Plasma thrusters: A new frontier in Advanced propulsion

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The following paper is in accordance with the ending requirements set by the Undergraduate research opportunities program at the University of Minnesota at Twin Cities. The report demonstrates the final work and progress made over the fall semester for the proposal of "Plasma-Based Electric Propulsion for Deep Space Exploration –Part I: Design of an Experiment." The paper describes the literature reviewed and some data generated during the process. It will also give an overview of an Atmospheric Pressure Plasma Jet (APPJ) as a primary design starting point for advanced propulsion technologies. Using the basic anatomy of the APPJ, future designs will be made and fabricated for a more elaborate research effort. A simple draw.io diagram for the APPJ would be demonstrated along with some CAD renders to set up expectations for the final design. This will also set goals for future research ideas following, which will involve fabrication and testing.

Introduction

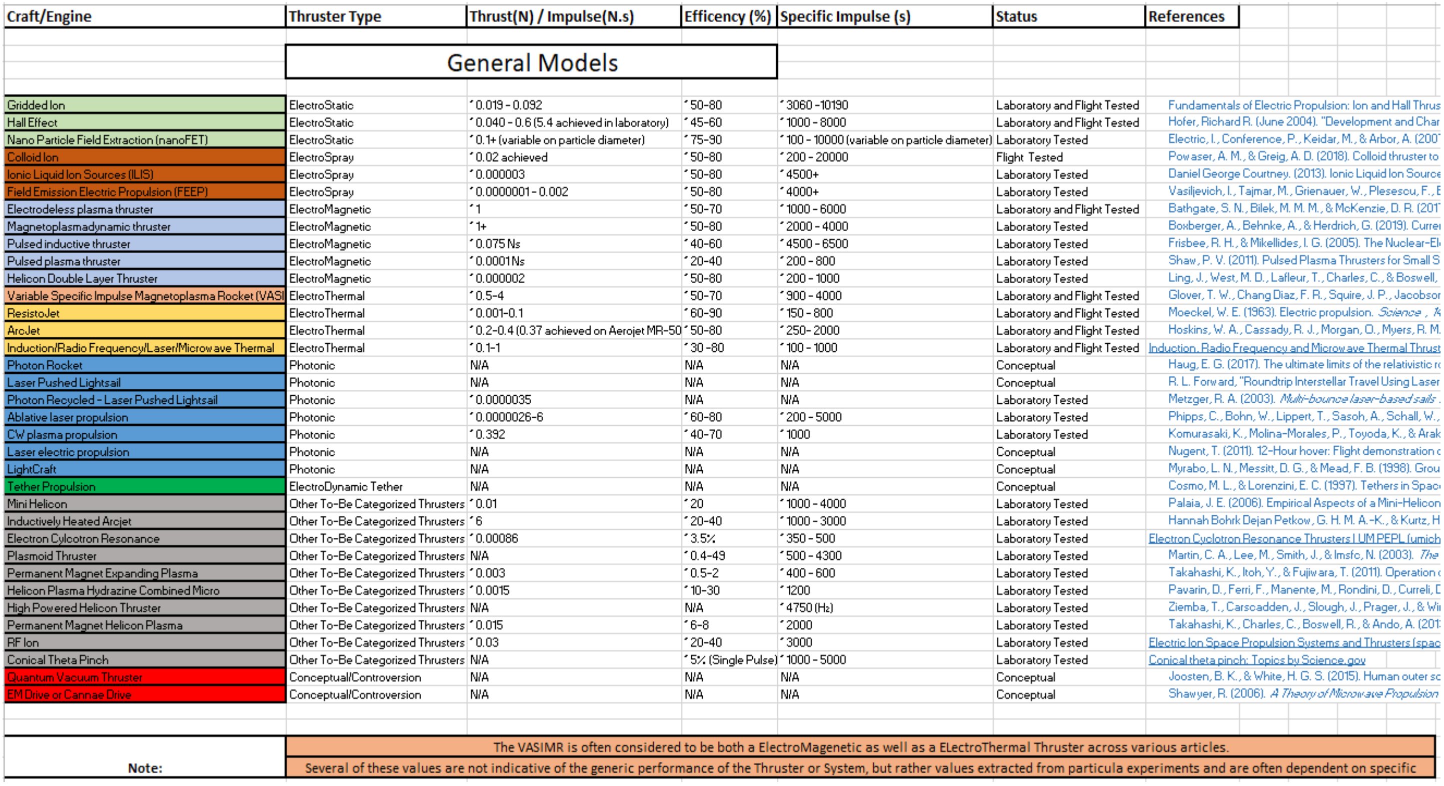
As interplanetary travel becomes more interesting, the viability of chemically propelled rockets and spacecraft lessens [1]. It is not practical and, at times, nearly impossible to carry fuel (liquid or solid) and oxidizer for long-distance space flight run by air-breathing or any combustion-based chemical propulsion systems. A viable propulsion system for deep space exploration must use a smaller and lighter propulsion unit with a high degree of controllability and employ a working fluid that is easy to store and use. Several unconventional propulsion systems such as the electron, ion, photon, and plasma-based propulsion systems meet these criteria [3]. These advanced propulsion strategies provide new and improved methods that promise spectacular results, albeit with some compromises, when it comes to long-distance space missions. Leaving aside the immense positive impacts on reducing the damage on earth's environment at launch due to the toxic byproducts of conventional rockets and the enormous economic benefits due to the increased efficiency of these systems, these new advanced strategies are almost compulsory for most long-distance interplanetary missions reaching the edge of the solar system and beyond.

