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ABSTRACT

Current satellite propulsion technology relies heavily on hydrazine and other propellants that provide a severe negative environmental impact. Alternatives to these propellants are of significant interest to space programs around the world. Since the 1960s, several alternatives have existed, but hydrazine continues to dominate in the rocket propulsion field. Alternative propellants also lend themselves to alternative methods of ignition and combustion that cause fewer negative effects on the environment. Development of an ignition system for a specific alternative fuel source, hydroxylammonium nitrate (HAN: \( \text{NH}_2\text{OH} \cdot \text{HNO}_3 \)), is the focus of this thesis. HAN has higher burn efficiency and produces fewer toxic bi-products than hydrazine, and is also less toxic to handle for prep crews prior to launch. After three trials using 13 % molar solution of HAN in water, the method of ignition proved successful using 500 W of microwave input power to create the helium carrier plasma and ignite the propellant.
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Completion of this thesis project relied on the research of Dr. Michael M. Micci and his team of undergraduate and graduate students for the last 20 years. His generosity in allowing another member to join his team is duly noted and appreciated. Dr. Sven G. Bilén also assisted a great deal in Dr. Micci’s absence when he was on sabbatical. Mr. Brian Lani, a graduate student in Dr. Micci’s research group was essential in conducting this research and provided a wealth of photographic and video evidence of each experiment. I would also like to dedicate this thesis and my research to the Challenger 7 Astronauts, who inspired me at age 10 to follow in their footsteps and look towards a career as an astronaut. The support from family, friends, co-workers past and present, and the faculty and staff of both the Aerospace Engineering and Engineering Science Departments is also tremendously appreciated.
Chapter 1: Introduction

Objectives

The primary objective of this thesis is to determine the feasibility of igniting hydroxylammonium nitrate (HAN: NH₂OH•HNO₃) with a microwave plasma torch. A feasible ignition method is a basis for creating a new satellite thruster. The logic in approach is that a thruster based on this concept would have a 25% reduction in overall system weight. [1] HAN is also a much more environmentally friendly propellant than many of the ones currently used.

Literature Review

Since the inception of space exploration in the 1950s and 1960s, solid and liquid propellants have introduced damaging products to the environment. As the world becomes increasingly “green” in response to resource depletion, climate change, species extinction, and eco-system disruption, researchers are seeking alternatives to the hydrazine (N₂H₄); ammonium perchlorate, AP (NH₄ClO₄); nitrogen tetroxide, NTO (N₂O₄); and other traditional propellants. Ammonium dinitramide, ADN (NH₄⁺N(NO₂)₂), and hydroxylammonium nitrate, HAN (NH₃OHNO₃), are currently under consideration by several entities as greener alternatives to traditional propellants.
The primary reason for reducing the use of hydrazine is to stop the impact its use causes on the environment. During combustion, hydrazine reduces to hydrogen (H) and nitrogen (N) or nitrogen (N) and ammonia (NH₃). [2] Combustion of hydrazine and ammonium perchlorate produces a chlorine gas highly toxic to the environment. In addition, hydrazine is carcinogenic if ingested and through repeated exposure. [3] During the last 50 years of the U.S. space program, ammonium perchlorate compounds also caused respiratory problems for those exposed, and had a negative impact on the ozone layer. [4] As space programs seek to become more “green”, they seeking alternative propellants that are not only less environmentally damaging but also more efficient and productive at moving a vehicle from the ground into space, as well as maneuvering the vehicle once on orbit. In Appendix C, Table 1, the common propellants and their uses and environmental impacts are summarized.

Liquid propellants typically come in two forms: monopropellants and bipropellants. Monopropellants are a single mixture of the necessary chemicals to burn and sustain the combustion reaction. Bipropellants typically come in a fluid form, and have the oxidizer and fuel in two separate compounds. The oxidizer and the fuel are injected into a combustion chamber and then the reaction between them is ignited by a spark, by heating the chamber, or, if it is a hypergolic mixture, simply bringing the substances in contact with each other is sufficient for the reaction to begin. HAN and ADN are both monopropellants. Hydrazine is also a common component in bipropellant systems, but it also sees use as a monopropellant for small satellite thrusters. Table 1 in Appendix C delineates hazard properties and applications of various propellants.
The effectiveness of a propellant is measured by specific impulse, $I_{sp}$, which is the specific force imparted to a vehicle by each unit of mass in the propellant. The accepted unit for this measurement is seconds, primarily due to its common use between unit systems in both the metric and English systems. Table 2 in Appendix C summarizes data available on the $I_{sp}$ of various propellants. The equation governing this measurement is as follows:

$$ I_{sp} = \frac{F}{\dot{m}g_0} $$

(1)

where $F$ is the propulsive force, $\dot{m}$ is the mass flow rate of the propellant, and the $g_0$ is the gravitational acceleration constant at sea level.

