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Designing an Accessible Hall Effect Thruster

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Design of a Hall Effect Thruster

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Abstract

A group of three Mechanical Engineering students have selected to design a 200 W Hall Effect Thruster to fulfill the Mechanical and Aeronautical Engineering senior design project. Preliminary studies were performed on the theory behind electric propulsion and plasma physics. The group designed the Western Hall Thruster and used COMSOL Multiphysics® simulation software to refine the magnetic circuit. The group then fabricated and performed magnetic testing of their thruster in Western Michigan University's Aerospace Laboratory for Plasma Experiments. This testing will seek to prove that a standard research HET can be built by universities without substantial financial resources.

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Nomenclature

A_d	channel cross section area
B	magnetic field
E	electric field
e	electron charge
I_d	discharge current
I_{mag}	wire current capacity
J_d	current density
k	Boltzmann constant
L	characteristic channel length
L_{coil}	coil length
L_o	original part length
L_{mag}	total coil wire length
ΔL	change in part length
ΔT	expected temperature change
M	spacecraft mass
m_e	electron mass
m_i	ion mass
$\dot{m}_a$	anode mass flowrate
$\dot{m}_c$	cathode mass flowrate
r	Larmor radius
r_e	electron Larmor radius
r_i	ion Larmor radius
P_k	cathode power
P_d	discharge power
P_{mag}	total magnet power
T_{eV}	temperature in electron volts
T	thrust
$v_\perp$	velocity perpendicular to applied field
v_e	electron velocity
v_i	ion velocity
V_d	discharge voltage
V_b	beam voltage
V_{cg}	cathode to ground voltage
w	channel width
α	thermal expansion coefficient
η_c	cathode efficiency
η_o	electrical utilization efficiency
η_T	thruster efficiency
ρ_{cu}	copper resistivity

1. Introduction

Electric propulsion (EP) thrusters are an attractive option in the space community for a several reasons. Unlike chemical rockets, EP thrusters use safe inert gases such as Krypton or Xenon. Although chemical rockets have the ability to produce more thrust, EP devices have a higher specific impulse (I_{sp}). I_{sp} roughly translates to the change in velocity (ΔV) achieved by a kilogram of propellant. A conventional chemical rocket may achieve an I_{sp} of 450 seconds, but some EP thrusters can achieve an I_{sp} of over 3000 seconds [1]. Therefore, with the same amount of propellant, a spacecraft with an EP thruster can reach significantly higher velocities or, conversely, consume much less propellant to achieve the same velocity as chemical propulsion. [2] In addition, a chemical rocket is limited to the energy stored in atomic bonds while EP is limited by a spacecraft's onboard electrical energy. An additional benefit to EP is their high efficiency, which can be as high as 80 percent. [2]

The Hall effect thruster (HET) shown in Figure 1, is a relatively simple type of EP device. Using a small number of components to produce an **E**x**B** field, an HET can accelerate ions to extremely high velocities to provide thrust. In addition, HETs can achieve an I_{sp} of up to 3000 seconds. [3]

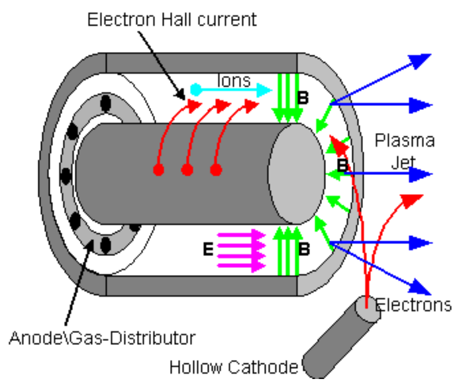

Figure 1 - Hall effect thruster cross section [4].

Xenon is a very attractive option in HETs due to its high mass. The low ion mass flow rate creates thrust of anywhere between 3 and 250 mN. [1] Although this thrust is low, the specific impulse is high, making HETs very efficient. Lastly, HETs have a wide throttling range. Throttling can conserve energy and make HETs a desirable option. HET efficiencies can typically range between 40 and 55 percent. [1]

1.1 Motivation

HETs can be designed for many applications ranging from satellite orbit correction to deep space missions and will play an exciting roll in the future of space travel. NASA has specifically tasked HETs for use in future missions in the Technology Roadmap. One such mission is to use four 10 kW HET to power a spacecraft for the Asteroid Redirect Robotic Mission (ARRM). [5] Our goal was to design and prototype a small HET that is accessible to any university with standard vacuum, electrical, and machining resources. This HET was a low-cost alternative that provides significant educational value to students working on the project. By opening this field of study to more researchers and encouraging more universities to become involved in EP research, more knowledge will be contributed to the understanding of HETs. This increased understanding will contribute to better HET designs and further our knowledge of the universe.

1.2 Hall Thruster Theory

A discussion of HET theory begins with the explanation of I_{sp} and its importance to the field of electric propulsion. It is known that the force acting on an object is governed by Newton's 2nd law:

$$F = Ma \tag{1}$$

where F is the force, M is the mass, and a is the acceleration. This can be rewritten as,

$$T = M\frac{dv}{dt} \tag{2}$$

where T is the thrust, M is the mass of the spacecraft, and the infinitesimal change in velocity is dv as a function of time, dt. Due to Newton's 1st law, the rate of change in momentum of the spacecraft must equal the negative rate of change in momentum of the propellant. However, the propellant mass, m_p, is a function of time due to propellant consumption. For a constant exhaust velocity, v_{ex}, the thrust can be represented as follows:

$$T = -\frac{d}{dt}(m_p v_{ex}) \tag{3}$$

Note also that because the change of mass of the spacecraft is assumed to be zero, the only change in mass is due to the change of mass of the propellant:

$$\frac{dM}{dt} = \frac{dm_p}{dt} \tag{4}$$

Therefore,

$$T = -v_{ex}\frac{dM}{dt} \tag{5}$$

Equation 2 and 5 equate to yield:

$$M\frac{dv}{dt} = -v_{ex}\frac{dM}{dt} \tag{6}$$

After cancelation and rearranging, this becomes:

$$dv = -v_{ex}\frac{dM}{M} \tag{7}$$

Taking the integral of both sides with the limits of dv set from the initial velocity, v_i, to the final velocity, v_f, and the limits of dM set from $m_d + m_p$ to m_d, the following result is obtained:

$$v_i - v_f = v_{ex}\ln\left(\frac{m_d}{m_d + m_p}\right) \tag{8}$$

Equation 8 is known as the Tsiolkovsky rocket equation and defines the change in velocity of which a spacecraft is capable for a given payload and propellant exhaust velocity. In addition, I_{sp} is defined as follows [2]:

$$I_{sp} = \frac{T}{\dot{m}_p g} \tag{9}$$

where $\dot{m}_p$ is the rate of change in propellant mass and g is the gravitational constant. Equation 9 can be manipulated easily by knowing that both:

$$\dot{m}_p = \frac{dm_p}{dt} \tag{10}$$

$$T = \dot{m}_p v_{ex} \tag{11}$$

to obtain:

$$I_{sp} = \frac{v_{ex}}{g} \tag{12}$$

Substituting equation 12 into Tsiolkovsky's rocket equation gives:

$$\Delta v = I_{sp} g \ln\left(\frac{m_d}{m_d + m_p}\right) \tag{13}$$

With equation 13, we can now make the important conclusion that I_{sp} plays a key role in the design of a space mission propulsion system. The spacecraft can optimize its payload with a given thruster and Δv, or conversely, a thruster can be designed to fulfill set mission requirements.

An HET fundamentally requires a Hall current, I_H to ionize incoming neutral propellant ions. This Hall current exists as spiraling electrons moving azimuthally near the channel exit at a speed of [2]:

$$v_e = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} = \frac{E_r}{B_z} \tag{14}$$

The Hall current may be approximated by integrating the magnitude of E_r/B_z along the acceleration region and multiplying the result by the electron charge density and width [2].

$$I_H \approx \frac{n_e e w V_d}{B} \tag{15}$$

With this approximation of Hall current, an expression for thrust may be formed (which will not be derived here):

$$T = I_i \sqrt{\frac{M V_b}{2e}} \tag{16}$$

where the beam voltage V_b is the difference between the anode voltage V_d and the cathode-to-ground voltage V_{cg} [2]. In addition, using conservation of momentum:

$$T = \dot{m}_\iota v_i \tag{17}$$

where

$$v_i = \sqrt{\frac{2eV_d}{M}} \tag{18}$$

Equation 17 may then be used to develop the estimated I_{sp} of an HET using the definition for I_{sp} and the thrust equation:

$$I_{sp} = \frac{T}{\dot{m}_\iota g} \tag{19}$$

Overall, thruster power is the summation of electrical power contributions from the discharge current, magnet current, and keeper voltage. Discharge current and magnet current will be discussed; however, the power contribution to keeper voltage will be neglected due to the low power requirements [2]:

$$P_T = P_d + P_k + P_{mag} \tag{20}$$

Discharge current (I_d) is defined as:

$$I_d = A_d J_d \tag{21}$$

where the target current density J_d for an optimized HET is between 0.1 and 0.15 A/cm^2. A_d is the discharge area and is a function of the outer and inner channel wall diameters. Power from the magnets, P_{mag}, is the I^2R losses due to the physical electromagnet windings at the operating temperature:

$$P_{mag} = I_{mag} \frac{\rho_{Cu} L_{mag}}{A_{wire}} \tag{22}$$

The determination of efficiency may then be approximated by separating the efficiency into the electrical input losses from the electromagnets and keeper, the cathode losses due to cathode gas supply, and the thrust achieved for the given gas flowrate. The overall efficiency, η_T becomes [2]:

$$\eta_T = \frac{Tv}{P_T} = \frac{T^2}{2(\dot{m}_c + \dot{m}_a)P_T} = \frac{T^2}{2(\dot{m}_c + \dot{m}_a)P_d}\eta_c\eta_o \tag{23}$$

where the cathode efficiency, η_c, and the electrical utilization efficiency, η_o, are defined as [2]:

$$\eta_c = \frac{\dot{m}_a}{\dot{m}_a + \dot{m}_c} \tag{24}$$

$$\eta_o = \frac{P_d}{P_T} \tag{25}$$

Several additional power loss mechanisms exist within an HET that decrease the thruster efficiency. These losses can be from:

- Electron and ion losses to the channel wall
- Electron migration to the anode
- Radiation losses from plasma to surrounding
- Incomplete neutral gas ionization

These power losses are significant yet difficult to calculate and are neglected for the scope of this project.

1.3 Channel Length and Scaling Laws

Another necessary consideration when designing HETs is the thruster dimensions. The channel length and width are calculated by solving for the Larmor radius, r, of both the electrons moving within the magnetic lens and the ions traveling down the channel. The force acting on a moving charged particle within a magnetic field is defined as follows:

$$F_c = q(\boldsymbol{v}_\perp \times \boldsymbol{B}) = \frac{m{v_\perp}^2}{r} \tag{26}$$

This is rearranged for an electron Larmor radius:

$$r = \frac{mv_\perp}{qB} \tag{27}$$

The energy balance between kinetic and electric potential energy is:

$$\frac{mv_\perp^2}{2} = qV_\perp \tag{28}$$

where $V_\perp$ is the electrical potential perpendicular to the magnetic field . Equations (27) and (28) can be combined to solve for a singly charged ion Larmor radius:

$$r_i = \frac{1}{B}\sqrt{\frac{2m_i V_\perp}{e}} \tag{29}$$

Equation 29 can be applied directly to a Xe ion with a mass of 131.293 AMU within an estimated maximum magnetic field of 600 G in a 300 V potential. This results in an ion Larmor radius of 476 mm. The channel length must be far less than this value to prevent ion bombardment on the wall surfaces.

$$r_i \gg L \tag{30}$$

Minimizing ion bombardment ensures the ions can travel the length of the channel and exit the thruster to contribute to thrust. For the electron radius, the equation above must be modified using the average thermal electron drift velocity:

$$v_{avg} = \sqrt{\frac{8kT}{\pi m}} = \sqrt{\frac{8T_{eV}}{\pi}} \tag{31}$$

Using this v_{avg}, and equation (28) we can derive the following electron Larmor radius:

$$r_e = \frac{1}{B}\sqrt{\frac{8m_e T_{eV}}{\pi e}} \tag{32}$$

For example, assuming a minimum of 100 G within the channel acceleration region and an electron temperature of 40 eV, the conservative Larmor radius of an electron within the magnetic lens is 2.4 mm. Therefore, to allow for electron mobility within the acceleration region the following requirement must be made:

$$r_e \ll L \tag{33}$$

Scaling was the next major consideration when developing the dimensions of the thruster. Using these basic scaling relations for an optimized HET [2]:

$$Power \propto Thrust \propto I_d \propto \dot{m} \propto R^2 \tag{34}$$

$$width = R(1 - Constant) \tag{35}$$

The widely studied Russian SPT-100 HET operates at a power of 1.35kW, a thrust of 80mN, a propellant flowrate of 4.96 mg/s, and a discharge current of 4.5 A. The SPT-100 has an outer channel wall diameter of 100 mm and a channel width of 15 mm [2]. This yields a width constant of 0.7, which was used as a starting point for this project's dimensional decisions. For example, if a target total power for an HET is 250 W, the previously mentioned scaling laws call for an R, thrust, propellant flowrate, discharge voltage, and the channel width to be approximated to 21.5mm, 14.8mN, 0.92mg/s, 0.83A and 4.4mm, respectively. This provided a starting place for design and fabrication considerations.

2. Design

HETs have relatively simple geometry compared to other EP thrusters, placing them within the capability of a senior capstone project. This design focuses on the main characteristics of an HET: channel dimensions, magnetic circuit, and anode. Successful design and operation of an HET will promote ongoing measurements and testing to be performed at the Aerospace Laboratory for Plasma Experiments (ALPE). Detailing the design and fabrication process will serve as an example for universities with limited resources to replicate and to improve upon in order to perform meaningful research on their own HET. The thruster designed in this report will be referred to as a 44mm Western Hall thruster (WHT-44).

2.1 The Iterative Process

Many iterations of the design were conceived. This process began with the assumption that the thruster would achieve a target discharge power of 250 W and be capable of being operated within the ALPE testing facility. Mathcad was used to generate the theoretical parameters such as required magnetic field, channel outer radius, width, thrust, propellant flowrate, etc. The basic dimensions were placed into COMSOL Multiphysics® followed by population of coil, anode, and shielding.

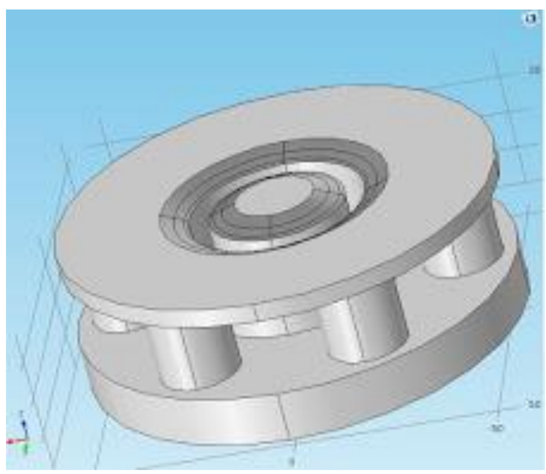

Figure 2 – WHT-44 solid model for use in magnetic simulations.

Many iterations were not accepted simply because the dimensions could not contain a center coil large enough to support the desired magnetic field, or a near zero magnetic field could not be achieved at the anode. Another common reason to reject an iteration was the issue of magnetic saturation. Saturation profiles were used when calculating the magnetic field throughout the thruster, and, in some cases, the applied magnetic field by the coils could not be supported by smaller diameter cores. To prevent the issue of magnetic saturation, core diameters would be increased to operate at the knee of the magnetic hysteresis linear region. This was repeated until all dimensional and magnetic requirements were met. Figure 2 shows a COMSOL Multiphysics® model used to determine the magnetic field characteristics.

