The Emissive Membrane Ion Thruster Concept

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Abstract: Experiments conducted on solid-state ionic membranes that convert atoms into ions that can in turn be extracted into energetic beamlets and thereby produce thrust are described. The capability of ionizing and transporting ions is shown to be both rapid (over 10 mA/cm^2) and efficient (of order 1 eV/ion). Although similar in appearance to cesium contact sources, solid-state ionic membrane devices are shown to operate successfully at lower temperatures (400 to 700 °C) thus making them much more efficient than cesium-based devices. The process of extracting the ions by field emission is shown to limit the extracted ion current density. The need to select an emissive surface material/propellant ion combination with a low work function is suggested. Based on successful demonstrations of ion extraction, the Emissive Membrane Ion Thruster is proposed and shown to offer the potential for substantial reductions in ion thruster system cost and complexity as well as improvements in scalability and reliability compared to existing ion thruster designs

Nomenclature

a & C	=	constants
J	=	current
V	=	voltage
V_T	=	total accelerating voltage

I. Introduction

THE use of electron bombardment ion thrusters in space, which began in the United States with the launch of Space Electric Rocket Test I (SERT I) in 1964,[1] has progressed to the point where over a hundred are now operating on geosynchronous communication satellites. In addition, the highly successful Deep Space 1 mission[2] has shown the usefulness and adaptability of such thrusters on ambitious high total impulse missions in hostile space

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environments. There is a tendency under such circumstances to seek only marginal thruster improvements through modest design refinements. It is, however, worthwhile to examine recent technological advances to determine if they enable dramatically different designs with markedly improved capabilities for space missions of current interest.

An evolving technology that holds great potential for ion thruster applications is that associated with solid-state ionic conductors.[3] Applications of this technology in everyday life are growing rapidly as a very wide range of new devices evolves. Presently solid-state ionic conductors are the key elements in the ubiquitous oxygen sensors used in automobile exhaust systems, in lithium ion batteries, in solid oxide fuel cells, in electrochromic windows and in some superconductors. They are a potentially attractive element for ion thrusters because they enable the production and delivery of ions to sites where they can be extracted into a beam without the complications of a plasma discharge chamber and all of its essential components.

This paper presents the results of preliminary experiments designed to investigate the feasibility of using a thin membrane ionic conductor as the element that ionizes neutral propellant molecules and enables their extraction into a collimated, energetic ion beam.

II. Basic Physical Model

Although amorphous ionic conductors exist, the typical building block of the membranes used in this study is a crystal like the one shown in Fig. 1. As the figure suggests, it contains propellant anions and cations that are bonded to them. The gray lines in Fig. 1 represent chemical bonds. In order to induce a high ionic conductivity, defects are created in the crystal structure by introducing dopants or deviations from stoichiometry. Grain size, membrane density and purity of starting materials are also important. In an application many crystals like the one in Fig. 1 would be coupled together to form the extensive structure through which ions could be conducted at reasonable current density levels from a region where they were produced to one where they would be extracted into beamlets. The overall sequence of events associated with ion membrane operation is shown in Fig. 2. Beginning at the left an ion is extracted from the anions available near the downstream surface at an anode layer. As ions continue to be extracted new ones that diffuse through the ionic conductor by jumping from one vacancy site to the next replenish the anion pool. These anions are drawn ultimately from a reservoir of propellant molecules adjacent to the cathode layer shown on the right in Fig. 2. The cathode layer, which is porous and in close contact with both the propellant and the ionic conductor, and is itself a good electrical conductor, plays a very important role. It is connected to an external current source and it thereby serves to transfer charge to propellant atoms as they pass through the layer to adjacent vacancies inside the membrane. In so doing atoms become anions and begin the process of transmission through the ionic conductor. Although the particular structure shown in Figs. 1 and 2 pertain to the flow of anions, which are negative, the process works equally well

