DEVELOPMENT OF A NITROUS OXIDE-BASED MONOPROPELLANT THRUSTER FOR SMALL SPACECRAFT

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ABSTRACT

There is a growing demand for small yet effective satellite technologies. One area which needs to be addressed is compact propulsion systems capable of performing on-orbit maneuvers, station-keeping, and de-orbit impulses. An important consideration for propulsion systems is the safety and ease of handling, integrating, and testing. Maintaining simplicity by avoiding toxic propellants such as hydrazine is of particularly importance for small satellite developers. This paper summarizes a Space Flight Laboratory research project aimed to improve the efficiency of an existing system: SFL's nitrous oxide resistojet. The resistojet is capable of providing 100 mN of thrust at a specific impulse of 105 s and input power of 75 W. The resistojet design was modified to achieve catalytic decomposition of the propellant. The monopropellant thruster prototype has successfully demonstrated sustainable nitrous oxide decomposition providing a thrust of 100 mN at a specific impulse of 131 s (25 % increase) and operational endurance of greater than 50 hours all while consuming minimal power. Ongoing research focuses on evaluating different catalysts in an effort to extend the operational lifetime of the system.

1 INTRODUCTION

The growing demand for smaller satellites with big performance has revealed a necessity for high performance propulsion systems designed for small spacecraft. An effective propulsion system offers many advantages to small satellite missions. The ability to perform orbit acquisition, station keeping, and collision avoidance impulses vastly expands the capabilities of a small satellite platform. For example, small satellites typically rely on aerodynamic drag (either by design or by including a dedicated device) to meet de-orbit guidelines. The effectiveness of this approach decreases with altitude, limiting these missions to below 800 km. A propulsion system enables access to a whole range of orbits above this limit. Clearly, the Space Flight Laboratory (SFL) and its industry partners require high-performance propulsion for its future missions.

In order to meet these needs SFL is currently undertaking the development of two parallel options for high performance, Canadian-alternative microsatellite propulsion systems: an electric propulsion system, described in [1], and a monopropellant thruster. The latter, referred to as the nitrous oxide monopropellant thruster (NMT), is the focus of this paper. The NMT research is aimed to improve the performance of SFL's nitrous oxide resistojet. Both systems system are derived from the highly-successful NANOPS and CNAPS propulsion systems that are currently flying on-orbit. CNAPS (Canadian Nanosatellite Advanced Propulsion System) in particular has been extensively operated on-orbit by the CanX-4 and CanX-5 satellites. It is a cold gas system that enabled the successful completion of the CanX-4&5 formation flying mission in 2014.

The NMT system uses nitrous oxide (N_2O) as the propellant. The benefits of nitrous oxide are that it is safe to handle, non-toxic, cost-effective, and much easier to access and transport than traditional propellants. Nitrous oxide also self-pressurizes to 50.5 bar (733 psi) at 20 °C and thus does not require the addition of a pump or pressurant gas to move the propellant. This allows the tank and feed system design to be simpler than that for liquid propellants. Perhaps the most intriguing aspect of nitrous oxide is that it can be exothermically decomposed and used as a monopropellant to provide high exhaust temperatures while consuming minimal electrical power.

The development of the NMT uses SFL's resistojet as a starting point. With nitrous oxide as a propellant, the resistojet delivers 100 mN at a specific impulse of 105 s with 75 W input electrical power. It becomes a monopropellant thruster by replacing the resistojet heat exchanger with a catalyst bed and mixing chamber. N_2O will decompose over the pre-heated catalyst bed, providing a significant increase in exhaust temperature and therefore efficiency over the resistojet mode using the same fuel.

2 NITROUS OXIDE as an ATTRACTIVE PROPELLANT

In order to further improve the performance of SFL's nitrous oxide resistojet system some significant changes would be required. As an alternative to resistojet, monopropellant thrusters offer substantial advantages specifically with respect to required input power and specific impulse. Several different propellants were initially considered including monopropellants such as hydrogen peroxide, hydrazine, and ADN-based substances.

