

Conceptual Propellant Feed System for Electrospray Thrusters and an Exploration into 3D Printed Millifluidic Manifolds

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Degree

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ABSTRACT

The miniaturization of satellites has led to a new era of miniaturized spacecraft technology, which includes propulsion systems. The full potential of CubeSats will be realized once they are equipped with miniaturized thrusters. One option being developed at the University of Tennessee Space Institute (UTSI) is a miniature electrospray device, Micro Scalable Thrusters for Adaptive Mission Profiles in Space (μ STAMPS). This device operates via electrospray principles and utilizes an ionic liquid (IL) propellant. μ STAMPS aims to provide CubeSats with maneuvering capabilities, including rapid deorbiting, station-keeping, and collision avoidance maneuvers (CAMs). An internal propellant reservoir can deliver enough propellant for CAMs; however, to achieve additional applications, an external propellant feed system is required. The focus of this thesis is to initiate the development of such a system. The first prototype employs a FEP bladder tank, a peristaltic pump, and an MSLA 3P printed (3DP) millifluidic propellant routing manifold (PRM). Primary goals were to develop a leak-free bladder tank to deliver 100 grams of IL and fabricate a 3DP millifluidic PRM to simultaneously distribute propellant to four thrusters. Seal strength tests (ASTM F88) were performed to determine the required tank thickness, which ended up being 0.1 in. However, the assembled prototype failed before any pressurization tests could commence. It was concluded that the current tank design was not ideal. The fabrication of the PRMs began with a comparison of print accuracy between Elegoo's Mars 2 Pro (M2P) and Mars 4 Ultra (M4U). Test prints were performed with various support strategies; it was found that the PRMs should be printed with lightweight supports at a support density of 80%. PRMs were then fabricated on both printers with differing orientations and channel designs. These iterations were subjected to several flow tests; the ideal orientation was to print the wide face of the PRM perpendicular to the bed with an inlet on the wide face. However, the current method of fabrication does not allow simultaneous flow through each channel due to internal deformations. Overall, while the initial prototype faced challenges, the project lays a foundation for future improvements which will ensure the success of μ STAMPS.

TABLE OF CONTENTS

Chapter 1: Introduction	1
1.1 CubeSats	1
1.1.1 Overview	1
1.1.2 A Brief History of CubeSats	1
1.1.3 CubeSat Growth, Applications, and Limitations Without Propulsion Systems	3
1.2 Electric Propulsion and Electrospray Thrusters	5
1.2.1 Overview	5
1.2.2 Electric Propulsion	5
1.2.3 Electrospray Propulsion	6
1.3 Micro Scalable Thrusters for Adaptive Mission Profiles in Space (μ STAMPS)	7
1.3.1 Overview	7
1.3.2 The μ STAMPS Emitter/Extractor Chip	11
1.3.3 μ STAMPS Device Design and Statement of Purpose	11
Chapter 2: Background	15
2.1 Propellant Management Devices	15
2.1.1 Overview	15
2.1.2 Noncapillary-Type Propellant Management Devices	15
2.1.3 Capillary-Type Propellant Management Devices	18
2.2 MSLA Additive Manufacturing	21
2.3 Microfluidics and Millifluidics	24
2.3.1 Overview	24
2.3.2 Traditional Manufacturing of Microfluidics and Their Applications	26
2.3.3 Manufacturing of Microfluidics and Millifluidics via MSLA 3D Printing and Their Applications in Space	26
Chapter 3: Conceptual Design of a Propellant Feed System for μ STAMPS	29
3.1 Overview	29
3.2 Overall Design	29
3.3 FEP Tank, Flange, and Propellant Routing Manifold Prototypes	32
Chapter 4: Test Methods	36
4.1 Seal Strength Testing	36
4.1.1 Overview	36
4.1.2 Sample Preparation	36
4.1.3 Test Setup and Procedure	36

4.1.4 Data Analysis	39
4.1.5 Challenges and Limitations.....	41
4.2 Elegoo Mars 2 Pro vs. Elegoo Mars 4 Ultra Dimensional Accuracy and Support Testing	41
4.2.1 Overview.....	41
4.2.2 Print Material, Setup, and Post-Processing.....	44
4.2.3 Test Procedure and Analysis.....	48
4.2.4 Challenges and Limitations.....	48
4.3 Flow Rate and Channel Volume Testing	48
4.3.1 Overview.....	48
4.3.2 Propellant Routing Manifold Designs, Print Setup, and Post-Processing.....	49
4.3.3 Test Setups and Procedures.....	53
4.3.4 Data Analysis	56
4.3.5 Challenges and Limitations.....	56
Chapter 5: Results and Discussion.....	58
5.1 FEP Seal Strength and FEP Bladder Prototype.....	58
5.1.1 Seal Strength	58
5.1.2 FEP Bladder Prototype.....	58
5.2 3D Print Test Results	64
5.2.1 Overview.....	64
5.2.2 Flat-on-bed Test Results	66
5.2.3 Sparsely Packed, Heavy Support Test Results.....	66
5.2.4 Densely Packed, Lightweight Support Test Results and Conclusions.....	72
5.3 Flow Rate and Channel Volume Test Results.....	72
5.3.1 Overview.....	72
5.3.2 Overall Flow Rate Test Results	76
5.3.3 Individual Flow Rate Test Results.....	82
5.3.4 Final PRM Iterations and Conclusions	87
Chapter 6: Conclusions and Future Work.....	92
Works Cited	95
Vita.....	100

LIST OF TABLES

Table 1.1 – Performance of Various Electrospray Devices [20].	10
Table 3.1 – Dolomite Peristaltic Pump Technical Specifications [51].	31
Table 4.1 – Differences Between the M2P and M4U [61,62].	43
Table 4.2 – First PRM Design Iterations and Print Orientations.	50
Table 4.3 – Final PRM Design Iterations and Print Orientations.	51
Table 5.1 – Maximum loads experienced by each sample.	61
Table 5.2 – Stresses from average maximum loads compared to theoretical tank stresses.	61
Table 5.3 – Dimensions of M2P cubes flat on build platform (mm).	68
Table 5.4 – % errors in M2P cubes flat on build platform from theoretical dimensions.	69
Table 5.5 – Dimensions of M4U cubes flat on build platform (mm).	69
Table 5.6 – % errors in M4U cubes flat on build platform from theoretical dimensions.	69
Table 5.7 – Dimensions of M4U cubes with sparsely packed, heavy supports (mm).	71
Table 5.8 – % errors in M4U cubes with sparsely packed, heavy supports from theoretical dimensions.	71
Table 5.9 – M2P Lightweight Support Density Dimensions (mm) and % Errors.	75
Table 5.10 – M4U Lightweight Support Density Dimensions (mm) and % errors.	75
Table 5.11 – Overall Flow Test Results (M2P) (numbers of output droplets observed).	77
Table 5.12 – Individual flow rate test results for M2P V1b.	85
Table 5.13 – Individual flow rate test results for M2P V1d.	85
Table 5.14 – Individual flow rate test results for M2P V2b.	85
Table 5.15 – Individual flow rate test results for M2P V2d.	85
Table 5.16 – Individual flow rate test results for M4U V1b.	86
Table 5.17 – Individual flow rate test results for M4U V1d.	86
Table 5.18 – Individual flow rate test results for M4U V2b.	86
Table 5.19 – Individual flow rate test results for M4U V2d.	86
Table 5.20 – Overall flow test results for PRMs V4d and V5d (M4U) (numbers of output droplets observed).	89

LIST OF FIGURES

Figure 1.1 – Stanford University’s SAPHIRE satellite [3].	2
Figure 1.2 – Stanford University’s OPAL [3].	2
Figure 1.3 – The current CubeSat family [5].	2
Figure 1.4 – CubeSats launched as of January 1 st , 2024 [7].	4
Figure 1.5 – Basic operation of an electrospray device.	8
Figure 1.6 – Thrust versus specific impulse of various propulsion systems [20].	8
Figure 1.7 – Power versus specific impulse of various propulsion systems [20].	9
Figure 1.8 – Thrust-to-power ratio versus specific impulse of various propulsion systems [20].	9
Figure 1.9 – Conventional electrospray emitter designs [26].	12
Figure 1.10 – μ STAMPS emitter/extractor chip design [26].	12
Figure 1.11 – Surface erosion of conventional electrospray emitters [26].	12
Figure 1.12 – Overspray in conventional electrospray devices [26].	13
Figure 1.13 – Backspray in conventional electrospray devices [26].	13
Figure 1.14 – μ STAMPS components [26].	14
Figure 1.15 – Fully assembled μ STAMPS prototype [26].	14
Figure 2.1 – Behavior of liquid during various launch stages [29].	16
Figure 2.2 – Busek’s CMNT bellows tank [32].	16
Figure 2.3 – Busek and NASA JPL’s new feed system [31].	16
Figure 2.4 – NASA JPL’s diaphragm tank for Busek’s CMNTs [31].	17
Figure 2.5 – Schematic of a piston tank feed system for a 1U CubeSat Hydrazine Adaptable Monopropellant Propulsion System (CHAMPS) [33].	17
Figure 2.6 – Trough PMD [29].	19
Figure 2.7 – Circular baffle welded to the interior of a tank [29].	19
Figure 2.8 – 3D model of a vortex suppressor [29].	19
Figure 2.9 – Total-communication vane PMD [29].	20
Figure 2.10 – Conceptual design of a cryogenic propellant tank for Hall-Effect thrusters [34].	20
Figure 2.11 – Total-communication sponge PMD [29].	22
Figure 2.12 – Sponge PMD for a cesium propellant ion engine [29].	22
Figure 2.13 – 3D model of a start basket [29].	22
Figure 2.14 – 3D model of a screen channel LAD used in the space shuttle’s reaction control system [29].	23
Figure 2.15 – MSLA components [36].	25
Figure 2.16 – MSLA part dimensioning guideline [36].	25
Figure 2.17 – Microfluidic and millifluidic scales [42].	25
Figure 2.18 – Lab-on-a-chip microfluidic [43].	27
Figure 2.19 – MSLA 3D printed millifluidics [42].	27
Figure 3.1 – Conceptual propellant feed system assembly.	30
Figure 3.2 – Conceptual propellant feed system exploded view.	30
Figure 3.3 – Inflated shape of a mylar balloon/the bladder tank [52].	33
Figure 3.4 – Bladder tank prototype with MSLA 3D printed flange.	35
Figure 3.5 – MSLA 3D printed flange iterations.	35
Figure 4.1 – Midwest Pacific MP-8C impulse heat sealer.	37
Figure 4.2 – MTS testing setup.	37
Figure 4.3 – ASTM F88 recommended specimen dimensions [54].	38
Figure 4.4 – 3D model of the MTS grip attachment.	40

Figure 4.5 – Example seal strength test result [54].	40
Figure 4.6 – Elegoo Mars 2 Pro [60].	42
Figure 4.7 – Elegoo Mars 4 Ultra [60].	42
Figure 4.8 – Print orientation of 20 mm ³ cubes flat on build plate.	45
Figure 4.9 – Print orientation of 20 mm ³ cubes with sparsely packed (50%), heavy supports.	45
Figure 4.10 – Print orientation of 20 mm ³ cubes with densely packed, lightweight supports.	46
Figure 4.11 – 20 mm ³ cubes with densely packed, lightweight supports (bottom view).	46
Figure 4.12 – M2P cube print settings in CHITUBOX.	47
Figure 4.13 – M2P cube print settings in CHITUBOX.	47
Figure 4.14 – Elegoo Mercury Plus Washing and Curing Station [60].	47
Figure 4.15 – M2P PRM print settings in CHITUBOX.	51
Figure 4.16 – M4U PRM print settings in CHITUBOX.	52
Figure 4.17 – Overall flow test setup.	54
Figure 4.18 – Individual flow rate test setup.	54
Figure 4.19 – Meniscus at inlet before beginning channel volume test.	55
Figure 4.20 – Inlet partial delamination.	57
Figure 4.21 – PRM with fillets.	57
Figure 5.1 – ASTM F88 3 mil fin sample test data.	59
Figure 5.2 – ASTM F88 5 mil fin sample test data.	59
Figure 5.3 – ASTM F88 6 mil fin sample test data.	60
Figure 5.4 – ASTM F88 8 mil fin sample test data.	60
Figure 5.5 – ASTM F88 10 mil fin sample test data.	61
Figure 5.6 – Material break failure mode [55].	62
Figure 5.7 – Adhesive peel failure mode [54].	62
Figure 5.8 – FEP bladder tank prototype.	63
Figure 5.9 – Foil party balloon creases [64].	65
Figure 5.10 – Hemispherical FEP diaphragm tank [65].	65
Figure 5.11 – Piston tank design [66].	65
Figure 5.12 – M2P flat on build platform cubes.	67
Figure 5.13 – M4U flat on build platform cubes.	67
Figure 5.14 – M2P cubes with elephant’s foot.	68
Figure 5.15 – M4U cubes with elephant’s foot.	68
Figure 5.16 – M4U cubes with sparsely packed, heavy supports.	69
Figure 5.17 – M2P cubes with sparsely packed, heavy supports.	70
Figure 5.18 – Failure modes present on M2P cubes printed with sparsely packed, heavy supports.	70
Figure 5.19 – Failed, sparsely packed, heavy support cubes remaining in the M2P vat.	71
Figure 5.20 – Deformations induced by excessive gaps between supports (not to scale, dimensions continue beyond figure).	73
Figure 5.21 – M2P support density cube print 1.	73
Figure 5.22 – M2P support density cube print 2.	74
Figure 5.23 – M4U support density cube print.	74
Figure 5.24 – M2P PRMs (inlet side/top).	77
Figure 5.25 – M2P PRMs (outlet side/bottom).	77
Figure 5.26 – V1a outlet warping (M2P).	78
Figure 5.27 – V1a outlet and edge warping (M2P).	78
Figure 5.28 – V1d inlet and edge warping (M2P).	79
Figure 5.29 – V1d outlet warping (M2P).	79

Figure 5.30 – V2a edge warping (M2P).....	80
Figure 5.31 – More resistant flow path in PRMs V2.	80
Figure 5.32 – Less resistant flow path in PRMs V2, despite warping.	81
Figure 5.33 – V2d edge warping (M2P).	83
Figure 5.34 – V2d outlet warping (M2P).....	83
Figure 5.35 – V3c inlet warping and elephant’s foot (M2P).....	84
Figure 5.36 – M4U PRMs (inlet side/top).	84
Figure 5.37 – M4U PRMs (outlet side/bottom).	84
Figure 5.38 – Deviation of inlet meniscus locations.....	88
Figure 5.39 – M4U PRM V4d and V5d (inlet side/top).....	88
Figure 5.40 – M4U PRM V4d and V5d (outlet side/bottom).	88
Figure 5.41 – V5d outlet warping (M4U).	91
Figure 5.42 – Multi-layered microfluidic design [69].	91

NOMENCLATURE

Constants

g_0	Gravitational Constant	9.81 m/s ²
π	Pi	3.14
p_{BMP}	Density of BMP-DCA	1.02 g/cm ³

Variables

T	Thrust	N
I_{sp}	Specific Impulse	s
u_e	Exhaust Velocity	m/s
Δv	Orbital Velocity Change Associated with Orbital Maneuver	m/s
$\dot{m}$	Propellant Mass Flow Rate	kg/s
m_i	Initial Spacecraft Mass	kg
m_f	Final Spacecraft Mass	kg
ρ	Density	kg/m ³
Q	Volumetric Flow Rate	m ³ /s
V_i	Induced Voltage	V
I_i	Induced Current	A
$\dot{m}_{ion}$	Ionized Propellant Flow Rate	kg/s
q	Charge	C
m_{BMP}	BMP-DCA Mass	g
V	Tank Volume	cm ³
a/r	Tank Aspect Ratio	--
τ	Tank Inflated Thickness	cm
k	Period for Moving Average	--
n	Number of Data Points in Set	--
p_i	Data Point in the i th Position	--
SMA	Simple Moving Average	--
μ	Average	--
σ_{STD}	Standard Deviation	--
x_i	Value from Population	--
N	Population Size	--
P	Pressure	psi
t	Tank Wall Thickness	in
σ_{tank}	Spherical Tank Stress	psi
F	Maximum Seal Load	lbf
A	Seal Cross-sectional Area	in ²
σ_{seal}	Seal Stress	psi
v_a	Actual Value	--
v_e	Experimental Value	--
δ	Percent Error	--
$m_{i,dry}$	Dry Mass of Cups	g

$m_{i,wet}$	Wet Mass of Cups	g
$m_{i,p}$	Mass Pumped	g
t_p	Time Spent Pumping	s
$m_{i,r}$	Mass Remaining in Channels	g
$\dot{m}_i$	Channel Mass Flow Rate	g/s
Q	Channel Volumetric Flow Rate	mL/min
$V_{outlet\ tube}$	Volume Remaining in Tube	mL
$m_{i,wet,r}$	Wet Mass Remaining in Channels	g
$V_{i,r}$	Volume Remaining in Channels and Tube	mL
V_i	Volume Remaining in Channels	mL

ACRONYMS

IL	Ionic Liquid
DARPA	Defense Advanced Research Projects Agency
OPAL	Orbiting Picosat Automatic Launcher
LEO	Low Earth Orbit
COTS	Commercial-off-the-shelf
NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
EO	Earth Observation
FCC	Federal Communications Commission
CAM	Collision Avoidance Maneuver
EP	Electric Propulsion
UTSI	University of Tennessee Space Institute
μSTAMPS	Micro Scalable Thrusters for Adaptive Mission Profiles in Space
ITO	Indium Tin Oxide
PGD	Porous Glass Disc
PEEK	Polyether Ether ketone
PPU	Power Processing Unit
BMP-DCA	1-Butyl-1-methylpyrrolidinium Dicyanamide
PMD	Propellant Management Device
LAD	Liquid Acquisition Device
CMNT	Colloid Micro-newton Thrusters
JPL	Jet Propulsion Laboratory
EMI-Im	1-ethyl-3-methylimidazolium Bistrifluoromethylsulfonylimide
AM	Additive Manufacturing
3DP	3D Printing
SLA	Stereolithography
MSLA	Masked Stereolithography
DLP	Digital Light Processing
UV	Ultra Violet
CAD	Computer Aided Design
STL	Standard Tessellation Language
IPA	Isopropyl Alcohol
LED	Light Emitting Diode
LCD	Liquid Crystal Display
FEP	Fluorinatedethylenepropylene
FDM	Fused Deposition Modeling
MEMS	Micro-electromechanical Systems
USD	United States Dollar
ISS	International Space Station
SPACEMATDB	Space Materials Database
ESMDB	European Space Materials Database
ID	Inner Diameter

UNC	Unified Course Pitch Threads
SAE	Society of Automotive Engineers
PRM	Propellant Routing Manifold
OD	Outer Diameter
PTFE	Polytetrafluoroethylene
ASTM	American Society for Testing and Materials
MTS	MTS Corporation
DAQ	Data Acquisition
PLA	Polylactic Acid
MATLAB	Matrix Laboratory
SMA	Simple Moving Average
STD	Standard Deviation
M2P	Mars 2 Pro
M4U	Mars 4 Ultra
ACF	Advanced Composite Film
DI	Deionized
DC	Direct Current
AVG	Average
CO2	Carbon Dioxide
PSA	Pressure Sensitive Adhesive
PC	Polycarbonate

Chapter 1: Introduction

1.1 CubeSats

1.1.1 Overview

The miniaturization of technology is a common theme seen throughout the history of science and engineering. Computers, once gargantuan instruments which required large volumes of space to store, are now small enough to hold and orders of magnitude more powerful in terms of computational ability. Within the last two decades, the same can now be said for spacecraft. CubeSats (and other small satellites) are a relatively new category of spacecraft and are considered a “disruptive technology,” meaning they can perform the same tasks as traditional satellites at a fraction of the cost [1]. These satellites are much smaller than traditional satellites, and have been standardized which greatly reduces their development times, further contributing to their disruptive nature. The initial conceptualization, evolution, and standardization of these systems are what led to their success. In addition to this, much of the information regarding these systems is open-source, and vast communities of CubeSat developers have formed over time throughout the world. The creativity and innovation sparked from these communities spawned an exponentially growing market in the private, scientific, and defensive sectors [1,2].

1.1.2 A Brief History of CubeSats

A graduate-student program for developing microsatellites began at Stanford University in 1994. The goal of this program was to take students through a complete life cycle of a microsatellite project: the design, development, fabrication, testing, launch integration, and space operations [3]. The idea was to develop a launch-ready satellite in one year, led and designed entirely by students, using commercial off-the-shelf (COTS) parts with a budget of \$50,000 [3]. The first satellite produced by this program was the SAPPHERE, a 20 kg, 18 in. diameter, and 12 in. height hexagonally shaped satellite; the SAPPHERE (Figure 1.1) was launched September 30, 2001 on an American rocket, Athena 1 [3,4]. The success of the development of SAPPHERE led to the continuation of the program. Beginning in early 1998 as a collaboration with the Defense Advanced Research Projects Agency (DARPA), an idea for the Orbiting Picosat Automatic Launcher (OPAL, Figure 1.2) was born [1,3]. This launcher was designed to carry six picosats (four with dimensions of 4 in.× 3 in.× 1 in., two with dimensions of 8 in.× 3 in.× 1 in.) which were deployed in Low Earth Orbit (LEO); OPAL was launched on January 22, 2000 on the American Minotaur Rocket [1,3]. The OPAL picosats proved to be practical tools for the space education program, and were the precursor to the first CubeSats.

Despite being a useful tool for educating students, the OPAL picosats were lacking in available power; to solve this problem, the satellites’ dimensions were increased to be a 4 in. per edge cube, as this shape would allow room for more solar panels [1,3]. Stanford then founded the CubeSat program, and invited several educational organizations worldwide to participate, 20 of which joined the initiative [1,3]. The initial plan of the program was to develop a standardized generic vehicle, the first constraints which were provided set the standard for what is now known as a 1U CubeSat: the satellite should be a 10 cm per edge cube approximately 1 kg in mass [1–3]. The program strived to make the reproduction of a 1U CubeSat cost around \$1,000 through the use of COTS products, strived to minimize the available power (around 1 W), and to simplify design aspects by efficiently stacking circuit boards and integrating multiple systems into one (e.g., using the solar panels as sun sensors) [1]. The 1U system eventually evolved such that multiple units could be put together to form larger units, which include (but are not limited to) 2U, 3U, 6U, etc. (Figure 1.3) [2,5]. Over time, the standard has been compiled and revised by California Polytech State University, and at the time of writing this Thesis the most recent standard is outlined by the CubeSat Design Specification Revision 14.1 [5].



Figure 1.1 – Stanford University's SAPHIRE satellite [3].

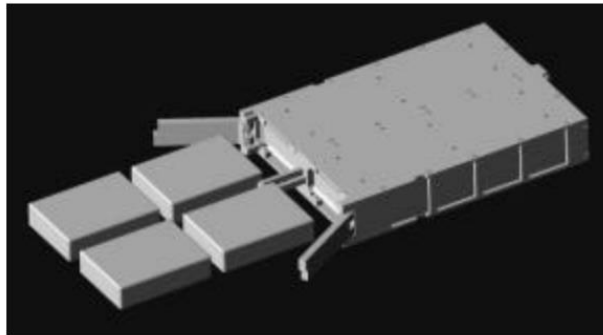


Figure 1.2 – Stanford University's OPAL [3].

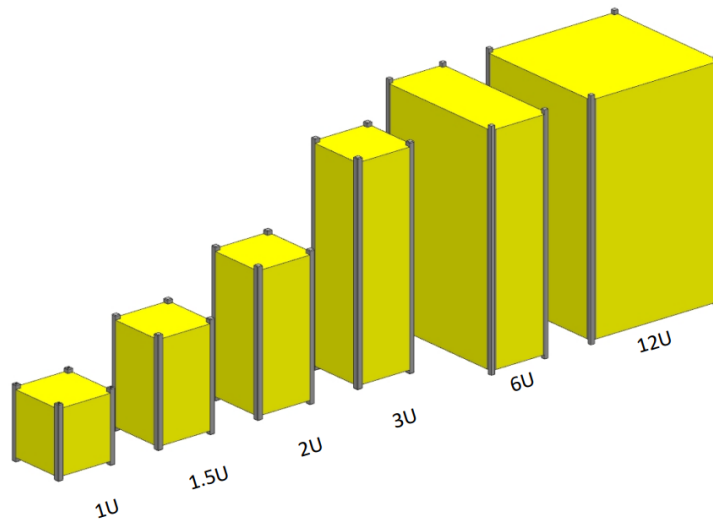


Figure 1.3 – The current CubeSat family [5].

The full potential of CubeSats was not immediately recognized by most of the space community; when they were first launched, CubeSats were perceived as “toy satellites,” simply designed to train students on the principles of spacecraft design [2]. The first CubeSats were developed entirely by students, so in many cases, the projects were expected to fail; for this reason, NASA ignored the importance of these spacecraft for nearly ten years [1,2]. In 2008, Dr. Terese Jorgensen of the National Science Foundation (NSF) organized a CubeSat conference and convinced NSF to offer contracts for scientific CubeSat missions; the successes produced by NSF’s involvement finally persuaded NASA to get involved in 2010 [1]. NASA eventually created the CubeSat Launch Initiative, which provides launch opportunities for U.S. educational institutions and non-profit organizations [6].

1.1.3 CubeSat Growth, Applications, and Limitations Without Propulsion Systems

The number of CubeSats launched into orbit began to grow exponentially around 2017 (Figure 1.4), with a projection of the 1000th CubeSat being launched by 2021 [2]. As of January 1, 2024, 2,323 CubeSats have been launched, approximately doubling the 2021 projection within the span of three years [7]. The adoption and now rapid growth of CubeSats were driven by several factors: 1) Accessibility—these devices are relatively simple and cost-effective; 2) Standardization—a reliable standard has been developed throughout the years to ensure the success of these systems; 3) Entrepreneurship—private sectors gained a significant interest due to CubeSats having a high return on investment; 4) Technology—technology continues to be miniaturized and autonomous flight has significantly improved; 5) Community—a strong community of CubeSat developers has evolved which helped the spread of knowledge and development [1,2,8–10].

CubeSats have enhanced several traditional satellite missions, which include Earth observation (EO) and remote sensing, telecommunications, and astronomy [1]. An example of an EO CubeSat was the ExoCube, a 3U system launched in 2015, tasked with characterizing densities of various elements/ions in the exosphere and ionosphere [11]. The RaInCube, a 6U telecommunications CubeSat launched in 2018, used the first Ka-band radar to track storm movements [8]. A 6U CubeSat used for a 2018 astronomy mission known as HaloSat measured x-ray emissions from ionized oxygen in the Milky Way’s galactic halo [8,9,13]. CubeSats are also excellent technology demonstrators for proof-of-concept missions [1]. The RemoveDEBRIS CubeSats were two 2U devices launched in 2018 which demonstrated four different methods of removing orbital space debris [14]. CubeSats also are capable of deep space exploration [1]. Two 6U satellites called MarCO were launched in 2018, which were the first interplanetary CubeSats; these devices were designed to relay critical data from Earth to Mars when landers or other orbiters are unable to [15]. Finally, CubeSats have been proposed for use in global constellations [1]. Kepler Communications plans to launch a constellation of CubeSats which provide high-bandwidth links to act as relays from satellites to ground stations [16].

Of the 2,323 CubeSats that have been launched, only around 8% have on-board propulsion systems [7]. CubeSats launched without propulsion systems, however, have limited capabilities. In LEO, CubeSats without propulsion systems are typically limited to an altitude of 400–600 km. This is because of a new Federal Communications Commission (FCC) regulation, which requires new satellites to deorbit within five years of completing their missions [17]. At these altitude ranges, CubeSats naturally decay and deorbit within several months to a few years, which complies with the new regulations [2]. Flying above these altitudes can span between tens to hundreds of years before a CubeSat naturally deorbits. Micro-propulsion devices are an excellent candidate for rapidly deorbiting spacecraft, and are another example of how the development of CubeSats stimulates the need to miniaturize conventional spacecraft technologies. At altitudes lower than 400–600 km, satellites will naturally decay in a matter of hours [2].

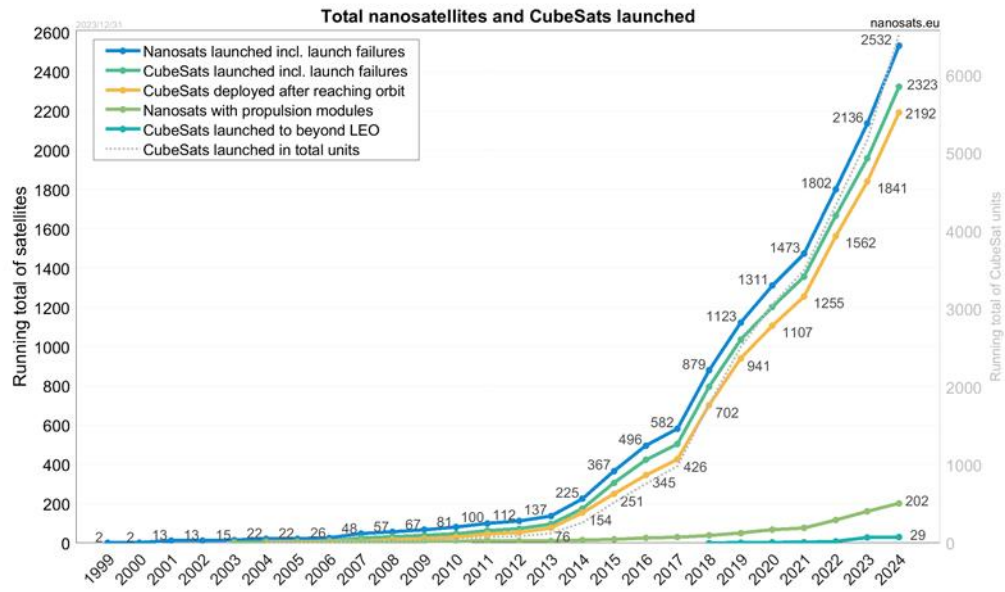


Figure 1.4 – CubeSats launched as of January 1st, 2024 [7].

To increase the mission life of satellites at these lower altitudes, boost burns known as “station-keeping maneuvers” are a must, and thus a need for propulsion systems arise. Another problem that CubeSats, as well as all other spacecraft, face is the threat of orbital debris. Throughout the years, space has become more cluttered with debris ranging from old rocket boosters to small fragments of satellites. Initiatives have been created, such as NASA’s Orbital Debris Program Office, to track and model orbital debris [18]. One mitigation technique to prevent the creation of more orbital debris is to provide spacecraft with the means to perform collision avoidance maneuvers (CAMs). These are short boosts from propulsion systems which slightly increase a spacecraft’s altitude in order to dodge incoming debris, and can typically be performed in such a way that does not waste propellant [19]. The addition of propulsion devices on CubeSats can provide the capability to alter their orbits. Certain missions may instead require orbital transformations. Another application where propulsion devices in CubeSats are required is deep space exploration missions for the purposes of coasting and orbital insertion. It is more cost-effective to equip satellites with thrusters for the coast and insertion phases than to employ the use of a rocket’s second stage. Finally, in order for a constellation of CubeSats to be possible, propulsion devices are required. Without onboard propulsion systems, satellites would not be able to properly spread out and form the constellation. As can be seen, the inclusion of propulsion devices in CubeSats greatly increases their mobility and thus mission capabilities, namely in the areas of deorbiting, station-keeping, CAMs, orbital transfers, deep-space exploration, and constellation formation.

1.2 Electric Propulsion and Electrospray Thrusters

1.2.1 Overview

There are many propulsion systems which have been miniaturized to fit within the form factors of CubeSats. These include cold gas propulsion systems, liquid propulsion systems, and solid rocket propulsion systems [20]. These systems are capable of delivering relatively large amounts of thrust; however, they tend to take up a significant amount of space within CubeSats and are limited in terms of efficient propellant delivery. To solve these issues, engineers have turned to the application of electric propulsion (EP) devices. The primary drawback of EP is that these devices produce much lower thrust values (on the scale of micro- to millinewtons) compared to conventional systems. EP systems that have been considered for CubeSats include resistojets, radio-frequency ion thrusters, Hall Effect thrusters, electrospray/colloid thrusters, and pulsed plasma thrusters [20]. This section will provide a basic overview of EP, with a focus on electrospray propulsion devices.

1.2.2 Electric Propulsion

EP is attractive because of its efficient utilization of propellant mass: smaller propellant loads result in more mass allocation for useful payloads [21]. Important factors for characterizing the performance of any propulsion system include thrust (T), specific impulse (Isp), effective exit/exhaust velocity (u_e), and delta- v (Δv); these performance terms are described in Equations (1.1)–(1.4) [20,21]. To begin, thrust of EP devices (T) can be approximated by multiplying the propellant mass flow rate ($\dot{m}$) by the exhaust velocity (u_e), shown in Equation (1.1). Spacecraft engines typically function based on the conservation of momentum: mass is accelerated and ejected, which imparts an equal but opposite force, thus moving the spacecraft forward [22]. For electric propulsion, the thrust can be approximated in terms of propellant mass flow rate and exhaust velocity:

$$T = \dot{m}u_e. \quad (1.1)$$

Isp is a measurement of the impulse generated per unit weight of propellant, and it depends on the thrust (T), propellant mass flow rate ($\dot{m}$), and gravitational acceleration (g_0), Equation (1.2) [20,22]. In other words, it is effectively a measure of spacecraft fuel efficiency.

Smaller propellant mass flow rates result in larger specific impulse values. By substituting Equation (1.1) into the thrust term of Equation (1.2), the specific impulse can be found simply from u_e divided by g_0 . Researchers are studying EP devices to limit propellant loads, since placing mass in orbit is expensive; for this reason, EP devices should obtain larger thrust and impulse values through high exit velocities, rather than excessive propellant ejection [21,22]. In conventional propulsion systems, excessive propellant ejection is required because attainable exhaust velocities are limited by three factors: 1) available energy of the combustion reaction/propellant properties; 2) heat transfer to the combustion chamber and nozzle; 3) “frozen flow” losses and radiation losses from the exhaust [21]. These limitations are circumvented by EP devices because the propellant can be accelerated to nearly unbounded limits with electric fields [21,22]. As a result, EP devices have significantly larger values of I_{sp} than conventional systems:

$$I_{sp} = \frac{T}{\dot{m}g_0} = \frac{u_e}{g_0}. \quad (1.2)$$

Rewriting Equation (1.2) provides a way to simply calculate the exhaust velocity from I_{sp} and g_0 , provided by Equation (1.3):

$$u_e = g_0 I_{sp}. \quad (1.3)$$

Finally, Equation (1.4) demonstrates the calculation of Δv , a parameter which describes the orbital velocity change associated with an orbital maneuver. This parameter is in terms of u_e , initial spacecraft mass before maneuver (m_i), and final spacecraft mass post-maneuver (m_f):

$$\Delta v = u_e \ln \left(\frac{m_i}{m_f} \right). \quad (1.4)$$

1.2.3 Electrospray Propulsion

There are three main categories of EP: 1) Electrothermal—propellant gas is electrically heated and expanded through a nozzle; 2) Electrostatic—ionized propellant is accelerated by electric fields; 3) Electromagnetic—ionized propellant is accelerated by magnetic fields with electric current driven through the stream [21]. Many EP devices are only suitable for larger satellites because, when scaled down, their performance diminishes, efficiency and lifespan in particular [23]. However, electrospray thrusters, which are electrostatic devices, scale well to small sizes [20,22–25]. Electrospray is a plasma-free propulsion system that uses electrostatic extraction to accelerate charged particles from a liquid propellant [20]. The most common form of propellant is ionic liquids (ILs), which are salts in the liquid phase at room temperature [20,23–25]. ILs are the primary choice of propellant based on their wide range of molecular masses and ion compositions, reduced corrosiveness (compared to liquid metals and acids), high electrical conductivity, and negligible vapor pressures [20,23–25].

The main components of electrospray thrusters include propellant storage, an emitter array, and an extractor electrode; these devices may also include an accelerator electrode to further accelerate the exhaust [20,23]. Propellant is fed to emitters via surface wetting or capillary tubes, and an electric field is established between the propellant and the extractor electrode [20,22–25]. Once a strong-enough field is applied, the propellant at the tip forms a conical shape, known as a Taylor cone; at a certain voltage threshold, ions or droplets are jetted from the cone’s apex and thrust is produced [20,22–25]. Electrospray thrusters that operate in droplet mode, or cone-jet mode, are occasionally referred to as colloidal electrospray thrusters; electrospray thrusters which operate in ion mode are called field emission/ion electrospray thrusters [24].

A schematic of the electrospray process is shown in Figure 1.5. Figures 1.6–1.8 provide comparisons of various types of propulsion systems, in terms of thrust capabilities, power, and thrust-to-power ratios with respect to I_{sp} [20]. Table 1.1 summarizes the performance of four electrospray devices that have been developed [20].

