Testing New Potential Fuels for Ion Electrospray Propulsion Systems

by

Daniel Getty

Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of Master of Science in Aeronautics and Astronautics at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2018

© Massachusetts Institute of Technology 2018. All rights reserved.

Signature redacted

Author .........................

Department of Aeronautics and Astronautics

August 23, 2018

Signature redacted

Certified by ......................

Paulo Lozano

M. Alemán-Velasco Professor of Aeronautics and Astronautics

Thesis Supervisor

Signature redacted

Accepted by ......................

Hamsa Balakrishnan

Associate Professor of Aeronautics and Astronautics

Chair, Graduate Program Committee
Testing New Potential Fuels for Ion Electrospray Propulsion Systems

by

Daniel Getty

Submitted to the Department of Aeronautics and Astronautics on August 23, 2018, in partial fulfillment of the requirements for the degree of Master of Science in Aeronautics and Astronautics

Abstract

Electrospray thrusters are a class of electric propulsion that extract and accelerate ions from the surface of an electrically conductive liquid surface. This liquid surface is that of an ionic liquid, a room temperature molten salt, applied to a porous substrate. The substrate is etched via laser to form a field enhancing structure off of which ions will be evaporated. This research expands on the field in two separate ways. First, it implements and evaluates a carbon xerogel emitter substrate as an alternative over current glass emitters. This substrate was found to fire stably and with higher stable currents than the glass alternative (1.5 - 2 times the maximum stable current). In addition, this work analyzes and evaluates two new high conductivity ionic liquid propellants, EMI-(HF)F and S111-(HF)F. Improvements or disadvantages of EMI-(HF)F over the current baseline of EMI-CF$_3$BF$_3$ were inconclusive. S111-(HF)F, however, showed a distinct improvement in specific impulse over EMI-CF$_3$BF$_3$ (3160 ± 290 s vs. 2140 ± 130 s) without a statistically significant drop in total efficiency. Future work could include the collection of time of flight data in the negative firing mode, as well as higher precision retarding potential data in both positive and negative polarities. Additional measures could also be taken to decrease the spacing between emitter tips on the carbon substrate, thereby increasing the current and thrust density of the thrusters.

Thesis Supervisor: Paulo Lozano
Title: M. Alemán-Velasco Professor of Aeronautics and Astronautics
Acknowledgments

I would like to thank my advisor, Professor Paulo Lozano for all of his help and encouragement throughout this process. It has been a pleasure to be a part of the Space Propulsion Lab and the amazing culture he has created here. I am extraordinarily thankful for his guidance and support as I worked my way through this journey.

Also, to everyone else in SPL, thank you all for your friendship and support. Thank you to David Krejci for introducing me to the lab and showing me the ropes. Also a big thank you to Elaine Petro and Jon Garcia-Urbieta for their immeasurable amount of support and assistance while I was collecting the data shown in this thesis.

To my parents and my brothers, thank you for all of your love and encouragement over the years. Thanks for sticking with me and believing in me through everything. I definitely wouldn’t be here without you guys. To my extended family: grandparents, aunts, uncles, and cousins, thank you for being such a constant source of support and positivity in my life.

To all the friends that I’ve made along the way, both in Connecticut and Boston, thank you so much for always being there for me. I will never forget the different ways that you all have impacted my life. You pushed me when I needed motivation, you propped me up when I needed support, and you helped me stay true to myself when at times, even I wasn’t sure who that was.

Finally, to all of my teachers and professors, from Quaker Hill Elementary all the way through to MIT AeroAstro, thank you for all of your lessons over the years. Thank you for nurturing the curiosity and love of learning that carried me through to this point.
## Contents

1 Introduction .................................................. 13

2 Test Materials .................................................. 17
   2.1 Substrate Selection ....................................... 17
      2.1.1 Carbon Xerogels ................................... 18
      2.1.2 Carbon Xerogel Downsides ......................... 19
   2.2 Ionic Liquids .............................................. 20
      2.2.1 Ionic Liquid Mixtures ............................... 21

3 Emitter Fabrication ............................................. 23
   3.1 Description of Final Samples ......................... 23
   3.2 Preparation of Carbon Emitter Chips .............. 24
      3.2.1 Preparation of PDMS Mold ....................... 24
      3.2.2 Mixing of Ingredients .............................. 25
      3.2.3 Curing Cycles ..................................... 25
      3.2.4 Pyrolysis and High-Temperature Annealing .... 26
      3.2.5 Filing ............................................. 27
   3.3 Bonding .................................................. 27
   3.4 Laser Patterning ......................................... 28
   3.5 Temporary Mount Assembly ............................. 29

4 Background and Theory .......................................... 31
   4.1 Meniscus Formation ..................................... 31
List of Figures

1-1 Electrospray principle ........................................ 14

3-1 40x SEM Image of Carbon Xerogel .......................... 24
3-2 4000x SEM Image of Carbon Xerogel ...................... 25
3-3 Dimensions of PDMS Mold ................................. 26
3-4 Resorcinol-formaldehyde curing process .................... 27
3-5 Carbon vs glass emitter patterns .......................... 29
3-6 Temporary mount used for testing ......................... 30

4-1 Meniscus modeling $E_0$ vs. $B$ solution plane .......... 33
4-2 Meniscus shapes ............................................. 34

5-1 Photograph of vacuum chamber ............................. 42
5-2 Experimental Configurations ............................... 43
5-3 CEM Operation Principle .................................. 45

6-1 EMI-CF$_3$BF$_3$ IV Curve ................................ 48
6-2 EMI-GaCl$_4$ IV Curve .................................... 49
6-3 21% EMI-(HF)F IV Curve ................................. 49
6-4 22% S111-(HF)F IV Curve ............................... 50
6-5 All IV Curves ................................................ 50
6-6 EMI-CF$_3$BF$_3$ RPA Plot .................................. 52
6-7 EMI-GaCl$_4$ RPA Plot ..................................... 52
6-8 21% EMI-(HF)F RPA Plot .................................. 53
6-9 22% S111-(HF)F RPA Plot ................................ 54
6-10 All RPA Plots .................................................. 54
6-11 EMI-CF₃BF₃ Angular Plot .................................. 56
6-12 EMI-GaCl₄ Angular Plot .................................. 56
6-13 21% EMI-(HF)F Angular Plot .......................... 57
6-14 22% Si111-(HF)F Angular Plot .......................... 58
6-15 All Angular Plots ............................................. 58
6-16 EMI-CF₃BF₃ TOF Signal ................................... 60
6-17 EMI-GaCl₄ TOF Signal ................................... 61
6-18 21% EMI-(HF)F TOF Signal ............................. 63
6-19 22% Si111-(HF)F TOF Signal ............................. 64
6-20 All TOF Signals .............................................. 65
List of Tables

2.1 Pure ionic liquid properties ............................................. 21
2.2 Ionic liquid mixture properties ........................................... 22
6.1 Calculated efficiencies ..................................................... 66
Chapter 1

Introduction

Small scale high-efficiency propulsion is a necessity in the growing field of small satellite implementation. Be it for scientific or commercial missions, these satellites require propulsion systems that allow for formation flight, orbit change maneuvers, and deorbiting, just to name a few [20]. What’s more, the small scales of these satellites do not often allow for large, heavy propulsion systems. The type of thruster studied in this thesis is a miniaturized, highly efficient electrostatic electrospray thruster complying with the stringent volume, mass, and power requirements imposed by small-scale satellites.

Electrospray thrusters are a class of electric propulsion that extract and accelerate ions from the surface of an electrically conductive liquid surface. This is done via the application of an electrostatic field over a wetted porous structure. In order to minimize the field strength necessary for charged particle extraction from the liquid bulk, the propellant is extracted from a field enhancing structure such as a needle, or in this case, an array of laser machined tips. These structures are used in conjunction with an extractor grid to force evaporation and acceleration of the ions through the grid. This process is visually represented in figure 1-1.

When exposed to a high strength electric field, the ionic liquid deforms into a sharp cone-shaped meniscus equilibrating electrical pull with surface tension and upstream pressure. This process will be covered in more detail in section 4.1. The increased electric field strength at the cone tip will extract charged particles from the meniscus,
which are then accelerated to produce thrust [14].

When firing these thrusters, two different regimes of operation (or a mixture of the two) can occur. The cone-jet regime occurs when the meniscus breaks up into droplets, which is to be avoided for our purposes. These heavy droplets possess a small charge to mass ratio, which leads to a much lower specific impulse. The preferred firing regime is called the pure ionic regime, which occurs when pure ions are extracted. This leads to a higher charge to mass ratio, and subsequently, a significantly higher specific impulse. Typically, the extracting of one charged species from the liquid bulk would lead to spacecraft charging in the opposite polarity. On the system level, this phenomenon is avoided by firing thrusters in pairs with opposite emitted currents. On the single thruster level, the polarity is alternated periodically to maintain chemical balance in the propellant and prevent electrochemical decay [11].

The propellants used in these propulsion systems are known as ionic liquids. These are room-temperature molten salts consisting of chemically stable mixtures of positive and negative charges. One advantageous property of these ionic liquids is their negligible vapor pressure [23]. This allows for passive feed systems, because there is no need for propellant pressurization. This renders hard-to-miniaturize components such
as valves unnecessary. Because the propellant exit velocities are not limited to chemically storable energy, these thrusters feature a much higher specific impulse when compared to chemical thrusters. On the other side, however, electrospray thrusters carry a lower thrust density when compared with chemical, or even other high-thrust electric propulsion systems.