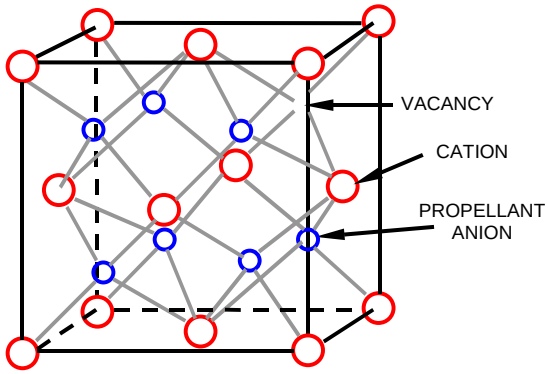


Fig. 1 Typical Binary Ionic Compound Structure

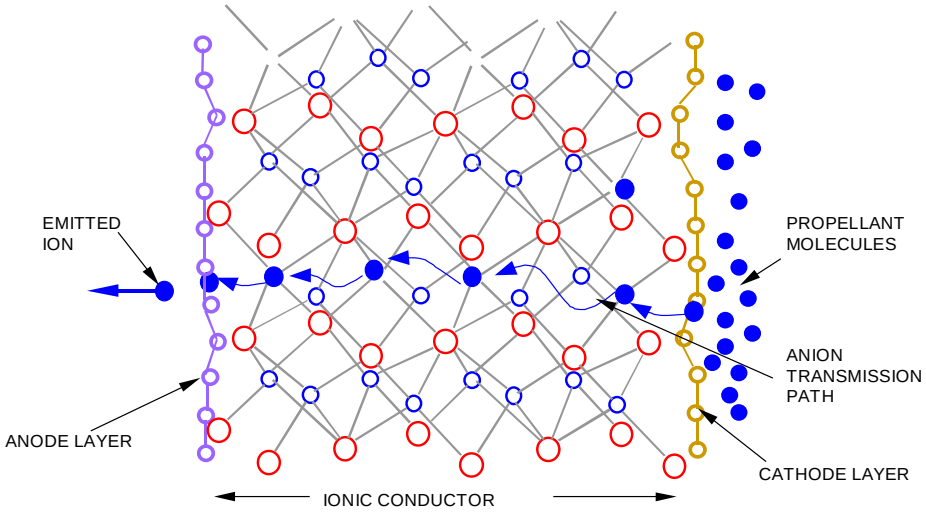


Fig. 2 Membrane Process Diagram for Anion Transmission

for positively charged cation transmission. In this latter case the anode layer would be on the right and the cathode layer on the left where electrons would be removed from the atoms to form the ions. Otherwise the process would be essentially the same. An ion thruster specialist might envision the downstream surface of the membrane as the replacement for the screen hole plasma sheath and the membrane itself as the replacement for the entire discharge chamber plasma.

The diffusion process through the ionic conductor is facilitated by greater temperatures and by electrical potential and anion or cation density gradients. If instead of extracting the ions from the left hand boundary using a strong electric field, electrons were removed from negative anions at the anode, they would again become atoms and would flow as neutral molecules directly into the vacuum environment downstream of the anode layer shown in Fig.2.

III. Apparatus and Procedures

In order to determine if solid state ionic conductors would be suitable for ion thruster applications a series of tests designed to identify promising features as well as potential problems associated with the technology were conducted. In order to do this work it was necessary to select a working fluid and its associated membrane. Solid state materials have been fabricated to conduct a number of elements, including silver, mercury, oxygen, hydrogen, lithium, lead and bismuth. Materials proprietary to Ceramatec, Inc. and suitable for use with oxygen were selected because they were available at reasonable cost and could be fabricated into a shape suitable for proof-of-concept testing in a reasonable time. The ceramic membranes fabricated and tested were typically flat discs ~ 1 mm thick and 0.64 cm in diameter. This active element was mounted in a 2-cm diameter inert ceramic disc of similar thickness, which was then bonded to a stainless steel tube and cup assembly in the manner suggested in Fig. 3. The membrane assembly was placed in a cryopumped vacuum chamber maintained in the high 10^{-7} Torr range during testing. The tube via a feed-through, in which it was mounted, supported this assembly. As Fig 3 suggests, a thermocouple (chromel-alumel) was placed through the tube so it was in good radiative communication with the membrane and could be used to sense its temperature. A swaged heater wrapped around the cup was used to heat the assembly and maintain its temperature. The oxygen, which flowed from left to right through the membrane during operation (Fig. 3), was also supplied through the tube and its pressure was measured using a baratron gauge. Preliminary tests suggested the magnitude of this pressure did not affect operation significantly but 10 Torr seemed reasonable, so this pressure was used throughout the study. The chamber and lines that supplied the oxygen were evacuated and refilled prior to each test to assure gas impurities did not accumulate next to the membrane. The residual gas analyzer shown in Fig. 3 was sufficiently sensitive to measure the partial pressures of oxygen ions that flowed through the membrane during the tests. These partial pressures were converted to oxygen flow rates using a correlation plot generated by feeding oxygen directly into the vacuum chamber and making simultaneous measurements of oxygen flow rate in the mAeq range and oxygen partial pressure.

