Electrostatics Application:

Ion Thruster

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**Project Directory**: https://GitHub.com/McCarts3/IonThruster

**I. Problem Statement**

Field-emission electric propulsion (FEEP) is an advanced electrostatic propulsion concept that is currently being used as a form of ion thruster in space travel. FEEP is based on ionization of a liquid metal, in this case Cesium, Indium, and Mercury. This type of ion thruster can use a large variety of liquid metals or alloys for propulsion, but the thruster is most efficient using high weight alkali metals such as Cesium. This is because of low ionization potential, good wetting capabilities (ability to maintain propellant flow through the emitter), and low melting points.

A strong electric field is created by applying a high voltage difference between the accelerator and emitter. This, along with other properties, causes the liquid metal to create what are known as “Taylor Cones”. When the electric field is high enough the atoms at the tip of the cone ionize and the other atoms reject the electrons. The result is an ion jet that propels the rocket.

For this project we modeled a rocket in a vacuum and simulated the rocket’s movement based on the necessary controlled variables. A rocket could not get enough force to propel it into space from electric propulsion. The rocket uses FEEP as an ion thruster to accelerate it while in space. The thrust generally produced by electric propulsion ranges in the micro to milli-Newton range. Because of this FEEP systems have been proposed for attitude control and orbit maintenance on small space crafts.

**II. Your Goals**

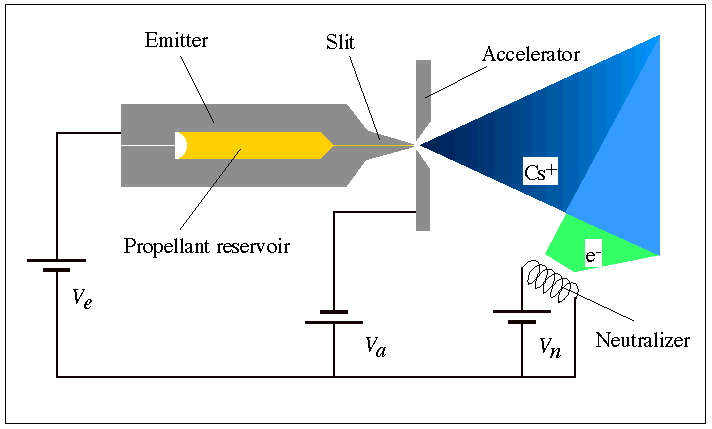
    Right now, FEEP ion thrusters are in development and much of the work being done is only feasible in a vacuum environment.  The goal of this project is to continue this work and gather theoretical data based off of different system parameters for an ion thruster.  The data we are observing includes the thrust of the FEEP related to time, the thrust related to various voltages applied to the ring, the acceleration of the rocket due to thrust, and the velocity of the rocket during the impulse time.

Though gravity and air friction would be factors in thrust, they are omitted to simplify calculations. In the model we had two separate variables that made up the total mass, first is the rocket mass without fuel is 1999.8 kg and the mass of the fuel initially is 200 g. Each liquid metal had different associated fuel loss related to the atomic mass. The acceleration of the rocket is constant up to when the fuel is completely used. The potential difference between the emitter and accelerator electrode is set to 10 kV for our model.

From various papers and websites, thrust for a FEEP thruster is ideally in the micro to milli-Newton range.  This is because FEEP is meant for finely tuned corrections to a rocket’s flight pattern in space, and not their main source of propulsion.

**III. Solution Development**

To begin our project, we first began researching the latest information and papers on FEEP ion thrusters, since most of the work being done on FEEP is in progress.  Some diagrams were helpful in giving us an idea of how this project related to the course material in electromagnetics.



**Figure 1:** Diagram of a FEEP Ion Thruster 3

From this diagram, we were able to see that the voltage Va could be changed to induce a different electric field in the ring. This is a very significant parameter that we determined we would change later in our experiment.

Next, we were able to find a research paper from the University of Michigan that included many equations related to thrust, voltage, mass of the rocket, and other variables we were interested in controlling in our simulation.

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| --- | --- |
| **Parameters** | **Realistic Values** |
| Specific impulse (seconds) | 6,000-12,000 |
| Thrust (N) | 1 µN - 1 mN |
| Common propellant | Indium/Cesium |
| Thruster mass (g) | 3-200 |
| Impulse bits (nN-sec) | 1-1,000 |
| Prop. electrical conductivity (S/m) | 100000 |

**Figure 2:** FEEP Values 1

These parameters were helpful because they gave us a number of realistic values for different variables so as to find realistic results for the other variables we wish to observe. We were able to find several equations related to FEEP thrusters that used these parameters.