Nitrous oxide has the benefits of being self-pressurizing (with a vapour pressure of 733 psi at room temperature), provides moderate performance (specific impulse 130 s to 160 s), is safe to handle, has space heritage in hot-gas systems, is well understood and is easy to obtain in high purity and quantity. Several of the other potential propellant selections offer significantly better performance than N_2O. However, the safety benefits, cost, and ease of access of N_2O out-weighed the efficiency advantage of the other options. In addition, SFL already has experience with N_2O in their nitrous oxide resistojet. It was therefore decided to pursue a nitrous oxide monopropellant thruster.

3 NITROUS OXIDE THRUSTER PERFORMANCE

3.1 Nitrous Oxide as a Resistojet Propellant

Fundamentally, nitrous oxide monopropellant thrusters are governed by the same basic principles as any other chemical rocket. Chemical rockets impart a force on the vehicle they are a part of by expelling mass at high speed. A more energetic exhaust will have higher exhaust velocities and will therefore impart a higher momentum transfer. A simple way to increase the momentum transfer is to increase the enthalpy of the exhaust gases by pre-heating using an electric heater: the higher the exhaust enthalpy is the higher resulting thrust per unit mass will be. This is the concept behind a resistojet. Figure 1 shows the theoretical performance of a nitrous oxide resistojet as a function of the stagnation temperature of the exhaust propellant.