As a bipropellant, hydrazine produces a specific impulse between 276–338 s depending on the oxidizer. Varying mixtures of hydrazine produce different specific impulses and also alter the freezing point making them more useful in space applications. Due to high toxicity and carcinogenic properties, hydrazine requires full hazardous materials precautions, including self-contained breathing suits for the crew working around it. [5] Despite the hazards, hydrazine powers most maneuvering thrusters for satellites and is a key component in the Space Shuttle’s Reaction Control System. When the Space Shuttle Columbia disaster happened in 2003, the hydrazine present in the debris from the breakup of the Shuttle made recovery difficult. It posed a threat to anyone who came in contact with the debris due to the highly reactive and toxic nature of the stored hydrazine.
Nitrogen tetroxide (NTO) in conjunction with hydrazine provides a potent mixture for satellite propulsion, since it is a hypergolic mixture. This means that it ignites when mixed without the need for an igniter. It also provides an ability to restart combustion, which satellite engines need to maneuver to new orbits without the need for an igniter such as a torch or spark. This capability creates storage issues because combustion can occur without the requirement of an oxidizer. [6] NTO is also toxic, which creates difficulties in handling it prior to launch and with the combustion products entering the atmosphere. As an oxidizer, though, it is possible to use other fuels such as hydrocarbon (HC) with the NTO to reduce the negative environmental impact. However, use of other fuels typically requires an additional source of ignition because the alternative formulations are not hypergolic. [6]

Ammonium perchlorate (AP) is another major solid propellant component and oxidizer used by several nations. During combustion of AP, the reaction produces hydrochloric acid (HCl), which can acidify the environment and cause damage to vegetation and animal life surrounding a launch site. The nature preserve surrounding Kennedy Space Center shows vivid evidence of this damage due to launches that use AP, NTO, and hydrazine. In addition, the chlorine in AP also contributes to disintegration of the ozone layer. [7]

Other propellants exist, such as liquid oxygen (LOX)–liquid hydrogen (LOH) systems, kerosene (C₁₂H₂₆), and hydrogen peroxide (H₂O₂). In addition, electric propulsion in various forms also exists for the application of in-space propulsion. But, each of these has benefits and problems when compared to hydrazine or AP systems. One
of the disadvantages of the LOX system is that it lacks hypergolicity. There needs to be a source of energy to ignite the propellant and begin combustion, provided by catalyst beds, torches, or sparks. [6] In many cases, the catalyst beds can degrade over time from repeated use, depending on the specific combustion temperatures and conditions in the chamber. The LOX–LOH system for the Space Shuttle is the fuel for the main engines, which share thrust responsibilities with the solid rocket boosters (SRBs). Due to the cryogenic nature of LOX–LOH propulsion systems, there is loss of the propellant to evaporation and burn off while the Shuttle is awaiting liftoff. Though this system is relatively environmentally benign, it does suffer from the expense of storage, transport, and fueling of the LOX–LOH. [8]

Kerosene is used by SpaceX and some other companies currently vying for the contracts to replace the Space Shuttle program for ferrying cargoes and personnel to the International Space Station (ISS). [9] Performance from kerosene propulsion systems compares well to traditional bipropellant systems, producing an $I_{sp}$ on the order of 331 s. [10] It does suffer from a few disadvantages, however, due to its hydrocarbon properties. During the combustion process, it can produce residues that coagulate and form layers on components in the engine. As this accumulation occurs, it reduces the diameter of the flow pipes on their way to the combustion chamber. It can also leave soot that can damage engine parts, especially the turbine blades. [11]

From the early days of rocketry, hydrogen peroxide has provided strong performance as a monopropellant. It also finds use as an oxidizer in conjunction with NTO and LOX. However, as propellant development has progressed, it has begun to lose
out to hydrazine and other compounds. Storage of hydrogen peroxide also proves challenging, due to an incomplete understanding of its degradation mechanism, and also a lack of understanding of its reactivity with various substances. British research on a project called Black Arrow focused on hydrogen peroxide as the primary propellant for a launch vehicle. Unfortunately, this research ceased before it could influence the increased use of hydrogen peroxide as a primary propellant. [12]

One specific area of monopropellant research focuses on combinations of ionic salts and water in varying concentrations, which provide higher $I_{sp}$ values than hydrazine and lower toxicity as well. Among these newer “green” propellants are ammonium dinitramide ADN ($\text{NH}_4^+ \text{N(NO}_2)_2$) and hydroxylammonium nitrate HAN ($\text{NH}_3\text{OHNO}_3$).