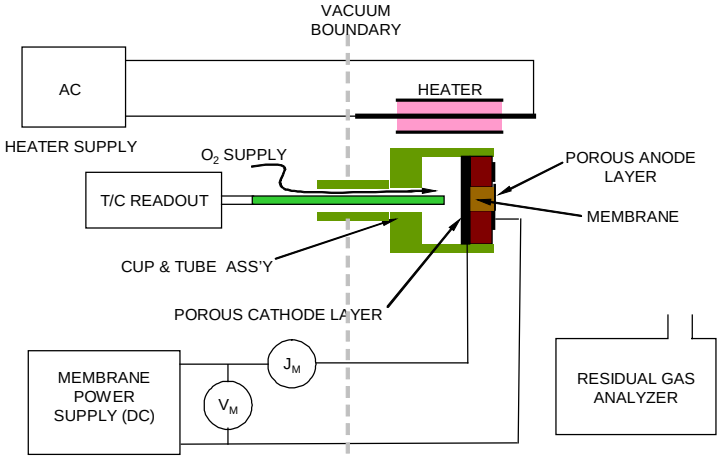


Fig. 3 Membrane Flow and Current Measurement Schematic

The membrane power supply shown in Fig. 3 was used to apply low voltages across the membrane via conducting layers on the cathode (upstream—10-Torr) and anode (downstream –high vacuum) sides. This arrangement was used only during the first set of tests in which the ionization and current carrying capabilities of the membranes themselves were measured. After these tests were completed, the membrane power supply was removed and a downsstream ion extraction (accel) electrode was installed along with high voltage power supplies used to apply bias voltages to the cathode and accel electrodes relative to ground. The second series of tests was designed to investigate the collective effects of ion production, ion transmission through the membrane, and ion extraction/acceleration from its downstream surface. The arrangement of the equipment used in these tests is shown

schematically in Fig. 4. Also shown is a mass spectrometer that was used to determine the relative currents of ions and electrons that were being extracted. This instrument, which was fabricated specifically for these tests, utilized a 20 Gauss magnetic field applied normal to the ion beamlet axis. At a nominal net accelerating voltage of 500 V this magnetic field yielded electron and ion cyclotron radii of 5-cm and 6-m for electrons and ions, respectively. The currents of these two streams of charged particles could then be measured to determine their relative contributions to the beam current.