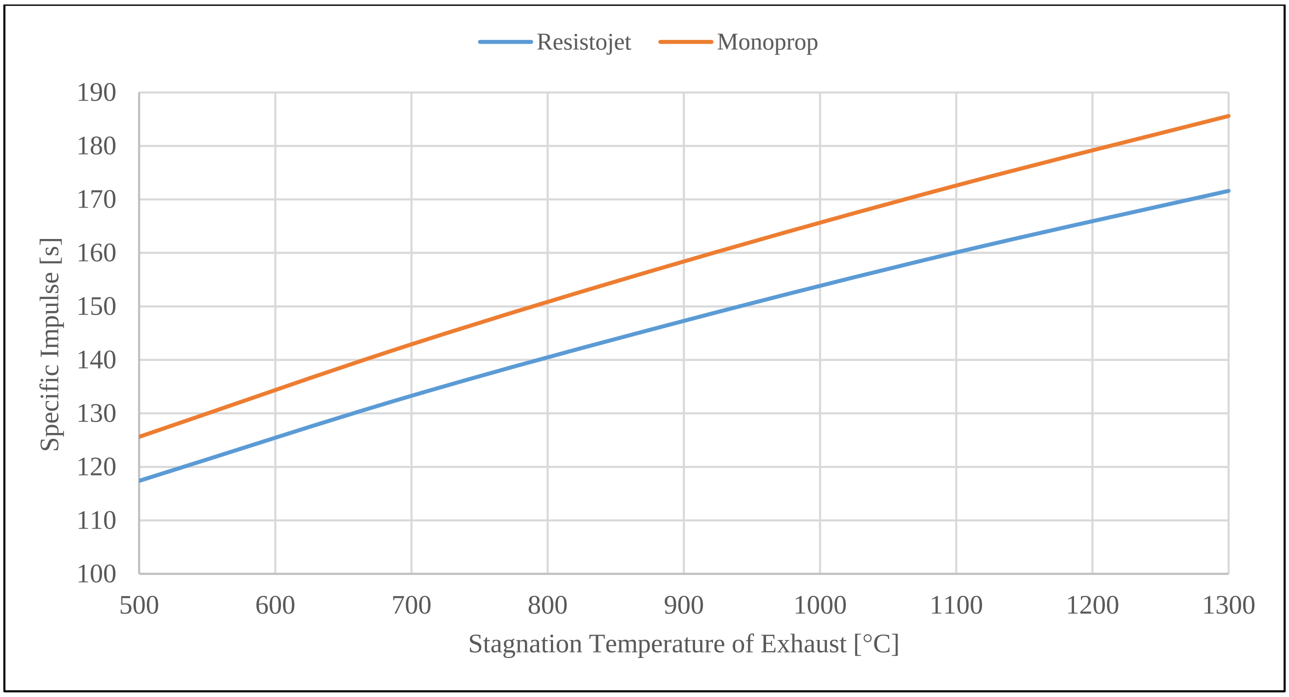

Figure 1. Theoretical performance of a nitrous oxide nitrous oxide monopropellant thruster. Assumes an ideal nozzle with expansion ratio of 200.

3.2 Nitrous Oxide as a Monopropellant

Additional performance can be gained if the propellant can be decomposed exothermically, releasing stored chemical energy. In the case of nitrous oxide, a relatively small amount of initial input energy is required to start the reaction. For example, by pre-heating a catalyst bed using resistive heaters. This is known as a monopropellant system. The decomposition of nitrous oxide can be expressed by Equation 1.

$$N_2O \rightarrow N_2 + \frac{1}{2}O_2 - 82\ \frac{\text{kJ}}{\text{mol}} \tag{1}$$

Where one mole of nitrous oxide is decomposed to form one mole of diatomic nitrogen and a half mole of diatomic oxygen. Note that the negative sign on the energy term indicates an exothermic reaction. Under appropriate conditions the exothermic release of energy can also make the reaction self-sustaining, allowing subsequent fuel flow to be decomposed with no energy input from the spacecraft. An additional benefit to decomposition is that the products are smaller molecules than the reactants, with smaller molar masses, which contributes to a higher specific impulse. For example, nitrous oxide has a molar mass of 44.01 g/mol. The products of its decomposition, nitrogen gas and oxygen gas, have molar masses of 28.01 g/mol and 32.0 g/mol, respectively. Two-thirds of the produced molecules are nitrogen gas, and the remaining one-third are oxygen gas. Therefore, the complete decomposition of 1 mol of nitrous oxide results in a product with an effective molar mass, $m_{M,P}$, given by Equation 2 where $m_{M,N}$ is the molar mass of nitrogen gas, and $m_{M,O}$ is the molar mass of oxygen gas.

$$\begin{gathered} m_{M,P} = \frac{2}{3}m_{M,N} + \frac{1}{3}m_{M,O} \\ m_{M,P} = 29.34\ \frac{\text{g}}{\text{mol}} \end{gathered} \tag{2}$$

Similarly, the specific heat ratio of the mixture, $\gamma_{M,P}$, is found according to the contribution of each of the components as described by Equation 3.

$$\gamma_{M,P} = \frac{2}{3}\, m_{M,N}\, \gamma_N + \frac{1}{3}\, m_{M,O}\, \gamma_O \tag{3}$$

Decomposition will also change the specific heat ratio of the mixture leaving the rocket's nozzle. More complex molecules will tend to have lower specific heat ratios than simpler ones, and this tends to drive the specific impulse down. However, the overall effect of decomposition is to increase system performance. Figure 2 shows how specific impulse rises as decomposition increases for a nitrous oxide system held at a constant temperature.