With the need to travel further into space, more propellant is required, which can only be solved by drastically scaling up our rockets until they reach a critical point of manufacturability and maintenance. From history and a very rough estimate using publicly available data, we can see that about 50% of the mass in the Saturn-V rocket was fuel weight. This does not even include the weight of the stages or containers that contained the fuel or any of the subsystems required to maintain the temperature and pressure of the fuel.

One of the biggest problems of exponentially scaling up chemical rockets, aside from the obvious manufacturability issues, is that they are not sustainable. Space junk is slowly becoming another problem for human pollution, and this is unacceptable under the guise of progress. The solution to this is thrusters of a small form factor that can be somehow accelerated just beyond the earth's gravitational pull so that it can then continue to use gravity assist and its own propulsion system to navigate through space.

Results and Discussion

After an extensive review of electric propulsion, the researcher has developed a few possible solutions for the design. One of the most important outcomes of this research effort was the construction of an Electric Thrusters database. The database is an updating non-exhaustive list of Electric propulsion systems that have been conducted into any stage of the Technology Readiness scale as formulated by NASA. While still in its infancy, the database will serve as the primary logging and categorization method for future electric thrusters developed by 3P labs.



Craft/Engine	Thruster Type	Thrust(N) / Impulse(N.s)	Efficency (%)	Specific Impulse (s)	Status	References
	General Models					
Gridded Ion	ElectroStatic	0.019 - 0.092	50-80	3060 -10190	Laboratory and Flight Tested	Fundamentals of Electric Propulsion: Ion and Hall Thrus
Hall Effect	ElectroStatic	0.040 - 0.6 (5.4 achieved in laboratory)	45-60	1000 - 8000	Laboratory and Flight Tested	Hofer, Richard R. (June 2004). "Development and Char
Nano Particle Field Extraction (nanoFET)	ElectroStatic	0.1+ (variable on particle diameter)	75-90	100 - 10000 (variable on particle diameter)	Laboratory Tested	Electric, I., Conference, P., Keidar, M., & Arbor, A. (200
Colloid Ion	ElectroSpray	0.02 achieved	50-80	200 - 20000	Flight Tested	Powaser, A. M., & Greig, A. D. (2018). Colloid thruster to
Ionic Liquid Ion Sources (ILIS)	ElectroSpray	0.000003	50-80	4500+	Laboratory Tested	Daniel George Courtney. (2013). Ionic Liquid Ion Source
Field Emission Electric Propulsion (FEEP)	ElectroSpray	0.0000001 - 0.002	50-80	4000+	Laboratory Tested	Vasiljevich, I., Tajmar, M., Grienauer, W., Plesescu, F., E
Electrodeless plasma thruster	ElectroMagnetic	1	50-70	1000 - 6000	Laboratory and Flight Tested	Bathgate, S. N., Bilek, M. M. M., & McKenzie, D. R. (201
Magnetoplasmadynamic thruster	ElectroMagnetic	1+	50-80	2000 - 4000	Laboratory Tested	Boxberger, A., Behnke, A., & Herdrich, G. (2019). Curre
Pulsed inductive thruster	ElectroMagnetic	0.075 Ns	40-60	4500 - 6500	Laboratory Tested	Frisbee, R. H., & Mikellides, I. G. (2005). The Nuclear-El
Pulsed plasma thruster	ElectroMagnetic	0.0001 Ns	20-40	200 - 800	Laboratory Tested	Shaw, P. V. (2011). Pulsed Plasma Thrusters for Small S
Helicon Double Layer Thruster	ElectroMagnetic	0.000002	50-80	200 - 1000	Laboratory Tested	Ling, J., West, M. D., Lafleur, T., Charles, C., & Boswell,