The variables are defined as the following:

Equation (1)

u is the velocity of the ejected particles

m is mass of rocket

dm/dt is the change in mass over change in time

a is acceleration of rocket

Equation (2)

Delta v is the acceleration of rocket

u same as equation 1

mi initial mass of rocket

mf final mass of rocket

Equation (3)

q charge of ejected ion

V voltage applied

m mass of ion

By manipulating equations 1, 2, and 3 we came up with this equation:

Is is ion per second

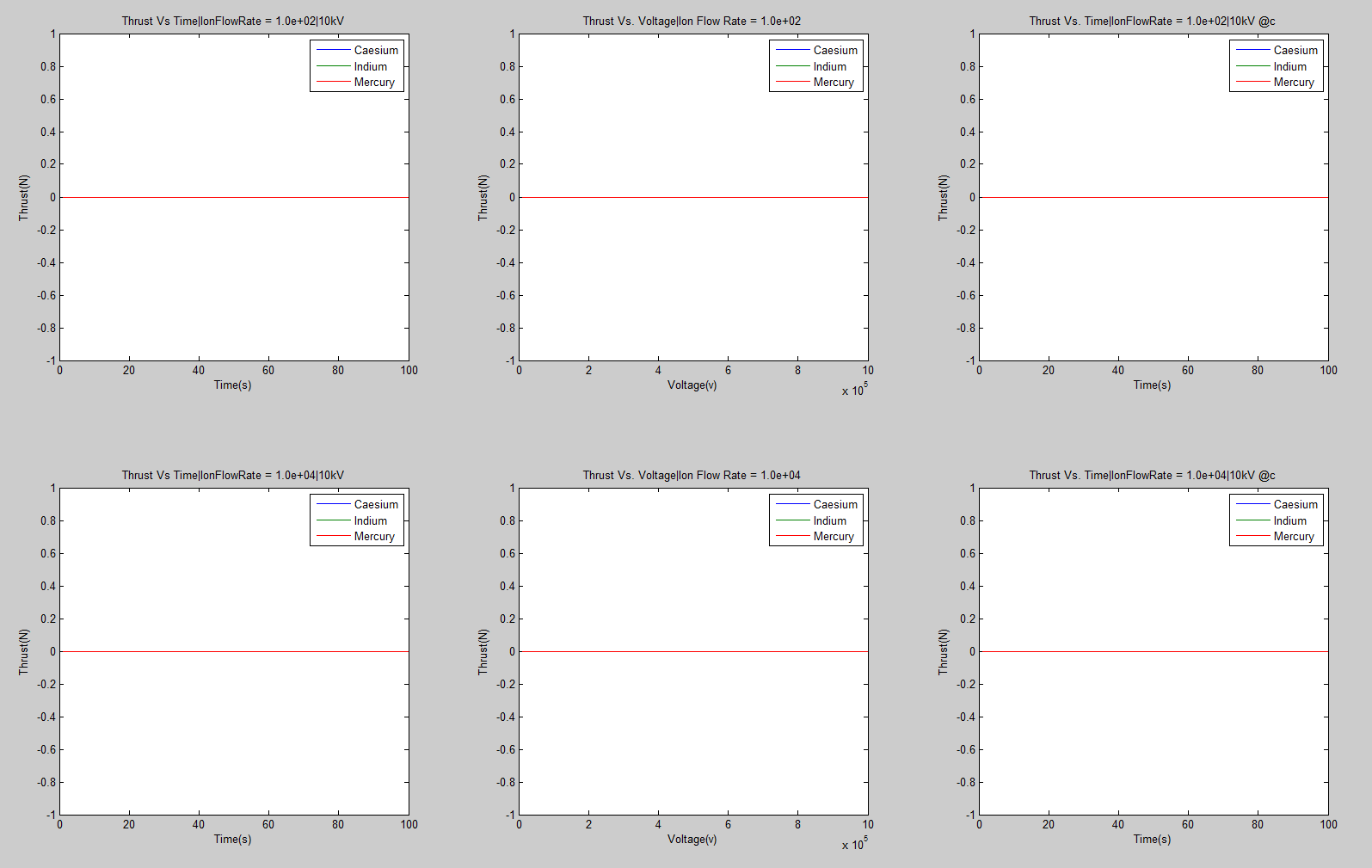
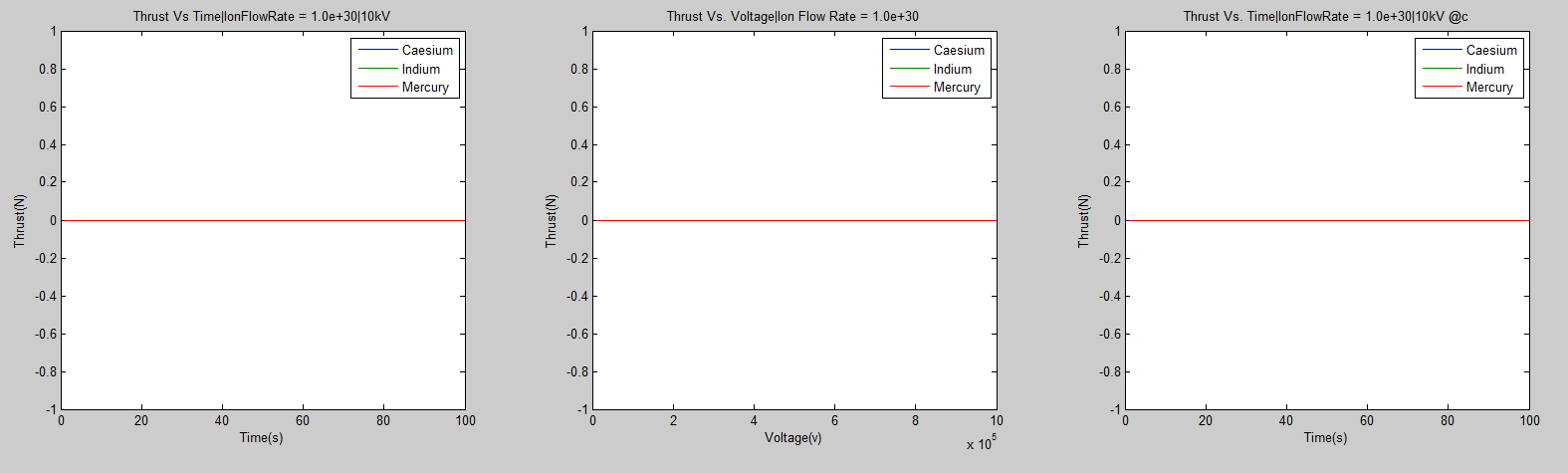
