiba 1250 M spectrophotometer with 2400 grooves/mm and a resolution of 0.006 nm over a range of 190 to 860 nm. For the experiments reported here, the instrument was scanned between 400 and 700 nm, with a step size of nm. The data was obtained in a single accumulation with a 1 second integration time and the signal was recorded by a PMT with a 950 V high voltage power supply. Figure 20 shows the quartz gas cell, Evenson microwave cavity and the fiber optic probe used to couple the emission to the spectrometer.

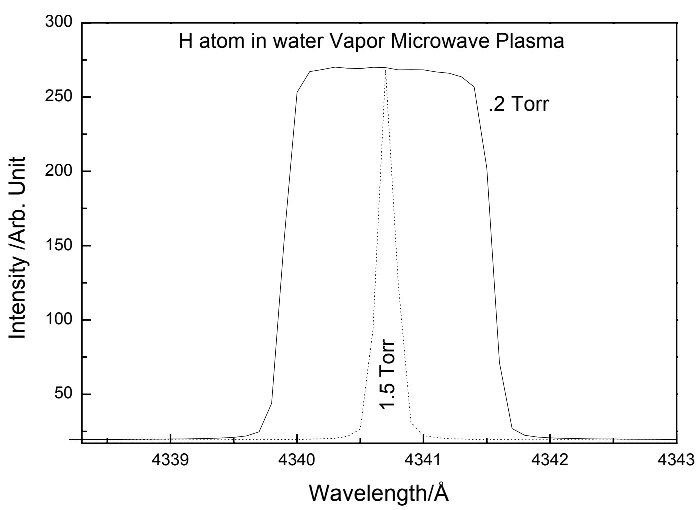


Figure 21. Hydrogen Balmer γ line for microwave generated water plasma at 0.2 and 1.5 Torr.

The experiments showed that under certain operating conditions, low pressure water vapor plasmas exhibited hydrogen line broadening and that the line broadening persisted at distances of 5 cm from the microwave cavity. Figure 21 shows one of these results. The figure shows the hydrogen Balmer γ line for microwave generated water plasma at 0.2 and 1.5 Torr, respectively. The results show that the line broadening phenomena occurs at lower pressures and diminishes as pressure increases. This result was comparable to results reported previously by Mills and coworkers (2002c). No broadening was observed in any of the measured oxygen lines. The preferential Doppler line broadening was observed in the atomic hydrogen emission spectra extremely high random translational velocity of H atoms within the plasma.

9.3 Inversion Of Line Intensities In Hydrogen Balmer Series

Recently, Mills and coworkers (2002c, 2002d) have reported another phenomena indicative of abnormally energetic mixed gas low-pressure hydrogen plasmas. Using a similar apparatus as that described in the previous section, Mills and coworkers (2002c) have reported dramatic inversion of line intensities of both the Lyman and Balmer series, suggesting the presence of a previously unobserved pumping mechanism. The results showed that a pure hydrogen microwave plasma exhibited no population inversion, whereas in microwave water plasmas at the same pressure and input power (approx. 0.2 Torr and 90 W, respectively) the Balmer n = 4, 5, 6 line were inverted with respect to the n=3 line. Inversion was measured in the microwave water plasmas even at a greatly reduced input power of 50 W. Moreover, no inversion at all was measured in similar water plasma experiments using an RF discharge system.

To evaluate the repeatability of the above results, experiments were performed as part of the present Phase I study. Using the same apparatus used for the line broadening experiments, an inversion of line intensities of the hydrogen Balmer series were also observed in microwave generated H_2O plasmas. Figure 22 shows the measured Balmer α, β and γ lines for microwave generated water plasma (90 W forward power, 5 W reflected power) at 1.5 and 0.2 Torr, respectively. The results show that, at 1.5 Torr, the Balmer series exhibits a expected Boltzmann distribution. At 0.2 Torr, however, the n=4 and 5 Balmer lines are far more intense than the n=3 line. The generation of non-Boltzmann distribution of electron populations is indicative of some form of pumping mechanism.

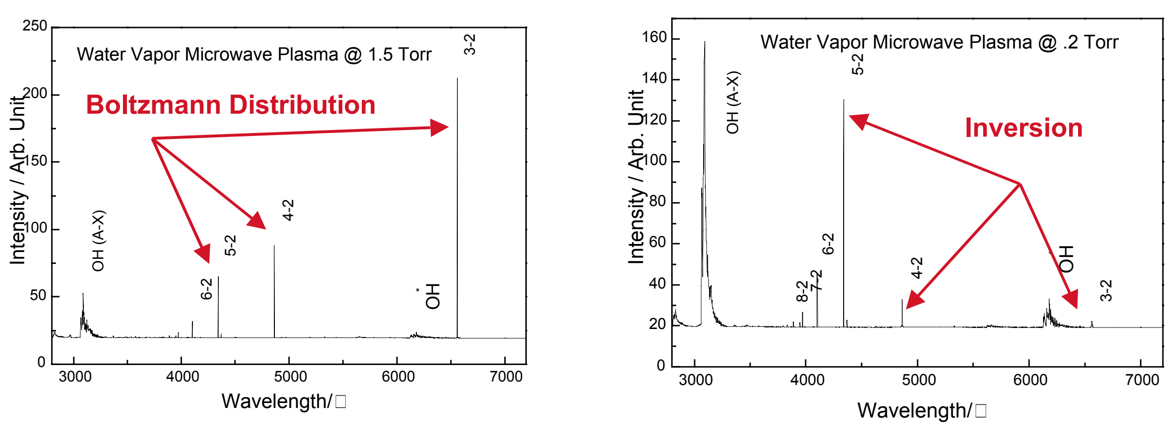


Figure 22. Hydrogen Balmer series for microwave generated water plasma at 0.2 and 1.5 Torr. The 1.5 Torr plasma exhibits the expected Boltzmann distribution whereas the 0.2 Torr plasma shows inversion.

9.4 Novel Vacuum Ultraviolet (VUV) Vibration Spectra Of Hydrogen Mixture Plasmas

A third spectroscopic measurement that suggests a novel phenomenon in low-pressure mixed gas hydrogen plasmas has been reported (Mills and coworkers, 2002b). This phenomenon, which is observed in the vacuum ultraviolet (VUV) spectrum, corresponds to novel "vibrational" peaks in the extreme ultraviolet (<90 nm). It has been reported in the previous studies that mixtures such as Kr/H_2 and Xe/H_2, which do not produce line broadening or population inversion also do not produce these novel VUV spectra.

