Developing Additive Manufactured Monopropellant Thrusters for Deep Space CubeSat Applications

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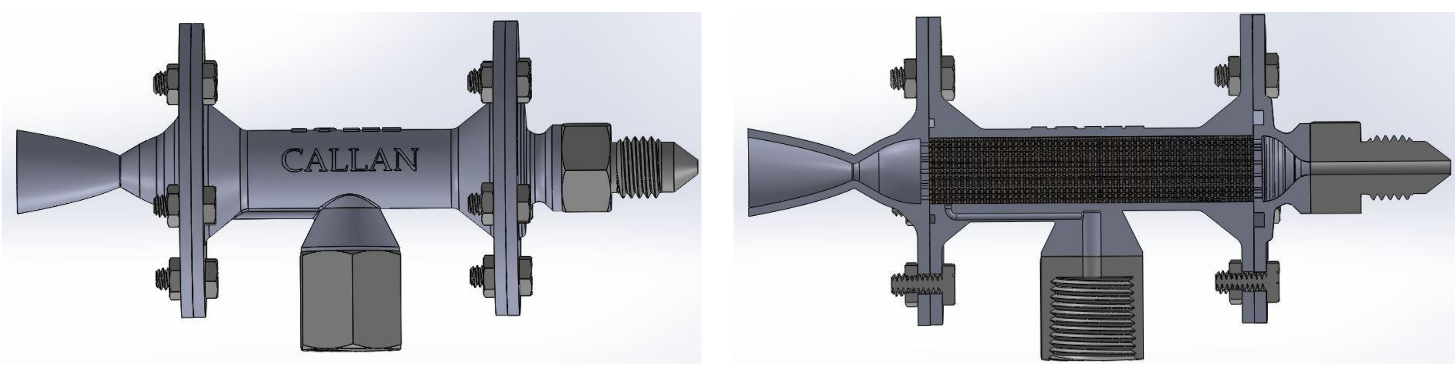
The authors of this technical report aim to present SEDS UCSD's (Students for the Exploration and Development of Space Chapter at the University of California, San Diego) design of their first additively manufactured monopropellant thruster, Callan. The purpose in this project is to further research and develop the feasibility of additive manufacturing as a means for the manufacturing processes of deep space rocket propulsion systems through the design of a fully operational, flight ready monopropellant thruster. It will serve as the sole propulsion system onboard a cube satellite, after a series of orbital maneuvers, to be injected into trans-lunar orbit. This report will explain the design process for the engine, named Callan, and provide information about the key features of the engine. This report aims to prove that additively manufactured rocket engines can not only be utilized as a means for producing test engines, but also in the production of a flight-ready engine for operation in space as evidenced by the development and extensive testing of Callan.



(a) **(b)**

Figure 1. A computer generated model of the monopropellant engine, Callan: (a) Exterior view, (b) Interior cross-sectional view.

I. Introduction

Designs for conventionally larger satellites have necessarily demanded, on average, $10-100 million to fabricate. In lieu of their increasing costs and scales of development, CubeSats have generated much attention by NASA. CubeSats, by contrast to their conventional, larger satellite counterparts, exhibit an extraordinary advantage over space exploration due to its significant reduction in mass, power,

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development time and cost. Specifically, NASA has declared a second Centennial Cube Quest Challenge in order to expand research of these nanosatellites, and different approaches must be considered in order to maintain the highest caliber of efficiency. Students for the Exploration and Development of Space at the University of California, San Diego (SEDS UCSD) will be approaching this challenge by designing Triteia: a 6U configuration CubeSat designed to achieve a polar lunar orbit from a trans-lunar injection trajectory through the SLS EM-1 secondary payload deployment sequence. Triteia transforms from an unassuming, ordinary CubeSat to, instead, an autonomously intelligent power management system with a state-of-the-art additively manufactured high test hydrogen peroxide (H_2O_2) propulsion unit. This is an unprecedented level of detail in design as Triteia's propulsion system utilizes a high test H_2O_2 thruster, which allows for extraordinarily faster in-space translational speeds, and it includes direct metal laser sintering (DMLS) techniques that manufacture the thruster as 3 separate modules: the diffuser plate, reaction chamber, and the nozzle, thereby allowing for unlimited customization and total, aesthetic control.