There are additional benefits for using electrospray propulsion beyond scalability. Before discussing those benefits, some important performance parameters must be described. Equations (1.5)–(1.7) show the charge-to-mass ratio ($\frac{q}{m_{ion}}$), exhaust velocity (u_e), and thrust (T) calculations for electrospray devices [20]. Charge-to-mass ratio, Equation (1.5), is important in determining the exhaust velocity and thrust; it is inversely proportional to the density (ρ) and volume flow rate (Q) of the propellant [20]:

$$\frac{q}{m_{ion}} = \frac{1}{\rho Q}. \quad (1.5)$$

The exhaust velocity, Equation (1.6) is a function of ion accelerating voltage (V_i), ion beam current (I_i), and charge-to-mass ratio [20]. By substituting Equation (1.5), u_e can be rewritten in terms of V_i , I_i , ρ , and Q :

$$u_e = \sqrt{2V_i I_i \frac{q}{m_{ion}}} = \sqrt{\frac{2V_i I_i}{\rho Q}}. \quad (1.6)$$

By substituting Equation (1.6) into the previously defined thrust equation (Eq. 1.1), where the mass flow rate is the mass flow rate of the ions ($\dot{m}_{ion}$), the thrust becomes a function of V_i , I_i , and $\dot{m}_{ion}$ [20]:

$$T = \dot{m}_{ion} u_e = \sqrt{2V_i I_i \dot{m}_{ion}}. \quad (1.7)$$

The first benefit is that the performance of electrospray can be varied by changing the voltage passed through the system [20,23,24]. For example, by altering the voltage, the thrust of these devices can be throttled [23]. Changing the voltage also alters the resulting droplet size, which permits control over the I_{sp} [23,24]. The use of ILs benefits these devices because of their ion compositions, high electrical conductivity, and negligible vapor pressures. Electrospray devices can operate in a pulsed mode of alternating polarity (unlike Hall and ion thrusters), which can extract an equal number of cations and anions from the IL propellants; this, in turn, eliminates the need for an external neutralizer and helps to minimize the system mass [20,22,25]. The highly conductive propellants also help to reduce the voltage required to power these systems [20]. Due to the negligible vapor pressures of ILs, the need for a pressurized propellant management system is eliminated, which further miniaturizes the system [20]. These facts make electrospray thrusters excellent candidates for improving the mobility of CubeSats.

1.3 Micro Scalable Thrusters for Adaptive Mission Profiles in Space (μ STAMPS)

1.3.1 Overview

The University of Tennessee Space Institute (UTSI) is developing a new patent-pending micro-propulsion device called Micro Scalable Thrusters for Adaptive Mission Profiles in Space (μ STAMPS). μ STAMPS aims to supply propulsion capabilities to CubeSats, such as deorbiting, station-keeping, and collision-avoidance maneuvers. The system is also designed to require lower applied voltages and mitigate common failure pathways of traditional electrospray systems.

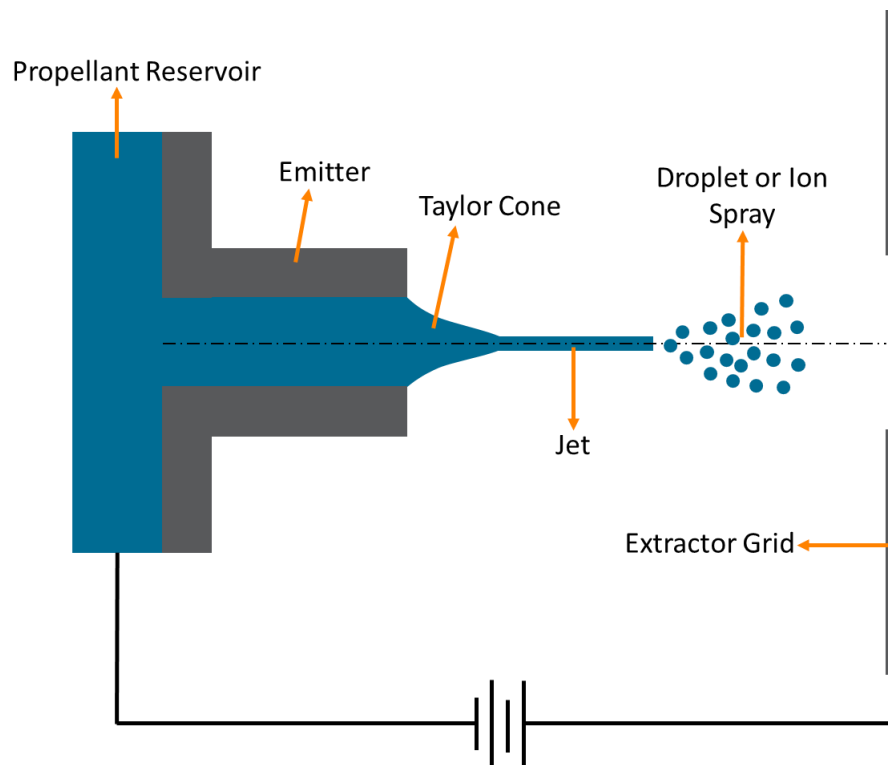


Figure 1.5 – Basic operation of an electrospray device.

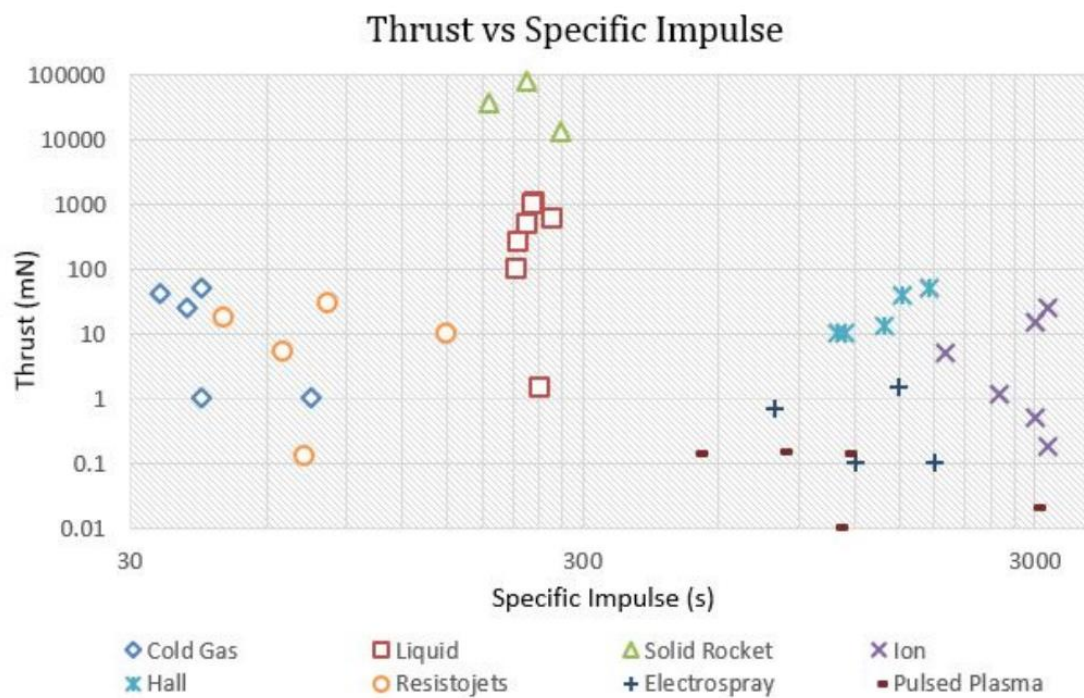


Figure 1.6 – Thrust versus specific impulse of various propulsion systems [20].

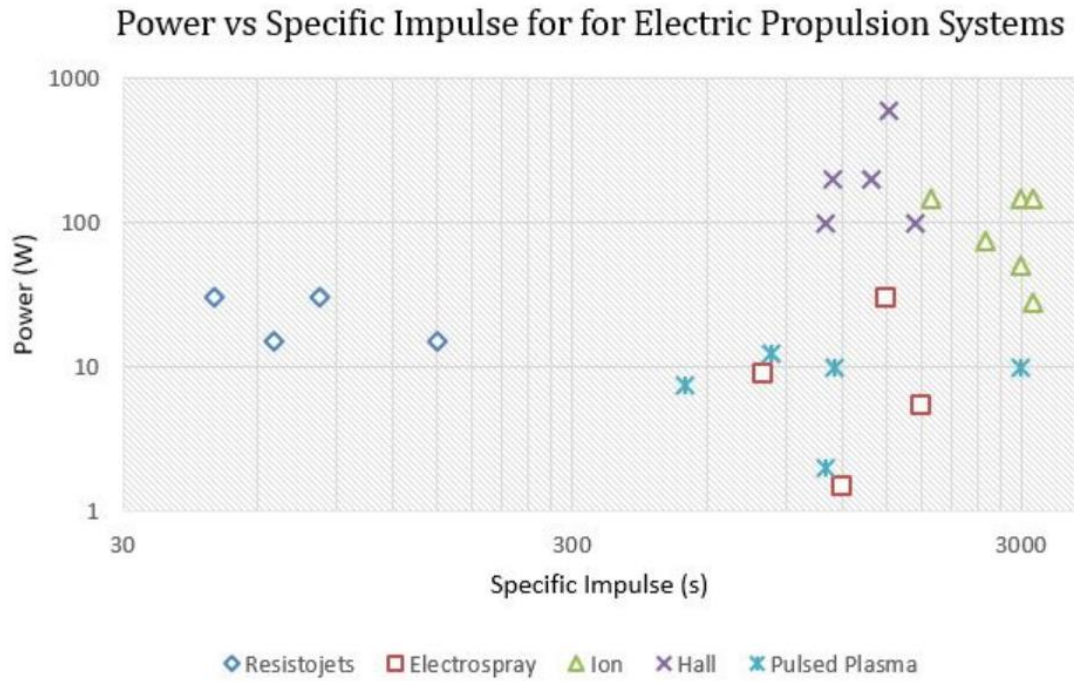


Figure 1.7 – Power versus specific impulse of various propulsion systems [20].

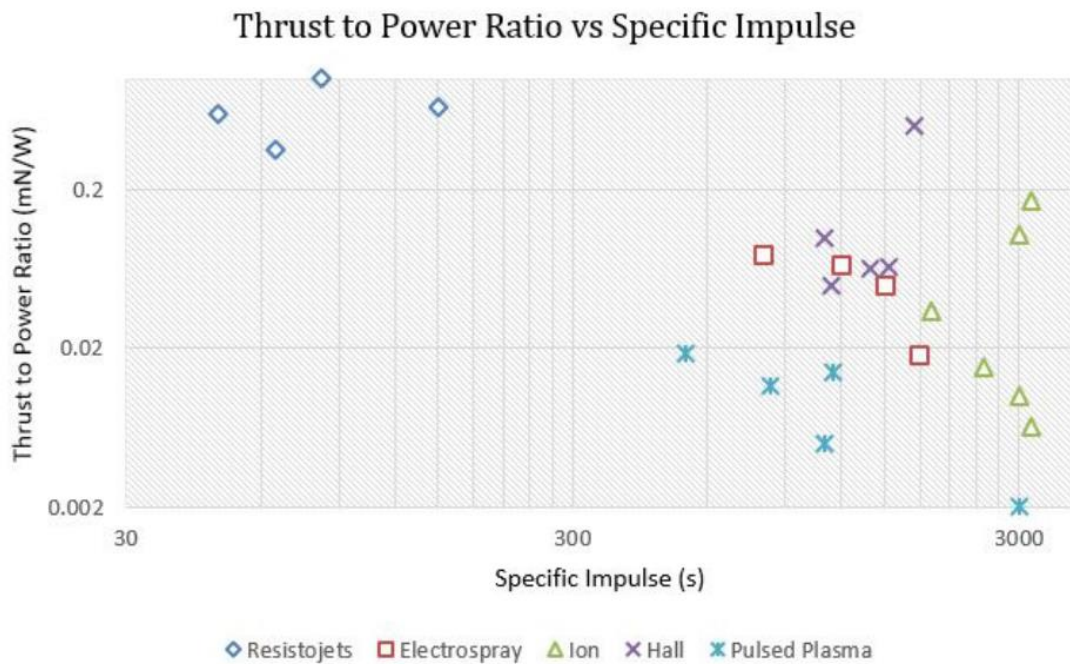


Figure 1.8 – Thrust-to-power ratio versus specific impulse of various propulsion systems [20].

Table 1.1 – Performance of Various Electrospray Devices [20].

Company	Engine	Thrust (mN)	Isp (s)	Power (W)	Propellant
MIT	S-iEPS	0.1	1200	1.5	IL
Accion Systems	TILE 5000	1.5	1800	30	IL
Busek	BET-1mN	0.7	800	<9	IL
Busek	BET-100	0.005–0.1	1800	5.5	IL

Significant work has been performed developing this system, including (but not limited to) preliminary simulations optimizing emitter/extractor geometries that minimize applied voltages, an exploration into potential failure modes, and simulations in LEO of a 3U CubeSat with μ STAMPS performing various maneuvers [26–28]. The following subsections will summarize this work, and finally state the ultimate purpose and goal of this Thesis.

1.3.2 The μ STAMPS Emitter/Extractor Chip

Traditional electrospray devices use emitter arrays with lithographically fabricated capillary needles, which can be internally wetted, porous, or externally wetted (Figure 1.9) [26]. An extraction grid is then aligned with the emitter array and spaced a certain distance away depending on thruster design requirements. These grids are typically metallic, however μ STAMPS uses a hybrid chip with a metallic grid coated onto a dielectric substrate, borosilicate [20,26]. The primary difference between traditional electrospray systems and μ STAMPS is that in μ STAMPS, the capillaries are embedded within the dielectric (rather than being protruding needles), and the extractor grid is applied directly onto the emitter substrate (Figure 1.10). These capillaries measure 1 μm in diameter and are 170 μm long; fabrication of the microscopic holes is made possible with the use of an ultrafast 20 W Amplitude laser (100 μJ maximum pulse energy @ 200 kHz, tunable 0.3–10 ps pulse length) [26,28]. By embedding the capillaries into the emitter chip substrate, the risk of damaging extremely fragile needles during testing, transport, and launch is eliminated. In addition, the risk of surface erosion of the capillaries (Figure 1.11) is eliminated, since the μ STAMPS capillaries are internally wetted [26]. The extractor grid is an electrically conductive coating of indium tin oxide (ITO) applied directly onto the emitter chip [26]. Since the extractor is applied directly to the emitter, the risks associated with overspray and backspray are reduced, as well as grid misalignment and flexure (Figures 1.12 and 1.13) [26].

1.3.3 μ STAMPS Device Design and Statement of Purpose

The current μ STAMPS device is relatively simplistic, and consists of five main components: a 3D printed enclosure, compression spring, porous glass disc (PGD), filter paper, and the emitter/extractor chip (Figures 1.14 and 1.15) [26]. The housing will be printed from polyether ether ketone (PEEK), a material well-suited for the harsh environment of space; the compression spring serves to maintain contact between components; the PGD acts as an internal propellant reservoir; and the filter paper will filter any contaminants from entering the chip. The dry mass of the thruster is about 7.68 g, and the assembled thruster dimensions, not including the power processing unit (PPU), is approximately $(25 \times 25 \times 6)$ mm [26,27]. IL propellant is fed to the chip via capillary action from the PGD, which is capable of storing about 0.2 g of 1-Butyl-1-methylpyrrolidinium dicyanamide (BMP-DCA) [26]. Orbital simulations of 3U CubeSats with μ STAMPS were performed at altitudes between 325–550 km; for a propellant load of 0.2 g it was shown that μ STAMPS can continually thrust for 3–4 hours [28]. This is plenty of propellant for short, sporadic maneuvers, including CAMs and attitude control; however, it was found that more advanced maneuvers required additional propellant. The other maneuvers which were studied included station-keeping and deorbiting. At altitudes between 325–375 km, a 3U CubeSat with μ STAMPS required 23.4 g of propellant to maintain its orbit for five years, and 43 g to deorbit within a five-year period; this results in a total of 66.4 g of propellant for these essential tasks [28]. As for altitudes between 500–550 km, 1.6 g were required for station-keeping and 79.2 g were required for deorbiting within a five-year period, resulting in a total of 80.8 g [28]. Based on these simulations, and the targeted applications of μ STAMPS, an additional propellant supply is required. The primary goals of this paper are to propose and evaluate an initial design for an additional propellant supply, present lessons learned during the conceptualization of this subsystem, and offer suggestions on how to improve the design to ensure the success of μ STAMPS.

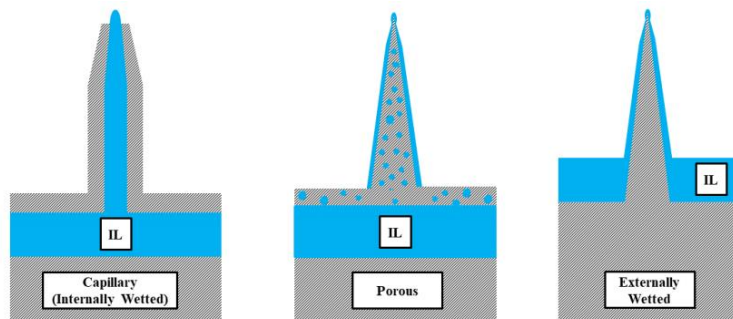


Figure 1.9 – Conventional electrospray emitter designs [26].

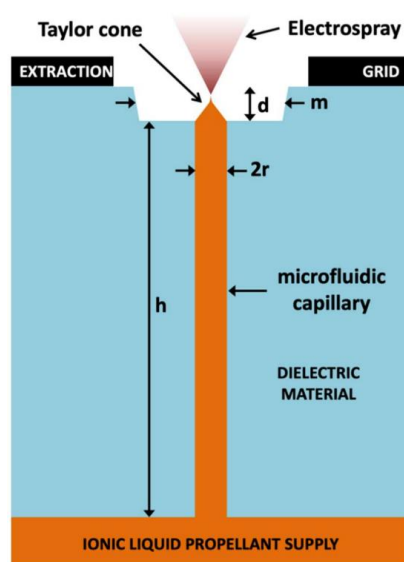


Figure 1.10 – μ STAMPS emitter/extractor chip design [26].

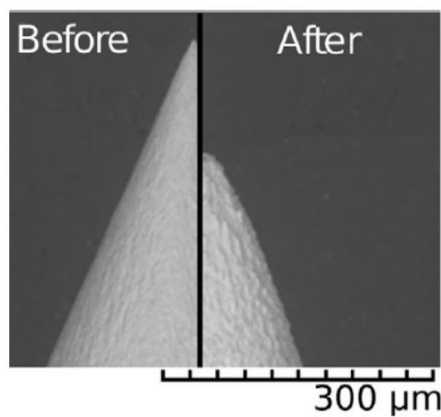


Figure 1.11 – Surface erosion of conventional electrospray emitters [26].

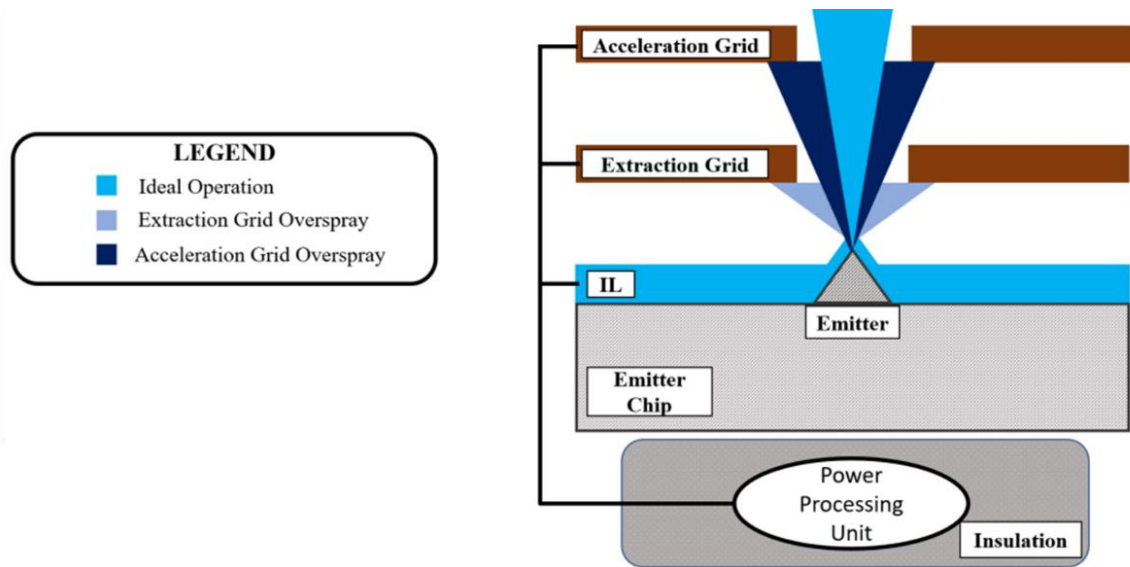


Figure 1.12 – Overspray in conventional electrospray devices [26].

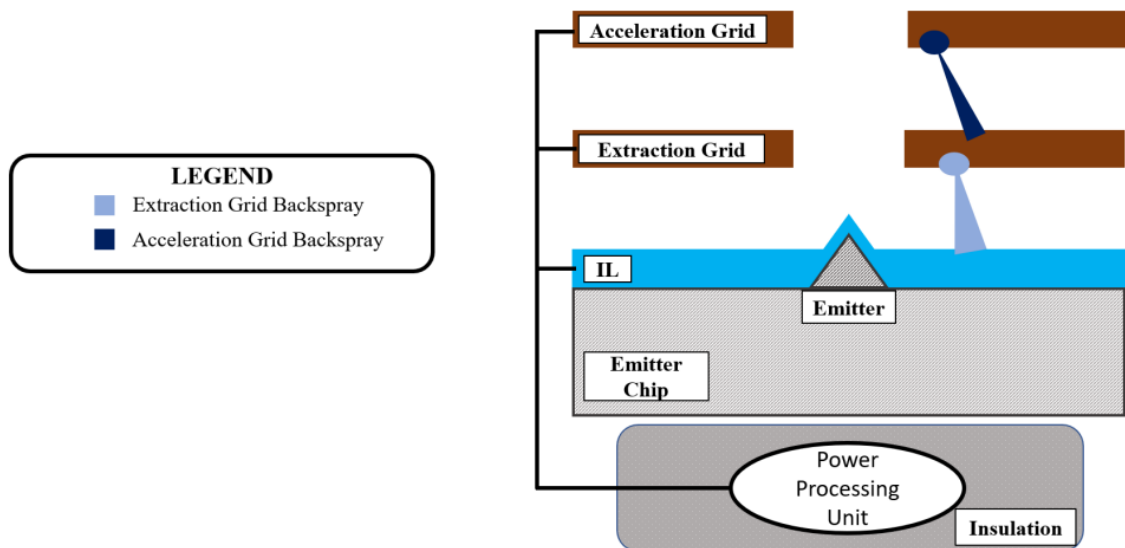


Figure 1.13 – Backspray in conventional electrospray devices [26].



Figure 1.14 – μ STAMPS components [26].

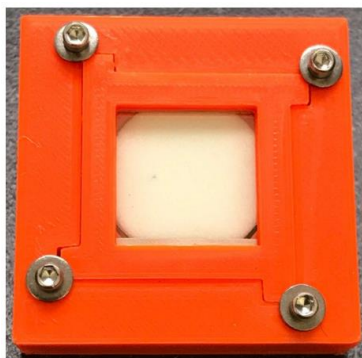


Figure 1.15 – Fully assembled μ STAMPS prototype [26].

Chapter 2: Background

2.1 Propellant Management Devices

2.1.1 Overview

Electric propulsion systems require various types of fluid propellants. This spans from critically stored gases to cryogenically stored liquids to ionic liquids. On Earth, gravitational forces pull liquid propellants down (towards the Earth) to have constant contact with tank outlets, but in a microgravitational environment, the liquids tend to float around and stick to the walls of tanks. In other words, fluid density determines the location of a liquid in a tank on Earth, whereas in orbit, surface tension becomes the controlling mechanism for phase separation [29]. This is problematic, because unless the craft is constantly undergoing a large enough acceleration that forces the liquid to make contact with the tank outlet, a void develops in the center of the tank. Figure 2.1 illustrates how liquids behave at various stages of launch, with and without the use of a propellant management device. After engine cutoff, the engines may need to be re-engaged for certain mission-specific maneuvers. Propellant management devices/liquid acquisition devices (PMDs/LADs) are essential in the successful restart of spacecraft engines and are designed to maintain a connection between the PMD, the liquid, and the tank outlet during any phase of the mission [29].

Several types of PMDs exist and may be used in combination with one another for redundancy and to ensure complete communication of the propellant with the tank outlet. These include noncapillary-type PMDs, partial communication capillary PMDs, and total communication capillary PMDs [29]. Noncapillary-type PMDs employ the use of positive expulsion devices, such as bellows, diaphragms, and pistons [29]. Partial communication capillary PMDs include traps, troughs, baffles, and vortex suppressors [29]. Total communication capillary PMDs consist of vanes, sponges, and screen channels [29]. These PMDs serve different functions and contain some advantages and disadvantages associated with each.

2.1.2 Noncapillary-Type Propellant Management Devices

Noncapillary devices strive to eliminate reactions between pressurant gases and liquid propellant and can be utilized in a wide range of orbital maneuvers [29]. As a thruster fires and the tank depletes, the expulsion mechanism effectively shrinks the tank volume, resulting in total communication throughout the process. For example, bellows can fold in on themselves and retract, maintaining a constant connection between the liquid propellant, tank walls, and outlet. A stainless-steel bellows system was utilized by Busek in their CMNT thrusters for the NASA ST7 mission, which can be seen in Figure 2.2 [30–32]. Similarly, elastomeric bladders shrink to expel the propellant. Diaphragms, typically hemispherical, are designed to invert on themselves as the tank depletes, maintaining constant communication. Busek was later contracted to employ their thrusters for Gravity Wave Observation Missions, which required larger propellant loads. To solve this problem, Busek teamed up with NASA JPL to design a stainless-steel diaphragm tank, shown in Figures 2.3 and 2.4 [31]. Piston devices behave similar to plungers in syringes, where the piston moves in the direction of the outlet as the tank expels propellant; some schematics of a piston PMD can be seen in Figure 2.5 [33].

Advantages of these systems include total communication of the propellant at all times, and in rare cases, do not require a pressurant gas. The NASA ST7 mission's propellant feed system employed the use of four constant-force springs in their design to pressurize the system [30]. However, these systems require a rigorous propellant conditioning and cleaning process, especially when being utilized for electrospray propulsion. Any water content remaining in the IL propellant will lead to the formation of outgassing bubbles, which will adversely affect thruster startup and performance; the same can be said for other contaminants imposed through the manufacturing and assembly of these devices [31].

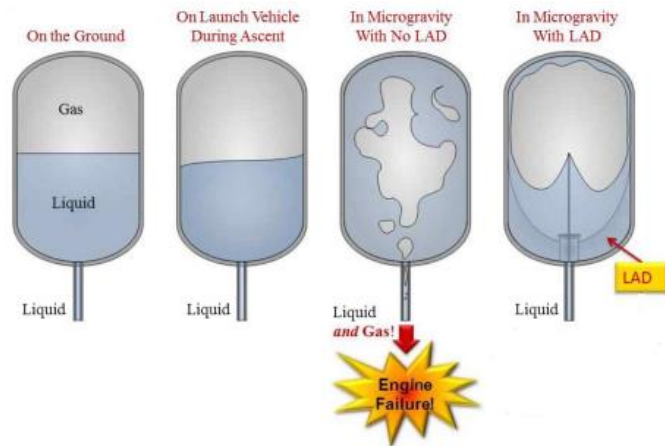


Figure 2.1 – Behavior of liquid during various launch stages [29].



Figure 2.2 – Busek's CMNT bellows tank [32].

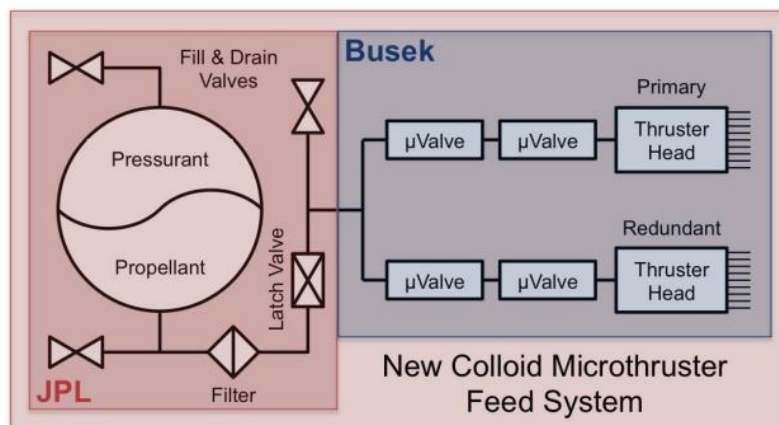


Figure 2.3 – Busek and NASA JPL's new feed system [31].



Figure 2.4 – NASA JPL's diaphragm tank for Busek's CMNTs [31].

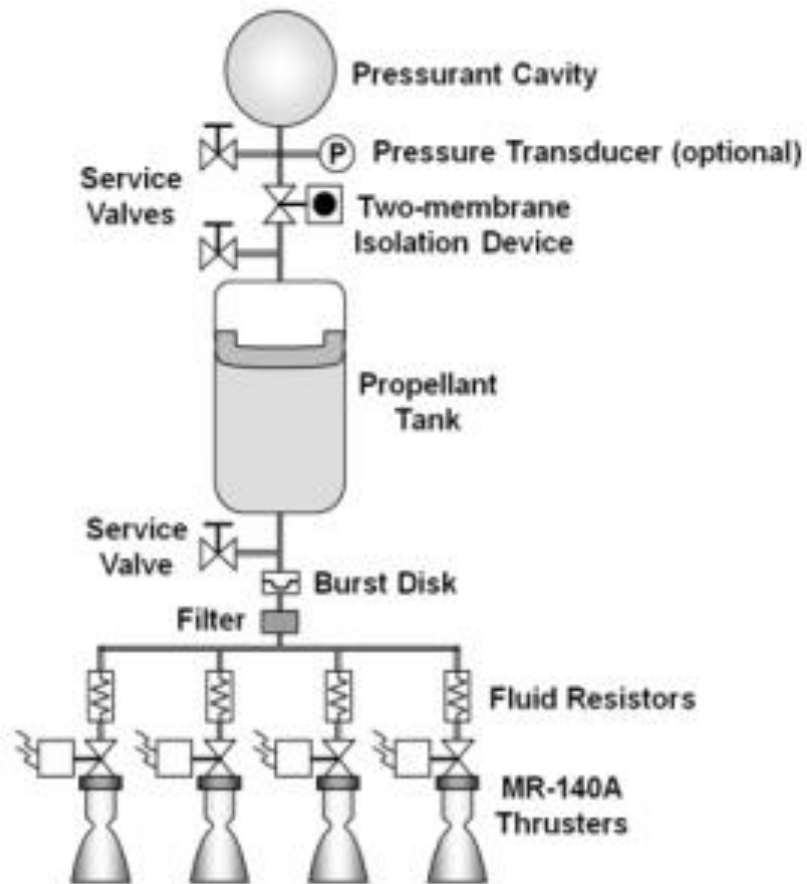


Figure 2.5 – Schematic of a piston tank feed system for a 1U CubeSat Hydrazine Adaptable Monopropellant Propulsion System (CHAMPS) [33].

These PMDs may also require precise flow control, especially in the case of electrospray thrusters, where flow rates are exceptionally low. Custom valves must be designed, which adds to the complexity of the system [30–32]. Noncapillary-type PMDs may also be heavy compared to other options, especially with the use of metallic components. Diaphragms experience mechanical fatigue and should be designed to undergo several cycles even if the mission does not include plans for in-orbit refueling. This is a challenge outlined by Busek, where their diaphragm design could only undergo two cycles when they needed a factor of safety of five [31]. Diaphragms and elastomeric bladders typically span the entire tank, which can make them impractical for large-scale use [29]. Elastomers are also not well-suited for long-life missions, and may be incompatible with some propellants, such as the EMI-Im propellant used in Busek’s CMNTs [29,31].

2.1.3 Capillary-Type Propellant Management Devices

Due to the potential complexity of non-capillary PMDs, newer missions tend to employ surface tension, or capillary, PMDs [29]. Capillary PMDs make use of capillary action to effectively deliver propellant within a tank in a microgravitational environment. These PMDs fall in one of two categories: partial communication or total communication. Partial-communication devices are typically used as simple control devices designed to ensure only liquid propellant is being extracted from the tank [29]. In contrast, total-communication devices maintain a constant connection between the propellant load and the tank outlet. In many cases, these devices are used in conjunction with one another [29]. Capillary devices vary in both function and complexity, and the type of device (or devices) to be used depends on the orbital maneuvers a spacecraft will perform.

Traps, troughs, baffles, and vortex suppressors are examples of partial-communication capillary PMDs [29]. Traps are designed to trap gas outside of the structure but allow liquid propellant to flow through and out of the tank [29]. These are reliable and can be lightweight, but they cannot passively reacquire propellant in microgravity [29]. Based on this, these devices are typically used for high-acceleration, one-time maneuvers such as station-keeping and launches [29]. Troughs are very similar to traps, their key difference being that troughs can be passively refilled via capillary action [29]. However, this extra functionality means that these devices are slightly more complex and add more mass to a system than traps [29]. An example of a trough can be seen in Figure 2.6 [29]. Baffles, on the other hand, serve an entirely different purpose. These devices are welded in tanks to reduce sloshing of the propellant during maneuvers and can take many different shapes [29]. Figure 2.7 provides an example of a circular baffle welded within a propellant tank [29]. Finally, vortex suppressors are important controlling devices for systems with high mass flow rates [29]. As a tank rapidly depletes of propellant, a vortex will develop, and gas may enter the system, resulting in engine failure. Vortex suppressors are designed to reduce or eliminate vortices at the tank outlet [29]. A model of a vortex suppressor is shown in Figure 2.8 [29].

The final category of PMDs are total communication capillary devices, which include vanes, sponges, and screen channel LADs. Of all the PMDs described, vanes have the simplest design; these devices are manufactured from thin metal plates and are mounted perpendicular to tank walls [29]. Vanes are sized so that they maintain constant communication between the propellant, tank walls, and vane [29]. Due to their simple design, however, vanes cannot supply propellant to systems that require medium to large flow rates [29]. In addition to this, vanes cannot maintain liquid-only flow during high-acceleration maneuvers due to their weak capillary forces [29]. To mitigate these issues, vanes are often used in combination with other PMDs, and they are selected for use with high surface tension propellants [29]. Figure 2.9 provides an example of a total-communication vane PMD. A cryogenic propellant storage system for use in a Hall-effect thruster can be seen in Figure 2.10; this device intends to employ the use of a cooled vane PMD [34].

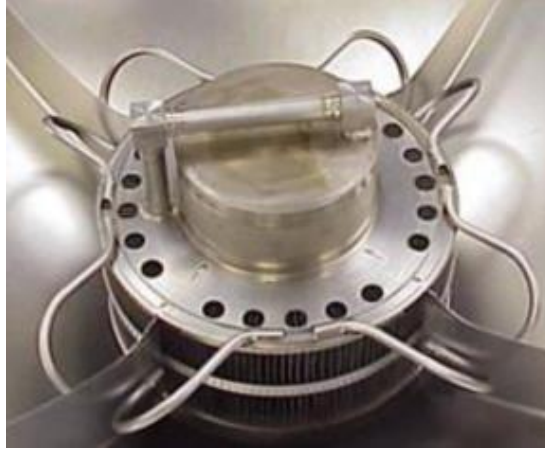


Figure 2.6 – Trough PMD [29].



Figure 2.7 – Circular baffle welded to the interior of a tank [29].

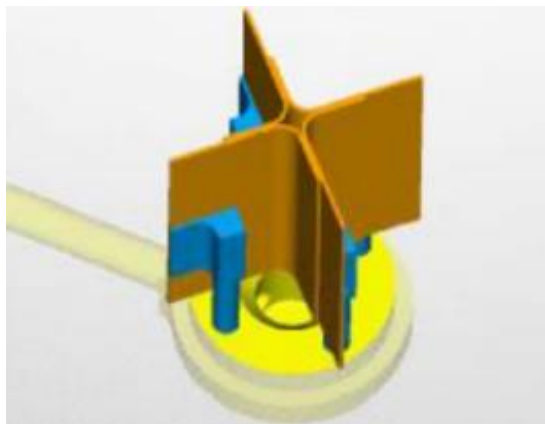


Figure 2.8 – 3D model of a vortex suppressor [29].



Figure 2.9 – Total-communication vane PMD [29].

