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A Student-Led, Virtually-Developed Suborbital Payload: Investigating the Structure of Polyurethane Foam in Microgravity

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Abstract

The global COVID-19 pandemic impacted student science-led initiatives globally, forcing them to either cancel, postpone, or re-imagine their efforts in order to serve and inspire students. One such initiative, Shad Canada, a month-long summer STEAM and Entrepreneurship program for Canadian high school youth, that challenges its participants to create novel solutions to grand global and human challenges. In typical years, participants congregate physically in campuses to work in teams to devise solutions to societal problems. In the era of COVID-19, Shad went virtual. The program devised a novel challenge for their 2020 cohort: to design a microgravity payload for suborbital flight that leverages space and microgravity in a meaningful and creative way with impacts for science, research and humanity - all while collaborating online. Shad partnered with Luna Design and Innovation to create Canada's first fully remote commercial space flight competition, offering one winning team 3-minutes of microgravity to test their research aboard Blue Origin's New Shepard reusable suborbital vehicle. Working with industry, academic partners, Canadian Space Agency engineers, and other mentors and experts, sixty-two teams of over 600 students took on the challenge, proving their ability to adapt, innovate, and come together under one common goal. A judging panel of Shad representatives and industry experts evaluated the final projects based on their impact, scientific merit, technical feasibility and project plan. Mous4Inc. was ultimately selected as the winner of the Shad 2020 Design Challenge, developing a project that investigates the formation and structure of polyurethane foam in microgravity. This diverse team of ten students from across the country continue to work with mentors to develop a spaceborne polyurethane foam, with potential terrestrial applications. In the end, having strong communication, teamwork, and a central goal of connecting their ideas and interests was able to help Mous4Inc. design this winning project. This presentation centers around the student team's experience with virtual suborbital payload development, believed to be the first student-led virtually-developed suborbital payload in Canada. This work will highlight both the novel virtual distributed payload development and building process, the value of such virtual payload development programs for other secondary students, lessons learned, and Mous4Inc.'s next steps with respect to launch, post-flight testing, publication and outreach.

Keywords: Microgravity, suborbital flight, payload, polyurethane foam, student-led, STEM

Acronyms/Abbreviations
A - Ampere
AC - Alternating Current
CAD - Computer-Aided Design
cm - centimeter
COTS - Commercial Off The Shelf
COVID-19 - SARS-CoV2 Novel Coronavirus
DC - Direct Current
ESA - European Space Agency
ISS - International Space Station
kg - kilogram
LED - Light-emitting Diode
NASA - National Aeronautics and Space Agency
PoSSUM - Polar Suborbital Science of the Upper Mesosphere
PDR - Payload Design Review
PI - Primary Investigator
PPE - Personal Protective Equipment
PDR - Payload Design and Review
R&D - Research and Development
STEAM - Science, Technology, Engineering, Art & Math

TEDP - Test Equipment Data Package
V - Volt
W - Watt

1. Background

The unexpected onset of the COVID-19 pandemic has changed the way we work. Payload design, construction and integration is no different. In typical years, payload conception, design, prototyping, assembly, testing and iteration would be done in person. However, COVID-19 has restricted that in-person interaction, making the process far more challenging. In the 39 years leading up to the COVID-19 situation, Shad Canada carried out in-person STEAM and Entrepreneurship summer programs for Canadian high school youths at different Canadian universities. In response to the pandemic, however, Shad Canada adopted an entirely virtual format. In the summer of 2020, Shad Canada collaborated with Luna Design and Innovation, a Canadian startup that helps researchers plan missions to space, and Blue Origin, a commercial launch provider, to create "Shad Online 2020," a fully-remote and national competition to design a suborbital Minipayload aboard a Blue Origin flight..

