Deliverable #3: Project Plans and Product Specifications

EML4551C-Senior Design Fall 2013

Team 20- Direct Drive Solar-Powered Arcjet Thruster

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1.0 Needs Assessment

The need for more efficient propulsion systems in space has been an ongoing issue since the space program was developed. The propulsion systems used in space must have high reliability, be able to withstand the hardships of performing in outer space, and provide substantial thrust for any mission. Two of the most popular forms of generating thrust are through the use of chemical reactions and electrical energy. Chemical propulsion generates high thrust at the cost of maintaining fuel supply throughout the mission. Alternatively, propulsion systems using electrical energy sources can provide low amounts of thrust for longer periods of time.

2.0 Project Scope

2.1 Problem Statement:

"Electric thrusters typically require a power processing unit (PPU) to convert the spacecraft provided power to the voltage-current that a thruster needs for operation. Size, mass, and cost can be significantly reduced if the thruster can be operated in a mode where it is directly powered by the power supply (typically solar) without any additional power conversion required.[1]"

The purpose of this project is to design, fabricate, and test an electric arcjet thruster that utilizes a direct drive system. This will eliminate the need for a PPU, thereby reducing weight, complexity, and cost while maintaining efficiency. In space it is common for many satellites to use solar energy, therefore the unit produced must be able to accept power from a solar array.

2.2 Background

An arcjet thruster is a type of electrical propulsion system that uses gas as a propellant and an arc to ionize the gas. This interaction produces a plasma that can then directed out of a nozzle through the use of magnets. These types of systems produce high specific impulses but low thrusts; these characteristics make well suited for maintaining orbits of spacecraft. Solar power has been used to power these thrusters for years but have always needed a power processing unit to create the desired voltage and current for operation.

NASA has expressed the need to eliminate the power processing unit from the system, making it a "direct drive". This is desirable because it reduces costs and weight, decreases complexity, and increases the efficiency. The PPU is one of the heaviest and most expensive components in the design but most importantly contributes largely to power losses and failure due to overheating. As opposed to direct drive mode, which will take un-transformed voltage and current directly to the load.

One of the primary design elements for this project is described by Paschen's curve. This curve relates the breakdown voltage of the gas to the type of the propellant, distance between the cathode and anode, and the pressure during the initialization of the arc. Operating near the minimum values of these curves is ideal to minimize the breakdown voltage which simplifies the circuit.

There's two options to create a voltage spike (breakdown voltage), which are capacitive or inductive circuits to store and rapidly release energy. The voltage across a capacitor doesn't change instantaneously, therefore it would be harder to produce a voltage spike to meet the required breakdown voltage. An inductive circuit would be more practical to implement because inductor can produce voltage that is given as $V = L\frac{di}{dt}$, so the breakdown voltage can be achieved easier by using a fast switching component to minimize dt, and draw a lot of current from a high inductance.

2.3 Objectives:

- Operate on direct drive by eliminating the PPU
- Generate an arc capable of breaking down a gas propellant
- Produce a current density that will sustain the plasma
- Produce a model that is scalable for NASA applications
- Design and build a reliable test model
- Create a space-like test environment
- Create and carry out an experiment to determine the amount of thrust produced

2.4 Methodology:

1) Theoretical Analysis:
    a. Research theory behind arcjet thrusters and direct drive operations
    b. Define required components
    c. Establish relevant equations
    d. Perform a system analysis
    e. Simulate the system using MATLAB, Creo, and Multisim 12.0
2) Experimental Analysis
    a. Produce necessary machine shop drawings for fabrication
    b. Determine hardware, construction materials, and testing equipment needed
    c. Verify Paschen's curve
    d. Create vacuum chamber
    e. Design experimental test procedure
    f. Final Testing

2.5 Constraints:

- Work within our budget of $500
- Time constraints of deliverables
- Minimize weight
- Set input power source (Solar arrays provided by NASA)

- Produce a pressurized gas within a vacuum environment

2.6 Expected Results:

- Produce a simple and robust operational system capable of producing a high voltage initial pulse
- Design and build a thruster capable of accepting power from a lab power source or solar arrays
- Test this design under vacuum conditions
- Execute a test plan to quantify the applicable range for operation
- Verify Paschen's curve experimentally

3.0 Deliverables

In order to complete the project on time and on budget a detailed task list and work breakdown structure are necessary. The following list is a breakdown of tasks necessary for the competition of the first stage of the project.