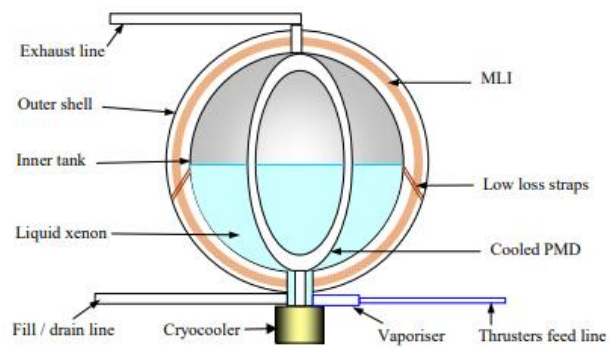


Figure 2.10 – Conceptual design of a cryogenic propellant tank for Hall-Effect thrusters [34].

Sponges are PMDs composed of an array of thin, lightweight metal fins which emanate from the center of the tank over the tank outlet, shown in Figure 2.11 [29]. These devices have the ability to maintain and refill propellant at the tank outlet [29]. Similar to vanes, sponges cannot support systems that undergo high-acceleration maneuvers, and their performance cannot be validated through ground testing [29]. These devices can also be much heavier than vanes [29]. Despite these disadvantages, sponges have the most flight heritage in comparison to the other PMD options and can be used in a wide array of non-cryogenic propulsion systems [29]. A sponge PMD used in a cesium propellant ion propulsion engine can be seen in Figure 2.12 [29].

Finally, screen channel LADs are some of the more complex and difficult to manufacture PMDs. These devices are defined as a closed channel with three solid walls and one porous wall [29]. The complexity of these designs stems from the manufacturing of the porous media. Screen meshes are woven, and the type of weave used is the most important parameter in these devices [29]. These weaves must then be extensively tested to ensure no bubbles form, resulting in failure of the thruster [29]. Compared to vanes and sponges, screen LADs can be a more robust solution that provides liquid acquisition to a broader range of thermal and gravitational environments [29]. Screen LADs are classified in two categories: start baskets and total-communication devices [29]. Start baskets are small devices that confine liquid directly above the tank outlet; an example of a start basket is shown in Figure 2.13 [29]. Total-communication screen LADs are much more complex and must be carefully designed to maintain communication during every phase of a mission; Figure 2.14 provides the screen LAD used inside the propellant tanks of the space shuttle's reaction control system [29].

2.2 MSLA Additive Manufacturing

Additive manufacturing (AM), also known as 3D printing (3DP), is a revolutionary and relatively new manufacturing process which has greatly improved engineering and design. This process functions by adding successive layers of material (ranging from polymers to metals) until a three-dimensional part is made. AM is the opposite of traditional subtractive manufacturing, where material is subtracted from a bulk mass to make a part. There are many subsets of 3DP methods, each of which manufacture parts in unique ways, and applications of these parts vary. Many advantages make 3DP a desirable manufacturing technology, which include freedom of design, customization, waste reduction, fast prototyping, and high precision [35]. This section will provide an overview of a subset of 3DP known as Stereolithography (SLA), more specifically, Masked Stereolithography (MSLA). The research presented in this paper is interested in MSLA for its low-cost, rapid prototyping capabilities, and dimensional precision.

SLA is a process known as vat, or bath, photopolymerization, and it is the earliest method of 3DP (patented in 1986) [36,37]. Currently, there are three main types of SLA: Laser SLA, Digital Light Processing (DLP), and Masked SLA (MSLA) [38]. These methods employ the use of a vat to contain liquid resin which cures under ultraviolet (UV) radiation. Curing of these resins is characterized by high-reactivity, fast transition from liquid to solid (gelation), and quick setting of the final mechanical properties (curing) [39]. Over the years, many photopolymer resins have been developed which vary in curing time, strength, and dimensional stability (namely surface accuracy and shrinkage) [40]. The typical order of operations for fabricating SLA parts are as follows: 1) use a Computer Aided Design (CAD) software to 3D model a part; 2) convert the 3D CAD model into Standard Tessellation Language, commonly known as an STL file; 3) import the STL file into a software called a slicer, which "slices" the STL file into 2D cross-sections and provides instructions for the printer; 4) transfer the sliced file into the printer and begin the print; 5) clean the part in isopropyl alcohol (IPA), dry it, and remove any supports; 6) post-cure the part in a UV light chamber.



Figure 2.11 – Total-communication sponge PMD [29].



Figure 2.12 – Sponge PMD for a cesium propellant ion engine [29].

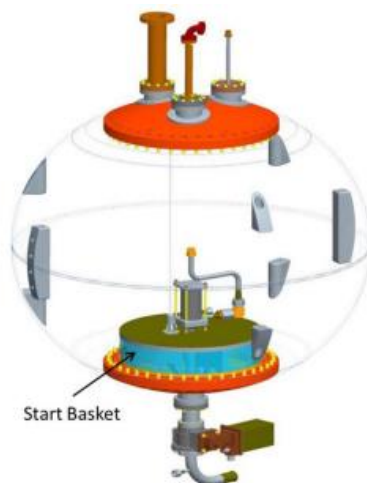


Figure 2.13 – 3D model of a start basket [29].

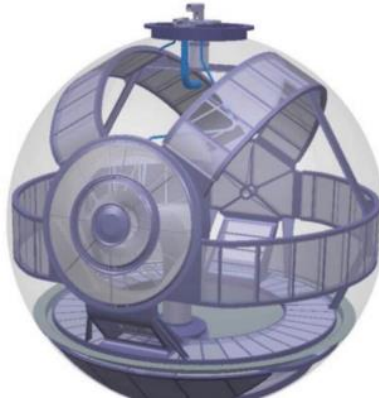


Figure 2.14 – 3D model of a screen channel LAD used in the space shuttle's reaction control system [29].

SLA employs the use of a high-power UV laser, which line-scans the sliced 2D cross-sections to cure the resin [36,38]. Wherever resin is exposed to light, the resin hardens, resulting in a solid layer; as consecutive layers form, a 3D object is created [38]. MSLA was derived from SLA by applying a mask in the shape of the 2D cross-section of the current part layer between the UV light source and vat [39]. This was first done with a powerful UV projector, but now an array of UV-LEDs produces the light and the mask is formed from a liquid crystal display (LCD) [36,38]. The LCD darkens areas of the cross-section not intended for curing, and translucent areas allow UV light to penetrate, thus curing an entire layer at one time [36]. The X- and Y-precision is determined by the pixel size of the LCD [36]. The underside of the resin vat is a clear polymer film, typically fluoroethylene propylene (FEP), and above the film is the resin and build area [36]. Figure 2.15 provides a schematic of the components involved in modern MSLA printing [36].

There are several advantages for employing MSLA printing, as well as a few drawbacks. The first advantage is shorter print times [36]. It does not matter how many parts are on the print bed, because an entire layer is cured simultaneously; the Z-direction is the primary factor that determines the print time. Parts produced by MSLA are more dimensionally accurate and have a better surface quality than parts printed with other 3DP technologies, such as Fused Deposition Modeling (FDM) [36,38,39]. Layer lines of MSLA parts are nearly undistinguishable. MSLA printers are also capable of producing more complex geometries than other manufacturing techniques [36]. In addition to complexity, MSLA is capable of producing extremely small features and it has even been employed to produce microfluidics (more details on those in Section 2.3) [36,41,42]. The disadvantages of MSLA stem from the resin properties. Resins have a limited shelf life, and they are irritants, so extensive protective measures need to be taken (e.g., gloves, exhaust systems) [36]. Cleanup and post-curing is messy and labor intensive, adding to the risk and time it takes to produce a part [36]. Finally, despite minor deviations in external dimensions and surface quality, there are often considerable deviations between theoretical and actual part dimensions, especially for internal geometries [36,38]. Fortunately, a guideline has been developed for these geometries using the Prusa SW1 MSLA printer (Figure 2.16) [36]. It should be noted, however, that every printer and resin combination is different, each having its own benefits and drawbacks, and this guideline is merely a starting point for dimensioning MSLA parts on low-cost, consumer-grade printers.

2.3 Microfluidics and Millifluidics

2.3.1 Overview

Another relatively new field of study/technology is microfluidics. Microfluidics is the science of precise control and manipulation of fluids constrained to a small scale [42]. Scientists and researchers consider microfluidics to be the study of the behavior of fluids through microchannels, whereas engineers consider microfluidics to be the technology of fabricated miniaturized devices containing chambers and tunnels through which fluids flow [42,43]. Typically, microfluidic channels are on the sub-millimeter scale and vary in size between 1 to 100 μm [41,42]. Similar devices which operate on the millimeter scale are known as millifluidics; these function in the same way as microfluidics and offer the same benefits, but are typically cheaper and easier to manufacture [42,44]. Figure 2.17 provides a scale that shows the dimensional ranges over which these devices operate [42]. Microfluidics and millifluidics function with tiny amounts of liquids, and these devices have high surface-to-volume ratios [42,43,45]. At this scale, gravity-induced effects such as density and buoyancy play a much less significant role than surface forces, namely surface tension and viscosity [45]. For this reason, these devices are an interesting technology for fluid handling in the environment of space, as they function identically, and in some cases, better than on Earth (e.g., capillary rise is significantly increased in a micro-gravitational environment) [45].

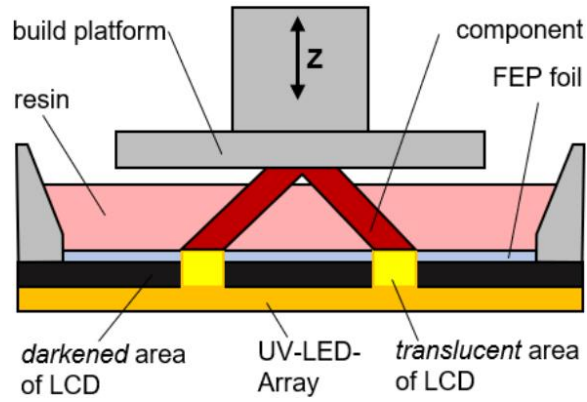


Figure 2.15 – MSLA components [36].

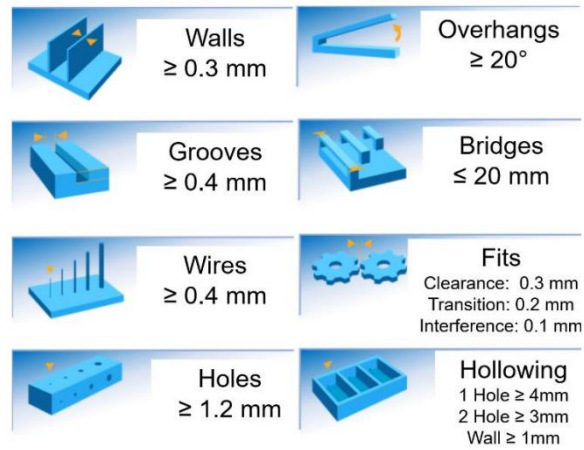


Figure 2.16 – MSLA part dimensioning guideline [36].

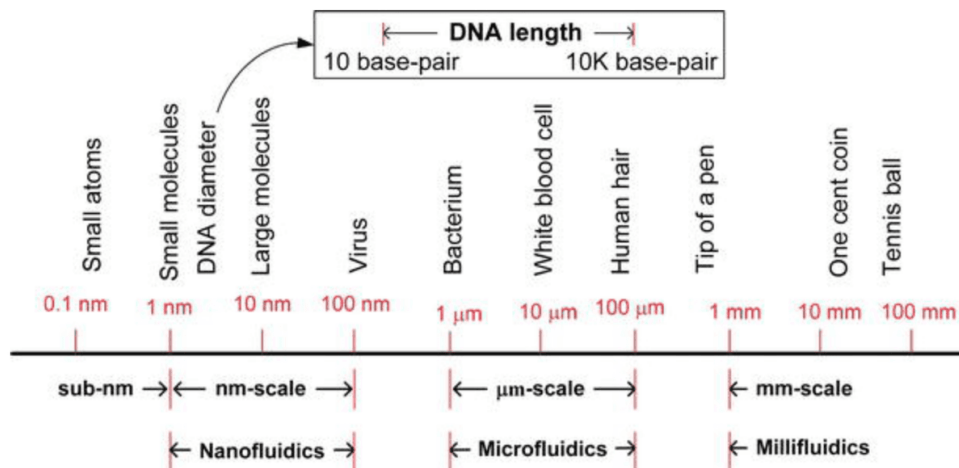


Figure 2.17 – Microfluidic and millifluidic scales [42].

The remainder of this section will explore traditional manufacturing techniques of microfluidics and applications, then move into new fabrication techniques (MSLA) and their applications in space.

2.3.2 Traditional Manufacturing of Microfluidics and Their Applications

Conventional microfluidic manufacturing derives from techniques widely used to fabricate Micro-Electromechanical Systems (MEMS) [41,46]. The most popular techniques include photolithography (UV light burns a desired pattern into a component) and wet/dry chemical etching, often used in conjunction [42–44,47]. Other traditional techniques include soft lithography (replica molding, microtransfer molding, micromolding of capillaries), thermoforming (hot embossing, micro-injection molding), and direct writing (laser photoablation, micro-milling) [42–44]. Critical properties of chip materials include optical clarity, biocompatibility, high precision, and toughness [44]. As a result, most microfluidic chips are fabricated from silicon, glass, and polymers using the previously mentioned techniques [42,43].

The current applications of microfluidics fall in the areas of biological systems (biotechnology, biodefense), chemical systems, chemical engineering, pharmaceutical engineering, and patient testing/diagnostics [41–44]. More specific applications include Lab-on-a-Chip (Figure 2.18), Organs-on-Chips, continuous flow microfluidics, digital/droplet microfluidics, optofluidics, acoustofluidics, electrophoresis, microelectronics, and electrochemistry [41–43]. Microfluidics are important in laboratory testing because they use extremely small sample sizes which are well-controlled and constrained [42]. This drastically reduces the volume of reagents needed for experiments, as well as improves the safety of experiments utilizing toxic chemicals [42]. In addition to this, microfluidic devices have faster reaction times, enhanced analytical sensitivity, temperature control, and portability (microfluidic chips can perform experiments that traditionally require an entire lab space) [43]. The primary disadvantages of microfluidic devices stem from the fabrication methods: because channels must be precisely manufactured, traditional technologies associated with fabrication come at high costs, ranging from thousands to hundreds of thousands of USD [41,47]. Also, microfluidic chips must be custom-fabricated for their specific applications, so many laboratories outsource the manufacturing of these devices, which results in long lead times, further increasing the cost [42,44,47].

2.3.3 Manufacturing of Microfluidics and Millifluidics via MSLA 3D Printing and Their Applications in Space

The advent of SLA printing, namely MSLA printing, has opened up an entirely new realm for prototyping microfluidic and millifluidic devices. Desktop MSLA printers have grown in popularity, precision, and affordability in recent years, piquing the interest of researchers who want to prototype inexpensive chips in-house [41]. It is possible to apply MSLA for prototyping of microfluidic chips; however, custom resins and/or printers typically need to be produced to achieve the desired precision [41, 48,49]. Commercially available MSLA printers and resins come at a low cost and are capable of rapidly prototyping millifluidics with precise dimensions, excellent surface quality, and 3D features (Figure 2.19) [41,42,44,47,48]. The cost of MSLA printers is as low as \$200, which is orders of magnitude lower than traditional methods; additionally, the lead time for producing parts via MSLA is merely hours, whereas conventional fabrication techniques can take several days or weeks to manufacture [44,47]. Some guidelines for printing millifluidics with commercial MSLA printers and resins are as follows: circular channels resolve around 700–800 μm and print more successfully than square or triangular channels, channels should be located 1–4 slice layers deep into a part, the layer height should be 50 μm (0.05 mm), and parts should be thoroughly cleaned inside and out to prevent unwanted excess resin curing [44,48]. Important factors to consider when printing these parts include light bleeding (resin exposed to stray light, which can cause channels to print smaller than designed or even clog) and print orientation (MSLA can produce warped parts, and orientation on the build platform contributes to how the parts warp) [44,48].

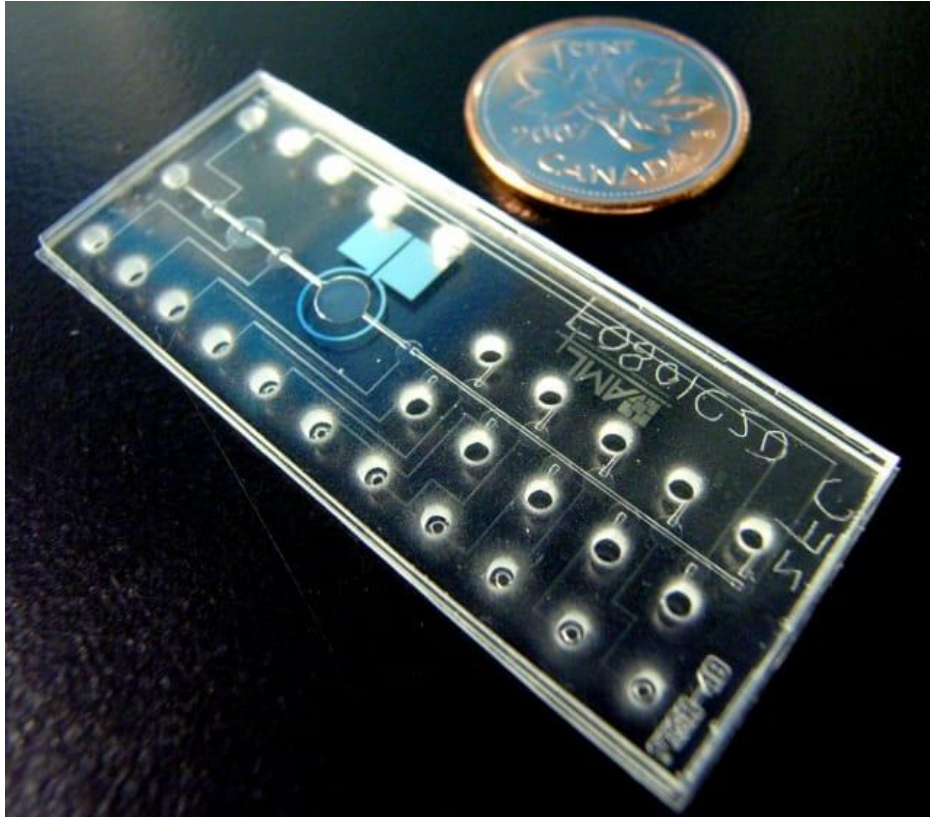


Figure 2.18 – Lab-on-a-chip microfluidic [43].

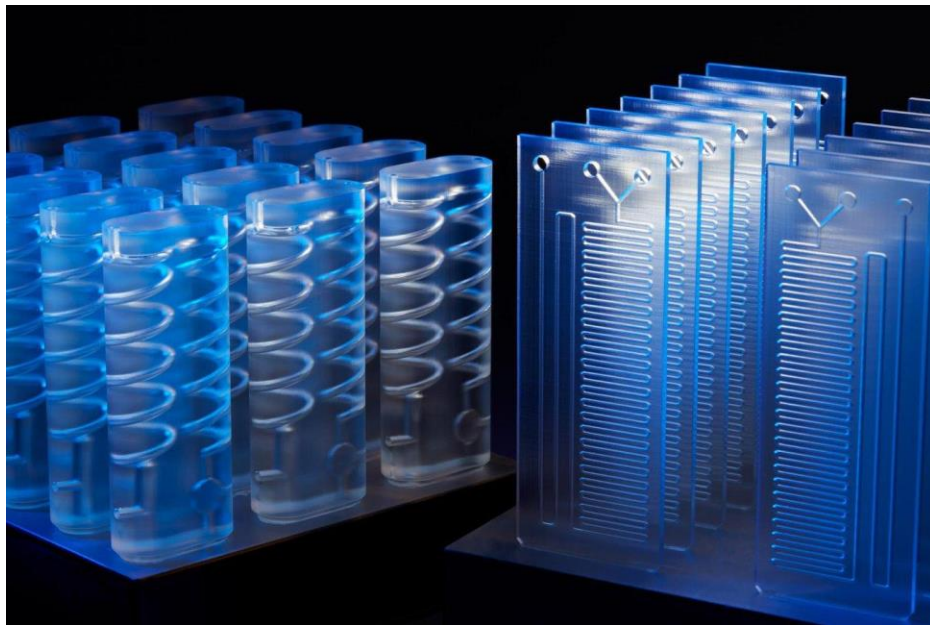


Figure 2.19 – MSLA 3D printed millifluidics [42].

Microfluidics and millifluidics have been recently implemented into a number of applications in space. The reason being is that in these devices, surface forces such as surface tension and viscosity dominate [42,43]. Space is a microgravitational environment, meaning that fluid handling is dominated through the very same forces that dominate microfluidics, making microfluidics and millifluidics excellent devices to transport fluids in and beyond Earth orbit [45]. One goal of space microfluidics is to simplify fluid handling systems via passive liquid delivery and thereby reduce overall weight and cost of systems [45]. In fact, μ STAMPS is a microfluidic device that does exactly this; an internal reservoir passively supplies an emitter chip consisting of microscopic capillaries with propellant through capillary action. A number of experiments have been performed on the International Space Station (ISS) involving macro-fluidic flow that are applicable in the microfluidic setting: passive gas removal, drinking in microgravity, watering plants in space, biosensors, and electrowetting heat pipes [45]. A new application this Thesis explores is the use of MSLA 3D printed millifluidic manifolds for routing propellant from an external tank to the μ STAMPS internal reservoir. The goal is to determine if propellant can be routed from a single inlet to four outlets equivalently on a millifluidic device printed with a commercially available, low-cost, MSLA printer and resin.

Chapter 3: Conceptual Design of a Propellant Feed System for μ STAMPS

3.1 Overview

The incorporation of thrusters within CubeSats will greatly increase their mission capabilities. The primary applications of μ STAMPS will include station keeping maneuvers, collision avoidance maneuvers, and rapid deorbiting maneuvers of five years or less. Other potential mission capabilities include more advanced maneuvers, such as orbital transfers, constellation formations, and travel to other celestial bodies within the solar system. The current μ STAMPS system can store 0.2 g of propellant, which is enough for around 3–4 hours of continuous thrust, but to achieve its full capability, an external propellant feed system is required. Initial studies have shown that to achieve the three primary applications of μ STAMPS, the system needs a propellant tank capable of storing and delivering at least 80 g of propellant. The following section outlines an initial concept for a propellant feed system that can store and deliver 100 g of BMP-DCA, which is the current propellant chosen for the task. This Thesis will then later demonstrate lessons learned upon prototyping and testing this design, as well as make suggestions on improving the design for the future success of μ STAMPS.

3.2 Overall Design

Figures 3.1 and 3.2 show the current design of the propellant feed system. For reference, the materials that were chosen for this design were selected from the Space Materials Database (SPACEMATDB), authored by Dr. Antonius de Rooij. This database combines data from a vast array of sources, including but not limited to the European Space Materials Database (ESMDB), NASA, and other sources of open literature [50]. According to Dr. Rooij, “The goal of SPACEMATDB is to provide a reliable data source for material properties for agencies and organizations present in the space community” [50]. This database was employed to assist in determining the metals (e.g., flange, screws), the polymers (e.g., tank shell, propellant routing manifold), and the films (e.g., bladder tank) to utilize in the design.

Figure 3.2 provides an exploded view of the propellant routing system, and in terms of CubeSat volume, the design aims to be contained within 0.5 U. All of the screws were chosen to be made from 18-8 stainless steel with a thread sizing of #2-56 (Imperial). Each screw should have hex drive heads, primarily to mitigate any potential stripping that may occur during assembly. The smaller screws (1) serve to mount the control circuitry (2) into corresponding standoffs (3). These standoffs are then secured into the top of the 3D printed PEEK tank shell (7). This system will employ the use of a peristaltic pump from Dolomite Microfluidics (4). Technical specifications of the pump are shown in Table 3.1 [51]. A PEEK barbed pipe adapter (6) serves to connect the pump to the 18-8 stainless steel custom machined flange (9). The barbed pipe adapter consists of a barb for connection to a 1.5 mm ID pipe and internal $\frac{1}{4}$ -20" UNC threads for an interface with the flange. To seal the flange, more screws (8) are used in conjunction with an SAE part number 210 Viton O-ring (10). This flange serves to allow propellant to be pumped from within a FEP bladder tank (11) out into a propellant routing manifold (PRM, 12). The PRM serves to split the input flow out to four individual thrusters. A few more screws (5) serve to secure the tank onto the PRM, which can then be mounted anywhere within the CubeSat, preferably near the location of the thrusters. Finally, ultra-fast miniature solenoid valves from The Lee Company (13) were selected, which were specifically designed for use in microthrusters and CubeSats.

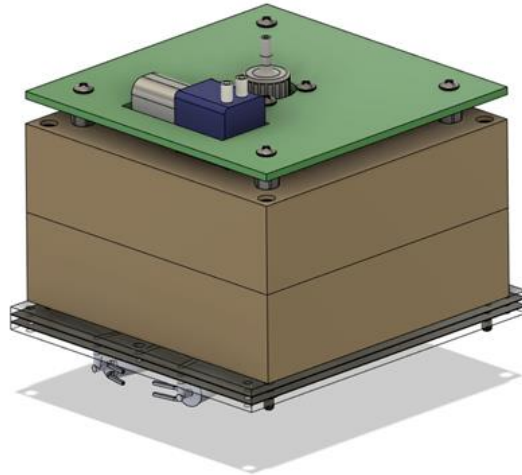


Figure 3.1 – Conceptual propellant feed system assembly.

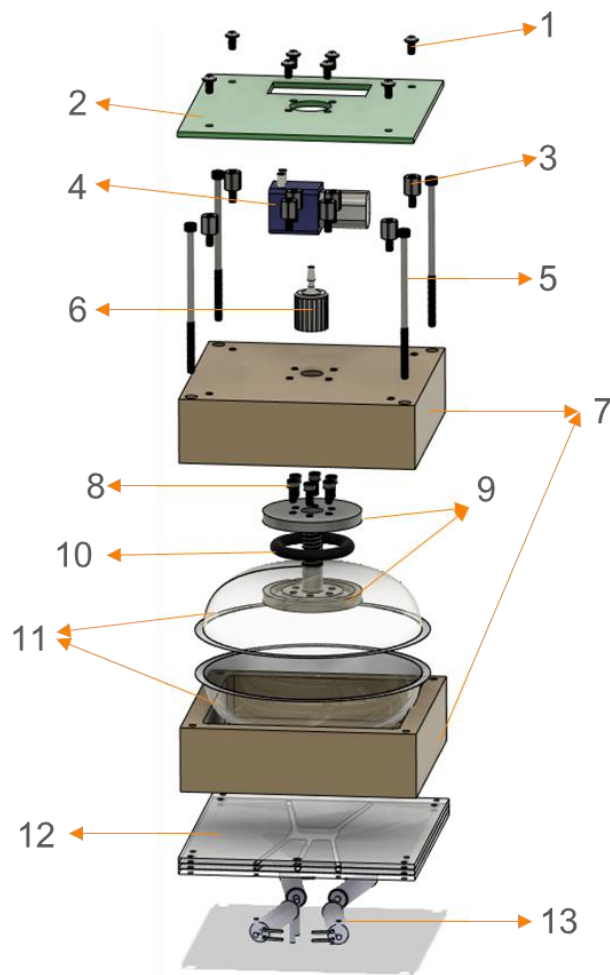


Figure 3.2 – Conceptual propellant feed system exploded view.

Table 3.1 – Dolomite Peristaltic Pump Technical Specifications [51].

Specification	Value
Dimensions	30 mm × 12 mm × 14 mm
Flow Rate	0.45 ml/min
Discharge Pressure	0–50 kPa
Tube Size	OD 2.5 mm, ID 1.5 mm
Tube Length	60 mm on inlet and outlet (approximate)
Tube Material	Silicone
Motor	DC Geared Motor
Voltage	3 VDC
Power Consumption	0.12 W
Weight	11 g

3.3 FEP Tank, Flange, and Propellant Routing Manifold Prototypes

The first parts that were prototyped included the FEP bladder tank, flange, and PRM. After establishing the propellant load requirement (100 g), the inflated dimensions of the tank were required. These dimensions are needed to determine the geometry of the tank shell, as well as to determine the radius of the FEP film to be cut. Figure 3.3 was used in conjunction with the following equations to determine these dimensions [52]. Starting with the required mass of the propellant ($m_{BMP} = 100$ g), the required tank volume (V) can be calculated from the density of the propellant ($\rho_{BMP} = 1.02$ g/cm³) using Equation 3.1 [53]. The tank volume was found to be 98.04 cm³:

$$V = \frac{m_{BMP}}{\rho_{BMP}}. \quad (3.1)$$

Equations (3.2)–(3.7) define the shape which two circular sheets of flexible material make when inflated. These were derived via parametric characterization of a generatrix (Figure 3.3) with radius r . The derivation of these equations is outside the scope of this thesis, and instead their application in relation to this work will be described. The primary goal for utilizing these equations was to determine the radius of the circular FEP sheets that needed to be cut. Equation (3.2) provides the inflated volume (V) of the tank. This is calculated in terms of the generatrix arc length, (a), and radius (r) [52]:

$$V = \frac{2}{3}\pi ar^2. \quad (3.2)$$

Equation (3.3) provides the ratio of a with respect to r :

$$\frac{a}{r} = 1.311, \quad (3.3)$$

where the value of 1.311 is the first lemniscate constant, derived from parametric characterization [52].

Rearranging Equation (3.3) for a yields Equation (3.4):

$$a = 1.311r. \quad (3.4)$$

Equation (3.4) is then substituted into Equation (3.2) to form Equation (3.5):

$$V = \frac{2}{3}\pi(1.311)r^3. \quad (3.5)$$

Equation (3.5) can then be solved for r , resulting in Equation (3.6):

$$r = \sqrt[3]{\frac{V}{\frac{2}{3}\pi(1.311)}}. \quad (3.6)$$

The volume, calculated previously to be 98.04 cm³, when plugged into Equation (3.6) results in an inflated tank radius of approximately 3.3 cm. It was found that the inflated tank will be about half the size of the deflated tank, so the FEP should be cut to a radius of 6.6 cm. The inflated radius is also important for determining the internal width of the tank shell.

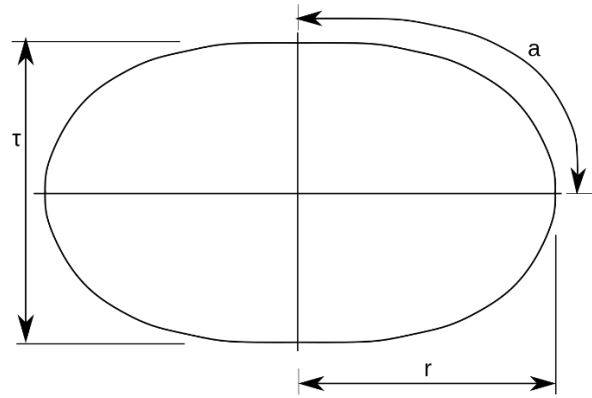


Figure 3.3 – Inflated shape of a mylar balloon/the bladder tank [52].

Finally, Equation (3.7) is used to calculate the inflated tank height (τ), which comes out to be approximately 3.95 cm. This was important for determining the internal height of the tank shell. The value of 0.599 is the second lemniscate constant, derived from parametric characterization [52].

$$\tau = 0.599 * 2r \quad (3.7)$$

Once the FEP was cut, the flange was inserted, and the tank was heat-sealed. The prototype bladder tank is shown in Figure 3.4. This design is unconventional compared to other bladders, which are typically manufactured from elastomers such as Teflon® Polytetrafluoroethylene (PTFE). FEP was chosen based on ease of manufacturability, since it can be heat-sealed at 550 °F, which is obtainable by the MP-8C impulse heat sealer, the mechanism selected to seal the tank. Several different flange designs were 3D printed (Figure 3.5) with different outlets, varying O-ring sizes, and varying O-ring positions. The initial plan was to test these designs and select the iteration(s) that resulted in no leakage. The chosen design would then be machined from stainless steel; however, the flanges never had the chance to be tested for reasons later discussed in Chapter 5. Work then pivoted to the development of a 3D printed PRM due to time constraints, which will be discussed in more detail in Chapter 4, Section 4.3.

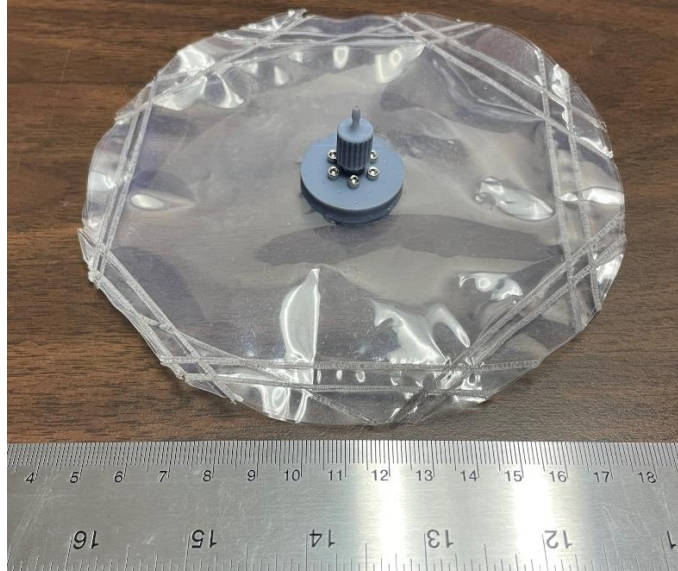


Figure 3.4 – Bladder tank prototype with MSLA 3D printed flange.



Figure 3.5 – MSLA 3D printed flange iterations.

Chapter 4: Test Methods

4.1 Seal Strength Testing

4.1.1 Overview

Before prototyping the bladder tank, it is important to know the strength of the seal. For this, the ASTM F88 standard was employed, which is designed specifically to measure the seal strength of flexible barrier materials, in this case, FEP film [54]. A roll of both 0.003 in. and 0.005 in. (3 mil and 5 mil) thick FEP was supplied by American DuraFilm. Five batches of five samples were prepared and tested; each batch consisted of a different sample fin thickness. A fin is the area of the sample that was gripped by the testing machine, and will be discussed further in Section 4.1.2. The first two batches were prepared from 3 mil and 5 mil films and had only one layer of film per fin. The fins were double-layered on the next three batches. This was done to effectively increase the thicknesses of the samples to 6 mil (2×3), 8 mil (3+5), and 10 mil (2×5). To seal the samples, a Midwest Pacific MP-8C impulse heat sealer was employed, shown in Figure 4.1. An MTS Systems Corporation (MTS) tensile testing machine with a 5 kip (5000 lbf) load cell was used to test these samples. The system was connected to a TestStar IIs data acquisition device (DAQ), and is outlined in Figure 4.2.

4.1.2 Sample Preparation

To begin the sample preparation, a seal configuration must be chosen. These configurations, whose dimensions are outlined in Figure 4.3, consist of a fin seal, a hot wire seal, or a lap seal. The fin seal configuration was chosen because it matches the configuration of an inflated bladder tank. From here, approximately 3 in. long and 1 in. wide strips of FEP were carefully cut and layered onto one another. The single-layered fin samples required two strips of film each (one strip per fin), and the double-layered fin samples required four strips (two per fin). These samples were then set aside for sealing.

The MP-8C impulse heat sealer functions by pressing two films together on a heated 0.0625 in. diameter wire protected by fiberglass tape. To begin sealing, the MP-8C's lever must be pushed down; this action turns the machine on and begins heating up the wire. After a few seconds, the sealer will turn off and the lever can be raised. The length of sealing time can be controlled by a dial on the front of the machine. For a proper seal, five consecutive lever pushes, or "stamps," must be performed at the maximum dial setting. This is because the FEP film has a relatively high melting point of 550 °F, and a single stamp was unable to develop a complete seal [55]. Before beginning to seal each sample, the MP-8C was treated with mold release to limit how much the FEP sticks to the tool. When stamping, a constant pressure was applied and held until the LED power indicator near the dial turned off. The samples were cleaned with IPA before this procedure was performed to ensure no dust or other contaminants were present. This step is important because any contaminants in the seal area may weaken the seal and adversely affect the results of the experiment.

4.1.3 Test Setup and Procedure

The tests that were conducted are like standard tensile tests. A machine grips two ends of the samples, the fins in this case, and slowly pulls the samples apart. The DAQ recorded load versus grip displacement with a sampling frequency of around 1250 Hz and stored the data in Excel format to be analyzed. According to ASTM F88, the grip displacement rate should be 8 in./min [54]. Many tensile testing machines can detect when a sample fails and stop automatically; however, the MTS machine stops the test at an absolute grip displacement end level. This end level was set to 3.5 in.; however, each sample failed before this limit and the tests were manually concluded.



Figure 4.1 – Midwest Pacific MP-8C impulse heat sealer.