The final channel outer diameter selected was 44 mm with a channel width of 5 mm. Applying the scaling laws allows the estimation of an anode mass flow rate of 0.96 mg/s of xenon and a discharge current of 0.87A.

The COMSOL Multiphysics® simulation shows the WHT-44 yielded a maximum radial magnetic fields strength that varied from 456 to 622 G. Figure 4 represents the magnetic field varying axially in the channel at different radial positions: inner, middle, and outer (Shown in Figure 3).

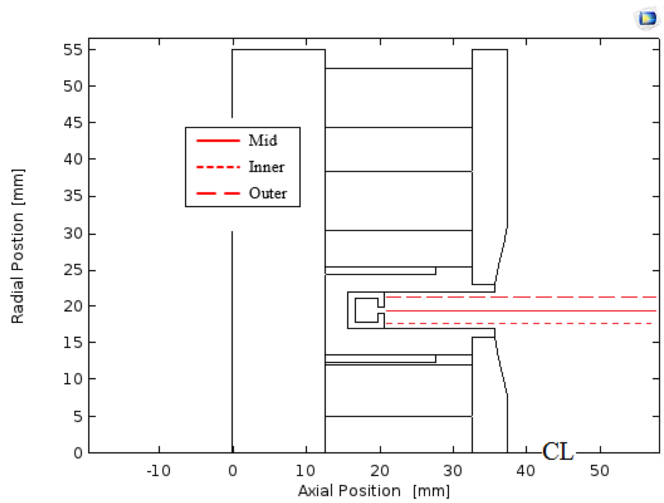

Figure 3 - A cross section of the WHT-44 showing where the mid, inner, and outer channels are located.

After simulation, the magnetic field strength profile along the WHT-44 channel was used to approximate the ionization region of the thruster, which can be determined where the Hall current is unsustainable due to the larger Larmor radius at the lower magnetic field strength. Retaining the assumption of an electron temperature of 40eV inside the channel and setting the Larmor radius of an electron to 2.5mm, we see that a magnetic field strength greater than 93 G will support electron mobility. This results in an ionization region length, L of about 7 mm. Consulting our previous conservative ion and electron Larmor radius equations, it is shown that the channel length satisfies the requirements:

$$2.4\, mm < L < 476\, mm \quad (36)$$

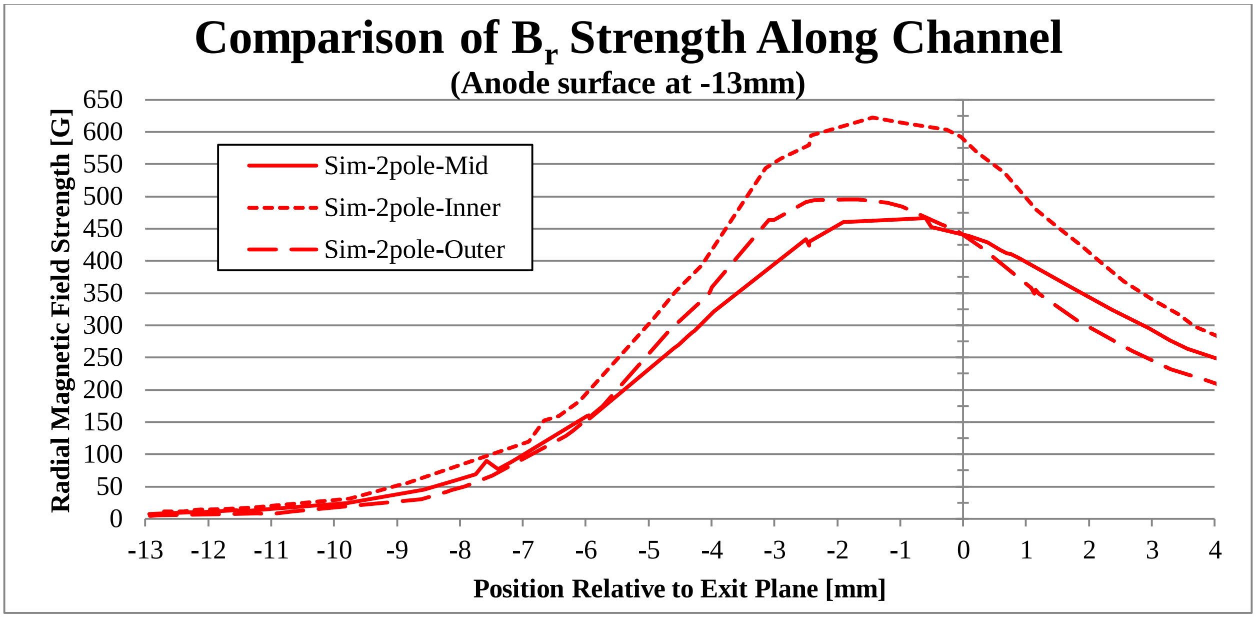

Figure 4 - COMSOL Multiphysics® simulation results for various positions along the WHT-44 channel.

The ion exit velocity and thrust are estimated using equation (18) to yield 18.5 km/s and 17.8 mN. Discharge power is approximated by multiplying the discharge area by our estimated current density of 0.1 to 0.15 A/cm^2. Therefore, our power ranges from 144-216 W. The coil resistance is calculated using a resistivity at an exaggerated temperature of 600 K to yield a total coil power consumption of 0.53 W. Electrical utilization efficiency then becomes 0.998. The cathode mass flow rate will be an estimated 0.3 mg/s, so our cathode efficiency will be roughly 0.762. Supplying these efficiencies into our total efficiency equation yields an overall maximum efficiency of 0.51.

2.3 Anode Flow Model

In order to prevent uneven gas distribution and discharge within a channel, the anode must be correctly designed. Two methods for analyzing gas flows are the continuum approach and rarefied flow modeling. The continuum approach treats the fluid as a whole and disregards the intermolecular interactions. Whereas rarified flow modeling is the study of gas flow at near vacuum and takes molecular interactions into account. Typically, a rarified flow model would be used to determine the flow from the anode to a vacuum; however due to the scope, required knowledge and computational power involved with performing a rarified study, the continuum approach was used as an approximation. The WHT-44 model was transferred to ANSYS® where analysis was performed.

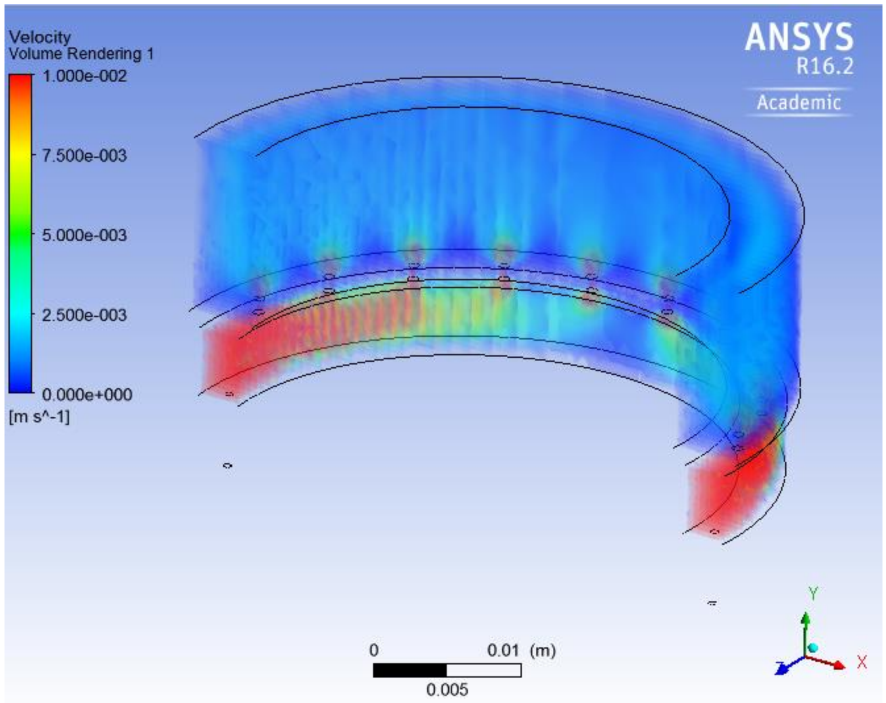

Figure 5 - An ANSYS® simulation was performed on the WHT-44 anode and channel to predict the uniformity of flow within the thruster channel. The method used does not account for transitional flow and may be overly optimistic.

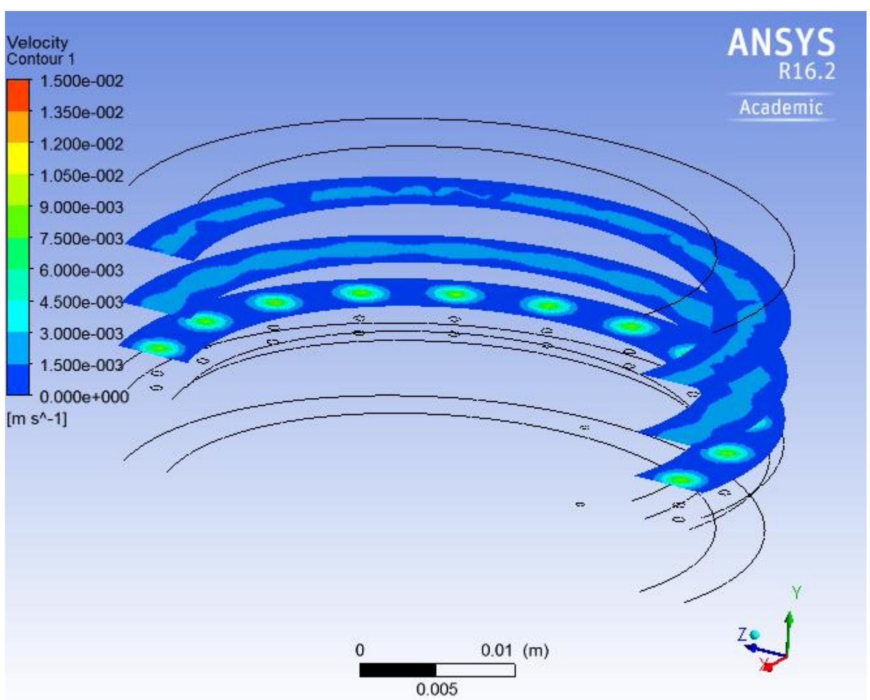

Figure 6 - Velocity contours at 2, 5, and 8mm above the WHT-44 anode.

From the ANSYS® simulations shown in Figure 5 and Figure 6, it is clear that the gas is evenly distributed within the channel between 2 and 5 mm from the anode plate.

2.4 Design of Magnetic Lens

The magnetic lens design has direct implications on lifetime and performance of HETs. An ideal magnetic lens is designed in such a way that magnetic field is strongest near the exit plane and quickly approaches zero just before the anode surface. The curvature of the magnetic field lines may also be designed to decrease ion bombardment with the channel walls and increase thruster life [2]. Once the channel walls are eroded the plasma will be in direct contact with the electromagnetic coils, and the thruster will fail. A thruster designed with a magnetic lens that nearly eliminates this bombardment is called a magnetically shielded thruster and requires complex designs that are outside the scope of this project. The magnetic lens is created with a magnetic circuit that consist of outer coils and one center coil. The WHT-44 magnetic lens shape is shown in Figure 7.

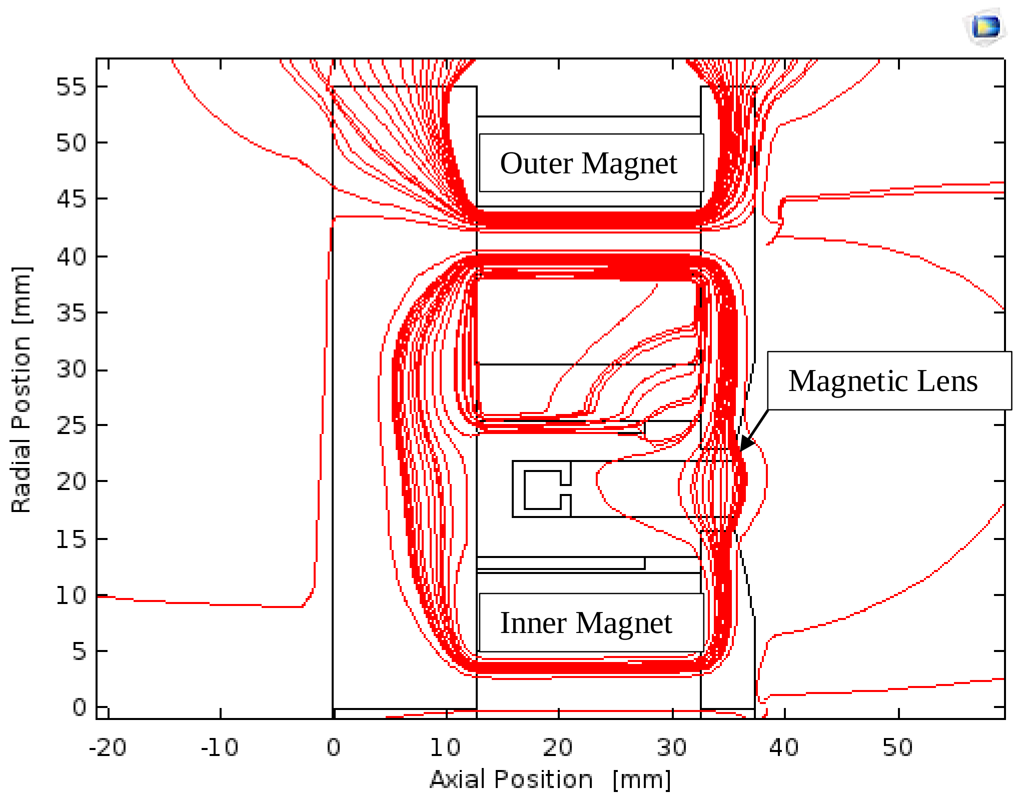

Figure 7 - Magnetic field varying axially in channel.

2.4.1 Magnetic Circuit Design

Figure 8 shows two flight tested thrusters. The SPT-100 thruster uses four outer coils, whereas the D-55 thruster uses three outer coils. These configurations suggest that the magnetic circuit can be generated in many different ways. Initial simulations lead to our thruster having six outer electromagnetic coils instead of the conventional 4 pole design. Six cores provide the thruster with the most consistent magnetic field at the exit plane. Several ideas for connecting the cores to the front and back plates were considered. The cores were held to the front plate by direct threading while the back was slipped through and held in place by a nut. This meant no material was removed from the core and therefore the magnetic resistance was minimized to the thread interfaces. The configuration of this assembly is shown in Figure 9. This method produces a strong magnetic field at the exit plane. Shielding was required to reduce the magnetic field at the anode. Internal trim coils could also be used to reduce the magnetic field strength at the anode by running the current in opposition with respect to the current in the coils [6]. While trim coils were considered, they would have increased the complexity of the thruster greatly and shielding was sufficient to modify the magnetic lens.

