MiXI Thruster Tungsten and Thoriated Tungsten Testing

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The purpose of this project is to build and evaluate a tungsten filament cathode for the 3-cm Miniature Xenon Ion (MiXI) thruster. The filament is to be used for future tests within the CP 3-cm MiXI and thoriated tungsten is to be examined as a possible alternative. No testing of these filaments was conducted, but the preparatory work has been conducted for future testing.

Nomenclature

A — Emission Constant (75 A/(cm^2*K^2))
Boltz — Boltzmann constant (8.62*10^{-5} ev/K)
C — Number of Coils
CA — Cross sectional area (cm^2)
D — Diameter (cm)
EEP — Electron Emission Power (W)
I — Current (Amps)
J — Emission Density (A/cm^2)
L — Length (cm)
Lang — Emissivity fit curve from Langmuir probe
R — Resistance (ohm)
RL — resistivity (ohm-cm)
RP — Radiated Power (W)
SA — Surface area (cm^2)
SB — Stefan – Boltmann Constant (5.67*10^{-8} W/(m^2*K^4))
T — Temperature (K)
TEC — Total Emission Current (A)
TIP — Total Input Power (W)
V — Voltage (V)
WF — Work Function (eV)

I.   Introduction

The 3-cm Miniature Xenon Ion thruster is a low-noise, low-contamination thruster that is currently being developed by Dr. Richard Wirz at UCLA. The Wirz Research Group, at the UCLA Advanced Propulsion Laboratory, is currently undergoing work on this thruster, and California Polytechnic University - San Luis Obispo is collaborating. This thruster is being designed to fulfill a technology gap between conventional Hall and Ion thrusters, that output more than 2 mN of thrust, and micro-thrusters that output less than .01 mN of thrust.

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This thruster is ideally suited for continuous, low-disturbance, solar torque compensation missions, precision repeat path or orbit control missions, and most importantly precision formation flying missions. Table 1 includes a lot of the expected characteristics of the MiXI thruster.

Thruster Technology	Ion
Thrust Range	.1-1.5 mN
Primary Thrust Control	Amplitude Modulated (PWM)
ISP	2,500-3,500 sec
Plume Divergence Half-Angle	5-15 deg.
Propellant	Xenon
Contamination Potential	Low
Technology Readiness Level	4

Table 1: Characteristics of the MiXI thruster.

Two original prototypes were made, MiXI I and MiXI II, however MiXI II had a serious issue with the thermal conditions. MiXI II ran too hot, so it could not run for any long period of time because it would cause other, more serious problems, most important of which being permanent magnet degaussing. Magnet degaussing means the magnets, which are a vital part of the thruster, would lose their magnetic strength. Once they have lost their strength, it is likely they will not produce a magnetic field strong enough to confine the electrons.

Coleman Younger, a master's student at Cal Poly in Aerospace Engineering, was tasked to build another model of the MiXI thruster and attempt to model and solve the thermal issues. Among other things, the thruster needed a cathode to be used in testing, and ultimately choosing a new cathode for the thruster would help reduce the thermal problems. This necessity led to an examination for the merits of a thoriated tungsten filament cathode over a more traditional pure tungsten filament. That examination is presented in the paper to follow.

Figure 1: MiXI thruster from UCLA[1]

II. Apparatus and Procedure

A. Lab Set up

This experiment was to be run in the vacuum chamber in the Thermodynamics Lab in the Aerospace Engineering Department at Cal Poly – San Luis Obispo. The MiXI thruster needs four or five power supplies, depending on if you are running a neutralizer cathode. Refer to Fig. 2 for a diagram of the wiring and power supplies. The power supply used to power the cathode is called the discharge cathode heater supply. The discharge cathode heater power supply must be able to supply around 5 amps and 15 volts, so we chose to use the HP 6263B DC power supply, which provides 0-20 volts and 0-10 amps.