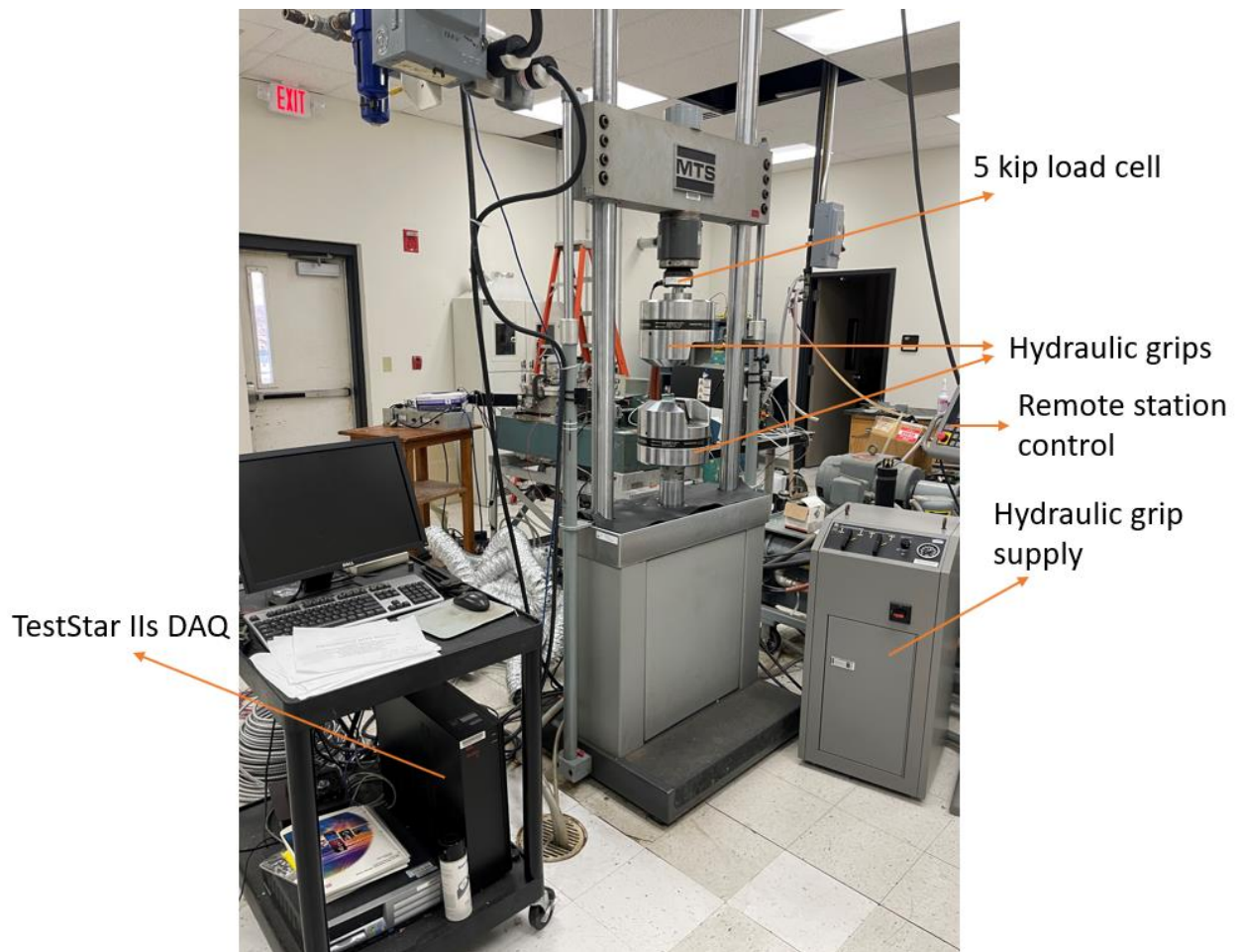


Figure 4.2 – MTS testing setup.

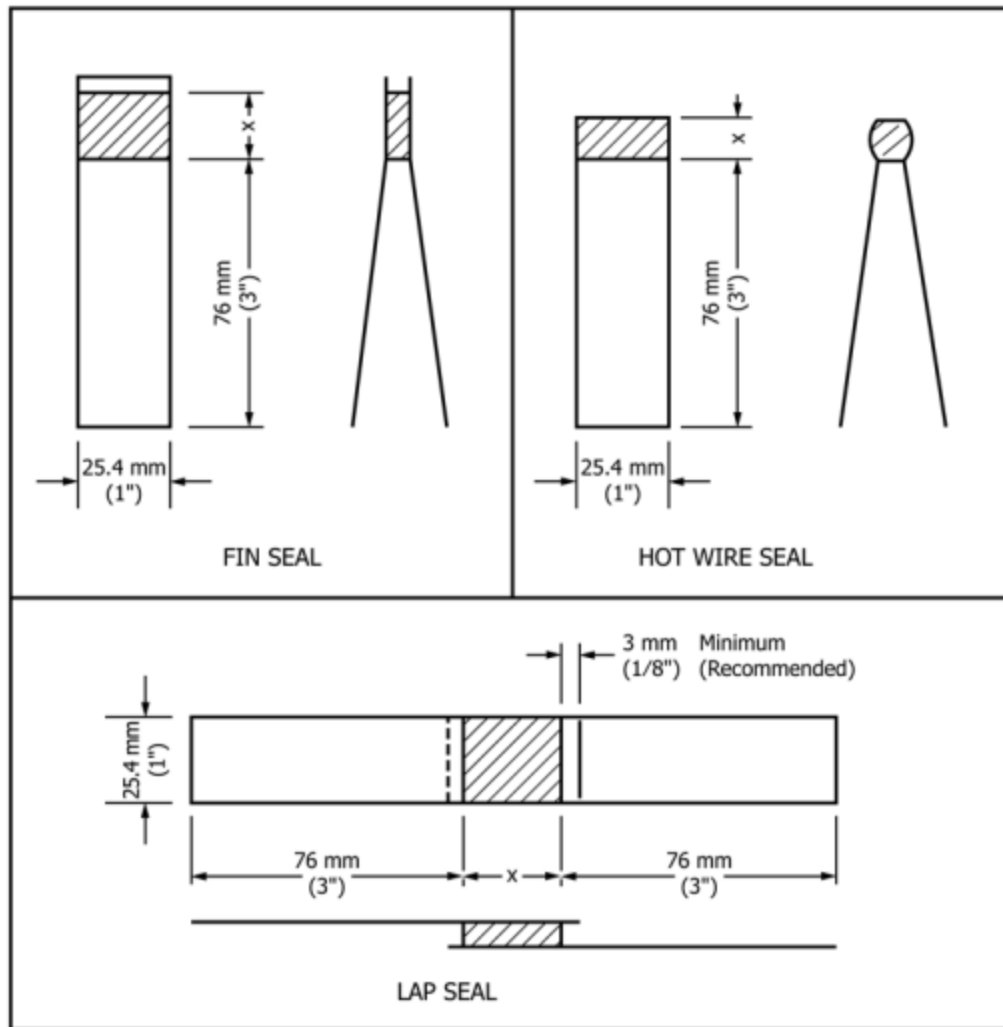


Figure 4.3 – ASTM F88 recommended specimen dimensions [54].

To properly accommodate the minute thickness of the samples and to prevent the grips from damaging the fins, inserts were designed and 3D printed from polylactic acid (PLA) filament. These inserts span the length and width of the grips, and are 0.125 in. thick, Figure 4.4 shows a model of the inserts. One fin was taped to the insert to easily mount in the grips, and to properly align the sample. About 0.5 in. of space was left between the top of the insert and the fin. This is because when fully mounted in the grips, the standard called for 1 in. of space between the grips. Once the sample was taped to one insert, the other insert could then sandwich the sample and be placed in the top grip. The grip was then tightened to about 290 psi. After the sample was secured in the top grip, the remaining inserts were placed into the bottom grip, and this grip was raised until there was 1 in. of space between them. This grip was also tightened to approximately 290 psi. From here, the test was performed, and the process could be repeated.

4.1.4 Data Analysis

To analyze these data, the raw force versus displacement files were imported into MATLAB. At this point, the data was noisy due to the small force levels being recorded from a 5 kip load cell. Fortunately, a trend was present, so a smoothing function was employed. MATLAB's "movmean" function was utilized to smooth the data. The formula for the moving average is shown by Equation 4.1, where k is the period selected for the moving average, n is the number of data points in the set, and p_i is the data point in the i^{th} position [56]. For the single-layered fins, a 5-point moving average was sufficient; however, for the double-layered fins, a 25-point moving average was performed. Both the raw and smoothed data could then be plotted.

$$SMA = \frac{1}{k} \sum_{i=n-k+1}^n p_i. \quad (4.1)$$

Once the data was plotted, the maximum load could be found. The standard (ASTM F88) provides an example of what the result of a test may look like, Figure 4.5 [54]. It recommends that the average should be taken of the maximum range in the plot. However, these tests resulted in one local maximum, rather than the plateau shape shown in the figure. Based on this, a simple maximum could be taken from the smoothed data using MATLAB's "max" function. From here, the averages (μ) and standard deviations (σ_{STD}) of the maximum loads between each sample could be found using Equations 4.2 and 4.3, where x_i is each value from the population and N is the size of the population [57,58]:

$$\mu = \frac{1}{n} \sum_{i=1}^n p_i, \quad (4.2)$$

$$\sigma_{STD} = \sqrt{\frac{\sum (x_i - \mu)^2}{N}}. \quad (4.3)$$

After these values were computed, the theoretical stress experienced within the bladder tank was calculated. Two assumptions were used to approximate the stress: 1) the tank will be spherical; 2) the pressure inside the tank will be 14.7 psig in a vacuum. A pressure of 14.7 psig was determined because the tank will not be pressurized on Earth, thus having a near-zero gauge pressure in atmosphere. In a vacuum, the gauge pressure will, in theory, increase from 0 to 14.7 psig, due to the lack of atmospheric pressure. These are not perfect approximations, because the tank will not be perfectly spherical when inflated; rather, the tank will be an oblate spheroid. Also, the IL propellant has a negligible vapor pressure. This means that in LEO, if perfectly conditioned to have no water content, the propellant should not outgas, and there will be a negligible gauge pressure.

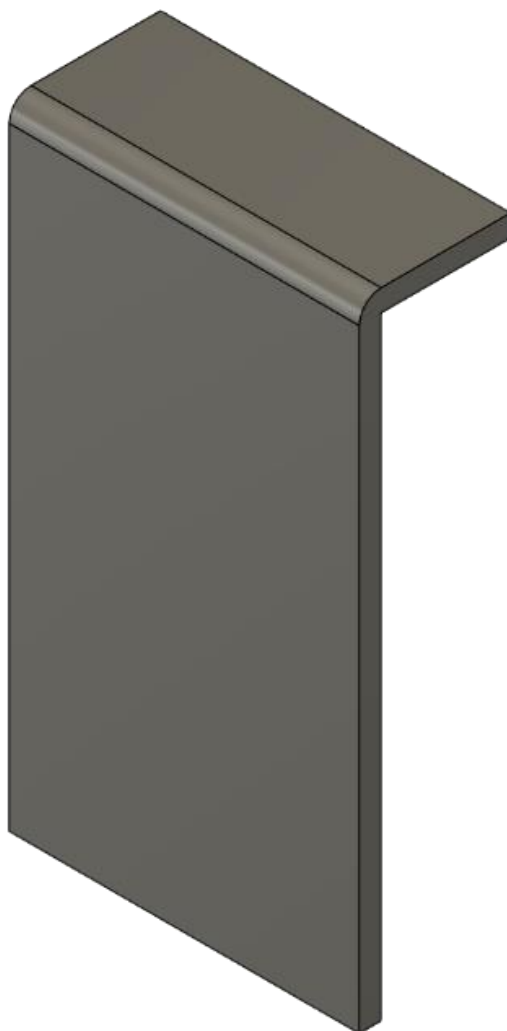


Figure 4.4 – 3D model of the MTS grip attachment.

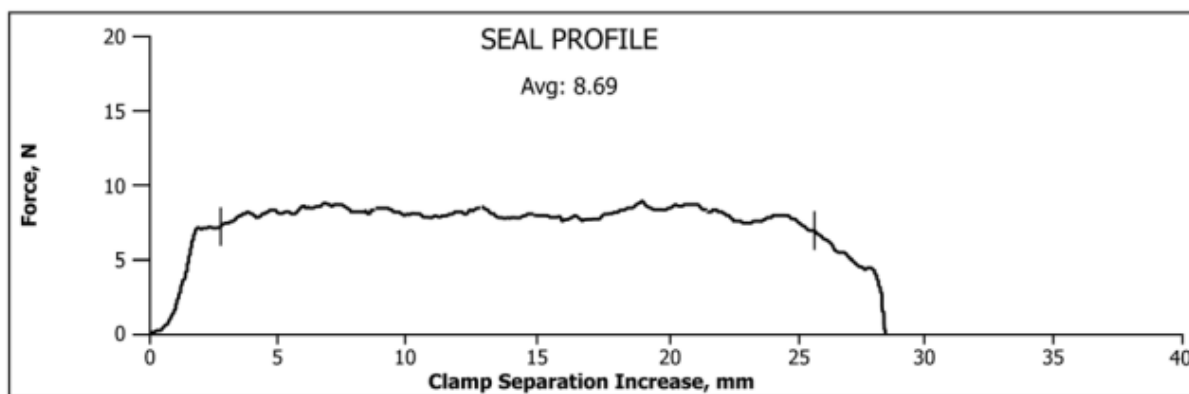


Figure 4.5 – Example seal strength test result [54].

Despite this, a comparison must be made based on the worst-case scenario. Equation 4.4 describes the theoretical stress experienced inside of a thin-walled spherical pressure vessel, where P is the tank pressure, r is the tank radius, and t is the thickness of the tank wall [59]:

$$\sigma_{tank} = \frac{Pr}{2t}. \quad (4.4)$$

Finally, the stresses experienced by each sample could be calculated. The standard (ASTM F88) states that any applicable algorithm can be applied to calculate the seal strength [54]. As will be seen in Chapter 5, nearly every sample failed just before the sealed area on the fin, rather than the seal itself pulling apart. Based on this, the stresses experienced by the samples were calculated via a simple relation (Eq. 4.5), where F is the average maximum load experienced by each sample, and A is the cross-sectional area of the fin:

$$\sigma_{seal} = \frac{F}{A}. \quad (4.5)$$

4.1.5 Challenges and Limitations

The first challenge came from the sample preparation. The samples must be cut as cleanly and evenly as possible. Any uneven or jagged cuts could negatively affect the flow path of the forces and create unwanted stress concentrations and moments. This could result in premature failure of parts, leading to greater errors and standard deviations between the samples. Next, the impulse heat sealer did not heat up enough to seal the samples completely with one application, so multiple consecutive stamps were employed. Once the FEP melted and a seal formed, the next challenge was safely removing the sample from the sealer. The FEP tended to melt into the weave of the protective fiberglass tape. This made the samples difficult to remove without damage. To mitigate this the MP-8C's working area was treated with mold release, and after sealing, the samples were removed slowly and steadily.

Other challenges stemmed from the test setup procedure. First, the test machine employed is typically used for testing high-strength, aerospace-grade metals. To establish a strong grip between these parts requires the grips to have small, jagged teeth. These teeth could damage the samples' fins and potentially result in them failing at the grips. In addition to this, the MTS manual recommends testing samples no thinner than 0.25 in. To mitigate these problems, four 0.125 in. thick inserts (two for the top and bottom grips) were 3D printed from PLA, designed to protect the sample and meet the 0.25 in. thickness requirement. Mounting and aligning the samples in the grips proved to be a challenge due to them being thin and flexible. Improper alignment could result in an extra torsional force, which would cause the seal to fail prematurely. Taping one fin to an insert beforehand allowed for the sample to be aligned before being placed in the grips. It also prevented the sample from shifting while the grips applied pressure. Finally, the load cell was rated for loads much higher than the loads experienced during these tests. Testing with this cell was deemed possible, however, because the standard was verified through a variety of different cells, one of which being a 5-kip cell [54]. This, however, resulted in noisy output data, which needed to be smoothened using a moving average function within MATLAB.

4.2 Elegoo Mars 2 Pro vs. Elegoo Mars 4 Ultra Dimensional Accuracy and Support Testing

4.2.1 Overview

Before printing any of the millifluidic devices, a printer must be chosen. The printers in question were the Elegoo Mars 2 Pro (M2P) and Elegoo Mars 4 Ultra (M4U), as shown in Figures 4.6 and 4.7 [60]. Both are MSLA printers, however there are a few key differences between each printer as shown in Table 4.1 [61, 62]. To help determine which printer to use, eight 20 mm³ cubes were printed without supports directly on the bed of each printer.



Figure 4.6 – Elegoo Mars 2 Pro [60].



Figure 4.7 – Elegoo Mars 4 Ultra [60].

Table 4.1 – Differences Between the M2P and M4U [61,62].

Specification	M2P	M4U
XY Resolution	50 μm $\times$ 50 μm (1620 $\times$ 2560 pixels)	18 μm $\times$ 18 μm (8520 $\times$ 4320 pixels)
Z-Axis Accuracy	0.00125 mm	0.02 mm
Layer Thickness	0.01–0.2 mm	0.01–0.2 mm
Printing Speed	30–50 mm/hr	$\leq$ 70 mm/hr
Build Volume	12.9 cm $\times$ 8 cm $\times$ 16 cm (L x W x H)	15.3 cm $\times$ 7.8 cm $\times$ 16.5 cm (L x W x H)
Vat Film	FEP	Advanced Composite Film (ACF)

Afterwards, eight more cubes of the same dimensions were printed with sparsely packed, heavy supports. These print orientations can be seen in Figures 4.8 and 4.9. The qualitative results of the prints were noted, as well as the actual dimensions of the cubes. These final dimensions could then be compared to their theoretical sizes. As will be seen in Chapter 5, the results from the cubes printed with this support strategy prompted another batch of testing.

Chapter 5 will show that sparsely packed, heavy supports are not ideal for the print orientations required, so instead, the use of densely packed, lightweight supports was explored. Based on these results, the next round of testing was designed to determine what support density to use on both printers. To determine the ideal support density, four 20 mm³ cubes were printed on both the M2P and M4U, each with a different density—75%, 80%, 90%, and 95%—which are outlined in Figure 4.10 and 4.11. To determine which printer and support strategy to employ, the print success rate, ease of support removal, and final dimensions were noted.

4.2.2 Print Material, Setup, and Post-Processing

Elegoo's Standard 2.0 Photopolymer Resin was selected for use. The 2.0 formulation, according to Elegoo, has reduced odor and volume shrinkage compared to its predecessor. The volume shrinkage is important because it may cause additional warping and deformations that will negatively affect certain parts. The CHITUBOX slicing software was utilized, and the print settings employed can be seen in Figures 4.12 and 4.13, which were provided by Elegoo. The "lift speed" (the rate at which the print bed lifts from the vat's film) and "rest time after retract" (the amount of time between print bed lowering to the bottom of the vat and projection of the UV light), however, were changed. The lift speed was decreased from Elegoo's recommendation to ensure smooth separation of part and vat film. Preliminary print tests with higher retract speeds occasionally resulted in total print failure. The rest time after retract was included because preliminary prints experienced a defect known as "blooming," where partially cured resin is left over on the edges of parts. This typically occurs when the resin is still moving upon curing of the layer, so adding this delay allows the fluid to settle and cure properly [63]. Finally, in the Chitubox slicing software, the light support preset was used; the only support settings that were changed were the support density for each cube (75%, 80%, 85%, 90%), and the Z-height of the supports (10 mm). The Z-height of the supports was changed from the default 5 mm simply because the taller Z-height made the samples easier to remove from the supports (more grip and leverage).

Once each cube was printed, they were removed from the print bed, supports were removed from the respective parts, and a two-stage washing process with 99% IPA was employed. The first stage involved an initial "dirty" clean, where the bulk of the uncured resin can be washed off. The reason this stage is being called a "dirty" clean is because the tub of IPA gets dirty quickly, since the parts are typically coated in uncured resin. The second stage of cleaning involves a second tub of IPA, which is kept relatively clean and clear because of the first stage of cleaning. This tub contains a magnetic stirring device which is controlled by the Elegoo Mercury Plus washing and curing station (Figure 4.14) [60]. The parts were then submerged in this tub of IPA, and the washing station was set to run for 5 minutes. Afterwards, the parts were removed, air dried, and post-cured for two minutes in the Mercury Plus.

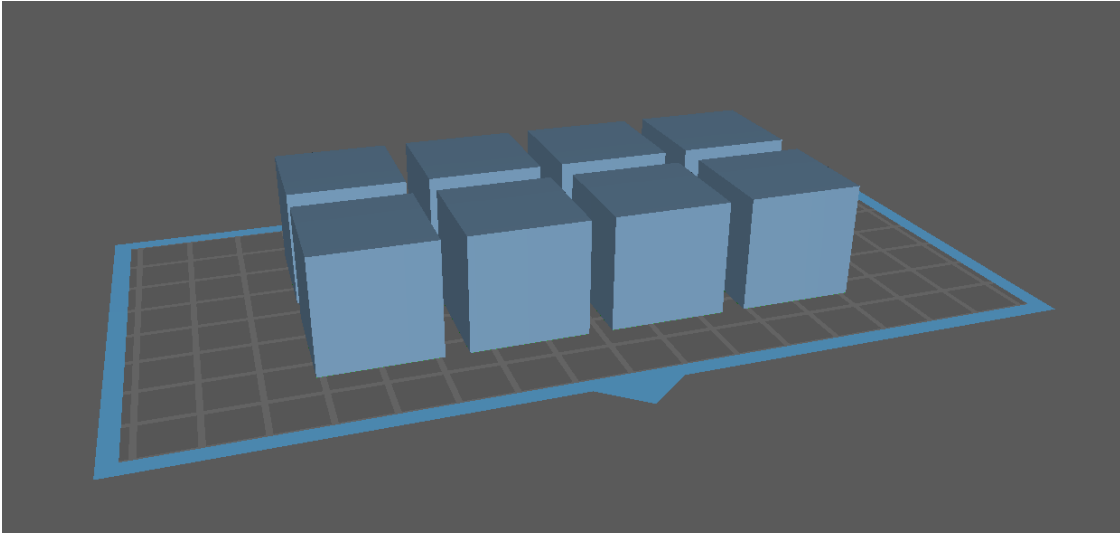


Figure 4.8 – Print orientation of 20 mm³ cubes flat on build plate.

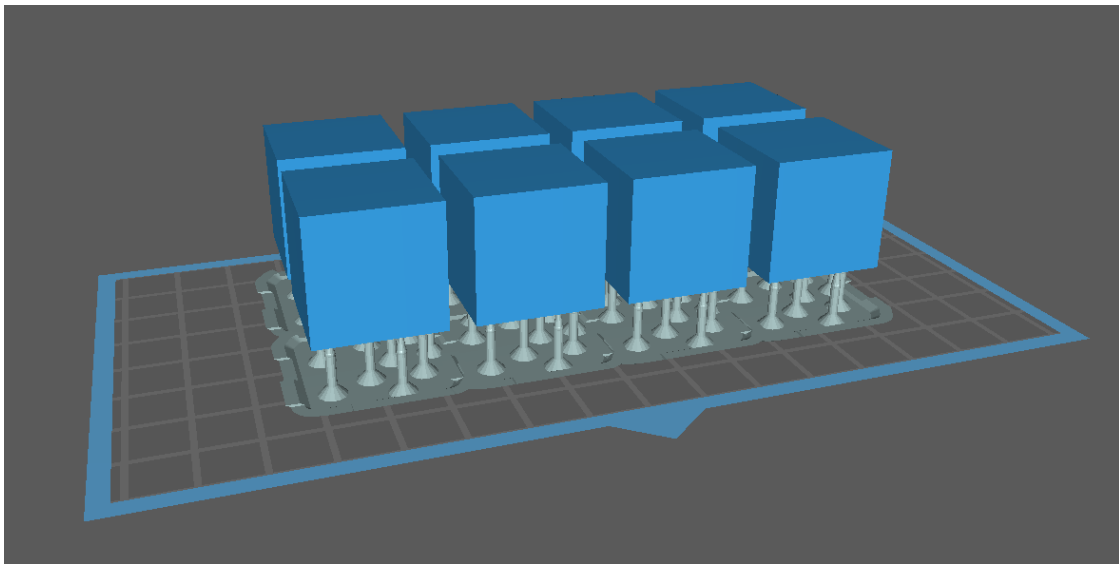


Figure 4.9 – Print orientation of 20 mm³ cubes with sparsely packed (50%), heavy supports.

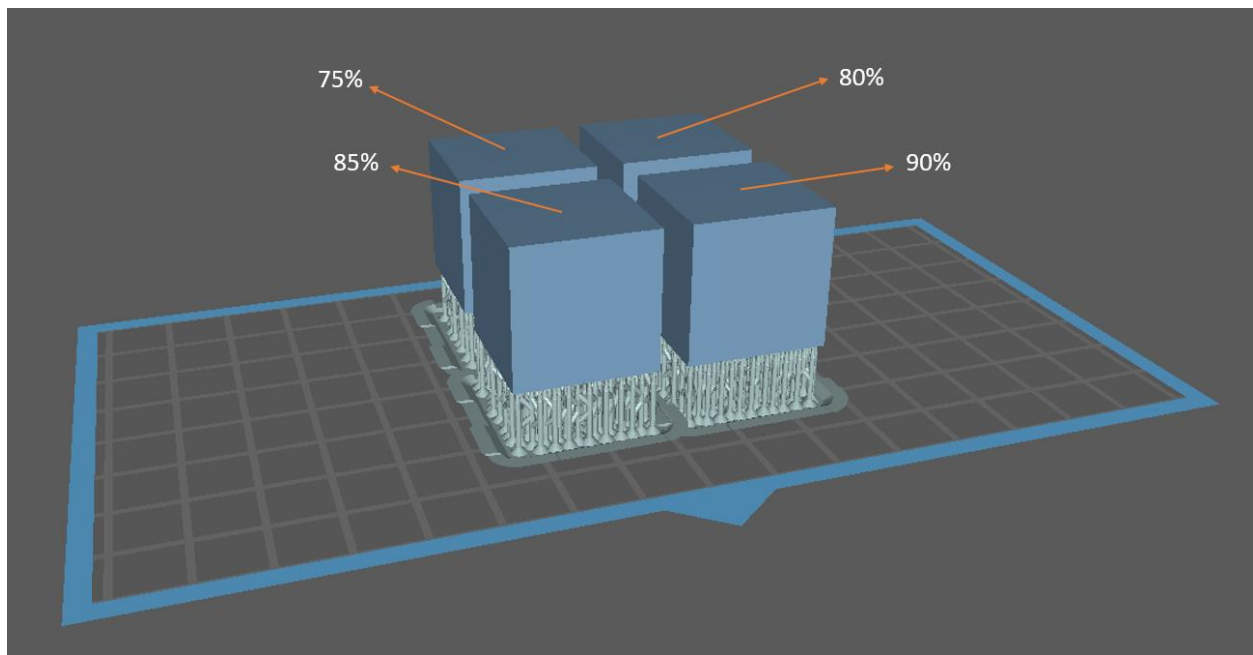


Figure 4.10 – Print orientation of 20 mm³ cubes with densely packed, lightweight supports.

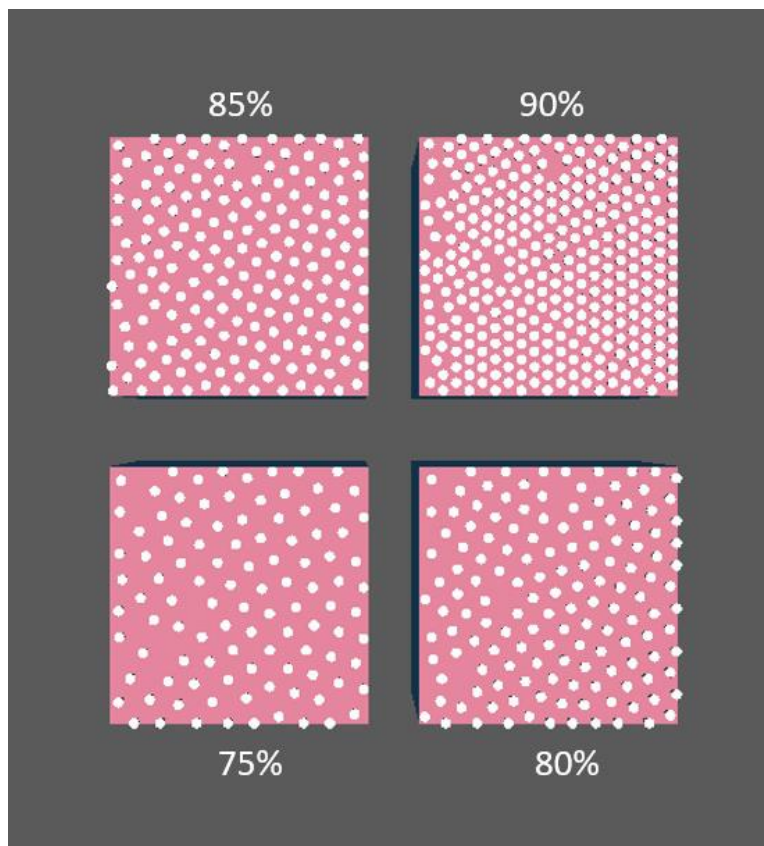


Figure 4.11 – 20 mm³ cubes with densely packed, lightweight supports (bottom view).

Layer Height:	0.050	mm	Bottom Lift Distance:	5.000	+	0.000	mm
Bottom Layer Count:	5		Lifting Distance:	5.000	+	0.000	mm
Exposure Time:	2.500	s	Bottom Retract Distance:	5.000	+	0.000	mm
Bottom Exposure Time:	30.000	s	Retract Distance:	5.000	+	0.000	mm
Waiting Mode During Printing:	Restin...		Bottom Lift Speed:	80.000	&	0.000	mm/min
Rest Time Before Lift:	0.000	s	Lifting Speed:	80.000	&	0.000	mm/min
Rest Time After Lift:	0.000	s	Bottom Retract Speed:	210.000	&	0.000	mm/min
Rest Time After Retract:	0.500	s	Retract Speed:	210.000	&	0.000	mm/min

Figure 4.12 – M2P cube print settings in CHITUBOX.

Layer Height:	0.050	mm	Bottom Lift Distance:	2.000	+	3.000	mm
Bottom Layer Count:	2		Lifting Distance:	2.000	+	3.000	mm
Exposure Time:	3.000	s	Bottom Retract Distance:	3.000	+	2.000	mm
Bottom Exposure Time:	30.000	s	Retract Distance:	3.000	+	2.000	mm
Transition Layer Count:	5		Bottom Lift Speed:	75.000	&	230.000	mm/min
Transition Type:	Linear		Lifting Speed:	75.000	&	230.000	mm/min
Transition Time Decrement:	4.500	s	Bottom Retract Speed:	230.000	&	75.000	mm/min
Waiting Mode During Printing:	Restin...		Retract Speed:	230.000	&	75.000	mm/min
Rest Time Before Lift:	0.000	s					
Rest Time After Lift:	0.000	s					
Rest Time After Retract:	2.000	s					

Figure 4.13 – M2P cube print settings in CHITUBOX.



Figure 4.14 – Elegoo Mercury Plus Washing and Curing Station [60].

4.2.3 Test Procedure and Analysis

After the parts were cleaned up and post-cured, the X-, Y-, and Z-dimensions could be measured, the X- and Y-axes defining the surface parallel to the print bed, and the Z-dimension being the height of the cube. Three measurements were taken along each axis, averaged, and the standard deviations were taken (Eq. 4.2 and 4.3). In addition to this, the percentage errors between the theoretical and actual cube dimensions were calculated using (Eq. 4.6). The actual dimensions of the printed parts are represented by v_A , and the expected values are represented by v_E :

$$\delta = \left| \frac{v_A - v_E}{v_E} \right| * 100. \quad (4.6)$$

The errors and standard deviations were useful in showing the accuracy of each print, as well as how the deformations in each part changed with respect to the varying print strategies. Qualitative results were noted as well, primarily noting which parts failed during printing (if any) and ease of support removal. It was imperative that the printer and print settings which were selected minimize warping effects, successfully print every time, and have quick post-processing times.

4.2.4 Challenges and Limitations

The primary challenges and limitations of this phase of testing are simply the standard challenges and limitations of MSLA printing. First, the print bed must be perfectly clean and level. Any contaminants or misaligned print beds will result in failed prints. By remaining consistent with a leveling and cleaning strategy, these problems should be easily mitigated. It may also be challenging deciding what print settings to use; fortunately, Elegoo has tested the ideal print settings for their products, and they have provided an open-source datasheet on their website [61]. In the case of industrial grade printers and resins, it may be more difficult to find similar information. Finally, MSLA printing is a messy process, and the resin is an irritant (skin, eye, and lung). By utilizing the proper tools, methods, and personal protective equipment, such as lunch trays for transferring parts and cleaning, working in a well-ventilated environment, and wearing gloves, a mask/respirator, and eye protection, the printing process becomes much cleaner and safer.

4.3 Flow Rate and Channel Volume Testing

4.3.1 Overview

The final phase of testing served to determine the ideal design and print orientation of the 3D printed PRMs. Every PRM iteration consisted of an inlet that separated into four different internal channels, each of which connected to its own outlet. Section 4.3.2 will discuss the designs and print orientations in more detail. Several iterations of the manifold were printed on both the M2P and M4U, and were subjected to two different flow rate tests. The first test involved pumping deionized (DI) water stored in a 60 mL syringe with the Dolomite Peristaltic Pump through the manifold. The purpose was to see whether or not flow was present in all four channels; this will be referred to as the “overall flow test.” Parts printed on the M2P were tested this way, with exception to the final two iterations printed on the M4U. The results of this test served to eliminate samples that did not experience flow through each channel. The samples that did experience flow did not evenly output water; therefore, those samples were subjected to further testing. The second round of testing was designed to determine the mass/volume flow rates of each channel individually, as well as predict the actual internal channel volumes; this will be referred to as the “individual flow rate test.” The individual flow rate test utilized the same syringe and pump setup, but with valves blocking all but one outlet. These data could then be compared, and a second round of elimination commenced. The results from this round served to decide the ideal print orientation of the PRM, as well as the ideal location of the inlet. Once the ideal print orientation and inlet location were established, further iterations of the internal channel geometry of the PRM were designed and tested in the same manner as the previous two rounds. The goal

of these tests is to develop a solution which results in uniform flow (or as close to uniform as possible) through each outlet.

4.3.2 Propellant Routing Manifold Designs, Print Setup, and Post-Processing

Several different PRM designs and print orientations were explored. To keep track of these iterations, a naming convention was established. The part designs were labeled V1–V5, and the print orientations were labeled as a–d. Tables 4.2 and 4.3 showcase the various PRM designs and print orientations that were evaluated. Orientations a, b, c, and d represent the following: a) 45° angle with supports; b) printing parallel to the bed with supports; c) printing directly on the bed without supports; and d) printing perpendicular to the bed with supports. Every PRM design was a 6.2 cm² square and features four outlets on the bottom of the part, each of which is 3.5 cm from the center and aligned with the corners of the PRM. Parts V1, V2, V4, and V5 had a thickness of 0.5 cm, whereas V3 had a thickness of 1 cm. Starting from the top, V1 represents the first PRM design; the key features of this design include an inlet on the top of the PRM and internal channels of 1.5 mm in diameter. Part V2's geometry is identical to V1; however, the inlet has been relocated to the narrow side of the part. Manifold V3 also had an inlet on the narrow side, but the thickness of the part was increased to allow room for supports on the inlet when printing flat on the print bed. These supports were required, because without them the inlet would not successfully print. Manifold V4 is nearly identical to V1; however, the internal channel diameters were reduced from 1.5 cm to 0.75 cm. Finally, part V5 was also similar in design to V1; however, the inlet was divided into four channels, each of which were connected to their respective outlets, isolating each outlet.

Printing began on the M2P, starting with parts V1a–d, V2a–d, and V3c. The parts that required supports were printed with heavy supports at first, however those printed at orientation b prompted the support density tests explained in Section 4.2. After performing the overall flow test to see which PRM designs experienced flow through each channel, parts V1a, V2a, and V3c were eliminated. At this point, parts V1b,d and V2b,d were printed again; however, this time on the M4U. The V1b,d and V2b,d manifolds printed by both the M2P and M4U were then subjected to the individual flow rate tests. This, in turn, eliminated V1b and V2b, which meant V1d had the ideal inlet location and print orientation. From here, iterations V4 and V5 were created and printed at orientation d. These parts were finally subjected to both of the flow rate tests discussed in this section. The print settings of these parts are reflected in Figures 4.15 and 4.16.

