Propulsion System Development
for the CanX-4 and CanX-5 Dual Nanosatellite
Formation Flying Mission

by

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for the degree of Master of Applied Science
Graduate Department of Aerospace Science and Engineering
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Abstract

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Master of Applied Science
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The Canadian Nanosatellite Advanced Propulsion System is a liquefied cold-gas thruster system that provides propulsive capabilities to CanX-4/-5, the Canadian Advanced Nanospace eXperiment 4 and 5. With a launch date of early 2014, CanX-4/-5’s primary mission objective is to demonstrate precise autonomous formation flight of nanosatellites in low Earth orbit. The high-level CanX-4/-5 mission and system architecture is described. The final design and assembly of the propulsion system is presented along with the lessons learned. A high-level test plan provides a roadmap of the testing required to qualify the propulsion system for flight. The setup and execution of these tests, as well as the analyses of the results found therein, are discussed in detail.
Acknowledgements

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List of Acronyms

ATO  Along Track Orbit
CANX  Canadian Advanced Nanospace eXperiment
CMM  Coordinated-Measure Machine
CNAPS  Canadian Nanosatellite Advanced Propulsion System
COTS  Commercial Off-The-Shelf
EM  Engineering Model
ESD  Electrostatic discharge
GNB  Generic Nanosatellite Bus
GPS  Global Positioning System
GSE  Ground Support Equipment
ISL  Intersatellite Link
LFFT  Long-Form Functional Test
NANOPS  NANOsatellite Propulsion System
OBC  On-Board Computer
PCO  Projected Circular Orbit
PEEK  Polyetheretherketone
PSLV  Polar Satellite Launch Vehicle
RTV  Room Temperature Vulcanizing, ie. RTV silicone
SF$_6$  Sulfur hexafluoride
SFFT  Short-Form Functional Test
SFL  Space Flight Laboratory
TVAC  Thermal Vacuum
UTIAS  University of Toronto Institute for Aerospace Studies
XPOD  eXoadaptable PyrOless Deployer
Chapter 1

Introduction

As the capability envelope of micro and nanosatellites is pushed, the need for more advanced systems becomes increasingly important. These include systems to provide propulsive capabilities for such tasks as formation flying, attitude control, and orbit maintenance. Formation flying is one of the needs for a propulsion system at the nanosatellite scale that has gathered much interest in recent years.

1.1 Formation Flying Missions

Satellite formation flying can be defined as the active control of relative position and velocity between two or more spacecraft. There are no restrictions on the mass or separation distance of these two objects. The concept of formation flying holds several advantages over conventional mission designs, including [1]:

- For certain applications, a reduction in development time and associated costs since large satellites could be replaced by several smaller satellites flying in formation;
- Greater mission flexibility;
- Increased robustness in that the failure of one satellite does not necessitate the failure of the mission;
- The ability to distribute scientific instruments throughout the formation; and
- The ability to reconfigure or augment the mission by launching more satellites.

These advantages lead to more innovative missions which are designed around this concept. Several formation flying missions have been flown over the past several years, ranging from massive spacecraft to small satellites, and each with varying performance criteria. In 2007, the United States Defense Advanced Research Projects Agency (DARPA) launched its Orbital Express mission that demonstrated the capability to autonomously rendezvous,

\[1\text{Nanosatellite is a term used to classify satellites in the mass range of 1 kg to 10 kg}\]
inspect, capture, refuel, and perform a component exchange with a non-thrusting spacecraft [2]. The spacecraft were massive in this mission, with the thrusting satellite weighing over 700 kg and the passive spacecraft weighing 224 kg. Another example of formation flying performed at a large scale is NASA’s Gravity Recovery and Interior Laboratory (GRAIL) mission, which launched in September 2011 [3]. Each spacecraft in the GRAIL mission weighed 200 kg, and together performed gravitational mapping of the Moon as they flew in formation. The Gravity Recovery and Climate Experiment (GRACE) was launched in 2002 into a 500 km altitude polar orbit of the Earth. GRACE performs Earth gravity field mapping by making accurate measurements between the two satellites [4]. For this mission, post-processed absolute and relative positions were used for the gravitational mapping, as only coarse formation keeping was applied to maintain the satellites within 50 km of their desired separation [1].

The PRISMA mission, launched in 2010, made use of a passive (attitude stabilized) satellite of a 40 kg mass and an active (thrusting) satellite of 150 kg mass to demonstrate sub-meter relative orbit determination in order to perform Low Earth Orbit (LEO) formation flying [5]. A large variety of relative orbits have been flown over the course of the mission, with distances ranging from 2 m to 30 km in along-track separation, and up to 1 km and 2 km in cross-track and radial separations, respectively. During a 2 m proximity approach, the active satellite was controlled to the sub-meter level. The PRISMA mission also successfully performed its ARV (Autonomous RendezVous) experiment where the active spacecraft was allowed to autonomously detect the passive spacecraft and manoeuvre from a separation distance of 30 km to 50 m. Another mission, the planned JC2Sat mission, is a joint collaboration between the Canadian Space Agency (CSA) and the Japan Aerospace Exploration Agency (JAXA). With each satellite weighing approximately 18 kg, this mission will demonstrate the feasibility of autonomous formation flight based on aerodynamic differential drag only [6].

The Canadian Advanced Nanospace eXperiment (CanX)-4 and CanX-5 is a dual nanosatellite formation flying demonstration mission designed and built at the University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS/SFL). It involves two nanosatellites, weighing less than 7 kg each, flying autonomously in precise formations in a low Earth orbit. Compared to the PRISMA mission, the CanX-4/-5 spacecraft are both an order of magnitude less massive but will aim to achieve the same level of relative position determination and control. They will be the first on-orbit platform to demonstrate nanosatellite formation flight with the goal of sub-meter formation control (Chapter [2]). Unlike previous formation flying missions, CanX-4 and CanX-5 will deploy from the launch vehicle separately. This is due to constraints imposed by the launch vehicle provider. Deploying separately adds complexity that will require both satellites to be commissioned independently while drifting apart, perform thrusting manoeuvres to arrest and recover their relative drift, and then
initiate autonomous formation flight.

There are several applications for formation flying at the nanosatellite, microsatellite, and small satellite scales. These include, but are not limited to: high resolution interferometry, on-orbit servicing and inspection, Ground Moving Target Indication (GMTI), Earth Observation (EO) missions requiring images at either varying viewing angles or observation times, as well as EO missions carrying different instruments to measure different things but are required to stay within a certain distance of one another to facilitate concurrent science.

\section*{1.2 Propulsion}

These aforementioned formation flying missions, with exception of JC2Sat, require a propulsive capability to maintain formation. Many of the technological efforts on the development of nanosatellite propulsion systems focus on either the development of new technology or the miniaturization of conventional technology. There are advantages and disadvantages to each approach. University of Washington’s Dawgstar Satellite in the ION-F formation flying experiment makes use of a pulsed plasma thruster (PPT) to control the 15 kg spacecraft \[7\]. This propulsion system creates thrust when solid Teflon\textsuperscript{®} is ionized by a pulsed, high-current electric arc and accelerated by a combination of electromagnetic and gas dynamic forces. Thrust levels range from 60 to 275 $\mu$N with specific impulses up to 266 seconds \[8\]. Disadvantages of these pulsed plasma thruster systems are that they often require high power, produce magnetic fields, and although they have a high thrust-to-mass ratio for an electric propulsion system, are still larger than most nanosatellite payloads.

In June 2000, Surrey Space Center launched SNAP-1, a 6.5 kg nanosatellite, which contained a butane liquefied-gas propulsion subsystem to meet the spacecraft’s mission requirement of 1 m/s $\Delta V$. This propulsion system stored 32.6 grams of propellant in a liquid state and used a heating element to ensure full vaporization of the fuel as it was expelled \[9\]. Resistojets have also been used to increase the performance of a propellant. These thrusters heat the propellant to just over 300°C before it enters the system’s expansion nozzle. However, even low-power resistojet thrusters can consume up to 15 W to power these heaters \[10\] which is out of the capability range for most nanosatellite buses.

The Canadian Nanosatellite Advanced Propulsion System (CNAPS) will provide the CanX-4/-5 mission with propulsive capabilities to carry out its mission objectives. CNAPS is a liquefied cold-gas thruster system capable of delivering a total $\Delta V$ of approximately 13.5 m/s while consuming only 0.25 W of power. The selected propellant is sulfur hexafluoride (SF$_6$). It was chosen for its high storage density, non-toxicity, and chemically inert properties. CNAPS will strive to build on the Space Flight Laboratory’s success of the NANOPS propulsion system on the CanX-2 spacecraft. Similar to SNAP-1’s propulsion system, the propellant within CNAPS is stored in a liquid state to increase its storage density.
To reduce power consumption, instead of using a heating element, a secondary volume is placed between the high pressure storage volume and the nozzles. This volume ensures that the stored liquid is vaporized prior to exiting the divergent nozzles. CNAPS uses four nozzles that thrust from a single face of the spacecraft; these nozzles are independently controlled in order to reduce the impact of any misalignments on momentum build-up within the spacecraft bus. The thrusting satellite will slew to various attitudes in order to point the thrust vector into the desired direction.

### 1.3 Formation Flight at the Nanosatellite Scale

There are a few contributing factors as to why formation flight has not been successfully demonstrated at the nanosatellite scale to this date. Precise relative position determination using the Global Positioning System (GPS), high-performance nano-attitude control systems, and reliable nanopropulsion systems required technological advancement before the pursuit of the CanX-4/-5 mission goals [11]. Since its launch in April 2008, the CanX-2 nanosatellite has explored studies such as GPS occultation and effects of spacecraft slew rate on GPS performance. In addition, CanX-2 has demonstrated the application of a cold-gas single-thruster Nanosatellite Propulsion System (NANOPS) [12]. The use of these systems has not only provided valuable results but also flight heritage to the hardware and design, especially in the case of selected commercial off-the-shelf components [13]. The AISSat-1 spacecraft, launched in July 2010, has proven the Generic Nanosatellite Bus (GNB) designed by SFL. The GPS receiver and antenna flown on this mission are identical to those selected for the CanX-4/-5 mission. The flight heritage and performance characterization acquired from these components work to mitigate risk in the CanX-4/-5 mission design.

### 1.4 State of Work

At the time the author joined the Space Flight Laboratory, the majority of the CanX-4/-5 propulsion design had been completed [14] and most of the components had been procured. Some part level testing had been performed and a representative test bed, referred to as FlatNAPS, was used to test the interaction of key components. In addition, a wire harness plan and assembly procedure was created, and a complete assembly of CNAPS was attempted using this procedure [15]. However, there were several issues encountered with this first assembly, thus providing a source of lessons learned. The author was challenged with the goals of successfully assembling two leak-tight CNAPS units based on these lessons learned, performing the entire campaign of propulsion system-level testing, which would both verify performance parameters and instil confidence of survivability, and finally, ensuring seamless integration with the CanX-4 and CanX-5 satellites.
Chapter 1. Introduction

1.5 Scope

This thesis aims to convey the author’s contributions to the CanX-4/-5 formation flying mission, in particular to the propulsion system development of the Canadian Nanosatellite Advanced Propulsion System (CNAPS). In summary, these contributions include:

- Assembly of the two flight candidate propulsion units;
- Development of the CNAPS qualification and acceptance test plan;
- Development of a fill procedure;
- The setup, execution, and analysis of protoflight vibration testing to qualify the design of the propulsion system;
- The setup, execution, and analysis of thermal vacuum testing;
- The setup, execution, and analysis of the thrust performance characterization of both units;
- The establishment of an accurate and reliable leak rate determination method; and
- The design, execution, and analysis of several leak test campaigns at various environmental conditions.

This thesis addresses the above contributions made and provides the appropriate background information necessary for the reader’s understanding. It begins with the motivation, mission architecture, and design of the CanX-4/-5 dual nanosatellite formation flying mission (Chapter 2). This chapter also outlines the components of the Generic Nanosatellite Bus (GNB), which was developed at SFL and provides the foundation for CanX-4/-5. Chapter 3 overviews the history, requirements, design, fluid control architecture, and major components of the Canadian Nanosatellite Advanced Propulsion System. Chapter 4 presents the author’s assembly of the two flight candidate propulsion units to be used for the CanX-4/-5 mission. Also discussed here are the modifications made to the previously developed assembly procedure. Chapter 5 contains the high-level test plan for both propulsion systems to transition from newly assembled units to official flight hardware ready for integration with the satellites. This discussion includes the goals, justification, and expected results for each test. Chapter 6 details the setup and execution of the test plans laid out in the previous chapter as well as the analyses of the results found therein. Major tests within this chapter include protoflight vibration tests, thermal vacuum tests, including thrust performance characterization, and propellant leakage rate tests. Chapter 7 concludes the thesis with a brief summary of the results from the propulsion system-level testing. A summary of future work is also presented, providing a guide for what is required to bring the CanX-4/-5 mission to flight readiness.
Chapter 2

CanX-4/-5 Mission Overview

CanX-4 and CanX-5 (Figure 2.1) are a pair of identical spacecraft designed and built by the Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS). Each satellite has a cubic form factor of 20 cm a side and weighs less than 7 kg. Currently, the CanX-4/-5 mission is scheduled to launch early 2014 aboard a Polar Satellite Launch Vehicle (PSLV). The goal of the mission is to demonstrate precise, autonomous formation flying in four different configurations: a 1000 m along-track orbit (ATO), a 500 m ATO, a 100 m projected circular orbit (PCO), and a 50 m PCO [16]. In order to achieve autonomous control, CanX-4/-5 will utilize novel carrier-phase differential GPS techniques to obtain relative position measurements with less than 10 cm accuracy [17]. The formation control error is to be within 1 m [1], with other mission performance parameters listed in Table 2.1. Each satellite will take on one of two roles, the deputy or the chief. The deputy satellite will perform thrusting manoeuvres to maintain formation with the uncontrolled chief satellite. At the same time, the chief satellite will mimic the attitude of the deputy to ensure the same GPS satellites are visible to both spacecraft [18].

Figure 2.1: CanX-4 and CanX-5 mission patch
Table 2.1: CanX-4/-5 formation flying performance parameters [18]

<table>
<thead>
<tr>
<th>Performance Requirement</th>
<th>Minimum Requirement</th>
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<tr>
<td>Position Control</td>
<td>1 m</td>
</tr>
<tr>
<td>Relative Position Determination</td>
<td>10 cm</td>
</tr>
<tr>
<td>Minimum Relative Distance</td>
<td>50 m</td>
</tr>
<tr>
<td>Maximum Relative Distance</td>
<td>1000 m</td>
</tr>
<tr>
<td>Attitude Control</td>
<td>5°</td>
</tr>
<tr>
<td>Intersatellite Link Range</td>
<td>5 km</td>
</tr>
<tr>
<td>Intersatellite Link Data Rate</td>
<td>10 kbps</td>
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CanX-4/-5 will utilize the Canadian Nanosatellite Advanced Propulsion System (CNAPS), an innovative liquefied cold-gas thruster system, for formation control. The mission has been designed such that the fuel within one satellite will be sufficient to complete the baseline mission requirements of 10 orbits within each formation. This allows for the redundancy of one full propulsion system as well as the possibility for further formation experiments to be performed. These two identical nanosatellites will separate from the launch vehicle from two independent eXoadaptable PyrOless Deployer (XPOD) Generic Nanosatellite Bus (GNB) deployment systems, also developed at SFL. According to the initial mission plan, the spacecraft were to be deployed together from a single XPOD DUO\(^1\) in order to better control the initial conditions of formation flying. However, this plan was abandoned due to restrictions set by the launch vehicle. The worst-case $\Delta V$ between the two spacecraft after deployment is 2.2 m/s. This $\Delta V$ will need to be corrected by an initial drift recovery manoeuvre. Although this initial $\Delta V$ is not ideal from a fuel budget perspective, it will showcase the CanX-4/-5 mission flexibility. Before the drift recovery phase, the commissioning of both spacecraft will be on-going for an estimated 5 months after launch, while all systems are powered on and their functionality is validated.

As mentioned above, CanX-4 and CanX-5 are based on the SFL developed Generic Nanosatellite Bus (GNB), a bus design that allows for adaptability primarily to various low Earth orbit missions. It is a low cost spacecraft bus ideal for scientific and technology demonstration missions. The GNB has a 20 cm cubic form factor with nearly 30% of the mass and volume dedicated to mission specific payloads. The overall bus layout consists of two avionics trays containing the bulk of the spacecraft electronics and a central 17 cm x 13 cm x 8 cm payload bay; see Figure 2.2 for an exploded view of a typical GNB layout. Power is generated by multiple strings of body mounted triple-junction photovoltaic cells with energy storage in an on-board lithium-ion battery. The GNB also comes equipped with a suite of three-axis attitude determination and control components to provide high precision.

\(^1\)XPOD DUO refers to a specific design of the XPOD deployment system that has the capacity to deploy two GNB sized spacecraft simultaneously
The attitude control is provided by three orthogonal reaction wheels mounted within the central bus, and three orthogonal magnetic torque coils mounted on the inside of each face of the spacecraft. The attitude determination sensors consist of six fine/coarse sun sensor pairs, one for each face of the spacecraft body, and a three-axis magnetometer located inside the tip of a pre-deployed boom, away from the spacecraft body. A three-axis rate sensor supplements the attitude determination of CanX-4 and CanX-5 during eclipse.