Over 600 students were assembled in virtual teams across 10 online campuses, competing to design a research payload that would be sent to space on New Shepard, Blue Origin's reusable suborbital vehicle. Shad and Luna Design and Innovation partnered together to develop the competition, challenging students to leverage space as a creative medium or research platform to advance humankind. Research proposals were evaluated on 4 key criteria:

- Impact (30%)
- Scientific Merit (30%)
- Technical Description and Feasibility (30%)
- Project Plan (10%)

During the 4-week program, students engaged with government leaders and scientists, working closely with 23 microgravity experts from across North America to help them develop 62 diverse research proposals for suborbital spaceflight. Our team, Mous4Inc., was one of 6 teams belonging to the Pleiades virtual campus. A total of 10 virtual campuses participated in Shad 2020, as represented in **Figure 1** below.

Members of Mous4Inc. sought to design a scientific payload that would capitalize on the flight's 3-minute microgravity period. Inspired by ESA's experiences testing foam in microgravity [1], the team devised a novel plan to send foam ingredients to space, with the objective to create "space foam." Based on previous work, we hypothesized our space foam to be stronger and more stable compared to its Earth counterpart, owing to the ability to form larger, more evenly distributed foam bubbles in microgravity [2]. . Polyurethane foam was selected for this experiment due to its fast reaction rate, so as to be able to nearly completely solidify within the microgravity period of the flight profile [3].

Figure 1. Organization of Shad Spaceflight Challenge Teams and Finalist Selection.

During the initial competition phase, the team first iterated upon the payload concept, while simultaneously working to create multiple deliverables, including a business report, scientific report, video pitch, budget, timeline, and initial computer-aided design (CAD) models. After the initial 4 week competition period, Mous4Inc.'s project was chosen to represent the Pleiades campus in the final rounds of evaluation against nine other finalist projects from the remaining campuses.

Project evaluators consisted of space experts from industry, academia and the Canadian Space Agency. These experts conducted an initial evaluation phase, whereupon the 10 finalist teams were narrowed down to 5 projects, which then underwent a second round of evaluation. Of these finalists, Mous4Inc. was selected as the winner of the Shad Online 2020 Spaceflight Challenge.

Mous4Inc. was introduced to one of the evaluators as a Primary Investigator (PI) with payload development experience to supervise the project in order to further iterate upon, design, assemble, test, and fly their payload. The remaining evaluators were asked to stay on as mentors given their breadth of expertise with payload development and integration.

Since Fall 2020, Mous4Inc. members have worked virtually to develop a payload with the purpose of studying the formation and physical properties of polyurethane foam in a microgravity environment. Due to the pandemic and geographical barriers, tasks related to design, testing, and assembly that would normally be completed in person have been delegated and accomplished virtually.

In this paper, we will share the conceptualization process, workflow, assembly, testing, outreach methods, current status and lessons learned regarding virtual payload design and assembly during the COVID-19 pandemic.

Once flown, Mous4Inc.'s experiment will be the first-ever Canadian high school student-developed commercial payload on New Shepard and proposes to offer novel insights regarding the physical and structural properties of manufacturing polyurethane foam manufacturing in space.

2. Methods

Concept Evolution

Once selected as the winners of the Shad 2020 summer design challenge, Mous4Inc. picked up their work with their new PI on this project in October 2020. Using Zoom as a primary method of communication at weekly meetings, and several Instagram chats and a Discord channel to provide the team with more immediate updates and feedback, Mous4Inc.'s initial work took place entirely through virtual collaboration. Members collaborated solely on an online platform without ever meeting each other. Prior to the commencement of payload construction, Mous4Inc. was further briefed on the payload's mass, power, and volume constraints **(Table 1)** [4], and also iterated upon the initial concept after reviewing initial feedback from the judges' summer evaluations as well as payload design constraints restricting, for example, compressed air canisters, or the concurrent use of both batteries and liquids.

Payload Constraints	
Mass	0.5kg
Volume	10x10x20cm
Power	5 VDC / 4.5 W / 0.9 A

Table 1. Mini-payload mass, power, volume constraints.