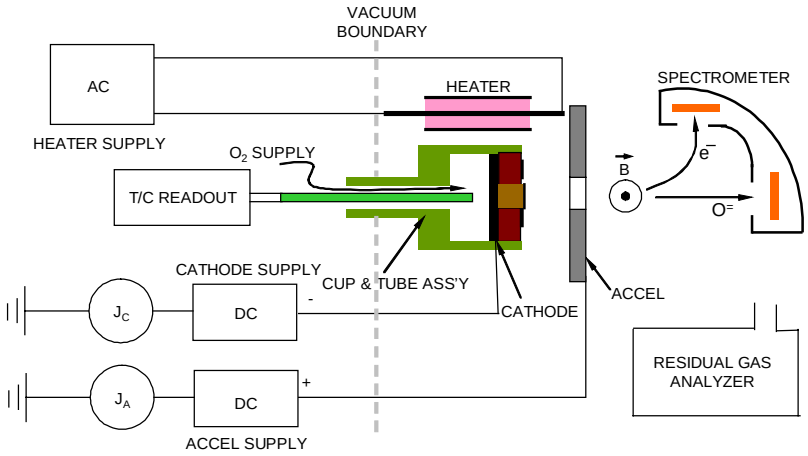


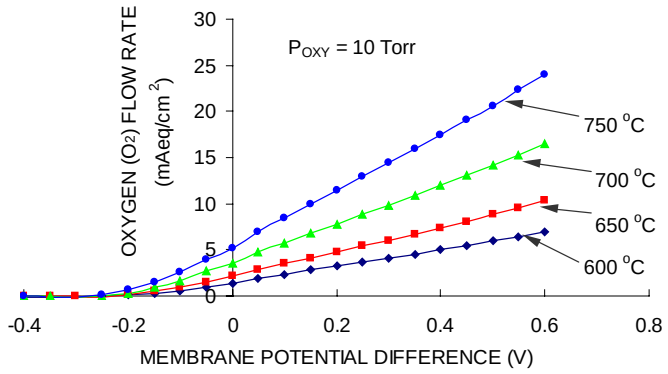
Fig. 4 Schematic of Apparatus for Ion Extraction Testing

Because the cost of developing the concave membranes required for focused beamlets would have been substantial, it was decided that preliminary tests would be conducted using flat ones. As a result essentially all of the ions emitted from the membrane struck the accel electrode. The small fraction of these ions that passed through the 4.8-mm diameter hole in the accel electrode were typically only a few percent of the emission current (J_C in Fig. 4).

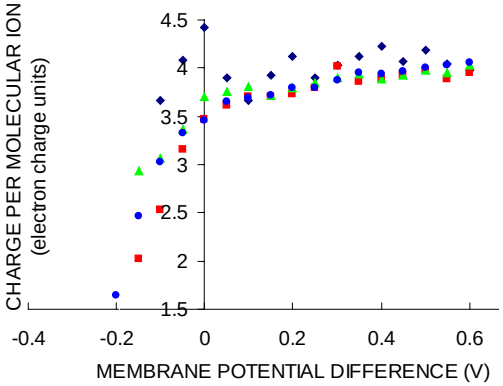
For most of the tests conducted to measure the ion emission current capabilities of membrane assemblies the cathode and accel power supply voltages were set at –500 V and 2000 V, respectively. The membrane temperature was increased from ambient temperatures to 600 °C at a rate of 5 °C/min and data were recorded using Labview. During the first of these tests both cathode emission (J_C) and accel collection (J_A) currents were measured using high accuracy electrometers. After several tests, however, it was determined, that these two currents always agreed within a few percent and it was decided to measure only the cathode emission current along with membrane temperature, oxygen supply pressure and in some cases the ion and electron spectrometer currents.

IV. Experimental Results

Initial tests were conducted using the test configuration shown in Fig. 3 to measure the oxygen flow and ion current that could be drawn through the membrane as functions of the voltage applied across it and its temperature. Typical data obtained from these tests are shown in Figs. 5a and b. Figure 5a shows the oxygen flow rate determined from ion current measurements plotted against the anode-to-cathode potential difference applied across



a) Oxygen Flow



b) Charge per Molecular Ion

Fig. 5 Membrane Performance without High Voltage Ion Extraction

the membrane with membrane temperature as a parameter. These data indicate the following:

1. The ion current increases as the anode is biased more positive relative to the cathode. Hence the oxygen ions formed at the cathode are negatively charged.
2. Oxygen ions form and flow even when the voltage applied across the membrane is zero or slightly negative. Hence the modest pressure difference applied across the membrane (10 Torr) is sufficient to induce substantial anion formation and diffusion.
3. The rate of oxygen ionization (i.e. electron attachment) at the cathode and flow through the membrane can be significantly greater than that associated with conventional electron bombardment thrusters (several mA/cm^2) when modest voltages and reasonable temperature are applied. Hence ionic membranes are capable of producing and transporting ions at higher ion current densities than conventional ion thrusters.

The companion data in Fig. 5b are also important. The vertical axis values in this plot were obtained by dividing the measured ion current flow through the membrane by the molecular oxygen flow determined from corresponding oxygen partial pressure measurements. Each data point in Fig. 5b corresponds to a data point of the same color in Fig. 5a. Disregarding the data at potential differences below zero and recognizing that molecules migrate in their smallest (monatomic) state, this plot suggests that each anion that forms at the cathode receive two electrons. Hence the model of the process that evolves for oxygen is that diatomic oxygen dissociates and each O receives two electrons as it passes from the cathode layer onto the membrane matrix. It migrates as $O^{=}$ until it reaches the downstream side of the matrix, where it gives up its electrons to the anode. Two atomic oxygen atoms are then able to recombine and flow into the vacuum chamber. Ion migration through the matrix is sustained by a combination of the applied electric field and the cathode-to-anode ion concentration gradient. In this experiment all electrons removed from the ions at the anode flow back to the membrane power supply via the circuit shown in Fig. 3. It is noted that the ion charge per molecular (4 electron charge units) was used to convert ion current flow through the membrane into molecular oxygen flow rate.