1) **Understand Project – 7 days**
    - Research MPDs and other Thrusters
    - Ask Questions of Sponsor and Advisors
    - Understand Project Scope
2) **Ideation/Invention – 12 days**
    - Thruster Design
        - Product/Design Specs – 7 days
        - Project Plans – 5 days
    - Circuit Design
        - Product/Design Specs – 7 days
        - Project Plans – 5 days
3) **Design – 30 days**
    - Mechanical Design
        - Material Research and Selection – 5 days
        - Gas Valve Selection – 5 days
        - Thruster Housing Design – 12 days
        - Anode/Cathode Spacing/ Orientation – 7 days

        Nozzle Design – 4 days

        Vacuum Chamber Design – 9 days

    Electrical Design

        Circuit Design – 10 days

        Magnet Design and Selection – 7 days

        Pulse Width Modulator – 6 days

        Solar Panel Integration – 7 days

4) Measurement Device Selection – 5 days

    Pressure Gauge – 1 day

    Multimeters – 1 day

    Load Cell – 2 days

    Calipers – 1 day

5) Fabrication Planning – 18 days

    Engineering Drawings – 18 days

    Machine Shop Advice - 7 days

3.1 Task Dependencies

The following figure represents the dependent tasks for the project. Table 1 acts as a key to define the tasks shown in the flow chart in Fig. 1.

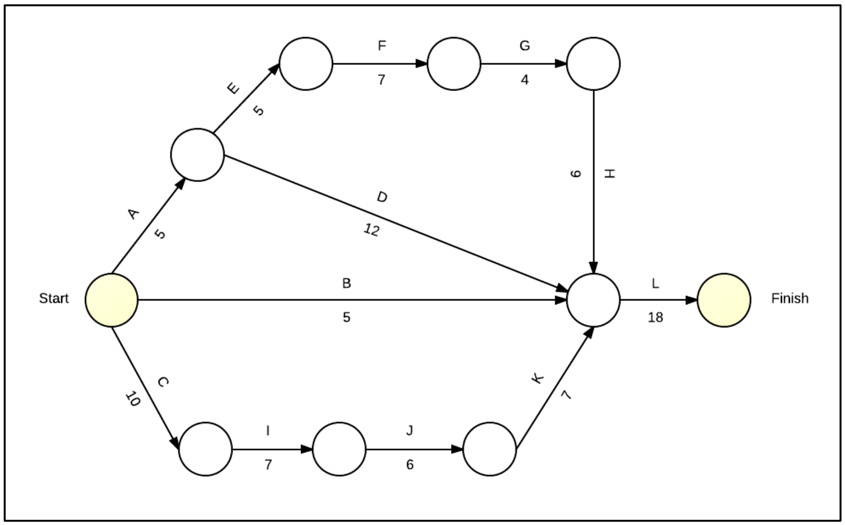


Figure 1. Critical Path Flow Chart

Table 1. Critical Path Flow Chart Key

Task	Description	Duration (Days)
A	Material Research and Selection	5
B	Measurement Device Selection	5
C	Circuit Design	10
D	Thruster Housing Design	12
E	Gas Valve Selection	5
F	Anode/Cathode Spacing/ Orientation	7
G	Nozzle Design	4
H	Vacuum Chamber design	9
I	Magnet Design and Selection	7
J	Pulse Width Modulator Selection	6
K	Solar Panel Integration	7
L	Fabrication Planning	18

4.0 Resource Assignments

The tasks required for the project will be split up between various team members based on individual skills and interests. The list below shows the breakdown of responsibilities for certain tasks. For some tasks, multiple team members are responsible due to the large work load and to ensure quality of these aspects of the project.

1) Tara Newton
    a. Material Research and Selection
    b. Thruster Housing Design
    c. Nozzle Design
2) Cory Gainus
    a. Material Research and Selection
    b. Nozzle Design
    c. Anode/Cathode Spacing/ Orientation
    d. Gas Valve Selection
3) Griffin Valentich
    a. Material Research and Selection
    b. Thruster Housing Design

    - c. Vacuum Chamber Design

4) Chris Brolin
    - a. Material Research and Selection
    - b. Vacuum Chamber Design
    - c. Anode/Cathode Spacing/ Orientation
    - d. Gas Valve Selection

5) Shane Warner
    - a. Circuit Design
    - b. Pulse Width Modulator Selection

6) Gerard Melanson
    - a. Circuit Design
    - b. Solar Panel Integration
    - c. Magnet Design and Selection

5.0 Product Specifications

The product specifications consist of both design specifications as well as performance specifications. Design specifications consists of characteristics important to the design and manufacture of the product. Performance specifications describe how the product should perform when operated as designed.