Variable Specific Impulse Magnetoplasma Rocket (VASI	ElectroThermal	0.5-4	50-70	900 - 4000	Laboratory and Flight Tested	Glover, T. W., Chang Diaz, F. R., Squire, J. P., Jacobson
ResistoJet	ElectroThermal	0.001-0.1	60-90	150 - 800	Laboratory and Flight Tested	Moeckel, W. E. (1963). Electric propulsion. *Science* ,
ArcJet	ElectroThermal	0.2-0.4 (0.37 achieved on Aerojet MR-50	50-80	250- 2000	Laboratory and Flight Tested	Hoskins, W. A., Cassady, R. J., Morgan, O., Myers, R. M.
Induction/Radio Frequency/Laser/Microwave Thermal	ElectroThermal	0.1-1	30 -80	100 - 1000	Laboratory and Flight Tested	Induction, Radio Frequency and Microwave Thermal Thrust
Photon Rocket	Photonic	N/A	N/A	N/A	Conceptual	Haug, E. G. (2017). The ultimate limits of the relativistic r
Laser Pushed Lightsail	Photonic	N/A	N/A	N/A	Conceptual	R. L. Forward, "Roundtrip Interstellar Travel Using Laser
Photon Recycled - Laser Pushed Lightsail	Photonic	0.0000035	N/A	N/A	Laboratory Tested	Metzger, R. A. (2003). *Multi-bounce laser-based sails*
Ablative laser propulsion	Photonic	0.0000026-6	60-80	200 - 5000	Laboratory Tested	Phipps, C., Bohn, W., Lippert, T., Sasoh, A., Schall, W.,
CW plasma propulsion	Photonic	0.392	40-70	1000	Laboratory Tested	Komurasaki, K., Molina-Morales, P., Toyoda, K., & Arak
Laser electric propulsion	Photonic	N/A	N/A	N/A	Conceptual	Nugent, T. (2011). 12-Hour hover: Flight demonstration
LightCraft	Photonic	N/A	N/A	N/A	Conceptual	Myrabo, L. N., Messitt, D. G., & Mead, F. B. (1998). Grou
Tether Propulsion	ElectroDynamic Tether	N/A	N/A	N/A	Conceptual	Cosmo, M. L., & Lorenzini, E. C. (1997). Tethers in Spac
Mini Helicon	Other To-Be Categorized Thrusters	0.01	20	1000 - 4000	Laboratory Tested	Palaia, J. E. (2006). Empirical Aspects of a Mini-Helicon
Inductively Heated Arcjet	Other To-Be Categorized Thrusters	6	20-40	1000 - 3000	Laboratory Tested	Hannah Bohrk Dejan Petkow, G. H. M. A.-K., & Kurtz, H
Electron Cylcotron Resonance	Other To-Be Categorized Thrusters	0.00086	3.5%	350 - 500	Laboratory Tested	Electron Cyclotron Resonance Thrusters | UM PEPL (umich
Plasmoid Thruster	Other To-Be Categorized Thrusters	N/A	0.4-49	500 - 4300	Laboratory Tested	Martin, C. A., Lee, M., Smith, J., & Imsfc, N. (2003). *The*
Permanent Magnet Expanding Plasma	Other To-Be Categorized Thrusters	0.003	0.5-2	400 - 600	Laboratory Tested	Takahashi, K., Itoh, Y., & Fujiwara, T. (2011). Operation
Helicon Plasma Hydrazine Combined Micro	Other To-Be Categorized Thrusters	0.0015	10-30	1200	Laboratory Tested	Pavarin, D., Ferri, F., Manente, M., Rondini, D., Curreli, D
High Powered Helicon Thruster	Other To-Be Categorized Thrusters	N/A	N/A	4750 (Hz)	Laboratory Tested	Ziemba, T., Carscadden, J., Slough, J., Prager, J., & Wi
Permanent Magnet Helicon Plasma	Other To-Be Categorized Thrusters	0.015	6-8	2000	Laboratory Tested	Takahashi, K., Charles, C., Boswell, R., & Ando, A. (201
RF Ion	Other To-Be Categorized Thrusters	0.03	20-40	3000	Laboratory Tested	Electric Ion Space Propulsion Systems and Thrusters (spac
Conical Theta Pinch	Other To-Be Categorized Thrusters	N/A	5% (Single Pulse)	1000 - 5000	Laboratory Tested	Conical theta pinch: Topics by Science.gov
Quantum Vacuum Thruster	Conceptual/Controversion	N/A	N/A	N/A	Conceptual	Joosten, B. K., & White, H. G. S. (2015). Human outer sc
EM Drive or Cannae Drive	Conceptual/Controversion	N/A	N/A	N/A	Conceptual	Shawyer, R. (2006). *A Theory of Microwave Propulsion*