ADN was developed in the USSR in 1971, and use of the substance was limited at the time to Soviet intercontinental ballistic missiles. The Soviet government severely limited access to this research at the time, and ADN was all but unknown outside of the research centers in the USSR. Research in the former USSR continues to present day, specifically focused on determining the flame structure of and how it burns in the presence of specific additives, and decreasing the environmental impact of solid rocket motors. Almost two decades later, in 1988 researchers in the United States “discovered” ADN. In the early 1990s Swedish researchers began searching for minimum smoke propellants for military missile purposes, investigating the feasibility of ADN as a propellant. [13] Recent Swedish developments show that ADN is a viable alternative to hydrazine systems. The Swedish designed Prisma program flew a combination of two propulsion systems, one using hydrazine and another using ADN. These satellites were
launched from a site in Russia, in June of 2010. The two systems were compared side-by-side in how they performed orbital change maneuvers and station-keeping for the satellite. The ADN system provided a 6–8% improvement in $I_{sp}$ over hydrazine during tests on the *Prisma* satellite. [14]

Hydroxylammonium nitrate in monopropellant form ignites typically with a catalytic system, which exothermically decomposes the HAN. It possesses a higher $I_{sp}$ at 276 s than hydrazine ($I_{sp}$ 239 s), as well as a lower freezing point. It is also much less toxic than hydrazine, making it a leader in the “green propellant” race. However, HAN suffers from one key drawback: its ignition temperature (adiabatic flame temperature), which is twice that of hydrazine. This can severely degrade the catalyst in the combustion chamber during repeat firings. As technology and materials develop, catalysts are in development capable of handling the temperatures necessary for HAN systems. [15]

HAN usage began with the US Army employing it as part of a liquid gun propellant project. Based on the results of these tests, HAN proved safer and less environmentally damaging than hydrazine. In addition, its performance, material properties, and handling procedures all proved better than hydrazine. NASA further evaluated HAN as a propellant and found, due to the differences in density and output, that fuel mass, volume, and storage tank sizes were all reduced for HAN when directly compared to hydrazine. [16] Primary safety advantages for HAN over hydrazine are that the propellant itself and the combustion products are innocuous. For individuals handling the propellant, simple water-repellant clothing, safety glasses, and protective gloves provide ample protection. HAN is non-carcinogenic and non-mutagenic, and direct
inhalation of the fumes from HAN will not cause respiratory distress. Additionally, at standard pressure HAN is non-flammable and not sensitive to friction. [16],[17]

Propellants are one component in the overall propulsion system for any spacecraft. In an electric propulsion system, the propellant is accelerated using one of three methods, either through heat (electrothermal), electric fields (electrostatic), or through a combination of electric and magnetic fields (electromagnetic). Electrothermal systems use electricity to heat a propellant and then the products are expanded through a nozzle. Within the electrothermal thruster class, there are four primary methods for heating the propellant: resistive wire, electrical arc, radio frequency (RF/microwave), and laser. Electrostatic systems employ a constant electric field to accelerate ionized propellant, providing a propulsive force by ejecting the ionized propellant through a nozzle. Electromagnetic systems rely on constant or transient electric and magnetic fields to accelerate ionized propellant. Electric propulsion systems provide a higher $I_{sp}$ than chemical rocket motors and much higher exhaust velocity.

In some electrothermal thruster systems, an electrode provides the heating method for the propellant, and through direct contact with the plasma arc can wear out over time. Microwave heating avoids this problem. One system developed at Penn State over the past 25 years uses microwaves to produce a plasma to heat a propellant. In 1992, Mueller and Micci [18] published research that plasmas in waveguides tend to move towards their power source once generated, and require stabilization to be useful for space propulsion applications. Their experiments demonstrated that a stable plasma stream can exist in the middle of a waveguide chamber, with the addition of a bluff body placed in the
waveguide. Experimentation led to the assessment that using these plasmas in a thruster would create a highly efficient method of heating a gaseous propellant. [18] Later research performed by Micci and his staff at the Propulsion Engineering Research Center demonstrated a proof-of-concept design for igniting HAN. The igniter designs developed in this research suggest that an improvement of the ignition system through use of microwaves can reduce overall system mass by 25% and decrease the volume of a given propulsion system by as much as 40%. [1] Due to the extremely high temperatures that HAN requires to burn, the catalyst method of ignition was impractical due to the materials needed. The method of ignition proposed by Micci [1] employed a microwave plasma torch that ignited the HAN in an electric field. This microwave torch functions with a waveguide providing a path for the microwaves that turn helium gas flow into a stable plasma stream. The system uses one of three main varieties of microwave “torches” that exist which are waveguide, in which the torch itself is within the waveguide, and emits a stream of plasma from that point; coaxial, in which the plasma is emitted at an elevated point independent of a waveguide; and a hybrid version that incorporates both, putting the coaxial output right in the stream of the waveguide.