Each manifold was cleaned and post-cured in a similar manner to the methods described in Section 4.2.2. A part was first washed in a dirty container of 99% IPA to remove most of the remaining resin. From here, the supports were carefully removed, and the part was washed again in the Mercury Plus washing and curing station for five minutes. Afterwards, a syringe with a Luer Lock barb adapter for 1.5 mm tubing was filled with 50 mL of clean IPA. Silicone tubing was then attached to the syringe and the inlet of the part, and the internal channels were washed to remove resin remaining within the channels. Any resin remaining within the part will result in a clogged channel upon post-curing. Air was then pumped via the syringe through the channels at least three times to dry residual IPA. Attempting to post-cure wet parts will result in sticky, partially cured surfaces, which may negatively affect flow rate tests. Finally, each part was post-cured in the Mercury Plus for 2.5 minutes. At this point, the parts were labeled and ready for testing.

Table 4.2 – First PRM Design Iterations and Print Orientations.

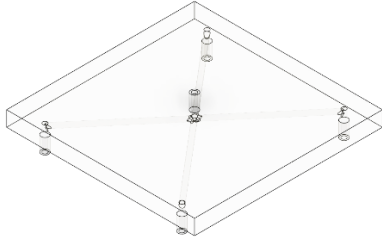
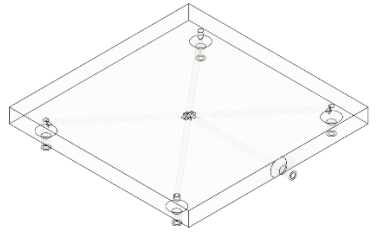
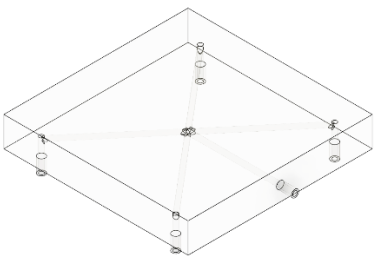
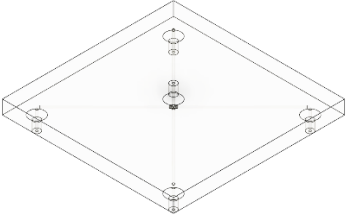
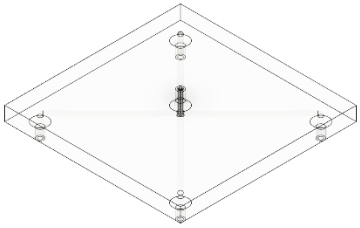
Part	a	b	c	d	Notes	
V1		45°	Wide face parallel to build platform	N/A	Wide face perpendicular to build platform	Inlet on top w/ 1.5 mm ID channels
V2		45°	Wide face parallel to build platform w/ supports	N/A	Wide face perpendicular to build platform w/ supports	Inlet on side w/ 1.5 mm ID channels
V3		N/A	N/A	Wide face flat on bed w/o supports	N/A	Inlet on side w/ 1.5 mm ID channels

Table 4.3 – Final PRM Design Iterations and Print Orientations.

V4		N/A	N/A	N/A	Wide face perpendicular to build platform w/ supports	Inlet on top w/ 0.75 mm ID channels
V5		N/A	N/A	N/A	Wide face perpendicular to build platform w/ supports	Inlet on top designed to isolate each channel. 1.5 mm ID channels

Layer Height:	0.050 mm	Bottom Lift Distance:	5.000 + 0.000 mm
Bottom Layer Count:	5	Lifting Distance:	5.000 + 0.000 mm
Exposure Time:	2.500 s	Bottom Retract Distance:	5.000 + 0.000 mm
Bottom Exposure Time:	30.000 s	Retract Distance:	5.000 + 0.000 mm
Waiting Mode During Printing:	Restin... ▼	Bottom Lift Speed:	5.000 & 0.000 mm/min
Rest Time Before Lift:	0.000 s	Lifting Speed:	40.000 & 0.000 mm/min
Rest Time After Lift:	0.000 s	Bottom Retract Speed:	210.000 & 0.000 mm/min
Rest Time After Retract:	0.500 s	Retract Speed:	210.000 & 0.000 mm/min

Figure 4.15 – M2P PRM print settings in CHITUBOX.

Layer Height:	0.050	mm	Bottom Lift Distance:	2.000	+	3.000	mm
Bottom Layer Count:	2		Lifting Distance:	2.000	+	3.000	mm
Exposure Time:	3.000	s	Bottom Retract Distance:	3.000	+	2.000	mm
Bottom Exposure Time:	30.000	s	Retract Distance:	3.000	+	2.000	mm
Transition Layer Count:	5		Bottom Lift Speed:	5.000	&	230.000	mm/min
Transition Type:	Linear	▼	Lifting Speed:	40.000	&	230.000	mm/min
Transition Time Decrement:	4.500	s	Bottom Retract Speed:	230.000	&	75.000	mm/min
Waiting Mode During Printing:	Restin...	▼	Retract Speed:	230.000	&	75.000	mm/min
Rest Time Before Lift:	0.000	s					
Rest Time After Lift:	0.000	s					
Rest Time After Retract:	2.000	s					

Figure 4.16 – M4U PRM print settings in CHITUBOX.

4.3.3 Test Setups and Procedures

Both test setups consisted of a 60 mL syringe, deionized water, a Dolomite Peristaltic Pump, Luer Lock 1.5 mm barb adapters, 1.5 mm internal diameter silicone tubing, a 150 mL beaker, a 50 mL beaker, a laboratory stand, laboratory stand clamps, a stopwatch, small plastic cups, an Ohaus Pioneer scale with 0.001 g precision, and a BK Precision DC power supply. For the individual flow rate tests, additional Luer Lock valves were required. The pump was operated at 3 VDC and 40 mA; under these conditions, the pump has a volumetric flow rate of about 0.45 mL/min [51]. The setup began by labelling the channels of the PRM 1–4. Once that was completed, the laboratory stand was set up with the proper clamps. One clamp was used to hold the syringe, and the other clamp was for holding the pump. The syringe, which has the Luer Lock barb adapter attached to it, was then filled with DI water and placed in the clamp. The inlet of the pump could then be attached to the outlet of the syringe. From here, about 3 cm of tubing was attached to each of the outlets of the PRM. For the overall flow test, the PRM was ready to attach to the pump.

For the individual flow rate test, three valves with Luer Lock barb adapters were attached to three of the outlets to prevent flow, while one outlet remained open without a valve. At this point, the inlet of the PRM was connected to the pump and the PRM was placed atop the 50 mL beaker. The reason for not clamping the PRM as well was to keep the device as level as possible; when angled, the outlets angled down tended to experience flow more often. Finally, the power supply was ready to be turned on, set to the proper current and voltage (40 mA/3 VDC), and connected to the pump. Both test setups can be seen in Figures 4.17 and 4.18.

The overall flow test consisted of two stages. The first stage began by engaging the pump and observing the PRMs' behaviors. To begin, each channel was primed with water. This was done by plugging three out of the four outlets and engaging the pump until the channel was full. The channels were primed by repeating this process for each outlet. Once primed, the pump ran for five minutes, and qualitative observations were noted. The primary focus was to observe which PRMs experienced flow through each channel. The devices which experienced flow in each channel were noted and moved on to the second stage. The second stage involved the same process as before, priming the channels and engaging the pump for five minutes. While the pump ran, the number of droplets output through each channel were noted. These tests assisted in providing initial insight on how the PRMs would function, as well as eliminating samples not worth testing further for the sake of time.

The PRM samples that passed the second stage of overall flow test could now have their channels tested individually to determine flow rates and channel volumes. Once set up, the channel being tested was primed with water. The small plastic cups were labeled 1–4 (corresponding to outlets 1–4); their dry masses were measured five times and averaged. Following this, the first cup could be placed underneath the first outlet to collect the water output by the PRM. The pump was engaged for two minutes, and the wet mass of the cup was measured. To test the volume of the channels within the PRM, the methods were similar. However, an additional step was taken when priming the channels. Once the channels were fully primed, the inlet of the pump was disconnected from the syringe, and the water remaining in the pump line was removed. To do this, the pump was simply reengaged and run until the meniscus of the water in the pump lines was at the same level as the inlet of the PRM (Figure 4.19). After the additional water was removed, the volume of water remaining in the PRM should be the volume of the individual channel, plus the short length of tubing attached to the outlet in question. This water was finally pumped out into the channel's respective cup, and the cup's wet mass was measured. Both the flow rate and channel volume tests were repeated five times per channel.

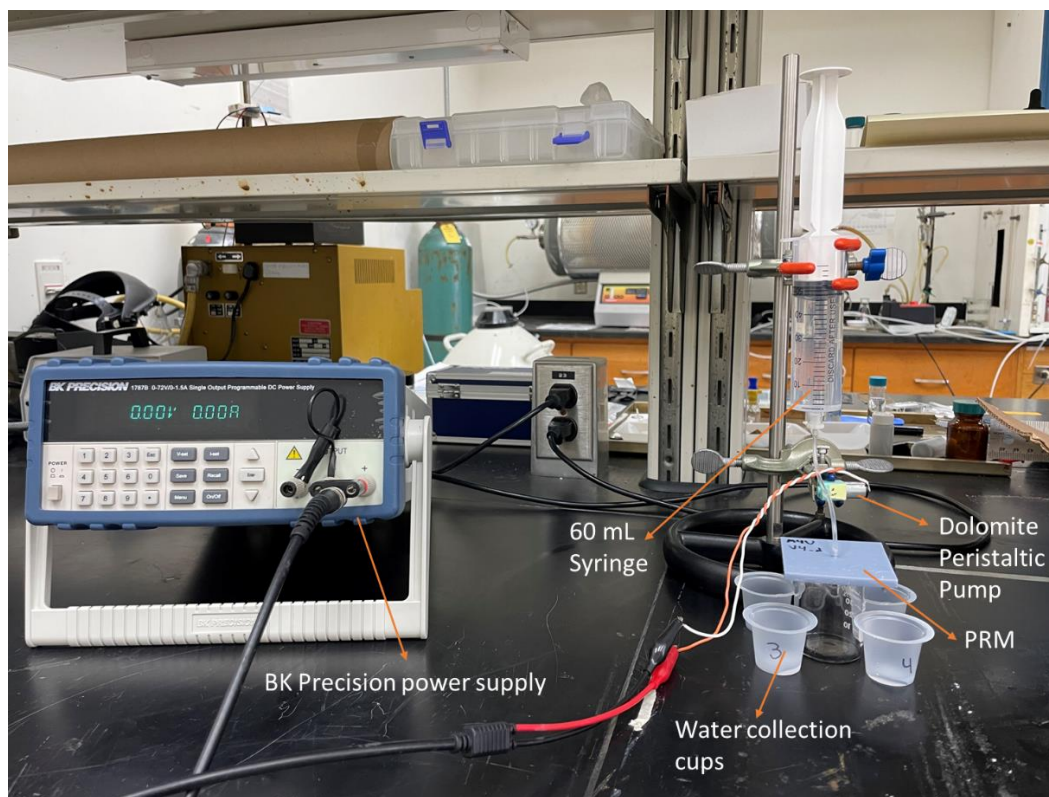


Figure 4.17 – Overall flow test setup.

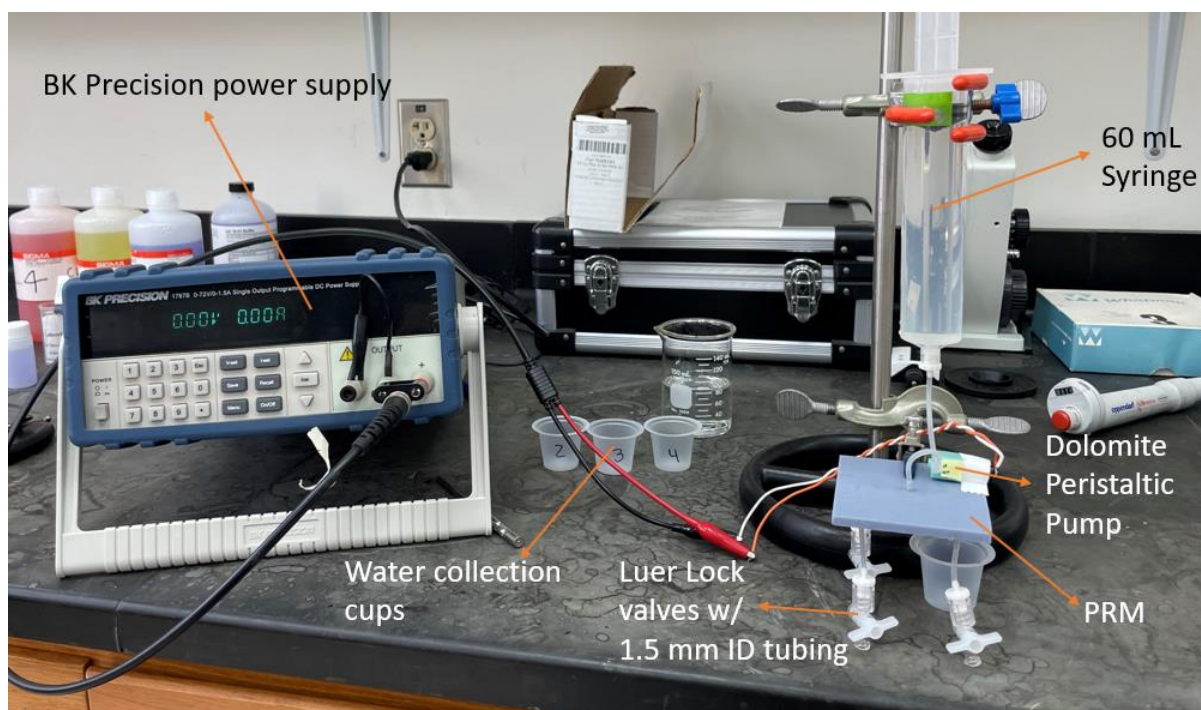


Figure 4.18 – Individual flow rate test setup.

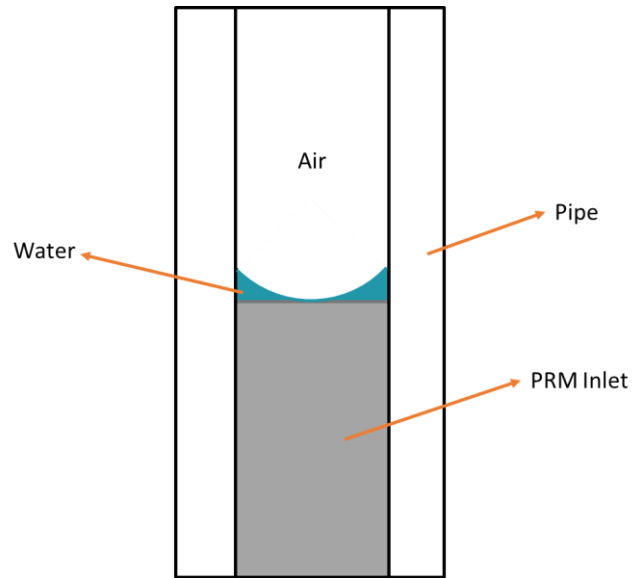


Figure 4.19 – Meniscus at inlet before beginning channel volume test.

4.3.4 Data Analysis

The methods employed to analyze these data are relatively simple. First, the dry masses of the cups ($m_{i,dry}$) were subtracted from the wet masses ($m_{i,wet}$) to obtain the mass of the water pumped in two minutes ($m_{i,p}$), Equation (4.7):

$$m_{i,p} = m_{i,wet} - m_{i,dry}. \quad (4.7)$$

Equation (4.8) determined the mass of water remaining in the channels ($m_{i,r}$) by subtracting the wet mass of the cup containing the remaining water from the channels ($m_{i,wet,r}$) by $m_{i,dry}$:

$$m_{i,r} = m_{i,wet,r} - m_{i,dry}. \quad (4.8)$$

The mass flow rate of the individual channel ($\dot{m}_i$) was calculated by dividing $m_{i,p}$ by the time spent pumping (t_p), which was approximately two minutes (Eq. 4.9):

$$\dot{m}_i = \frac{m_{i,p}}{t_p}. \quad (4.9)$$

Since one gram of water equals one milliliter of water, the conversion from mass/mass flow rate to volume/volumetric flow rate (Q_i) was simple, as they are equivalent in this case. To match the flow rates to the flow rate of the pump (mL/min), simply multiply the mass flow rate by 60 (Eq. 4.10):

$$Q_i = \dot{m}_i * 60. \quad (4.10)$$

To account for the volume of water remaining in the outlet tube ($V_{outlet\ tube}$), $V_{outlet\ tube}$ was subtracted from the volume of water remaining in the channel and outlet tube ($V_{i,r}$) to obtain the volume of water remaining in the channel (V_i), provided by Equation (4.11):

$$V_i = V_{i,r} - V_{outlet\ tube} \quad (4.11)$$

Each of these values were finally averaged, and their standard deviations were taken. The samples with the lowest standard deviations were selected for further design iterations.

4.3.5 Challenges and Limitations

Once again, most of the challenges stem from the typical challenges and limitations of MSLA printing. To begin, preliminary test prints did not experience uniform flow through each channel at one time. The non-uniform flow prompted further iterations and testing. This was likely due to a few reasons, such as a low pump flow rate, designed channel geometry, and non-uniformly printed channel dimensions caused by deformations induced by the printing process. Next, orientation b proved difficult to print. Initial attempts failed, which prompted the orientations tests described in section 4.2. Once the new support strategy was established, they became more difficult to remove. Extreme care was taken to not damage the inlets and outlets when removing these supports. Finally, the inlets and outlets proved to be fragile, and occasionally printed partially delaminated from the PRM (Figure 4.20), adding to the fragility. This defect would also induce air bubbles within the system, which would affect the test results. To mitigate this issue, 0.15 cm radius fillets were added to the base of each outlet (Figure 4.21), increasing their strength and print success rate.

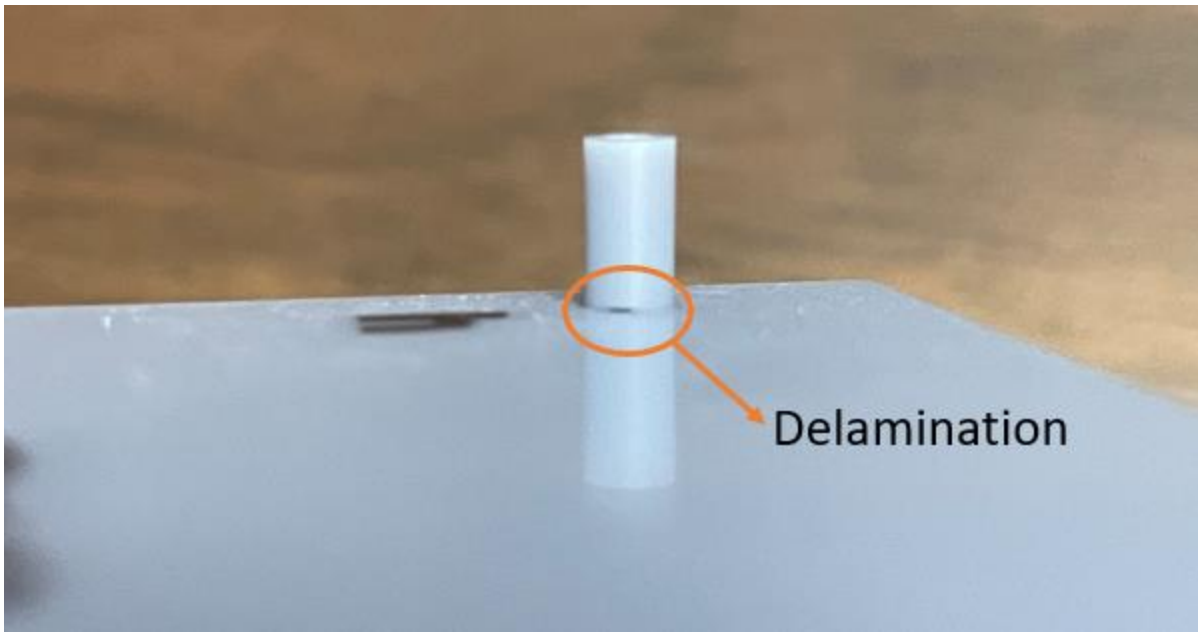


Figure 4.20 – Inlet partial delamination.

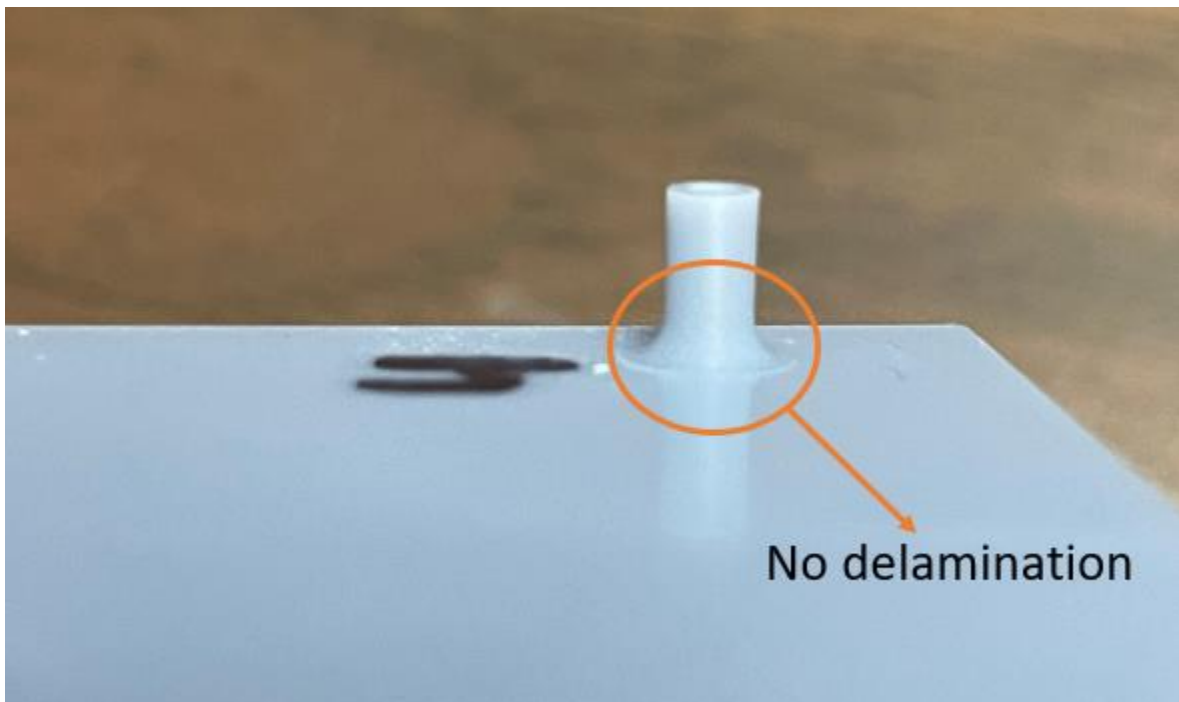


Figure 4.21 – PRM with fillets.

Chapter 5: Results and Discussion

5.1 FEP Seal Strength and FEP Bladder Prototype

5.1.1 Seal Strength

The data acquired from these tests were utilized to understand the performance of the bladder tank. In addition, the yield stresses of the ASTM F88 samples were calculated and compared to the theoretical stresses that may occur within the bladder tank. Figures 5.1–5.5 showcase the load (lbf) versus grip displacement (in.) measured during the experiments. The blue lines in these figures are the raw data, and the red line represents the data after performing a simple moving average for smoothing. Table 5.1 provides the maximum loads experienced during the tests, which were taken from the smoothed data. Table 5.2 outlines the stresses (psi) experienced by the seals and compares them to the theoretical stresses (psi) the tank may encounter. The failure modes experienced between each sample were consistent. The single-layered fin samples experienced material break at the seal edge, reflected in Figure 5.6 [54]. The double-layered fin samples experienced a combination of failure modes. The layer that was directly exposed to the heating element of the MP-8C typically first exhibited a material break (Figure 5.6) [54]. This break can be seen in Figures 5.3–5.5 as a sharp decrease in load. The layer opposite to the heating element then experienced an adhesive peel failure mode (Figure 5.7), which appears in the data as a steady decrease in load [54].

As seen in Figure and Table 5.1, the first sample of the 3 mil thick fin yielded an inconclusive result. This is due to a sampling rate being too low to show the trend. The sampling rate was then increased for the following samples, and trends became apparent. As expected, as the fin/seal thickness increased, the average maximum load increased. The standard deviations of the tests were higher than desired, which is a result of two factors. The first factor came from the resolution of the load cell. The load cell, rated for 5 kips (5000 lbf), was almost too strong for these samples, since the samples that were tested only experienced loads between 5 and 11 lbf. This also contributed to the noisiness of the data. The second factor contributing to the increased standard deviations was imperfect and inconsistent seals. Any slight contamination, mainly dust from the air, affects the strength of the seal. In addition to this, it was difficult to obtain consistent and quality seals of the FEP with the MP-8C sealer, especially as the thickness of the seals increased. A more consistent sealing method may be employed in the future; one recommendation would be to use a heated press to seal the samples. This would provide precise control over the heating of the seal, as well as the application of consistent pressure between sealing each sample. Shown in Table 5.2, as the fin thickness increases, the stresses experienced by the seals decrease on average as expected, with exception to the sample whose fin thickness is 0.008 in. This discrepancy is explained by the outlier present in the maximum average load data, likely due to an imperfect seal. Based on the analysis, a perfect FEP tank with a thickness of 0.01 in., pressurized to 14.7 psig should not fail at the seal. A FEP bladder tank with 0.01 in. thick walls was then cut and sealed for further testing.

5.1.2 FEP Bladder Prototype

Figure 5.8 shows the rough prototype of the FEP bladder tank, and before inflation several problems became apparent. Four layers of 5 mil FEP were cut into 6.6 cm radius circles, two layers for the bottom half and two for the top half of the tank. Holes for the flange were also carefully cut on the top half of the tank. The flange easily screwed in, however creases formed around the flange that could pose an issue resulting in tank leakage. The next issue with the tank came from sealing. The MP-8C heat sealer can only seal straight lines, so a series of short lines had to be sealed in series to fully encapsulate the circle. To be safe, the edges of the tank were double sealed. This was extremely difficult to do perfectly by hand, and the areas where the seals overlapped became sharp corners. These corners were areas of stress concentration.

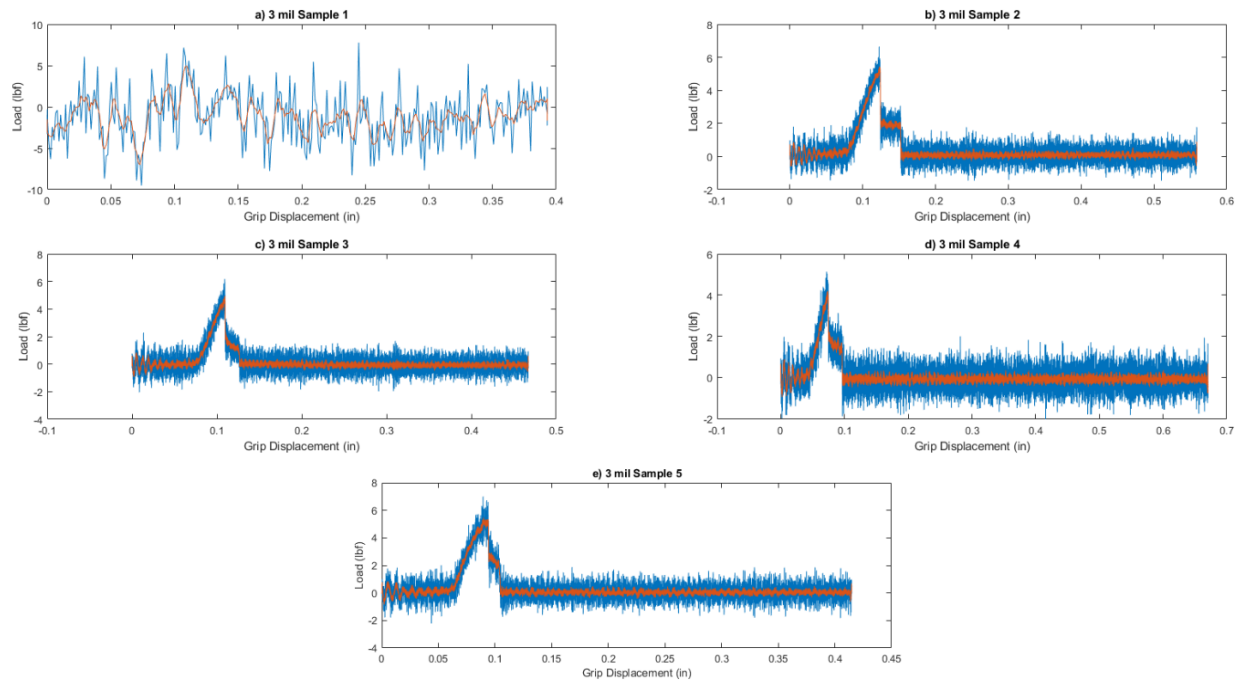


Figure 5.1 – ASTM F88 3 mil fin sample test data.

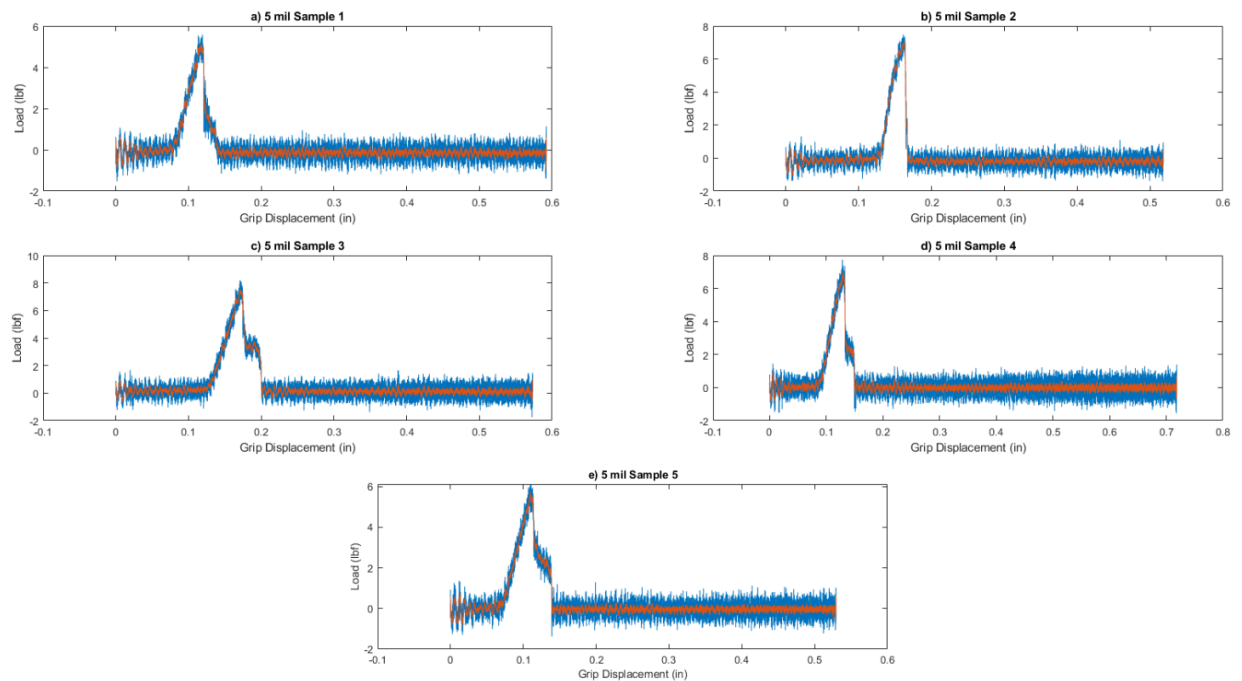


Figure 5.2 – ASTM F88 5 mil fin sample test data.

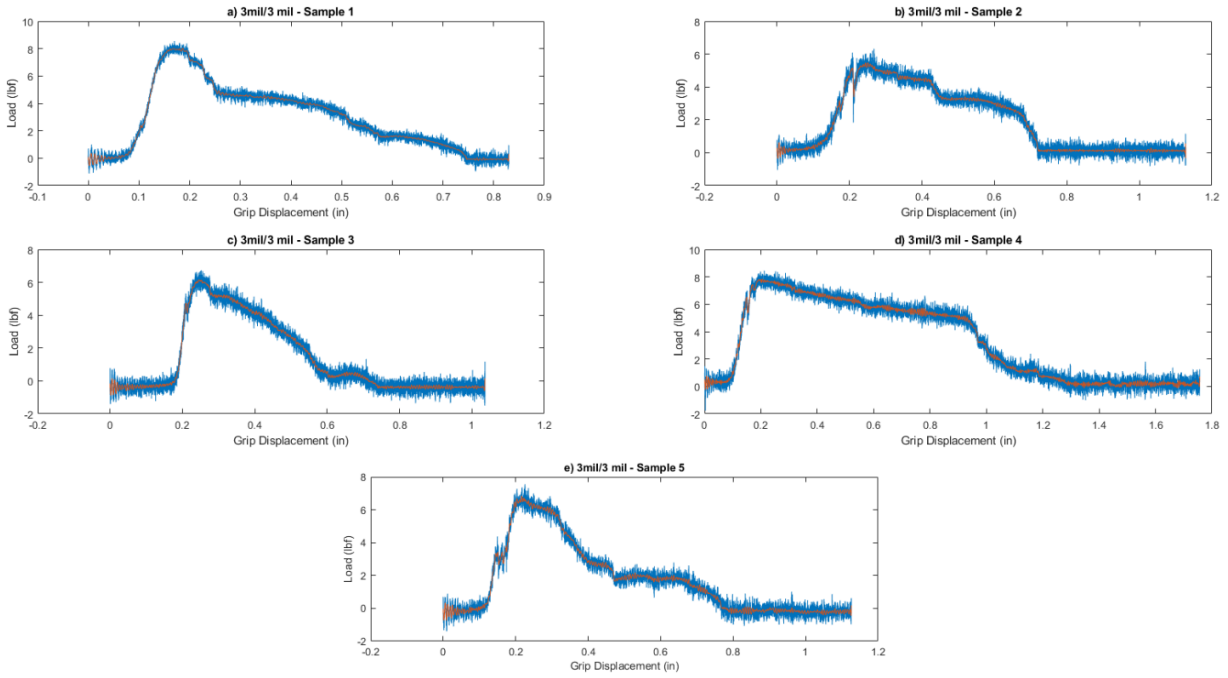


Figure 5.3 – ASTM F88 6 mil fin sample test data.

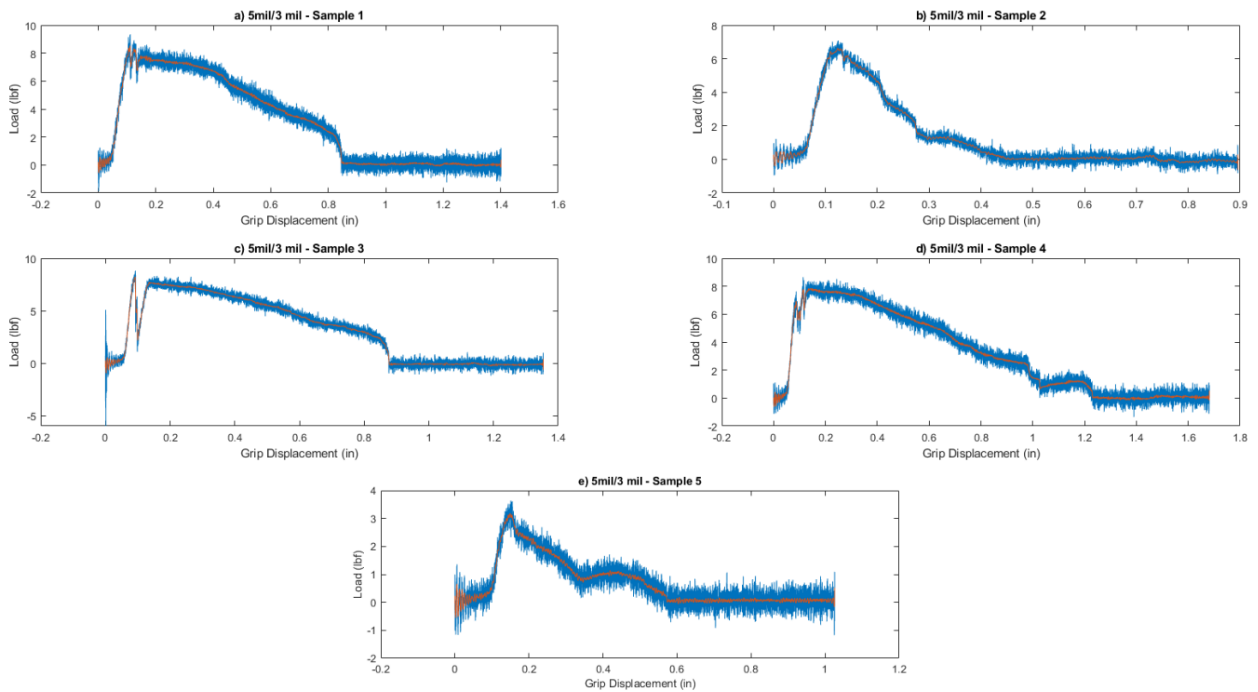


Figure 5.4 – ASTM F88 8 mil fin sample test data.