Note:

The VASIMR is often considered to be both a ElectroMagenetic as well as a ELectroThermal Thruster across various articles.

Several of these values are not indicative of the generic performance of the Thruster or System, but rather values extracted from particula experiments and are often dependent on specific

Fig 1: Screenshot Visualization of the current state Thrusters Database

The database is still under active development and may contain minor errors that we hope to resolve during the experiment.

We have investigated several possibilities of Thruster design, including the Gridded ion[11], Hall effect[10], Laser Plasma accelerator[5], Lightcraft[6], and Magneto Plasma Dynamic[2] [4] [9]. One of the main problems that we ran into during the literature review portion of the research was choosing the class of thrust we would want from our thruster. While we can obtain a very high impulse and efficient thruster, the thrust may be in the order of micronewtons. We looked for solutions for this using a variety of methods. We have been suggested to use an analytical approach to measure thrust, but that has been deemed not to provide enough valuable real-world data. We ventured into the possibility of using a load cell method of directly measuring thrust, but we could not find a commercially available load cell that could measure thrust of that order without error, which is also within the budget of this project. We tried contacting a few companies, including Honeywell, for sensors, but we could not find anything specifically suited for our needs. We did find a few papers on scratch-built methods of building ultrasensitive cantilever or torsion balances that can measure thrust of that order; however, we had a time constraint as well as the problem of finding an environment with low enough noise from wind or vibrations not to disturb the thrust measurements of such an insignificant level. While we understand that direct load cell measurement of micronewton-thrust is possible and demonstrated in previous research efforts, we have deemed it out of scope for a micronewton thruster design.

Hence, we have decided to select a thruster design that can output thrust on the order of newtons, so it can be measured using load cells much more effortlessly and other methods for multiple modes of thrust measurements. This will help us during our experiment report's verification and validation stage. We have now decided to move forward with a straightforward design based on the concept of an atmospheric pressure plasma jet (APPJ). One of the advantages of atmospheric pressure plasma is that, as the name suggests, due to its ambient pressure, there is no need for a reaction or pressure vessel to maintain its performance. This significantly reduces manufacturability issues as well as design constraints. As a bonus, the plasma jet is also low enough temperature to reduce safety hazards for this project. We have investigated a few different operating principles for this thruster, such as a DC plasma jet, an AC plasma jet, and a Microwave plasma jet. While this is still an active area of questioning, we have found promising papers on simple high voltage-based APPJ thrusters.