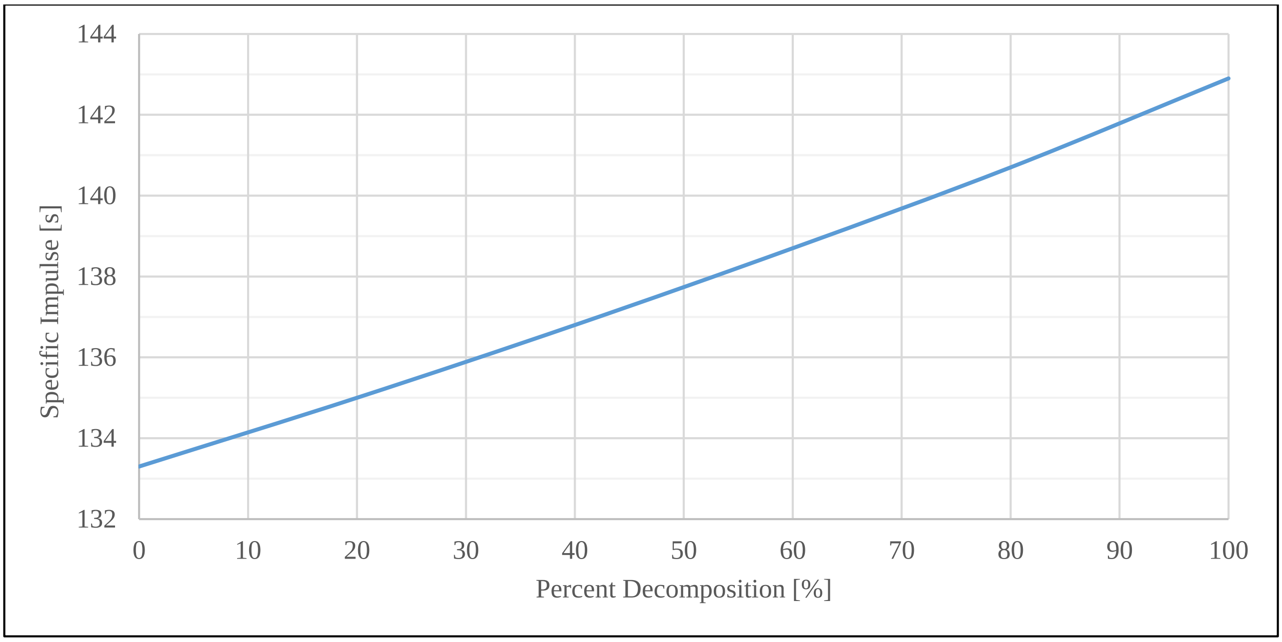

Figure 2: Theoretical specific impulse as a function of decomposition percentage for a nitrous oxide monopropellant system with an exhaust temperature of 700 °C. Assumes an ideal nozzle with an expansion ratio of 200.

4 THRUSTER DESIGN

A CAD model of the NMT prototype is shown in Figure 3. The achieved performance of the thruster as well as key design parameters are summarized in Table 2.

Figure 3: CAD model of the nitrous oxide monopropellant thruster prototype.

4.1 Performance Requirements

The NMT system was designed to meet the requirements of a reference microsatellite. The reference spacecraft was the result of consultations among SFL, the Canadian Space Agency, and industry partners. The spacecraft propulsion requirements are summarized in Table 1.

Table 1: Propulsion requirements of the reference mission.

Spacecraft dry mass [kg]	150
Total ΔV [m/s]	100
Thrust [mN]	100

4.2 Decomposition Chamber

The catalyst bed length, l_c, is found empirically through experimentation with different flow rates and catalysts. The chamber must be long enough to allow all of the propellant to decompose, but any longer than that and energy is wasted through heating additional catalyst and chamber mass as well as additional radiative losses from a larger-than-required thrust body. An investigation into catalyst bed lengths is given in [3].

The thrust chamber diameter was determined using a model developed and validated by Zakirov in [3]. A similar chamber diameter of 15 mm was used for the NMT prototype.

4.3 Catalyst Selection

The catalysts that are typically used with nitrous oxide are precious metals or oxides of such metals supported on a substrate; they tend to be expensive. Because of this, initially only one catalyst was selected from the several that seemed to have promise. The two catalyst types that showed the most promise, as summarized in [3] and [4], are rhodium- and iridium-based catalysts. Both catalysts have their precious metals supported on an aluminum oxide substrate. Iridium catalyst has been used for over 50 years and most monopropellant systems developed in that time have used it. It has a higher sublimation temperature than rhodium, and decomposes nitrous oxide at about 450 °C, but it is considerably more expensive to acquire [3]. Experiments have found rhodium to be a promising alternative to Iridium [3] and [4], with a lower activation temperature of 250 °C and a comparatively lower cost. For these reasons, a rhodium based catalyst was selected for the prototype.