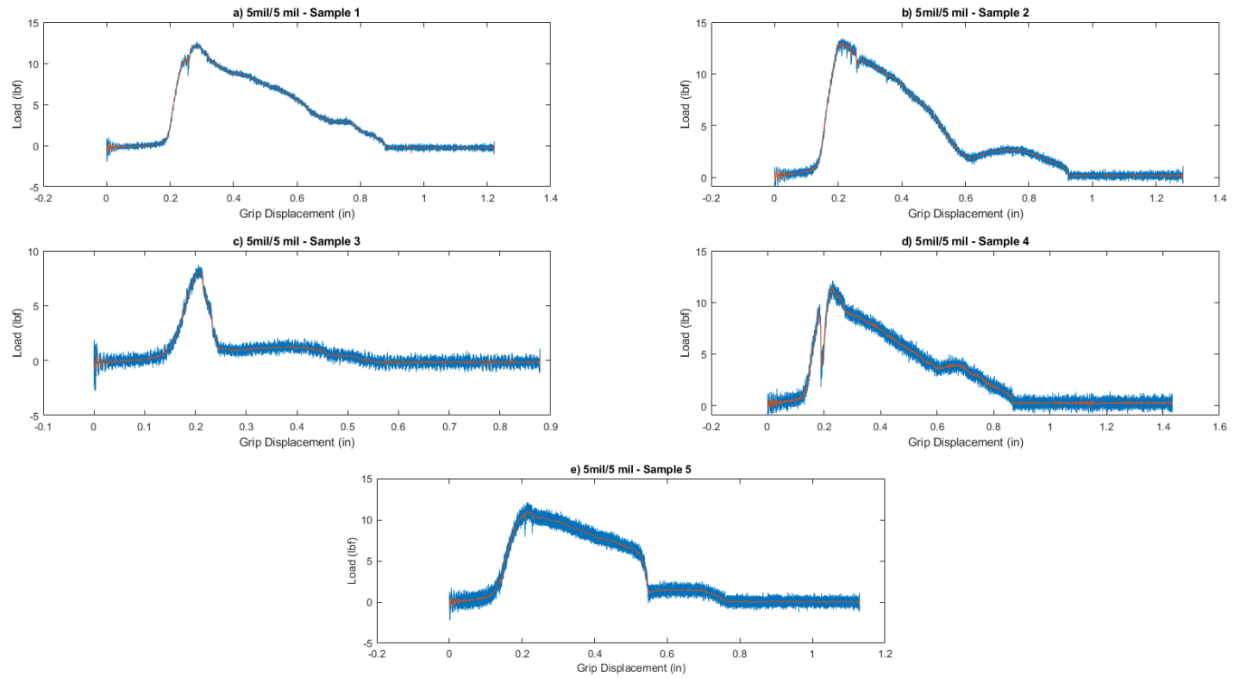


Figure 5.5 – ASTM F88 10 mil fin sample test data.

Table 5.1 – Maximum loads experienced by each sample.

Fin Thickness (in.)	1 (lbf)	2 (lbf)	3 (lbf)	4 (lbf)	5 (lbf)	AVG (lbf)	STD (lbf)
0.003	N/A	5.441	4.953	4.201	5.475	5.018	0.5942
0.005	5.102	7.030	7.535	7.063	5.765	6.499	1.020
0.006	8.043	5.479	6.167	7.840	6.850	6.876	1.089
0.008	8.534	6.630	8.233	7.854	3.185	6.887	2.192
0.010	12.19	13.07	8.119	11.50	11.05	11.19	1.876

Table 5.2 – Stresses from average maximum loads compared to theoretical tank stresses.

Fin Thickness (in.)	Average Load (lbf)	Seal Stress (psi)	Tank Stress (psi)	Tank failure?
0.003	5.018	1673	3185	Yes
0.005	6.499	1300	1911	Yes
0.006	6.876	1146	1593	Yes
0.008	6.887	860.9	1194	Yes
0.010	11.19	1119	955.5	No

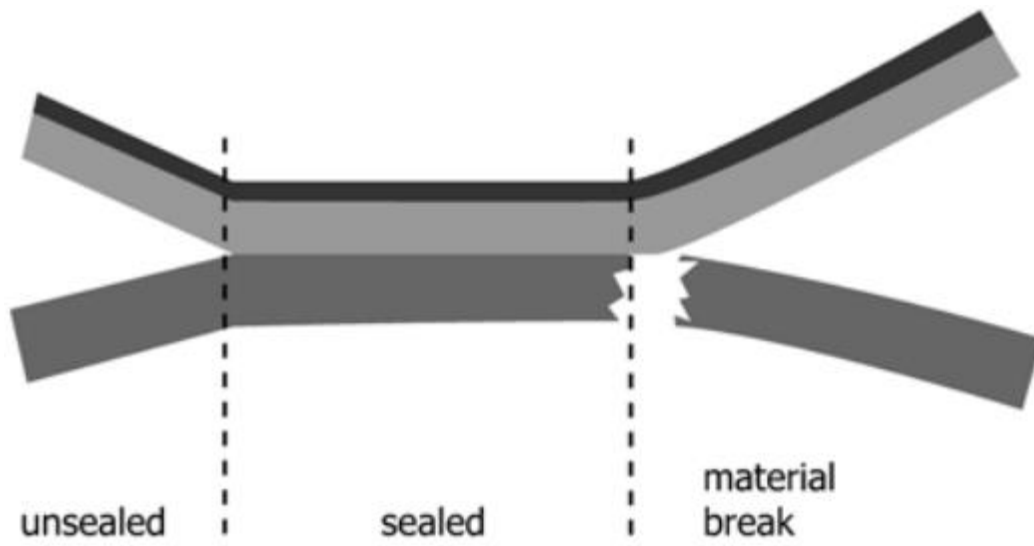


Figure 5.6 – Material break failure mode [55].

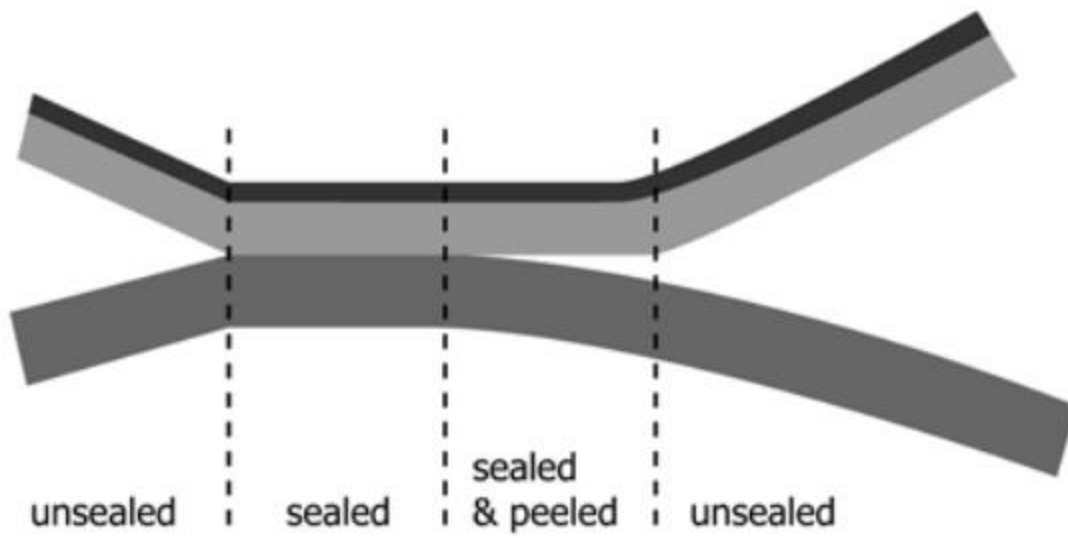


Figure 5.7 – Adhesive peel failure mode [54].

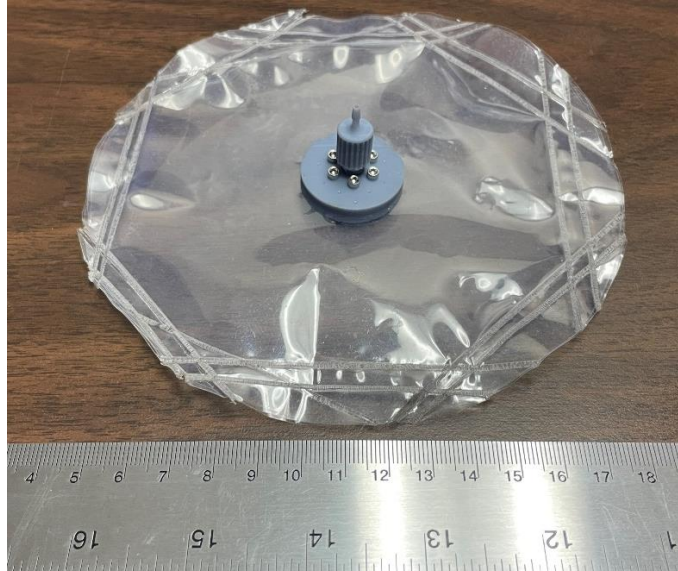


Figure 5.8 – FEP bladder tank prototype.

The tank was then filled with air, and it quickly became apparent that the design in its current state was simply not feasible, not even for pressurization tests. The tank failed before any significant pressure measurements could be taken. The sharp corners where the seals overlapped were the first to fail and leak air. Upon inflation, the tank folded at those corners, identical to the creases one would see on a foil party balloon (Figure 5.9) [64]. Even if the seal was perfectly round, those creases would still form, bend, and break the seal prematurely due to the stiffness of the FEP seal.

A significant amount of time was spent to get to this point, so the decision was made to note these results, speculate on what could be done to improve upon this design, and move forward in prototyping the PRM. Keeping with the bladder tank design, it would be beneficial to continue with a more conventional approach. A custom injection-molded Teflon® PTFE bladder tank would be ideal; however, the design and fabrication of the mold would be expensive and time consuming. Keeping with FEP, the ideal application would be for a diaphragm tank. A custom vacuum formed hemispherical diaphragm could be purchased from commercial vendors, like the one shown in Figure 5.10, or manufactured in-house [65]. Regardless, this would also be expensive, however, potentially less time-consuming than the previous solution mentioned. A potential issue may arise from a FEP diaphragm, due to the stiffness of these diaphragms, external pressurization may be required to achieve the desired expulsion efficiency of propellant if the micropump is not strong enough. Finally, a cylindrical piston tank was proposed. This design would likely be the cheapest to manufacture; however, to achieve the desired propellant load, it may only be suitable for a 3U CubeSat or larger. In atmosphere, the Dolomite Microfluidics peristaltic pump is strong enough to pull water from a standard 60 mL syringe, however the standard syringe design may not be capable of properly containing the liquid in a vacuum due to outgassing in the event of the IL not being properly conditioned, a risk that must be accounted for. The liquid may leak from between the piston and syringe walls, and the vacuum of space could even pull the piston back and out of the syringe entirely. Thus, the main concern of a piston tank would be obtaining a strong-enough seal between the piston and tank walls while still allowing it to actuate from the suction of the micropump. Conventionally this is done with a two-layered tank and a pressurant, such as Helium (Figure 5.11); however, the goal of this propellant feed system is to eliminate the need for a pressurant gas, which adds to the system's mass, risk, and complexity [66]. Taking inspiration from LISA Pathfinder, a spring could be employed to generate extra pressure on the piston, one strong enough to prevent the piston from reversing its direction and to assist the micropump in performing its task [32].

5.2 3D Print Test Results

5.2.1 Overview

The results from these tests served to provide insight on the dimensional accuracy of parts printed with different support strategies on two different commercially available MSLA printers. These strategies included cubes printed flat on the bed without supports, elevated with sparsely packed heavy supports, and elevated with densely packed lightweight supports. The printers which were compared included Elegoo's M2P and M4U. This analysis determined what support strategy was ideal for the PRM design iterations that required supports and determined which printer to use for the final iterations of the PRM. The actual dimensions of the cubes, the standard deviations between them, percent errors from the theoretical dimensions, and the print success rates were taken into account when making this decision.

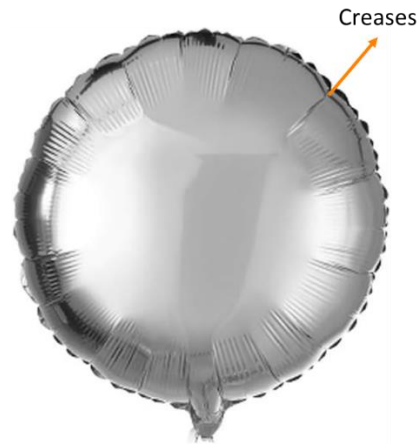


Figure 5.9 – Foil party balloon creases [64].



Figure 5.10 – Hemispherical FEP diaphragm tank [65].

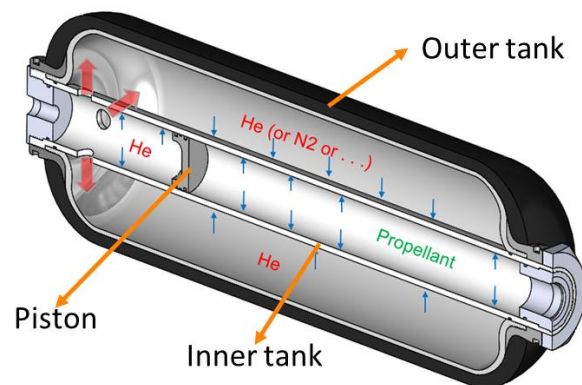


Figure 5.11 – Piston tank design [66].

5.2.2 Flat-on-bed Test Results

As can be seen in Figures 5.12 and 5.13, both successfully printed all eight parts. Looking closer at the parts, the surfaces attached to the print bed appear to have a slight bulging lip, commonly referred to as “elephant’s foot,” (Figures 5.14 and 5.15). Elephant’s foot is present on these cubes because the first 5 layers of the print had a longer exposure time than the remaining layers. The reason for this was to ensure adequate adhesion to the print bed, and this practice should be employed on most prints to ensure their success. This defect is typically mitigated by raising the part off of the bed with supports.

After the parts were removed from the bed, cleaned, and post-cured, they could then be measured. Tables 5.3–5.6 show the final part dimensions, averages, standard deviations between each cube, and percent errors from the theoretical part dimensions. The standard deviations of the X- and Y-dimensions appear to be fairly consistent between both printers. The X-dimension standard deviation of the M2P cubes was slightly higher than those of the M4U cubes. These tables also show that the Z-dimension was the least accurate on both printers when printing flat on the bed. The standard deviations in the Z-direction were higher on the M4U than the M2P. As for the percent errors, the M4U was slightly higher than the M2P in the X- and Y- dimensions, likely as a result of a more-pronounced elephant’s foot. However, the error in the Z-dimension was about 2.5 times lower than that of the M2P. This is likely due to the fact that the M4U has a more precise bed-leveling procedure, which results in more accurate layer heights compared to the M2P. Averaging all of the errors between each cube and dimension results in an overall average error of 0.55% from the M4U and a 1.09% error from the M2P; so far, the M4U was proven to be more accurate with some room for improvement.

5.2.3 Sparsely Packed, Heavy Support Test Results

To further improve the accuracy of the cubes, it was decided to print them elevated off the print bed with sparsely packed, dense supports. Eight cubes were oriented identically to those of the previous flat-on-bed test and queued up to print. The M4U successfully printed all eight cubes (Figure 5.16), however the print failed on the M2P (Figure 5.17). Five M2P cubes completely delaminated from the supports, seemingly on the layer that transitions from the final support layer to the first layer of the cube. The cubes that did survive were partially delaminated from the supports and extremely deformed (Figure 5.18). These delaminations were a result of the peel force induced by the cross-section of the cube against the FEP sheet in the vat. For the severely deformed parts, the peel force was much stronger than the bond between the supports, and thus the parts partially delaminated. As for the fully delaminated parts, it can be seen in Figure 5.19 that some cubes are more complete than others, and they do not appear to be as deformed. This suggests that the cyclic peel force, as the bed repeatedly retracts into the vat and lifts from the FEP sheet, caused the cubes to delaminate from the supports due to fatigue. Interestingly, the cubes on the M4U did not experience the same failure. This is because the vat utilizes an ACF sheet rather than a FEP sheet, which has a lower peel force than FEP, thus the ACF results in more successful prints [67]

Since the cubes printed from the M2P either failed entirely or were severely deformed, they were not suitable for measuring. The M4U, on the other hand, showed promising results (Tables 5.7 and 5.8). First, the standard deviations were fairly comparable to the flat-on-bed test cubes. The X- and Y-dimensions between cubes had standard deviations which were only slightly increased, but the averages between the cubes were exactly 20 mm. The Z-dimensions, however, showed an increased standard deviation compared to the flat-on-bed test and were measured to be greater than 20 mm. As for the percent errors, the X- and Y-dimensions were much lower than those printed flat on the bed. In contrast, the Z-dimension experienced a higher percent error than the flat-on-bed M4U parts. Also, when averaging all of the errors, the M4U has an overall average error of 0.60%, which is a slight increase from the previous test. These increased Z-dimension values were a result of the deformations induced by sparsely packed supports.

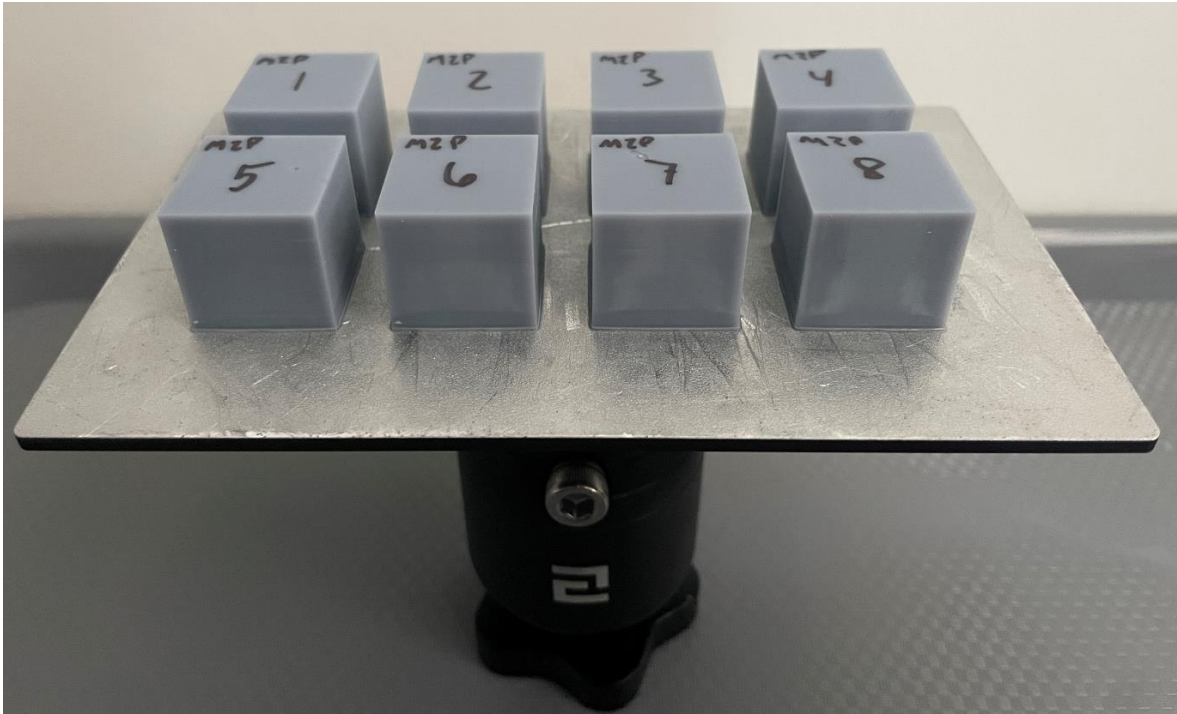


Figure 5.12 – M2P flat on build platform cubes.

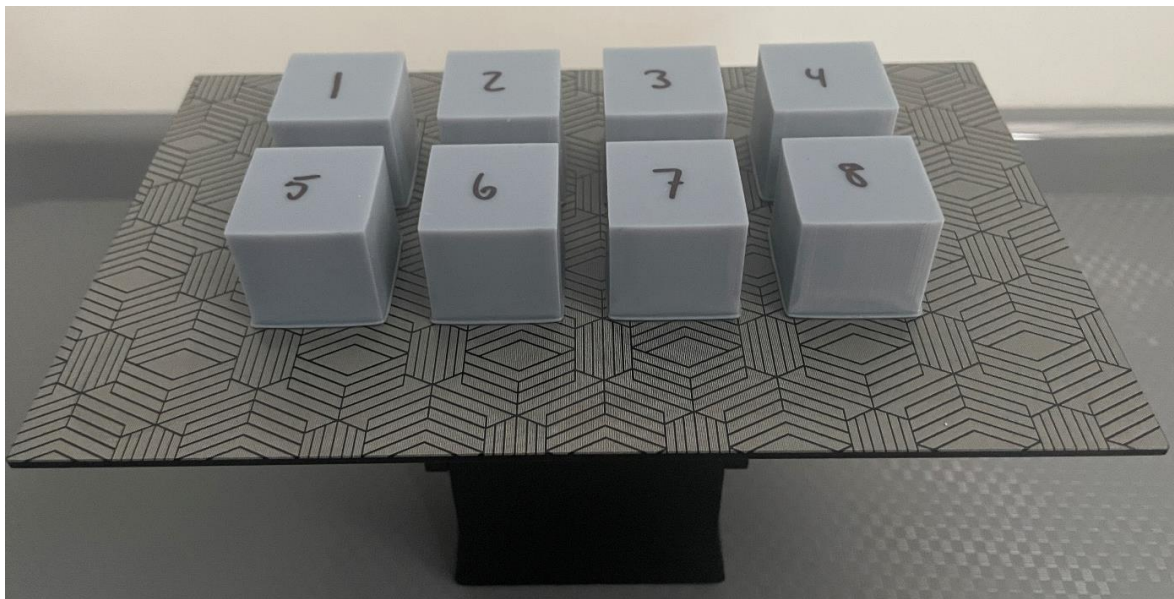


Figure 5.13 – M4U flat on build platform cubes.

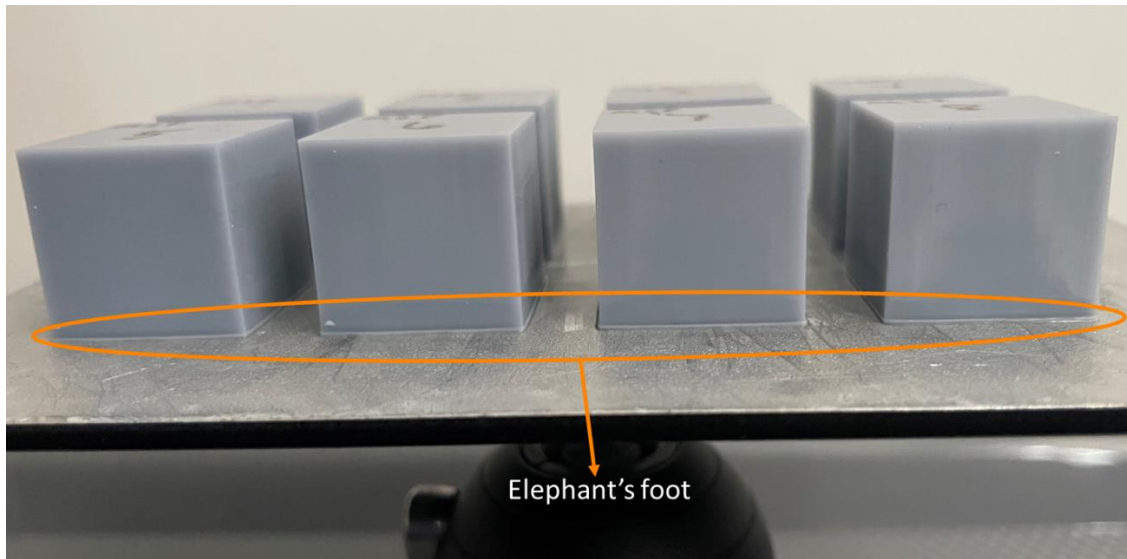


Figure 5.14 – M2P cubes with elephant's foot.

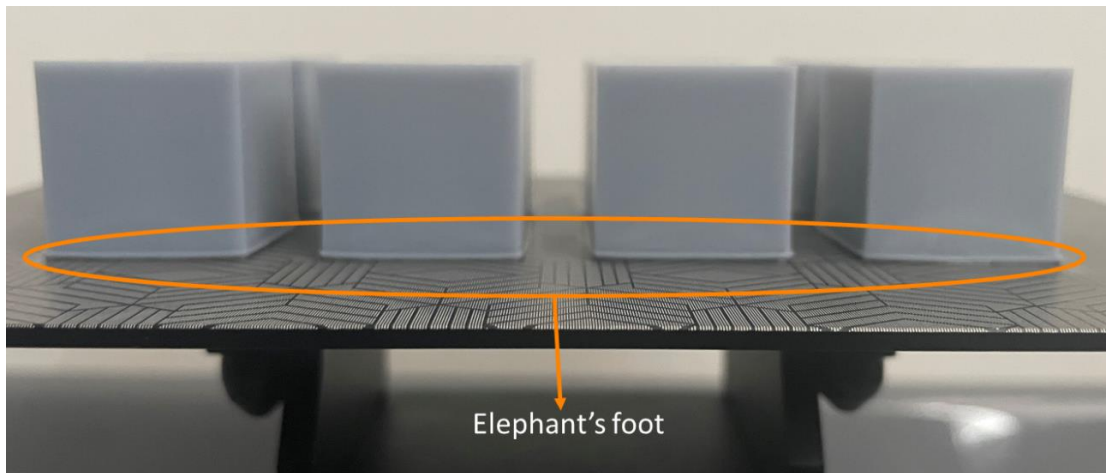


Figure 5.15 – M4U cubes with elephant's foot.

Table 5.3 – Dimensions of M2P cubes flat on build platform (mm).

	1	2	3	4	5	6	7	8	AVG	STD
x	20.00	20.02	20.01	20.06	20.01	20.02	20.05	20.02	20.02	0.020
y	20.05	20.02	20.03	20.06	20.03	20.02	20.04	20.04	20.04	0.013
z	19.41	19.41	19.42	19.44	19.40	19.40	19.38	19.42	19.41	0.016

Table 5.4 – % errors in M2P cubes flat on build platform from theoretical dimensions.

	1	2	3	4	5	6	7	8	AVG
x	0.00%	0.12%	0.07%	0.32%	0.03%	0.12%	0.23%	0.08%	0.12%
y	0.25%	0.08%	0.15%	0.30%	0.15%	0.12%	0.20%	0.22%	0.18%
z	-2.93%	-2.97%	-2.92%	-2.80%	-3.02%	-3.02%	-3.08%	-2.92%	-2.96%

Table 5.5 – Dimensions of M4U cubes flat on build platform (mm).

	1	2	3	4	5	6	7	8	AVG	STD
x	20.05	20.05	20.04	20.07	20.04	20.03	20.04	20.06	20.05	0.012
y	20.04	20.06	20.03	20.05	20.04	20.04	20.02	20.06	20.04	0.014
z	19.75	19.73	19.80	19.79	19.74	19.74	19.75	19.80	19.76	0.026

Table 5.6 – % errors in M4U cubes flat on build platform from theoretical dimensions.

	1	2	3	4	5	6	7	8	AVG
x	0.25%	0.25%	0.22%	0.35%	0.22%	0.15%	0.18%	0.32%	0.24%
y	0.22%	0.32%	0.13%	0.27%	0.22%	0.18%	0.10%	0.28%	0.21%
z	-1.23%	-1.33%	-1.02%	-1.03%	-1.28%	-1.32%	-1.23%	-1.02%	-1.18%

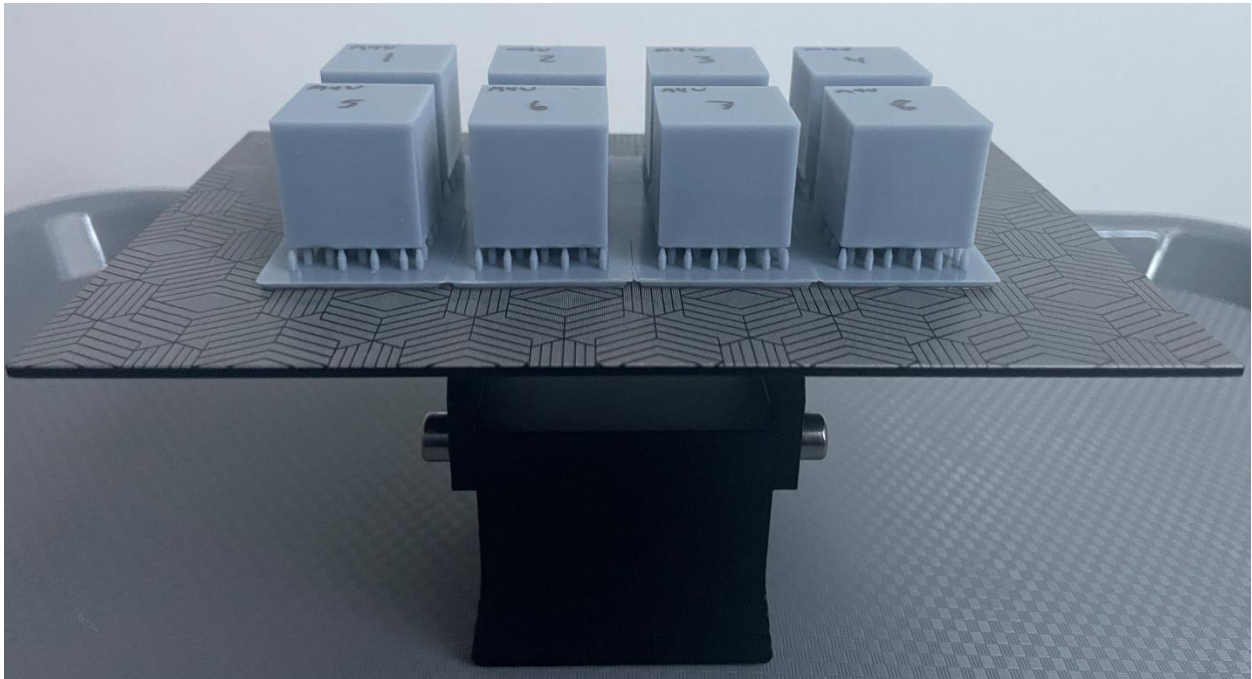


Figure 5.16 – M4U cubes with sparsely packed, heavy supports.

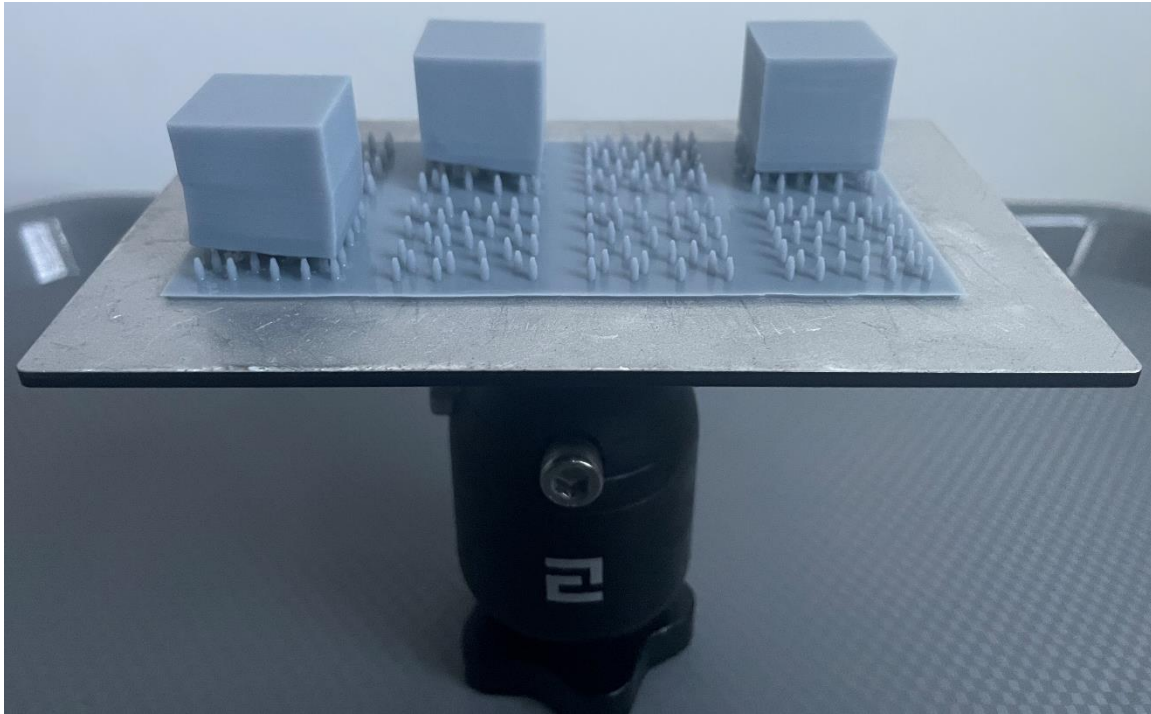


Figure 5.17 – M2P cubes with sparsely packed, heavy supports.

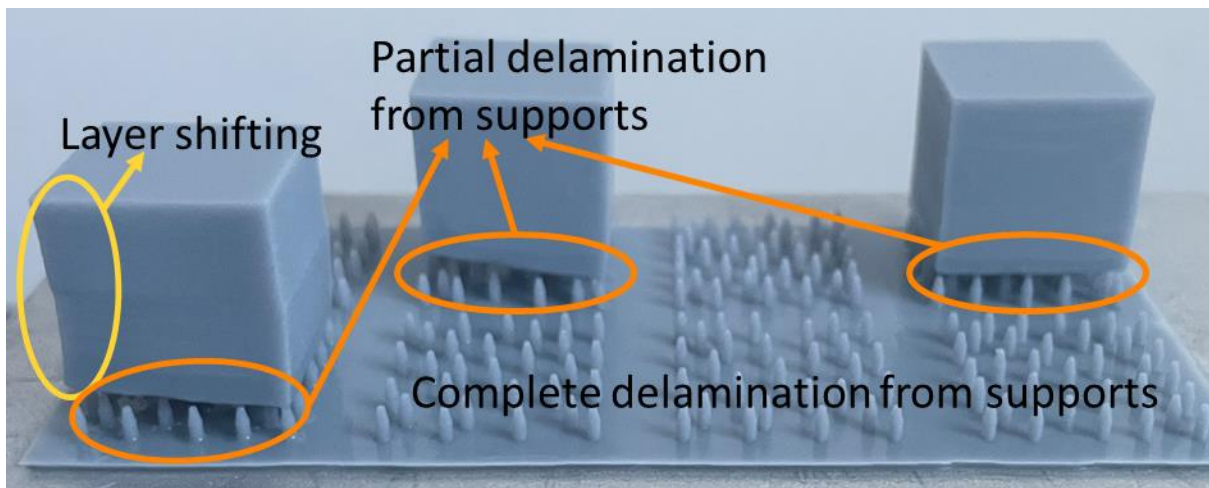


Figure 5.18 – Failure modes present on M2P cubes printed with sparsely packed, heavy supports.