While usually APPJ thrusters often use noble gases such as Xenon as the primary chemical propellant, due to the handling qualities of Xenon and availability, it has been deemed out of scope. A much suitable alternative candidate for chemical propellant that has been used before is iodine.[13] [14] [17] A simple MS paint sketch has been made to demonstrate the basic operational principle of this design.

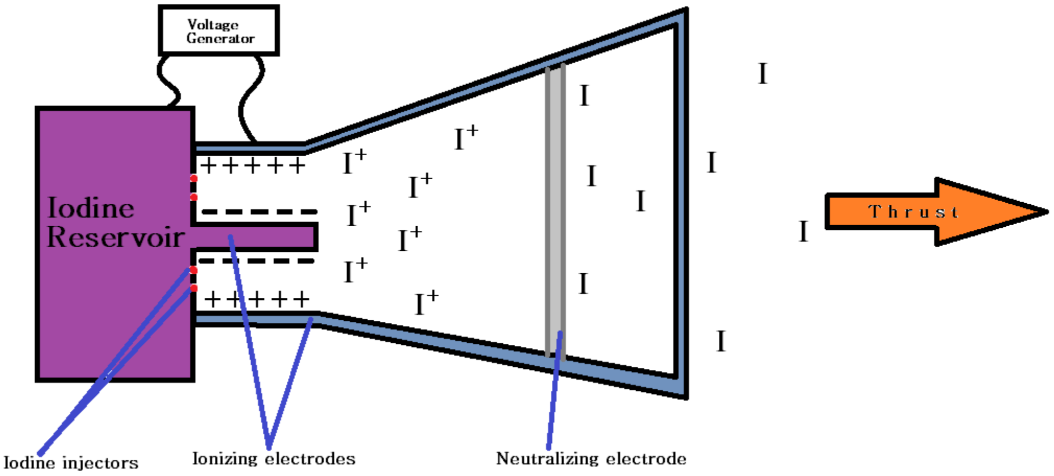


***Fig 2:* Iodine based plasma thruster**

The Iodine reservoir will slowly inject fuel through the injectors into the chamber with the Ionizing electrodes. There will be a high voltage supply that ionizes the central electrode and the radial electrode around the inside lining of the cylindrical section of the Nozzle chamber system. As Iodine particles are excited to the plasma state by the high voltage ionizing electrodes, they are repelled away by the radial electrode. There will be another high voltage electrode just downstream of the flow. This can be either a radial electrode or a mesh-type electrode. This will attract the Iodine ions towards it. By combining the attractive forces of the neutralizing electrode and the repelling force of the ionizing radial electrode, the ions will accelerate to a hopefully significant enough speed to expel out of the back of the nozzle and produce thrust. We will mathematically design the dimensions of the nozzle and ionizing chamber to achieve optimal thrust and impulse. [15] [16]

A preliminary CAD model has been formulated, as demonstrated below. This will serve as the basis of our design that will be iterated upon for optimization.