To evaluate the reproducibility of these experimental results, experiments were performed as part of the present Phase I study using a similar microwave discharge cell to that described above. In this case, H_2/He mixtures, H_2/Ar mixtures and pure H2 gas microwave discharge experiments were performed. A McPherson Model 248/310G 4° grazing incidence VUV spectrometer was used to measure vacuum ultraviolet emission (25 to 90 nm) for helium and hydrogen/helium microwave plasmas.

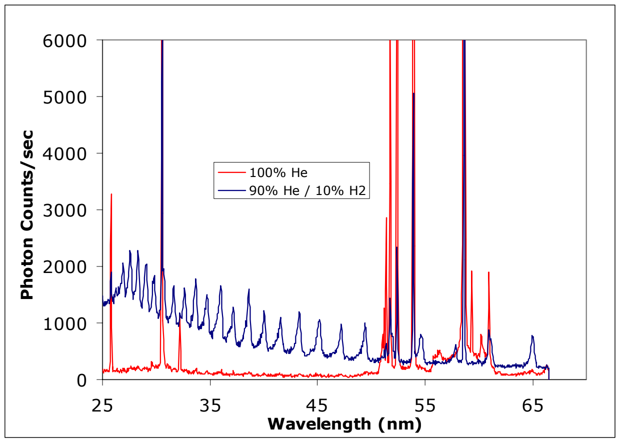


Figure 23. Novel VUV emission spectra for He/H_2 microwave discharge plasmas at 0.77 Torr.

As shown in Figure 23, the He/H_2 microwave plasmas show novel "vibrational' peaks in the VUV, whereas the pure helium plasma shows only the expected helium electronic emission lines. It should be noted that previously reported results suggest that pure hydrogen microwave plasmas should not exhibit these novel "vibrational" lines. However, in the experiments performed in this study, these lines were observed for pure hydrogen as well. Recent observations by Mills and coworkers verify this observation (Mills, 2002f). Specifically, pure hydrogen microwave plasmas have been shown to exhibit this phenomenon whereas RF discharge hydrogen plasmas do not.

9.5 Water Bath Calorimetry Experiments Showing Increased Heat Generation

To evaluate previously reported data on excess power in mixed gas hydrogen systems, an Evenson cavity and quartz tube plasma reactor similar to those described above were tested using water bath calorimetry as shown schematically in Figure 24. To perform these tests, the Evenson cavity and plasma reactor were fitted with a water-tight stainless steel housing. The 4x4x2 cm rectangular stainless steel housing was welded to a 6 inch CF vacuum flange, which was mated to a 6" blank CF flange. The blank flange was modified to include a stainless steel thermocouple well and a 1" OD coaxial cable housing for the microwave power feedthrough. The housing was suspended from a 2 inch thick acrylic plate by four support rods and immersed in a water bath calorimeter as shown schematically in Fig. 24. The top acrylic plate contained sealed penetrations for the thermocouple well feedthrough, the gas feedthrough, the vacuum line feedthrough and the coaxial microwave cable. The acrylic plate was used to suspend the entire system in the water bath calorimeter system described below.

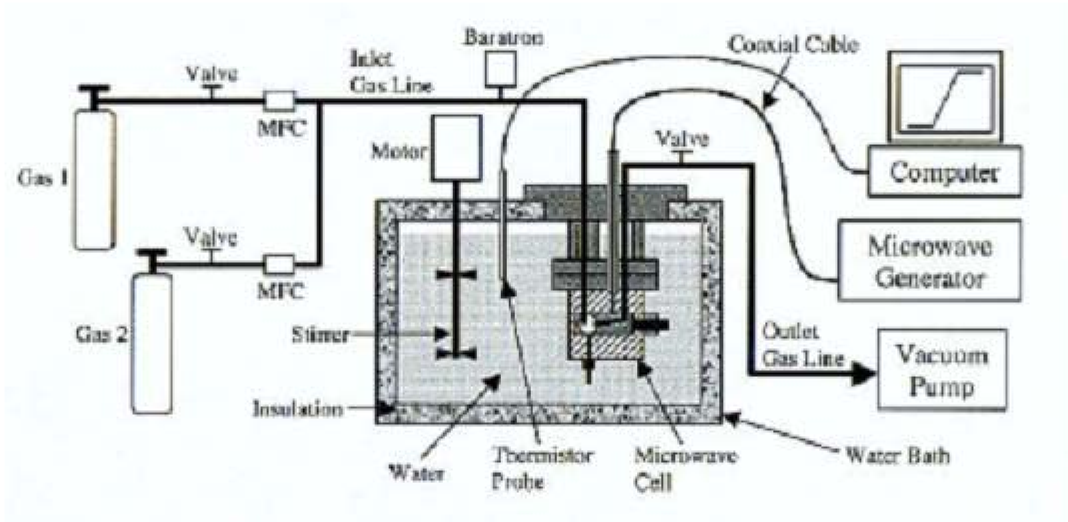
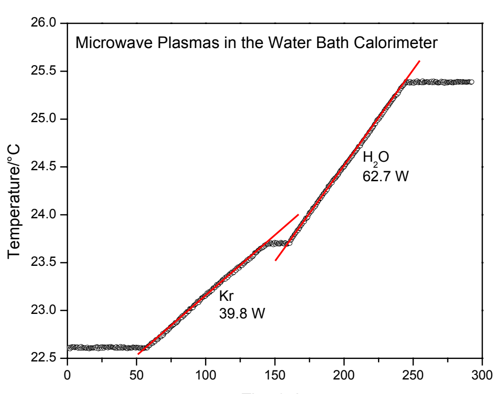


Figure 24. Schematic diagram of water bath calorimeter experiment (Mills and coworkers, 2002f).

The water bath calorimeter is described in detail in Mills and coworkers (2002f). The system was fabricated from an insulated reservoir, which was filled with 45 liters of distilled water. The water was continuously stirred by an electrically driven stirring paddle. A high precision Omega OL-703 thermistor probe was used to record the temperature of the water bath as a function of time. The water bath was calibrated by a high precision Watlow 125CA65A2X heater, which was connected to a 0-1200 W Xantrex DC Power supply. The heat capacity of the system was measured for various input powers and found to be constant to less than 0.05%. The entire system is capable of measuring the heat transfer rate into the water to an accuracy of better than 1 W.