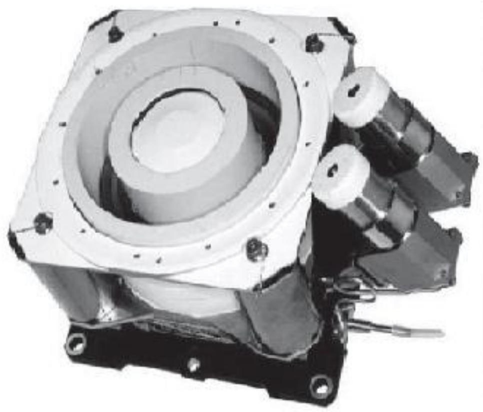

Figure 8 - Represents the number of outer coils. left: SPT-100 HET. Right: D-55 anode layer HET. [2], [7]

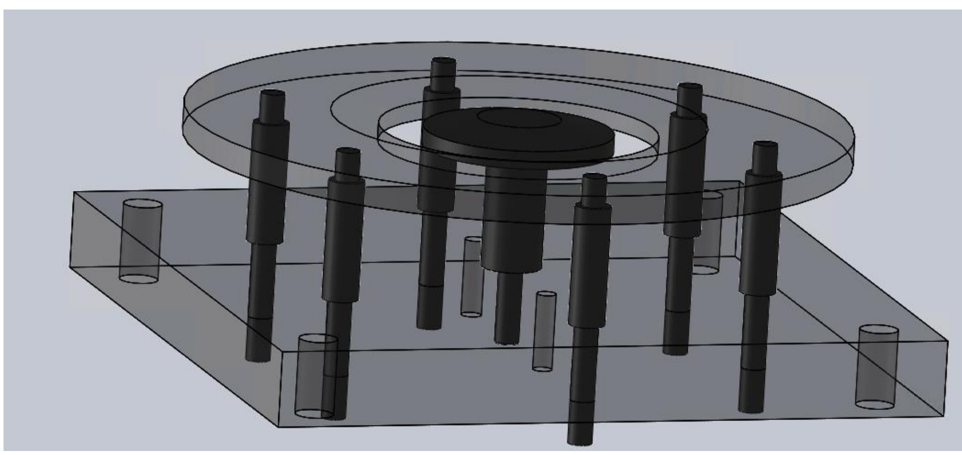

Figure 9 – All iron components of the WHT-44. Some are shown as opaque for clarity.

2.4.2 Magnetic Saturation

The core material and shielding have non-linear magnetic saturation limits that require special consideration. The B-H curves shown in Figure 10 were used to determine when magnetic saturation would occur at a given applied magnetic field. The iron (core material) and MuMetal® (shielding) magnetically saturate around 1.6 and 0.6 Tesla, respectively. The shielding is placed around the inside and outside of the channels as shown in Figure 11. The effects of various shielding thicknesses and widths were simulated and the dimensions chosen provided a balance between a strong exit plane magnetic field and the desired magnetic field shape along the channel.

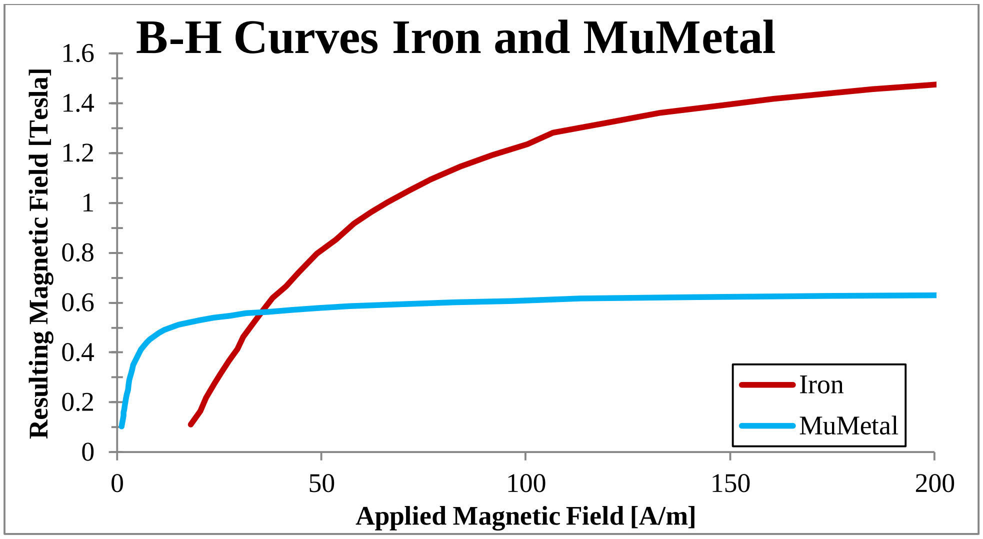

Figure 10- Saturation curves for pure iron and MuMetal®. These curves were used by COMSOL Multiphysics® to determine the non-Linear Magnetic Behavior of the Thruster.

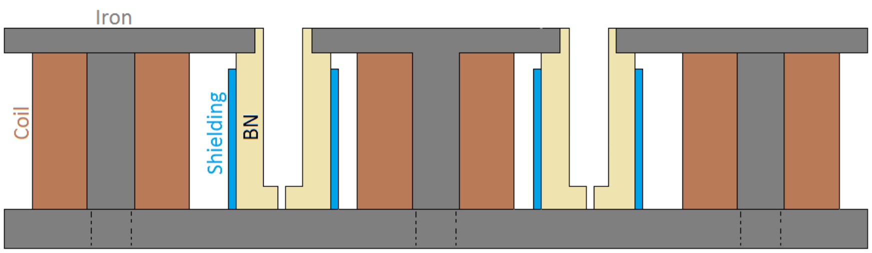

Figure 11 – Basic cross section of the WHT-44 showing the shielding (blue), coils (brown), BN channel (ivory), and the iron (gray)

2.4.3 Coil Analysis

Due to a constant packing factor, the number of turns on each coil did not have a notable impact on the results of the magnetic lens. If a smaller wire was used, the number of turns increased by the same factor that the current capacity of the wire decreased, resulting in the same overall coil current density. For ease of fabrication, high temperature 22-gauge magnet wire was chosen to reduce the number of turns needed to exactly 300. The current ratio between outer and inner coils was also investigated. Figure 12 shows the currents that were evaluated to achieve the desirable magnetic field at the exit plane.

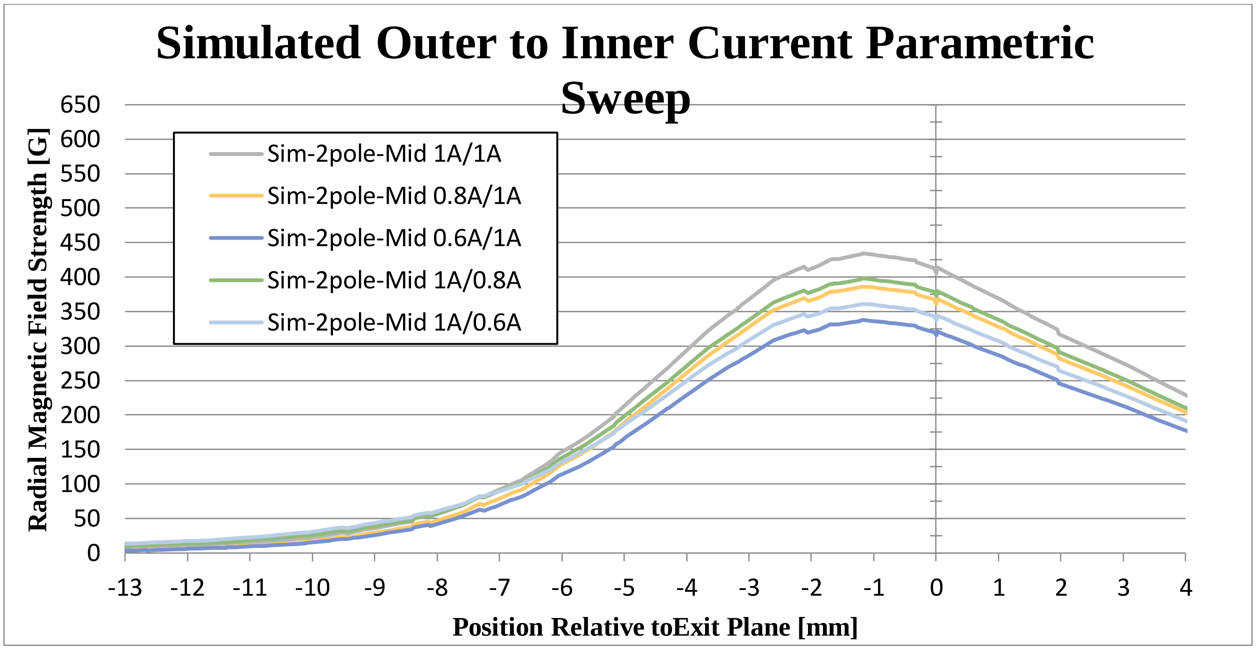

Figure 12 - The COMSOL Multiphysics® simulation results for various outer and inner coil currents in the WHT-44. In the plot, the outer and inner coil currents are designated as outer/inner.

From the COMSOL Multiphysics® simulation results of the outer/inner current sweep (shown in Figure 12), it is clear that a ratio of 1 is ideal.

2.5 Thermal Considerations

Due to the temperature increase of all thruster components, thermal expansion of the components was accounted for when designing the thruster. For these calculations, a temperature rise of 300 K was used. [8] Thermal expansion coefficients were determined using material properties obtained from an online database. [9] The material properties used are listed in Appendix 3. The following equation was used to calculate the change in the dimension expected from the temperature change.

$$\Delta L = L_o \Delta T \alpha \tag{37}$$

With the expected expansion of each component calculated, the next step was to find the areas where expansion could cause damage. Worst case scenarios were used by assuming that only one part would expand at a time and checking for interference. The areas of most concern were where the anode and center core contact the boron nitride (BN). Once the dimension changes were identified, the model was updated.

3. Fabrication

All major components were machined on provided lathes and mills. Special tooling had to be purchased to drill exceptionally small holes, machine tough material, and ream holes for tight tolerances. Each material has ideal cutting tool materials and speeds that increase surface finishes and part accuracy. Parts were practiced on aluminum stock of the same size to determine the most ridged and logical machining process, preventing machining errors. The fabrication process develops dust, chips, and oil contaminates onto the material. For this reason, nearly all components were cleaned in an ultrasonic bath and dried just before final assembly. The BN and coils were not cleaned using this method, and great care was taken during the machining process to prevent oil and dust contamination.

3.1 Machining Considerations

3.1.1 Boron Nitride

The boron nitride was generally very easy to machine. No lubricant was used due to the material being self-lubricating. Care was taken to continuously remove any dust using compressed air and vacuum. For turning, milling, or drilling, a cutting speed of 70-100 surface feet per minute (SFM) was used. High speed steel (HSS) or sharp carbide tools were preferred as it allowed for light cuts with minimal cutting forces.

3.1.2 Stainless Steel (316)

The 316 stainless is difficult to machine and requires great care to prevent breaking tools. Carbide tooling was almost exclusively used for stainless steel components. A cutting speed of 100 SFM was used normally when using carbide for milling and turning. However, 30 SFM was used when drilling holes using HSS. A feed rate of 0.0015" per revolution for parting operations was found to be ideal for minimizing chatter. A normal cutting fluid was used to keep the stainless steel cool and prevent gumming. The gas feed tubes were attached to the anode using furnace brazing.

3.1.3 Pure Iron

Pure iron was machined with both carbide and HSS tooling, and it was found that HSS tooling yielded much better surface finishes. A cutting speed of 80 SFM and cutting fluid was used during all operations with both HSS and carbide.

3.2 Front and Back Plates

The front and back plates were machined from 0.195 in and 0.495 in thick iron plates, respectively. The front plate was threaded for attachment of the magnet cores while the back plate had reamed 4 mm holes for slipping the magnet cores through. Holes were added in the four corners so that the thruster may be mounted within the vacuum chamber. A chamfer was placed on the front plate to minimize the thin BN lip formed around the thruster mouth. Figure

13 shows the front and back iron plates nearly complete; excluding the center coil feed through hole.

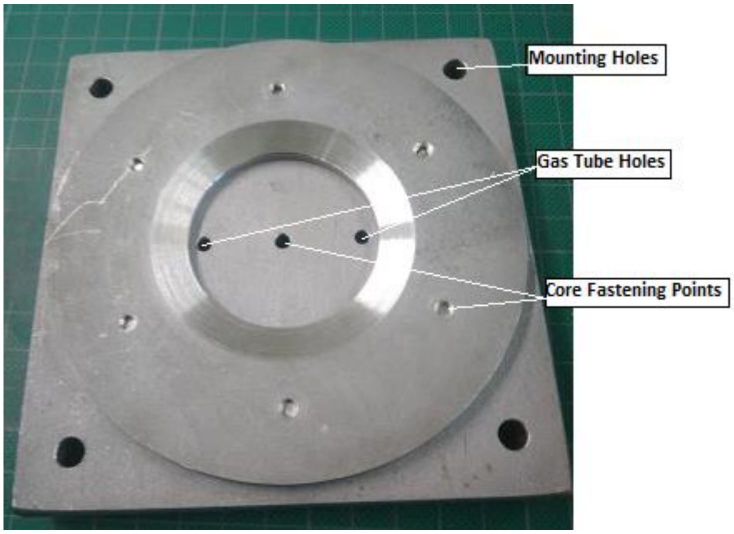

Figure 13 - This Image shows the nearly completed back and front WHT-44 plates.

3.3 Center and Outer Cores

Six outer magnet cores and one inner core were turned. The outer cores directly thread into the front plate while the opposite end slides through the back plate and is fastened with a stainless steel washer and nut. The center core was turned from a solid iron cylinder to prevent any magnetic resistances near a magnetically dense portion of the thruster. Continuity testing showed that two coils where shorted, when slid onto the cores. This was correct by wrapping the cores in Kapton® tape (shown in Figure 14).

Figure 14 - This shows the six outer and center cores used in the thruster. The anode is partially shown in the upper-right.

3.4 Magnetic Coils

The magnets were wound on an aluminum rod, which was cut to a diameter 0.005" greater than the core diameters. This allowed the magnets to fit snuggly over the cores while making them easy to install and remove. Figure 15 shows the result of continuously potting the magnet cores with alumina Ceramabond™. After curing, the core was slipped off the aluminum rod. A small amount of shielding had been removed from the inner windings while removing the coils from the aluminum rod. There is room to improve this process to prevent damage to the coils.

Figure 15 - This shows the center coil. Each coil was potted in alumina Ceramabond™ and cured. The potting allowed for coil modularity during assembly/disassembly.

3.5 Boron Nitride Channel

The ceramic channel was machined from a solid 2-in-diameter rod of HP grade BN. The channel was created with a square end mill used in conjunction with a milling machine, rotary table, and three jaw chuck. All other features were turned on a lathe. The shelves shown in Figure 16 when combined with the front plate and inner core hold the channel in place for assembly. Additional room for shielding was turned on the outside and inside diameters.

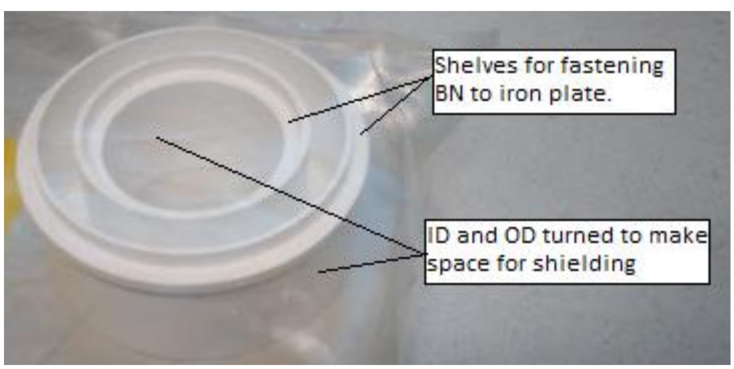

Figure 16 - The BN channel. The channel protects the iron and coils in addition to acting as an electrical insulator.

The anode is made up of four parts: the front plate with 20-0.03-in-diameter holes, the channel with two 1/16 in gas tube holes, and two gas tubes. All anode components were machined from 316 stainless steel. The anode front plate and anode channel were spot welded together, at the inside lip, at 6 points. The gas tubes were brazed onto the channel part using Safety-Silv 50N brazing alloy. The brazing alloy contains 28% zinc, yet it is used in very low amounts and should not be problematic for use in a vacuum chamber.