In order to produce a greater potential difference, the heater power supply needs to be electrically isolated from the power rack, or 'floated.' To float the heater power supply, acrylic boxes was made that the heater can fit inside and move freely. This acrylic box was made by cutting the appropriate size pieces to fit, then using acrylic adhesive to fuse the pieces together. Also, a front plate made of acrylic was mounted on the power supply using nylon screws and nylon spacers. Nylon screws and spacers were used so a user can change the settings of the power supply without touching the metal face and risking electrocution.
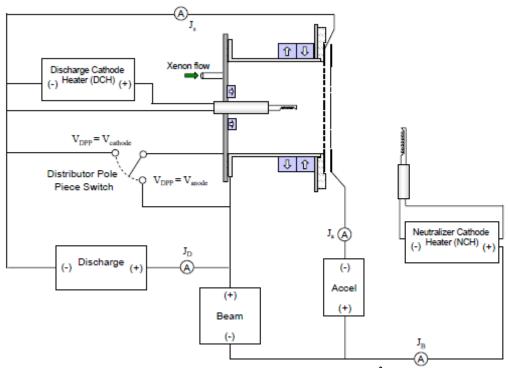

Figure 2: Wiring Diagram of MiXI Thruster[2]

B. Making the Filament

Due to the small size of the thruster, the coiled tungsten filament cathode must be designed in a hairpin configuration as in Fig. 3. Using a spreadsheet designed by Dan Goebel, it can be determined that this wire is 10.5 coils at a .1 inch diameter for the loop. Dan's spreadsheet takes the length and the diameter of the wire as inputs, and using the equations found in the analysis section its main outputs are emission density and the heater power supply voltage and amperage. Since the leads from the power supply cannot be hooked up directly inside of the thruster, and 5 mil wire cannot carry current any significant distance, the current has to be transferred to the 5 mil hairpin through 10 mil tungsten wires. The 10 mil tungsten wires form loops and the 5 mil coil attaches to it.

Figure 3: Cathode Hairpin Configuration

The 10 mil wires feed from the coiled filament through a piece of double bore alumina that is attached to the back of the thruster. The double bore alumina gives the 10 mil wire something firm and electrically isolating to feed through. Once the wires come out the back, they are covered in heat shrink to electrically isolate them until they reach the power supply leads.

Making the tungsten cathodes is rather easy. The tungsten wire is wrapped tightly around the correct diameter rod and then the wire is pulled slightly apart to separate the coils. The top and bottom coils are bent into hooks to attach onto the 10 mil leads.

C. Testing Procedure

To run these tests, the cathode is mounted inside of the double bore alumina. The bottom of the thruster is mounted to a Plexiglas stand that is inside of the vacuum chamber, and the 10 mil tungsten electrical leads are run out of the bottom of the thruster and through the stand. Alligator clips from the power supply are then connected to the electrical leads, but it is important that the supply is externally grounded. Place thermocouples at desired locations on the thruster, so temperatures of these strategic locations can be recorded during the test.

The chamber is then brought down to vacuum, which usually takes around three and a half hours. First the chamber must be roughed to the crossover pressure, which is about 1 torr in our lab. Roughing the chamber means using a mechanical pump to bring the chamber under as much vacuum as possible. Next, activate the roughing interlock and rough the cryopump down to 50 millitorr. Then activate the compressor, which automatically begins turning the cold head on the cryopump. Allow the cold head to run until it reaches a second stage temperature of 17-20 K. Then turn off the roughing line and activate the pressure interlock, then open the gate valve. Observe the convectron gauge until it reaches a zero reading. Once the zero reading is achieved, turn on the ion gauge and ensure the pressure is in the 10^{-4} torr range or lower. Continue to run the cryo pump until the chamber reaches cathode testing pressure between 2×10^{-5} and 5×10^{-5} torr. Now the chamber is ready to begin testing.

Now that the chamber is under vacuum, turn the power supplies on and set the voltage and current to the desired setting from the spreadsheet. Once the filament heats up to the desired temperature it should start emitting electrons. Observe the current and voltage on the supply, and once you are at the correct emission current, run the cathode for thirty minutes to an hour. Ensure that the temperatures are being recorded throughout the experiment. Determine the actual breaking point of the filament, it is expected to be 2.41 amps, but it theoretically will not break until 3 amps. If the filament breaks, the chamber must be brought back to atmospheric pressure, the filament replaced, and then pumped all the way back to the desired pressure again.