As the first undergraduate student organization in the world to have successfully fabricated a full-size, additively manufactured, liquid-fueled rocket thruster, SEDS UCSD has patented two additively manufactured engines to date: the Vulcan-1 and the Tri-D. With funding and advisorship from NASA MSFC, both rocket thrusters have been tested using an in-house fabricated static fire system, and experimental results have been published accordingly.[3] For this application, SEDS UCSD has embarked on designing an entirely new, Hydrogen Peroxide (H_2O_2) monopropellant propulsion system with never-before seen Delta-V and thrust capabilities onto the 6U Triteia CubeSat. Upon anticipation for securing the Lunar Derby prize in NASA's Cube Quest Competition, this sophisticated propellant structure will be one of the pioneers of its kind to evolve away from the conventional electric propulsion thrusters.

As monopropellant engines comprise mainly of a decomposition chamber, the capability of additive manufacturing techniques enables the designer to not only print the chamber, but additional interchangeable diffuser plates and nozzles placed on either side of the engine, in order to optimize the testing of reaction and expansion of the propellants. Doing so will rapidly reduce the time to develop the most efficient thrust design for an already limited, low thrust propulsion system. The main advantages of utilizing the additive manufacturing process are to allow for optimal design efficiencies, decreasing the production lead time and time interval between testing, in order to develop a flight-ready, small spacecraft thruster. This will further drive down the production costs and enable rapid prototyping for the variety of mission applications of the growing CubeSat industry.

II. Method of Creation

The entirety of the Callan engine, with the exception of the catalyst package, was designed to be additively manufactured using the Direct Metal Laser Sintering (DMLS) style printing. The engine will be printed though the support of the manufacturer, Metal Technologies Inc. (MTI), based in Albany, Oregon. From the main purpose of the project in utilizing additive manufacturing as its source of production, post-production processes will be kept to a minimum. The only subtractive processes to be used will be light machining of the o-ring and c-ring grooves on the respective modules.

[3] Atyam D. and Nguyen N, "Designing and Testing Liquid Engines for Additive Manufacturing," SEDSUCSD, AIAA Paper 2015 - 4051, April 2015

III. Design Constraints/Features

The Callan engine is designed to power Triteia, with the ultimate goal of propelling the 6U CubeSat into polar lunar orbit from a trans-lunar injection through the Space Launch System Explorer Mission - 1 (SLS EM-1) secondary payload deployment sequence. In order to do so, the engine will produce 2 burn maneuvers. The first maneuver will be during cruise shortly after the deployment of the CubeSat from the deployer during the cruise phase for a Trajectory Correction Maneuver (TCM) with a Delta-V of 45 m/s. This maneuver will require a burn time of 85.25 seconds. The second maneuver will be during orbit insertion into performing a Lunar Orbit Injection (LOI) with a Delta-V of 350 m/s requiring 571.203 seconds. While undergoing this burn sequence, the real-time thruster performance as well as control algorithms of the thruster will be analyzed during mission operation.

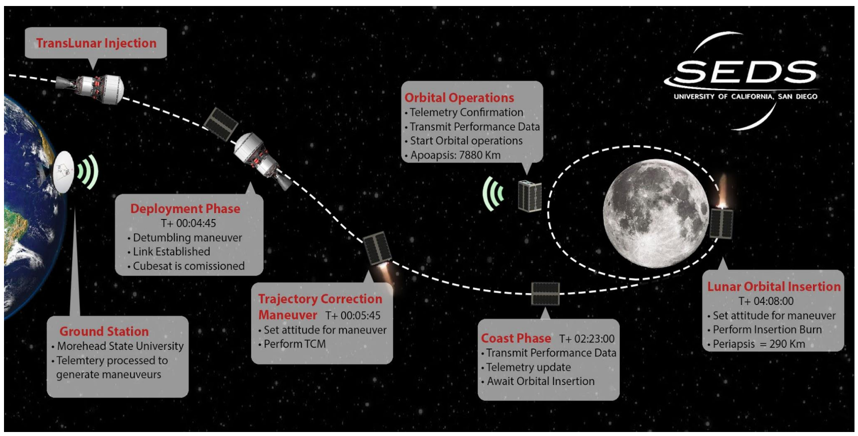


Figure 2. Concept of Operations Diagram illustrating the mission trajectory of Triteia, SEDS UCSD's first cube satellite.

Designed to produce 1lbf of thrust, the Callan thruster will be printed out of Inconel 718 for its material and thermal compatibility with hydrogen peroxide (H_2O_2). This will produce a specific impulse, I_{sp} , of 125 psia. Utilizing a blow down system within the CubeSat, the Callan engine will also feature a dual tank propellent feed system for optimal stabilized control.