This work takes steps to increase the thrust density of electrospray propulsion systems. The first of which is through the changing of the substrate material from porous glass to carbon xerogel. This material allows for more uniform patterning at small scales, and for a smaller radius of curvature at each tip. This uniformity could also allow the future manufacturing of emitter arrays with tip separation of 225 or 110 microns. The second step taken in increasing the thrust density of these emitters is the testing of new ionic liquids that display very high electric conductivities, in solution with existing ILs. These liquids are capable of reaching a much higher emitted current when compared with their earlier counterparts, such as EMI-BF₄. This work will present several propellant beam measurements, to include current vs. voltage data, time-of-flight mass spectrometry, retarding potential analysis, and spatial beam analysis. This will allow the characterization of important performance parameters such as thrust, thrust efficiency, and specific impulse.
Chapter 2

Test Materials

There are two main areas in which this research augments current knowledge on ion electrospray propulsion systems. The first of these is in the adoption of carbon xerogels as the substrate used for emitter arrays. This area of work borrows from the previous work of Jimmy Rojas-Herrera, a former undergraduate researcher in the MIT Space Propulsion Laboratory [18]. The second area is in the adoption of new ionic liquid mixtures, EMI-CF$_3$BF$_3$ combined with either EMI-(HF)F or S111-(HF)F. This area borrows from the work of Caroline Bates, a fellow graduate student in the Space Propulsion Laboratory.

2.1 Substrate Selection

Porous substrates are ideal materials for this application due to their ability to transport liquids via capillary forces. They are used both to transport the conductive ionic liquid propellant from a reservoir and to provide a suitable emitter structure to enhance the electric field and facilitate the evaporation of ions directly from the liquid-vacuum interface. With these substrates, the hydraulic impedance of the emitter structure must be tailored to create a high ratio of electrical conductivity to liquid flow rate. When this is accomplished, the pure ionic regime of emission can be achieved [7].

The current substrate of choice for flight-quality emitters is porous glass. While
this substrate is reliable and flight-proven, there are certain properties of these porous
glass emitters that make it an unfavorable choice for this application. First, these
emitters are made of individual micron-scale particles of varying sizes, which means
they possess a wide distribution of pore sizes. In addition, the new ionic liquids being
tested in this work can release small amounts of hydrofluoric acid (HF) in vacuum.
This HF would eat away at the glass in these emitters, potentially destroying the field
enhancing structure. Therefore, carbon xerogel is being considered as an alternative
to glass substrates.

One footnote with respect to HF degradation of glass emitters relates to the
HF loss described in more detail in section 2.2.1. If all of the free HF has been
evacuated from the ionic liquid prior to being applied to the emitter, this liquid could
theoretically fire stably from a glass emitter without degradation of the emitter array.
This exact scenario may have been inadvertently tested already in lab. Time of flight
tests were performed using glass emitters with what was believed to be EMI-CF$_3$BF$_3$.
However, the mass spectrum (analyzed by fellow SPL student Jon Garcia-Urbieta)
showed a distinct peak very near the dimer mass expected for S111-(HF)F. This very
well could have been due to contamination of the EMI-CF$_3$BF$_3$ ionic liquid with
S111-(HF)F. If this thruster was indeed fired with a mixture of EMI-CF$_3$BF$_3$ and
S111-(HF)F, it provides evidence that S111-(HF)F could be fired stably from a glass
emitter once the excess HF is removed.

2.1.1 Carbon Xerogels

Carbon xerogels possess several qualities which make them potentially suitable re-
placements in these emitters. They are well-wetted by ionic liquids, display out-
standing pore uniformity, and are easy to machine by both additive and subtrac-
tive processes [1]. This thesis will report the synthesis of a novel system for ion-
electrospray propulsion based on a carbon xerogel substrate, originally established
by Jimmy Rojas-Herrera in his undergraduate research in the Space Propulsion Lab.
This fabrication process will be discussed in detail in section 3.

The substrate pore size was tested by submerging the substrate in isopropanol and
Flowing nitrogen through them. By equating the pressure at which bubbles emerged from the substrate to the Young-Laplace pressure (assuming hemispherical bubbles on detachment and perfect wetting) the pore size was estimated by

\[ \Delta p = \gamma \left( \frac{1}{R_x} + \frac{1}{R_y} \right) = \frac{2\gamma}{R} \]  \hspace{1cm} (2.1)

or to express in terms of pore diameter, \( D \),

\[ D = \frac{4\gamma}{\Delta p} \]  \hspace{1cm} (2.2)

where \( \gamma \) = surface tension (.023 N/m for isopropanol); \( R \) = pore radius (assuming here that \( R_x = R_y = R \)); and \( \Delta p \) = burst pressure. The samples had a wide range of burst pressures, ranging from 20 and 60 psi, giving an approximate pore diameter of 0.2 to 0.6 \( \mu \)m. On the individual pore scale, this is a large range. However, this entire range is very small when compared to the length scale of individual emitter tips. Upon visual inspection, these pore sizes match closely with SEM images of the samples.

### 2.1.2 Carbon Xerogel Downsides

There are several hurdles that accompany the carbon xerogel substrate. Carbon xerogels are conductive substrates, and electrochemical decay could prevent stable single-polarity operation if the voltage was applied directly to the xerogel [11]. A charge double layer can be formed as ions of one polarity are extracted and counter ions accumulate on the emitter electrode. If the potential of the double layer exceeds the electrochemical window of the ionic liquid, degradation of the emitter array can occur. However, if the voltage is applied to the ionic liquid by using a distal electrode, the array will float electrically, following the liquid potential. This limits electrochemistry to the distal electrode and allows single-polarity operation with no degradation of the emitter tips [3, 2].

Additionally, oxygen radicals eat away at the carbon substrate. While not a problem in the laboratory environment, during operation in the higher layers of the
atmosphere, there is a high probability of exposure to oxygen radicals. To address this problem, the carbon emitter arrays are coated with a micron-scale thin layer of Cerium Oxide, using an in-house AJA International Orion series sputter coater. This process works by igniting an argon plasma near a Cerium Oxide target. This plasma dislodges individual molecules from the target, which then travel through vacuum and deposit on the emitter array. Cerium Oxide is also highly hydrophobic, ensuring that the ionic liquids will stay inside the substrate rather than flooding the array structure and shorting the extractor. The successful attachment of the cerium oxide was checked by coating a monitor glass slide along with the emitters. After coating, this glass slide was checked for hydrophobicity to ensure the coating was successful.

One final concern with the adoption of carbon xerogel is the possibility of electron emission off the carbon tips. Because carbon is a conductor, there is a chance that a strong enough enhanced field at the tips could extract electrons from the carbon itself. If this were the case, the electron emission would overpower the emission of ions and we would see an extremely asymmetrical IV curve with very large negative currents. This does not appear in the data reported here. However, it is a point to consider moving forward as emitters are patterned with tighter arrays and sharper tips.

### 2.2 Ionic Liquids

Electrospray propulsion is based on the electrostatic extraction and acceleration of ions from ionic liquid propellants, which are low-temperature molten salts with exceptionally low vapor pressure and relatively high electrical conductivity [13]. Ionic liquids can be exposed to vacuum without fear of out-gassing due to their negligible vapor pressure. They can also be electrically stressed to form sharp liquid structures (to be discussed in depth in section 4.1). At the top of these structures, very strong electric fields develop, inducing ion emission which can be used to produce thrust.

For this experiment, four different ionic liquids have been combined in different mixture concentrations. The relevant properties of these ionic liquids are summarized
2.2.1 Ionic Liquid Mixtures

The propellants used for the testing presented in this work consist of pure EMI-CF$_3$BF$_3$ and pure EMI-GaCl$_4$ as baseline measurements, in addition to solutions of aqueous EMI-(HF)F and S111-(HF)F in EMI-CF$_3$BF$_3$. These solutions arose by first making 25% by mass mixtures of EMI-(HF)$_{2.3}$F and S111-(HF)$_{1.9}$F with EMI-CF$_3$BF$_3$. It was soon established that under vacuum, the hydrofluoric anions would release HF and change to (HF)$_1$F$^-$. The EMI-(HF)F and S111-(HF)F that remains is a solid a room temperature and stays in solution with EMI-CF$_3$BF$_3$ as an aqueous species. This is, however, provided that the concentration is low enough. Studies conducted by another SPL student, Caroline Bates, showed that these species will super saturate around 60% by mass and come out of solution in crystalline form. In order to ensure this did not happen during testing, the initial solutions were kept to 25% concentration by mass. Matsumoto et al present this same HF loss as a result of heating the pure EMI-(HF)$_{2.3}$F ionic liquid to 400 K. This results in EMI-(HF)F crystals, with a melting point measured at 324 K [15].

The relevant properties for these ionic liquid mixtures, both before and after HF loss in vacuum, are presented in table 2.2.