In order to evaluate the overall performance capability of the membrane (i.e. ionization, membrane transmission, and emission/ acceleration) the membrane power supply shown in Fig. 3 was removed and high voltage power supplies in the configuration of Fig. 4 were installed. With cathode biased to –500 V and the accel electrode biased at 2 kV and positioned 1 mm downstream of the membrane a 2.5 kV/mm electric field was established at the membrane and negative oxygen ions were extracted into a beamlet. Figure 6 shows how the measured current varied as the membrane temperature was increased from ambient temperatures to 600 °C at a rate of about 5 °C/min. It shows currents, which were generally near 10 nA at low temperatures, began to rise near 300 °C and reached a maximum over 0.1 mA as 600 °C was approached. Since the active membrane area was 0.32 cm^2 this current corresponds to a current density near 0.3 mA/cm^2. This is about an order of magnitude below current densities achieved with ion thrusters where extraction occurs from a plasma. Considering the preliminary nature of this work and the fact that no steps were taken to enable good emission from the downstream membrane surface, , however, this result is considered to be a very promising one. It is also noteworthy that other researchers have reported extracted oxygen ion

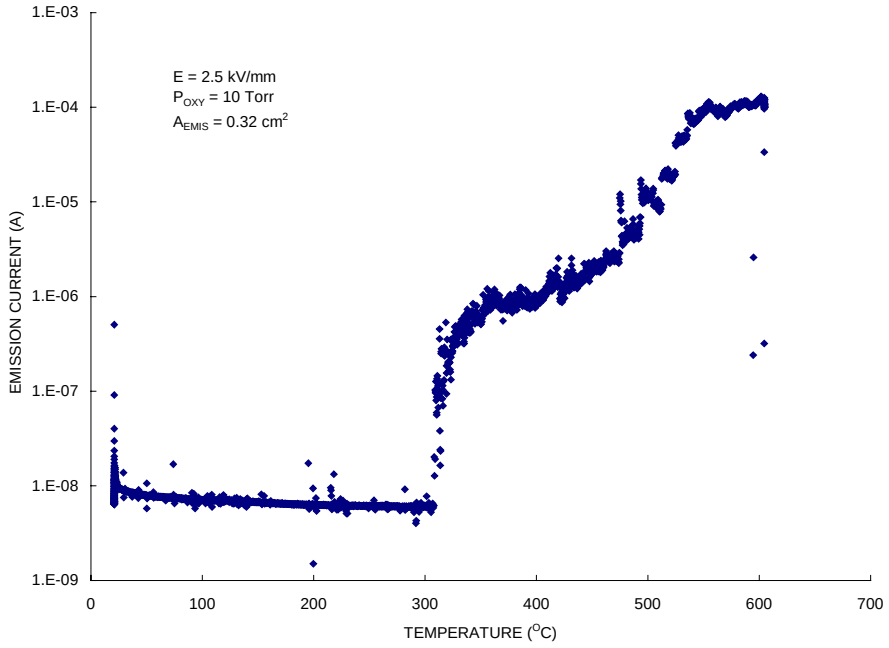
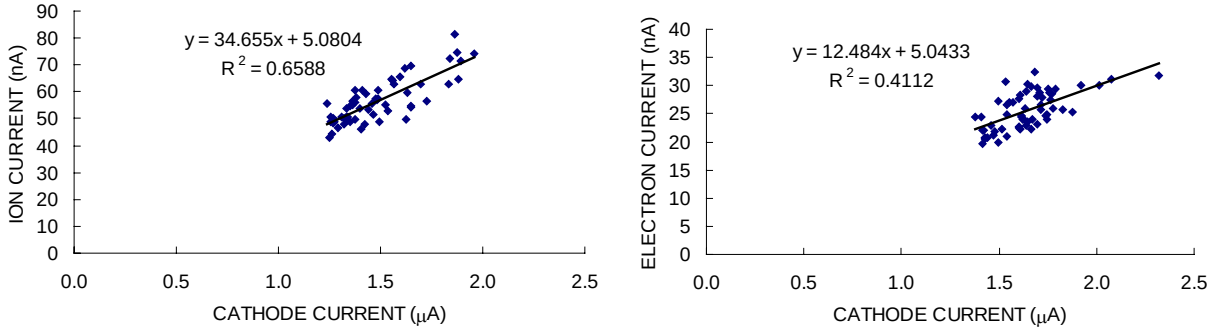