In general, the ultimate basis of any microwave power measurement is a direct absolute calorimetric determination on an instrument, which then serves as a primary standard for secondary measurements. Mills and coworkers (2002f) have used the water bath calorimeter as the absolute standard using fixed forward and reflected power diode settings. Thus, the quantification of the microwave input power to the plasmas was achieved by maintaining constant values of forward (e.g. 70 ± 1 W) and reflected powers (e.g. 16 ± 1 W) for all experiments. Specifically, for both the experimental and control plasmas, the power supply and Evenson cavity tuning were adjusted such that the forward and reflected powers indicated by the uncalibrated power reading diodes (Agilent) of the Opthos generator were constant for experiments.



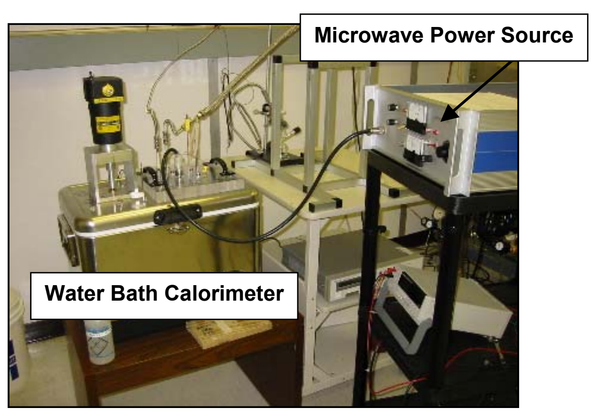


Figure 25. a) Experimental results of Temperature vs. time for water bath calorimeter experiment and **b)** experimental setup for the experiment.

For the experiments performed as part of this study, the microwave discharge gas cell was submerged in the calorimeter as shown in Figure 25b and operated with H_2/He mixtures, H_2O vapor and a variety control gases including N_2, Kr and H_2/Kr mixtures. In each case, prior to submerging the gas cell, the Evenson cavity was tuned so that the microwave power supply read 70 W forward power and 16 W reflected power, as indicated by its uncalibrated power diode meters. After submerging the system in the water bath calorimeter, the temperature of the water bath was accurately measured as a function of time and the heat transfer rate was calculated to within approximately 1 W. Figure 25a shows a typical result, in which for the same operating conditions, the heat transfer rate for the control gas plasma was < 40 W, while the heat transfer rate for the H_2/catalyst was between 55 and 62 W. The results shown in Fig. 25a compare the heat transfer rate for an H_2O vapor plasma vs. a krypton control gas plasma, both maintained at 0.200 Torr. As shown, the measured heat transfer rate was 62.7 W for the H_2O plasma and 39.8 W for the Kr plasma.

Mills and coworkers (2002f) interpret the power measured by the water bath using several control gas plasmas (39.8 ± 1W in each case) as the true microwave power delivered by the microwave source and the difference between the control power and the H_2/catalyst power (in this case 22.9 ± 1W) as "excess power" associated with the BlackLight process. In a variety of experiments performed as part of the Phase I study, there was indeed a clear, repeatable difference (approximately 20 W) between measured power corresponding to water bath heating rates for control gases vs. H_2/catalyst gases.

It is difficult to explain how (under the same microwave power input conditions) control gases and control gas/H_2 mixtures only produce approximately 40 W of heating, while H_2/catalyst mixtures such as H_2O, H_2/He, H_2/Ar mixtures, etc. consistently produce 55 to 62 W. Additional studies are required to rule out all other possible explanations other than "excess power" for these observations. For example, it is possible that microwave source delivers a different power level for the control gases vs. the hydrogen/catalyst gases. Or, in the case of the control gases, it is possible that heat is being dissipated at other locations in the system that are not submerged in the water bath calorimeter. Each of these possibilities will be examined in detail in future studies.

9.6 Summary of Experimental Evaluation

The spectroscopic and calorimeter data discussed above suggests that there does indeed appear to be something unique about certain low pressure mixed gas H_2 plasmas. For example, if one considers the line broadening results described above, the evidence is growing that low pressure mixed gas hydrogen plasmas can be created in which the hydrogen atoms have extremely high random translational velocity as demonstrated by the extreme levels of Doppler line broadening. The function of all thermal rocket propulsion devices is to convert random thermal energy to directed kinetic energy. Similarly, the objective of the present Phase I study was to determine the potential of converting the high random translation velocity of hydrogen atoms (i.e. fast H) present in low pressure mixed gas hydrogen plasmas into directed translational velocity for the purposes of space based propulsion systems (See Fig. 26). As described above, two thruster configurations were conceptualized, designed and built during the 6-month Phase I study with the goal of measuring exhaust velocity such that specific impulse and thruster efficiency could be measured.

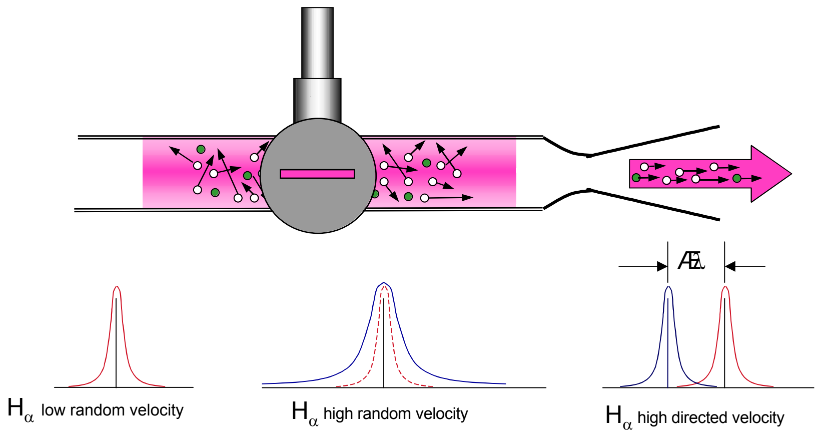


Figure 26. Conceptual model showing random translational velocity associated with low pressure mixed gas hydrogen plasmas converted to directed velocity for space propulsion purposes.