Samples of both mixtures were created and their mass was measured both before and after 48 hour-long exposure to low vacuum (< 10$^{-6}$ Torr). For EMI-(HF)F, the liquid mass decrease from 0.4104 g to 0.3317 g. This was a loss of 0.0787 g, while the
Table 2.2: Properties of ionic liquid mixtures at 298 K

<table>
<thead>
<tr>
<th>Ionic Liquid</th>
<th>Cation</th>
<th>Cation Mass</th>
<th>Anion</th>
<th>Anion Mass</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>25% EMI-(HF)$_2$F</td>
<td>C$<em>6$H$</em>{11}$N$_2^+$</td>
<td>111 amu</td>
<td>(HF)$_2$F$^-$, (HF)$_3$F$^-$, CF$_3$BF$_3^-$</td>
<td>59, 79, 139 amu</td>
<td>2.1 Si/m</td>
</tr>
<tr>
<td>21% EMI-(HF)F</td>
<td>C$<em>6$H$</em>{11}$N$_2^+$</td>
<td>111 amu</td>
<td>(HF)F$^-$, CF$_3$BF$_3^-$</td>
<td>39, 139 amu</td>
<td>1.8 Si/m</td>
</tr>
<tr>
<td>25% S111-(HF)$_2$F</td>
<td>(CH$_3$)$_3$S$^+$, C$<em>6$H$</em>{11}$N$_2^+$</td>
<td>77, 111 amu</td>
<td>(HF)F$^-$, (HF)$_2$F$^-$, CF$_3$BF$_3^-$</td>
<td>39, 59, 139 amu</td>
<td>2.6 Si/m</td>
</tr>
<tr>
<td>22% S111-(HF)F</td>
<td>(CH$_3$)$_3$S$^+$, C$<em>6$H$</em>{11}$N$_2^+$</td>
<td>77, 111 amu</td>
<td>(HF)F$^-$, CF$_3$BF$_3^-$</td>
<td>39, 139 amu</td>
<td>1.8 Si/m</td>
</tr>
</tbody>
</table>

Theoretical mass difference for a loss of 1.3 (HF) molecules is 0.0606 g. It is anticipated that this extra lost mass was due to the rapid bubbling of the liquid as it was exposed to vacuum. The container was closed as securely as possible, but in order to allow the HF to evaporate out, a small area had to be left open to the air. Likely, some of the liquid splattered out of this small opening when the HF boiled out of solution. For S111-(HF)F, the mass decreased from 0.3284 g to 0.2789 g. This was a loss of 0.0495 g, compared to a theoretical value of 0.0441 g. This mass loss was once again higher than expected, likely due to the same phenomenon described earlier. Due to the uncertainty regarding how much liquid is able to splatter out of the vial, more work could be done to ensure this phenomenon is behaving as we expect.

One item of note, if this phenomenon is occurring as we would expect, the concentrations should theoretically drop to 21% by mass for EMI-(HF)F and 22% for S111-(HF)F. These percentages are represented in table 2.2 and from here on, but once again, this is a theoretical calculation. Further study would be needed to confirm this concentration.

One unfortunate side effect of this HF loss is a reduction in the conductivity of the ionic liquid. As the HF is removed from the anion, the conductivity gradually decreases. Haviwara et al reported the conductivity of EMI-(HF)$_n$F as a function of $n$, the HF content of the anion. Testing at 298 K, they reported a decrease in conductivity from 10 S/m, to 5 S/m as $n$ decreased from 2.3 to 1.4 [5]. Note that since they were testing at room temperature, they were unable to decrease $n$ all the way to 1, since the pure EMI-(HF)F liquid would crystallize.
Chapter 3

Emitter Fabrication

There are several intermediate steps involved in taking the iEPS emitters from the starting block to fully assembled, testable thrusters. This process was analyzed and tailored to fit our purposes by Jimmy Rojas-Herrera, a former undergraduate researcher in the Space Propulsion Laboratory. Further information about this process can be found in Rojas-Herrera et. al. [19].

3.1 Description of Final Samples

The samples fired in the TurboVac chamber consist of an array of 480 emitter tips, manufactured by laser ablation out of a single piece of carbon xerogel with an approximate footprint of 1 cm x 1 cm. These tips are arranged in a triangular pattern (as shown in figure 3-1). The emitter tips have an average height of 200 \( \mu m \) and an apex radii between 4 and 6 \( \mu m \). Pore sizes can vary widely, but are typically found to be at or below 0.5 \( \mu m \). A zoomed in view of an emitter tip is shown in figure 3-2. At this magnification the tip radius and pore size can be much more clearly seen.
3.2 Preparation of Carbon Emitter Chips

3.2.1 Preparation of PDMS Mold

Firstly, a hydrophilic PEO-PDMS mold is prepared using the Sylgard 184 Silicone Elastomer Kit, containing polydimethylsiloxane prepolymer base, curing agent, and PDMS-b-PEO copolymer. 20 g of the prepolymer base is placed in an appropriately sized beaker. 2 g of the curing agent is added to the base, shortly followed by 0.38 g of the PDMS-b-PEO copolymer. This mixture is mixed and dessicated for 15 minutes to ensure there are no bubbles remaining in the mixture. It is then poured into the desired container. For our purposes, we use an aluminum mold machined to fit the desired pockets of the PDMS mold. The dimensions of said mold are shown in figure 3-3. The aluminum mold with the PDMS is placed into an 80°C oven for 2 hours. After this time the PDMS is solidified and ready to accept the resorcinol formaldehyde solution.
3.2.2 Mixing of Ingredients

All reagents in this process are used as received from Sigma-Aldrich Co. LLC. First, 2.46 g of resorcinol (0.112 mol) is added to 3.00 g of deionized water and stirred to ensure the complete dissolution of resorcinol. This is followed by the addition of 4.30 g (0.054 mol) of 37% formaldehyde solution. At this time the mixture is covered with a parafilm to avoid any evaporation, and swirled by hand for 5 minutes. Next, 0.088 g (1.5 mmol) is added to the solution. This mixture is transferred into the solid PDMS mold which is placed inside a seal-tight container, where it will remain throughout the curing process.

3.2.3 Curing Cycles

Once secure in the sealed container, the mold is left to sit in the fume hood at ambient temperature for 18 hours. It will then be placed in a 40°C oven for 6 hours, followed by a 60°C oven for 18 hours, and finally an 80°C oven for 30 hours. The chips are now solidified and take on an appearance shown in section (a) of figure 3-4.
Figure 3-3: Dimensions of PDMS-b-PEO Mold. The lengths L1, L2, and L3 signify the edge lengths of the square pockets and range in length from 13.3 mm to 14.2 mm. [19]

3.2.4 Pyrolysis and High-Temperature Annealing

At this point in the process, the resorcinol-formaldehyde (RF) chips will be removed from the PDMS mold and prepared for treatment in a high temperature argon-atmosphere furnace. The first furnace cycle is used in order to pyrolyze the RF chips, which will dehydrate the polymer that makes up the substrate, leaving behind a purely carbon structure. This is accomplished by heating the chips to a temperature of 1100°C under an atmosphere flowing argon at 400 sccm. Following this step, the chips will take on the appearance shown in figure 3-4 part (b). The final thermal challenge presents itself as the carbon chips experience significant hysteresis when exposed to cycles of low and high temperature. Because of these chips application under potentially high temperatures, this problem must be addressed before they can be properly operated. Early attempts resulted in the fracturing of samples as the carbon structure shrank significantly under high temperature. Less drastic effects also include the detaching of the carbon chips from their frames during the testing process. This problem is mitigated by the thermal cycling (in the same argon-atmosphere) of the RF chips from ambient temperature up to 110°C, 295°C, and 430°C then back down a total of six times. These cycles ensure that any shrinking of the chips will occur in the furnace and not during operation.
Figure 3-4: Resorcinol-formaldehyde substrate at various points during the thermal process. a) Xerogel chips following 30 hour 80°C oven cycle. b) Xerogel chips following pyrolysis. Careful measurements showed a shrinkage of 19.3±1.1%. c) Final xerogel chips after filing and removal of "skin" layer. [19]

3.2.5 Filing

Finally, the RF chips are filed in order to remove the "surface skin," a layer on the top of the chips (as they are sitting in the PDMS mold) about 50 microns thick that is much denser and smoother than the rest of the sample. This process brings the chips down to approximately 1.02 mm in thickness, which will allow them to align perfectly with the frames for laser patterning. This filing is performed using microfinishing discs with roughnesses of 8000 and 5000 nm, in that order. Once this process is completed, the chips resemble the state shown in image (c) of figure 3-4.

3.3 Bonding

The next step in the fabrication process consists of bonding the carbon xerogel chips to silicon frames. These frames allow for the patterning and alignment of the field augmenting emitter structures. The silicon frame features four corner posts which are designed to fit into square depressions in the extractor grid. Each of these four posts contain an insulating Pyrex layer to electrically insulate the high potential emitter grid from the extractor grid [8]. These posts are carefully designed to align the emitter tips with the various holes in the extractor. The bonding is accomplished using a One Component Epoxy Resin purchased from Epoxies, Etc. of Cranston, Rhode Island. The epoxy is carefully applied to the edges of the silicon frame before the chip and frame assembly is placed into the lab furnace for curing. A damaged piece of silicon is
used in conjunction with the assemblies to ensure that the epoxy is fully cured upon completion of the furnace cycle. Following the bonding process, the chips are polished in conjunction with the frames, using a microfinishing disc with a roughness of 5000 nm to ensure that the top plane of the chip and silicon frame are aligned. This will ensure that the apex of the emitter tips will align perfectly with the extractor grid later on in the process.

3.4 Laser Patterning

The bonded assemblies of carbon chips on frames are transplanted and secured with two sided tape onto glass slides. These slides are shipped up to Photomachining, Inc. of Pelham, NH where they are laser etched to create the emitter tip array. This etching process creates an array of 480 emitter tips, with an average emitter tip height of 200 microns and a tip radii of approximately 4-6 microns. The separation between adjacent emitter tips on the chip is 450 microns. Assuming the chip has been polished correctly into alignment with the top of the frame, these tips will be aligned in the same plane of the lower surface of the extractor grid. An SEM image of a fully patterned carbon chip is shown in figure 3-1.