Electrostatic propulsion systems rely on superheated and ionized gases that are ejected after electromagnetic acceleration. [19] The Deep Space 1 probe was a test bed for development of ion propulsion technology in the late 1990s. When Deep Space 1 launched in 1998, it was a mission that sought validation on a dozen new and developing technologies, including an ion engine propulsion system. By exciting xenon gas into a state where the atoms are ionized, and focusing the ions with magnetic fields, the particles are ejected through the exhaust of the engine. Ion engines do require a
significant amount of power to accomplish the ionization process, and to create and maintain the electric and magnetic fields necessary for thrust. Some ion engines are gridded and, as a result of the impact of the errant ions, which are not intended to hit the grids, can reduce their effectiveness over time. Deep Space 1’s ion engine was one of the first to use a solar power source to start the engine and then exhausted 70kg of xenon fuel over the course of the mission. [20]

**Design Needs**

The apparatus for this research builds upon existing equipment and testing procedures in place in the Propulsion Engineering Research Center. The apparatus consists of a microwave source, a gas source to excite to create the plasma, a torch assembly, a propellant pump, and necessary ducting to connect the various components. Previous research into CubeSats and microsatellites provides much of the needed equipment to perform the testing required.

Specific testing of HAN for this thesis involved creating a microwave plasma using helium, then injecting a stream of the propellant into the plasma torch stream, and verifying ignition of the propellant. Characterization of the power, amount of propellant, and concentration of propellant were performed after each trial.

**Current Research**

This research provides data on specific trials of a microwave plasma torch ignition system. It demonstrates the feasibility of HAN as a propellant in a microwave ignition system for an electrothermal thruster. The propellant formulation at the center of
the research is a 13 % molar HAN-water mixture. With water as a basis, this formulation is more environmentally friendly than hydrazine. This research sets out to prove that an ignition of the HAN-water mixture is attainable with the microwave igniter currently in the Propulsion Engineering Research Center.

**Overview**

Contained in the remainder of this document are the design of the experiment, an explanation of the equipment used, and a summary of the data collected. It also explains suggestions for future work and conclusions made from this research.
Chapter 2: Methodology

Experimental Design

This thesis work investigated the microwave ignition of water-based HAN propellant as the propellant flowed from an input tube into a plasma stream. Previous research provided a basis for the test procedures to carry out the necessary experiments and preparation of samples. [1]

The overall procedure for this project was as follows:

1. Design and fabrication of the microwave ignition apparatus;
2. Procurement of microwave components;
3. Design and assembly of the injector mechanism;
4. Inaugural testing of the ignition system with helium plasma;
5. Characterization of microwave igniter;
6. Testing the ability to ignite and sustain combustion for 13% molar HAN; and
7. Delineate and tabulate flow rate versus microwave power data. [1]

The results presented in this thesis prove that a microwave igniter is capable of igniting HAN without a catalyst bed in the reaction chamber. Results of this research provide a basis for further research into development of a HAN-powered thruster. This enhances the knowledgebase of HAN research and provides a new slant on the challenge of spacecraft propulsion.
Currently, in the Propulsion Engineering Research Center (117 Research East), there is an existing microwave plasma torch, created for the microwave electrothermal thruster (MET) project at Penn State. Assembly and preparation of this device as part of Steps 1–3 occurred during the Spring 2013 Semester and were performed by Brian Lani, a graduate student working in Dr. Micci’s propulsion group. This device is already assembled and ready for the testing of the HAN propellant. Its design incorporates a 2.45-GHz microwave source, helium feed system, reducing waveguide, moving short, Faraday cage, and the torch assembly. The magnetron in the microwave source provides the power for the unit and, for most of the test runs, provides 500 W of microwave power. The helium feed system comprised of a mass flow regulator, a helium tank, and necessary feed lines allows for the helium to be passed at a specific mass flow rate of 12.08 g/s to initialize the plasma in the waveguide. The waveguide components are: a reducing waveguide exiting the magnetron, a custom brass waveguide, with openings for the torch assembly to be inserted and protrude through the waveguide, and a moving short (See Fig. 1). This moving short provides the ability to create a standing wave specifically at the torch position. The Faraday cage also provides some insulation from ambient microwaves disrupting the equipment in the room.