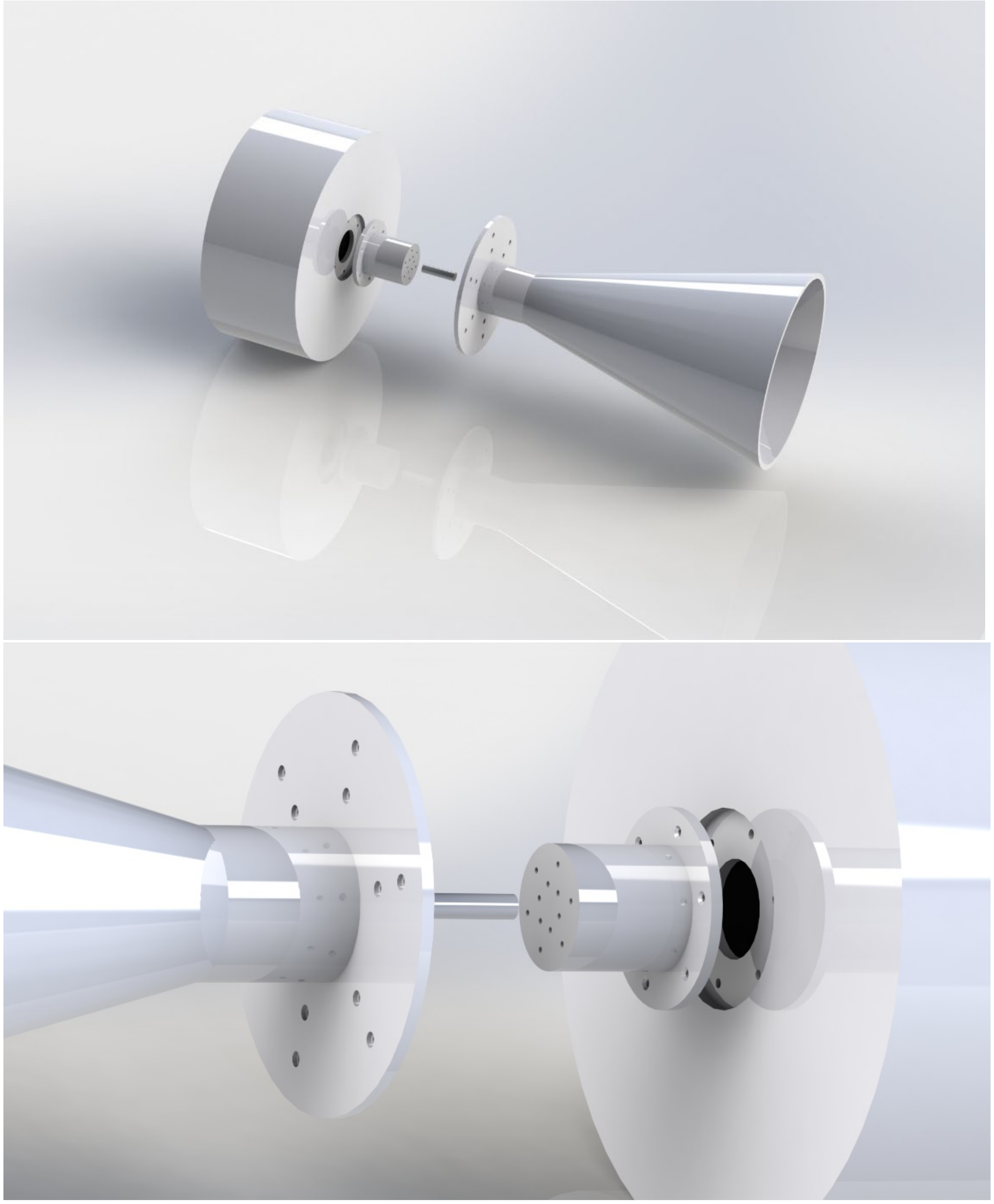


*__Fig 3:__ **A Solidworks CAD exploded view of the preliminary design***

Conclusion

With the advent of efforts for interplanetary travel by the aerospace industry, especially from governments around the world and private companies such as SpaceX. However, the industry is slowly realizing the limits of chemical propellant combustion-based propulsion for long-distance flights. Despite the energy density of current chemical propellants used in rocket propulsion, due to a few fundamental physics problems, it is impossible for large-interplanetary and beyond travel solely with the help of chemical propellants. We know from the Tsiolkovsky rocket equation that the amount of propellant required to propel a unit of mass to space is a logarithmic relation. Due to this, interstellar travel is impossible, with pure chemical combustion-based propulsion is impossible. Many research efforts have been made into the realm of what is commonly dubbed as "Advanced Propulsion" for electric-based propulsion systems. A class of propulsion systems specializing in high impulse and efficiency while maintaining low thrust for a prolonged lifespan could lead to remarkably high velocities in the long run. A sustainable class of propulsion systems that could take us to the stars.