5.1 Design Specs

5.1.1 Material Specifications

The arc jet thruster to be designed must be manufactured out of materials capable of withstanding high temperatures. Typical temperatures exiting a plasma jet thruster can be up to 10,000 K. Albeit, these temperatures are experienced at the exit plume of the nozzle, however radiation present will still heat the other components of the housing to high temperatures. Not only must the materials be able to withstand high temperatures, they must also have a high reliability and be corrosion resistant. Once an arc jet device is launched into space, it cannot be easily serviced. Therefore the materials must have a high life expectancy. A good candidate for a material that satisfies all of the above requirements would be stainless steel. Magnets will be used to protect the components of the design from high temperature plasma. These magnets will constrict the plasma and prevent it from contacting the walls the design and melting them.

5.1.2 Gas Valve Regulator

The gas valve used to regulate the flow of argon must be precise enough to control the pressure of argon entering the chamber on a scale of tens of Pascals. This is imperative to locate our test point near the minimum value of Paschen's curve.

5.1.3 Thruster Housing

The thruster housing has to be designed in the shape of a cylinder in order for ease of manufacturing and incorporating an annular anode, cathode, and magnets. The overall size of the housing must be about 12 to 18 inches long allowing for easy accessibility to components, yet small enough to fit in the test chamber. The best material choice for this would be stainless steel for the reasons mentioned above in the material selection design section.

5.1.4 Anode/Cathode Spacing

Paschen's curve relates the minimum breakdown voltage of various gasses to the product of cathode-anode spacing and gas pressure. In order to simplify the experiment and tests the cathode-anode spacing will be set to 0.15 in. The cathode is slightly offset from axial symmetry in order to better predict where the arc will occur on the anode. Both electrodes will be made of tungsten for its high conductivity and melting point. The conductivity 1.79×10^7 S/m.

5.1.5 Nozzle

The nozzle to be developed for use in this design will be a converging – diverging nozzle. This type will be used to accelerate the argon ions past sonic velocity. The area ratio between the throat and nozzle exit will be determined based on the minimum pressure required for ionization. It would be ideal for the nozzle to be made of a magnetic material to constrict the ions from hitting the walls of the nozzle/anode but concerns are raised about the magnets Curie temperature. Alternatively the magnets could be placed on the exterior of the nozzle and still influence the plasma.

5.1.6 Vacuum Chamber

The vacuum chamber must be able to hold a vacuum down to 1×10^{-4} torr to simulate the space environment. The vacuum chamber must be steel to withstand high temperatures. Windows can be placed at the nozzle position for visual observations. The chamber must have ports for the injection of argon, pressure sensors, and proper sealing. The sealing will be accomplished through the use of O-rings, silicone, and latches to clamp chamber lid.

5.1.7 Circuit Design

The electric circuit will operate using 4 Aleko 100 Watt solar panels. The circuit will also use a Pulse Width Modulator to control an Insulated-Gate Bipolar Transistor. Along with those input power components, the circuit will also use inductors to produce the required voltage spike, and resistors in order to protect the circuit and control the amount of current and voltage induced. A general design of the required circuit is shown in Figure 2 below. The voltage source V_{dc} represents the power from the solar panels. Inductor L_1 and resistor R_2 are arbitrary values, while "~SHORT" represents the resistance of plasma and is approximately a short circuit. After the initial arc across the "ANODE/CATHODE GAP" the argon will ionize completing an approximately short circuit, hence switch S_2 should switch from the "ANODE/CATHODE GAP" node to "~SHORT" node immediately after the voltage spike. The pulse width modulator will control this action by closing and opening the IGBT.