Fig. 6 Emitting Membrane Performance

currents from ceramic membranes, but the current densities they have achieved are orders of magnitude lower than the maximum values cited in Fig. 6[4, 5].

It is possible that both negative oxygen ions and electrons are being extracted from the membrane and that the data of Fig. 6 do not represent a pure ion current. The electron content of the beam was investigated by making mass spectroscopic measurements to determine the relative magnitudes of the electron and ion currents. Typical data are shown in Figs. 7a and 7b, for the ion and electron currents, respectively. It is argued that these currents are in the nanoamp range while cathode (emission) currents are in the microamp range because of the small fraction of



a) Ion Measurement b) Electron Meassurement

Fig. 7 Typical Corresponding Mass Spectrometer Data

the emission from the flat membrane that passes through the hole in the accel electrode. These figures also show substantial data scatter that is a reflection of an emission process noisiness that is also evident in Fig. 6. The data of Fig. 7 suggest an electron-to-ion current ratio (α) near 0.4. For the two reactions that can be expected to yield electrons [$O^{=} \rightarrow O + 2\,e^{-}$ and $O^{=} \rightarrow O^{-} + e^{-}$] one finds the ratio of the actual ion current to its maximum (zero electron emission) value is given by $1/(1+\alpha)$ so in the case of the data of Fig. 7 this ratio is about 70%. There is uncertainty in these data, however, and values of α are probably no more accurate than ± 50%. Still it is argued on the basis of results like those of Fig. 7 that emission currents shown in Fig. 6 are due primarily to ions. It is further noted that while electron emission is problematic with oxygen ions it would not be for the positive propellant ions that are preferred for an actual thruster application.

The question of why small voltages applied across the membrane yield order of magnitude greater currents (Fig. 5) than one observes when high voltages are imposed between the cathode and the accel electrode (Fig. 6) deserves further consideration. It could be that the membrane is a sufficiently good conductor that the full voltage drop develops between the downstream face of the membrane and the accel electrode and there is no voltage drop through the membrane. This possibility was investigated by measuring the voltage difference across the membrane when the high voltages were applied and ion emission was occurring. Voltage differences were found to be generally similar to those given in Fig. 5a. Hence it was concluded that it is the emission process occurring on the downstream membrane face that limits the beamlet current.

The mechanism of emission was investigated by varying the high voltage applied to the cathode while holding the accel grid at 2 kV and measuring the associated ion emission current. The most likely emission process for this situation can be expected to be field emission described by the Fowler-Nordheim equation[6] with the functional form $J = C\,V_T^2\,\exp\left[-a/V_T\right]$. When the cathode current v. total voltage data were plotted in the rearranged linear form of this equation, the results given in Fig. 8 were obtained. The high

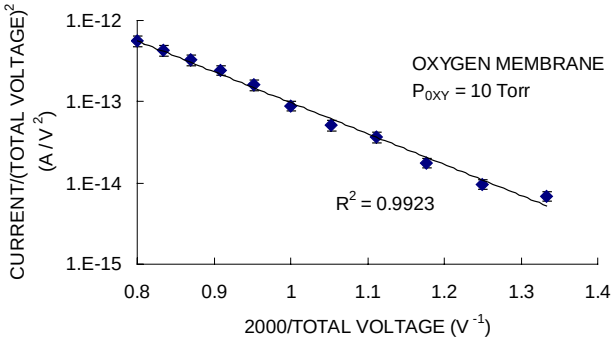


Fig. 8 Fowler-Nordheim Plot for Oxygen Membrane

degree of linearity of the data in this plot suggests that field emission is the likely mechanism of ion extraction from the surface. This in turn suggests that the ion current density from the device could be improved by reducing the work function for ion emission through an appropriate treatment of the membrane surface.