Figure 1: Custom Brass Waveguide with Moving Short.
Photo courtesy Brian Lani.
The initial torch assembly components are: a Swagelok tee, two concentric stainless steel tubes, and a mechanized flow regulator. The torch body itself consists of two concentric stainless steel tubes, 0.042"ID and 0.12"ID, respectively (See Fig. 2). The smaller diameter tube at the center provides the propellant flow, while the outer tube provides the helium source to create the plasma. In the early phases of the research, there were also drill blanks used to correctly align the tubes to allow for the flow of both the helium and propellant. A mount for the torch assembly soldered to the bottom of the waveguide allows passage of the tubes into the waveguide, and for the emission of the plasma stream through the top of the waveguide (See Fig. 3). The Swagelok tee used in this setup is brass, and allows for the propellant tube to run directly through the long side of the tee, exiting the bottom of the fitting, through a Conax pressure fitting (See Fig. 4). This attaches to a plastic tube that ties in through a Luerlock fitting to a syringe pump. At the top of the tee, the larger tube terminates after a short insertion into that end, allowing for the helium flow provided by the side port to fill the outer tube without any contamination of the propellant line. The syringe pump and the mass flow controller for the helium provided the proper levels of each component during tests of the torch.
Figure 2: Torch Tube Diameters.

Figure 3: Torch Mount Assembly.

*Photo courtesy Brian Lani.*
For the Step 4 test period, a mixture of 13% molar HAN with water is the chosen propellant. The ignition of each sample starts with a 5 mL/min pump rate. Each test begins with a syringe of 15 mL of propellant and the propellant pump provides the propellant at a rate that will vary between 5–10 mL/min. Each test lasts approximately 30–60 s depending on the flow rate and the specific ignition of the sample.

After initial testing, the outer stainless steel torch tubing was replaced by molybdenum tubing due to the extreme temperatures created by the helium plasma. Additional delays in conducting the testing occurred due to problems with the magnetron. Further testing of the water-based HAN mixture was not performed due to equipment malfunctions.
Chapter 3: Results

Data

Prior to the initial test with the water-based HAN propellant, the waveguide short was adjusted which changed the position of the standing wave in the waveguide. This adjustment was made to refocus the microwaves to straighten the plasma stream. Then the helium plasma was ignited (Fig.5). The initial conditions were: 12.08 mg/s mass flow rate for the helium at 70 psi, microwave power at 500 W, and 10 mL of the 13% molar HAN in the syringe at a rate of 5 mL/min. The plasma arced and contributed to welding the torch tubes together. Having a straight plasma stream is preferable, so that the propellant ignition occurs in a coaxial direction from the torch tip. During both of the tests sputtering was observed with some drops coming up from the propellant feed and occasionally igniting in the stream, producing a greenish orange flame. During the second
trial, the flow rate was upped to 14.09 mg/s and some of the propellant was simply ejected from the torch tube without ignition. A third test was performed after a quick grinding of the torch tubes, with the same initial conditions, and then increasing the mass flow rate of the helium to 14.09 mg/s during the test. This test produced more sputtering and some intermittent ignition of the propellant, but no consistent ignition after the initial flame. It is possible that the tubes melted too quickly and impeded the flow of the helium and the propellant to the torch tip. Results from these tests are summarized in Table 3 in Appendix C.
Analysis

Based on the results of the testing phase, the method of ignition is feasible, though the apparatus needs improvement. Ignition of the propellant did occur with different power inputs and flow rates. However, proper materials are needed to ensure that the torch is reusable over time. A thruster based on a torch design that melts to itself after use would not provide a reliable system for a satellite or other space vehicle.

Viscosity and formulation are two major elements of creating a feasible system for the basis of a microwave plasma thruster. Viscosity of the propellant is a primary concern in getting the propellant into the plasma stream in sufficient quantity for ignition. A flow rate in excess of 5 mL/min is a good baseline but further research into the specifics of flow rate is needed to fully characterize the results presented in this thesis. In addition to viscosity, the specific formulations also make a difference, not only from standpoint of viscosity but also from the standpoint of the base compounds being easier to ignite. The propellant stream was able to ignite through microwave plasma stimulation. Due to the limited duration of the tests, and the fact that the torch melted itself after each test, the flames observed as proof of ignition rarely lasted more than 5–10 seconds. The water-based HAN formulation proved difficult to ignite, but also provided a feasible propellant option.

Materials selection is also critical to proper system function, for the torch, the waveguide, and the magnetron itself. Initially, the setup included stainless steel tubes for the torch, which proved inadequate for the plasma temperatures involved in the experiments. Any thruster device would require a feed system that would accommodate
the flame temperatures produced by both the plasma stream and the propellant ignition. Since ignition of HAN reaches temperatures in excess of 1300 K, stainless steel is not a viable option. Molybdenum has a melting point of 2890 K, which makes it a good candidate for the necessary components for the torch. [21]
Chapter 4: Conclusions

Conclusions

This research did prove that the microwave plasma torch in the Propulsion Engineering Research Center is capable of ignition of 13% molar HAN water-based propellant. After the trials where the torch tubes melted, stainless steel is not a wise choice for the outer torch tube providing the plasma; molybdenum proved more durable for this purpose.