Each satellite is equipped with four UHF and four S-band antennas for communication (Figure 2.3 & Figure 2.4). Four quad-canted monopole UHF antennas provide near omni-directional coverage for data uplink from the ground station to the spacecraft. While this provides operators with the ability to send standard commands, it also allows new software to be uploaded onto the spacecraft to improve mission performance. Two S-band patches are mounted on the +Z and -Z faces to allow for downlink to the ground station. Another pair of S-band patches mounted on opposite faces are used in conjunction with an S-band radio transceiver to provide an Intersatellite Link (ISL) between the two satellites. The ISL is capable of communications at a data rate of 10 kbps while the satellites are separated by a distance up to 5 km. This allows for the satellites to share their absolute position, velocity, and attitude information with one another. Communications coverage for both the Intersatellite Link and satellite-to-ground link is designed to be near omni-directional.

In addition to the aforementioned components, both CanX-4 and CanX-5 are equipped with a few critical payloads to support the mission. These include: a single-frequency...
GPS receiver and antenna pair, which will be used for absolute and relative positioning of each satellite [1] (Figure 2.3), a dedicated formation flying on-board computer (OBC), and a liquefied cold-gas propulsion system used for on-orbit manoeuvres (Figure 2.5). This propulsion system is discussed in greater detail in Chapter 3.
Chapter 2. CanX-4/-5 Mission Overview

Figure 2.4: Reverse perspective view of the CanX-4 spacecraft

Figure 2.5: Propulsion system (CNAPS) stowed in the payload bay of CanX-4
Chapter 3

CNAPS Overview

This chapter provides an overview of the propulsion system and describes the latest state of design. Discussed are details such as the major components used and their associated flight heritage, the system requirements, and the protoflight approach used to qualify it. This information will aid the reader in further understanding the later chapters of propulsion system assembly, test plans, and test results (Chapters 4, 5, and 6).

3.1 Introduction

The Canadian Nanosatellite Advanced Propulsion System (CNAPS) is the primary payload in both satellites of the CanX-4/-5 dual nanosatellite formation flying mission (Chapter 2). CNAPS will provide the satellites with propulsive capabilities for two purposes:

1. To perform required orbital manoeuvres for formation reconfigurations; and

2. To allow the thrusting satellite (deputy) to perform station keeping manoeuvres to maintain a desired formation with respect to the uncontrolled satellite (chief).

As a risk-reduction activity for the CanX-4/-5 mission, a demonstration propulsion system was flown aboard CanX-2. The Nanosatellite Propulsion System (NANOPS) is a cold-gas propulsion system that uses sulfur hexafluoride ($\text{SF}_6$) for fuel. Due to the success of NANOPS, many of the components were integrated into the CNAPS design in order to maintain as much flight heritage as possible. The extent of this flight heritage is described in Section 3.4.

CNAPS, like NANOPS, is a liquefied cold-gas propulsion system designed primarily with commercial off-the-shelf (COTS) components. See Figure 3.1 for a perspective view of the solid model with major components identified. The selected propellant for CNAPS was also sulfur hexafluoride; it was desirable for its high storage density, non-toxicity, chemical inertness, and flight heritage on CanX-2. The propellant is stored in a liquid state in two identical
primary volume tanks at a pressure of 34.5 bar (500 psi) at +20°C. In order to produce the desired thrust, the propellant’s pressure is regulated down within a secondary tank volume through the use of an in-house designed pressure regulation algorithm. Approximately 237 grams\(^1\) of fuel is stored within each propulsion system that is designed to have a specific impulse of 35 seconds [22].

CNAPS is a more complex system containing a total of four thrusters compared to one thruster on NANOPS. When CNAPS is commanded to produce a thrust by the on-board electronics, each of the four nozzles is toggled independently. Varying the on-time of each thruster allows for fine-tuning of the thrust center position in this plane. The momentum management algorithm within CanX-4/-5 uses this capability to prevent the build-up of momentum stored in the three reaction wheels [23]. All four thrusters are positioned on the same face of the spacecraft bus which requires the satellite to be slewed to the desired attitude before commanding the thrust [1]. This necessary slew rate imposes requirements upon the attitude control system of the spacecraft that requires special attention of its own and is out of the scope of this thesis.

![Perspective view of the CNAPS solid model](image)

Figure 3.1: Perspective view of the CNAPS solid model

---

\(^1\)Testing has demonstrated that more propellant can be filled into the propulsion system without concern for overpressure events at the temperatures expected on-orbit. Final flight configuration has one CNAPS unit filled to 237 grams with the other filled to 258 grams.
3.1.1 Protoflight Approach

Rather than qualifying the design of the propulsion system by exposing the first assembled unit to high stress tests of qualification loads and durations, the protoflight approach was used for the development of CNAPS. This protoflight approach involves the first assembled propulsion unit to undergo tests of qualification magnitudes, but for acceptance-level durations. This first unit, referred to as the protoflight unit, underwent further leak tests under high vacuum to ensure the survivability of the components in flight-like conditions. Upon successful completion of the protoflight unit testing, this particular unit was promoted to a flight unit. The subsequently assembled CNAPS unit experienced acceptance-level tests to demonstrate that it will survive the expected flight environment conditions. Upon successful completion of the acceptance testing the second CNAPS unit was promoted to a flight unit.

3.2 Requirements

A list of CNAPS driving requirements is presented in Table 3.1. Requirements PR.18, PR.21, and PR.24 provided the motivation for leak rate, vibration, and thermal-vacuum tests as discussed in the later chapters of this thesis. The list of performance requirements with respect to impulse, thrust, and specific impulse presented the need to execute numerous performance characterizations of the propulsion system. These tests are presented at a high-level in Chapter 5 and are discussed in detail in Chapter 6.

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR.4</td>
<td>The propellant used by CNAPS shall be non-toxic, chemically inert, and non-combustible.</td>
</tr>
<tr>
<td>PR.7</td>
<td>The system shall be protected against over pressure.</td>
</tr>
<tr>
<td>PR.9</td>
<td>The system shall be capable of providing impulses between $I_{\text{min}} = 7.5, \text{mNs}$ and $I_{\text{max}} = 500, \text{mNs}$.</td>
</tr>
<tr>
<td>PR.10</td>
<td>The system’s impulse error distribution for a desired impulse, $I_{\text{des}}$, shall have a mean error less than $I_{\text{min}}$ (TBC), and shall have a 3-sigma error bound less than 15% of $I_{\text{des}}$.</td>
</tr>
<tr>
<td>PR.11</td>
<td>Total thrust level shall be greater than 10 mN.</td>
</tr>
<tr>
<td>PR.12</td>
<td>The minimum specific impulse of CNAPS shall be 25 s.</td>
</tr>
<tr>
<td>PR.18</td>
<td>The leakage rate of propellant stored in CNAPS shall be tested to verify the leakage rate is below 5.0 mg/hr.</td>
</tr>
</tbody>
</table>

*Continued on next page*
Table 3.1 – Continued from previous page

| PR.21 | A protoflight vibration test shall be performed on CNAPS at the unit level prior to integration with CanX-4/-5 in launch configuration [25]. |
| PR.22 | A vibration acceptance test (100% launch loads as specified by the launch provider) shall be performed after integration with CanX-4/-5 in launch configuration. |
| PR.24 | A thermal vacuum test shall be performed on a fully assembled CNAPS system prior to integration with CanX-4/-5, exposing it to a hard vacuum \(\leq 10^{-5}\) Torr) and temperatures of \(-10^\circ\text{C}, +25^\circ\text{C},\) and \(+40^\circ\text{C},\) with a functional test being performed both before and after each test as outlined in [26]. |
| PR.25 | CNAPS shall not exceed the provided volume of 7 cm x 12.5 cm x 18 cm. |
| PR.26 | The total wet mass of the propulsion system shall not exceed 1860 grams. |
| SYS13.2a | The propulsion system shall carry enough fuel to provide a total \(\Delta V\) of 16 m/s. |

### 3.2.1 Derivation of Leak Rate Requirement

The derivation of the leak rate requirement, PR.18, is highly important to the interpretation of the results of the propulsion system-level leak rates presented in Section 6.3. This value of 5.0 mg/hr represents the maximum allowable leak rate from the CNAPS propellant storage volume, referred to as the primary volume. The evolution of this requirement and the analysis of it with respect to the CanX-4/-5 fuel budget [27] is discussed below. This section also simultaneously addresses the propulsion system \(\Delta V\) requirement of 16 m/s (SYS13.2a), as this total \(\Delta V\) is intrinsic to the fuel budget which is ultimately used to derive the maximum allowable leak rate. In order to calculate the maximum allowable leak rate of the primary volume, a secondary volume leak rate must be assumed and tested, since for a large duration of the mission this volume will be pressurized to 6.9 bar (100 psi). However, the secondary volume is less susceptible to high rate leaking because it has fewer plumbing connections and a lower operating pressure.

**Original Requirement**

Originally, the maximum acceptable leak rate value was 11 mg/hr. This value was generated using the following assumptions:

- Initial fuel mass of 237 grams;
- Secondary volume leak rate of 2.0 mg/hr;
- Deployment of satellites from a single XPOD DUO, worst-case \(\Delta V\) of 0.1 m/s;
• Specific impulse \((I_{sp})\) of 35 seconds;
• Maximum 30 day wait time on launch pad;
• Maximum duration of 11 months from launch to start of formation flying (includes commissioning and drift recovery);
• 10 orbits per formation with worst-case \(\Delta V\) estimates to perform formation flying;
• Thrusting with propellant from one spacecraft only; and
• 20% fuel margin at end-of-mission.

This 11 mg/hr leak rate was developed before the decision to deploy the CanX-4 and CanX-5 satellites from separate XPODs was made, as discussed in Chapter 2. Now, in order to bring the spacecraft back into close proximity after deployment, an additional \(\Delta V\) of 2.2 m/s was required. This additional \(\Delta V\) reduced the fuel margin at the end-of-mission to 5%. At this time it was necessary to revise the fuel budget in order to determine the acceptable leak rate while maintaining the worst-case 20% fuel margin.

**Current Requirement**

In addition to the increase of budgeted \(\Delta V\) for the drift recovery, the specific impulse of 35 seconds used in the development of the 11 mg/hr value in PR.18 was overestimated. Upon thrust performance characterization, it was discovered that the specific impulse ranged from 40 seconds to 31 seconds across various nozzles and operating temperatures (Section 6.2.3.1). In order to more accurately, and conservatively, estimate the fuel required for all thrust manoeuvres, the designated specific impulse was amended to 30 seconds. A final analysis showed that with this new specific impulse value, a leak rate of 5.0 mg/hr will allow a worst-case 20% fuel margin at end-of-mission on the deputy spacecraft. For further clarification, the state of assumptions with this final leak rate requirement of 5.0 mg/hr are as follows:

*Initial fuel mass of 237 g;*
*Secondary volume leak rate\(^2\) of 2.0 mg/hr;*
*Deployment from separate XPODs in worst-case orientation (drift recovery \(\Delta V\) of 2.2 m/s);*
*Specific impulse \((I_{sp})\) of 30 seconds;*
*Maximum 30 day wait time on launch pad;*
*Maximum duration of 11 months from launch to start of formation flying (includes commissioning and drift recovery);*
*10 orbits per formation with worst-case \(\Delta V\) estimates to perform formation flying;*
*Thrusting with propellant from one spacecraft only; and*

\(^2\)Leak rate of 2.0 mg/hr within the secondary volume is a conservative estimate. Section 6.3.4 discusses the results of leak tests on the secondary volume segment.
• 20% fuel margin at end-of-mission.

This latest requirement of a 5.0 mg/hr maximum leak rate on the primary volume will be used for interpretation of the success or failure of leak rate tests presented in Section 6.3.

It should also be noted that these analyses assume a total fuel propellant of 237 grams within one propulsion unit. Through the later stages of testing, it was determined that more SF$_6$ propellant mass could be filled into the system and successfully undergo the required testing. The first propulsion unit experienced all of its protoflight testing with 237 grams fuel while the second unit was tested with 258 grams of fuel. Since these are the conditions under which these units were tested, this is the configuration in which they will fly. The latter unit with its larger fuel mass increases its fuel budget margin to 26% worst-case at end-of-mission.

### 3.3 Propulsion System Design

#### 3.3.1 Description of Components

The major components of the CNAPS design are described in detail below. Section 3.3.2 provides a high-level picture of how most of these components fit within the fluid control architecture of the system. In addition, the electronics board and software design are critical components of the propulsion system, however these are not covered below as they are out of the scope of this thesis. Further details of these components may be found in [28].

**Propellant Storage**

CNAPS consists of three tanks, two primary volume tanks for mission-duration propellant storage and one secondary volume tank to regulate the propellant down in pressure before thrusting (Figure 3.2). As commercially available tanks were either too heavy or too large to properly integrate with the structure, custom tanks were designed, built, and tested. The two primary tanks are made of Aluminum 6061-T6 thin-walled cylinders with thin-walled hemispheres welded onto either end. Flanges were also welded onto the tanks to allow for easy integration. These flanges allow for attachment to the remaining structure, adding significant structural rigidity to the entire system. The storage tanks have a combined internal volume of 236 cc. Ideally, one large tank near the spacecraft’s center would minimize the shifting of the center of mass as fuel is expended. However, this was not possible due to the volume and layout constraints, as well as the desire to have a cylindrically shaped tank to optimize the strength-to-mass ratio. Instead, the two designed primary volume tanks are placed symmetrically across the propulsion system’s center of mass.

Integrated centrally within CNAPS, between the two primary tanks, is the secondary tank. This tank is made of 316-stainless steel and has an internal volume of approximately
10 cc. This tank comprises of the majority of volume within the secondary volume segment of the fluid control architecture. The purpose of this tank is to provide an environment for the propellant to be regulated down to $6.9 \pm 0.69$ bar ($100 \pm 10$ psi) before and during thrust commanding. The volume of this tank has been sized to allow for the dampening of pressure transients that occur as the propellant rapidly flows in and out of it due to thrusting and active pressure regulation. Although a larger tank would be ideal, the volume and mass are limited, as with most nanosatellite designs.

To ensure these tanks were safe for use within the CNAPS maximum operating pressure of 68.9 bar (1000 psi), all tanks were hydrostatically tested at an external facility to 117.2 bar (1700 psi). This test involved gradually increasing the pressure at a rate of 23.4 bar/min (340 psi/min) until the test pressure of 117.2 bar (1700 psi) was reached, holding this pressure for 15 minutes, and then allowing the tank to vent at a rate of 11.7 bar/min (170 psi/min) until ambient pressure was reached \[29\]. A liquid dye penetrant inspection test was performed before and after the hydrostatic test to identify any cracks within the outer surface of the tank. To further ensure safety, coordinated-measure machine (CMM) measurements of the tank were compared from before and after to verify that no swelling of the tank occurred. A tank must successfully pass this series of tests to be qualified for flight.

**Solenoid Valves**

CNAPS contains five solenoid valves used to control the flow of propellant as it originates from the high pressure storage volume and moves to lower pressure regions throughout the entire fluid control architecture, and eventually expels out into the ambient conditions of the system. Figure 3.3 shows the placement of these valves within the fluid control system while Figure 3.4 presents one of the flight solenoid valves. One of these valves is referred to as the regulator valve, this valve controls the flow of propellant from the high pressure storage volume to the relatively lower pressure in the secondary volume. This valve is critical to
the ability of performing pressure regulation of the secondary volume before and during a thrust. The remaining four solenoid valves are used as thrust valves, each one is dedicated to a tubing path that leads to a single nozzle. This gives the system the capability to individually actuate which nozzles are used for thrusting while providing redundancy in this segment of the flow path. It is important to note that these solenoid valves fail-safe to the closed position when power is removed. This prevents any unexpected loss of propellant during a CNAPS loss of power event.

Figure 3.3: CNAPS fluid control architecture

Figure 3.4: Solenoid valve used to actively control the flow of propellant
Fill Port and Vent Valve

There are two passive mechanical valves within CNAPS that control the flow and pressure of the propellant during storage, shown in Figure 3.5. The fill port, also known as the fill valve, allows high pressure propellant to enter the propulsion system’s plumbing from the SF$_6$ supply tank but restricts any flow from exiting the system. This valve is a commercially purchased check valve that requires a pressure differential for pressure to enter the system. The check valve was press fit into a custom designed housing that allows integration with the structure and tubing of the propulsion system. The valve also contains a cap that must be installed after the system has been filled to ensure no significant leakage occurs.

The second passive valve within the fluid control architecture is the vent valve, which is also commercially purchased. This valve is more formally known as a back pressure regulator since it works to maintain an upstream pressure value lower than its own cracking pressure. For any unexpected overpressure events that may occur within the primary storage volume segment, this valve will open temporarily to relieve the pressure to the external environment. For the CNAPS design, this cracking pressure is set to 68.9 bar (1000 psi), the maximum system operating pressure. This pressure is limited by the maximum operating pressure of the solenoid valves. In the case of a pressure relieving event, the downstream segment of the vent valve has been pointed directly at a structural panel to aid in diffusing the momentum stream. The propellant would then exit various holes on different faces of the spacecraft in an attempt to avoid any unwanted torques being applied to the satellite. Testing at the component-level of these valves was performed in order to ensure these commercial parts are able to withstand the environments they will be used in.

![Fill and Vent Valves](image)

(a) Fill valve  
(b) Vent valve

Figure 3.5: Passive propellant flow control valves

Nozzles

Divergent nozzles are used to produce thrust in a controlled and efficient manner. Each thruster nozzle is located 17.5 mm from the geometric centre of the spacecraft in the plane perpendicular to the thrust vector. The set of four nozzles is arranged in a diamond pattern on the -X face of the system. These nozzles use an expansion ratio of 100 and a 30° divergent
cone to accelerate the flow supersonically. Figure 3.6 shows the two sets of flight monolithic nozzles used in the assembly of both CNAPS units.