Other observations from tests like those that yielded the data of Fig. 6 are that a membrane that had been heated to 600 °C and operated tends to exhibit low temperature ion emission currents near 1 μA rather than 10 nA. This apparent conditioning effect could be beneficial in an actual thruster application. On the other hand, operation for periods of hours at 600 °C resulted in a temporal degradation of the ion emission current that could be as great as an order of magnitude per hour. Operation at greater total accelerating voltages induced greater currents than those indicated in Fig. 6, but they also tended to degrade the membrane emission capabilities rapidly. These degradations are probably related to changes in the emissive surface texture and/or chemistry. They suggest the need for a more durable emissive surface.

V. Emissive Membrane Ion Thruster Conceptualization

The essential features of a module that might be incorporated into an array constituting an Emissive Membrane Ion Thruster (EMIT) are shown in Fig. 9. Its appearance is very similar to that of the cesium contact ion thrusters developed in the early 1960's.[7] Propellant supplied to the upstream side of the membrane would be ionized and transmitted to the downstream side where emission would occur. The membrane surface could be designed and shaped[8] to achieve a desired effect (e.g. maximum beamlet current or minimum beamlet divergence). Because the ionization and transmission processes are surface-defined the density of ions on the emission surface can be made uniform on this and all other modules of an array. This feature enables a very wide range of scalability on the levels of both the individual modules and the array to achieve desired thrust levels and specific impulses.

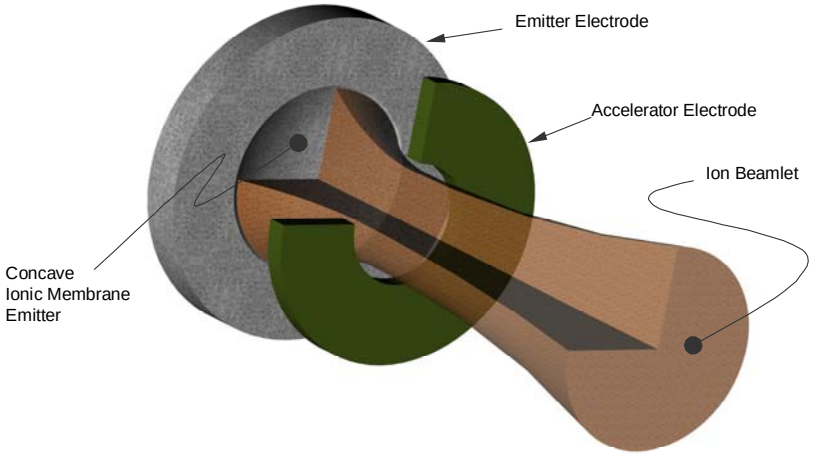


Fig. 9 The Emissive Membrane Ion Thruster Concept

As mentioned previously, good ionic conduction has been observed with many elements (e.g. silver and bismuth) from which a preferred propellant could be selected. Essentially all of those elements but oxygen produce positive ions and this desirable feature plus a preference for a heavy ion leads one away from oxygen for most thruster applications. It is noted that the propellant can be in a gas, a liquid or even a solid. In the latter case a liquid is used to transport solid particles and because the membrane is selective, only the solid particle atoms would be ionized and transported through it. In this regard it is noted that potential contaminants like the transport liquid and extraneous molecules generally do not affect the performance of ionic conductors unless they accumulate to the point where they block access to the membrane by the active element atoms.

The data of Fig. 5 show that ions can be produced at a very low energy cost per ion. One can expect that the energy cost of propellants other than oxygen would be similar to the value suggested by these data ($O^{=}$ ionization and transmission costs would be less than twice the maximum membrane potential difference --i.e. 1.2 eV/ion).

