

AFRL-AFOSR-VA-TR-2019-0029

Fluoro-Hydrogenated Ionic Liquids (FHIL) for High-Performance Electrospray Propulsion

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11/28/2018 Final Report

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REPORT DOCUMENTATION PAGE						Form Approved OMB No. 0704-0188			
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1. REPORT DA	TE (DD-MM-YYYY	) <b>2. REPOR</b>	ГТҮРЕ			3. DATES COVERED (From - To)			
05/11/2018		Final Rep	ort			8/15/2016 - 8/14/2018			
4. TITLE AND S	UBTITLE				5a. CONTRACT NUMBER				
Fluoro-Hydrogenated Ionic Liquids (FHIL)			) for High-Performance FA95!			50-16-1-0273			
Electrospray Propulsion			5b. C		5b. GR	RANT NUMBER			
	5с.			5c. PR	ROGRAM ELEMENT NUMBER				
6. AUTHOR(S)					5d. PR	5d. PROJECT NUMBER			
Paulo C. Loza	ano								
5e				5e. TA	ASK NUMBER				
					5f. WO	WORK UNIT NUMBER			
7. PERFORMIN	G ORGANIZATIO	N NAME(S) AND	DADDRESS(ES)			8. PERFORMING ORGANIZATION			
Massachuset	ts Institute of T	echnology				REPORT NUMBER			
77 Massachu	setts Avenue, 3	37-401							
Cambridge, N	/IA 02139								
9. SPONSORIN	G/MONITORING		(S) AND ADDRESS(ES)	)		10. SPONSOR/MONITOR'S ACRONYM(S)			
Air Force Office of Scientific Research - AFOSR									
875 N Randolph St Arlington V/A 22202			-						
Anington, VA 22205					NUMBER(S)				
12. DISTRIBUT	ION/AVAILABILIT	Y STATEMENT							
Distribution A	- Approved for	<sup>-</sup> Public Relea	ISE						
13. SUPPLEMENTARY NOTES									
14. ABSTRACT									
The goal of the proposed effort is to investigate the emission properties of Fluoro-Hydrogenated Ionic Liquids (PHIL) and their potential implementation in electrospray propulsion. FHILs properties set them apart from practically all other ionic liquids available in the market or described in the literature. In particular, their very high electrical conductivity and very low viscosity could enable an increase of emitted current and thrust of at least an order of magnitude over conventional liquids. Such an increase would allow electrospray thrusters based on arrays of individual emitters to perform at similar thrust.									
density levels (per unit area) as low power Hall thrusters but with vastly superior thrust per unit mass and volume.									
15. SUBJECT TERMS									
Electrospray thrusters, electric propulsion, space propulsion, ionic liquids									
16. SECURITY	CLASSIFICATION	OF:	17. LIMITATION OF	18. NUMBER	19a. NAME (				
a. REPORT	b. ABSTRACT	c. THIS PAGE		PAGES	Paulo Loza	ano			
U	U	U	UU	16	19b. TELEPH 617 25807	9b. TELEPHONE NUMBER (Include area code) 17 2580742			

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# Fluoro-Hydrogenated Ionic Liquids for High-Performance Electrospray Propulsion Grant FA9550-16-1-0273 (Mitat Birkan, Program Officer)

PI: Paulo C. Lozano (plozano@mit.edu) Massachusetts Institute of Technology, Cambridge MA 02139