Communications

Over the course of a year, since the beginning of the payload development process, Mous4Inc. members have attended weekly online meetings over Zoom to discuss updates and discuss problems as a group. The team has also communicated via email, Discord, and phone calls during the periods between these meetings. More recently, Mous4Inc. has begun to use Slack as a primary method of communication to allow for better organization. Large files such as CAD iterations, videos of testings, photos, and spreadsheets are organized on a shared Google Drive. This has allowed members to be aware of current updates and respond to questions prior to the weekly meetings in a timely fashion. Laboratory testing has been conducted in person

Subsystems Design & Acquisition

Payload designs were modelled, iterated and communicated using computer-aided design (CAD) software, a digital technology that automates the manual drafting process. Subsystem design further evolved over real-time Discord and Zoom meetings in-between 'official' team meetings. Once concepts were approved at team meetings, the PI went ahead and purchased the relevant components, concurrently, tracking the team's $2000 budget. Once purchased, subsystem assembly took place in two locations across the country, with one team member testing the stability and physical properties of the foam components, and the other team member assembling the rest of the subsystems. Subsystem updates were then relayed at weekly team meetings.

Ground Testing and Polyurethane Foam Evaluation

A series of ground tests to examine the physical properties of the polyurethane foams and the sturdiness of several subsystem components was devised for pre-flight testing. Initial foam testing took place under controlled settings in a private residence setting with adequate ventilation and full personal protective equipment (PPE). The purpose of this testing was to further delineate the physical properties of the foam components, notably how they behaved as individual components, as well as to perform initial calculations to determine the force required for a motor to depress a plunger to deliver each foam component through a syringe-tubing assembly into a final mixing chamber. Specific physical properties tested during this phase included:

- Settling time for each of the two components once poured;
- Observed (versus stated) solidification time for foam product;
- Maximal temperature of foam product during solidification process; and

- Volume of any off-gassing products.

Unfortunately, concerns regarding the adequacy and safety of ventilation despite precautions arose with residential testing. After conferring with the mentors, the foam testing was moved to another city, and in partnership with one of the mentor's labs, further foam property testing took place under laboratory conditions in a fumehood with full PPE, with the added benefit of being able to monitor and measure the results with high-definition cameras and laboratory-grade equipment under controlled settings **(Figure 2)**.

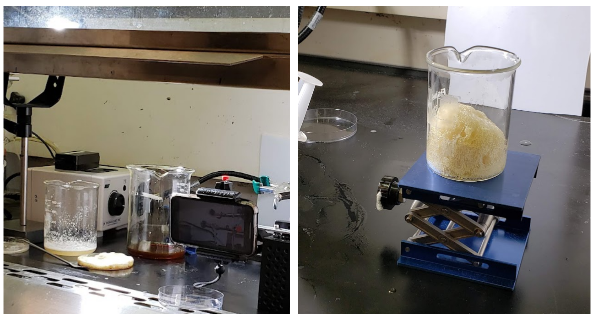

Figure 2. Laboratory set-up for pre-flight ground testing, with individual liquid polyurethane foam components mixing and solidifying in a fumehood under video observation (left) and post-solidification product (right).

Some surprises still arose during laboratory testing. When attempting to measure the volume off-gassing of the reaction by sealing a closed system of tubing and Pyrex glassware, the maximal temperature of the foam exceeded the melting point of the paraffin wax used to seal the connection points of the tubing to create a closed, thereby melting the seal **(Figure 3)**. This incident was particularly instructive in verifying the temperature ratings of all components used for subsequent testing as well as the final payload assembly.

Figure 3. Off-gassing test. In this set-up, the liquid polyurethane foam components mixed in a one-way nozzle, and then ejected to solidify to form polyurethane foam in a closed chamber (smaller Pyrex container depicted on left of image), with a single outlet of PVC tubing leading to an inverted Pyrex flask in a larger Pyrex container to measure the volume of any off-gassing substances produced. Unfortunately, in the first run of the experiment, the paraffin sealant used in the mixing chamber melted due to the exothermic nature of the reaction (maximal temperature of 76.2ºC), creating a hole in the seal and nullifying the results of the test. Subsequent tests employed temperature-rated materials.