The patterned tip structures are designed to maximize the hydraulic impedance of each emitter tip, which is given by

$$Z = \frac{\mu}{2\pi \kappa} \frac{1}{1 - \cos \alpha} \left( \frac{\tan \alpha}{R_c} - \frac{\cos \alpha}{H} \right)$$

where $H$ is the tip height, $\alpha$ is the tip half-angle, $R_c$ is the tip radius of curvature, $\kappa$ is the substrate permeability, and $\mu$ is the ionic liquid viscosity. The substrate permeability can be calculated as a function of the pore size $r_p$ and porosity $\Phi_p$ using

$$\kappa = \frac{r_p^2}{60(1 - \Phi_p)^2}.$$  

Maximizing the hydraulic impedance ensures that emission occurs within the pure ionic regime. For EMI-BF$_4$, for instance, the impedance $K$ must be above $1.5 \times 10^{17}$
In terms of laser patterning, it can be seen that in order to increase the impedance, we want to maximize the ratio of tip height to radius of curvature, from here on called the tip aspect ratio. By comparing SEM images of a carbon emitter side by side with a glass emitter, it is clear that carbon allows for a higher tip aspect ratio. This is demonstrated in figure 3-5.

### 3.5 Temporary Mount Assembly

For the purposes of this research, emitters tested in the lab were mounted on temporary mounts, as shown in figure 3-6. These mounts are quick to disassemble, clean, and reassemble. This is particularly useful in the case of repeatedly testing many different fuels one after another. The most difficult part of this mounting process is aligning the tips etched into the carbon chip with the holes machined into the extractor grid. This process is accomplished with great care under an optical microscope. First the carbon chip on its frame is placed on the top surface of the temporary mount. Then, the extractor grid is carefully placed onto the four posts, making sure the four posts fit comfortably into the depressions built into the extractor grid. Once these four posts are in place, the tips are fairly well lined up with the extractor holes. However, since there is still a little bit of travel allowed by the post-to-extractor joint,
a small amount of adjustment is required. This adjustment is done repeatedly as four plastic set screws are slowly tightened in order to secure the extractor and chip in place. Once the emitter and extractor are secure on the top half of the mount (but only finger tight) the mount is flipped over and ionic liquid is added to the backside of the chip until the carbon is saturated. Once saturated, 5 to 10 pieces of filter paper are added to the void on the back of the mount and these are also saturated with ionic liquid. This allows for a longer testing time, as there is more fuel available. Finally, the bottom half of the mount is prepared, along with a spring that will hold the filter paper in place, and screwed into the top half. Now the fully assembled temporary mount is prepared for testing. The emitter lead (built into the temporary mount) and the extractor lead (soldered to the edge of the extractor grid) will be attached to a power source by using two feedthroughs inside the vacuum chamber. This temporary mount is a much less time intensive method, that still allows for the analysis of emitter performance, but without the added effort of procuring a tank and carbon electrode necessary for the full assembly process.

Figure 3-6: Image of a temporary mount used for test firing.
Chapter 4

Background and Theory

This section will provide background information and theory in order to better describe the electrospray phenomenon, as well as explain how it is produced in the iEPS system.

4.1 Meniscus Formation

In order to fully understand the effect of different ionic liquid properties on thrust density, it is important to first understand the meniscus formation that proceeds assisted ion evaporation.

Ion emission from the meniscus of an ionic liquid in vacuum is taken to obey the kinetic law [6, 10]

\[ j_e = \sigma \frac{k_B T}{h} \exp \left( - \frac{\Delta G - G(E_n^\nu)}{k_B T} \right) \]

where \( j_e \) is the current emitted per unit area of the meniscus surface, \( \sigma \) is the density of surface charge, \( k_B \) is Boltzmann’s constant, \( T \) is the liquid temperature, \( h \) is Planck’s constant, \( \Delta G \) is the activation energy barrier for solvated species, \( E_n^\nu \) is the magnitude of the normal component of the electric field acting on the meniscus exterior, and \( G(E_n^\nu) \) is the reduction of \( \Delta G \) due to this field. The latter is assumed to take the form
\[ G(E_n^\nu) = \sqrt{\frac{q^3 E_n^\nu}{4\pi \epsilon_0}}, \quad (4.2) \]

based on the Schottky hump for polar media, when \( q \) is the charge state of evolving particles and \( \epsilon_0 \) is the permittivity of vacuum [4]. Since \( \Delta G/k_BT \) is large in situations of interest, meaningful evaporation can only begin when \( \Delta G - G(E_n^\nu) = \mathcal{O}(k_BT) \ll \Delta G \). This relation requires fields near the characteristic electric field

\[ E^* = \frac{4\pi \epsilon_0 \Delta G^2}{q^3}, \quad (4.3) \]

arising from the condition \( \Delta G = G(E^*) \). The length scale of the evaporation region at the tip, \( r^* = 4\gamma/\epsilon_0 E^*^2 \), is determined by balancing the electric stress (order \( \epsilon_0 E^*^2/2 \) [9]) and surface tension (order \( 2\gamma/r^* \) [22]).

The evolution of charge from this region reduces \( \sigma \) from its equilibrium value \( \epsilon_0 E_n^\nu \) [9] and permits electric fields of the order \( E^*/\epsilon \) where \( \epsilon \) is the dielectric constant of the liquid. This drives the characteristic conduction current density \( j^* = KE^*/\epsilon \) and total evaporation current, \( I^* = \pi r^*^2 j^* \).

For an order of magnitude analysis of the ionic liquids used in this study, the relevant intrinsic properties include the solvation energy \( \Delta G = 1 - 2 \) eV, the electrical conductivity \( K = 1 - 2 \) Si/m, the surface tension \( \gamma = 0.01 - 0.1 \) N/m, the dielectric constant \( \epsilon = 10 - 100 \). Using these parameters, we can expect \( E^* = 0.1 - 1 \) V/nm, \( r^* = 10 - 100 \) nm, and \( I^* = 100 - 1000 \) nA [4]. Note this analysis is for a single emitter site. For a full array, we can expect currents on the order of \( I^* = 50 - 500 \) \( \mu \)A.

### 4.2 Meniscus Modeling

Extensive work was done by Chase Coffman, a former SPL graduate student in modeling the menisci that form during assisted ion evaporation. Further detail about his work can be found in Coffman et. al. [4].

In his research, Coffman discovered a relationship between the shape of the meniscus and the three dimensionless parameters shown below.
Figure 4-1: $E_0 - B$ solution plane. Cross-hatched areas represent unstable meniscii. The vertical line at $E_0 = 0.52$ represents the turning location between rounded and sharp meniscii. The dash-dot curves represent the upper bounds for $C_R = 10^3$ and $C_R = 10^4$. [4]

$$E_0 = \frac{E_\infty}{E_c}, \quad B = \frac{r^*}{r_0}, \quad C_R = \frac{K E_c r_0^2 R_h}{p_c \rho (q/m)}$$

(4.4)

Where $E_\infty$ is the imposed electric field, $E_c$ is the electric field at the meniscus tip, $r_0$ is the base radius of the meniscus (which we’ll take to be the radius of curvature of the tip), $R_h$ is the characteristic impedance, $p_c$ is the capillary pressure of the substrate, and $\rho$ is the density of the liquid.

The relationship between these three parameters in shown in figure 4-1.

Figure 4-2 shows meniscus shapes and how they vary with $E_0$ in the non-dimension $z - r$ plane. Examples are shown for both the sharp and rounded meniscus regimes.

Notice that the meniscus shapes shown for $E_0$ values above 0.52 represent the cone-jet regime, where large, heavy droplets leave off the sharp singularity at the tip of the meniscus. In the pure ionic regime, individual ions leave the surface due to electrically assisted evaporation. Therefore, in this regime, the meniscus is a closed
Figure 4-2: Various meniscus shapes in comparison to the classical Taylor cone (dashed). a) Shape of the meniscus for $E_0 = 0.30, 0.40, 0.45, 0.48, 0.50, 0.51$, increasing in the direction of the arrow. b) Meniscus shapes for $E_0 = 0.62, 0.70, 0.80, 0.90$, increasing in the direction of the arrow.

surface, occurring for $E_0$ less than 0.52. Since $E_0$ is given by $E_0/E_c$, to get a value below 0.5, the field at the tip must be multiplied by at least a factor of two. This is accomplished by once again increasing the tip aspect ratio.

4.3 Specific Impulse

By using the time-of-flight data collected in TurboVac, we can estimate the specific impulse by using the thrust and mass flow as follows [8]

$$I_{sp} = \frac{F}{g_0 \dot{m}}$$  \hspace{1cm} (4.5)

where $g_0$ is the standard acceleration due to gravity, and the thrust ($F$) and mass flow ($\dot{m}$) values are calculated from the time of flight data as follows.