Final Report, November 2018

# **Summary:**

The objective of this work is to investigate the emission properties of Fluoro-Hydrogenated Ionic Liquids (FHILs) and explore their implementation in electrospray propulsion devices. FHILs properties set them apart from practically all other ionic liquids available in the market or described in the literature. It is hypothesized that their very high electrical conductivity and very low viscosity would allow an increase of emitted current and thrust of at least an order of magnitude over conventional ionic liquids. Such an increase would allow electrospray thrusters based on arrays of individual emitters to perform at thrust densities (per unit area) approaching those of low power hall thrusters, and with significantly higher thrust per unit mass and volume. During the period of performance of this work, our team carried out research that resulted in the selection of appropriate materials, design of experiments and performed characterization experiments. While FHILs have 10x higher electrical conductivity than state-of-the-art propellants used in electrospray thrusters, it was found that their use is not possible as neat substances due to their relative volatility under high vacuum. Instead, we discovered that the decomposition products of FHILs, which are also salts, albeit not liquid at room temperature, are stable and can be used as additives to SOA propellants to increase their electrical conductivity by a factor of up to 4. This provides a simple form of improving the performance of existing devices in which thrust can be increased by up to 4x by simply adding such substances. This work was carried out during a period of two years and resulted in two MIT Master theses, a paper presented at the 2017 International Electric Propulsion Conference (IEPC) and a paper published in the Journal of Non-Crystalline Solids:

- C. Bates, "Characterization of fluorohydrogenated ionic liquids for use in the ion electrospray propulsion system", MIT SM Thesis, Department of Aeronautics and Astronautics, June 2018
- D. Getty, "Testing new potential fuels for ion electrospray propulsion systems", MIT SM Thesis, Department of Aeronautics and Astronautics, June 2018
- C. Miller, D. Krejci, C. Bates, D. Getty and P. Lozano, "Characterization of EMI-(HF)2.3F Using Carbon Xerogel Electrospray Thrusters", IEPC-2017-210, 35th International Electric Propulsion Conference, October 8–12, 2017, Atlanta, GA.
- J. Rojas-Herrera and P.C. Lozano, "Mitigation of anomalous expansion of carbon xerogels and controllability of mean-pore-size by changes in mold geometry", Journal of Non-Crystalline Solids 458 (2017) 22-27

This report presents a summary of the tasks carried out during the period of performance of this research:

# Ionic liquid selection (Y1):

There are several FHIL's that could have been explored in this research. In particular, the room temperature melts shown in the table below were identified as potential propellants. All are based on different proportions of the HF<sup>-</sup> and F<sup>-</sup> anions and their synthesis and most of their properties have been described in the literature.

FHIL ionic liquid	pos ion	neg ion	Name	K (Si/m)	Density (g/cm <sup>3</sup> )	Viscosity (mPa s)	Т <sub>т</sub> (С)	T <sub>d</sub> (C)
MEPyrro-(HF) <sub>2.3</sub> F	C <sub>7</sub> NH <sub>16</sub>	F <sub>3</sub> H <sub>2</sub> ; F <sub>4</sub> H <sub>3</sub>	1-methyl-1-ethylpyrrolidinium fluorohydrogenate	7.46	1.07	9.9	(G) < -128	
MEPip-(HF) <sub>2.3</sub> F	C <sub>8</sub> NH <sub>18</sub>	F <sub>3</sub> H <sub>2</sub> ; F <sub>4</sub> H <sub>3</sub>	1-allylpyrrolidinium fluorohydrogenate	3.72	1.07	24.2	-36	
AMI-(HF) <sub>2.3</sub> F	$C_7N_2H_{11}$	F <sub>3</sub> H <sub>2</sub> ; F <sub>4</sub> H <sub>3</sub>	1-allyl-3-methylimidazolium fluorohydrogenate	9.0	1.11	5.5	(G) < -130	
S222-(HF) <sub>2.0</sub> F	$SC_6H_{15}$	$F_3H_2$	triethylsulfonium fluorohydrogenate	8.3	1.09	8.3	-56	420
S122-(HF) <sub>2.0</sub> F	SC <sub>7</sub> H <sub>17</sub>	$F_3H_2$	diethylmethylsulfonium fluorohydrogenate	9.1	1.11	8.9	(G) < -143	431
S112-(HF) <sub>2.0</sub> F	$SC_4H_{11}$	$F_3H_2$	ethyldimethylsulfonium fluorohydrogenate	11.1	1.14	8.2	-46	437
S111-(HF) <sub>1.9</sub> F	SC <sub>3</sub> H <sub>9</sub>	F <sub>2</sub> H; F <sub>3</sub> H <sub>2</sub>	trimethylsulfonium fluorohydrogenate	13.1	1.18	7.8	-31	447
EMI-(HF) <sub>2.3</sub> F	$C_6N_2H_{11}$	F <sub>3</sub> H <sub>2</sub> ; F <sub>4</sub> H <sub>3</sub>	1-ethyl-3-methylimidazolium fluorohydrogenate	10	1.13	4.9	-65	