III. Analysis

The tungsten wire needs to be coiled, both for emission and to properly fit inside of the thruster. The size of the wire can be calculated using:

$$\pi * D * C = L \tag{1}$$

Where D is the diameter, C is the number of coils, and L is the overall length. This allows us to cut the correct length of wire to make the cathode.

In order to get the internal resistance of the filament, the resistivity, RL, needs to be calculated.

$$RL = (2.6 * 10^{-8}) * T + (1.87 * 10^{-12}) * T^2 \tag{2}$$

Where T is the temperature.

Then the resistance is given by:

$$R = RL*L/CA \tag{3}$$

Where R is the resistance, and CA is the cross sectional area of the wire.

The emission density, J, can now be calculated, which is one of the main performance metrics of the filament. The emission density will determine if the filament is producing enough electrons or not.

$$J = A*T^2*e^{-WF/(Boltz*T)} \tag{4}$$

Where WF is the work function and Boltz is the Boltzmann constant.

Then we need the information to find voltage and current that needs to be supplied to the filament. First, the total emission current, TEC, should be calculated by:

$$TEC = SA*J \tag{5}$$

Where SA is the surface area of the filament

Then the electron emission power, EEP, of the filament is calculated by:

$$EEP = TEC * WF \tag{6}$$

Where WF is the work function, which is a constant of 4.55 eV.

Next, the radiated power can now be found using:

$$RP = SA*SB*Lang*T^4*SA/10,000 \tag{7}$$

Where SB is the Stefan-Boltzmann constant and Lang is the emissivity fit curve calculated from the Langmuir probe.

And then the total input power is calculated by:

$$TIP=EEP + RP \tag{8}$$

Where EEP is the electron emission power and RP is the radiated power.

This will now yield all of the information needed to find the current that needs to be run through the wire to produce whatever emission density we need.

$$I = (TIP / R)^{1/2} \tag{9}$$

And the voltage that the heater supply needs to be run at can be found with the voltage equation:

$$V= I*R \tag{10}$$

IV. Results and Discussion

A. Tungsten Filament

Coiled tungsten filaments are the cheapest and easiest cathodes to produce for this thruster. Unfortunately, it also runs the hottest of all the possible cathode candidates. However, tungsten filaments were still chosen to use for testing within Coleman Younger's MiXI thruster for worst-case thermal analysis purposes.

The tungsten filament needs to produce an emission density of .5-1.5 amps/cm^2 to get the proper electron emission; however, the tungsten filament has a max amperage that it can withstand before the filament burns out and becomes useless. The tungsten has a theoretical max of 3-4 amps, however Dr. Wirz observed a 2.41 amp breaking point in his testing[2]. Because of this current limit, these tungsten filaments have a maximum operating temperature of 2650 K.

To determine the length and diameter the tungsten filament needs to be, a spreadsheet written by Dr. Wirz was used. This spreadsheet allows you to change the size until you get the right outputs within the range you need. The filament needs to have an outer diameter of .005 inches, or 5 mil. The next largest size that can be purchased is 10 mil, and that wire requires an excessive amount of power to emit electrons, enough that would probably endanger the magnets and cause excessively high temperatures. However, this 10 mil wire will be good for something else that will be discussed later. A diameter of .005 inches, a length of 3.3 inches, 8.37 cm, turns out to be a great, workable point. The results of which can be seen in Table 2.

T(C)	T(K)	- J - Emission Density (A/cm^2)	Total emission current (A)	Electron emission power (W)	Resistance (ohms)	Current (A)	Voltage (V)	Heater Power (W)
2250	2523	0.39	0.13	0.59	5.13	2.20	11.28	24.84
2350	2623	0.94	0.31	1.42	5.36	2.38	12.79	30.50
2450	2723	2.11	0.71	3.21	5.60	2.60	14.55	37.78

Table 2: Tungsten filament cathode characteristics for 3.3 inch long .005 inch diameter.

The results we get from the testing we expect would closely match what we estimated in this table. Even though the thruster made by Mr. Younger has a larger cathode flange, the only difference we expect to see is some excessive heating at the wall.