10. BLPT and BLMPT Proof of Concept Test Firing

10.1 Experimental Apparatus and Vacuum Chamber

Both the BLPT and BLMPT thrusters have been successfully test fired. To perform the BLPT thruster experiments, a vacuum system was developed to simulate the space environment. As shown above (See Fig. 14), a "previously owned" vacuum chamber was purchased with funds from the NIAC budget and matching funds from the Department of Mechanical Engineering at Rowan University. The system, which has been conservatively valued at approximately $75,000 was purchased for $7,500. The system consists of a 13.25 inch vacuum chamber cube manufactured by MDC. The vacuum chamber has three 13.25 inch CF flange windows, one 13.25 inch door and multiple 2.5" CF flange feed throughs. The system has a Welch mechanical roughing pump and a Crytorr 8 vacuum pump that can be isolated from the chamber by a 13.25 inch vacuum gate valve manufactured by VAT.

The experimental setup for thruster testing, which is shown in Fig. 27, consisted of the vacuum chamber, CryoTorr vacuum pump, a H_2/Ne gas feed system, vacuum pump, DC power supply and data acquisition system. The hydrogen and neon gas flow rates are controlled using MKS 0-20 and 0-100 SCCM mass flow controllers, respectively. The vacuum pressure was maintained by a CryoTorr 8 cryopump, backed by a Welch mechanical roughing pump. The vacuum pressure was measured using a vacuum gage capable of measuring pressures of 1e-7 Torr.

As shown in Figure 28, the BLPT thruster was mounted horizontally in the test chamber and bolted in place into one of the 13.25 " CF vacuum flanges. In this configuration, the thruster exhaust plume spectra could be acquired parallel to the exhaust flow and perpendicular to the exhaust flow through two separate windows. The BLPT plasma within the thrust chamber was initiated and maintain by a Xantrex XFR600-2 (0-600V, 0-2A) DC power supply is used. The thrust chamber pressure was measured using an MKS Baratronic vacuum gauge.

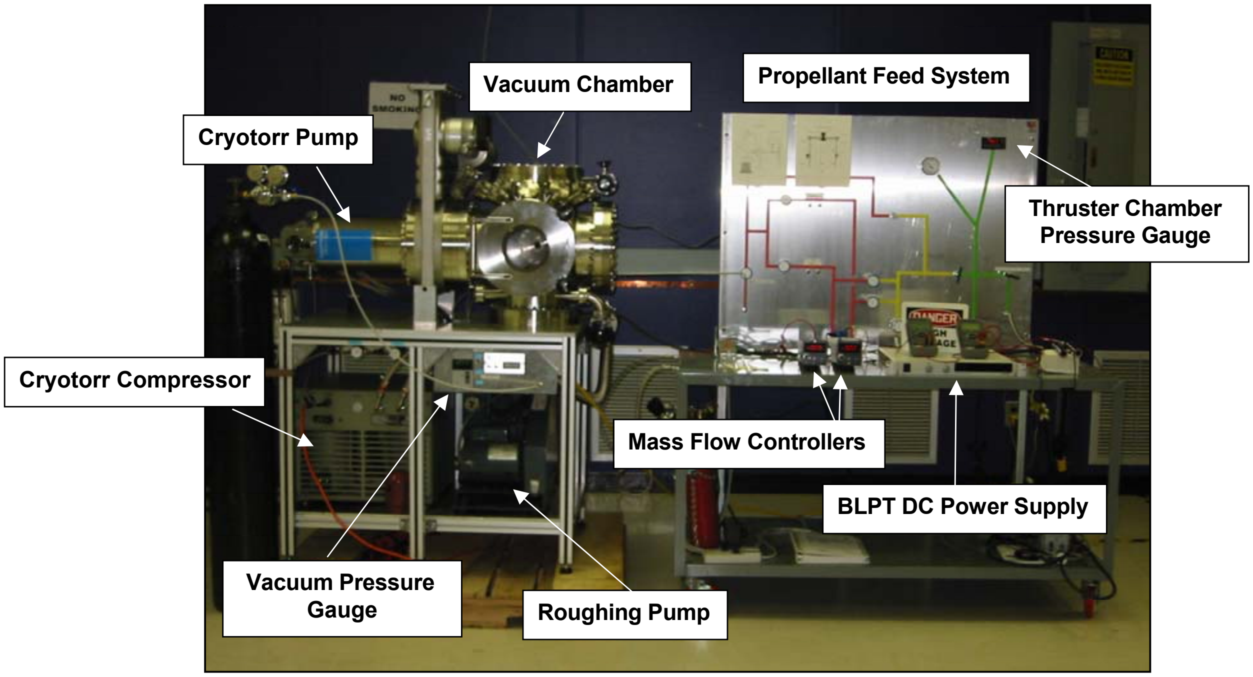


Figure 27. Vacuum test system for BlackLight Plasma Thruster (BLPT) testing.