According to most recent models [1], the magnitude of the ionic current I that can be field evaporated from ionic liquid electrosprays depends linearly on the electrical conductivity K through,

$$I\approx \frac{32\pi K\gamma^2}{\epsilon_0^2 E^{*3}}\frac{\epsilon}{(\epsilon-1)^2}$$

where  $\epsilon_0$  is the permittivity of vacuum, and  $\gamma$  and  $\epsilon$  are the liquid surface tension and dielectric constant, respectively.  $E^*$  is the critical field for emission that depends on the free energy of solvation of the emitted species in the ionic liquid. It can be seen that increases in electrical conductivity could increase the current, and therefore thrust, of electrospray thrusters. For instance, existing high-conductivity salts used in electrosprays (e.g., EMI-BF4, EMI-Im) have  $K \sim 1$  Si/m. According to this argument, it would be expected that increases in thrust could be achieved by simply changing the ionic liquid to one of the options above anywhere from ~3 to 13 times. Existing designs of electrospray thrusters make user of multiple emitter tips distributed in twodimensional arrays. Decreasing the spacing of tips in an array increases their number density and therefore thrust. To obtain an increase of ~10 times over state-of-the-art would need a decrease in tip spacing of about  $\sqrt{10}$ ~3 times. A goal of this research is to demonstrate that switching to a FHIL propellant would improve the SOA without the re-design of an existing array.

The synthesis procedure of all these liquids includes the use of concentrated HF solutions. The hazards related to HF make it imperative that the laboratory complies with all operational safety procedures and regulations. Fortunately, two of the most promising liquids, EMI-(HF)<sub>2.3</sub>F and S111-(HF)<sub>1.9</sub>F were provided by Prof. Rika Hagiwara's laboratory in Japan [2] to begin tests through our ongoing collaboration. These ionic liquids are not commercially available.

#### Material compatibility (Y1):

While the active precursor chemical for FHIL propellants is concentrated HF, the substitution reactions effectively remove most of the activity in the ionic melt. This fact has been verified by a number of studies [2]. However, EMI-(HF)2.3F will still etch silicates, albeit at significantly lower rates than very diluted HF solutions. The SOA in electrospray thrusters are machined in glass [3], and it has been found that glass tips quickly erode by these liquids, preventing them from firing with FHIL's. It is important to find new materials that are compatible with the acidic nature of these substances. Fortunately, one of the applications envisioned for these liquids are in the design of ultra-capacitors, in which electrodes are made of porous carbon materials [4]. A process has been developed during this period of performance to obtain stable monolithic carbon xerogel materials with controllable pore size in the "goldilocks" range centered at about 500 nm [5]. Such dimensions have been quite elusive to control, but are required to provide the hydraulic impedance to achieve the pure ionic regime in electrospray devices.

#### Single emitter testing (Y1):

The fundamental elements of an electrospray thruster include an adequate reservoir capable to operate in a passive way and deliver propellant to an emitter material, terminating in a sharp structure with radius of curvature of about ~10 um. The electric potential is applied to a distal electrode [6] located upstream of the emitter, but physically separated, such that electrochemical reactions, if any, are forced to take place at the electrode, and not the emitter. All these elements require compatibility with the FHIL propellant. To validate the research approach, a single tungsten emitter was preliminary characterized. The current vs voltage characteristics are shown in the plot below (left). As can be seen, the operation showed that more than a tenfold increase in current is possible compared to the state-of-the-art liquid EMI-BF. In addition, a retarding potential analyzer curve (right) shows that emission is favored towards higher energies and little fragmentation is displayed.