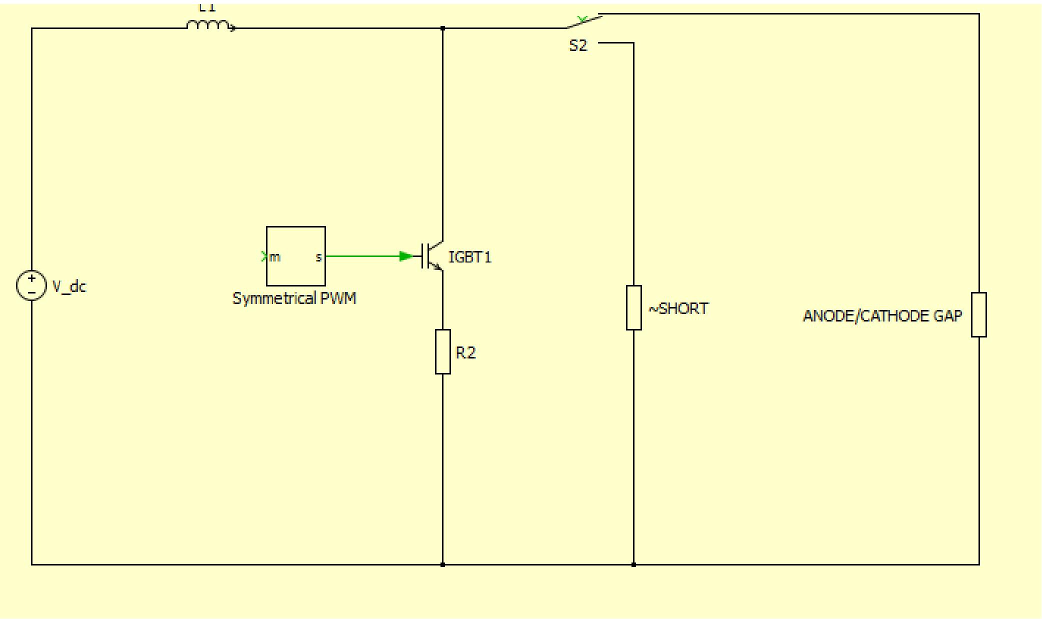


Figure 2. Circuit Schematic

5.2 Performance Specs

5.2.1 Thrust Produced

The power to be produced by this design will be approximately 1 kW. The thrust produced for our model will be approximately 50N. The design created must be able to be scaled up for use by NASA on various satellite configurations.

These scaled models will produce more thrust than our scaled model, up to a few hundred Newton’s.