First, we will assume that the kinetic energy of the beam particles is perfectly converted from the electric potential of the ions in the liquid bulk.

$$\frac{1}{2}mc^2 = qV_e$$  \hspace{1cm} (4.6)

The velocity of the particles in the beam is easily calculated as $L/t$, the gate-
to-detector length (102.5 cm) divided by the flight time of the particles. Combining these two, we have an equation for the mass of the particle as a function of its flight time.

\[ m = \frac{2qV_e}{L^2} t^2 \]  

(4.7)

We can note that the mass flow of the propellant is simply given by its current draw times the mass to charge ratio of the particles. This gives us

\[ \dot{m} = \frac{2I_eV_e}{L^2} t^2 \]  

(4.8)

This equation represents the mass flow for a single type of particle with a single flight time. Our beam, however, contains a distribution of different masses and flight times. To get the total mass flow, we must integrate this equation over the entire distribution.

\[ \dot{m}_{TOF} = \frac{2I_eV_e}{L^2} \int_0^{t_f} t^2 f(t)dt \]  

(4.9)

Once the collected current is normalized to run between 1 and 0, the density function with regards to time is simply given by the derivative of the collected current with regards to time.

\[ \dot{m}_{TOF} = -\frac{2I_eV_e}{L^2} \int_0^{t_f} t^2 \frac{dI_c}{dt} dt \]  

(4.10)

The time of flight data returns a curve of \( I_c \) as a function of \( t \). Ideally we would like to avoid taking the derivative of this curve. This can be accomplished if we integrate this equation by parts.

\[ \dot{m}_{TOF} = \frac{2I_eV_e}{L^2} \left( -t^2 I_c \bigg|_0^{t_f} + \int_0^{t_f} 2t I_c dt \right) \]  

(4.11)

Since \( I_c(t_f) = 0 \), the first term will evaluate to zero, leaving us with
\[ \dot{m}_{\text{TOF}} = \frac{4I_eV_e}{L^2} \int_0^{t_f} tI_c dt. \] (4.12)

Moving on, we will now calculate the thrust, \( F_{\text{TOF}} \). All that we must do is take \( \dot{m} \), given in equation 4.8, and multiply it by \( c \), once again taken as \( L/t \).

\[ F = \frac{2I_eV_e}{L^2} \frac{L}{t} = \frac{2I_eV_e}{L} t \] (4.13)

This equation is for a homogenous beam. We must integrate over the full distribution, once again taken as the negative derivative of the collected current.

\[ F_{\text{TOF}} = -\frac{2I_eV_e}{L} \int_0^{t_f} t \frac{dI_c}{dt} dt \] (4.14)

Integrating by parts,

\[ F_{\text{TOF}} = \frac{2I_eV_e}{L} \left( -tI_c \bigg|_0^{t_f} + \int_0^{t_f} I_c dt \right). \] (4.15)

The first term will again evaluate to zero and we are left with

\[ F_{\text{TOF}} = \frac{2I_eV_e}{L} \int_0^{t_f} I_c dt. \] (4.16)

We can now use \( F_{\text{TOF}} \) and \( \dot{m}_{\text{TOF}} \) to calculate the \( I_{sp} \), given earlier in equation 4.5.

### 4.4 Thruster Efficiency

#### 4.4.1 Transmission Efficiency

One important source of imperfect losses in the emitters is interception by the extractor grid. Any ions collected by the extractor grid cannot escape the thruster and provide thrust. This phenomenon is captured by the transmission efficiency, defined as the ratio of current passing through the extractor without being intercepted to the total emitted current.
The average value of $I_{ex}/I_e$ will be calculated from firing data. It will be seen in chapter 6 that the interception increases with the firing voltage in an exponential-like manner right up to the maximum stable firing voltage. For the calculation presented here, the average will be taken using this full range. During operation, one firing voltage and current would likely be selected for the entire mission. This voltage would be selected by balancing the mission’s thrust requirement with the interception losses incurred by firing at a higher voltage.

4.4.2 Polydispersive Efficiency

The polydispersive efficiency arises as a method for estimating the losses caused by the emission of particles with different masses and velocities. This efficiency can be determined from the time of flight data using

$$\eta_p = \frac{T_{TOF}^2}{2\hat{m}_{TOF}}$$

(4.18)

where the calculations for $T_{TOF}$ and $\hat{m}_{TOF}$ are the same as in section 4.3. Note that for a homogenous beam, this efficiency will be equal to one, regardless of the mass/flight time. To demonstrate this, we can substitute our time of flight distribution with a delta function placed at some arbitrary value $T$, and then calculate the thrust and mass flow.

$$F_{TOF} = \frac{2I_eV_e}{L} \int_0^{t_f} t \delta(T)dt = \frac{2I_eV_eT}{L}$$

(4.19)

$$\hat{m}_{TOF} = \frac{2I_eV_e}{L^2} \int_0^{t_f} t^2 \delta(T)dt = \frac{2I_eV_eT^2}{L^2}$$

(4.20)

The polydispersive efficiency is then given by

\[ 37 \]
\[
\frac{F^2}{2mV} = \frac{4I_e^2 T^2 J^2 / L^2}{1} \quad \text{(4.21)}
\]

We can clearly see that the homogeneity of the beam is what drives the value of \( \eta_p \).

### 4.4.3 Angular Efficiency

Another phenomenon that decreases the effective thrust of the emitter is the angular distribution of the emitted beam. This distribution is determined by spatial distribution measurements obtained using an RPA and a rotary motor. These distributions will be reported and discussed in further detail in chapter 6.

We can integrate this distribution to determine an angular efficiency according to

\[
\eta_\phi = \int_0^{\phi_0} f(\phi) \cos \phi d\phi \quad \text{(4.22)}
\]

### 4.4.4 Energy Efficiency

Many events can occur following emission to decrease the energy that is carried by the beam, the largest of these being fragmentation events. During the acceleration process, polymers can split up into separate groups, now with different masses. This process requires the conservation of momentum, but it leads to a decrease in energy transmitted by the (now two) particles. The energy resolving data given by RPA analysis allows us to derive an energy efficiency, defined as the expected ratio of effective beam acceleration potential to the applied emitter potential.

\[
\eta_E = E \left[ \frac{V_B}{V_e} \right] \quad \text{(4.23)}
\]

For simplicity, I will define a single variable \( \nu \) as the ratio of retarding potential to emitter potential. The ion energy distribution function is also calculated by taking the derivative of the normalized RPA signal as a function of this new variable \( \nu \). The
energy efficiency can now be written as

\[ \eta_E = \int_0^{\nu_f} \nu f(\nu) d\nu = - \int_0^{\nu_f} \frac{dI_c}{d\nu} d\nu \]  

(4.24)

As with the polydisperse efficiency, we would like to avoid differentiating the raw signal if possible. Once again, we will integrate this expression by parts.

\[ \eta_E = \left( -\nu I_c(\nu) \right)_0^{\nu_f} + \int_0^{\nu_f} I_c(\nu) d\nu \]  

(4.25)

Again, \( I_c(\nu_f) = 0 \), so the first term will evaluate to zero. We are then left with

\[ \eta_E = \int_0^{\nu_f} I_c(\nu) d\nu \]  

(4.26)

4.4.5 Total Efficiency

The total efficiency can now be calculated by combining the efficiencies from all the separate processes. This is given by equation 4.27 [12].

\[ \eta_{total} = \eta_i \eta_{ir}^2 \eta_\phi \eta_E \eta_p \]  

(4.27)

with \( \eta_i \) being the ionization efficiency taken as unity since no direct evaporation of neutrals is observed in ionic liquids.
Chapter 5

Experimental Methods

This chapter will discuss the experimental methods and hardware used in testing and analyzing the electrospray thrusters created for this work.

5.1 Testing Environment

All tests were done in a 16” diameter x 32” length cylindrical vacuum chamber, pumped to pressures below $5 \times 10^{-6}$ Torr. An image of the chamber with the retarding potential analyzer and time of flight apparatus is shown in figure 5-1.

5.2 Emission Current and Interception

Emitted current as a function of applied emitter voltage was determined through the application of three successive voltage scans in a triangular profile over the investigated voltage range ($-V_{max}$ to $+V_{max}$ with a period of 30 seconds. High voltage was generated and measured using a Matsusada AP-3B1-L2 with $\pm 1V$ accuracy in the voltage monitor. The emitted current (defined as the current drawn by the emitter from the laboratory power supply) and intercepted current (defined as the current measured from the extractor to ground) were recorded by measuring the voltage drop across a $1k\Omega$ resistor in conjunction with an isolation amplifier (Analog Devices AD210JN) leading, after calibration with the resistive load, to a measurement
Figure 5-1: Photograph of the inside of the chamber.
accuracy of $\pm 0.1 \mu A$ [8]. The recorded data was averaged, while incorporating error propagation.

### 5.3 Energy Distribution

The energy distribution of the emission beam was measured using a retarding potential analyzer (RPA). This analysis used a singly charged species approximation for the beam. The RPA instrument consisted of a Faraday cup with a $1/4"$ (6.35 mm) aperture and grounded entrance grid, followed by a retarding potential grid and a bias grid for electron repulsion upstream of the Faraday cup. The RPA detector was positioned 20 degrees off the central axis of the chamber at a distance of 20 cm from the extractor grid. The emitter was rotated using a rotary electric motor in order to switch between time-of-flight and RPA measurements. A schematic of the RPA set-up (not drawn to scale) is shown in figure 5-2, part a.

The current was measured using a Keithley 6517 electrometer with femtoampere current accuracy. Measurements were performed by operating the emitter at a single polarity, with 4 successive scans of the retarding potential from zero to the emitter potential. The scans are incremented by 100 V both increasing and decreasing, with a long period of 60 s to account for the long time constant of the Keithley electrometer measurement. The recorded data was then reduced by averaging over all of the scans,
incorporating error propagation. The largest error contribution in the experiment was found in the voltage ripple of the retarding grid of ± 5 V.

5.4 Spatial Beam Distribution

The angular beam distribution was recorded using the same Faraday cup described in section 5.3. In this case, however, the thruster was rotated on a rotary arm 20 cm from the RPA detector and capable of rotation from -70 to +110 degrees from the RPA’s central axis (note that this is -90 to +90 degrees from the central chamber axis). The rotational motion was controlled by an electric motor in conjunction with a solid shaft rotary feedthrough and position switches at ±90 degrees. The measurement principle is represented in figure 5-2, part a.

The angular position was read using an incremental angular encoder with 2500 counts per revolution. 4 scans over the entire hemisphere were performed, with the thruster continuously operated in single polarity at the stated current. Data was reduced though averaging, incorporating error propagation. As in section 5.3, current was measured using a Keithley 6517 with femtoampere current accuracy. The largest source of error was an offset present when aligning the thruster with the rotation instrument’s zero axis upon thruster mounting. This was estimated as less than 5 degrees. The error introduced by approximating the emitter grid as a point source was estimated to be less than 2.5 degrees [8].