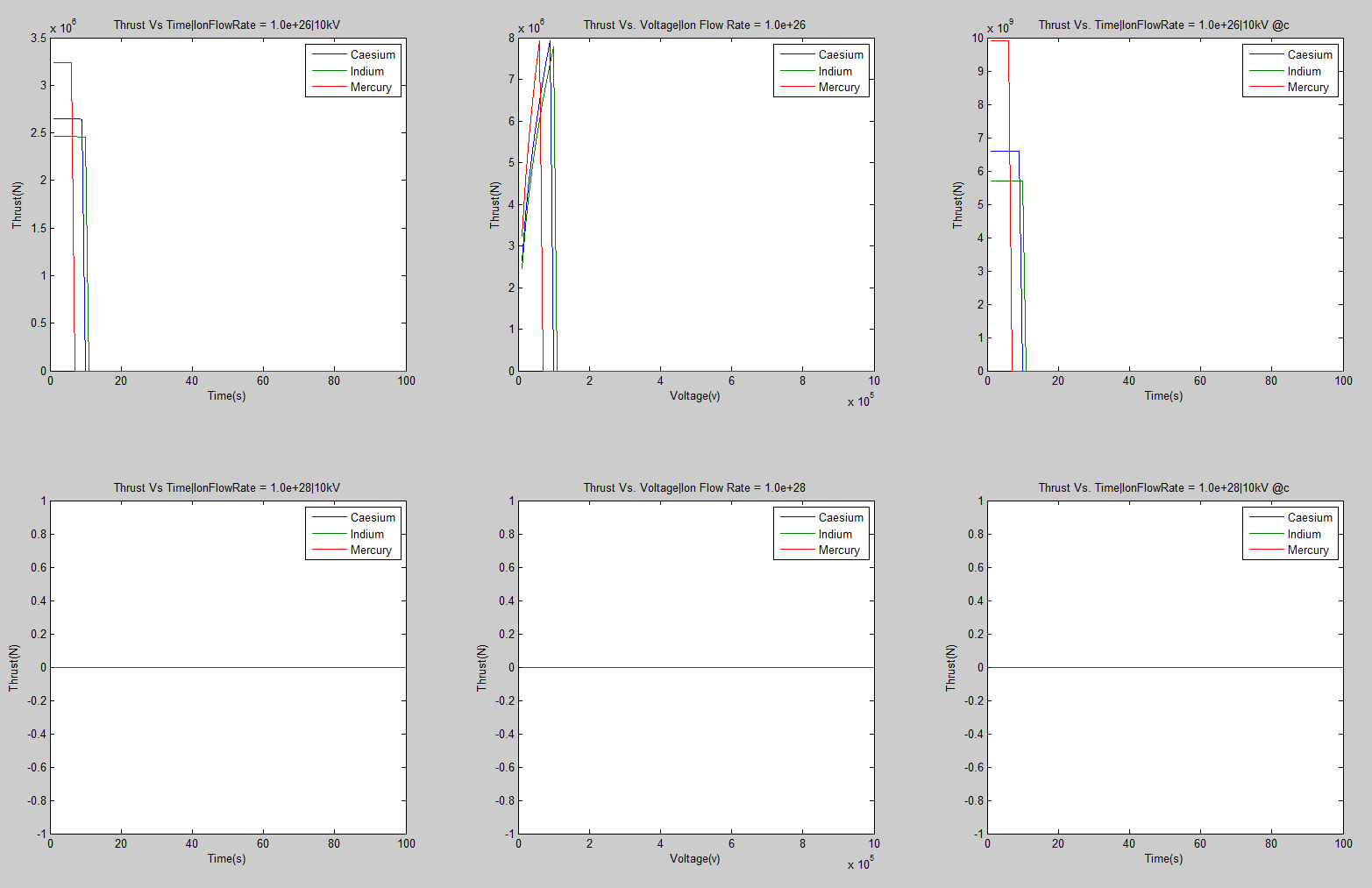
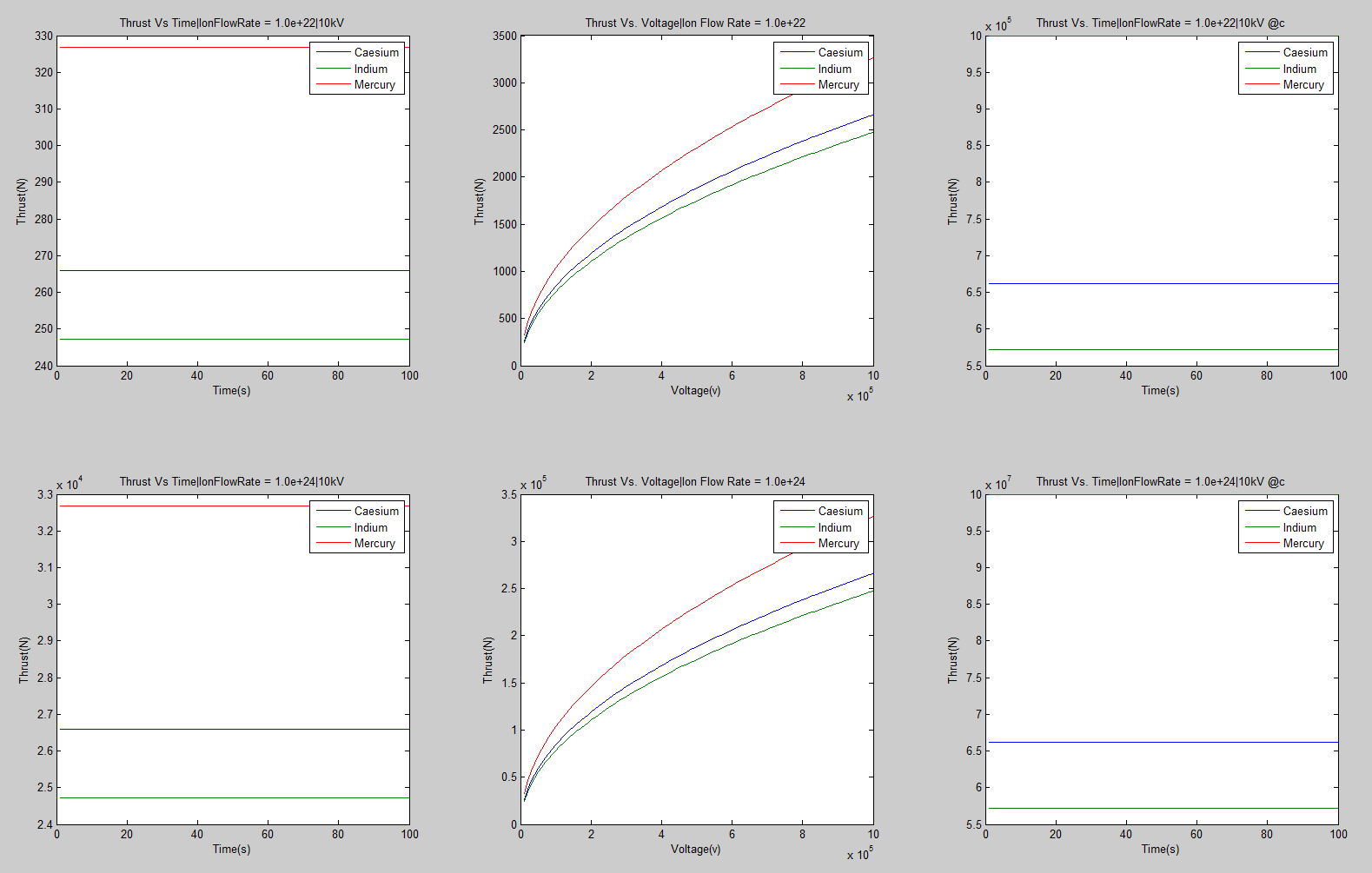
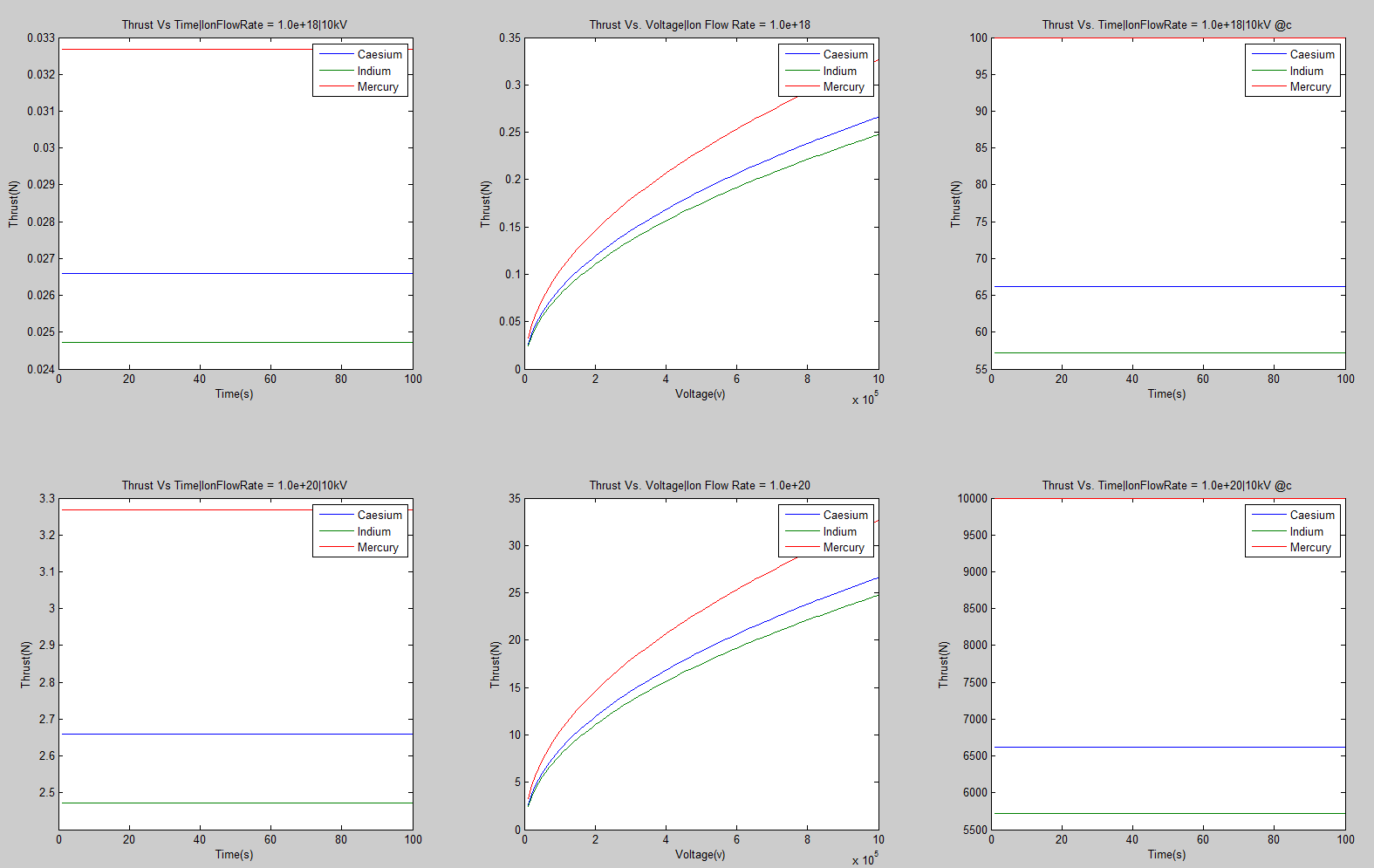