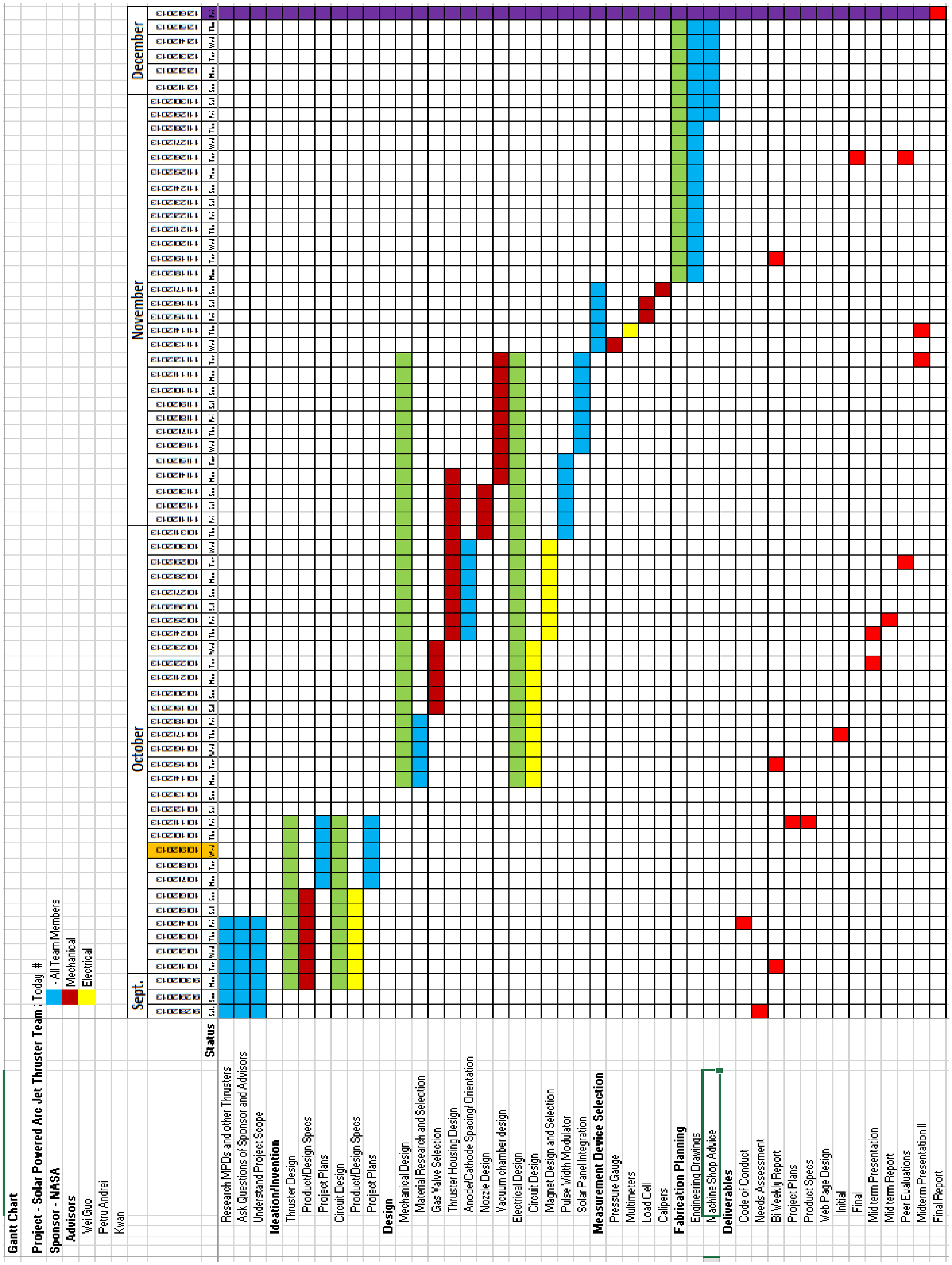
5.2.2 Continuous Operation

The arc jet thruster must also be able to operate continuously if desired. The plasma must be self-sustaining when a voltage of about 80 V is present across the anode and cathode. Also, we must eliminate the use of a Power Processing Unit (PPU) in the circuit design. This component was specifically stated to be bypassed to simplify the design.

5.2.3 Circuit Performance

The circuit will need to produce a minimum voltage spike of 137V across the anode-cathode gap, which is an open circuit initially. This value assumes the minimum point on a Paschen’s curve graph for Argon based gas, which relates the pressure of Argon gas and the distance between anode and cathode to the voltage needed in order to achieve breakdown of the gas into ions. The circuit should also be able to be easily reconfigured so that the voltage can vary by a few hundred volts in order to verify Paschen’s curve, and also in case other molecules are present besides pure argon gas. This will be achieved by changing the resistor R_2 (figure 2) values, which will dictate the initial voltage spike. After producing this breakdown voltage, the circuit needs to maintain a current density high enough to keep the plasma between the anode and cathode ionized. This value should be close to 5.5 amps.

6.0 Gantt Chart



Gantt Chart

Project - Solar Powered Arc Jet Thruster Team : Today : #

Sponsor - NASA

Advisors

Wei Guo

Petru Andrei

Kwan

🟦 - All Team Members

🟥 Mechanical

🟨 Electrical

Research MPDs and other Thrusters
Ask Questions of Sponsor and Advisors
Understand Project Scope

Ideation/Invention
- Thruster Design
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  - Project Plans
- Circuit Design
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Design
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  - Thruster Housing Design
  - Anode/Cathode Spacing/Orientation
  - Nozzle Design
  - Vacuum chamber design
- Electrical Design
  - Circuit Design
  - Magnet Design and Selection
  - Pulse Width Modulator
  - Solar Panel Integration

Measurement Device Selection
- Pressure Gauge
- Multimeters
- Load Cell
- Calipers

Fabrication Planning
- Engineering Drawings
- Machine Shop Advice

Deliverables
- Code of Conduct
- Needs Assessment
- Bi Weekly Report
- Project Plans
- Product Specs
- Web Page Design
- Initial
- Final
- Mid term Presentation
- Mid term Report
- Peer Evaluations
- Midterm Presentation II
- Final Report