Future Work

Further testing of the water-based HAN mixture is necessary for a better understanding of what flow rates are necessary for the most efficient ignition. Future work on this project could improve on the materials used for the torch assembly as well as investigate whether or not the size of the waveguide has any effect on the efficiency of the plasma production. It is plausible that a thruster based on this technology could be developed and employ the microwave source as more than simply a supplier of plasma for the torch to ignite the propulsion system. The microwave source could also be used for communications and take advantage of the weight cost necessary for this system onboard a satellite. Further analysis of the temperature of the flame when the propellant is ignited would also assist in assessment of the materials needed. Ideally, the flame
would be constrained to a coaxial position within a thruster, and that would reduce the need for heavily insulated walls for the combustion chamber. Though the testing capabilities of this project were limited due to equipment failure, the basis is there for further research.
References


Appendix A: Team Members:

Dr. Michael M. Micci – Professor of Aerospace Engineering

Dr. Sven G. Bilén – Associate Professor of Engineering Design, Electrical Engineering, and Aerospace Engineering

Brian Lani – Masters Candidate, Aerospace Engineering
Appendix B: Tools

The tools/materials used for this research project were:

Daihen SGM-15A Microwave Magnetron 1500 W
Daihen SGM-15A Power Source 1500 W
Daihen SMA-10 Microwave tuner
Waveguide with moving short
Helium feed with flow regulator
Custom built torch - Swagelok® valve and stainless steel or molybdenum tubing
Syringe Pump with feed system for propellant
Faraday cage
Water-based HAN propellant, 13% molar
Dremel® Rotary Tool
Reamer
### Table 1: Propellant Hazards and Thruster Applications

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Hazmat Info</th>
<th>Type of Thruster</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrazine</td>
<td>Full self-contained suits and special shipping/handling</td>
<td>Chemical</td>
<td>Satellite stationkeeping, OMS on Space Shuttle</td>
</tr>
<tr>
<td>Ammonium Perchlorate</td>
<td>Full self-contained suits and special shipping/handling</td>
<td>Chemical</td>
<td>Primary propulsion for lift-off, satellite stationkeeping</td>
</tr>
<tr>
<td>Nitrogen Tetroxide</td>
<td>Full self-contained suits and special shipping/handling</td>
<td>Chemical</td>
<td>Primary propulsion for lift-off, satellite stationkeeping</td>
</tr>
<tr>
<td>Hydrogen Peroxide</td>
<td>Basic protective gloves, mask, clothing, shippable through regular mail carriers</td>
<td>Chemical</td>
<td>Primary propulsion for lift-off</td>
</tr>
<tr>
<td>Ammonium Dinitramide</td>
<td>Basic protective gloves, mask, clothing, shippable through regular mail carriers</td>
<td>Chemical, electrothermal</td>
<td>Satellite stationkeeping, ballistic rocket primary propulsion</td>
</tr>
<tr>
<td>Hydroxylammonium Nitrate</td>
<td>Basic protective gloves, mask, clothing, shippable through regular mail carrier</td>
<td>Chemical, electrothermal</td>
<td>Liquid gun propellant</td>
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<td>Xenon</td>
<td>Inert gas</td>
<td>Ion, Hall</td>
<td>Primary in-space propulsion for satellite</td>
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<tr>
<td>Kerosene</td>
<td>Basic protective gloves, respirator, clothing</td>
<td>Chemical</td>
<td>Primary propulsion for lift-off</td>
</tr>
<tr>
<td>LOX–LOH</td>
<td>Cryogenic storage necessary</td>
<td>Chemical</td>
<td></td>
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</table>
Table 2: Rocket Propellant Performance [2]