5.5 Mass Distribution

Knowledge on the mass distribution of the beam allows corrections for different fractions of charged ions, droplets, or fragmentation products in the beam. This allows the determination of the average charge-to-mass ratio of the entire emission beam, which in turn allows estimation of the specific impulse. In order to determine the beam composition, time-of-flight (TOF) measurements were taken in the TurboVac chamber. The TOF collector was placed with a free drift length of 102.5 cm between
the collector and the electrostatic gate. The collector itself consisted of a deflector plate, a Channeltron Electron Multiplier (CEM), and a collector plate. The CEM operation principle is represented in figure 5-3. The signal from the collector was amplified by a custom-made transimpedance amplifier and recorded by an oscilloscope (Agilent Technologies DSO-X 3024A) set to 4096 trace averaging. A stopping gate was used to interrupt the emitted ion beam. In this configuration, the gate was switched on and off using a fast square waveform, interrupting the emitter beam. A high-voltage pulse of approximately 1000 V was applied downstream of a 1/8" gate aperture. The high voltage leads were enclosed on both the upstream and downstream sides by grounded grids to ensure a potential free drift zone. This setup is represented in figure 5-2, part b. This time of flight set-up was designed by Catherine Miller and built by Elaine Petro.
Chapter 6

Results and Discussion

This chapter will present the results recovered from the firing of emitters with the four ionic liquids discussed here. These results will include current vs voltage (IV) behavior, retarding potential analysis (RPA), angular distributions, and time of flight (TOF) curves. All data is presented with a 90% confidence interval. All efficiencies will be presented side-by-side in section 6.5.

6.1 IV Curves

In order to record the following IV data, the thrusters were first fired briefly, in order to establish the maximum stable firing voltage in both the positive and negative modes. The smaller of these two maximums was selected as $V_{\text{max}}$. The firing voltage was then varied in a triangular waveform, oscillating between $+V_{\text{max}}$ and $-V_{\text{max}}$. The current drawn from the power supply (the emitted current) was recorded, along with the current collected by the extractor grid (the intercepted current). The ratio of these two values was also recorded and is presented below as interception as a function of firing voltage. Note that this data consistently reports higher than normal interception values for thrusters of this type. This is a likely in large part a result of using 120 $\mu$m extractors, as opposed to the 40 $\mu$m extractors used in flight thrusters. This increased thickness allows more surface area where emitted ions can impact the extractor.
Figure 6-1 shows the current vs voltage behavior for pure EMI-CF$_3$BF$_3$. The current reached a positive maximum of 430 $\mu$A at 1015 V, and a negative maximum of -335 $\mu$A at -1013 V. The maximum observed interception was 28% in the positive mode, and 18% in the negative mode. This plot was the most asymmetrical of the four, with a significantly lower current in the negative mode as compared with the other side.

Figure 6-2 presents the IV behavior for EMI-GaCl$_4$. The emitted current reached maxima of 699 $\mu$A at +1313 V and -769 $\mu$A at -1314 V. The maximum positive and negative interception were 27% and 16% respectively.

Figure 6-3 shows the IV behavior for 21% EMI-(HF)$_2$F. This liquid reached a maximum positive current of 474 $\mu$A at 1120 V, and a maximum negative current of -361 $\mu$A at -1103 V. The maximum positive interception was 17% and the maximum negative interception was 13%.

Figure 6-4 shows the IV behavior for 22% S111-(HF)$_2$F. The maximum currents were 609 $\mu$A at 1264 V and -576 $\mu$A at -1262 V. The interception reached maximums of 12% in the positive mode, and 5% in the negative mode.

Figure 6-5a plots the behavior of all four curves on the same plot. We see that the maximum stable current is highest for EMI-GaCl$_4$ and S111-(HF)$_2$F, but surprisingly, for any single given voltage, the currents are almost identical to each other. The
Figure 6-2: IV Curve (a) and Interception Plot (b) for EMI-GaCl₄

Figure 6-3: IV Curve (a) and Interception Plot (b) for 21% EMI-(HF)F
Figure 6-4: IV Curve (a) and Interception Plot (b) for 22% S111-(HF)F

Figure 6-5: Original IV Curves (a) and IV Curves Adjusted for Starting Voltage (b)
EMI-CF$_3$BF$_3$ curve reports slightly higher currents, which is the opposite of what we would expect given its low conductivity. When corrected for the starting voltage, this behavior goes away. Figure 6-5b plots the same curves, but adjusts the starting points to account for different startup voltages. Once again, the four curves are almost identical. Here the curve for EMI-GaCl$_4$ exhibits some interesting behavior. While it attains a higher current-per-voltage at negative values, the trend is reversed in the positive mode, emitting the lowest current at all positive voltages.

One finding of note is that the interceptions are consistently lower in the negative mode than in the positive mode. This is easily explained as the interception of ions of either polarity with the extractor lead to the emission of secondary electrons. When the emitter tips are positively biased, these electrons are drawn back to the emitter. When the tips are negatively biased, the electrons are repelled. This increases interception in the positive mode and decreases interception in the negative mode, consistent with what is seen here.

6.2 RPA Curves

This section will report the energy resolving retarding potential analysis collected for all four ionic liquids. This data was collected by first finding a stable emitter voltage and current, usually a low current, for the purpose of conserving propellant. The retarding grid on the RPA was then exposed to a triangular high voltage wave, running from zero volts to 100 volts above the firing voltage. The collected current in the RPA was then plotted as a function of the stopping potential over the emitter potential. The results were averaged over multiple sweeps and a curve was fit over the data.

Figure 6-6 shows the RPA curves collected for both positive and negative polarities for pure EMI-CF$_3$BF$_3$. The proportion of the beam with energies greater than 90% of the firing potential is equal to 67% in the positive mode, and 58% in the negative mode.

Figure 6-7 shows positive and negative RPA curves for EMI-GaCl$_4$. The propor-
Figure 6-6: Positive (a) and Negative (b) RPA Plot for Pure EMI-CF$_3$BF$_3$

Figure 6-7: Positive (a) and Negative (b) RPA Plot for EMI-GaCl$_4$
tion of the beam with energies greater than $0.9 \, V_e$ is equal to 63% in the positive mode and 56% in the negative mode.

Figure 6-8 shows the RPA curves recovered for 21% EMI-(HF)F. The percentage of the beam with non-dimensional energies over 0.9 is 46% for the positive mode and 36% for the negative mode.

Figure 6-9 shows the RPA curves recorded for 22% S111-(HF)F. The percentages of the beam with energies over $0.9V_e$ were 72% for the positive mode and 50% for the negative mode.

Figure 6-10 shows RPA plots for all four liquids on the same set of axes. Once again, the curves fell very close to one another. In the positive mode, the EMI-GaCl$_4$ and EMI-(HF)F curves separated themselves significantly from the other two, possessing lower proportions of high energy particles. The other two RPA curves are almost identical to each other. In the negative mode, the 21% EMI-(HF)F curve showed a significant separation towards the higher energies, while the other three stayed within range of each other throughout the energy spectrum.

One phenomenon not reflected in this data is a sharp drop off that we would expect to see early in the signal. This drop corresponds to emitted dimers that broke up after passing the extraction grid. After this drop, we would see a downward slope corresponding to dimers broken up in the acceleration region. It is this phenomenon...
Negative Mode RPA Signal: $\eta_g = 0.75$

Positive Mode RPA Signal: $\eta_g = 0.87$

Figure 6-9: Positive (a) and Negative (b) RPA Plot for 22% S111-(HF)F

Figure 6-10: Positive (a) and Negative (b) RPA Plots for All Liquids
and this phenomenon only that leads to efficiency losses. Ions that break up after the acceleration region will not hurt efficiency, because the thrust has already been delivered to the thruster. Once these molecules pass the extraction grid, they are no longer the working propellant. Given the absence of this vertical drop in these signals, this cannot be taken into account in the efficiency calculation. If this feature were visible, however, a more accurate representation of the energy efficiency would involve a piecewise calculation of efficiency for each individual mass species (monomers, dimers, etc.) then the weighted averaging of these efficiencies into one single value.

This signal feature would likely be visible given a more precise, less noisy signal. This could theoretically be accomplished by measuring the voltage drop across a resistor with a resistance above 1 kΩ. The RPA signal has been measured across a 1 MΩ resistor with almost identical results to the Keithley electrometer. By measuring across a 10 or 100 MΩ resistor, the signal could potentially be recorded with higher resolution than what is reported here.

6.3 Angular Distribution

This section will outline the angular distributions recorded during firing tests. This data was recorded by first finding a stable firing voltage and current (once again, typically a low current in order to preserve propellant). Once the thruster was firing stably, the angular motor was rotated through four sweeps running from -90° to 90°. In post-processing, the angular measurements were shifted to correct for the off-center placement of the RPA within the vacuum chamber.

Figure 6-11 shows the angular distribution for EMI-CF₃BF₃. Both the positive and negative angular distributions show a plateau-like shape in the distribution, with a flat peak, but relatively steep sides. The signal stayed near its max until 10 degrees off center. During the negative mode, the beam also appeared to be slightly skewed in the negative direction.

Figure 6-12 reports the angular distribution recorded for EMI-GaCl₄. This pro-
Figure 6-11: Positive (a) and Negative (b) Angular Distribution for Pure EMI-CF$_3$BF$_3$

Figure 6-12: Positive (a) and Negative (b) Angular Distribution for EMI-GaCl$_4$
Figure 6-13: Positive (a) and Negative (b) Angular Distribution for 21% EMI-(HF)F propellant produced the most narrow beam of the four. In the negative mode it once again produced somewhat of a plateau shape, perhaps skewed slightly to the right, although this is not nearly as pronounced as with EMI-CF₃BF₃.