Electrical Subsystem Assembly and Iteration

The remainder of the payload subsystems, including electrical components, coding, hardware testing and assembly of the non-foam subsystems took place in another location across the country in tandem with the foam testing.

During initial electrical subsystem testing, motor issues as well as issues with ejecting the foam arose as a result of limited power and amperage received from the Raspberry Pi. These power limitations were further amplified when the circuit was connected to other components, like the camera. Other initial motor choices were demonstrated to run well on AC power, but proved unable to run on the Raspberry Pi. This led to several iterations before the ultimate selection of a new set of motors that could generate the force needed to expel the liquid foam components while respecting power and mass constraints, as well as sequencing the initiation of the motor deployment and camera capture accordingly.

Optimization of Foam Formation Video Capture

Part of the data to be captured includes video data of foam solidification in microgravity. To optimize this, we opted to mount LED lights around the periphery of the mould, adding matte coverings, to minimize glare. Our initial solution consisted of matte acrylic paneling, however this quickly caused us to exceed our mass budget. We subsequently opted to line the mould with lightweight dark matte corrugated plastic sheets that also met our temperature limits. The mass constraints would drive numerous subsystem selections, as the team was mindful of the mass occupied by the payload box itself, as well as initially 'negligible' components that were added to secure, seal and steady various subsystems, including 3D-printed parts, and foam components for dampening.

Payload Orientation Reconfiguration and Redesign

Throughout the subsystem design and assembly process, several 'ground-truthing' events made clear that theory and practice sometimes differed. In the course subsystem integration, it became clear that we would best be able to optimize the volume of the payload box for foam formation by reorienting electrical and syringe-tubing subsystems to align along the long axis of the payload box (along the 4” x 8” face), rather than along the height of the box, wherein we would have had to section off these subsystems horizontally, creating two (4” x 4” x 4”) sections, one for the mould and one for the subsystem, thereby leaving less volume for foam expansion upon mixing. The old and the new configurations of the payload are depicted in **Figure 4** below.

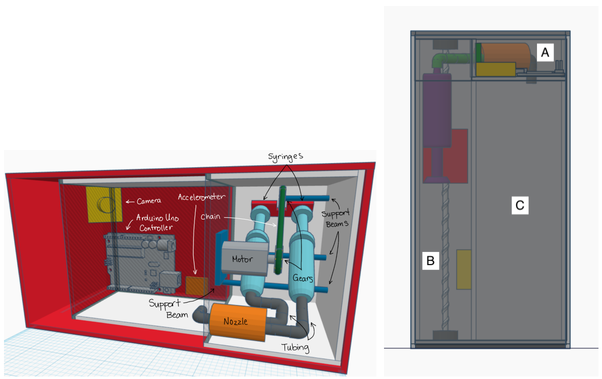

Figure 4. Side-by-side comparisons of the earliest payload design (left) in a horizontal configuration, compared to the current payload configuration, in an upright configuration (right). In the current design, the payload box has been reoriented along the long axis to maximize the volume for foam formation in the final mixing chamber (labelled C). In the new configuration, the motors are isolated from the liquid foam components in chamber B, and the liquid components mix together in chamber A before being ejected together to solidify in chamber C.

3D Printed Elements

Where available, Mous4Inc. tried to incorporate commercial off-the-shelf (COTS) parts to build out, link and fasten the payload subsystems as needed. However, after five major iterations since initial conception, it became clear that certain components would require a custom solution so as to be able to meet the payload objectives, as well as the accompanying mass, volume, power and structural loading constraints. As such, we opted to 3D-print several subsystems. It has taken a year to evolve to the current finalized design from our initial concept. The Mous4Inc. mentors were instrumental in helping bring the 3D components to fruition, reaching out to trusted experts within the Shad Alumni Network to offer feedback and print components in a timely fashion.