<table>
<thead>
<tr>
<th>Oxidizer</th>
<th>Fuel</th>
<th>Hypergolic</th>
<th>Mixture Ratio</th>
<th>Specific Impulse (s, sea level)</th>
<th>Density Impulse (kg-s/l, S.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Oxygen</td>
<td>Liquid Hydrogen</td>
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<td>124</td>
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<td>1.29</td>
<td>269</td>
<td>264</td>
</tr>
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<td>Liquid Oxygen</td>
<td>Kerosene</td>
<td>No</td>
<td>2.29</td>
<td>289</td>
<td>294</td>
</tr>
<tr>
<td>Liquid Oxygen</td>
<td>Hydrazine</td>
<td>No</td>
<td>0.74</td>
<td>303</td>
<td>321</td>
</tr>
<tr>
<td>Liquid Oxygen</td>
<td>MMH</td>
<td>No</td>
<td>1.15</td>
<td>300</td>
<td>298</td>
</tr>
<tr>
<td>Liquid Oxygen</td>
<td>UDMH</td>
<td>No</td>
<td>1.38</td>
<td>297</td>
<td>286</td>
</tr>
<tr>
<td>Liquid Oxygen</td>
<td>50-50</td>
<td>No</td>
<td>1.06</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Liquid Fluorine</td>
<td>Liquid Hydrogen</td>
<td>Yes</td>
<td>6.00</td>
<td>400</td>
<td>155</td>
</tr>
<tr>
<td>Liquid Fluorine</td>
<td>Hydrazine</td>
<td>Yes</td>
<td>1.82</td>
<td>338</td>
<td>432</td>
</tr>
<tr>
<td>Liquid Fluorine</td>
<td>Kerosene</td>
<td>Yes</td>
<td>3.80</td>
<td>320</td>
<td>385</td>
</tr>
<tr>
<td>Nitrogen Tetroxide</td>
<td>Kerosene</td>
<td>No</td>
<td>3.53</td>
<td>267</td>
<td>330</td>
</tr>
<tr>
<td>Nitrogen Tetroxide</td>
<td>Hydrazine</td>
<td>Yes</td>
<td>1.08</td>
<td>286</td>
<td>342</td>
</tr>
<tr>
<td>Nitrogen Tetroxide</td>
<td>MMH</td>
<td>Yes</td>
<td>1.73</td>
<td>280</td>
<td>325</td>
</tr>
<tr>
<td>Nitrogen Tetroxide</td>
<td>UDMH</td>
<td>Yes</td>
<td>2.10</td>
<td>277</td>
<td>316</td>
</tr>
<tr>
<td>Nitrogen Tetroxide</td>
<td>50-50</td>
<td>Yes</td>
<td>1.59</td>
<td>280</td>
<td>326</td>
</tr>
<tr>
<td>Red-Fuming Nitric Acid</td>
<td>Kerosene</td>
<td>No</td>
<td>4.42</td>
<td>256</td>
<td>335</td>
</tr>
<tr>
<td>Red-Fuming Nitric Acid</td>
<td>Hydrazine</td>
<td>Yes</td>
<td>1.28</td>
<td>276</td>
<td>341</td>
</tr>
<tr>
<td>Red-Fuming Nitric Acid</td>
<td>MMH</td>
<td>Yes</td>
<td>2.13</td>
<td>269</td>
<td>328</td>
</tr>
<tr>
<td>Red-Fuming Nitric Acid</td>
<td>UDMH</td>
<td>Yes</td>
<td>2.60</td>
<td>266</td>
<td>321</td>
</tr>
<tr>
<td>Red-Fuming Nitric Acid</td>
<td>50-50</td>
<td>Yes</td>
<td>1.94</td>
<td>270</td>
<td>329</td>
</tr>
<tr>
<td>Hydrogen Peroxide</td>
<td>Kerosene</td>
<td>No</td>
<td>7.84</td>
<td>258</td>
<td>324</td>
</tr>
<tr>
<td>Hydrogen Peroxide</td>
<td>Hydrazine</td>
<td>Yes</td>
<td>2.15</td>
<td>269</td>
<td>328</td>
</tr>
<tr>
<td>Hydrogen Peroxide</td>
<td>HTPB (solid)</td>
<td>No</td>
<td>6.48</td>
<td>248</td>
<td>290</td>
</tr>
<tr>
<td>Chlorine Pentafluoride</td>
<td>Hydrazine</td>
<td>Yes</td>
<td>2.12</td>
<td>297</td>
<td>439</td>
</tr>
<tr>
<td>Ammonium Perchlorate</td>
<td>Aluminum + HTPB (a)</td>
<td>No</td>
<td>2.12</td>
<td>277</td>
<td>474</td>
</tr>
<tr>
<td>Ammonium Perchlorate</td>
<td>Aluminum + PBAN (b)</td>
<td>No</td>
<td>2.33</td>
<td>277</td>
<td>476</td>
</tr>
</tbody>
</table>
### Table 3: Propellant Test Results

<table>
<thead>
<tr>
<th>Test</th>
<th>Propellant Formulation (base)</th>
<th>Helium Flow Rate (%)</th>
<th>Mass Flow Rate (mg/s)</th>
<th>Propellant Flow Rate (mL/min)</th>
<th>Microwave Power (W)</th>
<th>Ignition Achieved</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HAN 13% Molar (in H₂O)</td>
<td>60</td>
<td>12.08</td>
<td>5</td>
<td>500</td>
<td>No</td>
<td>Plasma not cooperative, needles melted quickly</td>
</tr>
<tr>
<td>2</td>
<td>HAN 13% Molar (in H₂O)</td>
<td>70</td>
<td>12.08</td>
<td>5</td>
<td>500</td>
<td>No</td>
<td>Needles melted almost instantly when plasma ignited</td>
</tr>
<tr>
<td>3</td>
<td>HAN 13% Molar (in H₂O)</td>
<td>60–70</td>
<td>12.08</td>
<td>5</td>
<td>500</td>
<td>Yes</td>
<td>Sputtering, intermittent flashes of ignition. Ignition not sustained</td>
</tr>
</tbody>
</table>
Appendix D: Broader Impact