Figure 6-13 shows the angular distribution recorded for 21% EMI-(HF)F. It should be noted for this angular sweep, an issue arose where the emitter was firing perfectly in the positive mode, but firing very low currents in the negative mode. This is likely a result of running this test last, so that the propellant was running low at this time. This caused the error to make up a much larger proportion of the signal, leading to the larger uncertainty in that distribution.

Figure 6-14 presents the angular distribution for 22% S111-(HF)F. Of all the liquids, this distribution is the closest representation to a standard Gaussian distribution. However, it is actually a fairly wide distribution compared to the others.

Figure 6-15 shows all four angular distributions on the same plot. In the positive mode, it is fairly clear that EMI-GaCl₄ leads to the narrowest beam width. However, with regards to the other three liquids, not much can be said. In the negative mode, EMI-GaCl₄ once again has a narrow beam width, but 21% EMI-(HF)F also produces a narrow beam. That said, the uncertainty in the 21% EMI-(HF)F measurement makes it difficult to draw a meaningful comparison. The other two liquids produce wider beams.
Figure 6-14: Positive (a) and Negative (b) Angular Distribution for 22% S111-(HF)F

Figure 6-15: Positive (a) and Negative (b) Angular Distribution for All Liquids
It should also be noted that an issue was encountered where at high currents and voltages, the beam became more and more asymmetrical. This is one more reason why the currents were kept low for the angular sweep measurement. One hypothesis for this phenomenon was the fact that the metal standoffs that made the connection between the emitter and the power supply rose up a significant amount (5 mm) above the extractor grid for some of these tests. It is hypothesized that these could potentially distort the spatial distribution of the beam. Further testing would need to be done to confirm or disprove this theory. If this is true, this is an effect that is isolated to the temporary mounting system used in these tests, and would not be present if the emitters were mounted and fired on a tank.

6.4 TOF Curves

This section will report and discuss the data found from time of flight testing. Once again, the thruster was set up to fire at a low, stable current. At this point the deflector gate was activated and fed a square wave with a 100 Hz frequency. The Channeltron detector was fed into an oscilloscope which was set to trigger on the falling edge of the square wave fed to the deflector gate. The oscilloscope signal was set to average over 4096 points in order to reduce the noise in the signal. The signals recovered from this process are shown below.

Figure 6-16 shows the time of flight data for pure EMI-CF$_3$BF$_3$. The thrust was calculated as $13.0 \pm 0.8 \, \mu\text{N}$ at a voltage and current of 861 V and 168 $\mu$A. The specific impulse was calculated as $2140 \pm 130 \, \text{m/s}$. There were two large mass peaks at 121 amu (close to 111 amu, the mass of EMI$^+$), and 375 amu, which is only slightly greater than the expected dimer mass of 359 amu.

Figure 6-17 presents the time of flight data recorded for EMI-GaCl$_4$. The thrust was calculated to be $4.3 \pm 0.1 \, \mu\text{N}$ at a voltage of 858 V and a current of 55 $\mu$A. The specific impulse was $2140 \pm 40 \, \text{s}$. The monomer mass peak was very close to the expected value (123 amu measured vs. 111 amu theoretical). The location of the dimer peak, however, was very unexpected. The measured peak was at 325 amu, while...
Figure 6-16: TOF Signal (a) with Mass (b), Thrust (c), and Exit Velocity (d) Distributions for pure EMI-CF$_3$BF$_3$. Vertical blue lines represent theoretical values for (left to right): EMI$^+$ monomers, EMI$^+$-EMI-CF$_3$BF$_3$ dimers
Figure 6-17: TOF Signal (a) with Mass (b), Thrust (c), and Exit Velocity (d) Distributions for pure EMI-GaCl₄. Vertical blue lines represent theoretical values for (left to right): EMI⁺ monomers, EMI⁺-EMI-GaCl₄ dimers.
the theoretical dimer mass for this ionic liquid is 432 amu. This is a result that only appeared in the EMI-GaCl₄ run. Fragmentation events within the acceleration region can artificially move the mass peak slightly to the left, since after fragmentation, the electric field is accelerating a lighter ion. It remains unclear, however, why such a distinct mass peak would arise so far from the theoretical value. One theory was possible contamination of the sample with EMI-CF₃BF₃, but even in this case, the dimer mass is still too low (325 amu compared with 359 amu for EMI⁺-EMI-CF₃BF₃). This phenomenon certainly begs for more study in order to work out what is occurring in this signal.

Figure 6-18 shows the time of flight data for EMI-(HF)F. The thrust for this run was measured as 7.5 ± 0.2 μN, at a voltage and current of 806 V and 104 μA. The specific impulse came out to 2150 ± 50 s. Despite the fact that there were two different ionic liquids in the mixture, there were only two mass peaks. The first peak was at 125 amu vs. the 111 amu mass of EMI⁺. Note that in this case it isn’t possible to tell which ionic liquid is responsible for these ions, since they contain the same monomer. The second large peak comes at 325 amu, which is greater than 261 amu, the mass for the EMI⁺-EMI-(HF)F dimer but less than 359 amu, the mass of EMI-CF₃BF₃ dimers. The time at which the second drop begins corresponds closely to the calculated flight time for EMI-(HF)F dimers, which would seem to indicate that EMI-(HF)F ions are dominating the beam here. However, it is hard to say without further study.

Figure 6-19 shows the time of flight data recorded for the 22% S₁₁₁-(HF)F mixture. The first item to notice about this curve is that it indicates a much higher proportion of monomers than any other curve. This leads to a much higher specific impulse, but a much lower polydispersive efficiency. The thrust was equal to 2.8 ± 0.3 μN, at a firing voltage of 911 V and a current of 54 μA. The specific impulse was calculated as 3160 ± 290 s. Once again despite containing two different ionic liquids, only two main peaks arose, both fairly well attributed to the monomer and dimer mass expected of S₁₁₁-(HF)F. The first fell at 83 amu, very near the S₁₁₁⁺ mass of 77 amu. The second peak fell at 261 amu, which is far from the S₁₁₁⁺-S₁₁₁-(HF)F mass of 193 amu. However, this signal shows a high amount of fragmentation in the
Figure 6-18: TOF Signal (a) with Mass (b), Thrust (c), and Exit Velocity (d) Distributions for 21% EMI-(HF)F. Vertical blue lines represent theoretical values for (left to right): EMI⁺ monomers, EMI⁺-EMI-(HF)F dimers, EMI⁺-EMI-CF₃BF₃ dimers.
Figure 6-19: TOF Signal (a) with Mass (b), Thrust (c), and Exit Velocity (d) Distributions for 22% S111-(HF)F. Vertical blue lines represent theoretical values for (left to right): S111$^+$ monomers, EMI$^+$ monomers, S111$^+$-S111-(HF)F dimers, EMI$^+$-EMI-CF$_3$BF$_3$ dimers.
1.2 TOF Curves

Figure 6-20: TOF Signals for all Four Ionic Liquids

beam. This will blur the demarcation between intact dimers and trimers that broke up in the acceleration region. When looking at the raw time of flight curve, the dimer drop begins very near where we would expect it to for S111-(HF)F dimers, but it drags on with a shallow slope, owed to fragmentation in the beam. This drags the dimer mass peak out to the right. There were no large peaks seen near the EMI+ mass of 111 amu. There is what appears to be a small signal out past the EMI+-EMI-CF3BF3 dimer mass of 359 amu, but it is very small and could be a noise artifact. The absence of EMI-CF3BF3 ions presents strong evidence that when this emitter was tested, the beam was heavily dominated by the S111-(HF)F ions that were pulled out of solution.

Figure 6-20 presents all four time of flight curves on one set of axes for comparison. Here we can directly see the trends of all four curves. Note that the horizontal position of the curves which corresponds to time should not be read into too heavily. This value depends on the emitter voltage, which was different for every test. If this were held constant, we would expect the EMI-GaCl4 curve (in orange) to begin at the same time as the two right-most curves, since these three all share the same monomers.
What can be compared in this plot is the vertical distribution of these curves. We can see that the curve for 22% S111-(HF)F has a large initial drop corresponding to the monomer fraction, and then a smaller drop later on, which corresponds to dimers. The other three curves have a smaller initial drop and a larger secondary drop, since they have a larger percentage of the beam consisting of dimers.

One area of potential future study would be to analyze the evolution of the mass spectrum for 21% EMI-(HF)F and 22% S111-(HF)F as the propellant is gradually fired and depleted. For both these propellants, the beam appeared to be dominated by the hydroflouric ionic liquids, as opposed to the EMI-CF₃BF₃ solvent. If this was the case, then eventually we would expect the hydroflouric liquids to run out and the EMI-CF₃BF₃ mass distribution to become more evident.

### 6.5 Efficiency Analysis

Table 6.1 reports the efficiencies calculated using the interception, retarding potential, angular, and time of flight data.