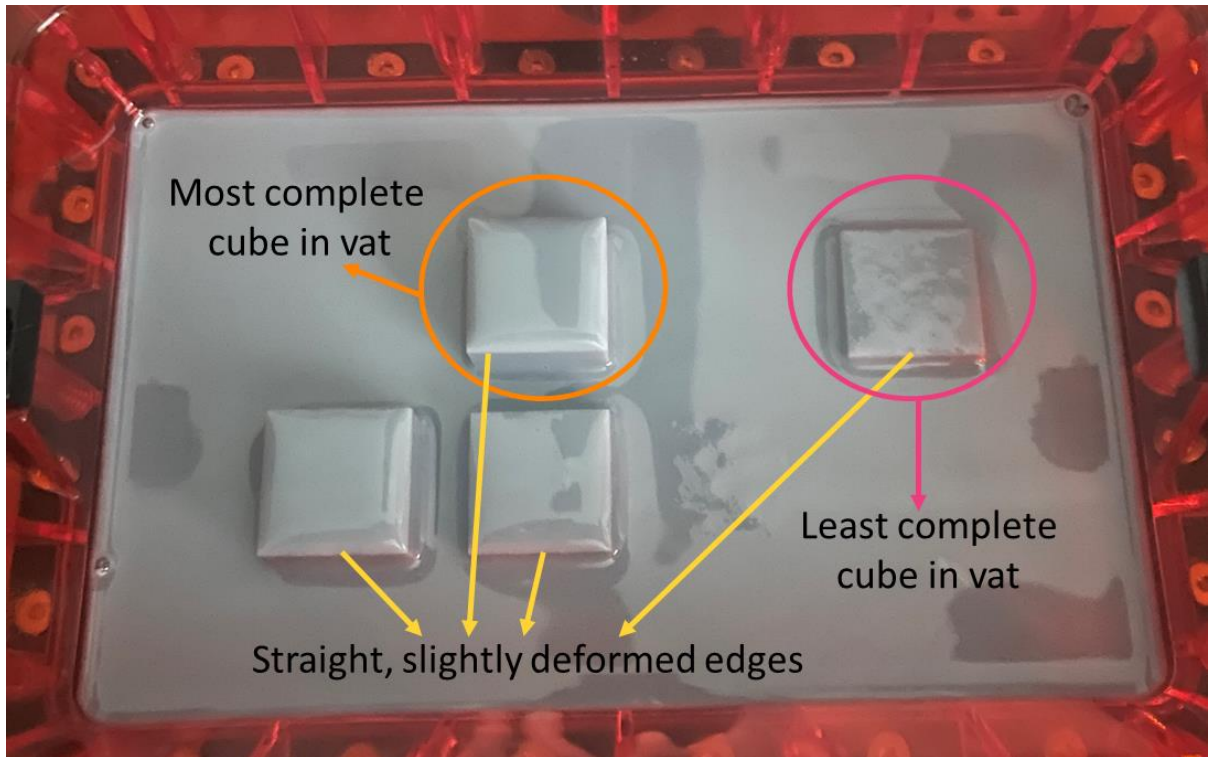


Figure 5.19 – Failed, sparsely packed, heavy support cubes remaining in the M2P vat.

Table 5.7 – Dimensions of M4U cubes with sparsely packed, heavy supports (mm).

	1	2	3	4	5	6	7	8	AVG	STD
x	19.99	19.98	19.99	19.99	20.01	20.02	20.01	20.02	20.00	0.014
y	19.99	19.98	19.98	20.00	20.02	20.03	20.00	20.02	20.00	0.017
z	20.31	20.37	20.27	20.42	20.36	20.34	20.27	20.31	20.33	0.049

Table 5.8 – % errors in M4U cubes with sparsely packed, heavy supports from theoretical dimensions.

	1	2	3	4	5	6	7	8	AVG
x	0.03%	0.08%	0.03%	0.07%	0.05%	0.08%	0.05%	0.12%	0.06%
y	0.05%	0.08%	0.10%	0.00%	0.08%	0.13%	0.02%	0.12%	0.07%
z	1.53%	1.87%	1.37%	2.10%	1.82%	1.72%	1.35%	1.53%	1.66%

Figure 5.20 shows an exaggerated view of the surface connecting the supports to the cube; due to the peel force of the ACF, gaps between supports result in small humps. Bigger gaps between supports result in larger humps, so in order to reduce these deformations, the density of the support placement should be increased [68]. More densely packed supports should also help solve the delamination issues experienced by the M2P.

5.2.4 Densely Packed, Lightweight Support Test Results and Conclusions

The final test cubes that were printed included four cubes produced by both the M2P and M4U with densely packed, lightweight supports. The support densities explored included 75%, 80%, 85%, and 95% coverage of the cube face closest to the print bed. Cubes printed on the M4U were successfully manufactured on the first attempt, but those printed on the M2P required two print attempts. The results of these prints are shown in Figures 5.21–5.23. On the first print attempt with the M2P (Figure 5.21), the 75% support density cube partially delaminated from the supports, which resulted in a severe deformation of the part. On the second print attempt (Figure 5.22), the 75% support density cube did not delaminate from the supports; however, the 90% support density cube delaminated from the print bed. Between these print attempts, four cubes from both the M2P and M4U were cleaned, post-cured, and measured. This time, however, the standard deviations were taken between the measurement points in the X-, Y-, and Z-dimensions on each cube rather than between each cube like the previous tests. The percent errors were found in the same manner as the previous tests.

Tables 5.9 and 5.10 showcase the print measurements, deviations, and errors. The M2P showed higher standard deviations and errors in the X- and Y- dimensions than those printed with the M4U. In contrast, the Z-dimensions of the cubes printed by the M2P had lower standard deviations and errors. In either case, the dimensions were closer to the theoretical dimension of the cubes, especially in the Z-dimension. The surface connecting the cube to the supports was much smoother than those printed with the sparsely packed, heavy supports. This shows that the densely packed, lightweight supports properly mitigated the hump defects. For these reasons, densely packed, lightweight supports were chosen as the ideal support strategy. A trend between each printer was apparent, which was used to determine the ideal support density to employ. The standard deviations and errors decrease from the 75% to 85% support density, then increase once at 90% support density. Based on this, a support density of 85% was initially selected to print the PRMs. A test print of PRM V1b was conducted to see how the part would look, and it was determined that at an 85% support density, the supports were far too difficult to remove without damaging the PRM. So, a final support density of 80% was selected to print the PRMs. As for which printer to use moving forward, the M4U was selected. This decision was made based on its superior X- and Y-dimensional accuracy in every test case, as well as its print success rate compared to the M2P.

5.3 Flow Rate and Channel Volume Test Results

5.3.1 Overview

Two types of tests were conducted on a variety of part designs and print orientations printed from both Elegoo's M2P and M4U. These tests included an overall flow rate and individual flow rate test. The overall flow rate test was designed to examine if the parts experienced flow through each channel, and the individual flow rate test served to explore the flow rates and channel volumes of each channel individually. The chronological order of the tests was as follows: parts V1a–d, V2a–d, and V3c were printed with the M2P and underwent the overall flow rate test. Complications from the printing procedure, as well as the results of these tests, led to the desire to reprint these parts on a new printer, the M4U. In addition to this, a study comparing these printers was prompted. This study and its results were discussed in previous sections (Sections 4.2 and 5.2).

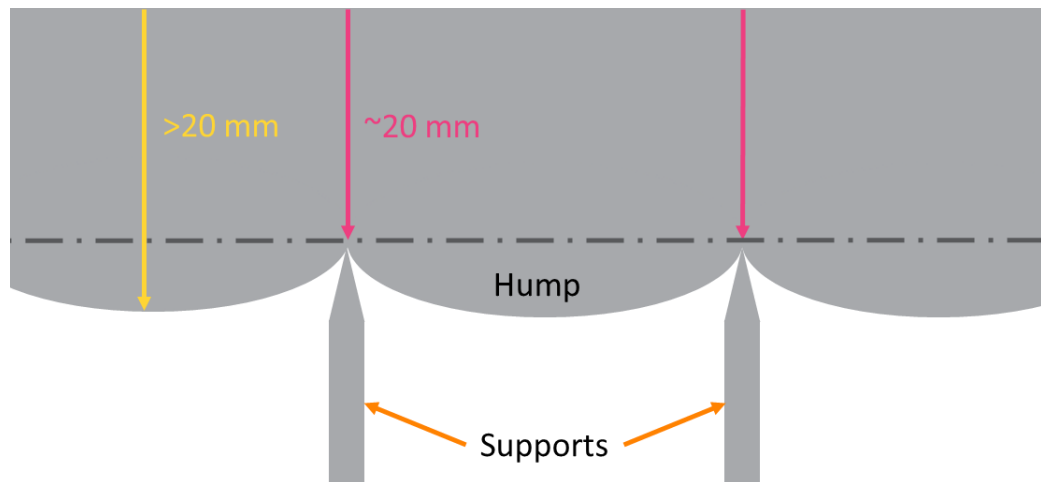


Figure 5.20 – Deformations induced by excessive gaps between supports (not to scale, dimensions continue beyond figure).

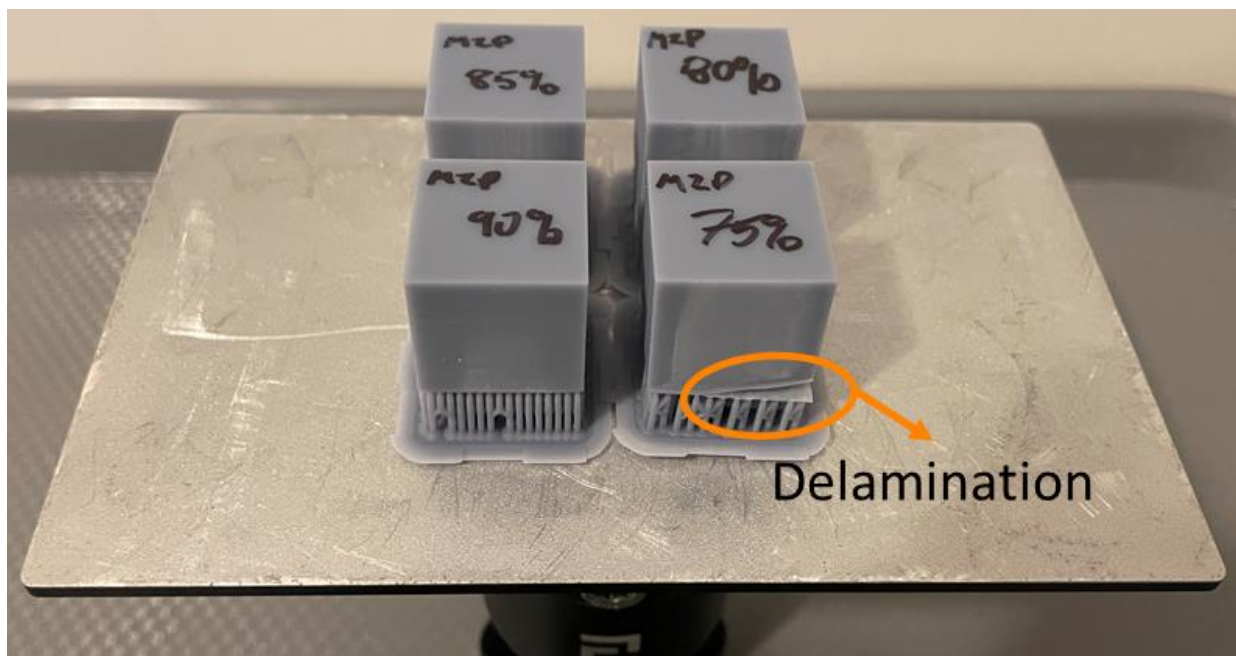


Figure 5.21 – M2P support density cube print 1.

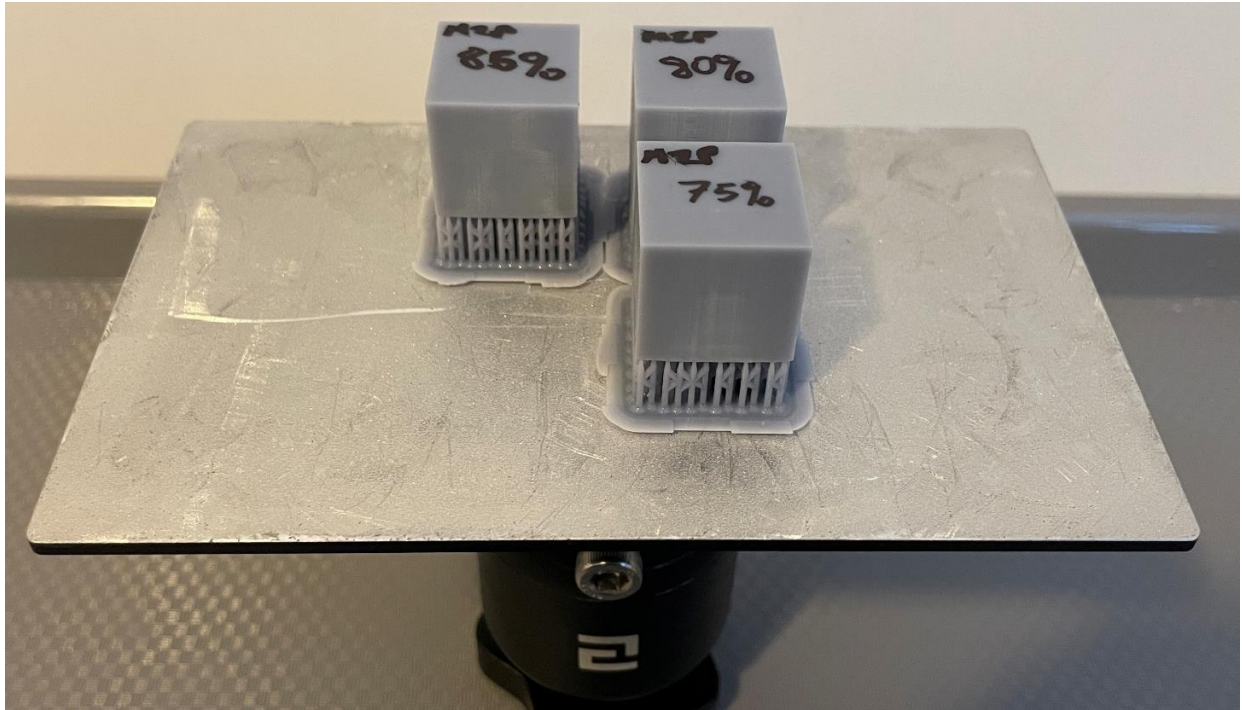


Figure 5.22 – M2P support density cube print 2.



Figure 5.23 – M4U support density cube print.

Table 5.9 – M2P Lightweight Support Density Dimensions (mm) and % Errors.

		1	2	3	AVG	STD	Error
75%	x	20.07	20.00	20.04	20.04	0.029	0.18%
	y	20.04	19.99	20.02	20.02	0.021	0.08%
	z	20.04	20.20	20.08	20.11	0.068	0.53%
80%	x	20.08	20.01	20.04	20.04	0.029	0.22%
	y	20.08	20.00	20.01	20.03	0.036	0.15%
	z	20.06	20.19	20.06	20.10	0.061	0.52%
85%	x	20.07	19.99	20.02	20.03	0.033	0.13%
	y	20.06	20.01	20.03	20.03	0.021	0.17%
	z	20.04	20.17	20.08	20.10	0.054	0.48%
90%	x	20.05	19.99	20.02	20.02	0.024	0.10%
	y	20.05	20.00	20.01	20.02	0.022	0.10%
	z	20.06	20.18	20.07	20.10	0.054	0.52%

Table 5.10 – M4U Lightweight Support Density Dimensions (mm) and % errors.

		1	2	3	AVG	STD	Error
75%	x	20.01	19.95	19.97	19.98	0.025	0.12%
	y	20.00	19.98	20.00	19.99	0.009	0.03%
	z	20.19	20.39	20.23	20.27	0.086	1.35%
80%	x	20.01	19.96	19.98	19.98	0.021	0.08%
	y	19.99	19.96	20.00	19.98	0.017	0.08%
	z	20.12	20.32	20.16	20.20	0.086	1.00%
85%	x	19.99	19.96	20.01	19.99	0.021	0.07%
	y	20.00	19.96	20.02	19.99	0.025	0.03%
	z	20.15	20.29	20.11	20.18	0.077	0.92%
90%	x	20.00	20.00	19.95	19.98	0.024	0.08%
	y	20.01	19.96	20.00	19.99	0.022	0.05%
	z	20.20	20.38	20.08	20.22	0.123	1.10%

Indicated by the results of the overall flow rate tests, parts V1b,d and V2b,d were reprinted on the M4U; furthermore, the individual flow rate tests were performed on parts V1b,d and V2b,d produced by both the M2P and M4U. These data were analyzed, and in view of the findings of the individual flow rate tests and printer accuracy tests, the M4U was chosen as the ideal printer for the final two PRM design iterations (V4d and V5d). One final round of overall flow rate tests was performed on these designs to determine if equal flow in all channels was possible with the current manufacturing method. Considering these outcomes, suggestions were made for future PRM designs.

5.3.2 Overall Flow Rate Test Results

For the overall flow rate test, the number of droplets output by each channel were tallied. Table 5.11 outlines the results of the overall flow rate test. Figures 5.24 and 5.25 show PRM parts V1a–d, V2a–d, and V3c printed by the M2P. Starting with part V1a, flow was present through channel 1. A droplet of water attempted to form through channel 2; however, it never fully developed. As channel 1 deposited water, the droplet forming in channel 2 would be pulled back into the PRM. There was no sign of flow through channels 3 and 4. Based on these observations, this part was deemed a failure and therefore the droplets were not tallied. Channels 3 and 4 appear to be more warped than channels 1 and 2, and the same can be said for the sides nearest those respective channels (Figures 5.26 and 5.27). The warped side of this part was the edge closest to the print bed, a pattern that will be present in parts that were not printed with orientations b and c. The warping of channels 3 and 4 is likely the reason they did not experience flow.

As for PRM V1b, channel 2 was the first to experience flow, followed shortly by channel 1. Not long after, channels 3 and 4 began depositing water. At this point, a five-minute period of tallying began with channel 1 depositing the most water, followed in descending order by channels 4, 2, and 3. Any deformations present in V1b appear to be consistent throughout the part, because it was printed parallel to the print bed. These deformations seem to mostly be surface level, because at this point, the parts printed with the M2P were done so with sparsely packed, heavy supports. This part was then set aside for further testing, and would be reprinted on the M4U with the new densely packed, lightweight support strategy. Part V1d first saw flow through channel 1, followed by channel 4. Eventually, channel 3 deposited water followed shortly by channel 2. Once flow was seen through all channels, tallying could commence. Channel 1 resulted in the most flow, followed by channels 2, 4, and 3. Slight warping was present on the edge of the print closest to the print bed; however, it is not as prevalent as the warping seen on V1a. In addition to this, the inlets and outlets were warped (Figures 5.28 and 5.29). The deformations of the connections were a result of them being printed parallel to the print bed with supports, rather than the connections being printed perpendicular like in part V1b. This part was set aside for further testing and would be reprinted on the M4U with the new support strategy.

Parts V2a–d experienced similar trends to PRMs V1a–d. Beginning with PRM V2a, channel 4 was the first to experience flow. Soon after, channel 3 deposited a drop of water. Eventually, water could be seen attempting to form a droplet from channel 2, but the droplet never fully formed. Like V1a, the drop would be pulled back into the part while another channel deposited water. Due to these observations, the droplets were not tallied, and the part was considered a failure. The edge nearest to channels 3 and 4 was warped identically to part V1a (Figure 5.30), however this warping did not affect V2a in the same way it did to V1a. Recall that V1a first experienced flow in the channels opposite to the warped side. The reason V1a had flow on the warped side was due to the inlet orientation. To deposit water from channels 1 and 2, the water would need to sharply turn back towards the edge of the part with the inlet (Figure 5.31) which was apparently more difficult to do than to deposit water from the warped side (Figure 5.32), since the flow path from the inlet to channels 3 and 4 had a smoother transition.

Table 5.11 – Overall Flow Test Results (M2P) (numbers of output droplets observed).

Part	Channel 1	Channel 2	Channel 3	Channel 4
V1a	N/A	N/A	N/A	N/A
V1b	10	3	2	6
V1d	12	10	3	7
V2a	N/A	N/A	N/A	N/A
V2b	2	10	6	6
V2d	11	3	3	2
V3c	1	1	14	11

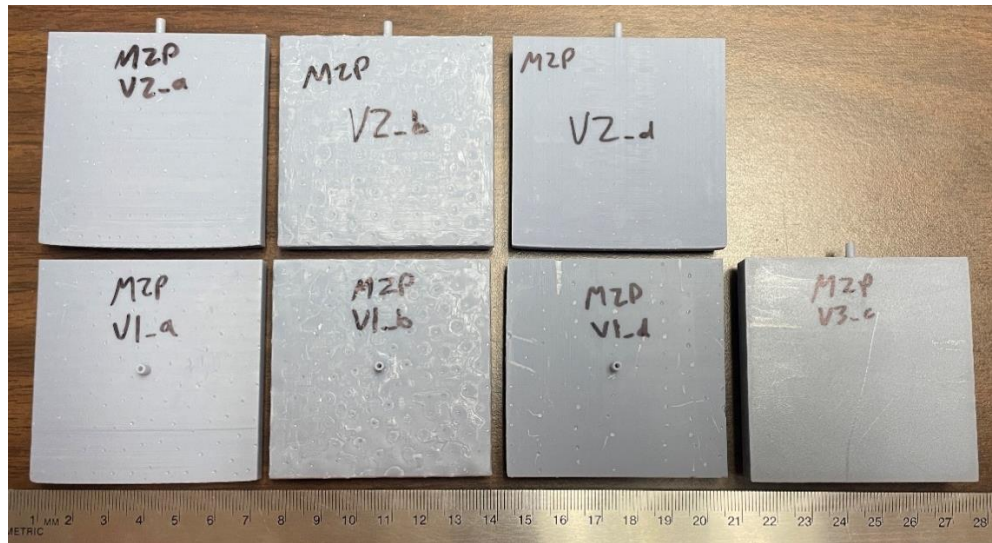


Figure 5.24 – M2P PRMs (inlet side/top).

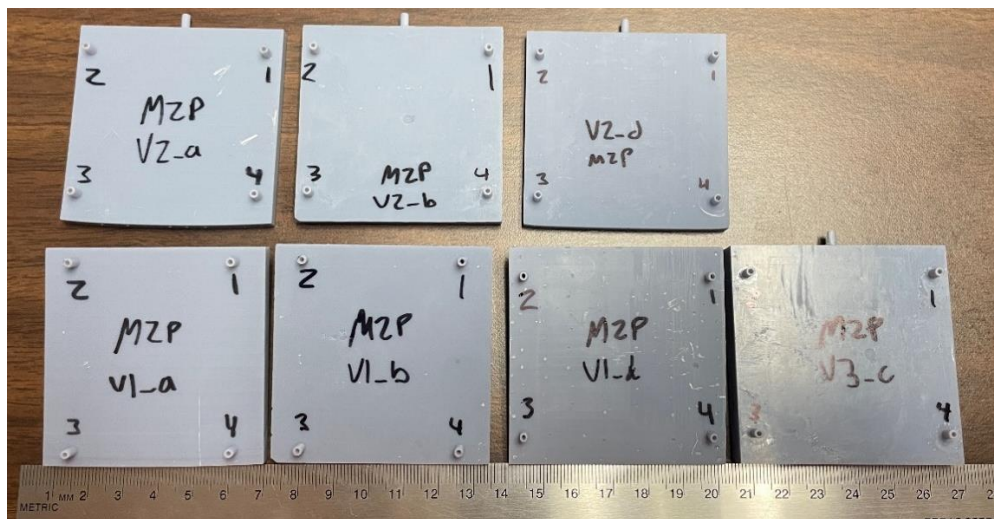


Figure 5.25 – M2P PRMs (outlet side/bottom).

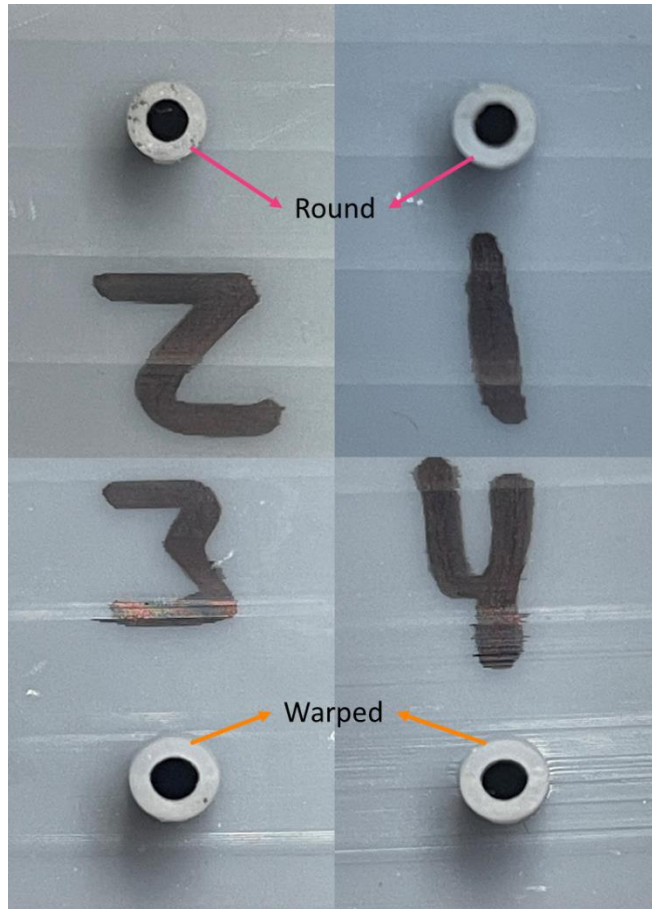


Figure 5.26 – V1a outlet warping (M2P).

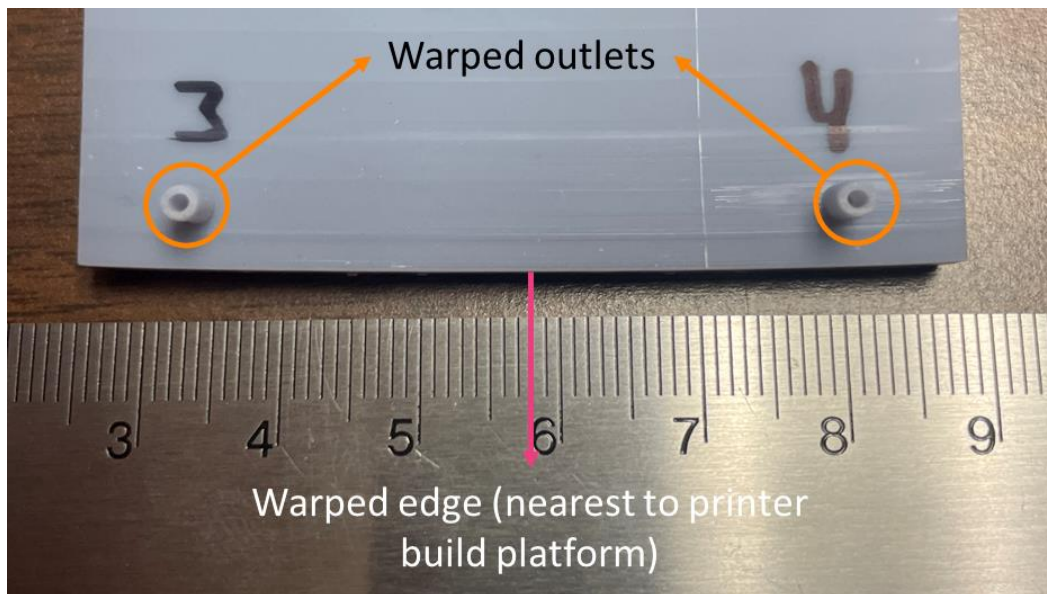


Figure 5.27 – V1a outlet and edge warping (M2P).

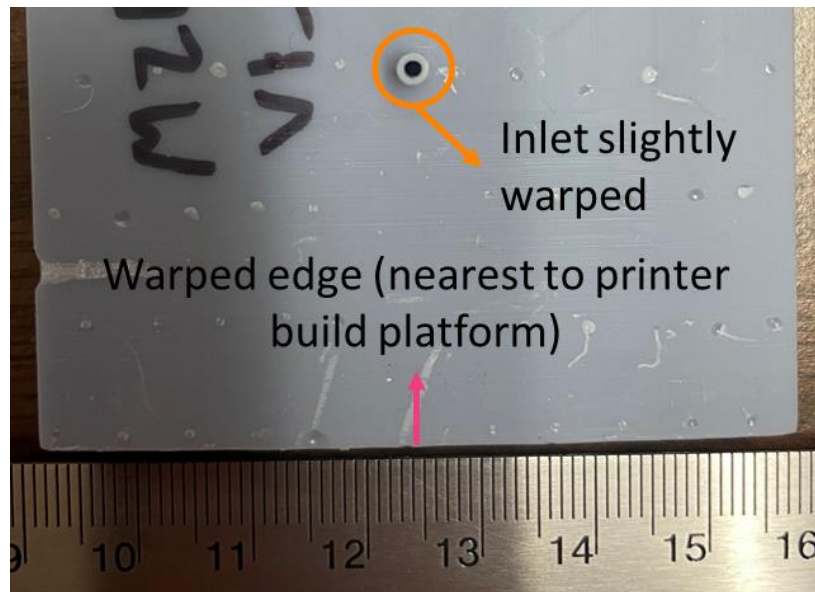


Figure 5.28 – V1d inlet and edge warping (M2P).

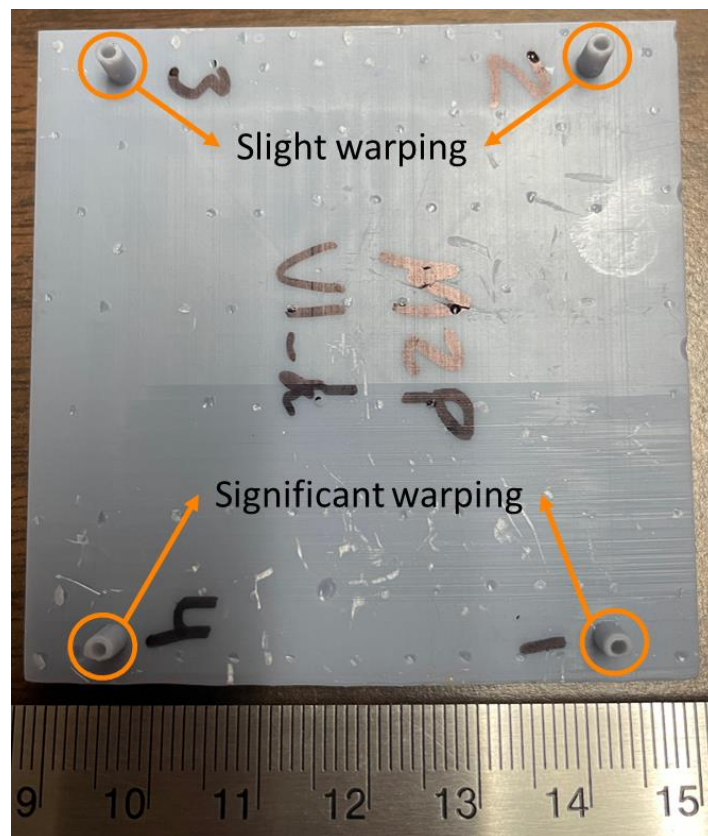


Figure 5.29 – V1d outlet warping (M2P).

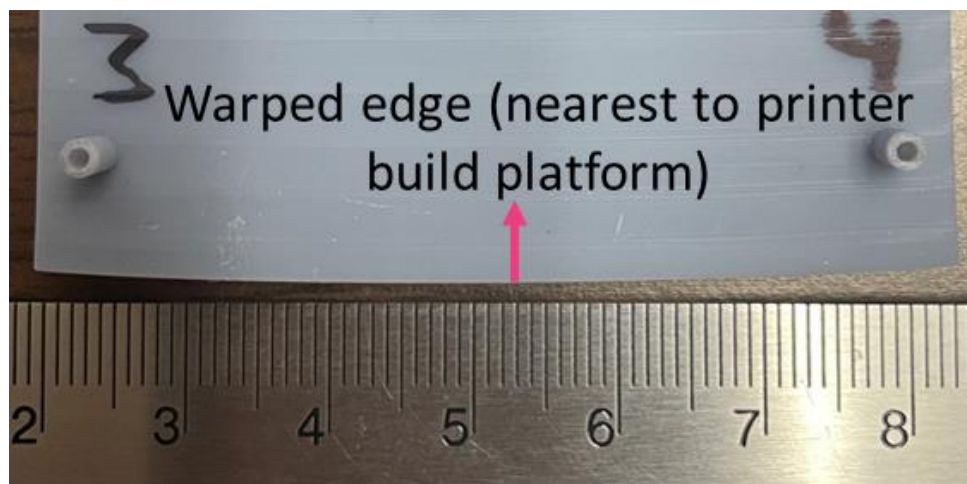


Figure 5.30 – V2a edge warping (M2P).

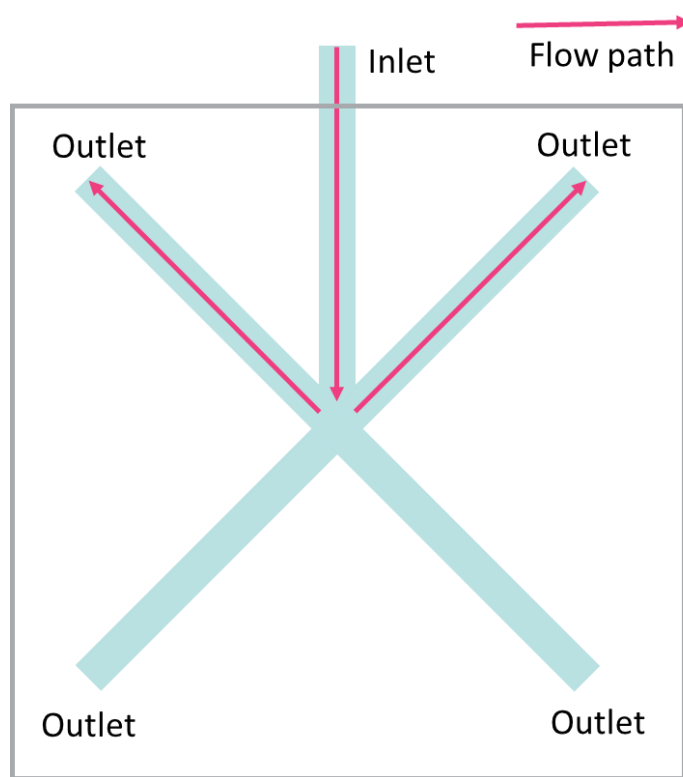


Figure 5.31 – More resistant flow path in PRMs V2.

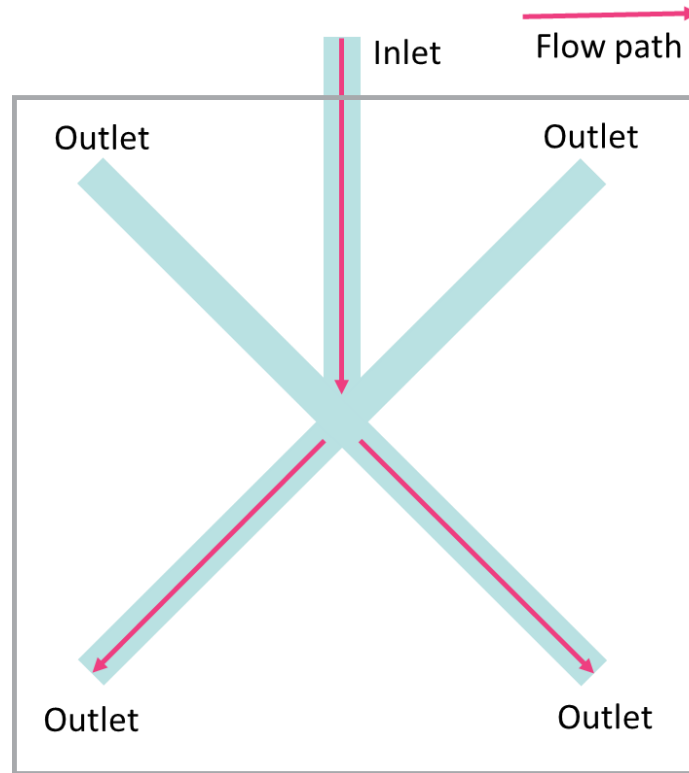


Figure 5.32 – Less resistant flow path in PRMs V2, despite warping.

Part V2b first experienced flow through channel 2, followed by channel 1 shortly after. After some time, channels 3 and 4 deposited water, respectively. Channel 2 exhibited the most flow, followed by a tie between channels 3 and 4, and the least amount of water was expelled through channel 1. Like part V2a, V2b had consistent deformations throughout the part, caused by the non-ideal support strategy. Part V2b was then set aside for further testing and would be reprinted on the M4U with the new support method. Channel 1 of part V2d was the first to have flow, followed shortly by channel 2. Droplets alternated between these channels before any were present in channels 3 and 4. Eventually, channel 4 produced droplets, followed by channel 3. This part had nearly identical deformations to part V1d; the edge closest to the print bed was partially warped (Figure 5.33) and the outlets were slightly deformed (Figure 5.34). The main difference between the defects of parts V1d and V2d was the inlet. The inlet on V2d was not deformed on account of it being printed perpendicular to the print bed. The numbers of droplets through each channel were tallied; channel 1 expelled the most water, followed by a tie between channels 2 and 3, and channel 4 expelled the least. Part V2b was then set aside for further testing and reprinted on the M4U with the new support strategy.