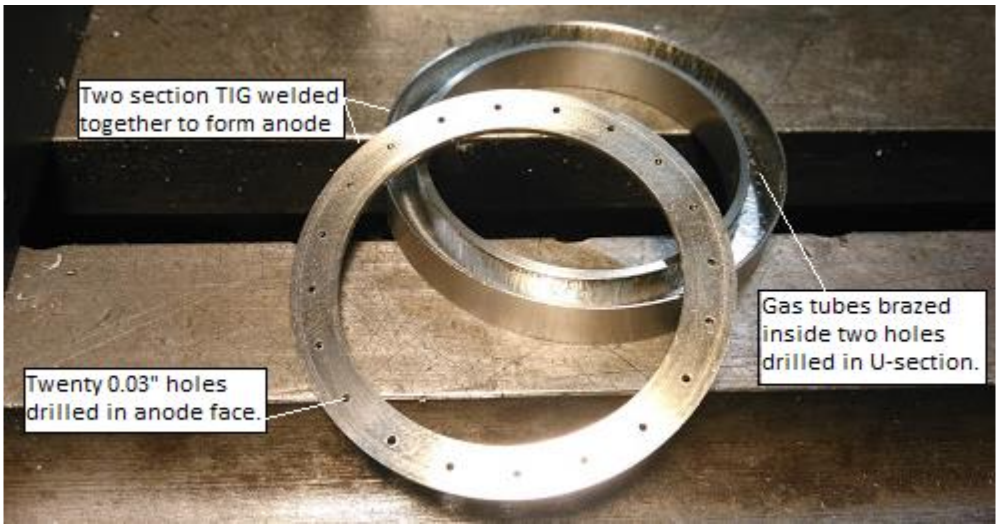

Figure 17 - These are the two primary components making up the anode. These were spot welded together and two gas tubes were affixed to the back side.

The gas supply was made up of several Swagelok components. Beginning with the vacuum chamber feedthrough the feed system consists of flexible tubing, dielectric break, straight tube section with electrical connection and finally a 1/4 in to 1/16 in tube size adapter (Figure 18). The gas was then split to the two gas tubes using a T-joint and two 90° elbow Swagelok fittings (Figure 19).

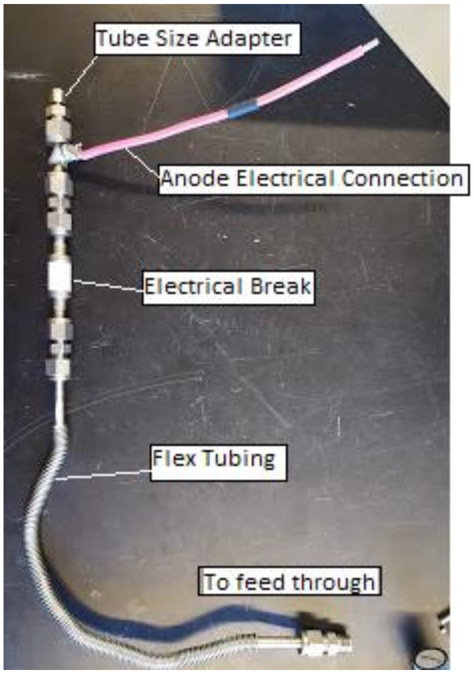

Figure 18 - This image shows the Swagelok components used to deliver the gas to the anode. The flexible tubing prevents the delicate gas tubes from being rigidly mounted to the chamber. The electrical connection is used to hold the anode to the desired voltage. The electrical break is used to prevent the anode from shorting to the vacuum chamber.

Figure 19 - This image shows the back of the thruster with the final components of the gas delivery system. This includes one T fitting and two 90° elbow fittings. About 4 in of tubing are left exposed in the event the Swagelok fittings need to be destructively removed for disassembly.

4. Testing

Upon fabricating the WHT-44 (Shown in Figure 20 through Figure 22 below) testing was performed at ALPE on the thruster's magnetic circuit. Results of this testing were compared to COMSOL Multiphysics® simulations. Future operational testing will be performed in the ALPE vacuum chamber.

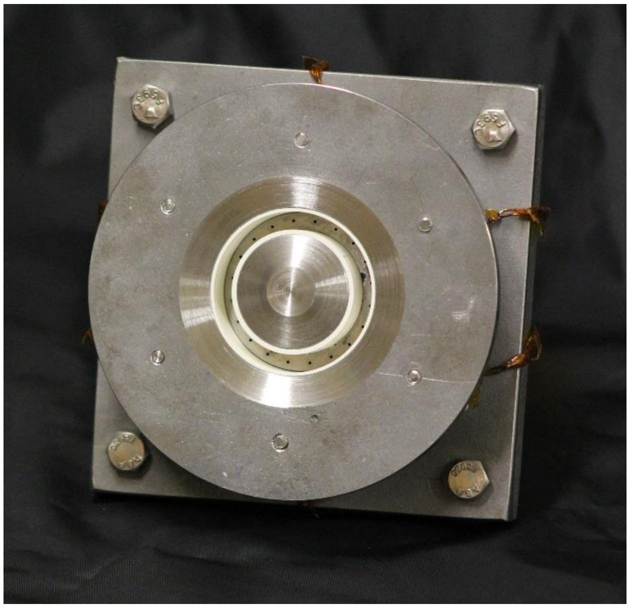

Figure 20 - Front view of the completed WHT-44.

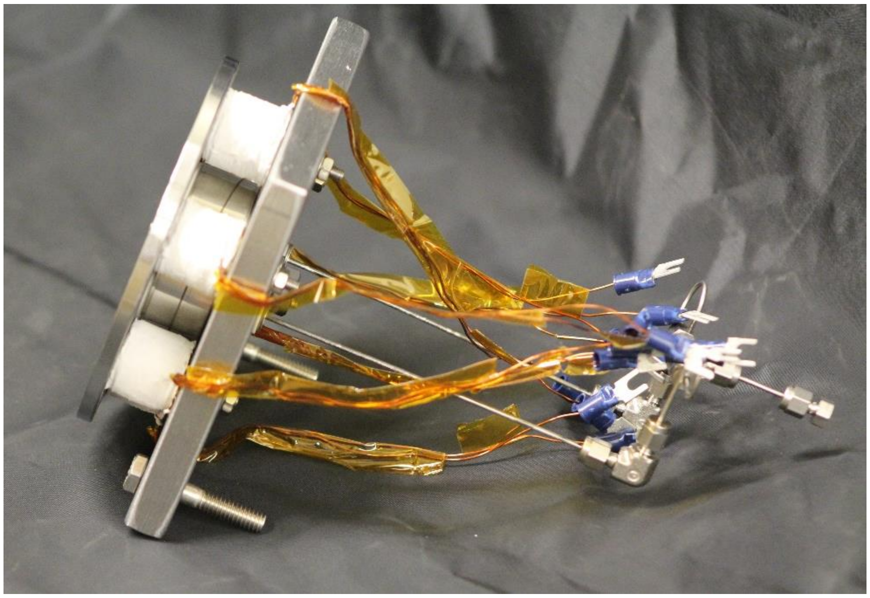

Figure 21 - Side View of the WHT-44.

Figure 22 - Back view of the WHT-44.

4.1 Facility

The test facility is Western Michigan University's ALPE. ALPE's vacuum chamber uses a Turbovac 1100C DN 250 turbo pump with pumping capacity of 1,050 l/s nitrogen and an Edwards 80 E2M80 roughing pump that has a capacity of 53 cfm. The vacuum chamber is 41-in-diameter and 66.5–in-long. Chamber pressure is measured by cold cathode and thermocouple gages. Foreline pressure between the turbopump and roughing pump is measured by a thermocouple gage. This facility is capable of a base pressure around 1E-6 torr. Data collection was performed using a National Instruments USB-6356 DAQ X connected to a desktop housing an Intel Xeon E31275 8-core CPU with 24GB of memory. A Barium–Oxide (BaO) cathode was made available to the ALPE facility for testing.

4.2 Experimental Setup

4.2.1 Magnetic Mapping

A VI was written in LabVIEW to automatically map and log the magnetic field strength axially along the WHT-44 channel. The gaussmeter used was the Lakeshore Model 425 with an 18-inch aluminum stem probe. Samples were taken at 0.5 mm steps from 4.18 mm above the anode surface to 40 mm beyond the exit plane. The probe could not indicate within 4.18 mm due to the sensor location inside the probe. This information was exported to excel and compared to the simulated data. Figure 23 shows the setup used to map the magnetic topography of the WHT-44.

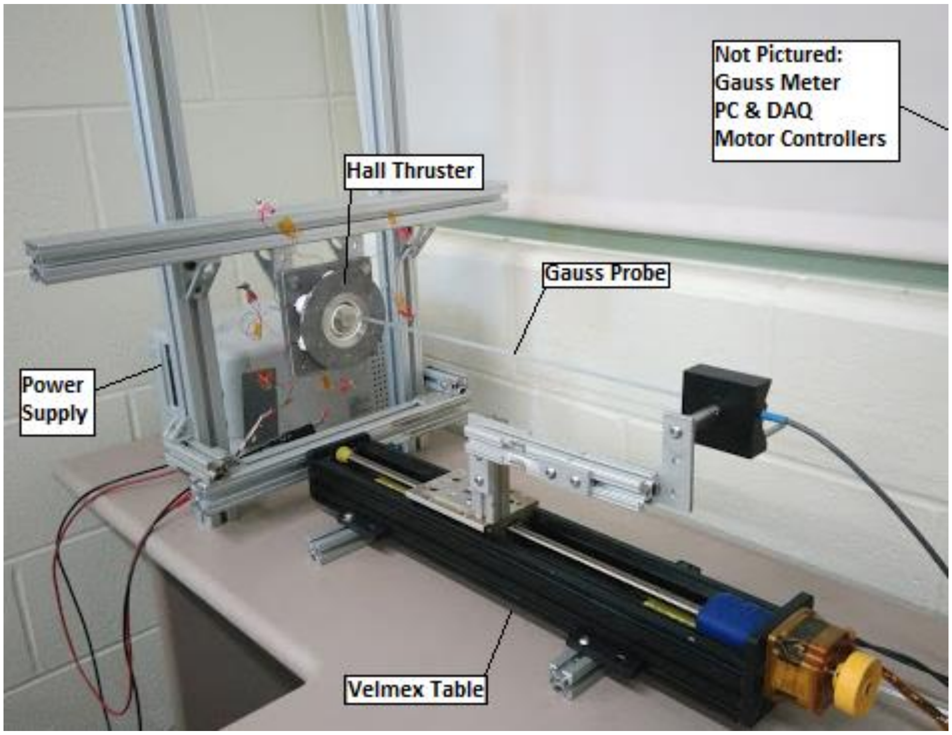

Figure 23 – The above setup was used to determine the magnetic field of the WHT-44 and includes the support structure, gauss probe and Velmex table. Results were recorded by a LabVIEW VI and stored in an Excel spreadsheet.

4.2.2 Vacuum testing

A VI was written in LabVIEW to assist with data acquisition during the HET testing. The program recorded voltages and currents for the cathode heater, cathode keeper, HET magnetic coils, and the test anode. The program took averages of 100 samples every 1 second to display voltage, current, and power. The program continuously outputs the data to an excel spreadsheet. To start the cathode it was recommend to use a test anode. The test anode, shown in Figure 24, is set to a high potential relative to the cathode, this promotes electron mobility out of the cathode. Figure 25 show how the position of the WHT-44 respect to the cathode.

Five power supplies were set up to operate the WHT-44. A Lambda EMS 60-18 was used to power to the cathode heater. A Sorensen DLM600-6.6E was used to power to the cathode keeper. The test anode was powered by a Lamdba EMS 60-40 power supply. All seven magent coils in the WHT-44 were wired in series and supplied by a Lambda GEN100-15 power supply. The WHT-44 discharge power supply was a Sorensen DCS300-3.5.

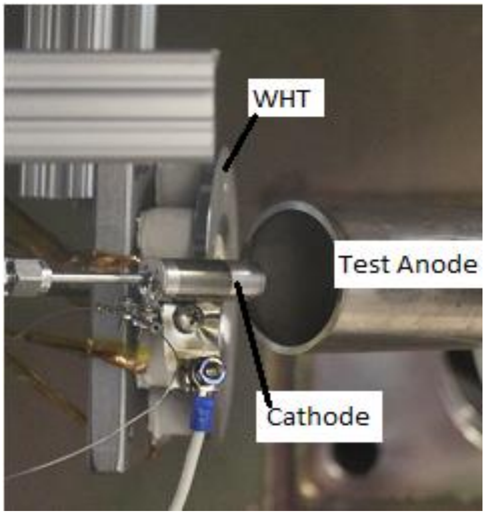

Figure 24: Side view of WHT-44 in Vacuum chamber

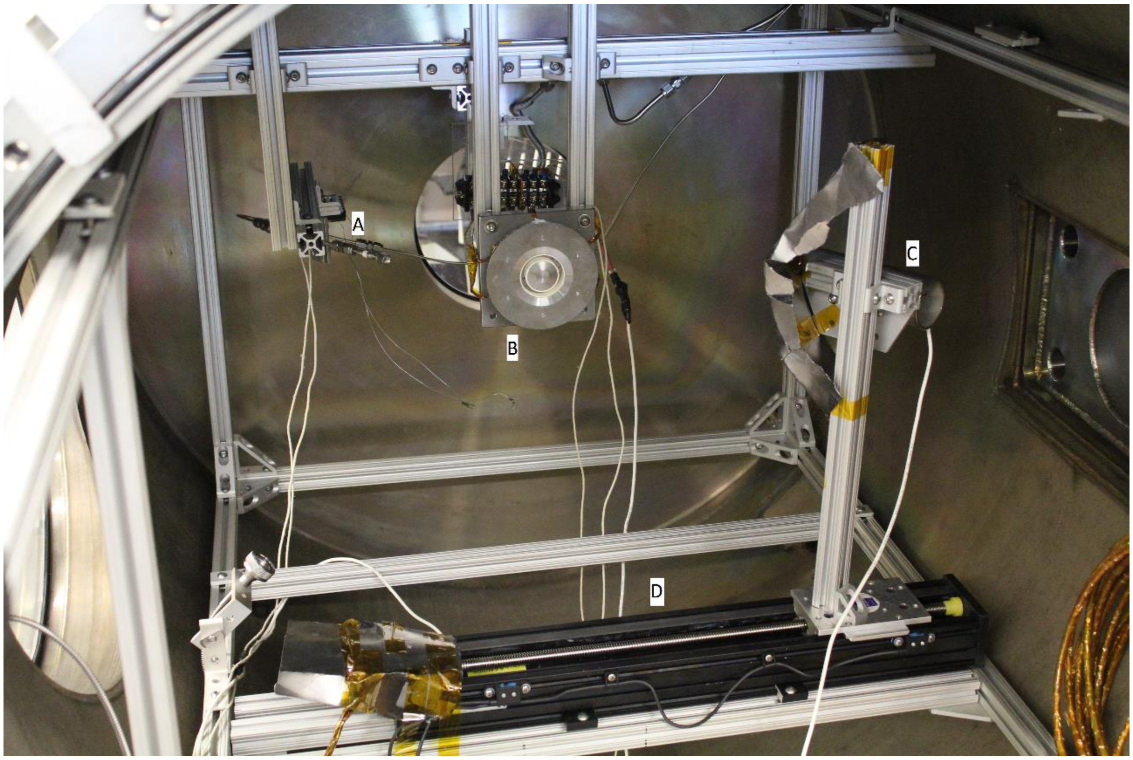

Figure 25: Forward view of WHT-44 in vacuum chamber. A) Cathode position, B) WHT-44 C) Test anode D) Velmex motorized table to move the test anode in place.