<table>
<thead>
<tr>
<th>Property</th>
<th>EMI-CF₃BF₃</th>
<th>EMI-GaCl₄</th>
<th>21% EMI-(HF)F</th>
<th>22% S111-(HF)F</th>
</tr>
</thead>
<tbody>
<tr>
<td>ηᵣ</td>
<td>0.90 ± 0.01</td>
<td>0.92 ± 0.01</td>
<td>0.95 ± 0.01</td>
<td>0.97 ± 0.01</td>
</tr>
<tr>
<td>ηₑ</td>
<td>0.86 ± 0.02</td>
<td>0.80 ± 0.03</td>
<td>0.76 ± 0.02</td>
<td>0.87 ± 0.02</td>
</tr>
<tr>
<td>ηₒ</td>
<td>0.82 ± 0.02</td>
<td>0.79 ± 0.03</td>
<td>0.71 ± 0.02</td>
<td>0.75 ± 0.03</td>
</tr>
<tr>
<td>ηₒ</td>
<td>0.95 ± 0.06</td>
<td>0.95 ± 0.07</td>
<td>0.95 ± 0.03</td>
<td>0.94 ± 0.04</td>
</tr>
<tr>
<td>ηₒ</td>
<td>0.94 ± 0.07</td>
<td>0.96 ± 0.05</td>
<td>0.94 ± 0.15</td>
<td>0.93 ± 0.05</td>
</tr>
<tr>
<td>ηₒ</td>
<td>0.94 ± 0.06</td>
<td>0.95 ± 0.02</td>
<td>0.95 ± 0.02</td>
<td>0.88 ± 0.08</td>
</tr>
<tr>
<td>ηₒ</td>
<td>0.60 ± 0.10</td>
<td>0.61 ± 0.07</td>
<td>0.60 ± 0.08</td>
<td>0.63 ± 0.11</td>
</tr>
</tbody>
</table>

Table 6.1: Efficiencies Calculated from Firing Data

There are several trends at play here. First of all, I’ll discuss the results of the transmission efficiency calculations. This is arguably the most difficult efficiency to accurate report, as it is heavily dependent on human error. There are several different factors that will effect this measurement, the first of which being the thickness of the extractor. The thicker the extractor is, the more ions will collect on its surface as they are evaporated from the liquid bulk. The vertical alignment of the extractor with respect to the emitter tips will also impact this efficiency. The closer the tips
are to flush with the bottom plane of the extractor, the higher this efficiency will be. If the tips are set back a large distance from the bottom plane of the extractor, the ion beam has more vertical space to expand and be partially intercepted by the extractor. Finally, the transmission efficiency is heavily impacted by the horizontal (both in the x & y directions) alignment of the emitter tips with the extractor holes. The extractor contains depressions which align it with the posts on the silicon frames, however, there is still a fair amount of freedom even when engaged. The only way to align the extractor after this process is to carefully apply pressure to its sides, while looking at the extractor under a microscope. In general, this alignment will be accurate to within approximately 10% of the hole diameter. However, with the human eye, it cannot generally be aligned reliably more accurately than this.

The formula to calculate the total efficiency calls for one single value for the energy efficiency, and so it was necessary to consolidate the separate efficiencies from the positive and negative modes into one number. This was done by taking the geometric mean of the two efficiencies, the square root of their product. The energy efficiency in the negative mode was consistently lower than that of the positive mode. This could arise from the fact that, in the case of both EMI-CF₃BF₃ and EMI-GaCl₄, the cation is much lighter than the anion. In addition, EMI’s ring structure may make it less likely to break apart during flight. In the case of EMI-(HF)F and S111-(HF)F, this argument does not apply. However, as these are only 21% and 22% concentrated in solution with EMI-CF₃BF₃, the same effect described before may be driving the trend.

With regards to the angular efficiency, once again the total efficiency calculation calls for one single number, so the geometric mean of the positive and negative values was taken. Note that here, this is much less meaningful, since the positive and negative efficiencies were in very strong agreement, identical with the small exception of S111-(HF)F.

Because of the time of flight set up, only the polydispersive efficiency for the positive polarity was testable. A highly recommended course of action for future work would be to compile time of flight data for these four liquids in the negative mode as
well. This is an important field of data that was unable to be resolved in this study. With the exception of 22% S111-(HF)F, the polydispersive efficiencies in the positive mode were very near each other. The reason for this likely being the high percentage of monomers present in the S111-(HF)F beam compared to the other samples. More specifically, these were sulfonium monomers which possess a smaller molecular weight compared with EMI (77 vs. 111). This means a lower mass flow, but also a lower thrust per unit power delivered to the thruster. Since the efficiency’s dependence on thrust is second order, as opposed to its first order reciprocal dependence on mass flow, this is what dominates. It should be noted, however, that because of its light ions the average exit velocity and therefore the specific impulse of S111-(HF)F is the highest of the four. One interesting thing to note is that the (HF)F negative ions in both EMI-(HF)F and S111-(HF)F are very light, only 39 amu. It is anticipated that the negative mass spectra of both these ionic liquids would contain a large proportion of very light and very fast ions. This would likely cause similar repercussions to those in the case of the positive emission of S111-(HF)F, but even more overstated. These would likely show a very low thrust, but an extremely high specific impulse at the same time.

The total efficiency takes into account all of the parameters discussed above, and combines everything into one number. I believe with a more careful alignment process and with a carbon thruster mounted on a tank, fed through a carbon electrode, this efficiency would improve. However, for the purposes of comparing these four ionic liquids side by side, it serves its purpose here. While conclusions can be drawn about certain components of the total efficiency, specifically the energy and polydispersive efficiencies, no strong conclusions can reasonably be made about the total efficiency. It can be noted that 22% S111-(HF)F had a slightly higher calculated total efficiency. However, this is well within the uncertainty of the calculation, so it is difficult to make a definitive statement about its superiority in terms of this parameter.
Chapter 7

Conclusions and Future Work

This work was undertaken with a two-fold purpose. First, to successfully implement and test ion electrospray thrusters with a carbon xerogel emitter substrate. In this regard, this research was a success. Several unforeseen issues and pitfalls arose along the way, however, they were addressed and solved. In the end, thrusters were assembled and tested using carbon emitters that stably and reliably fired with currents that greatly exceeded those possible with glass emitters (typically by factors of 1.5 or 2).

The second goal of this research was to analyze the effect of new, high conductivity hydrofluorinated ionic liquids. In most respects, this was also a success. The test plan had to be revised along the way to account for an unforeseen phenomenon, the release of HF in vacuum. This not only changed the conductivity of the liquids being tested, but also the state of the liquid, transforming the ionic liquid to a crystalline solid under vacuum pressures. By adapting these propellants into an aqueous solution with EMI-CF$_3$BF$_3$, several conclusions about their firing behavior were able to be drawn.

With regards to energy efficiency, EMI-(HF)F showed a large degree of ion fragmentation in both the positive and negative mode. This lowered the energy efficiency greatly, resulting in this liquid having the lowest energy efficiency of the four. S111-(HF)F showed a very low rate of ion fragmentation, particularly in the positive mode. The fragmentation was much greater in the negative mode, which hurt the overall energy efficiency of the thruster. However, the averaged energy efficiency still put this
liquid close to EMI-CF$_3$BF$_3$. The beamwidth for all ionic liquids was extremely close, with any differences in angular efficiency falling well within the 90% confidence interval for the calculation. Finally, the time of flight results shed light on the thrust and specific impulse behavior of these two new liquids. EMI-(HF)F demonstrated time of flight behavior that was similar to EMI-CF$_3$BF$_3$ and EMI-GaCl$_4$. All three of these liquids showed a small percentage of monomers present in the beam, with the rest of the beam largely dominated by dimers. This characteristic led to a high calculated thrust and a high polydispersive efficiency. S111-(HF)F, on the other hand, showed an extremely high proportion of monomers in the beam. These light ions imparted a much higher specific impulse to the thruster when compared to the other three propellants. On the other hand, this led to a very small calculated thrust, and therefore a smaller polydispersive efficiency than that calculated for the other three. In the end, the total efficiency calculated for all four ionic liquids was well within the 90% confidence interval of each other. This meant that in terms of total efficiency, no statistically significant declarations could be made regarding one propellants superiority over another. However, with regards to specific parameters, this was not the case. In terms of thrust, EMI-CF$_3$BF$_3$ showed the greatest value, with a thrust of 13 $\mu$N at a firing voltage of 861 V, while S111-(HF)F showed the least with a calculated thrust of 2.8 $\mu$N at a firing voltage of 911 V. With regards to specific impulse, S111-(HF)F had by far the highest value, at 3160 s. These findings leave us with a characterization of these ionic liquid propellants that can assist with propellant selection, dependent on mission parameters.

In terms of future work, there are many different ways in which this research could be augmented. The first area that would greatly improve the conclusions of this work would be in collecting the negative mode time of flight data for these ionic liquids. This would be extremely valuable data, particularly for the two hydrofluorinated ionic liquids. The negative monomers for these ionic liquids have very small masses which, if they were to make up a large proportion of the beam, would lead to a very high calculated specific impulse for these thrusters. This would greatly increase the span of missions for which these propulsion systems are well-suited. Another area in which
this research can be improved is with regards to the retarding potential measurements taken for these arrays. With a higher precision measurement, the energy spectrum of the beam can be more accurately studied to produce a higher fidelity estimate for the energy efficiency of the thruster. The carbon xerogel emitters also have a large amount of potential in terms of shrinking down the pattern to fit more individual emitters on a single chip. As long as the coating process continues to contain the ionic liquid within the tip array, the distance between emitter tips should easily be able to be halved or even quartered. Of course, more tips with a smaller separation distance would lead to more collisions and fragmentation within the beam. But this could all be studied and a decision could be made to decide at what point the increase in thrust is overshadowed by the potentially negative effects on thruster efficiency.

In summary, high conductivity ionic liquids, particularly S111-(HF)F, in conjunction with carbon xerogel emitter substrates present a promising augmentation to the current state of the art. With further analysis and testing, these new components could certainly move from the experimental to the operational phase.
Bibliography


73