Despite these encouraging results, it is clear that emission is quite unstable. At the time, it was thought this behavior was due to the poor permeability of externally wetted tungsten emitters. Our team decided then to focus on the xerogel material described above, as it would enable a much more effective transport, while still providing enough hydraulic impedance to operate in the pure ionic mode.



**Design and preliminary fabrication of carbon en** To synthesize carbon xerogel substrates, a resorcir square molds. Next, the molds are heated in an ove the temperature of the oven is raised from 40°C to removed from the molds and exposed to pyrolysis and shaped to 1x1x0.1 cm pieces (c) as shown in th



More information can be found in [5], but these pieces needed additional annealing to prevent hysteresis in their thermal expansion characteristics, so they can be used in our application. Next, the finished parts are taken to a nano-second, solid state laser, and a pattern of lines is run to create microscopic tips. The image below shows an example of the results when using this laser process to shape a tip array.

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This emitter substrate contains 480 emitters tips. The next step involves mounting this substrate on a test-setup for firing. This includes adding FHIL on the back and verifying transport to the emitter surface and attachment (and isolation) of a matching extractor plate. Full emission characterization with the experimental suite described below was performed during the second year of this effort.

## Design, construction and testing of instrumentation for beam characterization (Y2):

A new set of characterization tools were built for this project. The characterization involves testing single emitters and thrusters. The current and voltage from these devices is measured directly from signals in the power supply, while a Retarding Potential Analyzer (RPA) and a Time of Flight spectrometer (TOF) are used to determine the energy distributions and the beam composition, respectively.



### Initial characterization of carbon emitter arrays (Y2):

Microfabricated electrospray thrusters were prepared according to procedures described elsewhere [3]. Carbon substrates were synthesized using the process developed in this research (Y1) and were integrated with silicon frames for tip processing. Arrays of emitters where then produced using laser microfabrication and the devices were mounted on an experimental jig for testing in a vacuum chamber at pressures below ~5 microTorr (shown below). These results are described in more depth in [9].



Similar to the results obtained with the tungsten single emitter, carbon thrusters exhibited significant unstable behavior. For instance, the plot below shows the voltage and current (emitted and intercepted by the extractor) produced by the thruster in a short window of time, in which voltage alternation can be clearly observed. Voltage alternation is applied to prevent electrochemical reactions from damaging the electrodes or emitter tips [6].



Two things are clear in this experiment. First, intercepted currents are quite high, which is both a symptom of unstable operation and device misalignment. Second, current signals are quite noisy. Nevertheless, levels of emitted current reached about 1 mA, which is much higher than the 100-300 uA currents observed when using SOA ionic liquids. Given the instability of the current, it

was difficult to obtain repeatable current vs voltage characteristics. An example of an attempt to perform this characterization is shown below.



It is quite clear that emission is unstable, both in the positive and negative emission mode, although the instability tended to be more pronounced in the positive polarity. Despite these instabilities, it was possible to obtain some TOF measurements. These are shown in the next figure. The beam composition fluctuated in a very significant way in time and also with respect to operational conditions. Some signals were nearly pure ionic, while other showed a significant contribution of droplets.



Both the single emitter and array results indicated that FHILs indeed can be used to produce high emission current over SOA propellants and that such emission could be ionic. However, they also showed that under practically all conditions, emission was quite unstable making the use of FHILs impractical in the proposed configuration. More research was then required to determine the root cause for such instability, leading to the research activities carried out during Y2.

#### Vacuum decomposition of FHILs (Y2):

During a standard test with a carbon emitter, it was observed that severe current fluctuations prevented stable operation when using neat FHILs. This was described in the previous section. However, for this particular test the emitter was left inside the vacuum chamber for a period of two days, after which it was clearly observed that a white, powder-like substance appeared and surrounded the whole emitter. It was also noticed that emission would not be possible in that state. Once venting the vacuum chamber to atmospheric conditions, the white substance would "melt", producing once again a liquid on the emitter. This observation suggested that a transformation might be occurring to the FHIL when exposed to vacuum.