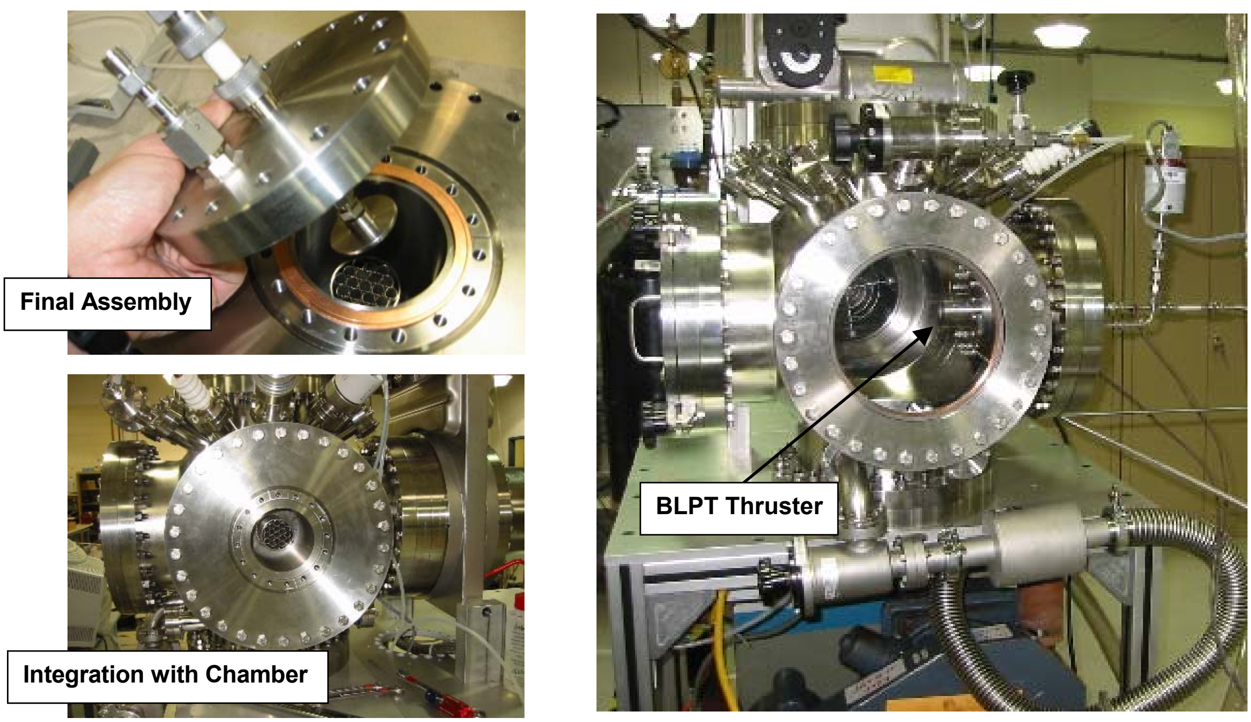


Figure 28. Final assembly and installation of BLPT into vacuum test chamber.

10.2 Test Firing of BLPT Thruster

As described above, calculations had been performed to determine the required throat diameter for a given propellant mass flow rate. Based on these calculations, a throat diameter of 0.100” was chosen. In addition, the experiments on the Ne/H_2 test cell were performed which showed that the plasma was most stable and energetic at 0.5 to 1.0 Torr. During the first test firing of the BLPT thruster, it was found that at the maximum system propellant flow rate (15 SCCM) a chamber pressure of only 0.200 Torr was obtainable. Accordingly, a series of inserts were fabricated out of brass, which had an outer diameter of .100" and inner diameters varying from 0.025" to 0.075". Experiments performed using the 0.050" throat diameter insert, a chamber pressure of 0.600 Torr was maintained.

Figures 29a and 29b show a test firing of the BLPT thruster along with a plot of C* as a function of chamber pressure. The characteristic velocity (C*) is a parameter that can be calculated theoretically as a function of chamber temperature. Experimentally, for a given nozzle throat area, C* can be measured by simply measuring the chamber pressure and the mass flow rate and the throat area. For perfect expansion in a nozzle, C* is related to the specific impulse as follows:

$$I_{sp} = C_F C^*/g_o$$

where C_F is the thrust coefficient and g_o is the acceleration due to gravity. The thrust coefficient is a function only of the expansion in the supersonic nozzle, whereas C* is a function only of the energetics of the plasma within the plasma chamber. Moreover, since the thrust coefficient is generally between 1.0 and 2.0, a measurement of C* gives a good indication of the performance of the thruster.

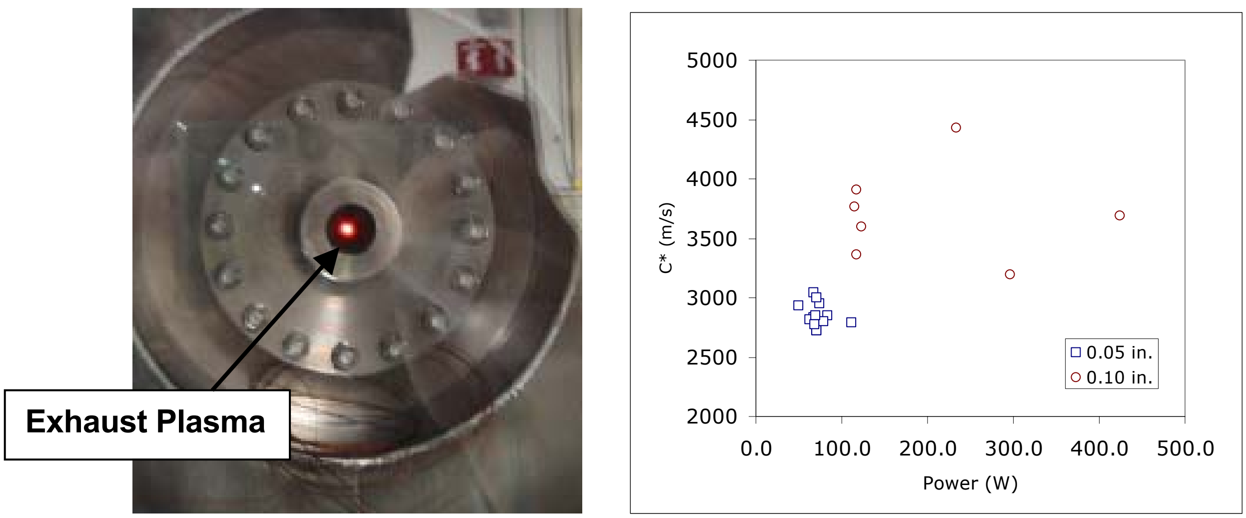


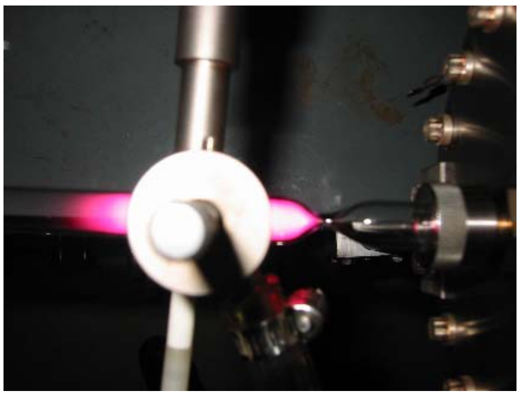
Figure 29. a) Test firing of BLPT thruster and **b)** measured C* as a function of input power.

As shown in Fig. 29b, the measured C* values are on the same order as those measured for chemical rocket propulsion, which is reasonable for the first proof of concept test. Tests are ongoing to determine optimum chamber pressure, optimum Ne/H_2 ratio as a function of power input. The C* parameter is a convenient parameter to monitor as these parameters vary since it is quite simple to measure and it is a function of the effective thrust chamber temperature. Tests are ongoing to identify optimum operating conditions.