B. Thoriated Tungsten

Two percent thoriated tungsten is an ideal replacement for a tungsten filament during the testing phase. Thoriated tungsten is tungsten that is impregnated with thorium in order to get higher electron emissions at lower temperatures. It has a much lower max temperature of 1900K, versus tungsten's max temperature of 2650K. Thoriated tungsten has a smaller max electron emission than standard tungsten, but it is still sufficient for this application.

In order for thoriated tungsten to operate properly, the thorium needs to be activated first. The thorium is initially impregnated in the middle of the wire, but if the wire is heated quickly to 2900K, then ran at 2050K for thirty minutes, most of the thorium will move to the surface. With the thorium at the surface, the wire can be run at a lower temperature than tungsten and still yield desired electron emissions. Not much is known about activating thoriated tungsten, especially for the scenarios this thruster is likely to encounter. It is not known whether heating the wire up to 2900K will cause adverse thermal effects to the thruster or burn out the thorium. These questions and more suggestions for future work are addressed in the conclusion.

However, thoriated tungsten will not be the ideal end product for this thruster, because filament cathodes still have their drawbacks. They have much higher max temperatures than hollow cathodes, and they have reliability and lifetime issues. They cannot support the higher emission currents at lower temperatures that are needed. A hollow cathode can get about 280 mA of discharge current with a max temperature of 1675 C[1].

Thoriated tungsten is still a much better candidate than tungsten during validation and testing because of the thermal issues associated with tungsten, and because of the price and availability of hollow cathodes. The thruster should not overheat as much it did with tungsten when basic tests are trying to be run. Hollow cathodes are likely a better end candidate for this project, but they are much more expensive and a lot less available than thoriated tungsten. At this moment, only one company, AP Tech, is known to make an appropriate hollow cathode. As this

project gets nearer to completion, hollow cathodes will still have to be tested and verified, but at this stage in the MiXI thruster's development, thoriated tungsten is possibly most cost effective and time saving solution.

V. Conclusion

The preparation for testing the tungsten filament has been done, however the testing needs to be completed once working facilities available. Testing was planned to have been completed with this project but the facilities were not in working order. A number of test filaments have been made and are ready for testing for future students to continue work on, using this paper as a guide.

Thoriated tungsten still has some questions that need to be answered to find out if it is a useful candidate for a cathode. When activating the thorium, it is unknown if the high heat will cause issues with the rest of the thruster, especially the magnets. One possible work around to this problem would be to activate the thorium, and then install the rest of the thruster around it after it has been activated. This raises another issue, once the thorium has been activated and you stop the experiment, at what point will the thorium have to be reactivated. If the thorium has to be reactivated after a certain amount of hours of being cool, then it might not be a feasible candidate for use in the MiXI thruster, especially if it causes issues with the magnets whenever it is activated.

References

1   Wirz, R., Goebel, D., Marrese, C., Mueller, J., "Development of Cathode Technologies for a Miniature Ion Thruster," *AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, AIAA, Washington, DC, 2003, pp. 1-12

2   Wirz, Richard E. "Discharge Plasma Processes Of Ring-Cusp Ion Thrusters." Diss. California Institute of Technology, 2005. Pg 45.

Appendix

Tungsten Filament Electron Emitter

S-B const	5.67E-08	W/(m^2*K^4)
Boltz	8.62E-05	eV/K
electron charge	1.60E-19	J/eV
OD	**0.0127**	cm
length	**8.3786276**	cm
Surface area	0.3343	cm^2
Cross sectional area	0.0001	cm^2
A(const)	75.00	A/(cm^2*K^2)
Work function	4.55	eV