A number of experiments were performed, in which a controlled amount of FHIL was deposited on a Teflon surface, followed by exposure to high vacuum (< 1 microTorr) [7]. An example is shown in the image above. The frames show the state of the FHIL as exposed to vacuum for a period of three hours. In can clearly be seen that just after initial pumping, the FHIL will behave as a normal ionic liquid (leftmost frame), but after some time an apparent crystallization is evident, first by showing signs of discrete solid regions in the liquid, until complete solidification occurs (rightmost frame). Similar to the emitter experiment mentioned above, these solid materials would become liquids when exposed to atmospheric conditions after chamber venting. Such a clear transformation indicates that these ionic liquids are not stable under hard vacuum conditions. Initially, it was hypothesized that the solidification was due to liquid freezing as water was released from the liquids (as many other ionic liquids, FHILs are hygroscopic to some extent), thus cooling down the substances below their melting points. However, this explanation was not plausible, since the melting points of EMI-(HF)<sub>2.3</sub>F and S111-(HF)<sub>1.9</sub>F are -65C and -31C, respectively. Additionally, the temperature in vacuum was controlled to values of about 40C without changes to the solid material.

While most ionic liquids have practically zero vapor pressure, it would seem that FHILs have a finite value. This is not described in the literature. In fact, works related to these substances indicate that the last step in their synthesis involves exposure to vacuum to remove solvents used in the process. However, it is also described that these liquids would decompose under vacuum *and* high temperature according to the reactions [10]:

 $\begin{array}{rcl} \mathsf{EMI-(HF)}_{2.3}\mathsf{F} & \rightarrow & \mathsf{EMI-(HF)F} + & 1.3\mathsf{HF}\uparrow\\ \mathsf{S111-(HF)}_{1.9}\mathsf{F} & \rightarrow & \mathsf{S111-(HF)F} + & 0.9\mathsf{HF}\uparrow \end{array}$ 

The resulting substances EMI-(HF)F and S111-(HF)F are then created through the release of HF molecules. These substances are solid at room temperature (EMI-(HF)F has a melting point of about 50C) and are also extraordinarily hygroscopic.

According to this information, our observations at high vacuum suggest then that HF molecules must be evaporating to produce the salts EMI-(HF)F and S111-(HF)F. These are solid at room temperature, but become liquid when exposed to the environment as they readily absorb moisture from air. This argument is supported by the fact that mass loss corresponding to the stoichiometric proportions removed by HF evaporation from the original molecules was measured in experiments described in [7,8] and matches expectations.

Given these results, it is clear that neat FHILs cannot be used in our application, unless the liquids are sealed from vacuum before injecting into the emitters. However, the decomposition products

deed stable salts that could potentially be used in electrospray thrusters.

# g FHILs decomposition products as propellant additives (Y2):



are two ways in which FHILs could still be used in electrospray propulsion applications. the neat ionic liquids could be allowed to decompose, thermally or under vacuum, to produce MI-(HF)F and S111-(HF)F substances. Then, operation could be achieved by increasing the erature of the thruster elements to at least their melting points (~50C). The plot below [10] s the electrical conductivity of EMI-(HF)<sub>2.3</sub>F and EMI-(HF)F as a function of temperature.

Before vac After vac



It can be observed that the to the conductivity of E substances should be compotential of non-heated in liquid containing the EM stable at room temperature low hygroscopicity and le popular, but highly hygro



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	Relative co	Propellant		
Mixtures	Defere Veeuum	After Veenum	Conductivity	
	Belore vacuum	After vacuum	(Si/m)	
EMI-CF <sub>3</sub> BF <sub>3</sub>	1	1	1.5	
10% EMI-F(HF)	1.8	1.2	1.8	
25% EMI-F(HF)	3.7	2.6	3.9	
50% EMI-F(HF)	5.5	3.8	5.7	
10% S111-F(HF)	1.8	1.2	1.8	
25% S111-F(HF)	2.3	1.6	2.4	
50% S111-F(HF)	3.4	2.3	3.45	