Review Process

Throughout the initial planning and designing phases, the team would meet up with various mentors at approximately monthly intervals. The team would explain their most recent design, as well as changes from previous iterations of their project, to garner feedback and inputs from the mentors with expertise within these domains. The mentors were an integral part in this part of the process as they brought attention to several problems that the team didn’t have the experience to foresee, particularly with respect to structural analysis, engineering and microgravity integration. Given that the payload was designed according to guidelines set out for the Blue Origin Mini Payload, the team liaised with Blue Origin payload integration experts at regular intervals to ensure compliance and ask for the occasional clarification. Part of this process included the submission of initial and final Payload Development Reviews (PDR) to ensure adherence to the payload framework requirements.

Outreach

Outreach has been an important part of Mous4Inc.’s payload development process; as such, the team has made concerted efforts to reach out and present to like-minded communities throughout the payload development process. The first team showcase took place in December 2020 with the PoSSUM13 (Polar Suborbital Science of the Upper Mesosphere) Parabolic Flight Challenge, where we were asked to share our development process with that microgravity competition finalists, who also comprised of high school students, albeit for a parabolic flight competition. Several months later, one of the team’s engineering mentors, a professor of engineering, asked the team to present the latest payload design and virtual payload development process to his group of undergraduate students, who were also in the midst of developing a high altitude balloon payload.

In addition to targeted presentations with similar groups, our group has maintained an active social media presence on Instagram throughout the payload development process, allowing us to share the diversity of the team’s composition, payload progress, team updates and celebrate space news with the general public (**Figure 5**). Social media outreach has also facilitated the development of constructive relationships within the industry. Online events and platforms such as the “2021 NASA and the Rise of Commercial Space” event and LinkedIn, for example, have allowed us to virtually connect with the research and development (R&D) team at Adidas, an international shoe brand that has famously manufactured foam for running shoes in space [5]. This connection was particularly invaluable in offering further perspectives regarding R&D and manufacturing various types of foam in the microgravity environment - in this case the International Space Station (ISS), which in turn informed our work.

Other examples of outreach include sharing the team’s journey and virtual payload development evolution on a variety of digital media platforms, including a national Canadian space podcast [6] and digital press releases in partnership with Shad (**Figure 5**).

In summation, these outreach experiences have been both instrumental and instructive for sharing our lessons learned with respect to virtual, distributed payload development during a pandemic, as well as learning about other available of microgravity testbeds for payload testing, including parabolic flight, high altitude balloons, and sounding rockets from peers at a similar experience and education level as ourselves, that is high school and undergraduate levels.

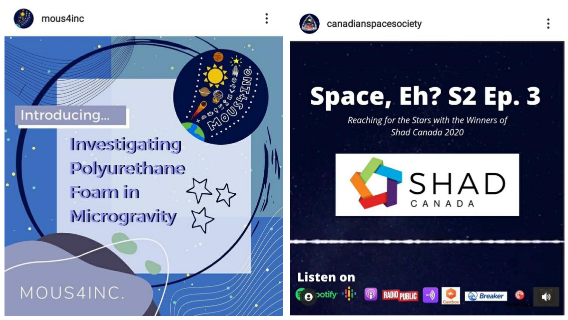

Figure 5. Mous4Inc.'s outreach activities include a social media page on Instagram (left), and interviews with digital media channels, such as the Canadian Space Society's "Space, Eh?" podcast (right) [6].

3. Current Status & Next Steps

One year into development, the Mous4Inc. payload has been finalized after numerous revisions and iterations, and the final Payload Design Review (PDR) has been submitted to Blue Origin for review. Individual team members have nearly all relocated to different cities in Canada to begin their university studies. As such, the payload components have been shipped to another city for assembly. Hardware assembly is currently underway, and once complete, the payload will undergo further pre-flight testing, both in a 1g laboratory testing, and subsequently in parabolic flight, following ground-test review and finalization of the microgravity flight Test Equipment Data Package (TEDP). Further payload revisions will be made as necessary, along with PDR updates. Once complete, the payload will be ready for launch aboard a New Shepard suborbital flight at a future date. Following launch, the payload and data will be retrieved for further analysis and ground testing, to determine differences in properties in polyurethane foam formed in 1g versus microgravity.