![Figure 3.6: CNAPS flight nozzles (two sets)](image)

**Pressure and Temperature Sensors**

CNAPS gathers pressure and temperature telemetry through several sensors to monitor its health status and to actively perform thrusts (Figure 3.7). There are nine temperature sensors, one located on each of the following: primary tank A, primary tank B, secondary volume tank, each of the solenoid valves, and vent valve. There is a single pressure sensor onboard which monitors the pressure within the secondary volume segment of the fluid system. See Figure 3.3 for the location of the pressure sensor within the plumbing architecture. This pressure telemetry is used in the active pressure regulation algorithm which actuates the regulator valve to maintain a pressure of 6.9 ± 0.69 bar (100 ± 10 psi) during thrusting. This controller is able to accommodate continuous thrusting. The temperature sensor on the regulator valve will be used to study the endothermic reaction that occurs as liquefied SF$_6$ expands to a vapour when it flows to the low pressure environment of the secondary volume. Precautions were taken to ensure a high thermal conduction path between the regulator valve and the entire structure, allowing heat to flow into the valve during this endothermic process. Tests were performed to demonstrate that there is no concern of the valve temperature dropping below its operational limits as a result of the longest duration thrust.

**SF$_6$ Propellant Filtration**

Two in-line filters have been placed into the fluid control system of CNAPS (Figure 3.3). Specifically, a stainless steel frit filter has been used rather than a screen type filter. This frit filter is essentially a porous piece of metal that the flow must pass through, with each filter removing particles larger than 2 $\mu$m. One filter that has been placed directly after the fill valve is designed to remove any particulate as soon as it has entered the system, before it
has the potential to harm any of the valves or nozzles downstream. The other filter has been placed directly upstream of the vent valve to ensure there are no particles that may stop this valve from opening in an event of an overpressure, or prevent it from fully closing once it has actuated to relieve this overpressure. It is important to note that once the propellant has passed the fill valve filter, its flow path will be unobstructed from the primary volume tanks to the nozzles, with only the solenoid valves controlling the flow. This was done in order to ensure there are no major pressure drops within the system that may affect thrusting performance.

Throughout the numerous propellant fills associated with assembly, testing, and flight operations, neither of these filters are expected to form a clog that will obstruct the flow path. However, preventative measures must be taken to ensure this. An aggressive filtration system was implemented within the fill line that flows SF₆ from the high pressure supply tank to CNAPS’ fill valve. This fill filtration system comprises of a 2 µm frit upstream of a 0.5 µm frit, both filter the propellant before it enters the propulsion system.

### 3.3.2 Fluid Control Architecture

The fluid control architecture of the propulsion system can be divided into three main segments: the primary volume, used for mission-duration storage of the propellant, the secondary volume, used for regulation of the pressure down from the high-pressure storage volume, and the thrust tubes segment which allows for the propellant to flow from the secondary volume to the nozzles and into the external environment. Figure 3.3 illustrates these segments and the major components throughout. Each of these segments is separated by a controllable solenoid valve, one between the primary volume and secondary volume, and four between the secondary volume and the thrust tubes segment. These solenoid valves act as a check valve when closed, holding back the high-pressure propellant from flowing to the
lower-pressure volume. The system is filled through a Ground Support Equipment (GSE) segment that allows filtered high-pressure liquid SF\textsubscript{6} to flow through the fill valve and into the primary storage volume. Overpressure protection is provided by the vent valve that is connected to the primary volume segment. The stainless steel tubing within the primary and secondary volume segments has an internal diameter of 0.040 inches (1 mm). The thrust tubes that carry the flow to the nozzles have an internal diameter of 0.020 inches (0.5 mm) in order to reduce the amount of propellant that will exit the nozzles once the thrust solenoid valves have closed. A large volume within the thrust tubes can cause difficulties in accurately imparting the desired impulse across a wide range of values.

3.4 Flight Heritage

As described above, a Nanosatellite Propulsion System (NANOPS) was flown aboard CanX-2 as a technology demonstration for CNAPS. During the CNAPS design, usage of components from NANOPS was desirable where possible to make use of their flight heritage \cite{15}. Although some modifications were required, the following components maintained as much flight heritage as possible:

- Solenoid valves - Internal workings of the valve were maintained while flanges were added to aid in secure mounting to the structure.
- Temperature sensors - No modifications made.
- Stainless steel plumbing fittings - No modifications made.
- Nozzles - Critical dimensions were maintained.
- Pressure sensor - Same manufacture and model, however the CNAPS sensor is current driven and the NANOPS sensor was voltage driven.
Chapter 4

Propulsion System Assembly

This chapter overviews the author’s role in the assembly of the two flight candidate Canadian Nanosatellite Advanced Propulsion Systems (CNAPS), referred to as units AA9 and AMX, for the CanX-4 and CanX-5 satellites, respectively. Although the following is not a lengthy discussion, a significant amount of effort was put forth to assemble these two units such that they would pass the protoflight and acceptance tests laid out in Chapter 5.

At the time of the author’s joining of the project, an assembly procedure had been written [30] and an attempt at a complete assembly of the propulsion system had already been made [15]. There were many lessons learned throughout the course of this first attempt; this chapter also details these lessons and the solutions applied to all future assemblies.

4.1 Lessons Learned

The first attempt at a full assembly of the propulsion system was made without checking the quality of each plumbing connection as the build progressed. This resulted in an out-of-spec leak rate discovered at the completion of the assembly. The leak was located at one of the tank union connections and was significant enough to be audible. It was determined that an improperly mated connection was the cause. To avoid such instances, it was decided that a modified assembly procedure was needed to detect major leaks before the completion of the assembly.

Upon complete assembly, it was discovered that the epoxy sealant used on the outside of each pressurized fitting not only failed at sealing the connection, but also made it extremely difficult to de-mate and fix any fittings that were deemed faulty. For future flight assemblies, this epoxy sealant would not be used however; all connections would still be potted with room temperature vulcanizing (RTV) silicone to prevent any movement due to vibration or thermal expansion.
4.1.1 Integration of Leak Checks into Assembly Procedure

As mentioned above, with integrated leak checks throughout the assembly, the large leak at the tank union would have been detected before continuing with the assembly, thus decreasing the risk associated with the assembly. In order to perform leak checks throughout the assembly, a method of characterizing the quality of a particular connection or fitting was required. This was accomplished by pressurizing the newly mated fitting to flight operational pressures and using a handheld SF$_6$ detector to determine the approximate magnitude of its leak rate. This in-assembly check was performed on each of the 46 pressurized fittings within CNAPS. Figure 4.1 illustrates the leak checking of the fill valve filter as it is pressurized with sulfur hexafluoride.

![Figure 4.1: In-assembly leak check with handheld SF$_6$ detector](image)

4.2 Assembly of Flight Units

Two flight units of the CNAPS propulsion system, AA9 and AMX, were assembled by the author. The following section provides an overview of the process and illustrations of the assembly progression.
4.2.1 Preparation for Flight Assembly

Before any flight system is built, its hardware must be cleaned thoroughly. This is a critical step to ensure the proper functionality of the system, especially for propulsion and optical systems, where dust or small debris particles can cause significant performance degradation. All cleaning is performed as per SFL’s cleaning guidelines that were developed during the Microvariability and Oscillations of STars (MOST) satellite program, see [31]. All plumbing tubes and components that come into contact with the SF$_6$ propellant were exposed to an intensive cleaning procedure performed at an external facility. After cleaning, all components are transferred into SFL’s Class 10,000 clean room for assembly and integration. The clean room is a positive pressure environment in which the air entering the room is passed through several stages of filters, ensuring that any impurities that could cause issues are prevented from entering the room. The use of SFLs Class 1,000 laminar flow benches was not deemed necessary in the assembly of the propulsion system.

There are also several tasks performed before the final clean flight assembly and integration of the propulsion system with the spacecraft bus. These include the design review of the solid model, the manufacturing and procurement of the hardware, the insertion of Helicoils, a visual inspection of all parts, a fit check of the major structural components, and a dirty assembly of all components, where the bending of the propellant tubes and plumbing is performed while ensuring there are no unwanted interferences with other components. Once these steps have been completed, the hardware is cleaned as mentioned above and the flight assembly can commence.

4.2.2 Progression of Flight Assembly

The flight assembly of CNAPS requires several sub-assemblies to be completed throughout. The following steps explain these sub-assemblies and how they are integrated into the system to create a final product. These steps assume that the propellant tubes have been pre-bent in earlier fit checks of the structure. The bending of the rigid tubes is performed manually while ensuring the minimum bend radius is not violated.

Secondary Volume Sub-Assembly

The secondary volume, which consists of the secondary volume tank, manifold, union, and pressure sensor, is built (Figure 4.2). Plugs are then placed into the empty propellant fitting locations and the entire sub-assembly is leak checked.
Chapter 4. Propulsion System Assembly

Regulator Valve Sub-Assembly

The regulator valve sub-assembly is mated. This consists of a solenoid valve, cross-union, tubing paths, and fill valve filter. In order to properly align this sub-assembly, a partial surrounding structure is created as shown in Figure 4.3. Plugs and caps are then placed into the empty propellant fitting locations and the entire sub-assembly is leak checked.

Figure 4.3: Regulator valve, filter and tubing path sub-assembly

Vent Valve Sub-Assembly

The vent valve sub-assembly is mated and all connections leak checked. This consists of the vent valve, vent valve filter, and the tubing to connect these together and to the primary volume tank. Polyetheretherketone (PEEK) P-clips are used to mount these components for flight. In order to properly align this sub-assembly, a partial surrounding structure is created as shown in Figure 4.4.
Chapter 4. Propulsion System Assembly

(a) Leak check of vent valve filter  (b) Vent valve sub-assembly

Figure 4.4: Vent valve and tubing path sub-assembly

Thrust Valve Sub-Assemblies

All four thrust valve sub-assemblies are completed as shown in Figure 4.5. These consist of solenoid valves and PEEK union fittings which allow connections to the tubing path of the secondary volume and the thrust tube segments. The upstream side of the thrust valves and PEEK union fittings are then leak checked.

(a) Non-assembled parts  (b) Completed sub-assemblies

Figure 4.5: Solenoid thrust valve sub-assemblies

Nozzle Sub-Assemblies

The sub-assemblies of all four nozzles are also completed as shown in Figure 4.6. These consist of the monolithic divergent nozzles, PEEK nuts and ferrules, and the thrust tubes
which allow a flow path from the thrust valves to the nozzles. There is no leak check performed on the nozzle sub-assemblies since this section of volume is not used to store any propellant.

![Figure 4.6: Nozzle and thrust tube sub-assemblies](image)

(a) Non-assembled parts  
(b) Completed sub-assemblies

Figure 4.6: Nozzle and thrust tube sub-assemblies

**Center Tray Sub-Assembly**

The assembly of the center tray requires the attachment of the aforementioned thruster and nozzle sub-assemblies. To facilitate the alignment of the nozzles and their associated tubes, the -X panel and +Z panel of the propulsion system are used in this assembly step, shown in Figure 4.7. All of the required sub-assemblies are now completed.

![Figure 4.7: Center tray sub-assembly](image)

(a) Thrust valve sub-assemblies attached  
(b) Nozzle sub-assemblies attached

Figure 4.7: Center tray sub-assembly
Initial Core Structure Assembly

The assembly of the core structure of the propulsion system begins with the attachment of the regulator valve and center tray sub-assemblies onto the +Z panel. Figure 4.8 illustrates the integration of these assemblies which creates the fundamental structure for attachment of the remaining components.

![Figure 4.8: +Z panel with sub-assemblies attached](image1)

Integration of Primary Volume Tanks

The two primary volume tanks are integrated into the main structure. These tanks are connected to the primary volume tubing path and leak checked using the handheld SF₆ detector. The +X, +Y, and -Y panels are also attached at this stage of the assembly, see Figure 4.9.

![Figure 4.9: Primary volume tanks integrated into the flight assembly](image2)
Integration of Electronics Board

The assembly is ready for the integration of the electronics board once all of the plumbing connections have been mated and leak checked, the wiring harness has been zip-tied and properly secured, and all screws have been properly torqued and potted with RTV silicone. Figure 4.10 shows the state of the assembly prior to the attachment of the -Z panel and electronics board.

![Assembly set for integration of electronics board and -Z panel](image)

Figure 4.10: Assembly set for integration of electronics board and -Z panel

Completed Assembly

Figure 4.11 shows the completed assembly of both Canadian Nanosatellite Advanced Propulsion Systems. The first CNAPS unit, serial number AA9, underwent protoflight testing and was integrated with the CanX-5 satellite. The second CNAPS unit, serial number AMX, underwent acceptance-level testing and was integrated with the CanX-4 spacecraft.
(a) Completed assembly of CNAPS AMX unit

(b) Integration of CNAPS AA9 unit with the CanX-5 spacecraft

Figure 4.11: Completed flight assemblies of both CNAPS units
Chapter 5

Propulsion System Test Plans

Extensive testing is required to adequately determine how CNAPS will perform in various circumstances and to ensure that it will survive its operational lifetime. The majority of stress experienced by the system is attributed to the effects of vacuum, the launch vibration loads, and a wide range of temperatures. A propulsion system-level test plan, which includes the numerous leak tests, performance tests, vibration tests, and thermal vacuum tests, is provided below. The following chapter aims to detail the goals, justifications, and high-level test methods for each of these tests.

Functional tests were also performed as a subset of all major tests in order to verify the basic functionality of the system. As previously described, the development of CNAPS is being executed using a protoflight approach, that is, the first assembled unit will be deemed a flight unit only upon successful completion of protoflight tests. The propulsion unit to follow will proceed through acceptance level tests, which it must pass to become a fully qualified flight model. As such, certain tests described below will be specified as protoflight-level tests while others may be classified as both acceptance and protoflight-level tests.

Testing at a component level was performed previously and is not covered in this thesis. The details of the temperature sensors, pressure sensors, and vent valve testing can be found in [15].

5.1 Leak Test Plan

Once CNAPS has been filled for the last time before the launch, there is an appreciable amount of time until the satellites are fully commissioned and can commence formation flying. CNAPS contains multiple connection points within both the primary and secondary volume sections. In practice, even a properly mated connection will have a non-zero leak rate. As the number of connections increases, this non-zero leak rate for each connection becomes additive along with the increased chance of an improperly mated connection, both of which will increase the leak rate; the latter will be more prominent than the former.
CNAPS also contains several complex valves such as the solenoid valves, the fill valve, and the vent valve that act as possible leak sources.

Since the ability of CNAPS to maintain a leak rate below a certain threshold for the entirety of the mission is critical, a significant amount of leak rate testing under varying environmental conditions was performed.

**5.1.1 Leak Rate Determination**

The goal of the leak test is to determine the mass loss over time (mg/hr) of the propellant within the system. Several methods were considered before selecting a process to determine the leak rate; the advantages and disadvantages of each are discussed below.

**Mass spectrometer**
Pro: High accuracy and short test duration with a turnaround time of a few days.
Con: Very costly and must transport the system to an external facility for each test.

**Pressure drop measurement across time**
Pro: Only cost is labour, no capital cost.
Con: Not very accurate. Unable to correlate mass loss with the pressure drop if there is a liquid/gas phase within the system. In order to obtain results, one must stay within the vapour pressure of the SF$_6$, which is not fully representative of the operating conditions. In addition, the ideal gas law becomes less accurate for SF$_6$ as one approaches the vapor pressure. This method is also more complex as it requires active control of CNAPS to take measurements.

**SF$_6$ handheld detector**
Pro: Low capital cost. This method is relatively quick and can identify the location of a possible above-nominal leak rate.
Con: It is difficult to ensure the measured leak rate accounts for the entire system and not just the local area near the detector tip.

**Mass measurement across time**
Pro: Low capital cost, is simple and passive once setup, and can be performed in-house.
Con: Must ensure proper test setup to ensure environmental factors are taken into effect. The longer the duration of the test, the higher the accuracy obtained; CNAPS leak rate tests can take up to 7 days to fully execute.
It was first attempted to determine the leak rate in the primary volume through the use of the pressure drop over time method; a process was devised for this test. First, the regulator valve was held open while both the primary and secondary volume tracks were pressurized to a known value. The regulator valve was then closed and the secondary volume was evacuated through the thrust valves. After a predetermined period of time, the regulator valve was opened to allow the propellant in the primary volume to expand into the secondary volume where the pressure value was recorded.

A few issues quickly rose with this particular test method. Firstly, any change in temperature must be taken into consideration across each measurement. Secondly, since there is no pressure sensor integrated into the primary volume track, if one wanted to characterize the leak rate within this section of volume, one must allow the propellant to expand into the secondary volume for the pressure reading, thus increasing the difficulty to obtain an appropriate pressure measurement. In addition, the conversion from this pressure drop reading into a mass loss value becomes increasingly complex for a liquid/gas phase which is the nominal state within the primary volume track. The aforementioned difficulties pushed for the need to move away from the pressure drop measurement and develop a passive, more accurate leak rate determination method.

5.1.1.1 Massing Method for Leak Rate Determination

After attempting to use a pressure drop method to determine the leak rate, a more accurate and less intrusive leak rate determination method was adopted. The chosen method involved measuring the mass loss over time to determine the propellant leak rate.

Effects That Can Alter the Measured Weight at a Fixed Location

There are several factors that need to be taken into consideration in order to accurately compare two mass measurements from different times and environmental conditions, including:

- **Buoyancy** - Large volume objects weigh less than small volume objects of equal mass; this is because the larger volume displaces more air, which causes a larger upward force on the object. This buoyancy will vary with air density, which is a function of temperature, atmospheric pressure, and relative humidity.

- **Tidal variation** - The gravitational mass attraction to the sun and moon at a particular location may exhibit a variation as large as 0.003% of the acceleration of Earth gravity at certain times during the year when the sun and the moon align [32].