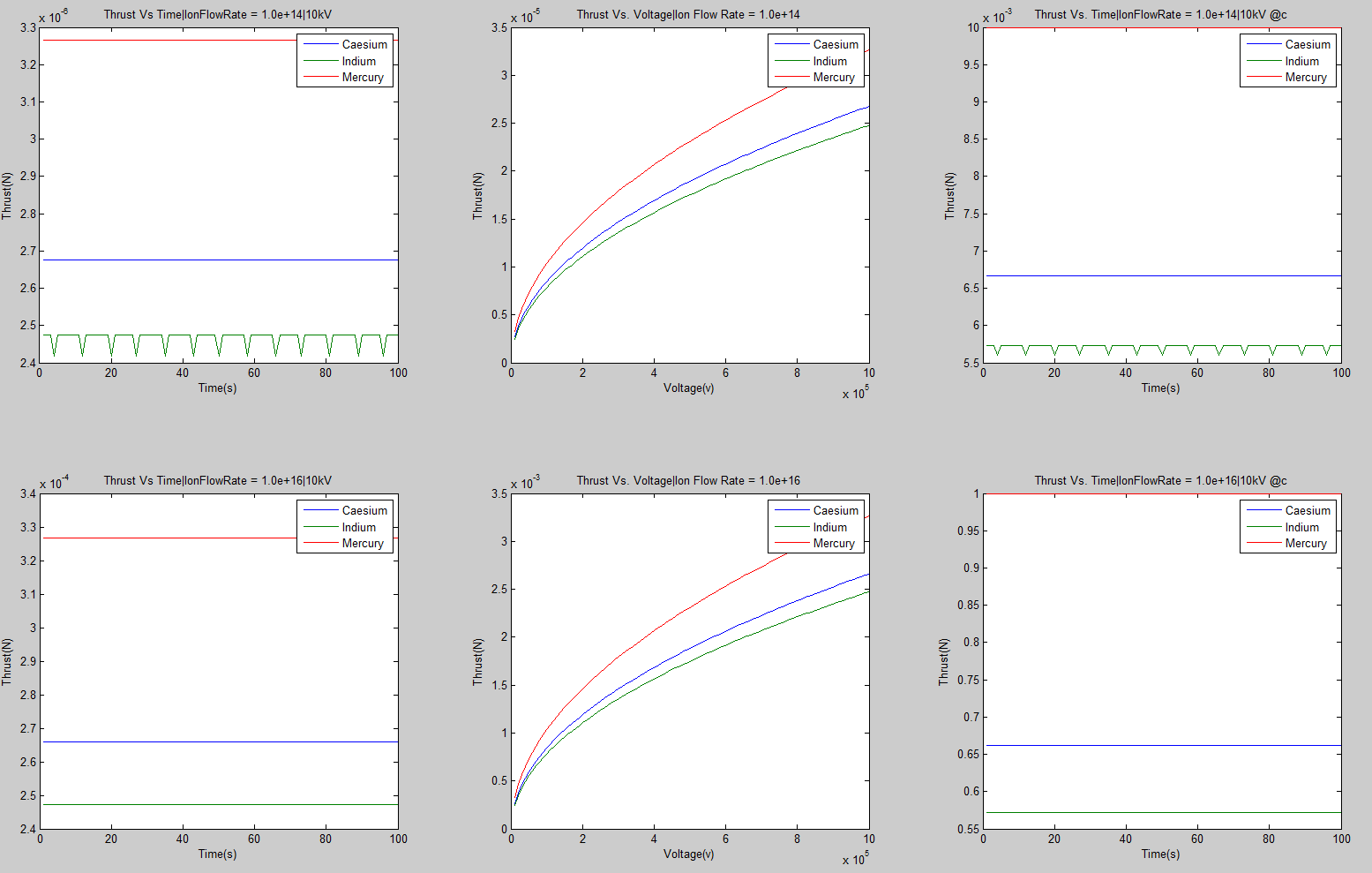
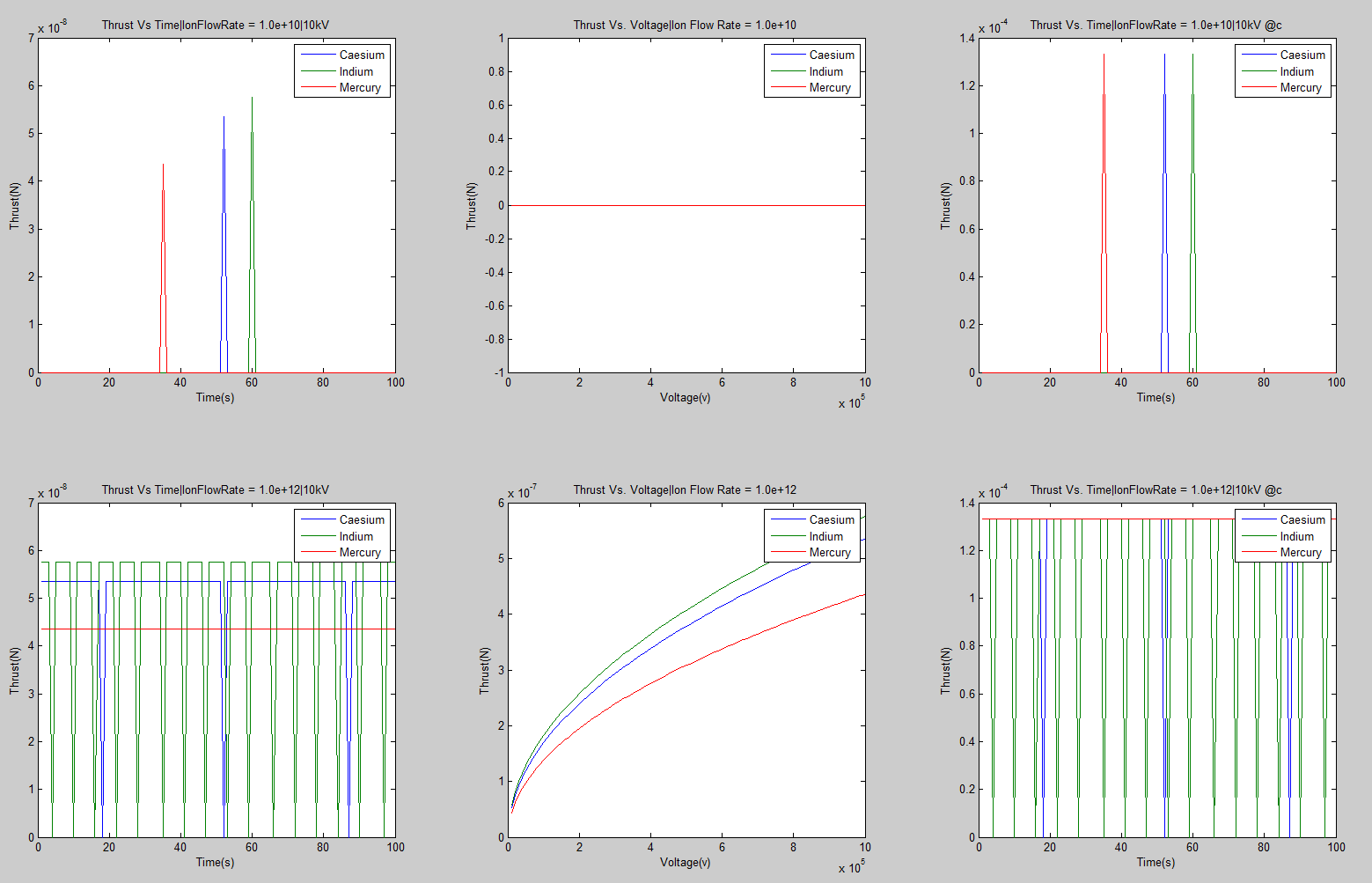
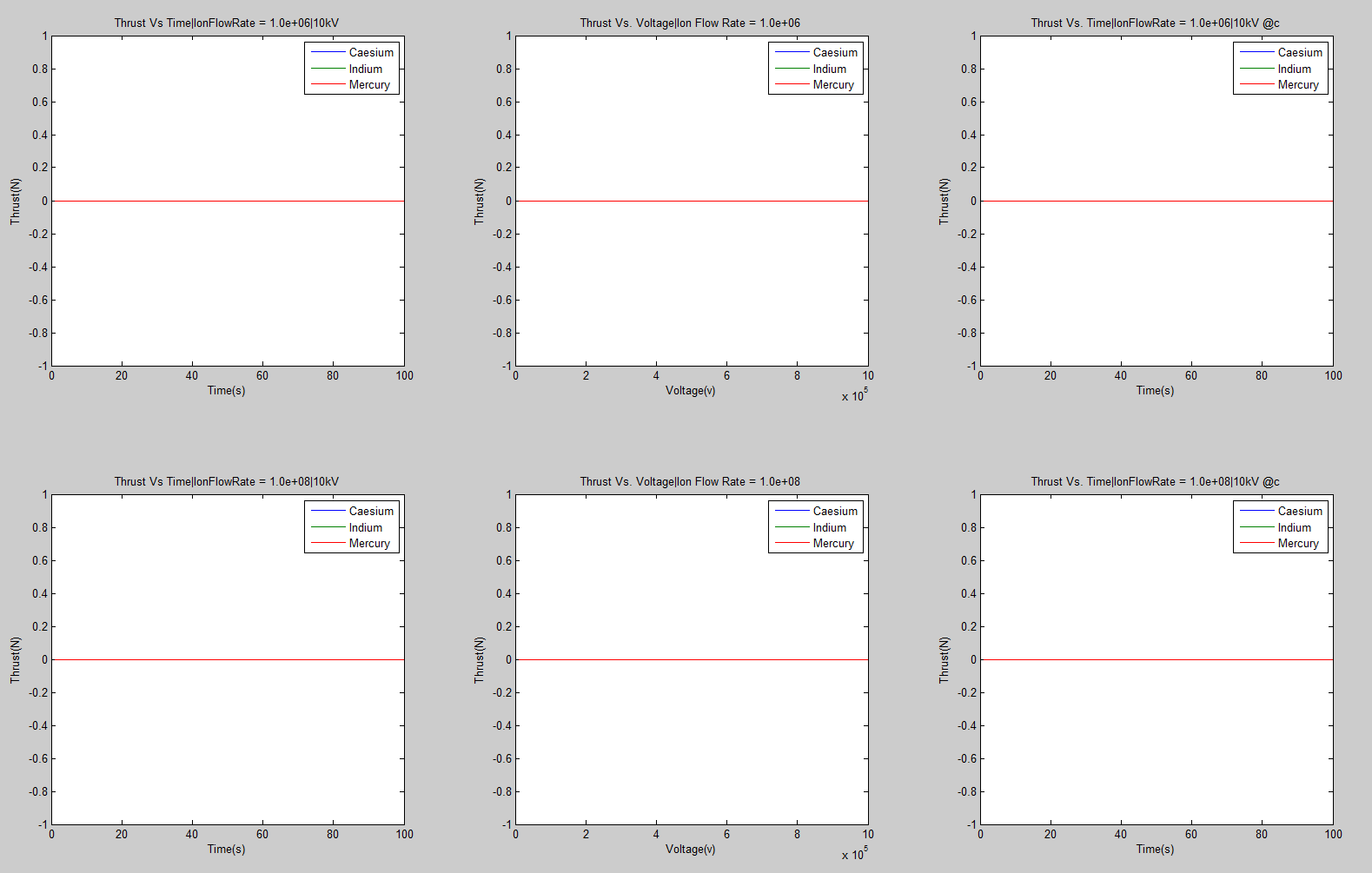
m is mass of ion (eg. kg/ion)