4.3.1 Magnetic Lens

The simulated magnetic field shows good agreement with the experimental results as shown in Figure 26. The magnetic field strength at the exit plane is approximately 450 G in both cases. The experiment shows higher values at the anode. This could be from the shielding material reaching saturation. Ideally the magnetic field strength at the anode surface is zero to prevent electron bombardment. Further testing will have to be done to determine if this is detrimental to the WHT-44 operation.

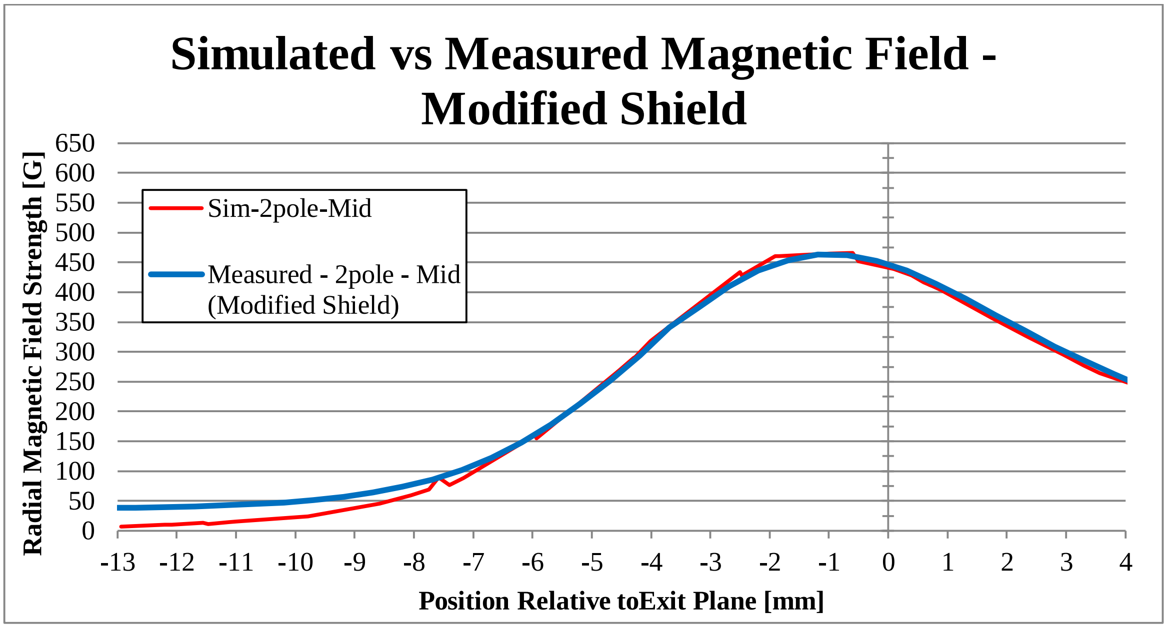

Figure 26 - The resulting magnetic field study plotted against the COMSOL Multiphysics® simulation results directly between the center and an outer pole in the middle of the channel.

4.3.2 Vacuum Testing

Complications with the cathode operation has limited vacuum testing, so as of writing this report, only magnetic lens testing has been performed on the WHT-44.

Future Improvements

After completing the prototype, the team realized that there are ways that the design of the WHT-44 could be improved. Specifically, one of the issues the team encountered was wire management for the magnet cores on the back of the thruster. A constant concern when installing the wires into the vacuum chamber was ensuring that the wires did not become shorted. The design could be modified to naturally accommodate the wires. Also, a redesign of the feed system might allow for a better electrical connection to the anode. This would make the rear of the WHT-44 more organized and easier to mount in a vacuum chamber.

The design could be further refined by finding a new material to act as the magnetic shield. MuMetal® is not recommended because it has a low saturation limit. The number of magnetic cores could be reduced to four. This will simplify the design and reduce construction time, while still maintaining a relatively constant magnetic field through the channel. There was excessive outgassing of the coils in the chamber due to the potting compound. Finding a way to wrap the coils without a potting compound would eliminate this problem.

Thermocouples could be installed on various components so that a temperature characterization of the WHT-44 can be developed. Thermodynamic simulation of the WHT-44 would allow more accurate calculation of expected thermal expansion values. This would allow for comparison of theoretical vs. actual thermal behavior that would lead to improved designs.

The Anode could be refined by finding a new material for fabrication, as stainless steel 316 is difficult to machine. Any replacement material would need to be chosen based on its ability to withstand high temperatures and sputtering. Further simulation of the WHT-44 with respect to rarified gas theory will help develop an anode with uniform gas flow. Testing the WHT-44 with a thrust stand would allow for comparison of actual thrust values to the theoretical thrust values.

5. Conclusion

Due to the complexities surrounding HETs design, COMSOL Multiphysics® and ANSYS® were used to simulate the magnetic lens and fluid flow, respectively. Shielding is required to help shape the magnetic field to minimize electron mobility to the anode surface. The machinability and assembly of the components must be considered when designing parts, to allow for a smooth transition from the designing to fabricating phases. In conclusion,

1. An HET can be built on a very small budget fabricated with typical university machining equipment.
2. COMSOL Multiphysics® can be used to accurately model the magnetic field of an HET.
3. The simulated magnetic field strength at the anode was 7 G while the actual magnetic field strength was 39 G. The simulated anode magnetic field strength is 1.5% of the maximum. The actual anode magnetic field strength is 8.5% of the maximum. It is likely that this error comes from the saturation of the MuMetal® that is still being used at the inner channel wall.
4. Shielding thickness and material requires optimization to maximize exit plane magnetic strength while maintaining the desired lens shape.
5. Magnetic field testing can be performed without the anode in place with negligible differences.

7. References

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[8] B. Reid and A. Gallimore, "Review of Hall Thruster Neutral Flow Dynamics," in *30th International Electric Propulsion Conference*, Florence, 2007.

[9] "MatWeb Material Property Data," [Online]. Available: http://www.matweb.com/.

8. Appendices

Appendix 1 – Design Parameters

The final model parameters are tabulated below:

Parameter,Symbol [Unit]	**Value**
Channel outer diameter,R [mm]	44
Channel inner diameter,r [mm]	34
Channel width, w [mm]	5
Channel depth to anode, L_a [mm]	13
Propellant mass flowrate, $\dot{m}_a$ [mg/s]	0.4-0.96
Discharge current, I_d [A]	0.61-0.92
Anode voltage, V_d [V]	250
Discharge power, P_d [W]	144-216
Wire size	22 AWG
Single coil turns, N	300
Single coil current, I_{mag} [A]	1
Coil power, P_{mag} [W]	0.53
Overall power, P_T [W]	216.5
Ion exit velocity, v_i [m/s]	18.6
Overall maximum efficiency, η_T	0.65

Material Properties						
Name	Density, g/cm^3	Relative Magnetic Permeability	Thermal Conductivity W/m-K	Specific Heat Capacity, J/g-K	Thermal Expansion Coef,10-6 K-1	Electrical Resistivity, Ohm-cm
Boron Nitride Grade HP	1.95	≈1	23 (28⊥)	0.8-1.8	0.4 (0.8⊥)	>1E15
316L Stainless Steel	8	1.008	14-15.9	0.5	16.6-18.2	7.40E-05
Iron (ASTM A848 Type 1)	7.86	*	-	-	13.6	1.30E-07
MuMetal Sheet	8.8	*	30-35	-	13	6.20E-05

- To start the cathode, begin by recording heater and keeper power supply voltages and currents.
- Xenon flow through the cathode is set to 0.1 sccm.
- Begin cathode heat-up by increasing heater current by 0.05 amps every five minutes.
- The cathode is considered at temperature when heater power is between 15-17 W.
- Power should be maintained for one hour and then place the test anode in front of the cathode as shown in Figure 27.
- Apply 15 volts to the test anode, and increase xenon flow rate to 3 sccm.
- Limit keeper current to 1 A and slowly increase keeper voltage to a maximum of 550 V.
- If cathode has not started by 550 V, begin "burping" xenon supply to cathode until cathode is lit.

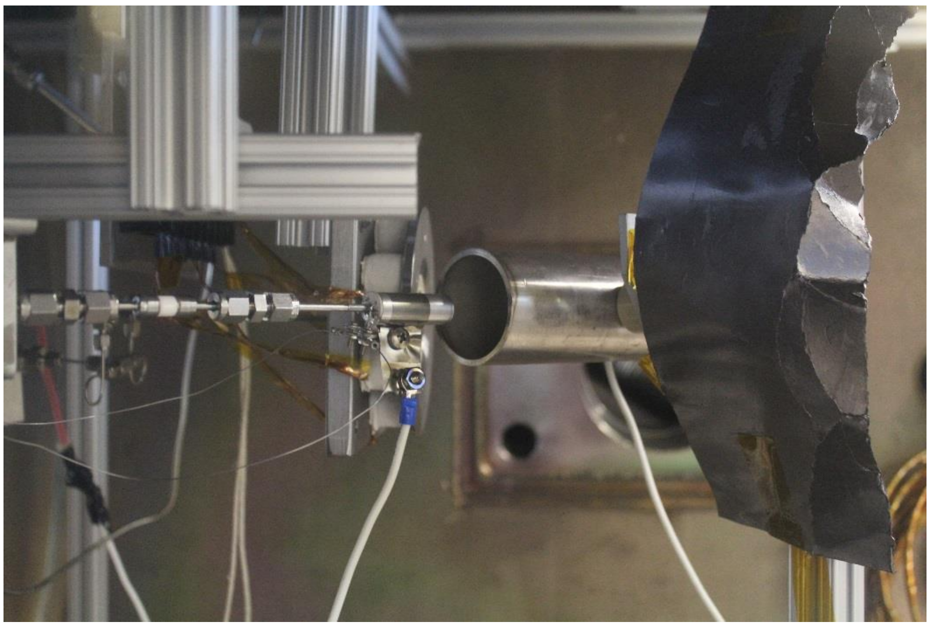


Figure 27 - A test anode was placed 1 cm away from the cathode to assist starting the cathode.

- Once the cathode has started, supply xenon to the WHT-44 at the desired flow rate with the discharge and magnet power supplies off.
- Turn on the discharge and magnet power supplies but, do not begin to apply a voltage or current.
- Set the discharge power supply to 1 A maximum/Voltage limited.
- Slowly increase discharge voltage and magnet current together until a discharge voltage of 230 V is achieved on the discharge power supply and 1 A is achieved on the magnet power supply.
- At this point the WHT-44 will be operating.

Appendix 4 – Gantt Chart

Task Name	Start Date	End Date
Project Start/End Date	**09/09/15**	**04/19/16**
Preliminary Research	**09/10/15**	**10/10/15**
Read 'Fund of EP' Text	09/10/15	09/25/15
Read PEPL Thesis	09/26/15	09/28/15
Visit Glenn National Lab	10/10/15	10/10/15
Modeling and Design	**10/05/15**	**12/22/15**
Complete Basic Hall Thruster Model	10/05/15	10/14/15
Build Basic Model of Final Thruster	10/18/15	11/10/15
Populate Thruster	11/12/15	11/27/15
Sweep Parameters for Optimization	12/02/15	12/16/15
Conference Call with Glenn	12/22/15	12/22/15
Fabrication	**12/15/15**	**02/29/16**
Create an Order List	12/15/15	01/12/16
Order Parts	01/15/16	01/26/16
Assemble Thruster	02/11/16	02/29/16
Testing and Troubleshooting	**03/29/16**	**04/19/16**
Initial Cathode Testing	03/29/16	04/08/16
Initial HET Testing	04/05/16	04/15/16
Present Report	04/19/16	04/19/16

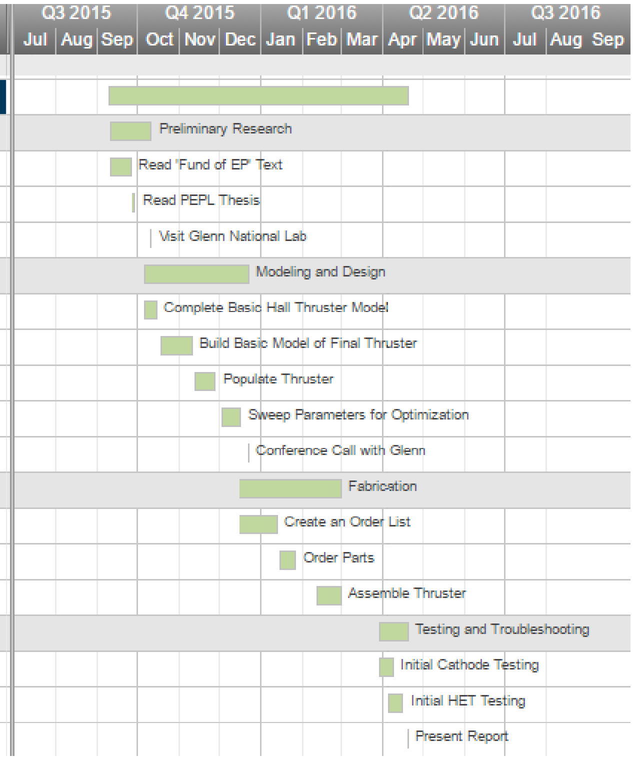


Figure 28 - Gantt Chart describing the initial timeline goal for this project.

Nagual Simmons, Joel Thompson and Matthew Baird have all received the Undergraduate Research Excellence Award. The award is for the amount of 700$ per person, totaling in 2100$. This will be our total budget for this project.

Our initial budget, estimations and costs are shown in Table 1 below:

Table 1 - Budget Information

Category	**Budget,$**	**Estimated Cost,$ (with shipping)**	**Actual Cost,$**
Hardware & Wire	100.00	56.62	181.37
Ceramic	600.00	427.00	512.00
Magnet Metal	300.00	200.00	267.35
Swagelok Fittings	200.00	320.27	297.51
H2 Annealing	100.00	100.00	0.00
Anode	50.00	10.60	61.00
Xe Gas	450.00	450.00	500.00
Carbide Tooling	50.00	50.00	37.65
MuMetal®	250.00	300.00	44.79
Total	**2100.00**	**1914.49**	**1901.67**

Many design alternatives had to be considered during preliminary research phase of this project. Table 2 represents a sample of the alternatives and the method by which design decisions were made.