- **Condensation** - If there is a significant temperature difference in a high humidity environment, condensation may form on the object, thus increasing its mass [32].
• **Electrostatic effects** - The weighing mechanism of some microbalance scales can be sensitive to electrostatics. It is important to ensure the object under mass measurement is grounded to the weighing pan of the scale.

• **Magnetic attraction** - If the object being massed contains permanent magnets or is magnetised in any way, there will be an attraction to any magnetic material near or on the scale. CNAPS does not contain any permanent magnets so this effect will be minimal.

• **Center of gravity on weighing pan** - There may be variations in mass measurements if the center of gravity is placed onto different locations of the scale’s weighing pan.

• **Drafts or air currents** - Downdrafts or updrafts can be created when there is a temperature difference between the object being massed and the ambient air due to convection heat transfer.

All of these effects were addressed in developing the leak test method that utilizes comparative mass measurements of the propulsion system. Both condensation and draft effects will be minimized by allowing the unit’s temperature to equalize with the scale’s environment before weighing it. To eliminate effects of magnetic attraction and variations of center of gravity on the weighing pan, the propulsion system will be placed in the same orientation and location on the center of the weighing pan for every massing. The system being massed will be grounded through the weighing pan to reduce any electrostatic effects in addition to preventing any Electrostatic Discharge (ESD) in harming the CNAPS electronics.

Control masses will be measured during each massing and used to calculate out the effects of varying buoyancy and tidal forces. Stainless steel calibration masses of 1000 grams and 2000 grams were selected as their averaged mass equals the approximate 1500 gram mass of the propulsion system and they were readily available. The calculations to adjust one mass reading to another and determine the overall leak rate can be found in the steps for the massing leak test outlined below.

**Steps of Leak Rate Determination Using Mass Comparisons**

1. Ensure microbalance has been connected to a power source for at least 30 minutes prior to massing to ensure electronics have reached a steady state temperature.

2. Record date, time, and atmospheric conditions such as ambient temperature, relative humidity, and atmospheric pressure.
3. Measure the mass of control mass A, control mass B, and CNAPS propulsion system a minimum of 5 times each while zeroing the scale between each measurement. Average each set of measurements and label as \((m_A), (m_B),\) and \((m_C),\) respectively.

4. Use the following equation to determine the average leak rate between this set of measurements and a previous one.

\[
\frac{\delta \text{leak}}{\delta t} = \frac{m_{\text{leak}}}{t_2 - t_1}
\]

\(m_{\text{leak}} = m_{C,t_2} - m_{C,t_1}\)

where \(m_{C,t_1}\) is the mass of CNAPS at time \(t_1\) and \(m_{C,t_2}\) is the mass of CNAPS at time \(t_2\). However the measured mass of CNAPS can change without any leaks because of atmospheric changes at the two time instances. Therefore, two controlled masses, control mass A \((m_A)\) and control mass B \((m_B)\), which have zero leaks or change in mass, were taken into account to detect and eliminate fluctuations in mass measurements due to factors such as buoyancy and tidal forces. Thus the leak mass can be calculated properly as:

\[
m_{\text{leak}} = \frac{1}{2} \left[ \frac{m_{A,t_1} + m_{B,t_1}}{m_{A,t_2} + m_{B,t_2}} \right] m_{C,t_2} - m_{C,t_1}
\]

Then, the average leak rate can be determined by:

\[
\frac{\delta \text{leak}}{\delta t} = \frac{m_{\text{leak}}}{t_2 - t_1}
\]

5.1.2 Leakage Tests

Several leak tests at varying environmental conditions are outlined below. All of these leak tests utilize the leak rate determination method as described in Section 5.1.1.1. In order to qualify the propulsion system design, there are several tests which only the protoflight unit underwent; the extent to which each test is to be performed is described below. In addition, see Section 3.2.1 for the reasoning behind the 5.0 mg/hr maximum allowable leak rate requirement for the following tests.

5.1.2.1 Atmospheric Leak Test

Classification: Acceptance and protoflight units

Goal: To determine if any components, or the connections to each of the components, have any leaks that will cause an unplanned loss of propellant while exposed to ambient atmospheric pressure and temperature.
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5.1.2.2 High-Vacuum Leak Test

Classification: Protoflight unit

Goal: To determine if any components, or the connections to each of the components, have any leaks that will cause an unplanned loss of propellant while exposed to high-vacuum at room temperature.

Justification: Leakage rates higher than anticipated could diminish or completely eliminate the amount of formation flying that could be performed once in orbit. The high-vacuum environment will cause out-gassing of components and will more closely represent the vacuum of space.
Test Method: The CNAPS primary volume track will be filled with 237 grams of fuel at room temperature and pressure bled down 34.5 bar (500 psi). It will then be allowed to sit undisturbed in a high-vacuum environment where the pressure is less than $10^{-5}$ Torr for at least 7 days. The mass of the system will be measured at the start of the test, 2 days into the test, and at the end of the leak test period. The leak rate can be calculated as described in Section 5.1.1.1 using the 2 day and end of test massing values. Using the 2 day test measurement for the initial massing condition will allow for the correction of any out-gassing mass loss that occurs in the first 48 hours.

Expected Result: Any observed leakage should have a rate no greater than 5.0 mg/hr (Section 3.2.1).

5.1.2.3 Leak Test at Extended Hot and Cold Temperatures

Classification: Protoflight unit

Goal: To determine if any components, or the connections to each of the components, have any leaks that will cause an unplanned loss of propellant while exposed to ambient pressure at both cold and hot temperatures.

Justification: Leakage rates higher than anticipated could diminish or completely eliminate the amount of formation flying that could be performed once in orbit. The hot and cold temperatures will stress components and the interfaces between them as will be experienced on-orbit.

Test Method: The CNAPS primary volume track will be filled with 237 grams of fuel at room temperature and pressure bled down 34.5 bar (500 psi). It will then be allowed to sit undisturbed in ambient pressure at temperatures of $+40 \degree C$ and $-10 \degree C$ for at least 5 days each. The mass of the system will be measured at the start and end of each temperature soak. It is important to ensure that the system reaches ambient temperatures before taking each mass measurement and to place 5-6 bags of desiccant in with the system for soaks at cold temperatures. The leak rate can be calculated as described in Section 5.1.1.1. This test will be performed twice, once each for soak temperatures of $+40 \degree C$ and $-10 \degree C$. 
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5.1.2.4 Leak Test Across Vibration Testing

Classification: Protoflight unit

Goal: To determine if any components, or the connections to each of the components, have any leaks that will cause an unplanned loss of propellant while exposed to vibration loads that are representative of the launch segment of the mission.

Justification: Leakage rates higher than anticipated could diminish or completely eliminate the amount of formation flying that could be performed once in orbit. CNAPS will experience a series of intense vibration events during launch and must be able to maintain its ability to store fuel.

Test Method: The CNAPS primary volume track will be filled with 237 grams of fuel at room temperature and pressure bled down 34.5 bar (500 psi). The system will then be massed, exposed to a series of vibration profiles and massed upon completion of the test. Information regarding the test setup and vibration profiles can be found in Section 6.1.2. The leak rate can be calculated as described in Section 5.1.1.1.

Expected Result: Any observed leakage should have a rate less than 5.0 mg/hr (Section 3.2.1).

5.1.2.5 Thermal Medium-Vacuum (TVAC) Leak Testing

Classification: Acceptance and protoflight units

Goal: To determine if any components, or the connections to each of the components, have any leaks that will cause an unplanned loss of propellant while exposed to medium-vacuum (< 1 Torr) and varying thermal conditions.
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Justification: Leakage rates higher than anticipated could diminish or completely eliminate the amount of formation flying that could be performed once in orbit. The medium-vacuum, hot and cold temperature soaks, and the temperature transitions between the extremes will all contribute to the stress on the system’s pressurized fittings. This test is favoured over Section 5.1.2.3 for acceptance testing since it allows for the detection of a significant leak event such as the failure of a vent valve. Any sudden increases in the bell jar chamber pressure reading can be used as evidence towards identifying the magnitude and timing of such an event.

Test Method: The CNAPS primary volume track will be filled with 237 grams of fuel at room temperature and pressure bled down 34.5 bar (500 psi). The system will be placed in a bell jar with a roughing pump pulling a vacuum of at least 1 Torr. This vacuum setup will then be placed into a thermal chamber which will cycle between +40°C and −10°C at 2°C/minute with 12 hour soaks at each plateau. Cycling will continue for at least 4 days, with mass readings of the system taken at the start and upon completion. The leak rate can be calculated as described in Section 5.1.1.1. To avoid introducing any errors due to out-gassing effects, placing the system into a vacuum chamber for two days prior to the test is encouraged.

Expected Result: Any observed leakage should have a rate no greater than 5.0 mg/hr (Section 3.2.1).

5.1.2.6 Secondary Volume Leak Testing

Classification: Acceptance and protoflight units

Goal: To determine the leakage within the secondary volume track (the regulator valve to the thrust valves).

Justification: Although the secondary volume is not the primary storage for the propellant, it will be pressured to 6.9 bar (100 psi) almost continuously during on-orbit operations of drift recovery and formation flying.
Test Method: With the CNAPS primary volume track filled, the regulator valve will be opened to pressurize the secondary volume to $6.9 \pm 0.69$ bar (100 ± 10 psi). The system will then be allowed to sit undisturbed in a room temperature and humidity controlled environment for a period of at least 24 hours; more time can be used if it is available. Record secondary volume temperature and pressure at the beginning and end of this period. Using the ideal gas law, estimate the mass loss, taking into account the changes in both temperature and pressure.

Expected Result: Any observed leakage should have a rate no greater than 2.0 mg/hr (Section 3.2.1).

5.2 Vibration Test Plan

Classification: Protoflight unit

Goal: The goal of the vibration test is to ensure that the propulsion system can endure the dynamic and static loads during launch. The test will ensure that none of the components within CNAPS are damaged due to these loads, and that the propellant leakage is not accelerated due to a mechanical failure at one of the connection points as explored in Section 5.1.2.4.

Justification: CNAPS will experience a series of intense vibration events during launch and must be able to maintain its ability to operate within requirements after such events.
Test Method: The filled CNAPS unit will be integrated into a Generic Nanosatellite Bus Engineering Model (GNB EM) structure where mass dummies will be in place to make the total mass of the system flight-representative. Some concerns with mounting a flight candidate unit within an EM structure may exist from the EM structure having experienced too much wear from previous tests, thus possibly exposing CNAPS to higher loads than it would normally experience in a flight GNB structure. The EM structure will be placed inside the XPOD GNB. This entire structure will undergo protoflight level vibration loads. Information regarding the test setup and vibration profiles can be found in Section 6.1.2. A Long-Form Functionality Test (LFFT) will be performed before and after the test to ensure that the valves, sensors, and electronics have not been damaged. A Short-Form Functionality Test (SFFT) will also be performed in between the vibration testing of each axis.

Expected Result: All CNAPS LFFTs and SFFTs should result in a full pass. There should be no permanent deformation of any structure or major wear on the CNAPS to GNB EM interface. In addition, the system's thrust performance of pre- and post-vibration testing should remain unchanged.

5.3 Thermal Medium-Vacuum Test Plan

Classification: Acceptance and protoflight units

Goal: To verify functionality and characterize the propulsion system’s performance as it is exposed to worst-case hot and cold conditions while in a medium-vacuum environment of pressures less than 1 Torr.

Justification: In addition to ensuring that propellant leakage does not accelerate while in vacuum and various temperatures, it is important to characterize the thrust performance of CNAPS across its range of operational environmental conditions as it is critical to the success of the formation flying.
Test Method: The CNAPS primary volume track will be filled with 237 grams of fuel at room temperature and pressure bled down 34.5 bar (500 psi). The system will be placed in a bell jar with a roughing pump pulling a vacuum of at least 1 Torr. This vacuum setup will then be placed into a thermal chamber. CNAPS will then be subjected to temperature extremes of +40°C to −10°C. Information regarding the test setup and thermal profiles can be found in Sections 6.2.1 and 6.2.2. Performance thrust testing will occur at temperature plateaus of +20°C, +40°C, and −5°C; these thrust tests are detailed in Section 5.3.1.

Expected Result: All CNAPS LFFTs and SFFTs should result in a full pass and thrust performance data should be within specification as defined below.

5.3.1 Thrust Performance Testing

A set of thrust tests to be performed at each plateau of the thermal medium-vacuum testing is outlined below. The setup of the thrust performance testing is described in more detail in the results, Section 6.2.1.1.

5.3.1.1 Thrust Determination

Goal: - To characterize the thrust produced by each of the CNAPS nozzles at various temperatures.
- To verify that the pressure regulation algorithm maintains a secondary volume pressure of 6.9 ± 0.69 bar (100 ± 10 psi) during thrusting.
- To determine the average $I_{sp}$ while thrusting through each nozzle at various temperatures.

Justification: Due to limitations in the manufacturing tolerances of the nozzles, it is important to characterize the thrust produced by each nozzle and search its dependence on system temperature. This information will be used to calibrate each thruster on time to produce the desired impulse.
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Test Method: CNAPS will be filled with SF$_6$ and placed on the microbalance in the bell jar. The system will then be commanded to thrust through a single nozzle for a 5 second duration. During this time, the pressure regulation algorithm will be running and be allowed to top up the secondary volume pressure as it sees fit. Each nozzle will be commanded to thrust at least 10 times. This test will be performed in a medium-vacuum at temperatures of $+20^\circ$C, $+40^\circ$C, and $-5^\circ$C.

5.3.1.2 Short Duration Thrusting

Goal: - To characterize the thrust profile of short duration thrusts ($< 1.5$ seconds) and to attempt to calculate the impulse imparted.

- To verify that the pressure regulation algorithm maintains a secondary volume pressure of $6.9 \pm 0.69$ bar ($100 \pm 10$ psi) during thrusting.

Justification: The total impulse created during short duration thrusts may diverge from the performance trend of longer duration thrusts, and any divergence must be understood in order to reduce or eliminate the negative impact this might have on formation maintenance.

Test Method: CNAPS will be filled with SF$_6$ and placed on the microbalance in the bell jar. The system will then be commanded to thrust through a single nozzle for durations of 0.5 seconds and 1.5 seconds. During this time, the pressure regulation algorithm will be running and be allowed to top up the secondary volume pressure as it sees fit. Each nozzle will be commanded to thrust at least 10 times for each duration. This test will be performed in a medium-vacuum at temperatures of $+20^\circ$C, $+40^\circ$C, and $-5^\circ$C.
5.3.1.3 Three Nozzle Impulse Verification

Goal: - To ensure that the impulse imparted by three nozzles is equivalent to that imparted by one nozzle for three times the duration.
- To verify that the pressure regulation algorithm maintains a secondary volume pressure of $6.9 \pm 0.69$ bar ($100 \pm 10$ psi) during the thrusting of three nozzles.

Justification: For impulses requiring less than 5 seconds of a single thruster firing, a single nozzle will be used. This is to increase the duration of low impulse thrusts in order for the microbalance to accurately profile the thrust during ground testing. For impulses larger than this, three nozzles will be selected. It is important to verify that the impulse imparted by the three nozzles will be equivalent to that of one.

Test Method: CNAPS will be filled with SF$_6$ and placed on the microbalance in the bell jar. The system will then be commanded to thrust through three nozzles simultaneously for 1.67 (or 5/3) seconds. The set of nozzles used in the thrusting will be rotated such that all four combinations of triads are used at least 10 times each. During this time, the pressure regulation algorithm will be running and be allowed to top up the secondary volume pressure as it sees fit. The impulse generated will be compared, and should be equivalent, to the values of a single nozzle thrusting for 5 seconds. All thrusts should meet the impulse requirement of PR.10. This test will be performed in a medium-vacuum at temperatures of $+20^\circ$C, $+40^\circ$C, and $-5^\circ$C.

5.3.1.4 Long Duration Thrusting

Goal: - To characterize the thrust profile of long duration thrusts (15 seconds) and to calculate the impulse imparted.
- To verify that the pressure regulation algorithm maintains a secondary volume pressure of $6.9 \pm 0.69$ bar ($100 \pm 10$ psi) during the thrusting of the three nozzles for a continuous thrust of maximum duration.
- To identify thermal characteristics of the solenoid valves during long duration thrusts.
Justification: It is important to verify that the thrust level is maintained at a constant level over long duration thrusts in order to produce the commanded impulse. In addition, due to the expansion of the liquid SF$_6$ to gas through the regulator valve it is important to verify that it does not experience a hazardous temperature drop during long tests.

Test Method: CNAPS will be filled with SF$_6$ and placed on the microbalance in the bell jar. The system will then be commanded to thrust through three nozzles simultaneously for 15 seconds. The set of nozzles used in the thrusting will be rotated such that all four combinations of triads are used. During this time, the pressure regulation algorithm will be running and be allowed to top up the secondary volume pressure as it sees fit. This test will be performed in a medium-vacuum at temperatures of $+20^\circ$C, $+40^\circ$C, and $-5^\circ$C.

5.4 Satellite System-level Vibration and Thermal Vacuum Testing

In addition to all of the aforementioned propulsion system-level tests, CNAPS will undergo both a vibration and thermal vacuum test at the satellite system-level after integration. These tests are performed as acceptance-level tests where the satellite will be stressed and exercised in its final flight configuration. It should be noted that not all of the propulsion tests performed at the unit-level can be performed at the system-level. Tests such as high-accuracy leak testing and thrust testing will not be completed at the satellite system-level. Leak testing at the system-level will consist of verifying that no anomalous large leak events occurred while being exposed to launch vibration loads or a flight representative thermal vacuum environment. Long-Form Functionality Tests will verify that the electronics, solenoid valves, and temperature and pressure sensors operate as expected before, during, and after these environmental tests.
Chapter 6

Propulsion System Test Results

The following chapter presents the results for both the protoflight and acceptance-level testing of the two CNAPS propulsion units for the CanX-4/-5 mission. This consists of system vibration tests, thermal vacuum tests including thrust performance testing, and leakage tests. Details of the major test setups are also described below. For the goals, justifications, and high-level test methods for each of these tests, see Chapter 5.