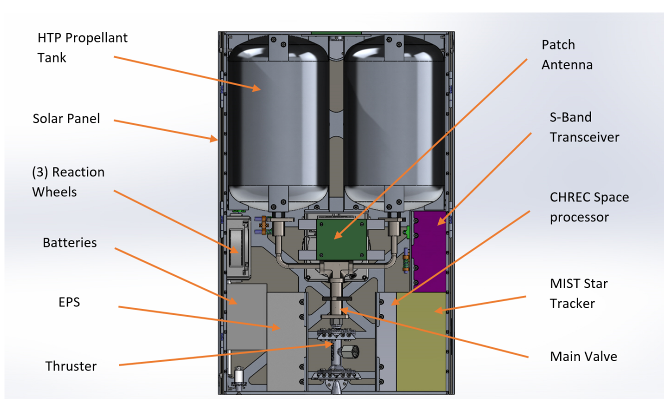


Figure 3. Computer generated model of the layout of various components within the Triteia cube satellite.

A. Front Diffuser

The front diffuser has the sole purpose of metering and distributing the flow of propellant to the reaction chamber where the catalyst material is housed. It features a central inlet that leads incoming propellant into a plenum-like chamber that meters the propellant flow into the catalyst pack through orifices at the bottom face of the chamber. The placement as well as the size of the orifices on the diffuser face were iterated so that the the outlet flow through the front diffuser would be as close to uniform as possible. These iterations determined that in order to achieve a close to uniform distribution and flow, multiple sized orifices were required. By utilizing different orifice diameters, propellant that enters the diffuser plenum through the central inlet can be redirected to orifices further away from the central axis. To further promote the diffusion of propellant upon entry into the diffuser plenum, the orifice pattern on the face of the front diffuser does not include a central orifice. Instead, a set of smaller diameter orifices were placed near the central axis, followed by a set of slightly larger orifices, and finally followed by a set of the largest diameters near the wall of the diffuser plenum. In other words, the diameters of the orifices starting from the central axis increased radially outwards. The front diffuser was designed to be a flight-ready component of the monopropellant engine. Consequently, an AN fitting was incorporated into the design of the inlet port on the diffuser. This allows for easy integration with any test stand that may be utilized to characterize the performance of the engine in addition to the propellant feed system that would be onboard the CubeSat during mission operation. The engine is composed of three modules that are mated together. The interface of the modules would require some sealing capabilities. The front diffuser module utilizes o-rings to seal the interface between itself and the reaction chamber module. In order to seat the o-rings and prevent any problems with an improper seal, o-ring grooves will be machined onto the diffuser face. This ensures a smooth enough surface roughness to properly seat the o-rings and provide a proper seal. The diffuser, along with the other components of the engine, were designed to be additively manufactured. In doing so, the geometry of the diffuser was carefully chosen to balance the performance aspect of the diffuser module as well as the manufacturability of the part. The front diffuser module is self-supporting, in that, the entirety of the front diffuser can be additively manufactured in the absence of support structure.