4. Discussion

Mous4Inc. has learned several key lessons about the engineering and payload development process, particularly as they pertain to distributed, virtual collaboration on a national scale, looking for alternate options when initial proposals did not work, and balancing this project with other responsibilities.

For many of the Mous4Inc. members, working with others on a project beyond traditional school assignments was a new experience. Working together in a virtual fashion in the context of the COVID19 global pandemic added another dimension of complexity as well. Through this experience, Mous4Inc. members gained much insight into the challenges, constraints, and even unexpected benefits, of working with team members residing in different geographic locales across the country.

As a team, we learned to leverage our geographical separation and take advantage of the diverse skill sets and access to resources that different team members have. Each team member brought diverse expertise to the table, from computer programming, to hypothesis-generation and design of a scientific method for ground testing, to computer-aided design, to social media and public communication, to graphic design, to project management and organization. As a result, different members were tasked with modelling, organizing, leading, communicating, constructing, and developing different aspects of the payload. Each team member similarly leveraged their local resources to advance payload development, so as to access both residential and laboratory testing facilities, gain access to several 3D printers, and facilitate connections for various media exposure opportunities.

That being said, several hurdles have been identified throughout the process, and we are sharing our lessons learned here, so that other teams may learn from our evolution.

As is often the case with payload assembly, the team found that there is sometimes a difference between theory and practice, despite pre-planning and preparation, and perhaps the greatest lesson was the ability to "adapt and overcome," followed by rigourous trade-off studies to find materials and components that best met the payload's needs, without exceeding mass, power, or volume constraints.

Several occasions arose wherein an initial proposed avenue proved to be unworkable. For example, initial design proposals included a compressed-air canister and a battery to advance the syringe plungers for liquid foam component delivery. This, however, was not permitted with the payload constraints, requiring a redesign to include motors, prompting a review and search for motors that would fit within the mass budget while generating enough force to successfully expel the liquid foam components. The payload design, layout and components similarly underwent numerous revisions to optimize visualization by changing camera placement, and maximize the volume allotted for foam solidification. Matte acrylic panels initially introduced to minimize glare to the cameras within the foam solidification mould as the polyurethane formed were replaced with lightweight corrugated plastic to stay within the mass budget. The timing of camera activation in relation to motor deployment was revised several times to strike the balance between adequate power for the motors, while starting visualization of the foam solidification early enough to capture as much of the formation process as possible. In addition to the power integration challenges between the motors and the Raspberry Pi mentioned above, the Raspberry Pi computer used for programming the electrical subsystem sequence initially shorted out, requiring replacement.

Next, the team learned to adapt to ‘blindspots’ that would affect the payload’s performance, and once identified, ensured that all payload components accounted for this going forward. For example, several considerations were identified and planned for early on in the design phase:

- Foam sheeting was included in the payload design for vibration dampening;
- Off-gassing was measured during laboratory testing and determined to be negligible;
- All components that would come into contact with the liquid polyurethane foam components were ensured to be inert, so no reactions of chemical changes could occur.

Despite these considerations,, however, during laboratory testing, due to the exothermic nature of the foam solidification reaction once the liquid components had mixed, and after one of the paraffin sealing components melted with heat exposure, it became apparent that all payload components with direct contact of the mixed foam components would have to be temperature-rated to be able to withstand at least the maximal temperature of the foam, 76.2ºC, ideally with a margin of safety above the temperature limit. All payload components with direct contact of the polyurethane foam have since been reviewed to ensure they meet these constraints.