6.1 Protoflight Vibration Testing

The first assembled CNAPS unit that was demonstrated to be leak tight, referred to as AA9, underwent a protoflight vibration test in order to qualify the propulsion system design. This test was completed at qualification-level magnitudes for acceptance-level durations in order to both qualify the design and allow the unit to remain flight worthy upon successful completion of the test. Major goals of the protoflight vibration test were:

- To expose the propulsion system to flight environment loads as laid out in the Polar Satellite Launch Vehicle (PSLV) manual, the launch vehicle in which CanX-4/-5 is scheduled for;
- To ensure that the structure and mechanical interfaces do not suffer any permanent deformation or significant wear;
- To assess the leak rate during the test segments of pre-vibe, across-vibe, and post-vibe;
- To ensure the functionality of the electronics, solenoid valves, and sensors remain unchanged; and
- To verify that the thrust performance of the system is not adversely affected by the vibration.

This section describes the test setup of the vibration fixture, vibration profiles, and results of the protoflight vibration test.
6.1.1 Test Setup

Rather than simply affixing CNAPS to a test fixture that interfaced directly with the vibration table, it was decided to use a more flight-like configuration to ensure a realistic transfer of the input loads, through the multiple interfaces between the propulsion system and the launch vehicle itself. This configuration consisted of integrating CNAPS into a GNB Engineering Model (EM) structure along with other masses to represent the center of gravity and mass of the various other components within satellite, as shown in Figure 6.1. The GNB structure with CNAPS and mass dummies was intended to represent a mechanical model of the flight-configured CanX-4 and CanX-5 satellites. It should be noted that all screws were torqued to the correct magnitude and were potted in place with RTV silicone to avoid loosening due to vibration as to be performed in the flight assembly.

![Image](image1.png)  
(a) Initial integration  
(b) Partial integration  
(c) Full integration  

Figure 6.1: Progression of the integration of CNAPS into GNB EM structure

The GNB EM with CNAPS was then placed into the XPOD deployment system and armed as it would be for flight. The fixture plate was then mounted to the XPOD, and finally, the entire assembly bolted to the vibration table representing the launch vehicle interface. Figure 6.2 shows the XPOD DUO mounted onto the fixture plate with GNB EM structure and a GNB mass dummy placed inside.

Upon commencement of the protoflight vibration testing, the CanX-4/-5 mission was set to make use of the XPOD DUO deployment system for flight. The XPOD DUO is a scaled up version of the XPOD GNB such that it can store and deploy two GNB sized spacecraft. When performing the vibe test with the XPOD DUO, a GNB sized mass dummy was used to represent the second satellite. However, nearing the end of the protoflight vibration test, it was confirmed that two XPOD GNBs, one for CanX-4 and one for CanX-5, would be used for the early 2014 launch. To ensure that the XPOD DUO test results were still valid as a representative way to expose CNAPS to the loads experienced during launch, a comparative vibration test was performed between the two XPODs. This comparison showed
that the spacecraft within an XPOD DUO experienced equal or higher amplification factors than spacecraft that were mounted in an XPOD GNB. Factors such as increased mass from having two spacecraft as payloads within the deployment system and a higher moment arm created by the much taller XPOD DUO, may add to this effect.

In order to record the loads experienced at various points of the test fixture and CNAPS itself, a total of 15 accelerometers were placed throughout the entire assembly. Nine accelerometers were placed on the CNAPS structure to monitor all three axes and determine if any components were moving independently of each other, as this would indicate a loose fitting or a problem with the dynamic response of the structure. The other accelerometers were used to monitor the motion and loads on the XPOD pusher plate, the XPOD door, the XPOD base plate, and the outer panel of the GNB EM structure. Figure 6.3 illustrates the placement of various accelerometers using wax for attachment and 1 cm cubes to analyse all three axes.

To verify that the functionality of CNAPS remains unchanged throughout the entire vibration test, multiple Long-Form Functional Tests (LFFTs), Short-Form Functional Tests (SFFTs) and leak tests were performed. The SFFTs which do not induce any valve actuation were used in between the vibration axes as to not alter the results of the important across-vibe leak test. An outline of the high-level steps of the vibration testing is as follows:

1. Pre-LFFT leak test;

2. CNAPS LFFT;
3. Post-LFFT leak test;

4. CNAPS visual inspection to note any anomalies before testing and mass to obtain pre-vibe measurement;

5. Integration of CNAPS into GNB EM structure and arm within XPOD;

6. CNAPS SFFT and vibration of Z-axis with profiles executed in sequence as laid out in Section 6.1.2;

7. CNAPS SFFT and vibe X-axis with profiles executed in sequence as laid out in Section 6.1.2;

8. CNAPS SFFT and vibe Y-axis (deployment axis) with profiles executed in sequence as laid out in Section 6.1.2;

9. Deployment of XPOD and visual inspection of CNAPS, XPOD, and EM structure;

10. Mass CNAPS to obtain across-vibe leak rate;

11. CNAPS LFFT; and


All three axes of the test assembly must be exposed to the frequency profiles and loads laid out in Section 6.1.2. This involved remounting the XPOD in various orientations on the vibe table as shown in Figure 6.4.
6.1.2 Flight Environment Levels

There are four types of vibration profile that run on each axis. These profiles define what acceleration level, measured in g’s, is used for testing across a range of frequencies. They also specify the upper and lower frequency bounds for each test in addition to the frequency sweep rate.

Low-level Sine Sweep

Typically, the low-level sine sweep test is performed as a standard SFL test to determine the natural frequencies of the test article. Furthermore, this test typically runs before and after each major test (sine burst, high-level sine sweep, and random vibration) to track changes in natural frequency; these changes can help determine whether any of the components or connections came loose. This test consists of a frequency sweep from 5 Hz to 2000 Hz at a rate of 2 octaves/minute, and at sinusoidal accelerations of 0.5 g [25].

Sine Burst

To simulate the quasi-static loads experienced during launch, the static and dynamic loads specified by the Polar Satellite Launch Vehicle (PSLV) manual in both the lateral and longitudinal directions are assumed to be acting simultaneously [34]. Assuming a 1.25 load factor, the vibration level for the sine burst will be 11.6 g. The duration will be for a minimum of 1 second across the frequency range of 9.9 Hz to 10.1 Hz [25].

High-level Sine Sweep

The sinusoidal levels for the high-level sine vibration sweep are presented in Table 6.1. This vibration profile contains both a constant displacement segment and a constant acceleration
segment as it sweeps from 5 Hz to 100 Hz. Again, this is performed at qualification-level magnitudes for acceptance-level durations.

Table 6.1: Sinusoidal vibration test levels [25]

<table>
<thead>
<tr>
<th>Frequency Range (Hz)</th>
<th>Qualification-level</th>
<th>Acceptance-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Displacement</td>
<td>5 - 8</td>
<td>17.25 mm</td>
</tr>
<tr>
<td>Constant Acceleration</td>
<td>8 - 100</td>
<td>4.5 g</td>
</tr>
<tr>
<td>Sweep Rate</td>
<td>5 - 100</td>
<td>-</td>
</tr>
</tbody>
</table>

Random Vibration

Table 6.2 outlines the qualification-level random vibration levels to be used. The duration of the test is specified to be 60 seconds, which is the acceptance duration as specified by [34].

Table 6.2: Random vibration test levels [34]

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Qualification-level PSD ($g^2$/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.002</td>
</tr>
<tr>
<td>110</td>
<td>0.002</td>
</tr>
<tr>
<td>250</td>
<td>0.034</td>
</tr>
<tr>
<td>1000</td>
<td>0.034</td>
</tr>
<tr>
<td>2000</td>
<td>0.009</td>
</tr>
<tr>
<td>gRMS</td>
<td>6.7</td>
</tr>
<tr>
<td>Duration</td>
<td>60 seconds</td>
</tr>
</tbody>
</table>

Order of Vibration Profiles

The order of the vibration profiles to be performed on each axis are as follows:

1. Low-level sine sweep;
2. Sine burst;
3. Low-level sine sweep;
4. High-level Sine sweep;
5. Low-level sine sweep;
6. Random vibration; and
7. Low-level sine sweep.
6.1.3 Protoflight Vibration Results

Overall, the CNAPS protoflight vibration test was a success. The propulsion system endured the full PSLV vibration specifications at qualification-levels for acceptance durations. All SFFTs were completed successfully in between each of the vibe axes and the post-vibration LFFT passed, indicating that the solenoid valves, sensors, and electronics functioned without issue. A visual inspection of the GNB EM structure and CNAPS showed no signs of wear or loosening of any screws. The only noticeable wear observed was on XPOD door surface as well as the cup and cone interfaces of the XPOD and satellite, however this is normal wear and is expected to occur during vibe.

The pre-vibe, across-vibe, and post-vibe leak rates were all found to be within specification, indicating that the system maintained a leak tight seal on the primary storage volume over the duration of the testing. See Section 6.3.2 for the detailed leak rate values.

The accelerometer data gathered from the low-level sine tests indicated that there was no unexpected shifting of the first natural frequencies of the components as the high intensity sine burst, high-level sine sweep and random vibe were performed. An example of the data collected during a Z-axis low-level sine and a X-axis low-level sine can be found in Figures 6.5 and 6.6, respectively. The first natural frequencies of the structure in these orientations were 75 Hz in the Z-axis and 70 Hz in the X-axis.
Some problems were encountered while performing the vibration profiles in the spacecraft Y-axis, more simply visualized as the XPOD deployment direction, as defined in Figure 6.4. During the first attempt at the 0.5 g low-level sine sweep of the XPOD DUO with CNAPS and the EM structure, it was found that a strong resonance was occurring. In order to safely proceed through the 5 Hz to 2000 Hz sweep without causing harm to the test specimen it was decided to perform a low-level sine sweep at 0.25 g’s. The accelerometer profile for this run can be found in Figure 6.7. This data shows that the XPOD stack, which consists of the XPOD spring, XPOD pusher plate, XPOD door, and the GNB spacecraft structures, experienced a very high amplification factor of 29 at the first natural frequency. Also shown is that the accelerations experienced by XPOD stack are much higher than those by the XPOD structure, indicating that the stack may be moving independently. To proceed in a safe manner, it was decided that the test setup be disassembled and an inspection of the assembly be performed.

Once the entire test setup was inspected and reassembled, the 0.5 g low-level sine test was run again, Figure 6.8. This profile resulted in a much lower amplification factor of 7.6. It is unknown why the high amplification factor was present before the test setup was reassembled. It may have been due to a reduction in the pre-load force acting on the stack within the XPOD, thus allowing it to move independently of the XPOD structure. It was determined
Chapter 6. Propulsion System Test Results

Figure 6.7: Accelerometer response of 0.25 g Y-axis low-level sine sweep with CNAPS in XPOD DUO, first attempt — only in-vibration (Y-axis) accelerometers shown.

That CNAPS was not the cause of the high amplification factor in the aforementioned 0.25 g low-level sine test, Figure 6.7. Any concerns of repeatability in the assembly will be resolved at the satellite system-level vibration test after the propulsion system is integrated into the spacecraft in its flight configuration.

As previously discussed, part way through the protoflight vibration test, it was decided that the CanX-4/-5 mission would use two XPOD GNBs in place of a single XPOD DUO. This resulted in the entire Y-axis of the protoflight vibration test being performed in an XPOD GNB as shown in Figure 6.9. An example of the 0.5 g Y-axis low-level sine performed with CNAPS inside the XPOD GNB can be found in Figure 6.10. The resulting first natural frequency in this orientation was 182 Hz. It was decided to not re-vibe the X and Z axes in the XPOD GNB configuration since it was shown, through examination of the acceleration plots, that CNAPS was already exposed to the required loads in these orientations. It is also important to not overstress this particular propulsion unit as it was destined to be a flight unit. Further details of the entire protoflight vibration test results can be found in [35].
Figure 6.8: Accelerometer response of 0.5 g Y-axis low-level sine sweep with CNAPS in XPOD DUO, reassembled — only in-vibration (Y-axis) accelerometers shown

Figure 6.9: XPOD GNB armed with CNAPS and GNB EM structure
Chapter 6. Propulsion System Test Results

Figure 6.10: Accelerometer response of 0.5 g Y-axis low-level sine sweep with CNAPS in XPOD GNB — only in-vibration (Y-axis) accelerometers shown
6.2 Thermal Medium-Vacuum Testing

Both assembled CNAPS units, serialized as AA9 and AMX, were subjected to a thermal vacuum (TVAC) test. This test was performed under a medium vacuum, instead of the standard high vacuum, since the focus was on testing the mechanical aspects rather than the electronics. With the voltages present in the electronics there was no concern of coronal discharge while operating within a pressure range of 50 mTorr to 1 Torr. As a precaution, the electronics were powered off while the system transitioned from 1 Torr to atmospheric pressure. Both propulsion units were subjected to a TVAC test under high vacuum at the satellite system-level. Major goals of the TVAC test were:

- To expose the propulsion system to its survival temperature limits while under vacuum conditions;
- To assess the leak rate across a set of thermal cycles between the system’s survival temperatures in vacuum;
- To characterize the thrust performance of the system at various points throughout its operational temperature range; and
- To ensure the functionality of the electronics, solenoid valves, and sensors remains unchanged.

This section describes the temperature profile and test activities, the test setup, and the results of the TVAC and system performance characteristics. It should be noted that the CNAPS electronics boards were subjected to their own full acceptance tests in high vacuum and thermal shock.

6.2.1 Temperature Profile and Test Activities

Typically, for a unit thermal vacuum or standard thermal test, the functionality checks and thermal cycling segments of the TVAC occur as one test and are performed under the same setup. However, for the CNAPS thermal medium-vacuum test, it was divided into two major segments as follows:

1. The thrust performance characterization and functionality checks of CNAPS; and
2. The thermal vacuum cycling leak test.

This division was necessary because a distinct massing measurement was required directly before and after the thermal cycling leak test, with no thrusting performed in between.

The setup for each segment of this test is described in Section 6.2.2.
6.2.1.1 Thrust Performance Characterization and Functionality Check

The purpose of this segment was to ensure the propulsion system can withstand its survival temperature extremes and can operate under specification within its operational temperature range. This needed to be accomplished without any failed sensors, valves, electronics, or components within the system.

Figure 6.11 outlines the temperature profile and activities to be performed. This temperature profile is derived from UTIAS/SFL's Thermal Vacuum Test Procedure [26]. The temperature extremes have been selected to reflect the actual on-orbit temperature extremes expected for the CNAPS units within both CanX-4 and CanX-5. Sufficient margin has been added to either side of these extremes. On-orbit data from AISSat-1’s payload, which is in a similar orbit to CanX-4/-5’s planned orbit, was used as a rough sanity check to help determine the validity of the temperatures selected.

Figure 6.11: Temperature profile for TVAC thrust performance and functionality check [26]

There are several temperature limits defined for the propulsion system. The limits in which CNAPS will be commanded to thrust are known as $T_{\text{hot,thrusting}}$ and $T_{\text{cold,thrusting}}$. The survival temperature limits of the system, known as $T_{\text{hot,survival}}$ and $T_{\text{cold,survival}}$, define a boundary in which the electronics must survive and the propellant leak rate must remain within specification, as per the requirements. The operational temperature limits for the electronics and functionality of the sensors and solenoid valves are defined as $T_{\text{hot}}$ and $T_{\text{cold}}$. All temperature limits are presented in Table 6.3.
### Table 6.3: Defined TVAC temperature limits

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{hot}$</td>
<td>+40</td>
<td>°C</td>
<td>Warmest temperature expected to tolerate when powered on.</td>
</tr>
<tr>
<td>$T_{hot,survival}$</td>
<td>+40</td>
<td>°C</td>
<td>Warmest temperature at which thrusting is performed.</td>
</tr>
<tr>
<td>$T_{hot,thrusting}$</td>
<td>+40</td>
<td>°C</td>
<td>Coldest temperature expected to tolerate when powered on.</td>
</tr>
<tr>
<td>$T_{cold}$</td>
<td>-10</td>
<td>°C</td>
<td>Warmest temperature the system is expected to survive.</td>
</tr>
<tr>
<td>$T_{cold,survival}$</td>
<td>-10</td>
<td>°C</td>
<td>Warmest temperature at which thrusting is performed.</td>
</tr>
<tr>
<td>$T_{cold,thrusting}$</td>
<td>-5</td>
<td>°C</td>
<td>Coldest temperature expected to survive.</td>
</tr>
<tr>
<td>$t_{soak}$</td>
<td>6 to 8</td>
<td>hours</td>
<td>Soak duration for system to reach steady-state temperature.</td>
</tr>
</tbody>
</table>

Activities such as the Long-Form Functionality Tests (LFFTs), performance thrust tests, and the powering-on of electronics are completed at each temperature plateau. LFFTs ensure the functionality of the solenoid valves, electronics, and sensors. Powering-on of the electronics, which occurs at the operational temperature limit after a soak at the survival temperature, ensures that energizing in this worst-case state does not cause issues. While slewing between temperature extremes, it is important to soak at each plateau for several hours. For the test setup with the microbalance inside the bell jar (Section 6.2.2.1), it takes 6 hours to reach a steady state temperature for the slew from ambient to hot, and 8 hours to slew from hot to cold.