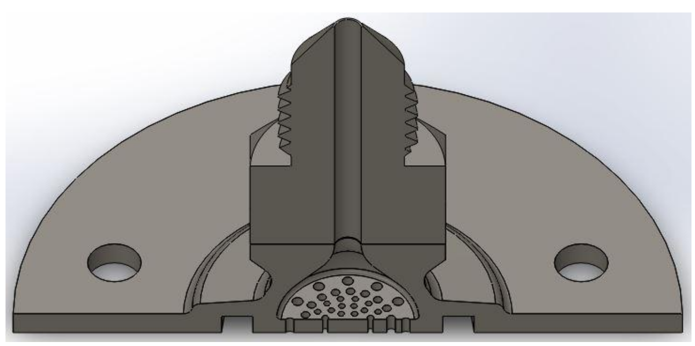


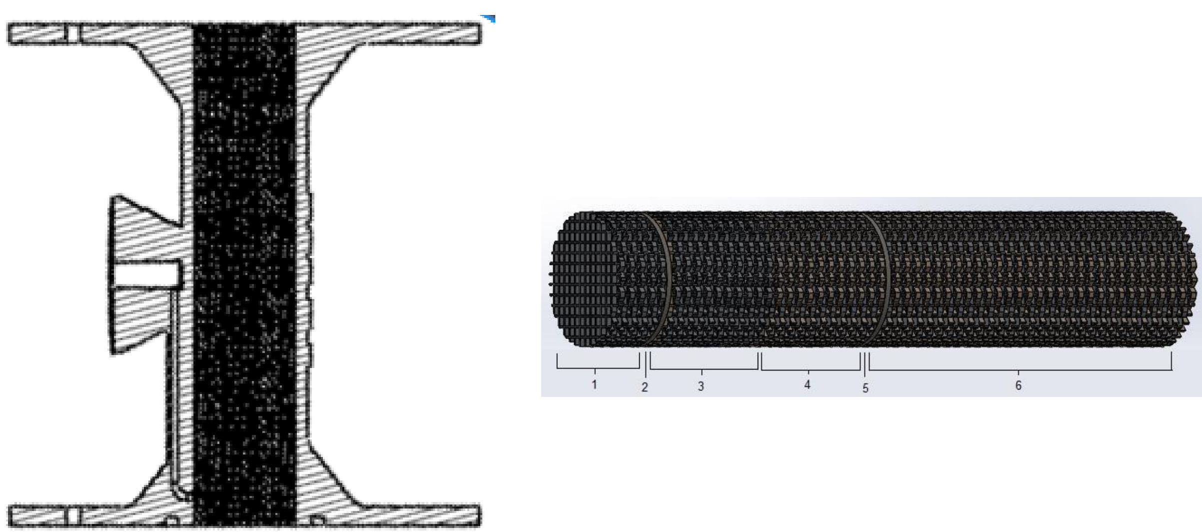
Figure 4. Computer generated model cut out view of the front diffuser plate on the Callan engine.

B. Reaction Chamber and Catalyst Pack

The second of three modular parts on the Callan engine is the reaction chamber. Its purpose is to house the catalyst pack and contain the hydrogen peroxide decomposition reaction. The chamber features one inlet and one outlet, both with the same dimensions. The main constraints in the design of the Callan engine came from its thermal and material compatibility restrictions. The chamber and nozzle modules were expected to have high thermal loads from the decomposition of the propellant. As a result, Inconel

718 was chosen for its high melting point and satisfactory compatibility rating with the propellant. Since the engine is designed to be tested and flight-ready, a pressure transducer port along with its service line is incorporated into the wall of the chamber. This allows for the acquisition of chamber pressure readings and provides real-time performance data to be collected during mission operation. In turn, a more accurate orbit trajectory or trajectory adjustment may be achieved. To further push its ease of integration with the CubeSat, an NPT fitting was included at the pressure transducer port. This module is sandwiched between the front diffuser and nozzle modules. Much like the diffuser module, the mating of the reaction chamber and its adjacent modules will require a proper seal to be formed. C-rings were utilized to seal the interface between the reaction chamber and the nozzle module. The grooves will be machined to ensure a smooth surface roughness, so that a proper seal can be formed. This module will also be fully additively manufactured. However, unlike the front diffuser or the nozzle, the part itself will have quite a bit of support structure in order to successfully print. This was the result of the need for flanges that will allow the engine to be assembled.

The catalyst pack was designed to jumpstart the exothermic decomposition of the propellant. It features an assembly of wire meshes that are compressed into one another. Silver will be utilized as the main catalytic material and will be featured as the first material the propellant will interact with upon exiting the front diffuser. Silver, being less structurally sound on its own, requires the use of a second material, Nickel 200, as a structural support. Both of these materials serve the purpose of the catalyst pack. After the catalyst pack is used for the first time, the wire screens that compose the pack will expand from thermal loads imparted on it during operation. Such expansions will cause the wires screens to crush its edges so that the outer diameter of the catalyst pack will be smaller than it was originally. When the engine is used for a second time, during the Lunar Orbit Insertion (LOI) Phase of the mission, the gap formed between the reaction chamber wall and the catalyst pack can allow propellant to seep through and "skip" the reaction path it was intended for. This can lower the efficiency of the engine as propellant is being unused and discarded. To combat this, anti-channel baffles, which are essentially thin rings, are placed in two locations within the catalyst pack to redirect any propellant flow away from the formed gap and into the reaction path. The catalyst pack was not designed to be additively manufactured. Instead, it will be fabricated and assembled via traditional methods.