T(C)	T(K)	Emissivity fit from Langmuir	Radiated power density (W/cm^2)	Radiated Power (W)	J(A/cm^2)	Total emission current (A)
1050	1323	0.162	2.81	0.94	**0.000**	**0.0000**
1150	1423	0.179	4.16	1.39	**0.000**	**0.0000**
1250	1523	0.195	5.96	1.99	**0.000**	**0.0000**
1350	1623	0.211	8.29	2.77	**0.000**	**0.0000**
1450	1723	0.225	11.26	3.76	**0.000**	**0.0000**
1550	1823	0.239	14.98	5.01	**0.000**	**0.0000**
1650	1923	0.252	19.56	6.54	**0.000**	**0.0001**
1750	2023	0.265	25.12	8.40	**0.001**	**0.0005**
1850	2123	0.276	31.81	10.63	**0.005**	**0.0018**
1950	2223	0.287	39.75	13.29	**0.018**	**0.0060**
2050	2323	0.297	49.08	16.41	**0.055**	**0.0182**
2150	2423	0.307	59.96	20.05	**0.152**	**0.0507**

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2250	2523	0.316	72.54	24.25	**0.390**	**0.1303**
2350	2623	0.324	86.97	29.07	**0.936**	**0.3128**
2450	2723	0.332	103.42	34.57	**2.112**	**0.71**
2550	2823	0.339	122.04	40.80	**4.511**	**1.51**
2650	2923	0.345	143.00	47.80	**9.169**	**3.07**
2750	3023	0.352	166.46	55.65	**17.825**	**5.96**
2850	3123	0.357	192.60	64.39	**33.277**	**11.12**
2950	3223	0.362	221.58	74.07	**59.885**	**20.02**
3050	3323	0.367	253.57	84.77	**104.217**	**34.84**
3150	3423	0.371	288.74	96.52	**175.900**	**58.80**
3250	3523	0.375	327.26	109.40	**288.674**	**96.50**
3350	3623	0.378	369.29	123.45	**461.695**	**154.34**

T(C)	Electron emission power (W)	Total Input Power (W)	Resistivity (ohm-cm)	Resistance (ohms)	Current (A)	**Voltage (V)**	**Heater Power (W)**
1050	0.00	0.94	3.77E-05	2.49	0.61	**1.53**	**0.94**
1150	0.00	1.39	4.08E-05	2.70	0.72	**1.94**	**1.39**
1250	0.00	1.99	4.39E-05	2.91	0.83	**2.41**	**1.99**
1350	0.00	2.77	4.71E-05	3.12	0.94	**2.94**	**2.77**
1450	0.00	3.76	5.03E-05	3.33	1.06	**3.54**	**3.76**
1550	0.00	5.01	5.36E-05	3.55	1.19	**4.21**	**5.01**
1650	0.00	6.54	5.69E-05	3.76	1.32	**4.96**	**6.54**
1750	0.00	8.40	6.03E-05	3.99	1.45	**5.79**	**8.40**
1850	0.01	10.64	6.36E-05	4.21	1.59	**6.69**	**10.64**

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1950	0.03	13.31	6.70E-05	4.43	1.73	**7.68**	**13.31**
2050	0.08	16.49	7.05E-05	4.66	1.88	**8.77**	**16.49**
2150	0.23	20.28	7.40E-05	4.89	2.04	**9.96**	**20.28**
2250	0.59	24.84	7.75E-05	5.13	2.20	**11.28**	**24.84**
2350	1.42	30.50	8.11E-05	5.36	2.38	**12.79**	**30.50**
2450	3.21	37.78	8.47E-05	5.60	2.60	**14.55**	**37.78**
2550	6.86	47.66	8.83E-05	5.84	2.86	**16.68**	**47.66**
2650	13.95	61.75	9.20E-05	6.08	3.19	**19.38**	**61.75**
2750	27.11	82.76	9.57E-05	6.33	3.62	**22.89**	**82.76**
2850	50.62	115.00	9.94E-05	6.58	4.18	**27.50**	**115.00**
2950	91.09	165.16	1.03E-04	6.83	4.92	**33.58**	**165.16**
3050	158.52	243.28	1.07E-04	7.08	5.86	**41.50**	**243.28**
3150	267.55	364.07	1.11E-04	7.34	7.04	**51.68**	**364.07**
3250	439.08	548.48	1.15E-04	7.59	8.50	**64.54**	**548.48**
3350	702.25	825.70	1.19E-04	7.85	10.25	**80.53**	**825.70**