**Performance Characterization**

The thrust performance characterization was performed at each temperature plateau for a total of four campaigns; this includes twice at +20°C, once at the commencement of TVAC and once at the end to identify any significant changes in performance. In order to achieve the goals of the performance analysis laid out in Section 5.3.1, the thrusts performed at each plateau as a thrust campaign are presented in Table 6.4. This table contains the commanded duration for each thrust, the identification of actively thrusting nozzles, the estimated impulse based on preliminary thrust testing, the number of repetitions for a particular thrust configuration, and the wait time between thrusts to allow the bell jar to pull the pressure back down to vacuum such that the back pressure remains constant value for the start of each thrust.
Table 6.4: Thrusts performed during a single thrust campaign

<table>
<thead>
<tr>
<th>Config. No.</th>
<th>Commanded Duration (s)</th>
<th>Nozzle ID</th>
<th>Estimated Impulse (mNs)$^1$</th>
<th>No. of Repeats</th>
<th>Thrust Delay (s)</th>
<th>Thrust ID No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>4.75</td>
<td>5</td>
<td>300</td>
<td>1 - 5</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2</td>
<td>4.75</td>
<td>5</td>
<td>300</td>
<td>6 - 10</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>3</td>
<td>4.75</td>
<td>5</td>
<td>300</td>
<td>11 - 15</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>4</td>
<td>4.75</td>
<td>5</td>
<td>300</td>
<td>16 - 20</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>1</td>
<td>14.25</td>
<td>5</td>
<td>360</td>
<td>21 - 25</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2</td>
<td>14.25</td>
<td>5</td>
<td>360</td>
<td>26 - 30</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3</td>
<td>14.25</td>
<td>5</td>
<td>360</td>
<td>31 - 35</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>4</td>
<td>14.25</td>
<td>5</td>
<td>360</td>
<td>36 - 40</td>
</tr>
<tr>
<td>3</td>
<td>5.0</td>
<td>1</td>
<td>47.5</td>
<td>10</td>
<td>600</td>
<td>41 - 50</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>2</td>
<td>47.5</td>
<td>10</td>
<td>600</td>
<td>51 - 60</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>3</td>
<td>47.5</td>
<td>10</td>
<td>600</td>
<td>61 - 70</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>4</td>
<td>47.5</td>
<td>10</td>
<td>600</td>
<td>71 - 80</td>
</tr>
<tr>
<td>4</td>
<td>5/3</td>
<td>1,2,3</td>
<td>47.5</td>
<td>10</td>
<td>600</td>
<td>81 - 90</td>
</tr>
<tr>
<td></td>
<td>5/3</td>
<td>1,2,4</td>
<td>47.5</td>
<td>10</td>
<td>600</td>
<td>91 - 100</td>
</tr>
<tr>
<td></td>
<td>5/3</td>
<td>1,3,4</td>
<td>47.5</td>
<td>10</td>
<td>600</td>
<td>101 - 110</td>
</tr>
<tr>
<td></td>
<td>5/3</td>
<td>2,3,4</td>
<td>47.5</td>
<td>10</td>
<td>600</td>
<td>111 - 120</td>
</tr>
<tr>
<td>5</td>
<td>15.0</td>
<td>1,2,3</td>
<td>427.5</td>
<td>1</td>
<td>960</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>1,2,4</td>
<td>427.5</td>
<td>1</td>
<td>960</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>1,3,4</td>
<td>427.5</td>
<td>1</td>
<td>960</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
<td>2,3,4</td>
<td>427.5</td>
<td>1</td>
<td>960</td>
<td>124</td>
</tr>
</tbody>
</table>

6.2.1.2 Thermal Cycling Leak Test

The thermal cycling leak test is the second segment of the overall thermal medium-vacuum test. For a standard TVAC campaign the thermal cycles would be performed without interrupting the test setup after the initial warm start, cold start and LFFTs. However, for this CNAPS thermal vacuum test, the microbalance was removed from the chamber as described in Section 6.2.2.2 following the thrust performance characterization and functionality checks. CNAPS was then massed, placed into the bell jar in the thermal chamber, and thermal cycles were commenced. A CNAPS SFFT was performed throughout the cycles, that is, all critical telemetry was polled every 5 seconds. Figure 6.12 details the temperature profile to which CNAPS was subjected. The temperature limits for this test were the operational

$^1$The value of Estimated Impulse (mNs), in Table 6.4, should only be used as a guide since it is calculated using an estimated thrust value of 9.5 mN per nozzle. This is a rough estimate of the thrust per nozzle from previous tests as it was later discovered that large variations between the nozzles exist. One of the purposes of this TVAC testing is to determine the actual thrust per nozzle and is discussed towards the end of Section 6.2.3.1.
temperature limits of the propulsion system, ensuring the system does not experience any venting events or accelerated leak rates while exposed to these temperatures. The number of cycles to which the system is exposed can vary depending on whether the operator observes any suspicious bell jar pressure fluctuations or temperature changes, although a minimum of four cycles is required.

Throughout all cycles:
SFFT - Polling CNAPS telemetry every 5 seconds.

Temperature soak for 12 hours

Initial mass measurement

All Slews at 2°C/min

Temperature soak for 12 hours

Temperature soak for 12 hours

Temperature soak for 12 hours

Temperature soak for 12 hours

Final mass measurement

Figure 6.12: Temperature profile for TVAC cycling leak test [26]

6.2.2 Test Setup

For the TVAC test, to simulate the effect of both vacuum and various temperatures, a bell jar and a roughing pump were used in combination with a thermal chamber. This equipment was both available and compatible with one another. The bell jar in this test setup was able to pull vacuum in the range of 80 mTorr to 700 mTorr. Ideally, a high vacuum environment would be used, however, these high vacuum chambers often utilize a turbopump as a fine pump to obtain vacuum levels below $10^{-6}$ Torr. This raised a concern as the turbopump may be susceptible to damage from SF$_6$ gas venting into the chamber from CNAPS, causing a sharp increase in pressure. For this reason it was decided to move forward with the bell jar and roughing pump as the source of vacuum in the thermal vacuum test.

As mentioned above, there are two major segments for this TVAC test. Each of these tests have a similar test setup, but for completeness, the details are presented below.

6.2.2.1 Thrust Performance Testing

The major Ground Support Equipment (GSE) required to perform the thrust performance and functionality testing segment of the TVAC test are as follows:
Chapter 6. Propulsion System Test Results

- Bell jar and baseplate with two electrical feedthroughs;
- Roughing pump;
- Large thermal chamber with programmable controller;
- Digital microbalance with 0.01 gram resolution and 10 Hz polling frequency;
- Digital vacuum gauge;
- Laptop computer; and
- DC power supply.

The bell jar and baseplate were placed into the thermal chamber with the roughing pump on the outside connected through the feedthrough of the thermal chamber (Figure 6.13). A digital vacuum gauge was placed onto the pump inlet such that the bell jar pressure could be measured and recorded throughout the entirety of the test.

![Figure 6.13: Bell jar placed into thermal chamber](image)

One of the major goals of TVAC was to characterize CNAPS’ thrust performance. This can be achieved by using a microbalance to measure the force exerted by the propulsion system. The microbalance needs to be vacuum compatible as it would be placed into the bell jar.

This microbalance was disassembled in order to protect the scale’s electronics from the harsh environment to which the sensing unit was exposed. Extreme care was required when handling the microbalance’s inner components, particularly the sensing unit. Figure 6.14 shows the disassembled components of the microbalance. An extension cable was used to connect the sensing unit from inside the bell jar to the electronics outside the chamber as found in Figure 6.15.
Figure 6.14: Microbalance components, from left to right, are: top housing, electronics and lower housing, sensing unit, TVAC baseplate for sensing unit, and TVAC extension cable.

(a) Electronics outside of the thermal chamber

(b) Sensing unit inside the bell jar and thermal chamber

Figure 6.15: Configuration of the microbalance for thrust performance testing.

Figure 6.16: CNAPS on the microbalance inside bell jar and thermal chamber.
CNAPS needs to be centered on top of the microbalance weighing pan and the stability of the entire setup checked to ensure that no small forces would allow the setup to wobble. The bell jar o-ring needs to be cleaned and vacuum grease applied in order ensure a high quality seal. The final setup for the TVAC thrust performance testing and functionality check is illustrated in Figure 6.16.

6.2.2.2 Leak Test

The test setup for the TVAC leak test is very similar to the test setup for the thrust performance testing and functionality checks. However, since the microbalance is not needed, as real-time mass measurements are not taken, it is removed from the bell jar. The baseplate of the bell jar is cleaned and CNAPS rested directly onto the surface. This allows for a much higher thermal conduction path between CNAPS and the baseplate, which allows for higher slewing rates of CNAPS while the thermal chamber cycles between the hot and cold survival temperatures. Removing the microbalance from the bell jar creates an unused bell jar electrical feedthrough. This feedthrough allowed temperature sensors to be attached throughout CNAPS on the critical components that ensure the system remains leak tight throughout the entire mission. Components such as the fill valve, solenoid valves, and vent valve are all examples of locations that have an increased chance of being the site of an unexpected venting event. During a venting event, temperature sensors placed around the leak may experience a significant temperature drop as SF$_6$ expands from a high pressure storage within CNAPS to the low pressure environment of the bell jar. This information can be used as a troubleshooting tool to indicate the location of the SF$_6$ venting. In addition, the bell jar vacuum pressure was recorded at an interval of 5 seconds in order to identify any dramatic pressure increases that may be attributed to propellant unexpectedly being expelled from the system. This interval was selected because the previously observed leaks from CNAPS affected the vacuum levels within the bell jar for a duration on the order of minutes to hours.

Figure 6.17: TVAC leak test setup
Figure 6.17 shows CNAPS in the TVAC leak test setup with numerous temperature sensors attached.

### 6.2.3 Thermal Medium-Vacuum Test Results

Overall, the results of both CNAPS units’ thermal medium-vacuum tests were a success. For both units, the LFFT ran successfully at each temperature plateau as the test plan requested in Figure 6.11. This indicates that the combination of the medium-vacuum and temperature extremes did not negatively affect the mechanical operation of the solenoid valves, passive control valves, sensors, or tubing connections.

An overview of the thermal-medium vacuum test results has been divided into the following two sections, thrust performance analysis and leak test results. Some details are presented in these sections to provide insight to the analysis performed, however due to the volume of raw data, not all of it could be presented in this thesis.

#### 6.2.3.1 Thrust Performance Analysis

As mentioned in the thrust performance test setup, a microbalance was used to record the force exerted from the expelling SF\(_6\) gas through CNAPS’ nozzle(s). The microbalance was recording at its maximum polling rate, approximately 10 Hz, throughout the entirety of the thrust performance campaign at each plateau. This 10 Hz polling frequency was limited by the microbalance’s capabilities, ideally this value should be as large as possible. In addition, the vacuum gauge on the bell jar was polling the chamber pressure at 5 second intervals in order to monitor the back pressure acting on the nozzles at the start of each thrust. CNAPS telemetry, such as secondary volume pressure, all nine temperature sensors, bus voltage and current, and regulator valve cycles, were also polled, at 30 second intervals. This CNAPS telemetry was used to identify the health status of the propulsion system throughout testing. It is also important to note that throughout the thrust campaign, the pressure regulation mode of the CNAPS on-board software was set to continuous mode, meaning that the regulator valve will open as necessary to maintain a secondary volume pressure of 6.9 ± 0.69 bar (100 ± 10 psi).

#### Collection and Post-Processing of Raw Data

There are several steps to post-processing the raw microbalance data from each campaign. The top plot in Figure 6.18 shows an example of the raw data gathered from a 15 second, 3 nozzle thrust, in ambient temperature. The sharp rise in the mass reading results from the force of the CNAPS thrust vector pushing onto the scale while the sharp decrease to a steady state value results from the thrust valve closing, thus stopping the flow of SF\(_6\) from the exit area of the nozzle. One can observe that there is an offset from the steady mass reading.
before and after the thrust has been performed. This difference stems from the mass of SF$_6$ fuel being expelled from CNAPS and is noticeable throughout the duration of the thrust, as can be observed from the downward slope of the mass reading. This mass loss effect must be removed as it complicates the calculation of the thrust and the impulse imparted.

![Mass Measurement - Raw (g)](image1.png)

![Mass Measurement - Processed (g)](image2.png)

**Figure 6.18**: Example of the data collection on a 15 second thrust

To remove the mass loss effect through the duration of the thrust, a bias curve representing this mass loss is created. This curve is generated by first subtracting a section of averaged steady state values on either side of the thrust in order to remove the noise in the microbalance reading. The difference between these values is known as the fuel consumed across the particular thrust; this value will be used for later analysis of the thrust’s specific impulse. At this point, a constant fuel consumption rate across the entirety of the thrust is assumed. The new thrust plot, shown as the bottom plot of Figure 6.18, is generated after removing the fuel consumption bias from the mass balance data.

With the bias in the mass measurement removed, the thrust level can be easily calculated. Using $F = ma$, where $F$ is the thrust applied by CNAPS in millinewtons (mN), $m$ is the mass reading from the microbalance in grams (g), and $a$ is the acceleration due to gravity...
Figure 6.19: Sample 15 second duration thrust using three nozzles — pressure regulation ripples in thrust value and large increase in back pressure are visible on Earth, equal to 9.81 m/s². The same thrust, as shown in the raw mass balance data, Figure 6.18, is now presented in Figure 6.19, where the thrust in millinewtons has been calculated for the duration of the thrust.

Also plotted in Figure 6.19 is the vacuum chamber pressure on the same time scale as the thrust is being performed. A sharp rise in the chamber pressure is observed as the thrust commences. The pressure continues to increase throughout the duration of the thrust, since the roughing pump attached to the bell jar does not have the ability to remove the SF₆ gas from the chamber at the rate it is being expelled from CNAPS. This pressure increase in the bell jar chamber fundamentally acts as a back pressure on the nozzles of CNAPS. This back pressure can affect essential thrust characteristics such as the specific impulse, thrust level, and thus, the total impulse imparted. A wait time of several minutes between thrusts is necessary to ensure the chamber pressure is given sufficient time to reach a steady vacuum level before starting each thrust, and reduce the influence of back pressure. The chamber back pressure across two approximately 50 mNs and two 400 mNs impulses is shown in Figure 6.20. It is also because of this effect that the long 15 second, three nozzle thrust, is not used for average thrust level or specific impulse characterization of the system as
presented later in this section. However, this 15 second thrust can be used to verify that the pressure regulation algorithm can maintain a secondary volume pressure for long duration thrusts.

![Figure 6.20: Back pressure variations caused by two 50 mNs impulses followed by two 400 mNs impulses with wait time in between to allow for bell jar vacuum pull-down to steady state](image)

Following the development of the thrust over time plot (Figure 6.19), the impulse, in millinewton seconds (mNs), can be calculated by integrating the force across each time step over the entire duration of the thrust. Even though the duration of a thrust is commanded by the electronics, the output duration of the thrust can be calculated using the rising and falling edge of the thrust as determined by a specified threshold. A three sample offset (approximately 0.3 seconds) is used on either side of these edges to adjust for the internal delay of the microbalance along with the ramp-up and ramp-down time of the thrust. The average thrust, $F_{\text{thrust, avg}}$, can be calculated by dividing the impulse imparted by the nozzles, $I$, by the calculated duration of the thrust, $t_{\text{thrust}}$, as follows:

$$F_{\text{thrust, avg}} = \frac{I}{t_{\text{thrust}}}$$  \hspace{1cm} (6.1)

This average thrust is important for calibration of the thrust durations as each nozzle produces a different force based on manufacturing tolerances. Finally, the $I_{sp}$, or specific impulse, of the thrust can be calculated using the impulse imparted, $I$, the acceleration due to gravity, $g$, and the previously calculated fuel consumed across the thrust, $m_{fc}$, as follows:

$$I_{sp} = \frac{I}{(gm_{fc})}$$  \hspace{1cm} (6.2)

The above analysis is performed for each individual thrust commanded in a campaign at
each temperature plateau within the thermal vacuum test. In doing so, the values of average thrust level (mN), specific impulse (s), duration (s), fuel consumed (g), and impulse (mNs) for each thrust can be calculated.

During early attempts to obtain thrust performance characterizations of the propulsion system, a setup in the vacuum of a bell jar without a thermal chamber was used. It was discovered that the HVAC (heating, ventilation, and air conditioning) system of the building was not able to maintain the constant temperature required for the test. Since the steady state vacuum pressure of the bell jar is a function of temperature, this effect was observed in the chamber pressure as multiple thrusts were performed throughout a 17 hour period (Figure 6.21). This shifting temperature, and thus varying vacuum pressure, caused noticeable error. Therefore, all further thrust tests were performed under the accurate (±2°C) thermostatic control of a thermal chamber. This ensured that the fluctuations in vacuum pressure, as thrusts are performed, are consistent throughout a thrust campaign.

![Figure 6.21: Back pressure across a 17 hour period of 120 thrusts with the variation in settling pressure caused by ambient temperature variations](image)

**Pressure Regulation and Regulator Valve Cycles**

As the mass exits the secondary volume during a thrust, a drop in pressure is observed on the pressure sensor attached to this volume. To compensate for this pressure drop, the on-board software commands the regulator valve to open for a brief moment to top up the pressure to 6.9 ± 0.69 bar (100 ± 10 psi). A negative effect in doing so is the constant build up of cycles on the regulator solenoid valve. These solenoid valves have a rated lifetime of 1,000,000 cycles. A budget was created to ensure the valves will not exceed their rated number of cycles. It is expected that the regulator valve will only see approximately 1,500 cycles throughout the entire thermal medium-vacuum test, which includes four full thrust
performance campaigns, and approximately 5,000 cycles for one full tank of fuel throughout the mission; the regulator valve was detailed since it will be the most cycled valve. As such, there is significant margin in the regulator valve lifecycle. However, to be safe, all regulator valve cycles used during testing were recorded and stored in a single log. The calculated number of expected regulator valve cycles is significantly less than the number approximated at the time of the CNAPS design phase; this difference stems from the implementation of the pressure regulation algorithm and the additional knowledge regarding its performance [28].