The table above summarizes the results when mixing EMI-CF<sub>3</sub>BF<sub>3</sub> with EMI-(HF)<sub>2.3</sub>F and S111-(HF)1.9F at different FHIL concentration. We opted for this approach as opposed to first decompose thermally the FHIL and then mixing the solid salt with the conventional IL. The reason is that our laboratory is not ready to create HF vapors in the chemical synthesis hood, and therefore we opted for the vacuum decomposition approach discovered in this research. Still, care needed to be taken to vent the chamber exhaust through an adequate ventilation system capable of supporting the production of HF vapors. The table shows the relative conductivity of the different mixtures with respect to the baseline ionic liquid EMI-CF<sub>3</sub>BF<sub>3</sub>, and the corresponding conductivities of the final propellant mixtures. These data were obtained by measuring the resistance of a column of liquid contained in a capillary. The experiments are described in the detail in [7]. The first observation is that mixtures with lower than about 50% of FHIL in the baseline ionic liquid will remain as liquids after the HF molecules are removed from the salt. Higher concentrations will produce the formation of fragmented crystals upon exposure to high vacuum. While the conductivity of the propellant mixture increases with concentration (as expected), we focus on concentrations of 25% for further experimentation, to reduce the risk of crystal formation after long vacuum exposures and since the final conductivities are as high or higher than any other conventional ionic liquid described in the literature.

### Single carbon emitter results (Y2):

Before characterizing the emission of the new propellant mixtures on thruster arrays, we investigated the behavior of the resulting propellants at different concentrations on single emitters. Single emitters tests are the core of electrospray propulsion, since they provide the most fundamental characterization of the emission process. Unlike the set of single emitters tests performed during Y1 of this research, carbon emitters were prepared to ensure a platform compatible with FHIL ionic liquids. The carbon material was synthesized following the RF approach described in this report, except the shapes from the molded xerogel was cylindrical and a platinum wire was embedded in the RF solution to provide the electrical connection. RF cylinders were pyrolized and the resulting carbon was finally sharpened by precise turning on a machining

lathe. The carbon tips were mounted on a Teflon reservoir, where the liquids would be injected prior to setup assembly (note that these liquids have been already exposed to hard vacuum to create the propellant mixture). The emitter is then mounted on a 3D stage, so that a stainless steel aperture could be aligned with the tip apex. More information about this setup can be found in [7]. An image of the single emitter experiment is shown below.



Since the radius of curvature (about 20-30 microns) and the extractor aperture diameter (about 1.5 mm) of the carbon tip are relatively large, the startup voltages for emission resulted to be on the order of 2 kV, which is somewhat higher than usual. However, it was quickly observed that the behavior of the emission was as stable as that obtained for other ionic liquids. This suggests that the approach to first mix FHILs with a baseline liquid and then removing HF produces a stable compound that has negligible vapor pressure. The plot below shows examples of current vs voltage curves for the baseline liquid and several mixtures with the S111-(HF)<sub>1.9</sub>F FHIL.



This plot indicates that the current will increase with concentration, up to a point. The 50% concentration liquid actually showed a current behavior similar to that of the 10% concentration liquid, suggesting that under prolonged vacuum conditions, the 50% cases might be too close to begin the process of crystallization. Because of this, we selected the 25% concentration liquid as propellant for most thruster tests (next section), since this concentration resulted in stable currents even at long vacuum exposures. From the plot, we can also see that this particular concentration results in currents significantly higher than the baseline liquid alone. Normally, the baseline liquid (as other SOA highly conductive ionic liquids) will produce currents on the order of 100-300 nA in single emitters. We can see that the 25% concentration liquid yielded currents 4000 and 6000 nA in the negative and positive polarity, respectively. This reflects a significant increase in current emission capability.

Time-of-flight (TOF) mass spectrometer experiments were performed with liquids at different concentrations to determine the beam composition [7]. A sample of these measurements is shown in the figure below for mixtures with the EMI-(HF)<sub>2.3</sub>F FHIL.



TOF curves are shown at different emitted currents. The most salient feature of these measurements is the fact that only monomer and dimers ions, with a small population of larger clusters, are observed in the beam. There are no droplets, meaning that these liquid mixtures operate in the pure ionic regime.