r is mass of ion per second (mass lost due to fuel)

We modeled Thrust Vs. Time and Thrust Vs. Voltage for three different liquid metals, Cesium, Indium, and Mercury. To do this we used different ion mass. This ion mass is found using the atomic mass of the element divided by Avogadro’s constant. For these equations, we made the assumption that the mass of an ion is equal to the mass of an atomic and the charge would just be the charge of one electron. The rocket mass was set to 1999.8 kg and fuel mass of 200 g. An equation for r could not be found, thus 15 sets of graphs were generate each with varying r (IonFlowRate). The r value spans from 1\*102 to 1\*1030. A third plot was generate to test the Thrust Vs. Time for a ejected ion moving at the speed of light. The Thrust Vs. Time graphs were held at constant voltage (10kV). The Thrust Vs. Voltage graph was held at constant time. The time domain is from [1, 100] seconds and the voltage domain is from [10, 100] kilovolts.

**Results and Discussion**

Now that we had a set of equations to measure voltage, thrust, acceleration, and velocity, we were able to use the realistic parameters in Figure 2 to plot data over the period of fuel consumption for a FEEP ion thruster.

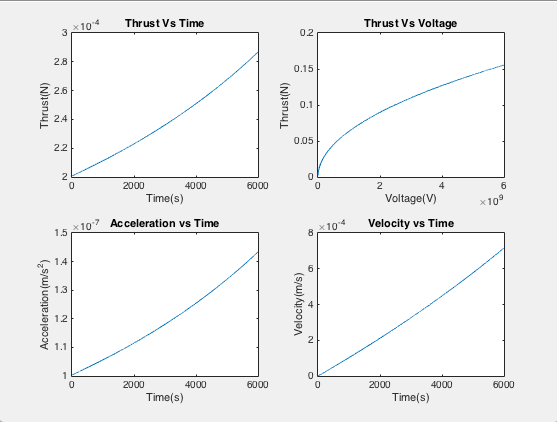


When the ion flow rate is between 1\*102 and 1\*108 the thrust is just 0. This because there not enough change in mass to produce a thrust. Once the ion flow rate reaches 1\*1010 we see a spike in thrust. Each element spike at a different point in time and with varying thrust. Mercury, the element with the highest atomic mass happens to spike first. Follow by Indium and Caesium. Surprisingly, Indium has the lowest mass of three elements. This shows that the spike occurrence is not determined by the atomic mass.

The Thrust Vs. Voltage graph is still 0 because the constant time I used was between 1 and 2 seconds, which is not where the thrust spikes. Once the ion flow rate reaches 1\*1012 we start to see harmonic rect waves with edges extremely close to each other. Caesium has a greater pulse width than Indium, however Indium has a great peak thrust than Caesium. Only mercury had a constant thrust, which was lower than the peak thrust of Caesium and Indium. In the graph the ion flow rate is 1\*1014. Caesium has lost it harmonic behavior. However, Indium is still the same as before, except with a higher thrust. The peak thrust ranking is reversed, with mercury having the greatest thrust, followed by Caesium and then Indium.

Cesium is the most common fuel for a FEEP ion thruster. With an ion mass of 133 amu, Cesium is the preferred fuel because of its high atomic mass, low melting point, and ionization energy. For 200 g of Cesium fuel for the ion thruster, we examined thrust, voltage, acceleration, and velocity over an impulse time range of 12,000 seconds.

We used the equation for thrust above, and divided the thrust by the rocket mass. The acceleration was then summated to acquire the velocity. The results below were gathered through the Matlab simulation.



The thrust calculated continues to be in the milli-Newton range, which is typical of a FEEP ion thruster. The shapes of the graphs are also intuitive. Since thrust is calculated with a constant ion flow rate and a decreasing rocket mass as more fuel is burned, the rate of thrust/s will increase slightly.

**V. Conclusions**

Through our Matlab simulations, we were able to gather data about thrust, acceleration, and velocity in relation to voltage and time based off of realistic FEEP parameters. Using the equations in our report, our simulation resulted in thrust between tens of microNewtons to a few milliNewtons. Thrust increased with increasing voltage and decreasing mass, just as expected. Thrust of course changed slightly when comparing the different fuels of Cesium, Indium, or Mercury, due to differing atomic masses. Nonetheless, the shape of the graph remained the same.

Through our research, we found that FEEP ion thrusters were used for minor adjustments to velocity and propulsion in space. This explains the low thrust in the graphs above, which led to the acceleration and velocities in the millimeters per second. These small velocities mean quite a bit to the minor adjustments to a spacecraft’s movement through space. Because of this, the FEEP ion thrusters are incredibly useful in minor adjustments, but not the main propulsion of the rocket.

Include stuff about the extreme cases

**VI. Works Cited**

1 http://ngpdlab.engin.umich.edu/files/papers/VanderWyst.pdf

2 http://ngpdlab.engin.umich.edu/electric-propulsion/field-emission-electric-propulsion

3 http://eotvos.dm.unipi.it/ggweb/phaseA/chapter4/chapter4\_2.html