The presence of the active pressure regulation algorithm can be easily observed in a long duration thrust. In Figure 6.19 thrust versus time plot, one can examine the ripple effects along the top of the thrust. The slight increases and decreases in the thrust are a result of the varying pressure within the secondary volume. The cycling is due to the opening and closing of the regulator valve as it controls the flow of the high pressure SF$_6$ from the primary storage volume to the secondary volume.

Sample Data - Ambient Thrust Performance Campaign

A sample of the results from the post-processing of the final ambient temperature thrust performance campaign of the CNAPS unit, serial number AMX, is provided below. Plots of specific impulse, average thrust level, duration, impulse, fuel consumed, and initial back pressure show the results of each particular thrust in the ambient performance campaign. Each of the 124 thrusts was given an identification number within the X-axis of the plot; this number corresponds to the “Thrust ID No.” in Table 6.4. The configurations in plots Figures 6.22, 6.23, 6.24, 6.25, 6.26, and 6.28 also correspond with the “Config. No.” column in Table 6.4. The following results were gathered at a temperature of $+20^\circ$C in a medium-vacuum environment. Each individual bar within the following plots represents a single thrust.

Figure 6.22 shows the measured duration of each thrust across the entire performance campaign at ambient temperature. Each configuration uses a different thrust duration as observed. Since the controlled variable in these tests is the commanded duration, the variation within each configuration is very small.
Figure 6.22: Summary of measured thrust durations from unit AMX in vacuum at +20°C.

Figure 6.23 presents the average thrust across each commanded thrust. Configurations 4 and 5 have an average thrust level that is approximately three times larger than the other configurations because three nozzles were fired simultaneously in this case compared to a single nozzle fired in other configurations. In Configuration 3, there are four distinct sets of thrust levels, found as thrust IDs 41 to 50, 51 to 60, 61 to 70 and 71 to 80. Each of these sets represents the thrusting of a different nozzle 1 through 4, respectively. As there are manufacturing limitations in the tolerances of the nozzle geometry, a different average thrust level is generated from each nozzle. Further, the geometry of the tubing path, from the thrust valve to the nozzle, is different for each nozzle, which may also play a small part in the variations in thrust. It is worth noting that the variations in pressure drop observed through each of the thrust tubes, due to the small inner diameter tubing, is minimal since identical length tubing was used for the path to each nozzle. The secondary volume pressure for all of the thrusts is within the specification of 6.9 ± 0.69 bar (100 ± 10 psi). This variation of between each nozzle force also causes four distinct plateaus within Configurations 2, 4 and 5. The more scattered data of Configuration 1 is due to the limitation of the mass balance at short duration thrusts, capturing only a few data points within a span of 0.5 seconds, as shown in Figure 6.27.
Chapter 6. Propulsion System Test Results

Figure 6.23: Summary of average thrust levels from unit AMX in vacuum at +20°C

Figure 6.24 illustrates the impulse imparted by each thrust. Again, it can be seen that there are four distinct sets of thrusts within Configuration 2, 3, 4, and 5. As expected, the impulses imparted vary with the thrust produced by each nozzle. These results have been generated with a constant commanded duration within each configuration. For on-orbit operations, the average thrust produced by each nozzle, will be used to calibrate the commanded durations in order to produce the correct impulse for each thrust.

Figure 6.24: Summary of impulse imparted per thrust from unit AMX in vacuum at +20°C
Figure 6.25 shows the fuel consumed by each thrust. Fuel consumed is one of the first parameters of the thrust calculated during the post-processing. It is measured as indicated in Figure 6.18.

![Figure 6.25: Summary of fuel consumed per thrust from unit AMX in vacuum at +20°C](image)

Figure 6.25: Summary of fuel consumed per thrust from unit AMX in vacuum at +20°C

Figure 6.26 presents the calculated specific impulse, or $I_{sp}$, in seconds for each thrust performed in the AMX unit ambient temperature close-out performance campaign. Ideally, for this plot, all thrust ID’s would have the same specific impulse throughout the entire campaign; all of the values presented are directly comparable to one another. However, one can observe that the $I_{sp}$ values for Configurations 1 and 2 are much lower than those found in other configurations. Initially, this may be alarming, but upon further investigation, it is found that the fuel consumed by each thrust within Configurations 1 and 2 are quite small. Thrusts of 0.5 seconds and 1.5 seconds duration use approximately 0.03 grams and 0.06 grams of propellant per thrust, respectively. The resolution of the microbalance, 0.01 grams, is only a few times smaller than the fuel consumption values being measured in this case. In addition, at the end of a thrust, when the thrust dissipates, the microbalance sometimes registers a small fluctuation in its reading as it settles from the removal of the force. This small fluctuation can be falsely averaged into the post-thrust mass and increase the calculated amount of fuel consumed. Figure 6.27 illustrates a 0.5 second thrust with these small fluctuations occurring afterwards. In this particular case, the fuel consumption was falsely increased by approximately 0.01 grams, resulting in a 50% increase. The specific impulse is equally decreased as it is directly related to the fuel consumed across the thrust. Due to the difficulty and lack of repeatability of accurately determining the fuel consumed...
from these short duration thrusts (0.5 and 1.5 seconds), it was decided to use longer thrust durations of 5 seconds, Configuration 3, to characterize the $I_{sp}$ and average thrust per nozzle. The current minimum specific impulse requirement is 30 seconds. Discussions regarding the overall $I_{sp}$ performance of the system can be found near Figure 6.31 in the Specific Impulse Comparison section.

Figure 6.26: Summary of specific impulse per thrust from unit AMX in vacuum at $+20^\circ$C

Figure 6.27: Sample 0.5 second duration thrust showing number of data points collected
Figure 6.28 illustrates the initial vacuum pressure within the bell jar at the commencement of each thrust. This pressure acts as a back pressure on the nozzles, thus affecting the thrust generated. The graph confirms that the back pressure started at a constant value of 0.17 to 0.18 Torr, which is an acceptable range for back pressures as it is much lower than the 3.31 Torr caused by long 15 second duration thrusts. The difference of force generated by a thrust with a back pressure of 0.17 to one of 0.18 Torr is not detectable with the current setup without running a very large sample size. The reason the back pressure for Thrust ID 1 is higher than the remaining thrusts is because the bell jar was not provided sufficient time to pull vacuum before the initiation of the automated testing, this did not affect the overall results of the campaign.

Figure 6.28: Summary of initial vacuum back pressure for each thrust from unit AMX at +20°C

**Thrust Level Comparison and Calibration**

As mentioned above, the single nozzle 5 second thrusts will be used to compare the thrust levels between all nozzles of both propulsion units. This thrust configuration was used in order to avoid the low signal-to-noise ratio of 0.5 and 1.5 second duration thrusts, as well as avoid the back pressure increase observed for long 15 second duration thrusts. Figure 6.29 provides an example of a 5 second thrust at +20°C that is used for the thrust level and specific impulse comparisons below. It is observed that the back pressure across this thrust increases from 0.17 Torr to 0.58 Torr, which is much lower than the 0.17 Torr to 3.0 Torr increase observed on a 15 second duration with a 3 nozzle thrust at +20°C (Figure 6.19).

The thrust level calculated across each actuation was averaged for each thrust campaign,
Figure 6.29: Sample 5 second duration thrust using a single nozzle with slight increase of back pressure shown

one for each propulsion unit and at each temperature plateau. All of the data collected under vacuum within the bell jar was performed with active pressure regulation to 6.9 ± 0.69 bar (100 ± 10 psi). The thrust campaigns available for comparison are as follows: baseline ambient, hot, cold, and closeout ambient campaigns from the thermal medium-vacuum testing (TVAC) for both units, as well as the two pre-vibration thrust campaigns performed on unit AA9. Figure 6.30 compares the averaged thrust of the four nozzles of unit AA9 and the four nozzles of AMX. It is clearly observed that the thrust produced varies with nozzle. As mentioned above, this may be due to manufacturing tolerances of the nozzle geometry or from the customized bending of each thrust tube path, although the tubes were bent in a similar fashion for either CNAPS unit. The standard deviation from the sample of thrusts performed at each plateau is indicated as error bounds on the plot. The intention of these error bars is to provide an idea of the variability within each data set with respect to the others. During AA9’s cold thrust campaign, there was an issue with the microbalance as the signal-to-noise ratio increased significantly. This affected the standard deviation for this set of thrust data, as shown in Figure 6.30. The force for each nozzle varied by a maximum of 11% from the higher thrust at cold (−5°C) to the lower thrust at hot (+40°C).

In order to generate the desired impulses on-orbit, the thrust for each nozzle will be
loaded onto the CNAPS on-board software as a calibration tool. This software will calculate and command a thrust of a certain duration for each nozzle using the desired impulse and calibration thrust level for that nozzle. Table 6.5 summarizes the thrust generated by each nozzle in vacuum at +20°C. This data is taken from the closeout ambient thrust campaign that concluded the thermal vacuum test. These values were used for thrust calibration because this particular campaign occurred in the middle of the thrusting temperature range and at a point when the SF6 fuel mass was at a half. This will mitigate any effects of a changing fuel mass on the thrust performance, although, several thrust campaigns were performed to ensure that this effect, if present, is not significant. It was decided that only a single calibration table, representing the data at +20°C, is to be implemented. During development, there was insufficient time for the implementation of various calibration tables over temperature. The data at +20°C was selected due to its close proximity to the average CNAPS temperature throughout nominal thrusting operations. However, the average thrust per nozzle data is available for both hot and cold temperatures, allowing for the possible future implementation of this calibration over temperature on the propulsion system.

Table 6.5: Average thrust level per nozzle of both CNAPS flight units in vacuum at +20°C

<table>
<thead>
<tr>
<th>Nozzle No.</th>
<th>Average Thrust (mN)</th>
<th>CNAPS-AA9</th>
<th>CNAPS-AMX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.83</td>
<td>10.17</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>9.65</td>
<td>11.06</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>11.43</td>
<td>7.62</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8.87</td>
<td>10.55</td>
<td></td>
</tr>
</tbody>
</table>
Comparison of Average Thrust per Nozzle Over Temperature with 100 psi Pressure Regulation and 5 second Duration

Figure 6.30: Thrust values compared among all nozzles of both propulsion units using 5 second thrusts
Specific Impulse Comparison

A comparison of the $I_{sp}$ calculated for each nozzle and averaged across each thrust campaign is presented in Figure 6.31. As performed with the thrust level comparison, the single nozzle, 5 second thrusts will be used to compare the specific impulses. The thrust campaigns available for comparison are as follows: baseline ambient, hot, cold, and closeout ambient campaigns from the thermal medium-vacuum testing (TVAC) for both units, as well as the two pre-vibration thrust campaigns performed on unit AA9. Again, the standard deviation of each data set is indicated on this plot as errors, where the intent is to compare the variability of each data set. All of the calculated specific impulses pass the minimum specific
impulse requirement for CNAPS of 25 seconds. However, it is desired for the specific impulses to be as large as possible as this value directly affects the CanX-4/-5 fuel budget. Currently the fuel budget assumes an $I_{sp}$ of 30 seconds and a leak requirement of 5.0 mg/hr, see Section 3.2.1. With the leak rates currently being observed, as described in Section 6.3, the fuel budget closes with a 20% worst-case fuel margin. As such, with the specific impulse values of all nozzles being greater than 30 seconds, at all conditions, the performance standards set out for the purpose of the formation flying mission can be confirmed as being met. It is observed that the specific impulse values at hot ($+40\degree C$) are larger than the specific impulse values at cold ($-5\degree C$) by a maximum value of 11%.

Table 6.6 summarizes the calculated $I_{sp}$ values for each unit and at each temperature plateau.

<table>
<thead>
<tr>
<th>Nozzle No.</th>
<th>Campaign</th>
<th>Temperature ($^\circ C$)</th>
<th>Specific Impulse, $I_{sp}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CNAPS-AA9</td>
<td>CNAPS-AMX</td>
</tr>
<tr>
<td>1</td>
<td>Ambient Baseline</td>
<td>+20</td>
<td>39.3</td>
</tr>
<tr>
<td></td>
<td>Hot</td>
<td>+40</td>
<td>38.2</td>
</tr>
<tr>
<td></td>
<td>Cold</td>
<td>-5</td>
<td>34.1</td>
</tr>
<tr>
<td></td>
<td>Ambient Closeout</td>
<td>+20</td>
<td>35.7</td>
</tr>
<tr>
<td>2</td>
<td>Ambient Baseline</td>
<td>+20</td>
<td>38.3</td>
</tr>
<tr>
<td></td>
<td>Hot</td>
<td>+40</td>
<td>38.3</td>
</tr>
<tr>
<td></td>
<td>Cold</td>
<td>-5</td>
<td>36.1</td>
</tr>
<tr>
<td></td>
<td>Ambient Closeout</td>
<td>+20</td>
<td>33.8</td>
</tr>
<tr>
<td>3</td>
<td>Ambient Baseline</td>
<td>+20</td>
<td>40.2</td>
</tr>
<tr>
<td></td>
<td>Hot</td>
<td>+40</td>
<td>37.8</td>
</tr>
<tr>
<td></td>
<td>Cold</td>
<td>-5</td>
<td>37.1</td>
</tr>
<tr>
<td></td>
<td>Ambient Closeout</td>
<td>+20</td>
<td>35.2</td>
</tr>
<tr>
<td>4</td>
<td>Ambient Baseline</td>
<td>+20</td>
<td>38.8</td>
</tr>
<tr>
<td></td>
<td>Hot</td>
<td>+40</td>
<td>37.4</td>
</tr>
<tr>
<td></td>
<td>Cold</td>
<td>-5</td>
<td>35.6</td>
</tr>
<tr>
<td></td>
<td>Ambient Closeout</td>
<td>+20</td>
<td>34.0</td>
</tr>
</tbody>
</table>

**Thrust Duration Comparison**

A comparison of the thrust durations was performed to ensure that each nozzle applies a force for the same amount of time. Variations in the duration of a thrust may stem from the geometry of the tubing path from the thrust valve to the nozzle. The length of each thrust tube is the same to mitigate this possible issue. Figure 6.32 provides a comparison between the 0.5, 1.5 and 5 second commanded duration thrusts for the CNAPS unit AMX, measured
at +20°C in vacuum. As seen in this plot, the variability of the thrust duration between each nozzle is on the order of 0.06 seconds, smaller than the 0.1 second polling period of the microbalance. It can be observed in Figure 6.32 that the duration is consistently measured to be 0.25 seconds shorter than commanded. This discrepancy is due to the method of post-processing in identifying the thrust rising and falling edges of each actuation. This figure is best used for comparison between variation of each thrust and among nozzles. The post-processing method was corrected for the analysis presented in Figure 6.33.

![Measured Duration of Single Nozzle Thrusts at +20°C](image)

Figure 6.32: Measured duration values compared against commanded duration for individual nozzles of CNAPS unit AMX

To ensure that this variability is small even for the minimum impulse thrusts, a large sample size of 400 thrusts was taken to study the duration of a 0.5 second commanded thrust. Figure 6.33 shows the results of the measured duration of these 400 thrusts where each nozzle was fired 100 times. The first 100 samples are measured from Nozzle 1, the second 100 samples from Nozzle 2, the third 100 samples from Nozzle 3, and the fourth set of 100 thrust samples from Nozzle 4. All of these thrusts were performed within 0.09 seconds of the desired duration, while the standard deviation was equal to 0.05 seconds. As one examines the point plot of Figure 6.33, it can be observed that the measured durations lay close to the 0.6, 0.5 or 0.4 second mark with noticeable space in between. This confirms that the microbalance is unable to resolve durations better than its 0.1 second polling period. Although this is a high performance microbalance, the polling rate cannot be increased for this particular model.
Calibrated Impulse Testing

All of the aforementioned thrust testing consisted of thrusting with each nozzle for an equivalent duration, effectively ignoring the differing force produced by the nozzles. This does not allow a consistent impulse to be commanded. During flight operations, as set out by the system requirements (Section 3.2), it is critical that CNAPS produces the impulse requested by the formation flying algorithm. To test this, the average thrust levels of each nozzle, provided in Table 6.5, were defined as parameters within CNAPS’ on-board software; these are known as the calibration thrust level values. The values were taken from the environmental conditions of +20°C in vacuum as this is the closest test value to the nominal operating temperature during formation flying. Future revisions of this thrust calibration can include the small variations observed in thrust levels at different temperatures. When a commanded impulse is provided to CNAPS, the on-board software uses the calibrated thrust level from each nozzle to calculate the duration for which each nozzle is actuated.