Based on the measured C* shown in Figure 29b, an estimate of exhaust velocity for the BLPT thruster in its present configuration would be approximately 5000 m/s. Given the present resolution of the spectrometer system used for Doppler shift experiments (approx. 2700 m/s) it will be quite difficult to measure this exhaust velocity of the BLPT with reasonable accuracy.

10.3 Test Firing of BLMPT Thruster

In a parallel effort, a BlackLight Microwave Plasma thruster was also developed as described above. Since the BLPT thruster was installed in the vacuum chamber described in section 10.1, the BLMPT was installed into a small cylindrical vacuum chamber (6" diameter by 8" length) with a transparent rear window. The vacuum chamber was connected to a molecular drag vacuum pump capable of maintaining a vacuum pressure of less than 0.01 Torr. Based on the line broadening and line inversion experiments measured in the experiments with H_2O plasma, the BLMPT thruster was initially tested with H_2O vapor as propellant. The thrust chamber pressure was maintained at 0.2 to 0.3 Torr since these pressures were found to result in the most dramatic line broadening. Figures 30a and b show a test firing of the BLMPT thruster with 0.025 inch and 0.100 inch throat diameter, respectively.



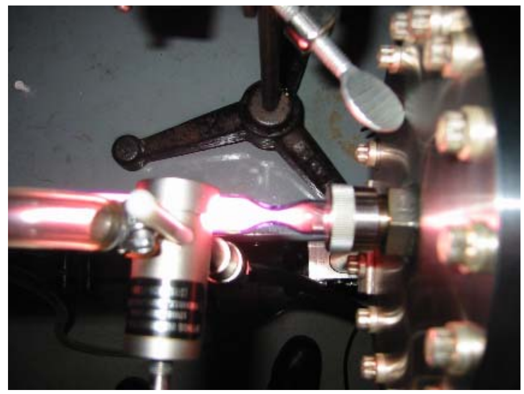


Figure 30. Test firing of BLPMT thruster with **a)** 0.025 inch throat and **b)** 0.100 inch throat.

As shown in Fig. 30, at a throat diameter of 0.025", the plasma quenched right at the nozzle throat. Since, the plan was to measure exhaust velocity using the Doppler shift of spontaneously emitting H atoms, it was imperative that the exhaust gases contained an emitting plasma of sufficient intensity. Figure 30b shows a similar setup, but with a 0.100 inch diameter nozzle throat. In this case, the plasma was able to traverse the throat. After several iterations a throat diameter of 0.057 inches was chosen. As described above, the goal of the experiments was to obtain emission spectra perpendicular and parallel to the exhaust flow and to measure a Doppler shift in a given emission line.

Spectroscopic data were obtained using a Jobin Yvon Horiba 1250 M spectrophotometer with 2400 grooves/mm and a resolution of 0.006 nm over a range of 190 to 860 nm. The data was obtained in a single accumulation with a 1 second integration time and the signal was recorded by a PMT with a 950 V high voltage power supply. Figures 31a and 31b show BLMPT thruster, microwave power supply and the JY Horiba 1250 M spectrometer used to perform the Doppler shift experiments. Due to its intensity, hydrogen Balmer γ (4340.4 Å) was chosen as the emission line for which the Doppler shift would be measured. Accordingly, for the experiments reported here, the instrument was scanned between 4335 and 4345 Å, with step size of 0.06 Å.

In performing the Doppler shift measurements, it is imperative that the fiber optic probe does not measure emission from within the BLMPT thrust chamber itself. Rather, the fiber optic probe must focus on a region that is entirely in the exhaust plume. Micci and coworkers (1999) accomplished this task by using a fiber optic feedthrough and placing the fiber optic probe inside the vacuum chamber and directly into the exhaust plume. To ensure that they were not measuring emission from within their microwave thruster, they placed the probe at the edge of the nozzle exit plane and at a slight angle with respect to the nozzle centerline.

In the present study, time and cost constraints prohibited the use of the fiber optic feedthroughs and longer fiber optic probes required to probe the exhaust in the manner described by Micci and coworkers. Instead, initial attempts were made to scan the emission spectra parallel to the exhaust plume by accurately moving the fiber optic probe across the window of the vacuum chamber perpendicular to the exhaust plume as shown in Fig. 31b. Based on the emission intensity, however, it was apparent that this technique was not successful in focusing on a point within the exhaust plume. Rather, it was hypothesized that the fiber optic probe was measuring reflected light from within the BLMPT thrust chamber. Figure 32 is a plot of the measured emission intensity (in arbitrary units) as a function of the lateral position of the fiber optic probe from the centerline of the rear window (See Fig. 31b). The plot shows that even at distances up to 1.2 inches from the centerline, the intensity of he measured signal did not decrease significantly from the maximum measured intensity. Since the nozzle exit plane is only 0.400" in diameter, it was concluded that the fiber optic probe was not focused on a point in the exhaust plume, but was measuring emission spectra from the entire vacuum chamber, which was receiving reflected light from the plasma within the thrust chamber.

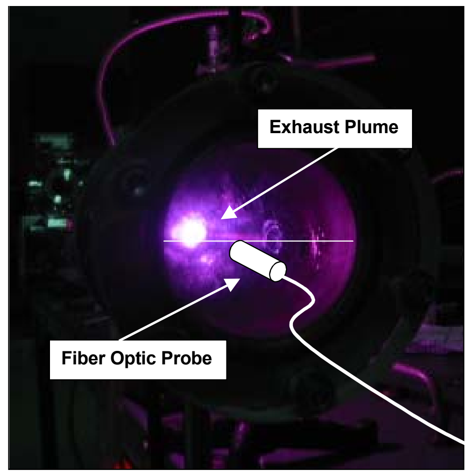


Figure 31. a) Experimental setup for exhaust velocity measurements for BLMPT and **b)** fiber optic probe positioning for exhaust plume measurements.

In an attempt to focus the field of view of the fiber optic probe, a pair of 50 mm diameter plano-convex lenses (Coherent 750 mm and 400 mm F.L) were purchased and used in conjunction with a laser alignment system made available by BlackLight Power at no cost to the project. The goal of this system was to focus the visible spectra from various points in the exhaust plume onto the fiber optic probe, which would then be coupled to the JY Horiba 1250 M spectrometer. The latter system was developed within the last remaining weeks of the present Phase I study and tests had begun at the time of this report.