The final part printed by the M2P to be tested this way was V3c. Channel 3 was the first to have flow, followed shortly by channel 4. After some time, water dropped from both channels 1 and 2. The only deformations present in V3c were a slight elephant's foot on the surface that was adhered to the print bed, and a warped inlet (Figure 5.35). Once again, the warping of the inlet is a result of the inlet being printed parallel to the print bed. Since flow could be seen through all channels, the part could be tallied. Channel 3 resulted in the most flow, followed by channel 4, and a tie between channels 1 and 2. Channels 1 and 2, however, only produced one droplet of water each near the end of the five-minute test. Based on the large discrepancy between outlet pairs, V3c was deemed unfit for further testing.

Considering these findings, the samples chosen for continued testing and reprinting on the M4U included parts V1b,d and V2b,d. For the sake of achieving flow through multiple channels, printing these designs at a 45° angle is not ideal. Printing these parts perpendicular and parallel to the bed results in more uniform cross sections, which is reinforced by the fact that orientations b and d tended to be much less deformed than those printed with orientation a. As for orientation c, part V3c appears to have been slightly pressed flat by the printing process, which is reflected through the shape of the deformed inlet. This slight flattening is reinforced by the results of Section 5.2.2, because the cubes that were printed flat on the bed had a smaller Z-dimension than the theoretical cube size. These deformations in orientations a and c adversely affected the flow within the parts, and thus the remainder of PRMs should be printed elevated from the bed with densely packed, lightweight supports at orientations b and d.

5.3.3 Individual Flow Rate Test Results

Once parts V1b,d and V2b,d were reprinted on the M4U (Figures 5.36 and 5.37), further analysis of the channel flow rates and internal dimensions could be performed. This round of testing was also performed on parts V1b,d and V2b,d printed from the M2P. Three out of the four outlets were closed with valves and water was pumped for roughly two minutes. The mass of the collected water was measured, and the mass/volume flow rates were calculated. The same channel was then primed with water, the pump was disconnected from the reservoir, and the water was pumped out. The mass of the water collected was measured, which provided an approximate internal channel volume of the PRM. These processes were repeated five times per channel, and the averages and standard deviations of the results are outlined in Tables 5.12–19. These data were compared, and a decision was made on which part had the ideal design (primarily with respect to the inlet location) and print orientation.

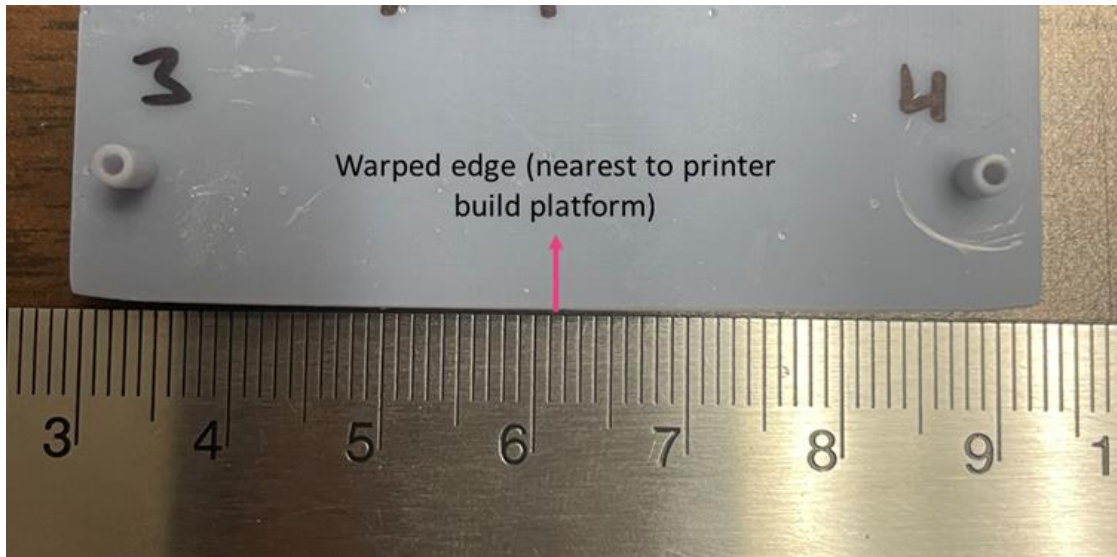


Figure 5.33 – V2d edge warping (M2P).

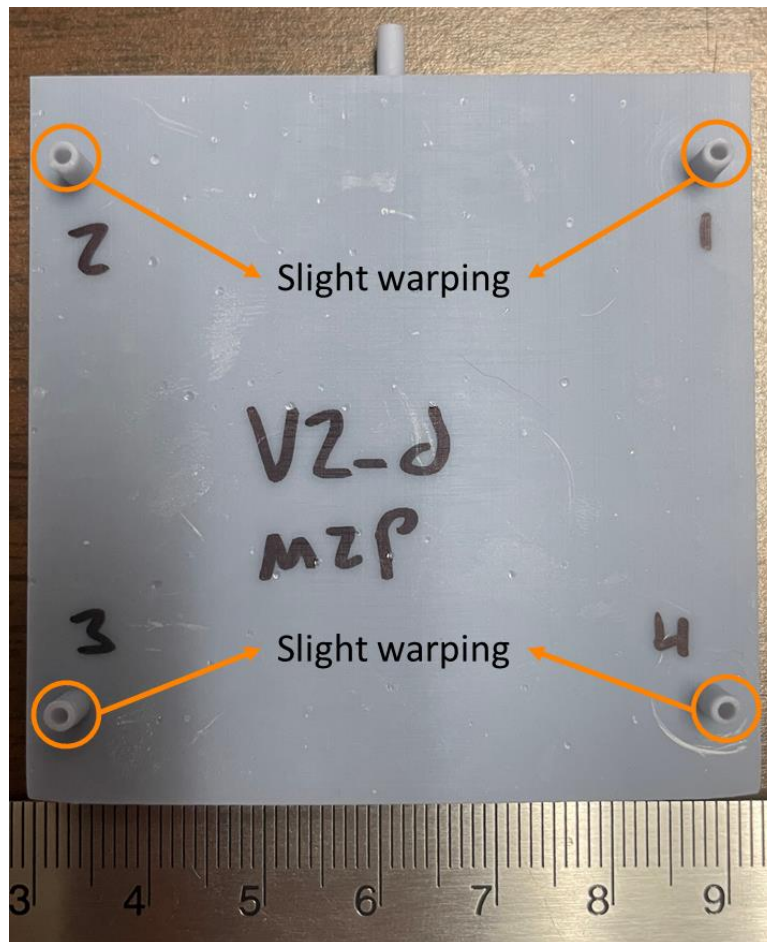


Figure 5.34 – V2d outlet warping (M2P).

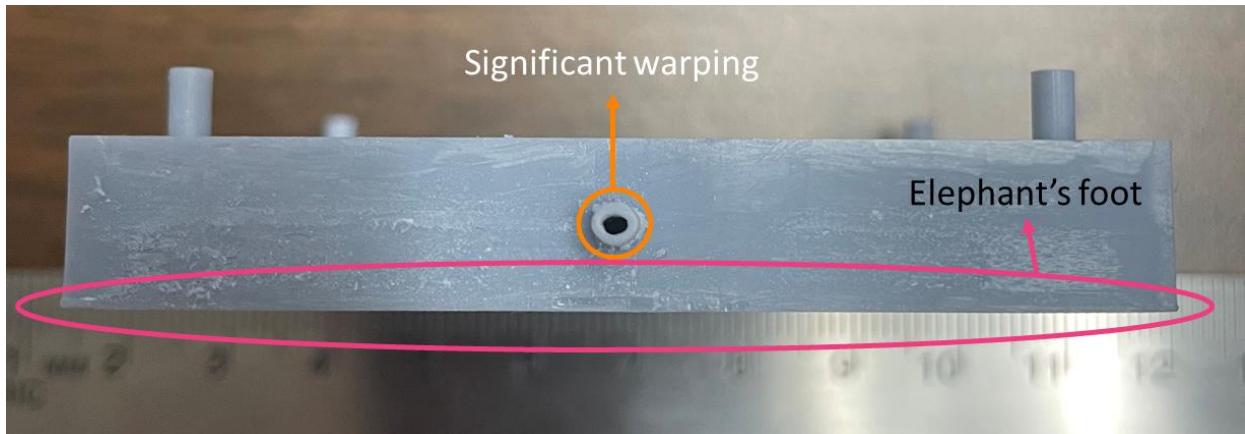


Figure 5.35 – V3c inlet warping and elephant's foot (M2P).

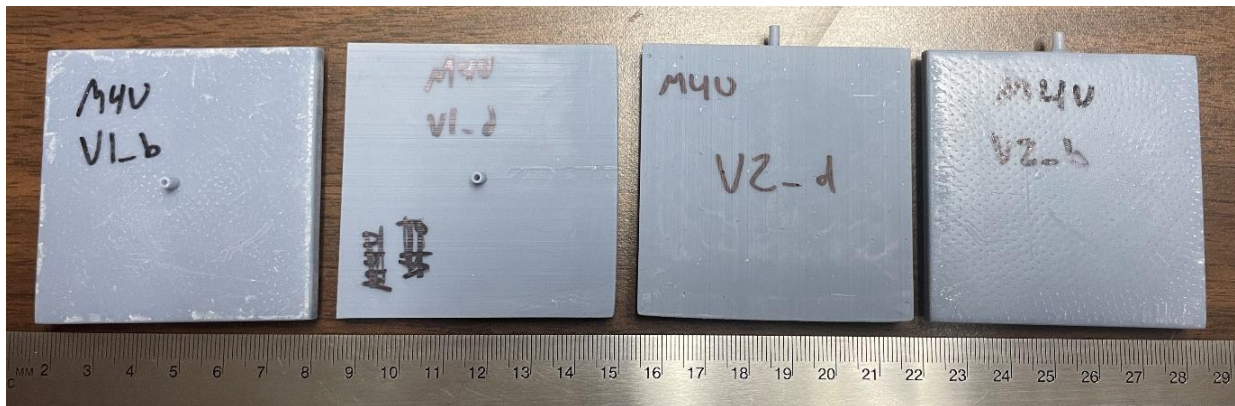


Figure 5.36 – M4U PRMs (inlet side/top).

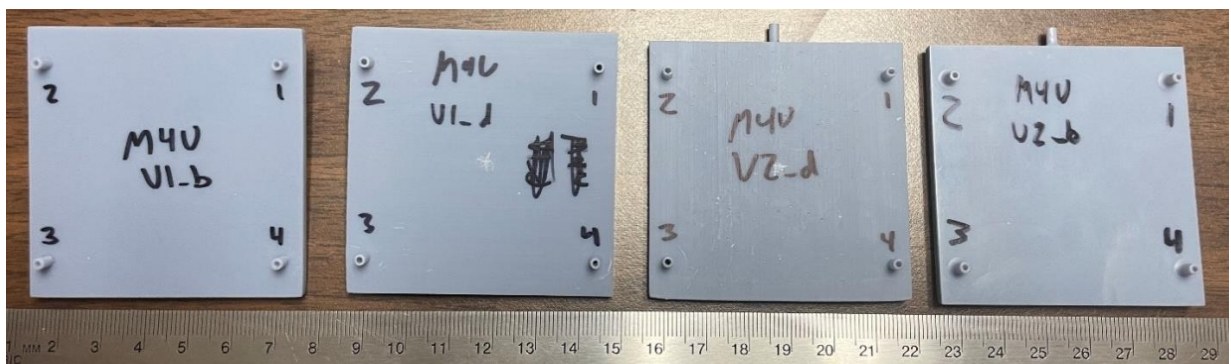


Figure 5.37 – M4U PRMs (outlet side/bottom).

Table 5.12 – Individual flow rate test results for M2P V1b.

Channel	Mass Pumped (g)	Pump Time (s)	Volume in Line (mL)	Mass Flow Rate (g/s)	Volume Flow Rate (mL/min)
1	0.8324	120	0.06720	0.006922	0.4153
2	0.8427	120	0.06750	0.007006	0.4204
3	0.8392	120	0.06934	0.006982	0.4189
4	0.8947	120	0.07048	0.007439	0.4463
Std	0.02479	N/A	0.001347	0.0002054	0.01232

Table 5.13 – Individual flow rate test results for M2P V1d.

Channel	Mass Pumped (g)	Pump Time (s)	Volume in Line (mL)	Mass Flow Rate (g/s)	Volume Flow Rate (mL/min)
1	0.8982	120	0.07308	0.007465	0.4479
2	0.8992	120	0.06774	0.007474	0.4484
3	0.9014	120	0.07164	0.007484	0.4491
4	0.89962	120	0.07656	0.007479	0.4488
Std	0.001158	N/A	0.003161	0.000007098	0.0004259

Table 5.14 – Individual flow rate test results for M2P V2b.

Channel	Mass Pumped (g)	Pump Time (s)	Volume in Line (mL)	Mass Flow Rate (g/s)	Volume Flow Rate (mL/min)
1	0.8712	120	0.09708	0.007248	0.4349
2	0.8789	120	0.1006	0.007307	0.4384
3	0.8775	120	0.1028	0.007302	0.4381
4	0.8735	120	0.1022	0.007265	0.4359
Std	0.003108	N/A	0.002223	0.00002482	0.001489

Table 5.15 – Individual flow rate test results for M2P V2d.

Channel	Mass Pumped (g)	Pump Time (s)	Volume in Line (mL)	Mass Flow Rate (g/s)	Volume Flow Rate (mL/min)
1	0.8928	120	0.1282	0.007420	0.4452
2	0.9000	120	0.1276	0.007487	0.4492
3	0.8191	120	0.1290	0.006805	0.4083
4	0.8298	120	0.1324	0.006890	0.4134
Std	0.036277	N/A	0.001868	0.0003052	0.01831

Table 5.16 – Individual flow rate test results for M4U V1b.

Channel	Mass Pumped (g)	Pump Time (s)	Volume in Line (mL)	Mass Flow Rate (g/s)	Volume Flow Rate (mL/min)
1	0.8707	120	0.07188	0.007235	0.4341
2	0.8682	120	0.07090	0.007213	0.4328
3	0.9103	121	0.06914	0.007549	0.4530
4	0.8942	121	0.07232	0.007421	0.4452
Std	0.01740	N/A	0.001222	0.0001385	0.008308

Table 5.17 – Individual flow rate test results for M4U V1d.

Channel	Mass Pumped (g)	Pump Time (s)	Volume in Line (mL)	Mass Flow Rate (g/s)	Volume Flow Rate (mL/min)
1	0.8992	121	0.07080	0.007453	0.4472
2	0.8993	121	0.07318	0.007440	0.4464
3	0.9021	121	0.07890	0.007468	0.4481
4	0.8943	120	0.07150	0.007435	0.4461
Std	0.002806	N/A	0.003183	0.00001278	0.0007667

Table 5.18 – Individual flow rate test results for M4U V2b.

Channel	Mass Pumped (g)	Pump Time (s)	Volume in Line (mL)	Mass Flow Rate (g/s)	Volume Flow Rate (mL/min)
1	0.8969	120	0.1029	0.007448	0.4469
2	0.8979	120	0.1050	0.007466	0.4480
3	0.8938	120	0.1082	0.007423	0.4454
4	0.9006	122	0.1068	0.007376	0.4426
Std	0.002439	N/A	0.001988	0.00003372	0.002023

Table 5.19 – Individual flow rate test results for M4U V2d.

Channel	Mass Pumped (g)	Pump Time (s)	Volume in Line (mL)	Mass Flow Rate (g/s)	Volume Flow Rate (mL/min)
1	0.8020	121	0.1239	0.006656	0.3993
2	0.8265	121	0.1288	0.006851	0.4110
3	0.8146	121	0.1262	0.006722	0.4033
4	0.8056	121	0.1237	0.006685	0.4011
Std	0.009454	N/A	0.002063	0.00007439	0.004464

The parts printed on both the M2P and M4U exhibited the same trend for the mass/volume flow rates. Part V1b had higher standard deviations than part V1d, and part V2b had lower standard deviations than part V2d. In other words, part V1d had more consistent flow between channels than V1b, and part V2b had more consistent flow between channels than V2d. As for the actual channel volumes, both printers showed that V1b had a lower standard deviation than V1d. This means that the channels of part V1b were more uniform than those of V1d. As for parts V2b and V2d, the M2P showed that V2b had a higher standard deviation of channel volume than V2d. The opposite was true on parts V2b,d printed with the M4U; V2b had a lower standard deviation of channel volume than V2d. It was expected that lower values of the standard deviation of channel volume would correspond to lower standard deviations between the channel flow rates. To put it more simply, more uniform channel volumes should have led to more equivalent channel flow rates; this correlation was only present in parts V2b,d printed with the M4U. Two factors may have contributed to this discrepancy, the first being human error. Upon disconnecting the pump from the reservoir, water remained in the pump lines. This extra water needed to be pumped out to achieve the same water level before each test. It was difficult to achieve this, and so the meniscus had slight deviations in starting positions (Figure 5.38). The second factor was a result of deformations in the inlets/outlets. In both cases, because such small volumes of water are being analyzed, any slight error induced by the water not starting at the same level and the inlet deformations have a greater effect on the results.

Regardless of this discrepancy, there is still clearly an ideal part design. From both the M2P and M4U, parts V1d and V2b provided the best results when compared to their counterparts. When compared to one another, however, V1d had a lower standard deviation of flow rates when manufactured from both printers. This means that further iterations of the design should: 1) consist of an inlet on the top surface of the part; 2) be printed at orientation d. Further iterations are required to determine if it is possible to achieve equivalent flow between each outlet simultaneously.

5.3.4 Final PRM Iterations and Conclusions

Two new part designs, V4d and V5d, were iterated to potentially achieve equivalent flow between each outlet simultaneously (Figures 5.39 and 5.40). From the results of the previous tests, these parts were designed to have an inlet on the top surfaces and were printed on the M4U at orientation d. The internal geometries of the channels, however, were altered. Part V4d was designed with smaller channel diameters than the previous parts. When cleaning the samples and flushing the internal channels with IPA, it was found that higher pressures resulted in the IPA flowing through all four channels simultaneously. So, by decreasing the channel diameters, the internal pressures should theoretically increase and potentially demonstrate equivalent flow through all channels. Part V5d, on the other hand, was designed to divide the flow at the inlet such that each channel was now separated. Both parts were subjected to one final overall flow rate test to determine if either iteration could distribute water simultaneously through each channel, and final conclusions regarding these results were made.

The results of the final flow test are outlined in Table 5.20. V4d first experienced flow through channel 4, followed by channel 3, then channels 2 and 1. Channel 4 produced the most droplets, followed by channels 3, 1, and 2 respectively. Despite the initial hypothesis, V4d did not exhibit equivalent flow through all four channels. Since the channel dimensions are so small, even the slightest deformations induced by the printing process result in non-ideal results. Part V5d was the closest iteration to achieve the goal of equivalent flow. Channels 3 and 4 were the first to experience flow, and droplets of water consistently alternated between them. The next channels to exhibit flow were channels 1 and 2, however these behaved similarly to the other parts tested in this way.

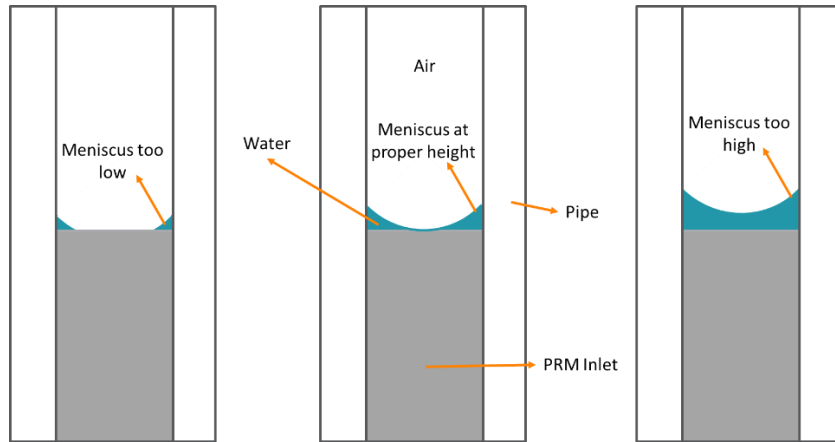


Figure 5.38 – Deviation of inlet meniscus locations.

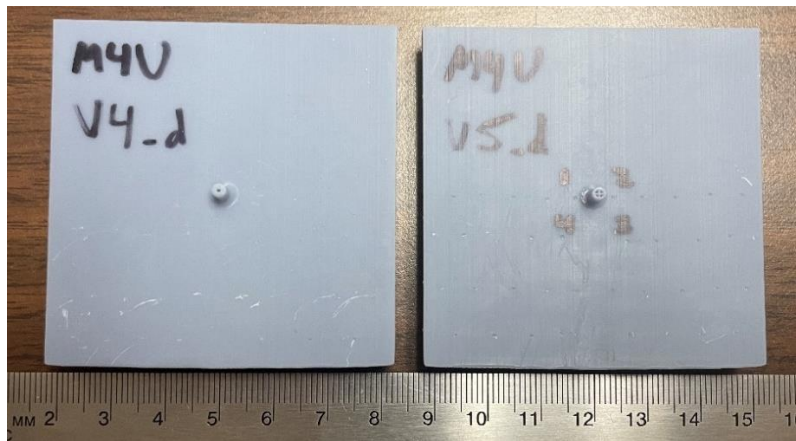


Figure 5.39 – M4U PRM V4d and V5d (inlet side/top).

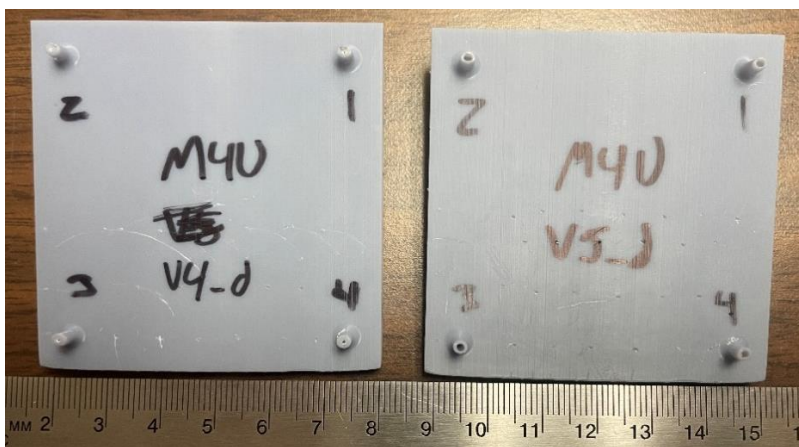


Figure 5.40 – M4U PRM V4d and V5d (outlet side/bottom).

Table 5.20 – Overall flow test results for PRMs V4d and V5d (M4U) (numbers of output droplets observed).

Part	1	2	3	4
V4d	6	3	35	20
V5d	8	5	27	28

Channel 3 deposited the most water, followed closely by channel 4 (only one droplet difference); whereas the least amount of water was dropped from channels 1 and 2. This discrepancy is likely due to the deformation of outlets 1 and 2 (Figure 5.41), induced by them being printed parallel to the print bed.

In lieu of these results, the current methods of producing manifolds at these geometries with commercially available MSLA 3D printers does not seem possible to achieve the desired flow characteristics. At these small channel dimensions, the slightest deformations cause large discrepancies in the flow, which leads to an unequal amount of water being deposited through each channel. It should also be noted that the actual propellant will not be water, and that these results have not been corroborated for the IL, which will likely have different surface contact and flow properties. However, for water, three potential solutions may be employed to achieve the desired flow characteristics with the current manifold design. First, a higher flow rate could be employed. The current design uses a peristaltic pump designed for extremely low flow rates, up to 0.45 mL/min. Increasing the flow rate with the use of a different pump could induce flow through each channel. This is because when flushing the pump channels with IPA, if the syringe's plunger was depressed harder, the IPA would flow through each channel. The second solution that may be considered is printing the manifolds with more accurate, industrial grade printers that offer higher resolutions and lower part deformations. The third solution would be to redesign the manifold and employ a different manufacturing method. In a biological study performed by the NASA Ames Research Center, a multilayered microfluidic was flown in space. This microfluidic was manufactured from polycarbonate and 3M 9495LE pressure sensitive adhesive (Figure 5.42), which were precisely machined with a CO₂ laser [69]. This method would result in uniform channel geometries, and potentially lead to the desired flow properties required for fueling μ STAMPS. Alternatively, if none of these methods result in equivalent flow through each channel, the thrusters can simply be fueled individually one at a time with the use of microvalves.

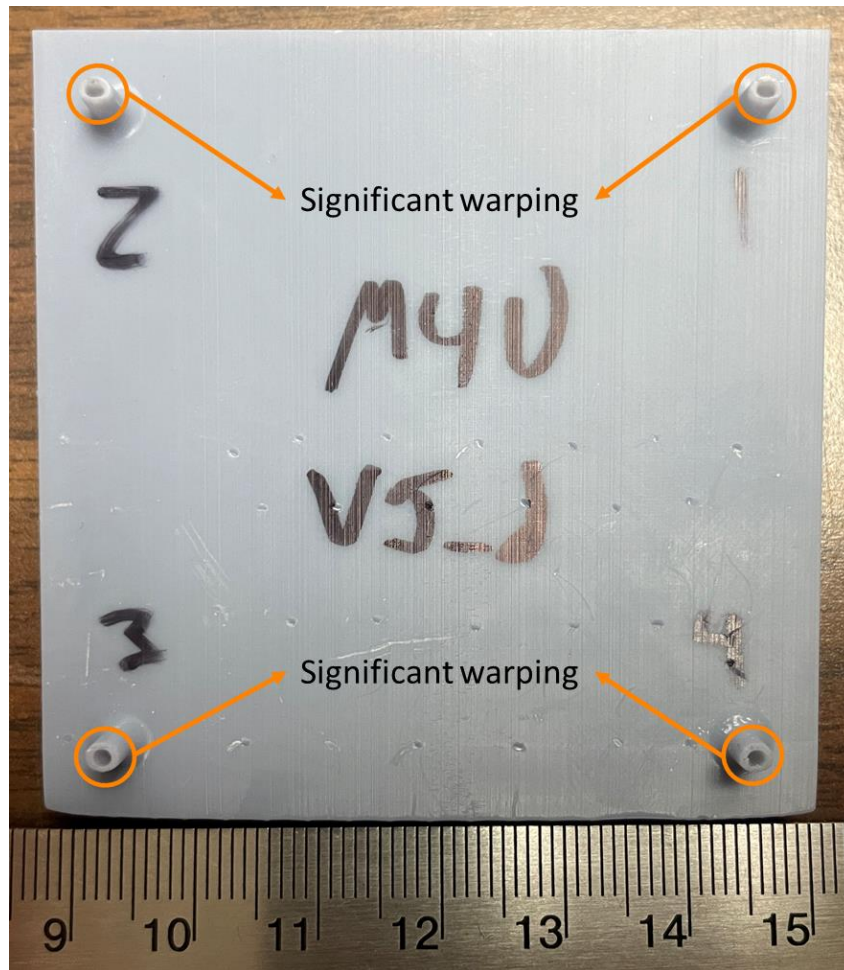


Figure 5.41 – V5d outlet warping (M4U).

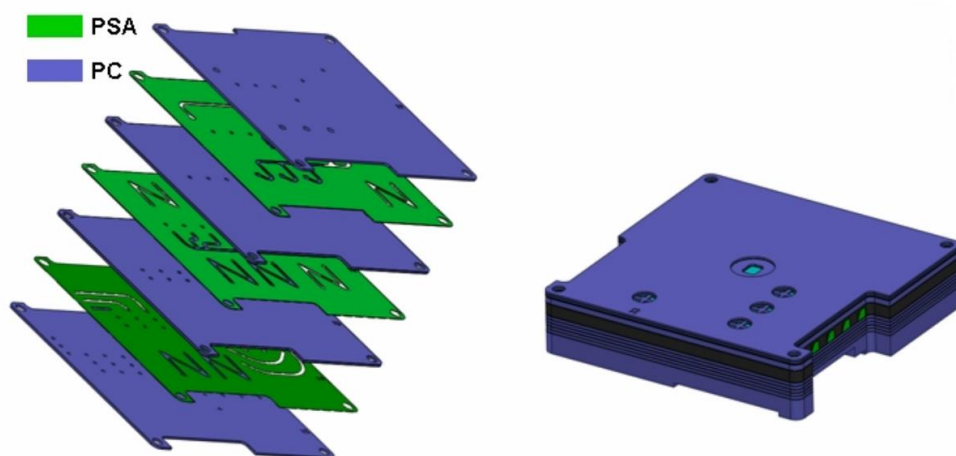


Figure 5.42 – Multi-layered microfluidic design [69].

Chapter 6: Conclusions and Future Work

CubeSats are an extremely promising new spacecraft technology that can serve a wide range of scientific, commercial, and defensive applications. Most CubeSats that have been deployed lack propulsion systems. By equipping these technologies with propulsion systems, the range of potential applications are significantly increased, spanning deorbiting, station keeping, collision avoidance, orbital transfers, and missions to other celestial bodies within the solar system. The μ STAMPS electrospray system serves to address this problem by adding another thruster option to the marketplace. To ensure the success of μ STAMPS, and to increase its own mission capabilities, a propellant storage system capable of storing at least 100 g of IL BMP-DCA (or another appropriate) propellant is required. The original goal of this project was to develop a complete and functional non-pressurized prototype propellant feed system; however, as problems arose and prototypes failed, the scope of the project narrowed. The new goal of the research presented here strives to establish a foundation for the future design of a propellant storage and feed system. This was done by exploring a conceptual FEP bladder tank system and studying the behavior of several MSLA 3D printed propellant routing manifolds. Additional research included seal strength tests (ASTM F88) on varying thicknesses of FEP films and performing a study comparing the differences between two commercially available MSLA 3D printers: Elegoo's Mars 2 Pro and Mars 4 Ultra. The lessons learned from these experiments should be taken into consideration, and suggestions were made to ensure the future success of this system.

The ASTM F88 seal strength tests served to evaluate the strength of the tank's seal at different tank thicknesses. The fins of the samples consisted of single- and double-layered fins; the single-layered seals had thicknesses of 3 mil and 5 mil, whereas the double-layered fins had thicknesses of 3 mil/3 mil (6 mil), 3 mil/5 mil (8 mil), and 5 mil/5 mil (10 mil). The single-layered fin samples experienced material breakage at the seal edge. The double-layered fin samples experienced a combination of two failure modes: the side of the seal directly exposed to the heating element of the sealer experienced material breakage at the seal edge, and the opposite side experienced an adhesive peel failure. The results of this test showed that a FEP bladder tank should have walls made from a double layer of 5 mil thick FEP, in other words have an effective tank thickness of 10 mil. Several challenges were present during the sample preparation and testing procedure. First, the samples needed to be cut perfectly; next, multiple stamps from the sealer were required to obtain a proper seal. Once sealed, the samples were difficult to remove from the sealer without damaging the seal/fins. Finally, the samples were difficult to perfectly align in the grips. The main limitation from these tests came from the load cell of the test machine. The tester was meant for thick, high-strength parts, so as a result the data was noisy and required a smoothing function to extract decent numbers. As a result, the standard deviations were higher than desired, however the data still provided good insight on the performance of these seals.

Once the ASTM F88 tests concluded, a prototype bladder tank could be manufactured. Once the flange was installed and the circumference was sealed, the tank was inflated with air. Upon inflation, the seal ruptured in multiple locations, and thus the prototype was a failure. Creases formed along the circumference of the tank, which caused the seals to bend and break before pressurization testing could commence. The primary challenge associated with the design was the sealing method: the impulse sealer could only seal straight lines. One solution would be to fabricate a circular mold to seal the edges of a bladder tank in a heated press. This would allow fine control over the temperature and pressure, resulting in a near-perfect and more consistent seal every time. It was obvious, however, that even if the tank had a perfectly rounded seal, it would still form creases along the circumference that could rupture the seal. The stiffness of the FEP seal was too great to retain its integrity, and thus a new tank design should be considered. In the sake of time and the need for more data, the research pivoted into manufacturing the manifolds.

Three rounds of 3D print tests were performed to analyze and compare the performance of Elegoo's M2P and M4U MSLA 3D printers. These included printing 20 cm³ cubes flat on the print bed, elevated off of the print bed with sparsely packed, heavyweight supports, and elevated off of the print bed with densely packed, lightweight supports. The flat-on-bed test showed that the M4U was more dimensionally accurate than the M2P. The least accurate dimension produced by both printers was in Z. The actual Z-dimensions were shorter than the theoretical Z-dimension on average when printed on both the M2P and M4U. As for the sparsely packed, heavy support test, all cubes printed successfully on the M4U, but no cubes printed successfully on the M2P. Five M2P cubes fully delaminated from the supports during the print, and three partially delaminated; the partially delaminated cubes were severely deformed. The peel forces off of the vat of the M4U is much lower than that of the M2P, and thus results in a higher print success rate. As for the surviving cubes, the X- and Y-dimensions were accurate, but the Z-dimensions were not. This time, the actual Z-dimensions of the cubes were greater than the theoretical dimensions, and the surfaces connected to the supports were severely deformed. This support strategy led to the development of humps between supports, which led to the desire to print these parts with more densely packed, lightweight supports. Four cubes with varying support densities (75%, 80%, 85%, and 90%) were printed on both the M2P and M4U. Once again, all cubes printed successfully on the M4U; however, two print attempts were required to obtain four complete cubes from the M2P. This print method resulted in the most accurate X-, Y-, and Z-dimensions compared to previous tests on both the M2P and M4U, with the 85% support density being the most accurate. The M4U was chosen to print the final PRM iterations due to its superior print accuracy and success rate with an 80% support density. A support density of 85% was not chosen because it was significantly more difficult to remove the supports without damaging the parts compared to 80%.

Several PRMs were designed and printed, and three rounds of testing commenced to determine the ideal design for achieving equivalent flow between each channel. Beginning with an overall flow test, a test where the number of water droplets produced by each channel outlet were tallied, was performed on parts V1a-d, V2a-d, and V3c printed from the M2P. None of these parts were capable of delivering an equal amount of flow between each outlet. The only parts that produced an adequate amount of flow through all four channels were V1b, V1d, V2b, and V2d. These parts underwent further testing and were reprinted on the M4U. The next round of testing was an individual flow rate test, where the flow rates of each channel were measured individually. Part V1d exhibited the most equivalent flow rate between each channel. New parts, V4d and V5d, were then designed based on V1 (inlet on the top surface of the PRM) and printed at orientation d (part perpendicular to the print bed) on the M4U. These iterations consisted of new internal channel geometries which would hopefully evenly distribute flow between each channel. One final overall flow test was performed on these parts; however, neither design was able to achieve the desired flow properties. It seems that at this scale, the slightest deformations within the channels adversely affect the flow, so MSLA 3D printing may not be a sufficient manufacturing method for the PRMs.

These results serve as a starting point in the development of a functional propellant storage and feed system for μ STAMPS. Despite the components that were developed and tested not functioning as intended, some suggestions can be made for future work on this system. First, the tank design should be reevaluated. The first proposed solution was to manufacture the bladder from a different material, such as Teflon® PTFE. If FEP is still the desired material of choice, then a vacuum-formed, hemispherical diaphragm tank is the better option. This will either need to be custom-made, or ordered from a vendor specializing in FEP diaphragms. The design work would then revolve around a leak-proof shell for the diaphragm. The final suggestion for a tank would be to design a piston tank system to deliver the propellant. These suggestions are discussed in greater detail in Section 5.2.1. As for the propellant routing manifolds, to achieve the desired flow characteristics, more-accurate and higher-tolerance printing methods may be employed, such as SLA 3D printing. Industrial grade printers may also be considered for this task. Another, likely cheaper,

option would be to find a pump capable of delivering a higher flow rate. The cheapest option would be to design a multi-layered manifold/microfluidic, where the channels are precisely laser cut in layers. If the desired flow simply is not possible even after these potential changes are explored, then fueling each thruster individually is a viable, and certainly the simplest, option.

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Vita

Tyler Matthew Sundstrom was born on March 14th, 2000, in Nashville, Tennessee. He attended the University of Tennessee in Knoxville, Tennessee and completed his undergraduate degree in Aerospace Engineering in 2022. During his time there, he was introduced to high-power rocketry and spent much of his time designing, building, and flying rockets outside of class for NASA's University Student Launch Initiative (2018-2020) and Tripoli's Argonia Cup (2020-2022). From 2020-2022, he worked as an Undergraduate Research Assistant at the Fibers and Composites Manufacturing Facility (FCMF), which introduced him to the world of research and Academia. In his final year, he met Dr. Trevor Moeller and Dr. Lino Costa to work on a project involving the μ STAMPS system, and they graciously accepted him into the University of Tennessee Space Institute (UTSI) family. In the fall of 2022, he was admitted into UTSI to earn a Master of Science in Aerospace Engineering working as a Graduate Research Assistant for Dr. Trevor Moeller, Dr. Lino Costa, and Dr. Brian Canfield.