This test was performed on CNAPS unit AMX at +20°C in vacuum. Each nozzle was commanded to thrust individually as well as a part of each triad combination. A total of 80 thrusts were performed across these configurations. Figure 6.34 shows the measured impulses from all 80 commanded thrusts. It is observed that all measured impulses are below the 50 mNs commanded impulse level. However, this remains a promising result as further calibration can be performed to increase the accuracy of the impulse provided. The variation between the measured impulses was found to be relatively small, Table 6.7 provides the averaged impulses and the standard deviation for each configuration.
Since all measured impulses are lower than the commanded value, it is likely that the calibrated thrust values loaded onto the on-board software are overestimating the actual force from each nozzle. The current thrust test setup only allows for the back pressure within the bell jar to be reduced to approximately 100 mTorr; even though this is a fraction of the atmospheric pressure, it is still several orders of magnitude higher than the pressure experienced in low Earth orbit. This lower pressure in space should theoretically increase the force provided by each nozzle. Although the exact percentage of increase has not been determined, it will be studied throughout the CanX-4 and CanX-5 drift recovery manoeuvre, where the on-orbit performance of CNAPS will be investigated. Table 6.7 can be used to perform another layer of calibration to further increase the accuracy of which CNAPS can perform requested impulses.
Table 6.7: Summary of impulses imparted by commanding a 50 mNs impulse using a calibrated thrust level per nozzle in vacuum at +20°C for unit AMX

<table>
<thead>
<tr>
<th>Nozzle No.</th>
<th>Impulse Imparted (mNs) Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49.06</td>
<td>0.18</td>
</tr>
<tr>
<td>2</td>
<td>48.06</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>47.65</td>
<td>0.23</td>
</tr>
<tr>
<td>4</td>
<td>47.70</td>
<td>0.24</td>
</tr>
<tr>
<td>1,2,3</td>
<td>47.31</td>
<td>0.15</td>
</tr>
<tr>
<td>1,2,4</td>
<td>47.37</td>
<td>0.19</td>
</tr>
<tr>
<td>1,3,4</td>
<td>47.76</td>
<td>0.25</td>
</tr>
<tr>
<td>2,3,4</td>
<td>48.48</td>
<td>0.22</td>
</tr>
</tbody>
</table>

6.2.3.2 TVAC Leak Test Results

In addition to the thrust performance characterization and functionality checks performed throughout the TVAC test, leak tests were performed over thermal vacuum cycles for each CNAPS unit. Descriptions of the temperature profiles (Section 6.2.1.2) and test setup (Section 6.2.2.2) used for the leak test were provided.

Both units successfully passed their thermal vacuum leak tests. All leak rates were demonstrated to be under the requirement of 5.0 mg/hr while the system was exposed to its survival temperature limits of +40°C to −10°C. Detailed results of this leak testing can be found in Section 6.3.3

6.3 Leak Test Results

The ability of the CNAPS propulsion system to maintain a propellant leak rate below the required value is critical to the success of the mission. The following section describes the results of the leak testing as outlined in the high-level test plan, Section 5.1. These tests were designed to subject the propulsion units to the environmental conditions expected throughout the entire duration of the mission, including the launch segment. As mentioned before, the first assembled unit experienced protoflight tests which included additional testing above and beyond the typical acceptance-level tests performed on subsequent units. Details of the maximum allowable leak rate requirement for CNAPS, 5.0 mg/hr, can be found in Section 3.2.1.
6.3.1 Results of the Protoflight Unit Preliminary Leak Testing

Prior to the major leak tests during vibration and thermal vacuum, the protoflight unit of CNAPS underwent leak tests in ambient conditions, high vacuum conditions, and extended soak durations at hot and cold temperatures in ambient pressure. Table 6.8 summarizes the leak rates experienced throughout these tests by unit AA9. It was found that a high vacuum condition of pressures less than $10^{-5}$ Torr did not cause the system’s leak rate to increase past the 5.0 mg/hr requirement.

Leak tests in both hot and cold temperatures at an ambient pressure were also performed. The survival temperature limits of the propulsion system were initially set at $+55^\circ C$ to $-25^\circ C$ for these tests. The leak rate was observed to increase to approximately 30 mg/hr for the hot soaks at $+55^\circ C$. It was hypothesized that the thermodynamic properties of the propellant mixture were affected by the supercritical temperature of sulfur hexafluoride at $+45^\circ C$. According to literature, the thermal diffusivity vanishes as one approaches the supercritical point of SF$_6$. “The time required for a fluid sample to reach thermal equilibrium increases rapidly as one approaches the critical-point. Time constants reach hours and even days for sample sizes of a few millimeters thickness [36].” A hot soak test was performed at $+40^\circ C$ in order to investigate the dependence of SF$_6$’s leak rate on temperature. It was suspected that this lack of thermal diffusivity may cause disturbances within the fluid, in which case, the pressure would increase above 68.9 bar (1000 psi) resulting in venting from the vent valve and thus increasing the observable leak rate at high temperatures. It is difficult to know whether the high leak rate resulted from this lack of thermal diffusivity or can be attributed to the degraded performance of a fitting or valve.

The extended cold leak test resulted in complete propellant venting during a cold soak at $-25^\circ C$, an anomalous result. The test was repeated three times successfully where an in-spec leak rate was measured, as shown in Table 6.8. This anomalous result was later explained through TVAC leak tests. It was determined that it was most likely due to a failure of the mechanical back pressure regulator valve at the cold temperature of $-25^\circ C$.

To ensure there were no major leak events within the survival temperature limits of the system, several months of TVAC testing was performed as detailed in Section 6.3.3. The results of this extensive TVAC testing were used to dispose of the negative results found in Table 6.8.

It should also be noted that the finalized flight-like fill procedure with pressure bleed down had not yet been implemented for the hot and cold leak tests summarized in Table 6.8. These results are only preliminary leak test data; nonetheless they are presented here for completeness. The propulsion system’s ability to hold propellant was more accurately demonstrated during the vibration and thermal vacuum leak tests which simulated the most realistic flight environments.
Table 6.8: Preliminary leak test rates for testing of CNAPS unit AA9

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Pressure</th>
<th>Temperature (°C)</th>
<th>Time at Conditions</th>
<th>Leak Rate (mg/hr) Across-Test</th>
<th>Post-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Vacuum</td>
<td>10⁻⁵ Torr</td>
<td>+20</td>
<td>11 days</td>
<td>4.8</td>
<td>n/a</td>
</tr>
<tr>
<td>Ambient</td>
<td>1 atm</td>
<td>+20</td>
<td>10 days</td>
<td>1.32</td>
<td>n/a</td>
</tr>
<tr>
<td>Hot 1</td>
<td>1 atm</td>
<td>+55</td>
<td>4 days</td>
<td>33.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Hot 2</td>
<td>1 atm</td>
<td>+55</td>
<td>4 days</td>
<td>32.6</td>
<td>n/a</td>
</tr>
<tr>
<td>Hot 3</td>
<td>1 atm</td>
<td>+55</td>
<td>4 days</td>
<td>30.0</td>
<td>10.6</td>
</tr>
<tr>
<td>Hot 4</td>
<td>1 atm</td>
<td>+40</td>
<td>4 days</td>
<td>10.4</td>
<td>2.6</td>
</tr>
<tr>
<td>Cold 1</td>
<td>1 atm</td>
<td>-25</td>
<td>4 days</td>
<td>1940.0</td>
<td>3.6</td>
</tr>
<tr>
<td>Cold 2</td>
<td>1 atm</td>
<td>-25</td>
<td>4 days</td>
<td>3.5</td>
<td>2.3</td>
</tr>
<tr>
<td>Cold 3</td>
<td>1 atm</td>
<td>-25</td>
<td>4 days</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Cold 4</td>
<td>1 atm</td>
<td>-25</td>
<td>4 days</td>
<td>5.0</td>
<td>3.8</td>
</tr>
</tbody>
</table>

6.3.2 Vibration Leak Test Results

The pre-vibe, across-vibe, and post-vibe leak rates were all found to be under the primary volume leak rate requirement of 5.0 mg/hr. Table 6.9 provides a summary of the measured leak rates at various points throughout the protoflight vibe of CNAPS unit AA9.

Table 6.9: Leak rates across protoflight vibration test of CNAPS-AA9

<table>
<thead>
<tr>
<th>Test Section</th>
<th>Measured Leak Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-LFFT</td>
<td>3.1 mg/hr</td>
</tr>
<tr>
<td>Post-LFFT and pre-vibe leak rate</td>
<td>2.6 mg/hr</td>
</tr>
<tr>
<td>Full Z- and X-axes and partial Y-axis vibe</td>
<td>3.3 mg/hr</td>
</tr>
<tr>
<td>Second attempt at Y-axis vibe</td>
<td>2.6 mg/hr</td>
</tr>
<tr>
<td>Ambient rate after second attempt Y-axis</td>
<td>2.6 mg/hr</td>
</tr>
<tr>
<td>Third attempt Y-axis (with XPOD GNB)</td>
<td>2.6 mg/hr</td>
</tr>
<tr>
<td>Post-vibe and post-LFFT</td>
<td>2.2 mg/hr</td>
</tr>
</tbody>
</table>

6.3.3 Thermal Medium-Vacuum Leak Test Results

The thermal medium-vacuum leak (TVAC) testing represents the most realistic flight environment that the propulsion system experienced through its protoflight and acceptance-level testing. Figure 6.12 shows the thermal cycle profile to which each CNAPS unit was subjected. This profile does not perfectly slew the system as it would experience during the transitions between eclipse and sunlight. The maximum slew rate of the test article in this setup, 0.4 °C/min, is slightly lower than the 0.5 °C/min slew rate observed by AISSat-1’s payload currently in orbit. Although, a separate high-rate slew test was performed to ensure
the system could survive slews up to 0.8°C/min. The thermal chamber soaks of 12 hours ensure that the propulsion system remains settled at each temperature extreme for at least a 6 hour period. At the time of this test, and for the CanX-4/-5 final thermal design, the survival temperatures of CNAPS were adjusted to be +40°C and −10°C. These values were used in determining the TVAC temperature plateaus.

During the thermal vacuum cycles, temperature sensors placed on various areas of interest on CNAPS and the bell jar chamber pressure were polled at 5 second intervals. CNAPS was also powered and recording telemetry in order to further test the electronics, as well as acquire secondary volume pressure and temperature data throughout the test. The bell jar pressure data was used to identify any sudden leak anomalies from CNAPS, while the temperature data would help determine the location of this leak event. Figure 6.35 shows a sample of this recorded telemetry across a set of thermal cycles. The pre- and post-massing

![Temperature and pressure telemetry](image-url)
values of CNAPS were used to determine the average leak rate across the duration of the thermal vacuum cycles.

The TVAC leak results for both flight candidate CNAPS units is presented in Table 6.10. In summary, all leak rates experienced by either unit and at varying propellant mass levels were found to be below the maximum allowable leak rate requirement of 5.0 mg/hr. As the propellant on-board CNAPS is expended for formation keeping manoeuvres, the thermal mass of the propellant decreased, adding another realistic condition that will be experienced throughout the duration of the CanX-4/-5 mission. The test exercised this aspect as CNAPS was subjected to thermal cycles at several fuel masses. This was performed to ensure the ability of the system to survive independent of the thermal mass of the SF$_6$ propellant within the storage tanks.

It should also be noted that the flight fill procedure was implemented for these TVAC leak tests. The procedure called for performing a fill while CNAPS is powered-on while the pressure within the primary volume tank is bled down to 34.5 bar (500 psi) at room temperature. This is extremely important for creating an initial condition for the storage tanks because it has been tested and is known to perform as expected under the flight environment. It also ensures that the verification of requirements in these tests will continue to be a valid for future fills of the propulsion system.

The measured average leak rate was observed to decrease with the decreasing mass of propellant at each set of thermal cycles, see Table 6.10.

Table 6.10: Leak rate results across thermal vacuum cycles of $+40^\circ$C to $-10^\circ$C for both propulsion units

<table>
<thead>
<tr>
<th>No. of Days Cycling</th>
<th>Mass of Fuel at Start of Cycles</th>
<th>Measured Leak Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNAPS Unit AA9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>228 g</td>
<td>4.3 mg/hr</td>
</tr>
<tr>
<td>4</td>
<td>228 g</td>
<td>4.0 mg/hr</td>
</tr>
<tr>
<td>7</td>
<td>138 g</td>
<td>2.4 mg/hr</td>
</tr>
<tr>
<td>5</td>
<td>78 g</td>
<td>1.9 mg/hr</td>
</tr>
<tr>
<td>CNAPS Unit AMX</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>258 g</td>
<td>4.4 mg/hr</td>
</tr>
<tr>
<td>6</td>
<td>152 g</td>
<td>2.0 mg/hr</td>
</tr>
<tr>
<td>4</td>
<td>80 g</td>
<td>1.6 mg/hr</td>
</tr>
</tbody>
</table>
6.3.4 Secondary Volume Leak Testing

Once the spacecraft have been commissioned, CNAPS has been powered-on, and the drift recovery manoeuvre is commenced, the secondary volume will be pressurized to 6.9 bar (100 psi). This pressure will be maintained for the entire duration in which CNAPS is required to perform frequent thrusting throughout the formation flying demonstration. The secondary volume is susceptible to propellant leakage during this period. The fuel budget solely dictates the maximum allowable leak rate of 2.0 mg/hr for CNAPS’ secondary volume [27]. It is important to demonstrate that this is a valid assumption.

A test of the secondary volume leak rate was performed on each of the propulsion units. Since the nominal operating pressure within this volume is well under the vapour pressure of SF$_6$, the ideal gas law was used in conjunction with pressure and temperature readings to determine the approximate mass leak rate.

The secondary volume segment of protoflight CNAPS unit AA9 was left pressurized for 2 weeks. The initial and final recorded pressures across this time were 6.9 bar (100 psi) and 6.2 bar (90 psi), respectively. Using the ideal gas law and a conservative volume of 15 cc, the leak rate from the secondary volume segment was estimated to be 0.18 mg/hr. This is an order of magnitude lower than the assumed leak rate value within the fuel budget.

In accordance with the project schedule, the secondary volume segment of CNAPS unit AMX did not have the availability to sit undisturbed for 2 weeks. Therefore, this volume was left pressurized for 24 hours with virtually no identifiable pressure change, with comparative readings taken at equal temperatures. It can be calculated that a leak rate of 2 mg/hr would have produced a pressure drop of 0.54 bar (7.8 psi) over the course of 24 hours with no temperature change, which verifies that the secondary volumes of both CNAPS propulsion units are well under the assumed leak rates used for the CanX-4/-5 fuel budget.
Chapter 7

Conclusions

The Canadian Nanosatellite Advanced Propulsion System (CNAPS) plays a critical role in the Canadian Advanced Nanospace eXperiment (CanX)-4 and CanX-5 dual nanosatellite formation flying mission. The objective of this work was to complete the assembly, testing, and analysis phases of both CNAPS units such that they will be ready for integration with the CanX-4 and CanX-5 spacecraft to meet the early 2014 launch date. This thesis describes the state of work and the challenges faced at the time of the author’s joining of the project, the steps required for a successful assembly of the two propulsion units, the methodology of the proposed test plan, the execution of such tests, and a summary of the results.

At the time of the author’s joining of the project, CNAPS’ design was completed along with an assembly procedure. Modifications to this assembly procedure were required to successfully assemble a flight worthy propulsion system. Leak check procedures were integrated into the process in order to verify the quality of each propellant plumbing connection before continuing on with the assembly. Hardware from the bill of materials, specifically the primary storage tanks, were procured, tested at the component-level, and fit checked. All propellant plumbing tubes were custom bent, cleaned, and fit checked with the structure. Two official flight units were assembled in a Class 10,000 clean room by the author. The first of the two units was to be subjected to protoflight tests while the second unit was to experience acceptance-level testing before flight.

A high-level protoflight and acceptance-level test plan for CNAPS was developed. This plan allows both propulsion systems to transition from newly assembled units to official flight hardware ready for integration with the satellites. An accurate and reliable method to determine the propellant leak rate was established. This method consisted of using control masses to minimize effects of buoyancy and tidal variation on the measurement of the change of CNAPS’ mass across time.

A detailed vibration test plan that included the test setup and vibration profiles was created. The protoflight unit was exposed to qualification magnitude vibration accelerations of the Polar Satellite Launch Vehicle (PSLV) for acceptance-level durations. The XPOD DUO
deployment system was used at the beginning; however the setup was changed to make use of an XPOD GNB deployment system to match the now planned flight configuration. This alteration did not affect the results negatively. CNAPS successfully passed all functionality and leak tests while being subjected to the desired launch environment loads. Therefore, the design of CNAPS is now qualified to survive the vibration loads on the PSLV.

A thermal vacuum test consisting of two major segments was planned and executed. This involved functionality and thrust performance tests across a temperature range as well as a thermal cycling leak test. The functionality testing of CNAPS across all temperatures in vacuum was successful. All thrust valve actuations and pressure regulation algorithms during thrusting ran as expected. Executed at various operational temperatures, the thrust performance testing characterized parameters such as the average specific impulse, the force produced per nozzle, and the ability to generate the desired impulse. The average specific impulse of both units met requirements while allowing the closure of the fuel budget with a 20% worst-case fuel margin, assuming a 5.0 mg/hr propellant leak rate. The force produced per nozzle was characterized and used to calibrate the thruster on-times of each nozzle in order to produce the desired impulse. This calibration was applied and tested. Although the generated impulses were within system requirements, these values can be fine-tuned by adjusting the calibrated thrust per nozzle through on-orbit calibration activities. Thermal cycling leak tests characterized the propellant leak rate of the propulsion system across its survival temperatures of $+40^\circ \text{C}$ to $-10^\circ \text{C}$. It was found that both propulsion systems were able to maintain a leak rate below the requirement of 5.0 mg/hr while subjected to thermal cycles in a medium-vacuum. The highest observed leak rate during these thermal vacuum cycles was 4.4 mg/hr.

From the successful conclusion of the assembly and testing, both Canadian Nanosatellite Advanced Propulsion System units have been cleared for flight. Assembly and integration of the spacecraft can now proceed, with satellite system-level vibration and thermal vacuum tests occurring upon completion. Following these achievements, the University of Toronto Institute for Aerospace Studies Space Flight Laboratory’s designed and built nanosatellite formation flying mission, CanX-4/-5, is expected to launch in early 2014.
Bibliography