Table 2 - Decision Matrix

Gas Tube Diameter					
Significance:	0.1	0.3	0.3	0.3	1
Diameter	**Cost**	**Flow Rate**	**Machinability**	**Workability**	**Score**
1/8"	1.0	3.0	3.0	1	73
1/16"	3.0	2.0	2.0	3	80

Number of Magnets					
Significance:	0.25	0.1	0.5	0.15	1
#	**Cost**	**Assembling Complexity**	**B Continuity**	**Power Required**	**Score**
4 Magnets	3	3	1	3	67
6 Magnets	2	2	3	2	83
8 Magnets	1	1	3	1	67

Body Material					
Significance	0.35	0.15	0.25	0.25	1
Material	**Machinability**	**Cost**	**Thermal Conductivity**	**Wear Properties**	**Score**
Boron nitride	3	1	3	3	90
Alumina	2	2	3	2	75

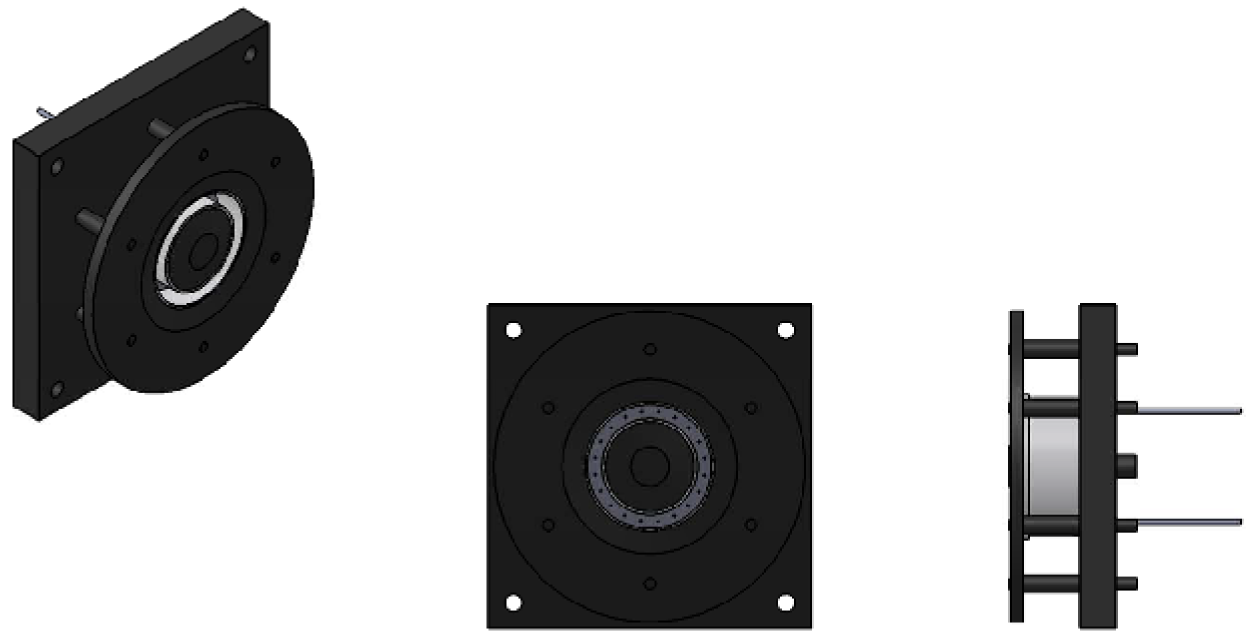
Core Material						
Significance:	0.1	0.4	0.2	0.2	0.1	1
Wire Gauge	**Cost**	**Permeability**	**Machinability**	**Availability**	**Erosion Resistance**	**Score**
Silicon Steel	2	3	2	2	2	80
Stainless Steel	2	2	3	2	2	73
Regular Iron	3	1	2	2	1	57

This will not be a consumer product; therefore, a more appropriate approach to benchmarking was taken. This modified approach consisted of challenging the conventional method of obtaining an HET for study by a research group. Typically, if a group wished to obtain an HET, they must contact a manufacturer and arrange to have one shipped. This is very expensive and may minimize educational value. This project proposes that the university is capable of building and operating an HET themselves. With this in mind, a comparison was made between building a HET and purchasing a comparable HET from a company.

Table 3 - Benchmarking

		Educational Value				Costs		Operation			
Model	**Company**	**Support Structure**	**Fabrication**	**Operation**	**Repair**	**Initial Cost**	**Upkeep**	**Estimated Lifetime**	**Thrust (mN)**	**Flowrate (mg/s)**	**Isp (s)**
BHT-200	Busek	Extensive	N	Y	N	$20,000.00	$1,000.00	15,000 Hours	13	0.84	1390
BHT-600	Busek	Extensive	N	Y	N	$800,000.00	$10,000.00	15,000 Hours	42	2.6	1650
BHT-1000	Busek	Extensive	N	Y	N	$1,2M	$20,000.00	15,000 Hours	58	3	1750
DIY	n/a	None	Y	Y	Y	$2,000.00	$1,000.00	800 Hours	5.5	0.84	594

The Following documents were created using SolidWorks®



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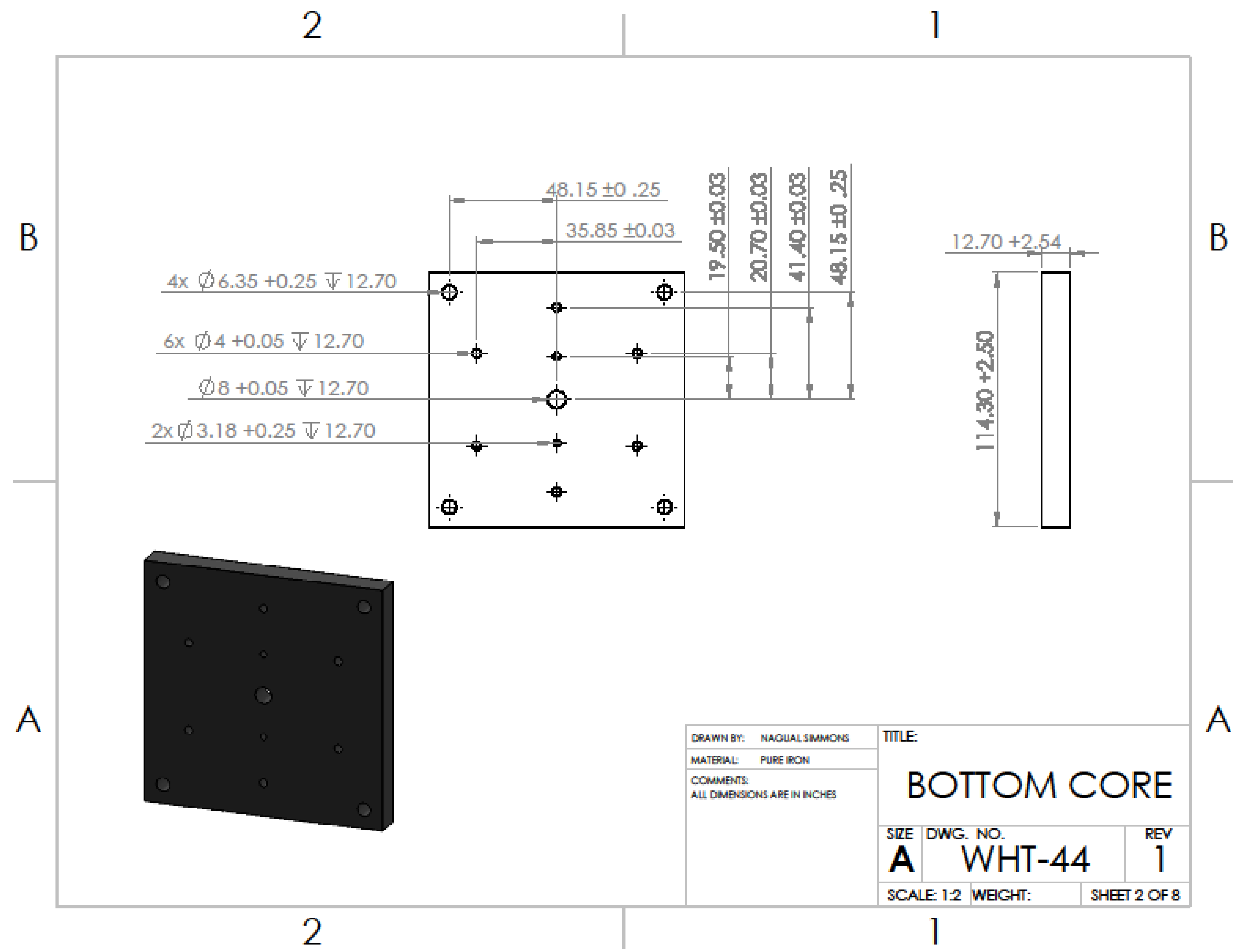
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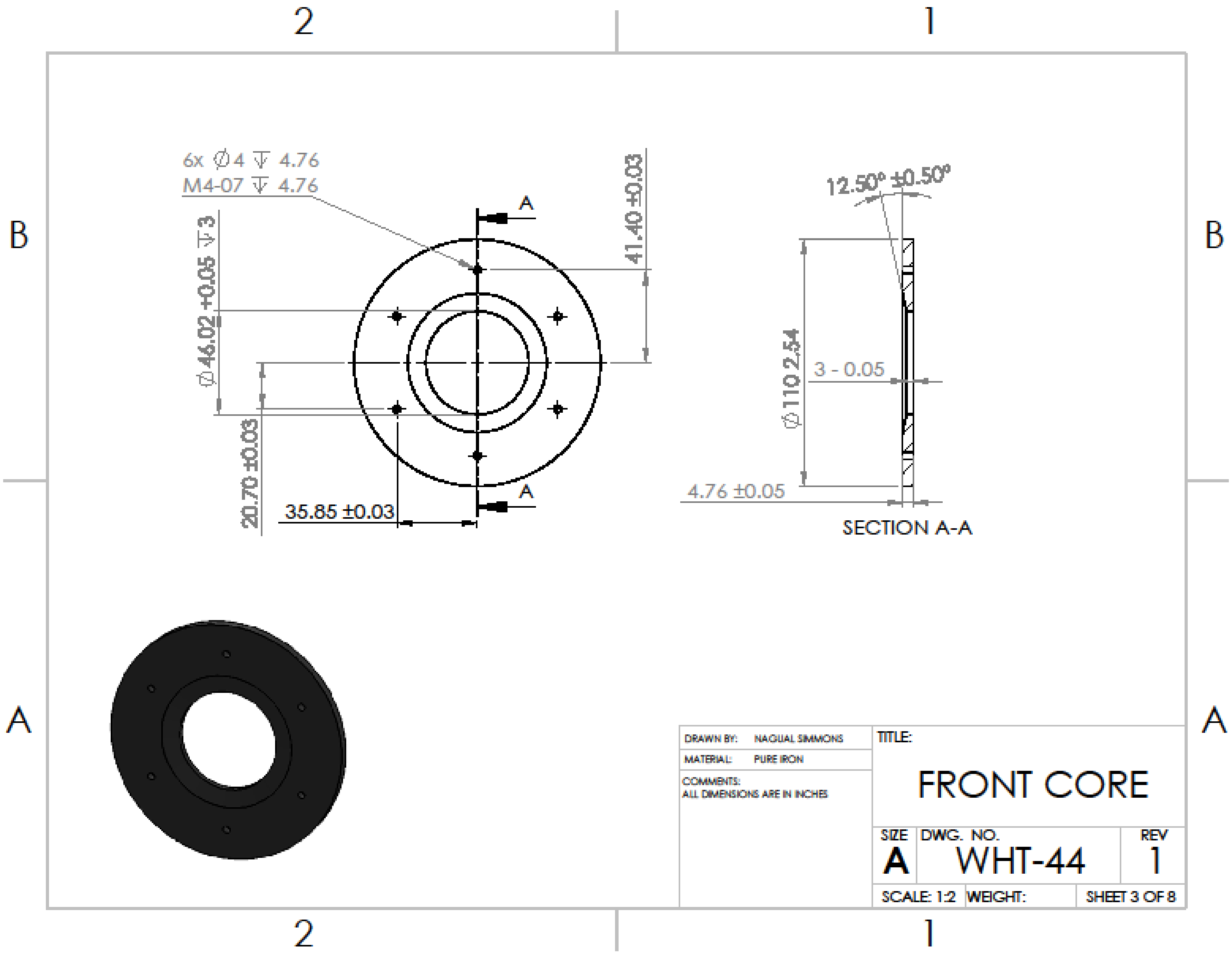
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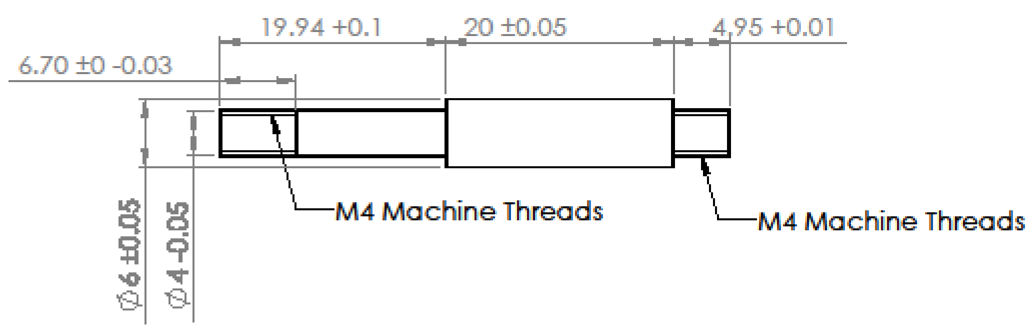

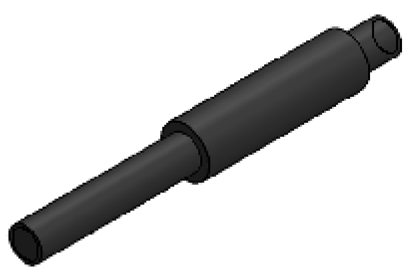

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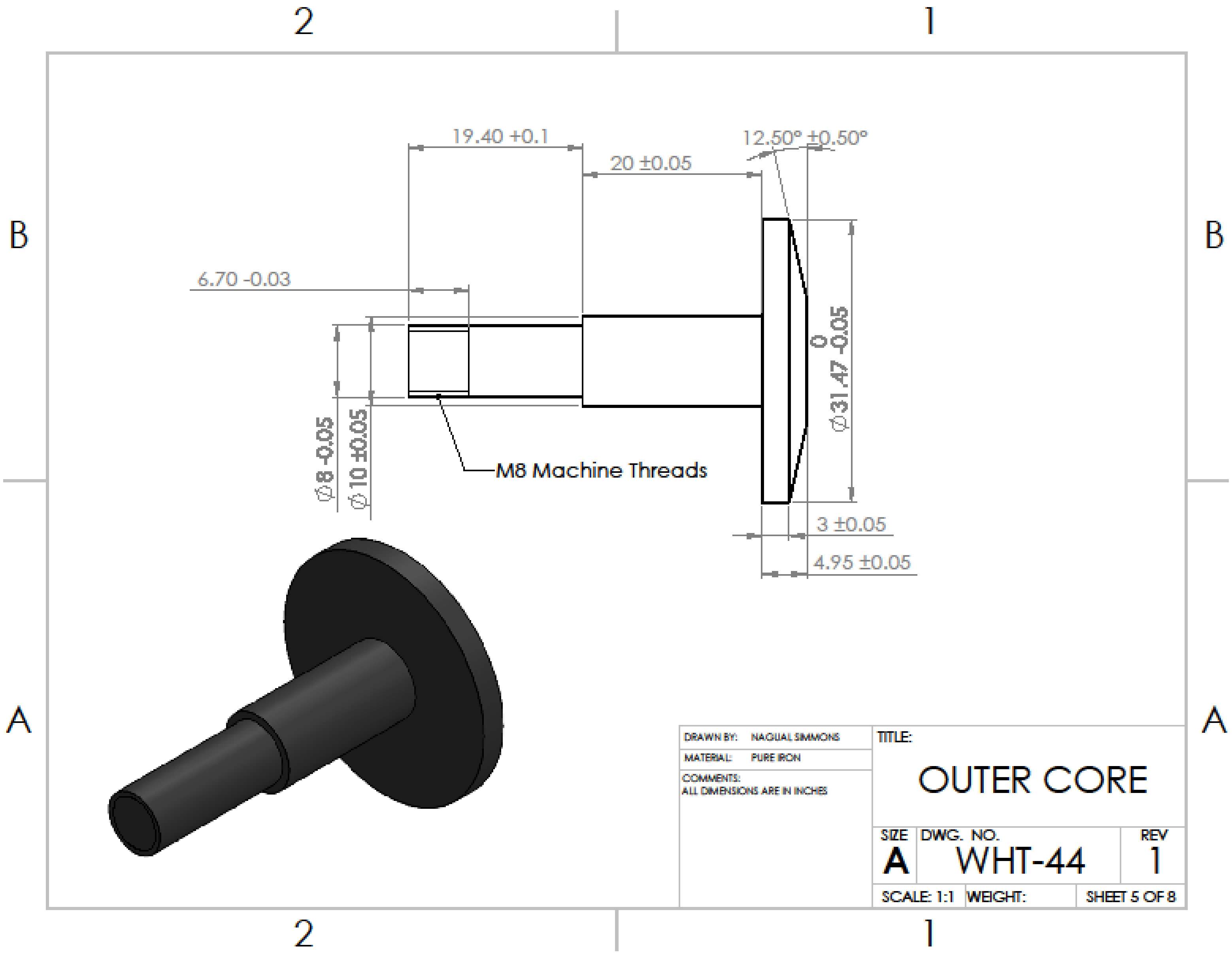