The population of dimers is quite unique, since it has a bimodal distribution of species, which is consistent with the fact that both substances in the mixture share the same positive monomer species (EMI+), but have two different dimers (EMI-EMI-CF3BF3+ and EMI-EMI-(HF)F+). This means that operation occurs with relatively low polydispersity, thus leading to high efficiency, since no droplets are present in the beam.

Pure ionic operation will then result in high specific impulse, since the (square of the) velocity of these ions is inversely proportional to the (relatively small) ion mass and proportional to the applied potential, which in this case is quite substantial (up to  $\sim 2kV$ ).

As a reference, the specific impulse of the baseline liquid and of some mixtures is shown in the plot below, as a function of accelerating voltage. While these estimates are not backed up by thrust and mass flow measurements, previous work [3] has demonstrated that the combination of TOF and RPA techniques provides a relatively accurate determination of the propulsive properties of electrospray thrusters. As can be seen in the plot, specific impulse as high as 6000 s could be potentially obtained with such mixtures.



## Single carbon emitter array results (Y2):

Carbon thruster arrays, similar to the one shown in the figure below were then tested [8] with the mixtures developed in [7].



The thruster package was fabricated in silicon using standard photolithographic techniques [3]. The package consists of a silicon frame layer on which a carbon xerogel substrate was bonded using epoxy. The second layer is made out of pyrex glass, providing electrical isolation with the third silicon layer, which contains a collection of 480 extractor apertures. The carbon material is patterned using a nano-second solid state laser to form 480 sharp tips that match the alignment of the extractor apertures. The thruster is then mounted on a platform made of peek plastic, which is

compatible with vacuum. A small reservoir is included on this platform, in which the liquid is injected. A small wick made from cellulose is used to transport the liquid from the reservoir to the back of the carbon substrate. A carbon electrode with a platinum wire is immersed in the liquid to provide the electrical connection. The thruster is then placed inside a vacuum chamber and tested for current vs voltage, retarding potential analysis and time of flight spectrometry. More details about these experiments can be found in [8].

Just as with single emitters, thruster arrays tested with mixtures with FHILs and the same baseline ionic liquid EMI-CF<sub>3</sub>BF<sub>3</sub> displayed outstanding stability. Also, the currents obtained from these devices using these mixtures were significantly higher than usual. For instance, the figure below shows and example of a current vs voltage measurement using the 25% FHIL concentration. The operational band of EMI-BF<sub>4</sub> is also shown for comparison.



Typical retarding potential analyzer curves for positive (left) and negative (right) operational modes are shown in the plot below.



The shape of these er the emission potentia downward variations, the internal energy ga fragmentation events a pure ion emission. To these mixtures. An ex

Towards a constrained of the second s

oenergetic population close to this). Distributions also show igmentations that occur due to n process. It is clear that these he energy distributions suggest measurements were done with

800

600

400

200

400

-600

Current [µA]

IV Curve

Intercepte

space propu

nassachusette



More examples of TOF measurements like the one above are described in [8] Practically all cases showed pure ionic emission, with monomers and din spectra. This is consistent with previous observations using single emitters.

## Conclusion

The use of FHIL in electrospray propulsion has the potential to increase the p of thrust density and specific impulse due to the high conductivity displayed b However, it was uncovered in this research that fluorohydrogenated room tem] are not stable under high vacuum exposure. Under these conditions, these su by ejecting HF molecules until stable salts are obtained. These salts are solid and therefore pose a challenge to the standard implementation of propell thrusters. An implementation path was developed here in which conventional ionic liquids were mixed with FHILs at different concentrations. These mixtures displayed increased conductivity, albeit not as high as the neat FHIL liquids. However, the current extracted from single emitters

and arrays of emitters was indeed higher than the current from the baseline liquid used in the mixtures. This suggests that while FHILs cannot be used directly as propellants, they are excellent additives that improve the performance of these propulsion devices. TOF spectrometry confirmed that emission is purely ionic in all cases, therefore opening an avenue for high specific impulse operation at high efficiency.

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