This project has the potential to provide baseline work for researchers developing a “green” propulsion system. As the space industry around the world continues to seek alternatives to hydrazine and traditional propellant ignition methods, the proof of ignition here offers an opportunity to reduce cost for satellite propulsion systems. This reduction in cost could enable other groups—countries as well as private corporations and interests—the opportunity to develop and launch their own satellites. As the technology develops it is also possible that it could have impact on other missions beyond simply Earth-orbiting satellites. If the microwave power and vehicle propellant capacity are matched properly, this technique could provide propulsion to Mars or other parts of the solar system.
Curriculum Vitae

Timothy F. Stefanoski
244 Westfield Road
Scotch Plains, NJ 07076
908-380-6709
bxs147@gmail.com

OBJECTIVE: Aerospace – hands on assembly or problem solving for satellites, rockets, or spacecraft

EDUCATION
The Pennsylvania State University - University Park, PA
Bachelor of Science in Engineering Science, Honors Curriculum focus: Aerospace Engineering
GPA – 2.83
December 2013
Relevant Courses: Aerospace System Dynamics, Fluid Dynamics, Orbital Dynamics, Spacecraft Design, Failure Analysis

Montclair State University - Upper Montclair, NJ
Bachelor of Fine Arts in Theater Design & Production
GPA – 3.67
May 1999
Relevant Courses: AutoCAD, Vectorworks, Drafting, Scenic Design

RELEVANT EXPERIENCE
Spring – Fall 2013
The Pennsylvania State University – Senior Thesis Project
Thesis work performed researching ignition of Hydroxylammonium Nitrate with microwave plasma torch.

Summer 2013
The Pennsylvania State University – Astrobiology Research Center Intern
• Constructed water sampling device, continuing work done during Spring Semester.
• Designed and constructed alternative deployment method for sensor probe.
• Enhanced functionality of sensor probe to track depth.

Spring Semester 2013
The Pennsylvania State University – Astrobiology Research Center Capstone Design Project Team Member
• Designed and constructed sensor probe capable of detecting pH, temperature, depth, and water sampling.
• Researched materials compatible with highly acidic volcanic lake environment.
• Tested deployment method and watertightness of the probe body.

Spring Semester 2013
The Pennsylvania State University – Society of Engineering Science RUBE Goldberg Team Captain
• Design and construct machine capable of hammering a nail.
• Led team of 10 students through design and construction of machine.
WORK EXPERIENCE
January 1, 2001 - present
LoThEMaR Opals          Owner, Lapidary, Jeweler
  • Create and sell handmade jewelry in sterling silver and gold, either wire-wrapped or hand fabricated.

September 1, 2002 – August 1, 2011
Scotch Plains-Fanwood Board of Education       Advisor to Stage Crew
  • Supervised use of high school auditorium for concerts, plays, and other events, maintained equipment.

November 7, 2001 – August 1, 2011
Scotch Plains-Fanwood Board of Education       Office Assistant
  • Coordinated health&dentalbenefitsforover 700 employees and 250 retired staff members.

January 1, 2000 - September 30, 2000
Circuit Lighting, LLC          Rental Manager
  • Managed a million-dollar inventory of theatrical and production lighting equipment.

SKILLS
SOFTWARE:
SolidWorks, MS Word, MS Excel
HANDS ON:
Team building, Team Leadership, Soldering, metalsmithing, carpentry, manual drafting, electrical wiring.

PROFESSIONAL MEMBERSHIPS / AFFILIATIONS
New Jersey Lapidary Society, President         September 2006 – Present
Society of Engineering Science, RUBE Goldberg Team Chair         September 2011 – Present
Central Jersey Geocachers, Member          May 2007 – Present

VOLUNTEER WORK EXPERIENCE:
April 1, 2001 – May 30, 2011
SMAC (Student Movement Against Cancer)          Volunteer/Team Captain
  • Led a team of adults and students and fundraised over $20,000 for the American Cancer Society.

January 15, 2001 – August 1, 2011
St. Bartholomew’s Church          Youth Group Adult Advisor
  • Supervised and guided 20-50 high school students during weekly meetings and on trips.

June 15, 2007 – Present
S.T.A.R.S. (Student Thespians Are Recreating the Stage)Theater Group     Technical Director
  • Supervised 8-15 student technical crew for outdoor children’s summer theater.