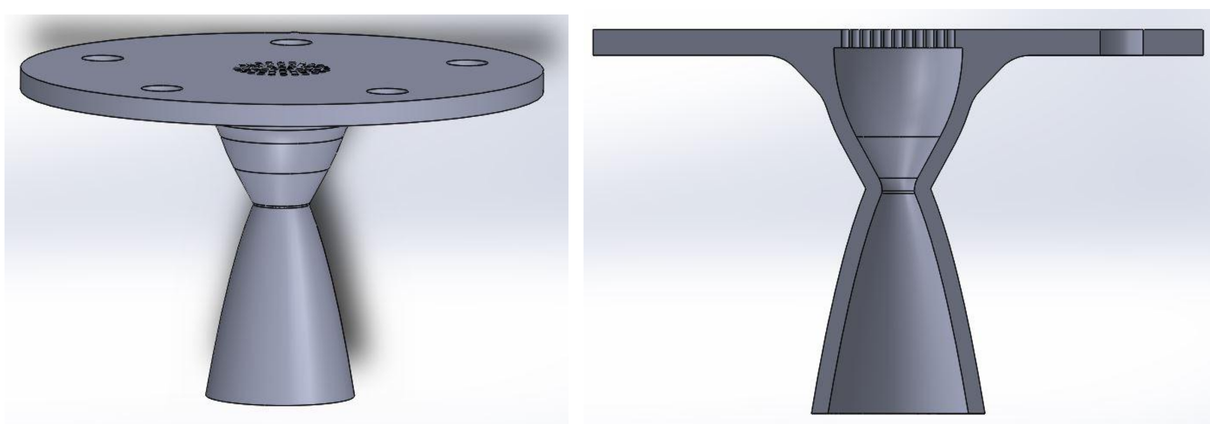


(a) **(b)**

Figure 5. (a) Computer generated drawing of the side cross section of the reaction chamber. (b) The metal mesh material pattern of the silver and nickel wire screens.

C. Aft Diffuser and Nozzle

The nozzle module combines the nozzle with the aft diffuser. The aft diffuser plays the same function as the front diffuser. However, the only difference exists in its key purpose, which is to hold the catalyst pack inside the reaction chamber. The aft diffuser contains a number of identical orifices that assist in the redirection of heated gases out of the reaction chamber and into the nozzle. The orifices are placed in a pattern around the central axis of the aft diffuser and extend out radially. Designed for operation in space, the nozzle is expanded so that operation in a vacuum is optimal. This presents a minor conflict in the ground testing of its performance as such an expansion at sea level could cause instabilities and violent acoustics that may destroy the engine. As a result, a separate, but similar nozzle module was designed for testing purposes. It features an exact replica of the fully expanded nozzle with the same expansion and contraction ratios. However, the nozzle of the test module was truncated, so that the exit pressure would be equal to atmospheric pressures and performance and longevity would not be dramatically negatively impacted. The nozzle module is designed to be additively manufactured. Much like the front diffuser, this module was designed and will be printed with no support structures.



(a) **(b)**

Figure 6. Nozzle module on the Callan engine: (a) Computer generated model of the nozzle module (b) Interior cross-sectional view of the nozzle module illustrating the orifices on the aft diffuser.

IV. Testing Schedule

The testing of the Callan engine will be conducted shortly after the completion of the print. A variety of CubeSat thruster test facilities have been looked into such as Parabilis Space Technologies, Aerojet Rocketdyne, Advanced Mobile Propulsion Testing, White Sands, and NASA's Marshall Space Flight Center in order to conduct the testing. However, with the founding president of the UC San Diego, SEDS Chapter, Deepak Atyam, as a graduate student in the Propulsion department at Purdue University, in addition to multiple contacts with NASA Advisers in close relation to this test facilities operators, the testing of the Callan engine has promising leads with the Purdue Propulsion Department.

The testing of this engine will focus primarily on measuring the load with a steady state pressure fed system, temperature gradient throughout the diffuser plate, decomposition chamber, and nozzle, the pressure of the decomposition chamber, and vibrational analysis of the engine. The testing will perform a series of burn sequences to understand the engine durability through fatigue and thermal cycling as well as for mission operation burn times. With a reasonable timeline intact, the analysis and test data of this engine shall be complete and finalized by mid-July of 2016.

The timeline of testing the engine will proceed as follows:

- **February 29th, 2016** - Deliver Statement of Work to Testing Facilities
- **March 15th - 22nd, 2016** - Print Callan CubeSat Thruster
- **April 4th - 29th, 2016** - Test Callan CubeSat Thruster
- **May 2nd - 6th, 2016** - Analyze test data
- **May 9th - 27th, 2016** - Make necessary design iterations
- **May 30th - June 15th, 2016** - Print 2nd Iteration of Callan CubeSat Thruster
- **June 20th - 24th, 2016** - Test Callan CubeSat Thruster Version 2
- **June 27th - July 1st, 2016** - Analyze test data
- **July 4th - 15th, 2016** - Generate Report and Publish Research Data