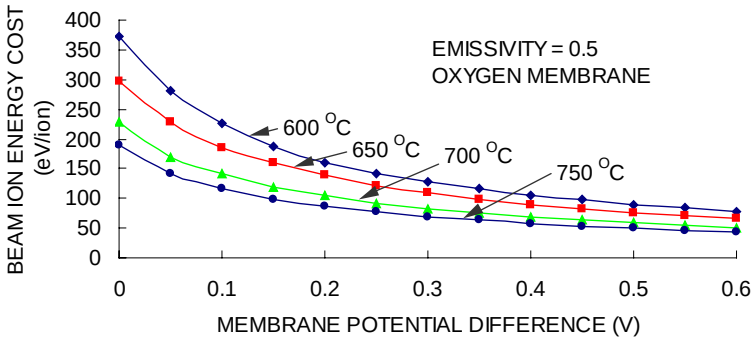


Fig. 10 Beam Ion Energy Cost Estimate Considering Radiation Losses

To this one would add the work function (a few eV) required for emission and the energy per ion radiated from each hot emitter surface. The operating temperature required for a cesium contact thruster was between 1100 and 1200 °C and as a result it had high thermal radiation losses[7] and this led to its demise. The operating temperatures suggested by the data of Figs. 5a and 6 are substantially lower and they will yield much lower radiated powers per unit area. When divided by a corresponding ion current density they will yield lower radiative-loss contributions to the beam ion energy costs. If one assumes Fig. 5 current densities and a membrane radiative emissivity of 0.5 could be realized, the beam ion energy costs plotted in Fig. 10 are obtained. It is noteworthy that energy cost drops as temperature increases over the indicated range because current density increases more rapidly with temperature than radiated power per unit area does. The beam ion energy costs in Fig. 10 are comparable to and less than those for state-of-the-art electron bombardment thrusters and this implies energy efficiencies of the EMIT could also be comparable to and greater than those for conventional thrusters.

Propellant utilization efficiency is probably even more important than energy efficiency because it affects specific impulse, charge-exchange ion production (hence thruster lifetime) and overall thruster efficiency. Typical values for electron bombardment thrusters are near 90%. For the cesium contact thruster they were closer to 98% and for the EMIT they should be even greater than this. Assuming positive ions would be used, no electron emission should occur. This coupled with the fact that neutral atoms would not be conducted through these membranes suggests that propellant utilization efficiencies approaching 100% can be expected.

A. Comparison with State-of-the-art Ion Thrusters

Comparison of key features of EMIT with those of a bombardment thruster like those of the Xenon Ion Propulsion System (XIPS) class suggests that EMIT would enable the following:

1. The discharge chamber including magnets and a hollow cathode would be eliminated along with its power supply.
2. Grid shorting concerns would be greatly mitigated because there would be no metal flakes generated from films of sputter-eroded material. In addition, because each module has the same efficiency and current, there is no need to use large diameter grid sets that can deflect and distort significantly.
3. The potential for substantially greater propellant and power efficiencies.
4. The potential for operation at higher current densities and therefore higher thrust densities over a wider range of specific impulses enabled by the flexibility to shape the membrane emissive surface[8] and also because neutral propellant losses should be negligible.
5. Much of the propellant feed system including flow regulators, valves and other hardware could be eliminated because the tests reported herein have shown it is necessary only to maintain a modest pressure on each membrane to effect its individual operation. The membranes automatically draw the propellant atoms they need as they are consumed.
6. Laminated Object Manufacturing (LOM) techniques with their potential for great cost savings can be used to fabricate lightweight EMIT arrays with modules of various sizes containing integrated flow passages and, if desired, conducting ceramic accel electrodes.

The system consequences of using EMIT as suggested by the above list are substantial. They include 1) lower system cost, mass, and complexity; 2) greater system reliability and failure tolerance; and 3) higher thrust-to-power capabilities especially at low specific impulses. These system features, which are greatly enhanced by scalability from multi-meter to nanometer dimensions without efficiency degradation, also means that the emissive membrane ion thruster technology is particularly well suited to micro thruster applications.

VI. Conclusion

Solid-state ionic conductors formed into membranes have properties that enable them to ionize propellant atoms at an upstream surface and transport them to a downstream one where they can be extracted by an electric field and formed into an ion beamlet. The processes of ionization and transport through the membrane are very efficient and yield current densities that are greater than those achieved in conventional electron bombardment ion thrusters. The field emission process limits the current density of ions that can actually be extracted from ionic conductor surfaces that have not been treated to effect a low work function for the emission of ions. There are many features of the Emissive Membrane Ion Thruster that make it an attractive competitor to conventional ion thruster technology.

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