The alignment issue, in the case of the BLMPT thruster has an added difficulty associated with the transparent nozzle. Specifically, even if the fiber optic probe is directed at the edge of the exhaust plane (as described by Micci and coworkers), there still exists a path for light to travel directly through the nozzle walls and into the thrust chamber. Therefore, experiments need to be performed at various angles and positions to guaranty that light from inside the thrust chamber is not being measured by the exhaust probe. Furthermore, it is clear that the small vacuum chamber constructed for use with the BLMPT has a high reflectivity that, even in the presence of the laser alignment and focusing optics, might ultimately result in measurements of light emitted from within the chamber. Therefore, the BLMPT must also be installed into the larger vacuum system described in the previous section. A system has been designed for installing the entire BLMPT thruster inside the vacuum test chamber. The proposed system is significantly more complicated than that described in this section since feedthroughs must be constructed for the microwave power lines, Evenson cavity tuning knobs and a cooling system for the Evenson cavity.

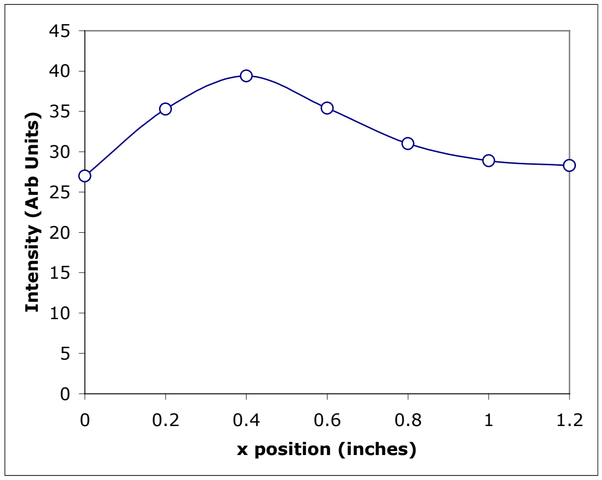


Figure 32. Measured emission intensity (in arbitrary units) as a function of the lateral position of the fiber optic probe from the centerline of the rear window.

Finally, once a system is developed which focuses directly onto a point in the exhaust flow field, it may indeed turn out that the spontaneous emission of exhaust plume does not have sufficient intensity for accurate measurement of a Doppler shift. As evident from Figure 30a, for example, the rapid pressure drop associated with the supersonic converging-diverging nozzle results in rapidly decreased emission intensity. Indeed, Micci and coworkers were unable to use the Doppler shift technique to measure exhaust velocity of their microwave thruster when they operated at lower thrust chamber pressures (1999). The chamber pressures necessary to create the BlackLight process are orders of magnitude lower than those used by Micci and coworkers, so it would not be surprising if other techniques such as Laser Induced Florescence Velocimetry or actual thrust measurements will be required to accurately measure the performance of both the BLPT and BLMPT thrusters.

11. Conclusions and Future Work

As described in this report, experiments were performed to characterize the BlackLight process, two separate proof-of-concept thrusters were designed and built, an apparatus was developed to measure exhaust velocity using a Doppler shift technique and both thruster systems were successfully test-fired. However, due to time and cost constraints of the 6-month study, successful measurements of the exhaust velocity have not been completed to date. While experiments are ongoing, the Doppler shift technique may ultimately not be feasible for these experiments as originally hoped due to the low pressure, weakly emitting exhaust plumes inherent in these systems. The Doppler shift technique (chosen here for its simplicity given the time and cost constraints) relies on the spontaneous emission of the high velocity exhaust gases. The BLPT and BLMPT thrusters, which are nominally operated at 0.2 to 1.0 Torr thrust chamber pressure, result in very low exhaust pressures, resulting in spontaneous emission intensity that might be too low to measure with the current spectroscopy system. However, a slightly more complicated (but realizable) system could be developed using Laser Induced Florescence Velocimetry, in which the exhaust gas is electronically excited. Alternatively, as was originally planned for the present study (but rejected due to time constraints), a low thrust thrust stand could be designed and built. These concepts will be proposed for an ongoing Phase II study.

Low-pressure, mixed gas hydrogen plasmas such as those studied in the present Phase I project have been largely unexplored for propulsion applications and only recently begun to be studied spectroscopically. The recent spectroscopic studies have revealed some surprising results, which suggest that a highly energetic low pressure mixed gas hydrogen propulsion system could be realized. Based on the quantitative results of the plasma experiments and the qualitative results obtained to date on the BLPT and BLMPT test firings, the team believes that

Phase II funding is justified to continue this work. Accordingly, the team plans to submit a Phase II proposal that will focus on the following objectives:

- Perform independent experiments with additional diagnostics and consult with plasma physics experts to validate previously published spectroscopic data on energetic mixed gas H_2 plasmas.
- Consult with experts to develop a method to validate excess energy experiments.
- Complete testing of BLPT thruster with various propellant combinations, pressures and power input to determine optimum operating conditions based on measured C*.
- Complete development of BLMPT thruster hardware, install BLMPT thruster into vacuum test chamber and probe exhaust flow using laser alignment system to attempt to measure exhaust velocity using Doppler shift.
- Run BLMPT with He/H_2, Ar/H_2, H_2O propellants and determine optimum operating conditions.
- Design, build and test a thrust stand to accurately measure thrust, specific impulse (I_{sp}) and overall thruster efficiency (η) for the BLPT and BLMPT thrusters.
- Develop a theoretical model of BLPT and/or BLMPT performance for integration into space vehicle mission studies.
- Examine other concepts to convert random fast hydrogen to directed fast hydrogen and examine other concepts to convert plasma power into useful power source for space-based applications.

Acknowledgements

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References

Beiser, A. (1987). Concepts of Modern Physics, Fourth Edition. *McGraw Hill Book Division*.

Bussard, R. W. (1960). Galactic Matter and Interstellar Flight. *Astronautica Acta*. **6:**179-194.

Chen, C., Wei, T., Collins, L.R. and Phillips, J. (1999). Modeling the Discharge Region of a Microwave Generated Hydrogen Plasma. *J. Phys. D: Appl. Phys*. **32**:688-698.

Choueiri, E.Y. and J.K. Ziemer. (2001). Quasi-steady magnetoplasmadynamic thruster measured performance database. *Journal of Propulsion and Power*, **17(5):**967--976.