Future research efforts

We hope that this design will evolve into a viable propulsion system design that can be fabricated and assembled for part two of this UROP, "Plasma-Based Electric Propulsion for Deep Space Exploration –Part II: Build, Test and Calibrate a Lab-Scale Thruster." The researcher plans to work with their research advisor, Dr. Sayan Biswas, from the Plasma, Power and Propulsion Lab at the University of Minnesota Twin Cities over the winter break. Once a feasible enough design can be optimized, the researchers will acquire parts and begin fabrication and assembly. We have looked into both load cell-based measurement methods as well as radiation pressure-based methods, such as the Langmuir probe.

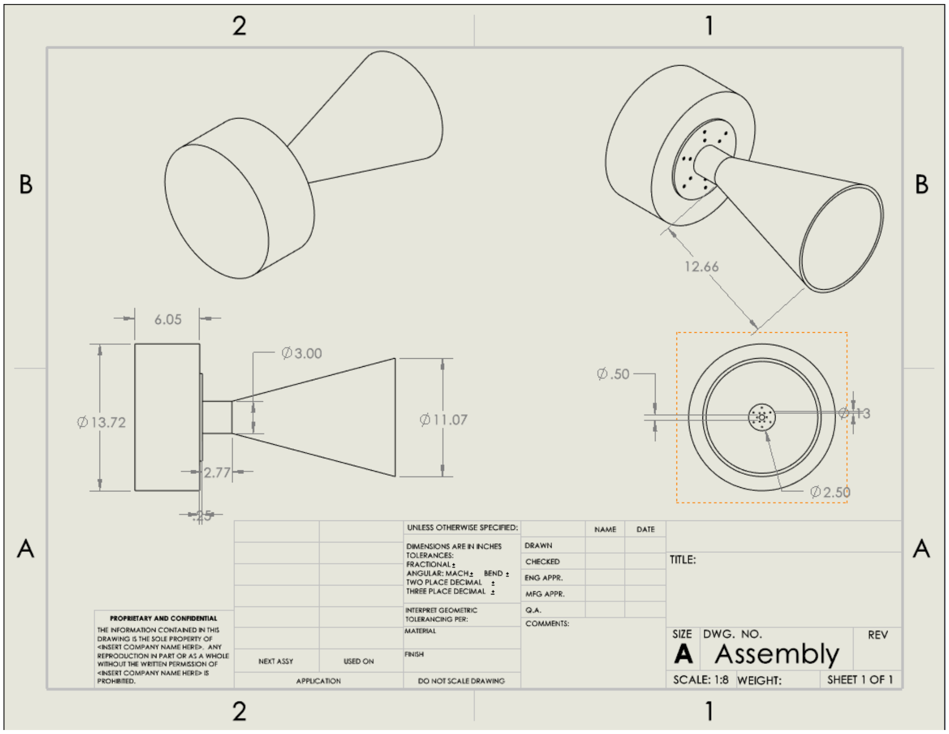


Fig 4: A Solidworks drawing of the preliminary design

Acknowledgments

The researcher in question has worked with Benjamin Mayhugh, Assistant Professor, Dr. Sayan Biswas, at the 3P labs (3p.umn.edu) under the MERL lab facility under the Mechanical engineering department. The researcher would like to acknowledge 3P labs, MERL Lab, Professor Peter Bruggeman and his graduate students, and Professor Ognjen Ilic for all the resources, support, and advice through email or otherwise during this research effort.

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UROP Evaluation

This was the first UROP of my college career, and I have been thrilled that I did it at the University of Minnesota. The UROP process was straightforward to navigate, even though it may look intimidating to beginners and freshmen going into research. I appreciate Dr. Sayan Biswas from the Mechanical engineering department for being my faculty advisor and guiding me through my first research exposure and 3P labs for accommodating me during my entire research journey. The UROP experience helped me realize my passion for research and convinced me to apply for graduate school at the University of Minnesota. I have learned a plethora of research ethics and knowledge from this experience and hope that it will serve me in my future as a fully-fledged researcher.