In addition to technical insights, many logistical lessons were learned. Canada spans 6 time zones; as such, real-time virtual meet-ups with all 10 Mous4Inc members, one PI, one Luna Design and Innovation representative, one Shad Canada representative, and multiple mentors, was not always possible. As such, the team learned to adapt and work asynchronously on weekly priorities, subsequently tagging up at mutually convenient times to discuss updates, pain points and next steps. Previously-mentioned online communication platforms, including Zoom, WhatsApp, Discord, Slack, and traditional email facilitated this work. In adopting additional virtual communication platforms as the project evolved, the team was able to decrease the time between design iterations, and also communicate more synchronously despite conflicting schedules.

Additional challenges involved with the subsystem design process include having little prior experience with certain payload design elements, particularly CAD, which created a steep learning curve. Future suggestions from the Mous4Inc. team to address this pain point would be to include a brief, formal introductory orientation to CAD software, if feasible.

To help address the team’s inexperience with the payload design and integration process, in addition to bringing in a PI with prior microgravity payload design and testing experience, the Shad competition mentors graciously agreed to continue on in their mentorship roles beyond their initial summer engagement, and would take part in occasional design review meetings to offer feedback and design optimization advice.

Materials and parts shipments were often delayed, and reconfiguration and design iterations to meet the payload constraints took additional time to implement, due to the full and often conflicting schedules of Mous4Inc team members. Completing assigned tasks, while balancing external school workloads and other responsibilities certainly posed a challenge throughout this project. Scheduling challenges were further compounded this past fall as Mous4Inc. members entered university, further restricting availability. As a result of this, members learned to manage their time and schedules more effectively.

In addition, the team had scheduled adequate buffer time in the project timeline to accommodate for delays, while still meeting critical milestones, such as the final PDR deadline submission, the TEDP development, as well as external presentations and papers. Similarly, the team’s financial budget was managed such that it was able to accommodate spare parts and subsystem redesigns.

The team also learned to leverage the expertise of its mentors and the Shad Alumni Network when faced with obstacles. In one instance, despite careful advance planning to use full PPE and performing initial foam component testing in an outdoor, ventilated space during initial testing, there was concern that this did not provide adequate ventilation from noxious gases. As such, the team partnered with one of its engineering mentors to continue testing in a laboratory with a fume hood. This further granted the team access to laboratory-grade equipment including high-resolution video and weigh-scales, improving the accuracy of observations taken during ground testing. In another instance, when 3D printing parts during a critical phase prior to PDR submission, the team was able to leverage the Shad Alumni Network to print high-quality parts with a quick turnaround time.

Finally, dedicating time to education and outreach initiatives via social media, digital media and presentations to student groups pursuing similar projects helped us share our experiences, gain insights from teams grappling with similar problems, and elevate the profile of our work.

5. Conclusion

Once flown, Mous4Inc.'s experiment will be the first-ever Canadian high school student-developed commercial payload on New Shepard. The team's experiences with suborbital payload development during the global pandemic demonstrate successful virtual, distributed payload conception, design, iteration, development, testing and assembly for a high school, and now undergraduate, student project, and serves as a model for future student-led virtual payload development.

As social distancing and COVID19 restrictions continue for the foreseeable future, student-led payloads must continue to adapt. Novel practices such as working remotely and communicating virtually are imperative for groups to operate. Overall, Mous4Inc.'s experiences demonstrate the feasibility of designing and building a payload despite restrictions introduced by the COVID-19 pandemic, as well as the value of such programs for encouraging future STEM and space professionals.

Mous4Inc.'s successes to date are a direct result of the time and effort individuals put into this project. Our experiences in this setting demonstrate the ability to adapt to atypical global circumstances, and proceed with the payload development process through the use of online communication channels, individual team skills, and mentor and alumni network expertise and resources. Furthermore, we have been able to successfully engage in outreach activities by capitalizing on the availability of virtual networking and social media channels. In addition to the lessons shared here regarding virtual, distributed payload development, system redesign, time, cost and mass budget management, the study of the physical properties of polyurethane foam formed in a microgravity environment promise to deliver much scientific return and impactful real-world applications for foam usage in everyday terrestrial application. We look forward to sharing the results of our experiment once the post-flight analysis is complete.

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