Curran, F. M. and Sarmiento, C. J. (1990). Low Power Arcjet Performance Characterization. *AIAA Paper 90-2578.*

Djurovic, S. and J. R. Roberts (1993). Hydrogen Balmer alpha line shapes for hydrogen-argon mixtures in a low-pressure RF discharge. *J. App/. Phys*. 74/11:6558-6565.

Fehsenfeld, F.C., K. M. Evenson and H.P. Broida. (1965). Microwave discharges operating at 2450 Mhz. *Review of Scientific Instruments*. 35/3:294-298.

Galecki, D. L. and Patterson, M. J. (1987). Nuclear Powered Mars Cargo Transport Mission Utilizing Advanced Ion Propulsion. *NASA TM 100109. AIAA-87-1903.*

Gordon, S. and McBride, B. J. (1971). Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouget Detonations. *NASA SP-273*.

Griem, H. R. (1964). Plasma Spectroscopy. McGraw-Hill, New York, 1964.

Hollander, A. and M. R. Wertheimer (1994). *J. Vac. Sci. Technol*. A. 12 (3):879-882.

Humble, R. W., Henry, G. N, and Larson, W. (1995). Space Propulsion Analysis and Design. *McGraw-Hill, Inc.*

Jannson, P. (1997). HydroCatalysis: A New Energy Paradigm for the 21st Century. Master's Thesis. Rowan University. Department of Electrical and Computer Engineering.

Kaplan, D. L. (1996). Mars Sample Return Using In-Situ Propellant Production. *Space V: Proceedings of the Fifth International Conference on Space '96*. American Society of Civil Engineers, pp. 717-723.

Kuraica, M. and N. Konjevic (1992). Line shapes of atomic hydrogen in a plane-cathode abnormal glow discharge. *Physical Review A*, 46/7:4429-4432.

Labov, S. and Bowyer, S. (1991). Spectral Observations of the Extreme Ultraviolet Background. *Astrophys J.* **371**, 810.

Marchese, A. J., Schmalzel, J. L, Mandayam, S.A. and Chen, J.C. (2001). A Venture Capital Fund for Undergraduate Engineering Students at Rowan University. *J. Eng. Edu*. **90**: 589-596.

Mills, R. L and P. Ray (2002a). Substantial changes in the characteristics of a microwave plasma due to combining argon and hydrogen. *New Journal of Physics*. 4: 22.1-22.17.

Mills, R. L. J. He, A. Echezuria, B. Dhandapani, and P. Ray (2002b). Comparison of catalysts and plasma sources of vibrational spectral emission of fractional-Rhydberg-state hydrogen molecular ion. *Vibrational Spectroscopy*. Submitted.

Mills, R. L., P. Ray and R. M. Mayo. (2002c). Stationary inverted Balmer and Lyman populations for a CW HI water-plasma laser. *IEEE Transactions on Plasma Science*. Submitted.

Mills, R. L., P. Ray, R. M. Mayo, M. Nansteel, B. Dhandapani and J. Phillips (2002d). Spectroscopic study of unique line broadening and inversion in low pressure microwave generated water plasmas. *Internal report*.

Mills, R. L., Ray, P., Dong, J., Nansteel, M., Dhandapani, B., and He, J. (2002e). Spectral Emission of Fractional-Principal-Quantum-Energy Level Molecular Hydrogen. *Submitted to Journal of Vibrational Spectroscopy*.

Mills, R. L., Chen, X., He, J. and Dhandapani (2002f). Plasma Power Source Based On A Catalytic

Reaction Of Atomic Hydrogen Measured By Water Bath Calorimetry. *Submitted.*

Mills, R. L, Ray, P., Dhandapani, B., Nansteel, M., Chen, X., and He, J. (2001). New Power Source from Fractional Quantum Energy Levels of Atomic Hydrogen That Surpasses Internal Combustion. Submitted.

Mills, R. L., Dong, J. and Lu, Y. (2000). Observations of Extreme Ultraviolet Hydrogen Emission from Incandescently Heated Hydrogen Gas with Certain Catalysts. *International Journal of Hydrogen Energy*. **25,** 919

Mills, R. L. (2000). The Hydrogen Atom Revisited. *International Journal of Hydrogen Energy*. **25**. 1171-1183.

Palaszewski, B. A. (1990). Metallized Propellants for the Human Exploration of Mars. *NASA TP 3062*.

Patterson, M. J. and Verhey, T.R. (1990). 5 kW Xenon Ion Thruster Lifetests. *AIAA Paper 90-2543*. July 1990.

Philips, J., Smith, J. and Kurtz, S. (1996). Report on Calorimetric Investigations of Gas-Phase Catalyzed Hydrino Formation. *Final Report, In Fulfillment of Service Contract with HydroCatalysis Power Corp. Pennsylvania State University. Department of Chemical Engineering.* December 1996.

Radovanov, S. B., J. K. Olthoff, R. J. van Brunt, and S. Djurovic (1995). Ion kinetic-energy distributions and Balmer-alpha (H_) excitation in Ar-H2 radio-frequency discharges. *J. Appl. Phys*. 78/2:746-757.

Radovanov, S. B., K. Dzierga, J. R. Roberts and J. K. Olthoff (1995). Time-resolved Balmer-alpha emission from fast hydrogen atoms in low pressure, RF discharges in hydrogen. *Appl. Phys. Lett*. 66/20:2637-2639.

Souliez, F. J., Chianese, S. G, Dizac, G. H. and Micci, M. M. (1999) Low Power Microwave Arcjet Testing. *AIAA 99-2717*.

Stwalley, W. C., Lyyra, A. M. and Zemke, W. T. (1991). Survey of Potential Novel High Energy Content Metastable Materials. *Proceedings of the High Energy Density Matter Conference*. Albuquerque, NM.

Sutton, G. P. (1992). Rocket Propulsion Elements: An Introduction to the Engineering of Rockets. *Sixth Edition. Wiley.*

Videnovic, I.R., N. Kojevic and M. Kuraica (1992). Spectroscopic investigations of a cathode fall region of the Grimm-type glow discharge. *Spectrochemica Acta*. 47:1173.

Zubrin, R., Price, S. Mason, L. and Clark, L. (1994). Mars Sample Return with In-Situ Resource Utilization. *AIAA-94-2844.*

Zurawski, R. L. (1986). Current Evaluation of the Tri-propellant Concept. *NASA TP 2602*.