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12.50° ±0.50°
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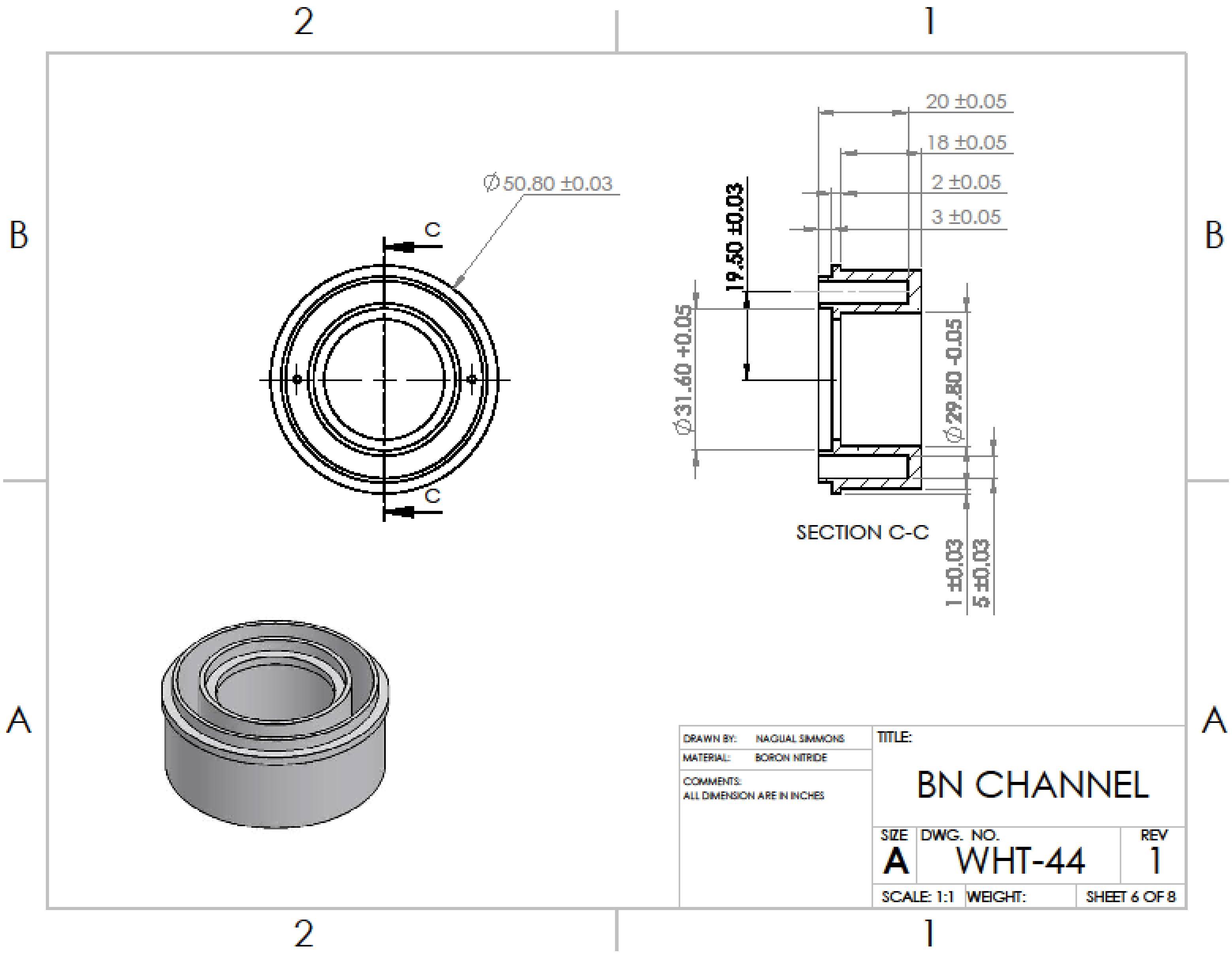
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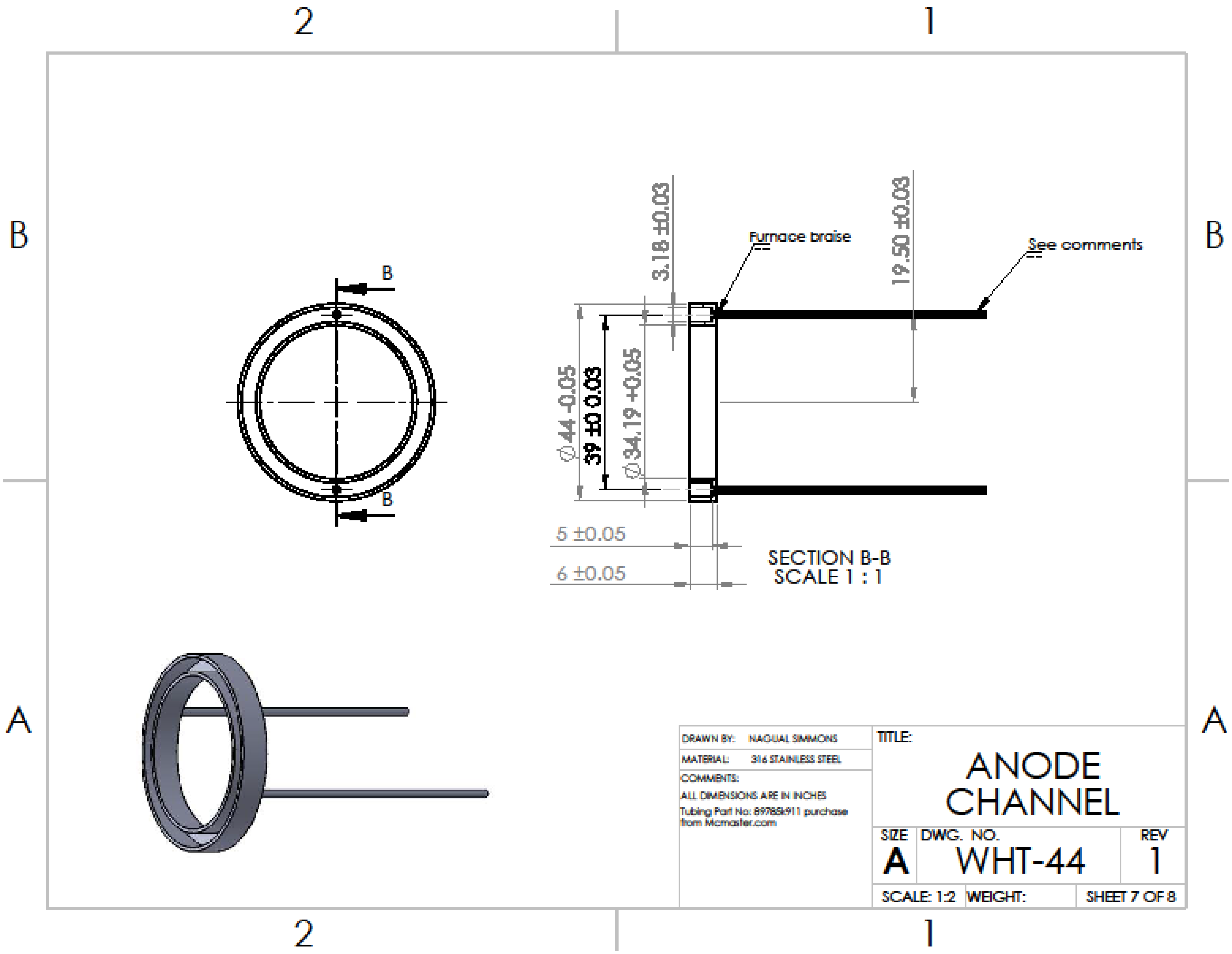
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SECTION B-B
SCALE 1 : 1
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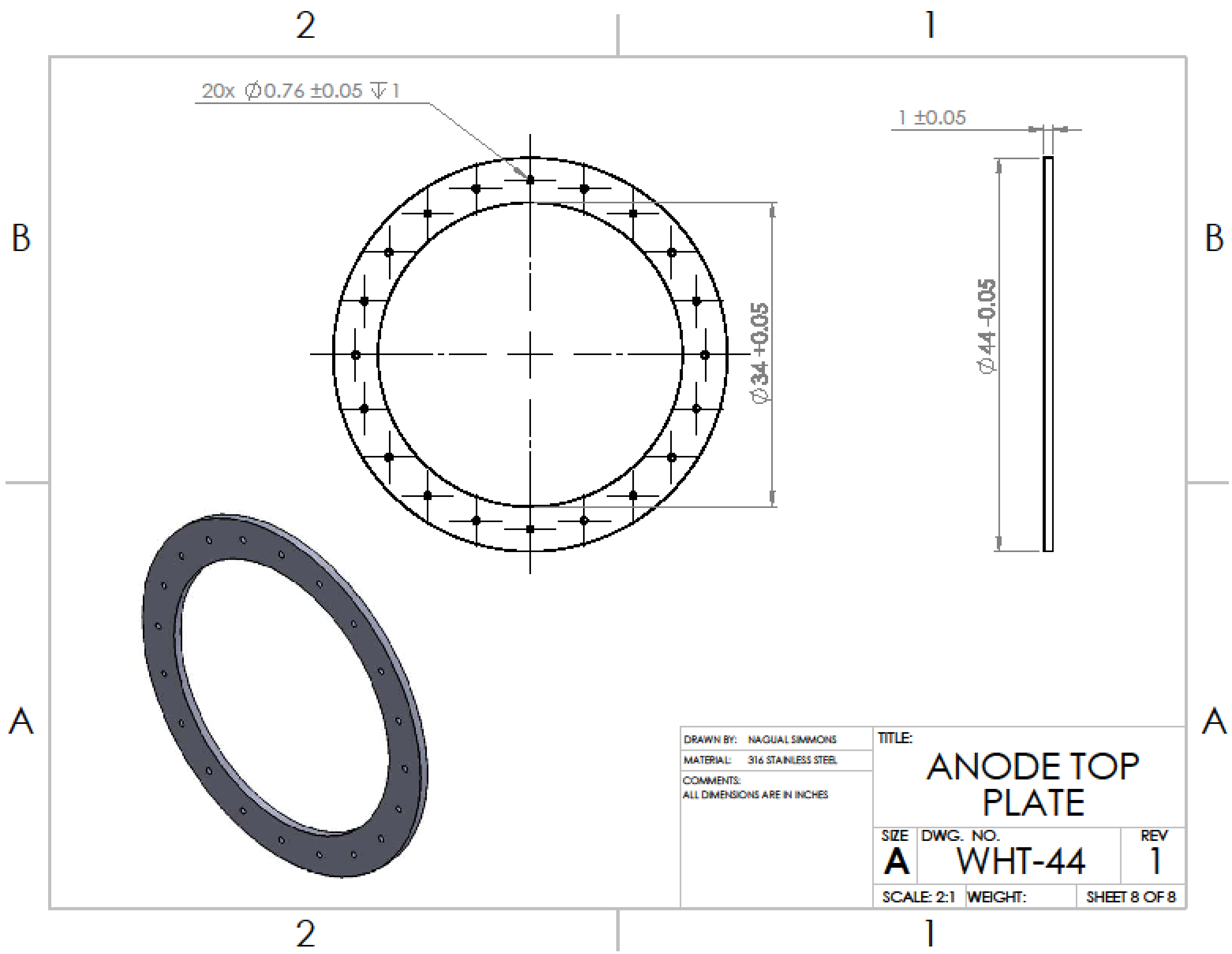
MATERIAL: 316 STAINLESS STEEL
COMMENTS:
ALL DIMENSIONS ARE IN INCHES
Tubing Part No: 89785k911 purchase from Mcmaster.com
TITLE:
ANODE CHANNEL
SIZE A
DWG. NO. WHT-44
REV 1
SCALE: 1:2
WEIGHT:
SHEET 7 OF 8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20x ∅0.76 ±0.05 ↧ 1
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∅44 -0.05
DRAWN BY: NAQUAL SIMMONS
MATERIAL: 316 STAINLESS STEEL
COMMENTS:
ALL DIMENSIONS ARE IN INCHES
TITLE:
ANODE TOP PLATE
SIZE A
DWG. NO. WHT-44
REV 1
SCALE: 2:1
WEIGHT:
SHEET 8 OF 8

Form 1
Student Completes

Assessment of Student Outcome #5
ME4800

The MAE faculty members have identified "**An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability**" as one of the student outcomes for both mechanical and aeronautical engineering programs. As part of your design project, we ask you to answer the following questions. You are required to submit the completed form with your final report in ME 4800. In your final report, please include page references in response to each question below.

Evaluation of student outcome "**An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability**"

1. This project involved the design of a: *system / component / process*

   Description:
   An iteritive design process that lead to the assembly of several components to create a Hall effect thruster.

2. The ***need***:
   By making Hall effect thrusters accessible to more university we hope to allow more students the opportunity to perform plasma analysis.

3. The **constraints**: (Explain and justify any constraint that was relevant to the project. At least 3 constraints must be addressed.)

   Economic:
   In order for Hall thrusters to be considered accessible it had to be built on a simple budget of $2100.00

   Environmental :

   Social:

   Political:

   Ethical:

   Health& Safety:
   Working with heavy machinery meant that precautions needed to be taken to ensure the safety of operators and bystanders.

Manufacturability:

The goal was to show that the thruster could be designed in house; Only a mill and lathe were used to machine the thruster.

Sustainability:

Others:

4. Is there a potential for a new patent in your design? Explain and compare with related patents.

No.

Form 2
Student Completes

<u>Assessment of Student Outcome #9</u>
<u>ME 4800</u>

The MAE faculty members have identified "**<u>A knowledge of contemporary issues</u>**" as one of the student outcomes for both mechanical and aeronautical engineering programs. **Contemporary issues are any issues that you hear on the news related to new and old products and their safety, new innovations, technologies, standards and regulations in general.** As you develop your proposal for your senior design project, we ask you to start answering the following questions. These questions will guide you in the development of ideas you need to include in your proposal and final project reports. You are required to submit the completed form with your final proposal in ME 4790 and again with your final report in ME 4800. In your proposal and report, please include page references in response to each question below.

Evaluation of student outcome "**<u>A knowledge of contemporary issues</u>**"

1. Why is this project needed now?

NASA has called out Hall thrusters for specific missions in their technology roadmap.

2. Describe any new technologies and recent innovations utilized to complete this project.

None.

3. If this project is done for a company—how will it expand their potential markets? ***---how will it improve satisfaction of the company's existing customers?***

NA

---identify the competitors for this kind of a product, compare the proposed design with the company's competitors' products.

NA

4. How did you address any safety and/or legal issues pertaining to this project (e.g., OSHA, EPA, Human Factors, etc.).

NA

5. Are there any new standards or regulations on the horizon that could impact the development of this project?

Many HETs, including ours, have a finite life due to corrosion of the channel. Recently, magnetically shielded HET prevents corrosion to obtain an almost infinite life.

6. Is there a potential for a new patent in your design? Please document related patents.
No.

Does this project impact:

Human health?
NA

Wildlife?
NA

Vegetation?
NA

Does this project improve:

Human interaction?
NA

Well being?
NA

Safety?
NA

Others?

Nagual Simmons

Form 4
Student Completes

Assessment of Student Outcome #13
ME 4800

The MAE faculty have identified **"A recognition of the need for, and ability to engage in life-long learning"** as one of the student outcomes for both mechanical and aeronautical engineering programs. As you develop your senior design project, we ask you to start answering the following questions. These questions will guide you in the development of ideas you need to include in your final project report. You are required to submit the completed form in the last appendix of your final report. Please include the page numbers of the report that addresses the answers to the following questions.

Your responses will be used in the Evaluation of student outcome **"A recognition of the need for, and ability to engage in lifelong learning."**

A well-organized team brings necessary backgrounds and talents together that are needed to successfully execute the design process. Each team member plays an important role on the design team. Individual members must be prepared to gain any additional skills necessary, and improve existing skills during project execution. Your response to the questions below will be evaluated for our ability to convey the need for lifelong learning and your ability to be creative in recognizing the need and acquiring the requisite knowledge.

ME 4800
Mechanical and Aeronautical Engineering Design Project

For each team member:
1. List the skills you needed to execute your responsibilities on the project as outlined in ME 4790.
My extended knowledge in Solidworks allowed for the creation of technical drawings and proved to be useful for working in COMSOL Multiphysics.

2. List how you gained the requisite skill, or enhanced your existing skill, to the benefit of your design team and the project.
This project allowed me to gain knowledge in fabrication and assembly processes. It also enhanced my ability to search and find scholarly articles.

Matthew Baird

Form 4
Student Completes

Assessment of Student Outcome #13
ME 4800

The MAE faculty have identified **"A recognition of the need for, and ability to engage in life-long learning"** as one of the student outcomes for both mechanical and aeronautical engineering programs. As you develop your senior design project, we ask you to start answering the following questions. These questions will guide you in the development of ideas you need to include in your final project report. You are required to submit the completed form in the last appendix of your final report. Please include the page numbers of the report that addresses the answers to the following questions.

Your responses will be used in the Evaluation of student outcome **"A recognition of the need for, and ability to engage in lifelong learning."**

A well-organized team brings necessary backgrounds and talents together that are needed to successfully execute the design process. Each team member plays an important role on the design team. Individual members must be prepared to gain any additional skills necessary, and improve existing skills during project execution. Your response to the questions below will be evaluated for our ability to convey the need for lifelong learning and your ability to be creative in recognizing the need and acquiring the requisite knowledge.

ME 4800
Mechanical and Aeronautical Engineering Design Project

For each team member:

1. List the skills you needed to execute your responsibilities on the project as outlined in ME 4790.

I regularly fabricate test equipment and prototypes for WMU's ALPE. This experience combined with his knowledge of electric propulsion assisted the group in the design, fabrication, and testing phases.

2. List how you gained the requisite skill, or enhanced your existing skill, to the benefit of your design team and the project.

I expanded my level of knowledge and experience into manufacturing materials that are more specialized. I have learned a great deal about design specific to electric propulsion.

Joel Thompson

Form 4
Student Completes

Assessment of Student Outcome #13
ME 4800

The MAE faculty have identified "**A recognition of the need for, and ability to engage in life-long learning**" as one of the student outcomes for both mechanical and aeronautical engineering programs. As you develop your senior design project, we ask you to start answering the following questions. These questions will guide you in the development of ideas you need to include in your final project report. You are required to submit the completed form in the last appendix of your final report. Please include the page numbers of the report that addresses the answers to the following questions.

Your responses will be used in the Evaluation of student outcome "**A recognition of the need for, and ability to engage in lifelong learning.**"

A well-organized team brings necessary backgrounds and talents together that are needed to successfully execute the design process. Each team member plays an important role on the design team. Individual members must be prepared to gain any additional skills necessary, and improve existing skills during project execution. Your response to the questions below will be evaluated for our ability to convey the need for lifelong learning and your ability to be creative in recognizing the need and acquiring the requisite knowledge.

ME 4800
Mechanical and Aeronautical Engineering Design Project

For each team member:

1. List the skills you needed to execute your responsibilities on the project as outlined in ME 4790.

I was responsible for finding and ordering the required parts to complete the prototype.

I also assisted with fabrication and design of the prototype.

2. List how you gained the requisite skill, or enhanced your existing skill, to the benefit of your design team and the project.

I gained an understanding of how to use equipment to manufacture percision parts and how to machine tougher materials. I learned about vaccum rated materials and other considerations when doing vacuum testing.

Attached are resumes for the following personnel:

Mathew Baird

Nagual Simmons

Joel Thompson

Matthew J. Baird

3315 Austrian Pine Way, Portage, MI 49024
269 270 5198 / baird.matthew.j@gmail.com

PROFESSIONAL SUMMARY

Enlisted in the United States Navy from 2006 to present. 4 years experience serving on a fast attack submarine as a nuclear trained laboratory and radiological controls technician with administrative, technical, and supervisory responsibilities. From January 2013 to present, seeking Mechanical Engineering degree with honors while working as a research assistant at Western Michigan University's Aerospace Laboratory for Plasma Experiments.

Western Michigan University, Lee Honors College — *Kalamazoo, MI*
Bachelor of Science in Engineering — **Anticipated Graduation: April 2016**
Major: Mechanical Engineering – Accelerated Degree Program — GPA: 3.97
Dean's List — January 2013-Present

US Navy Nuclear Training — *Goose Creek, SC and Groton, CT*
Operational Water Chemistry School — February 2009
Nuclear Power Training Unit — May 2007 to March 2008
Naval Nuclear Power School — November 2006 to May 2007
Nuclear Field Machinist School — July 2006 to November 2007

PROFESSIONAL EXPERIENCE

Western Michigan University — *Kalamazoo, MI*
Research Assistant — **September 2014 to Present**
- Designed and fabricated a 230W Hall effect thruster.
- Measured the 3D magnetic field around a cube satellite by creating an automated high resolution mapping system.
- Analyzed the vaporization byproducts of ionic liquids through the use of Residual Gas Analysis, Optical Emission Spectroscopy, and Liquid chromatography–mass spectrometry.
- Experimented with plasma generation using direct current and extracted emission data.
- Conducted materials research and wrote reports of findings, focusing heavily on electron dispersive spectroscopy.
- Operated, maintained, and troubleshot a scanning electron microscope with an energy dispersive system.

Assistant Machinist — **October 2014 to October 2015**
- Fabricated precision research equipment for mechanical, aerospace, and manufacturing engineering departments.
- Developed skills with a lathe, mill, and metrology.
- Experience operating a computer and numerical control milling machine.

US Naval Reserves — *Battle Creek, MI*
Active Reservist — **July 2014 to October 2015**
- Designed modifications to a new Safety Gangway, reducing manufacturing costs and making traversing moored ships much safer.
- Supported the Ship Repair Facility for Yokosuka, Japan.

USS Oklahoma City (SSN-723) — *Portsmouth, NH and Naval Base Guam*
Quality Assurance Inspector / Planner — **February 2011 to May 2012**
- Performed cleanliness inspections during maintenance and repairs for reactor and steam plant systems.

- Wrote 15 complex reactor plant repair procedures to the highest standards, requiring no rework.
- Approved over 50 preventative and corrective maintenance evolutions to ensure first time success of the job.
- Monitored mechanical and electrical maintenance to ensure compliance of procedures and safety precautions.

Leading Engineering Laboratory Technician **November 2010 to May 2012**

- Managed and trained a division of 5 junior personnel in the use of radiological controls, dosimetry processing, and water chemistry.
- Planned, staged, and directed radiological work of complex evolutions.
- Directed the control and analysis of primary and secondary plant chemistry, such as developing complex chemistry plans for start-ups, shutdowns, and fills.
- Processed dosimetry and tracked the radiation exposure for over 150 personnel.
- Directed and coordinated the cleanup actions of 11 radioactive spills minimizing work delays for Portsmouth Naval Shipyard.

Engine Room Supervisor **August 2009 to May 2012**

- Coordinated a team of 7 personnel, giving oversight to the safe and efficient operation of the steam and reactor plant during 2 overseas deployments and over 20 complex training evolutions.
- Operated and maintained electrical and mechanical equipment such as main and auxiliary pumps, steam generators, reduction gears, valves, turbines, refrigeration and distilling units.
- Supervised all aspects of 5 subordinate watch stations, including plant operations, maintenance, safety, and material condition.
- Directed and coordinated the response to abnormal, transient, and accident conditions, in accordance with approved procedures including combating fires on 2 occasions which may have resulted in damaged equipment or injured personnel.
- Trained and qualified personnel in basic and advanced fire-fighting techniques, first aid, and emergency rescue for response to plant emergencies and personnel injury and illness.

AWARDS AND ACHIEVEMENTS

- Presidential Scholar for Mechanical and Aerospace Engineering
- Undergraduate Physics Course Award
- 2 Undergraduate Research Excellence Awards
- 2 Kenneth Knight Scholarships
- 2 Navy and Marine Corps Achievement Medals
- 3 Good Conduct Medals
- Navy Operational Support Center Battle Creek Sailor of the Quarter

TECHNOLOGY SKILLS

COMSOL	MatLAB
MathCAD	LabVIEW
C++	Python
Autodesk AutoCAD & Fusion 360	LT Spice
Solidworks	ANSYS

INTERESTS AND ACTIVITIES

- Volunteer mathematics tutor for elementary and middle school students
- Summer science camp volunteer
- Physical fitness—trail running, rock climbing, and scuba diving.
- Enjoy programming, electrical, mechanical, and woodworking projects (home computers, automated film equipment, CNC router, Arduino, and furniture).

NAGUAL SIMMONS

1404 Howland Ave. Kalamazoo, MI 49001
Email: nasimmons87@gmail.com
Cell: 269-341-5854

OBJECTIVE

To obtain a career in the Mechanical Engineering industry that will not only provide me with a challenging opportunity but also utilizes my analytical and leadership skills.

CORE COMPETENCIES

CAD Design	Microsoft Office	MatLAB
Project and task management	Finite Element Analysis	Problem Analysis
Design and Development	Material Selection	Fabrication Techniques

EDUCATION

Western Michigan University Kalamazoo, MI
Master of Science in Mechanical Engineering April 2018

Western Michigan University Kalamazoo, MI
Bachelor of Science in Mechanical Engineering April 2016

WORK EXPERIENCE

Western Michigan University Kalamazoo, MI
Graduate Research Assistant, Jan. 2016- Present

- Conducted research to obtain a baseline for state-of-the-art CubeSat technologies.
- Critiqued team members to ensure convergence of mission.

Office Depot Kalamazoo, MI
Department Manager, Sept. 11' – Apr. 15'

- Eliminated inconsistencies in day-to-day task to provide exceptional customer service.
- Developed team-based atmosphere to increase Q1 14' sales numbers.

Hollywood Video Kalamazoo, MI
Store Manager, Nov. 06' – May 10'

- Introduced the idea of posting employee performance, which greatly increase accountability.

LEADERSHIP

President , Western Aerospace Launch Initiative (WALI), Jan. 16 - Present

- Coordinated conventions to recruit new members that increased the number of members
- Managed outreach projects to get kids in k-12 interested in the sciences.

PROJECTS

Accessible Hall Thruster Design, Fabrication, and Testing, Sept. 15' – Apr. 16'

- Created technical drawings for machining operations
- Conducted an iterative design process that lead to final product

Program Manager on Plasma Spectroscopy Mission, Jan. 16 – Present

- Created prioritization plan to ensure high priority processes are addressed.
- Delegated resources to teams that were falling behind schedule

Joel Benjamin Thompson

6827 Southwind Street, Kalamazoo, MI 49009
(269)364-0488 joel.thompson@wmich.edu

PROFESSIONAL SUMMARY

Enlisted in the United States Navy from 2006 to 2012. Four years of experience operating and maintaining nuclear systems onboard an aircraft carrier as a mechanic and watch standing supervisor. Active member of Western Michigan University's Sunseeker Solar Car team since 2012 and served as the team's mechanical lead for nearly two years. Currently working as a research assistant in the heavy machinery lab using Adams View to perform vibration analysis. Senior capstone project is the design and fabrication of an electric propulsion thruster.

EDUCATION

Western Michigan University	Kalamazoo, MI
Bachelor of Science and Engineering - Mechanical Engineering	Graduation: May 2016
Minor: Mathematics	GPA 3.32
Navy Nuclear Propulsion Program	Charleston, SC and Ballston Spa, NY
Navy Nuclear "A" School	September 2006 - December 2006
Navy Nuclear Power School	January 2007 - June 2007
Navy Nuclear Prototype	July 2007 - February 2008

HIGHLIGHTS OF QUALIFICATIONS

- Performed maintenance on four industrial turbine systems and their associated oil, high pressure and low pressure steam drain systems.
- Performed maintenance on three air compressor and pneumatic systems.
- Secret clearance expires 2016.
- Two years of experience as senior in plant watch stander.
- Led watch team of six people through Operations and Reactor Safety Examination and awarded an above average rating.
- Technical manual and system drawing reading experience for mechanical systems and using associated technical documents.
- Assured the safety of the ship's crew by preparing 500+ tag-outs for one main machinery room during a repair availability with no safety incidents.

RELEVANT EXPERIENCE

Sunseeker Solar Car Team **October 2012 - Present**

- Mechanical Lead from June 2014 to August 2015 and lead the team to a third place finish at the 2014 Formula Sun Grand Prix.
- Maintained 2 solar cars in good condition and prepared the most current car for the 2014 American Solar Challenge.
- Drove in two separate Formula Sun Grand Prix races and the 2014 road race with competitive finishes in all 3 races.
- Assisted with designing the 2016 solar car chassis and suspension to maximize dynamic stability during cornering and decrease energy losses of the car due to scrub while maintaining a structurally sound chassis.
- Mentored new Mechanical Lead and Assistant Team Lead to increase team knowledge retention.
- Taught the newest generation of Sunseekers on car maintenance and operation, assuring the team stays strong.

Western Michigan University **August 2015 - Present**

Senior Design Project

- Design and fabricate a prototype Hall Effect thruster.
- Create standardized model that can be used at other universities.
- Met objectives for low cost and easy manufacturability.

Research Assistant for Engineering Design, Manufacturing and Management Systems Dept.

- Design complex system in dynamics software to perform vibrational analysis.
- Compare results of vibrational analysis to the results from the machine to verify accuracy of the model.
- Recommended counter-weight system to fix vibrational issues with machine and safely increase operational speed of the machine.

United States Navy **July 2006 –July2012**

USS George Washington CVN-73

Chief Machinery Operator

- Supervised operation of two main engines, two distilling units, two high pressure air compressors and one low pressure air compressor.
- Trained and supervised six subordinate watch standers with no on watch injuries and quick response times to equipment malfunctions.
- Directly responsible for the production of 4160-volt electrical power and distribution of 200,000 gallons of potable water to the ship per day.
- Oversaw logistics for one main machinery room during 2009-2010 selective repair availability.
- Maintained high level of readiness of all plant components.

APPLICABLE CLASSES

Vehicle Dynamics, Machine Design, Heat Transfer, Thermodynamics, Control Systems, Instrumentation, Dynamics, Mechanics of Materials, Statics, Material Science, Machines and Electronic Circuits, Mechanism Analysis, Processes and Materials, Engineering Experimentation

AWARDS AND ACTIVITES

Student Veterans Association **October 2014 - Present**

- Student Senator from 2014 to 2015.

Academic Achievements

- Dean's list for two semesters.
- Inducted into Tau Beta Pie honor society in April 2015.
- Awarded the Undergraduate Research Excellence Award to conduct research on electric propulsion.

TECHNOLOGY SKILLS

Adams	COMSOL
MatLAB	Microsoft Suite
Autodesk Inventor	LabVIEW
Solidworks	Romax
ANSYS-Fluent	MathCAD