The rhodium catalyst is provided in the form of small pellets; more details of the form of catalyst are shown in Table 2. The pellets are contained in the thrust chamber using a metal filter screen. Together this is known as a catalyst bed. Catalyst bed loading factor, L_F, is a parameter which helps determine the allowable flow rate through a given catalyst bed; it is expressed by Equation 4 where $\dot{m}$ is the mass flow rate and A is the catalyst bed cross-sectional area.

$$L_F = \frac{\dot{m}}{A} \tag{4}$$

Examples in the literature show successful nitrous oxide decomposition with loading factors ranging from 0.12 kg/m^2/s to 15 kg/m^2/s [3], [5]. Larger loading factors allow for shorter catalyst lengths, which leads to power savings. However, after a certain point these large mass fluxes mean that not all of the propellant is decomposing, and chamber temperature suffers.

Table 2: Parameters of the nitrous oxide monopropellant thruster.

Thruster performance	
Thrust [mN]	100
Specific impulse [s]	131
Mass flow rate [mg/s]	78
Chamber details	
Diameter [mm]	15.0
Max. temperature [°C]	700
Casing material	Stainless steel 316
Radiation shield material	Aluminum 6061-T6
Temperature feedback	K-type thermocouple
Catalyst pack	
Catalyst material	Rhodium metal (Rh)
Support material	γ-alumina (γ-Al_2O_3)
Heater voltage [VDC]	28
Heater power [W]	30
Pre-heat	
Pre-heat temperature [°C]	400
Pre-heat duration [minutes]	<5

4.4 Heater

As previously discussed, the catalyst reduces the temperature required to decompose nitrous oxide. In the case of the selected catalyst material, decomposition can be initiated at catalyst bed temperatures as low as 250 °C. In order to pre-heat the catalyst bed, a heater is used. The heater is powered directly off a 28 VDC bus and pre-heats the catalyst bed to 400 °C within 5 minutes.

4.5 Nozzle

For the prototype thruster, it was decided to use a re-sealable decomposition chamber to facilitate the ability to refresh and inspect the catalyst bed as necessary. To achieve this, the nozzle was designed such that it threads onto the decomposition chamber body. A high temperature, vacuum rated, non-cementing thread sealant was used to seal the threads against leaking. The nozzle throat diameter was chosen to achieve the desired mass flow rate expressed in Table 2. The divergent section was manufactured by way of electric discharge machining (EDM). The approach of using a re-sealable combustion chamber proved invaluable throughout the testing of this prototype thruster. When the catalyst needed to be removed for inspection or refreshing, the nozzle was simply unthreaded and removed. Once the mating threads were cleaned the thread sealant was reapplied and the nozzle threaded back onto the decomposition chamber.

5 TESTING

5.1 Catalyst Lifetime Testing

Once the prototype thruster was manufactured, some proof of concept tests confirmed that the catalyst performed well at least for a short period of time. For these tests the catalyst bed was pre-heated to 350 °C, nitrous oxide was then allowed to flow through the catalyst bed at the nominal mass flow rate. The temperature began rising immediately and so the heater power was turned off. The chamber temperature continued to rise to temperatures above 1100 °C. This confirmed that the catalyst was effective in the decomposition of nitrous oxide.

The next step was understanding how the catalyst will perform over a long duration, specifically over the anticipated lifetime of the thruster system. A review of the literature has indicated that identifying a suitable catalyst that can last for a long period of time is one of the most difficult components to monopropellant development. In fact, to the authors' knowledge no one has yet been able to identify a catalyst that is robust to degradation in the high-temperature (>1000 °C) decomposition of nitrous oxide. Catalysts that have been tested seem to deactivate due to sintering or sublimation of the catalytic phase as summarized in [3], [4], and [6]. A dedicated test was performed in order to evaluate the longevity of the selected catalyst.

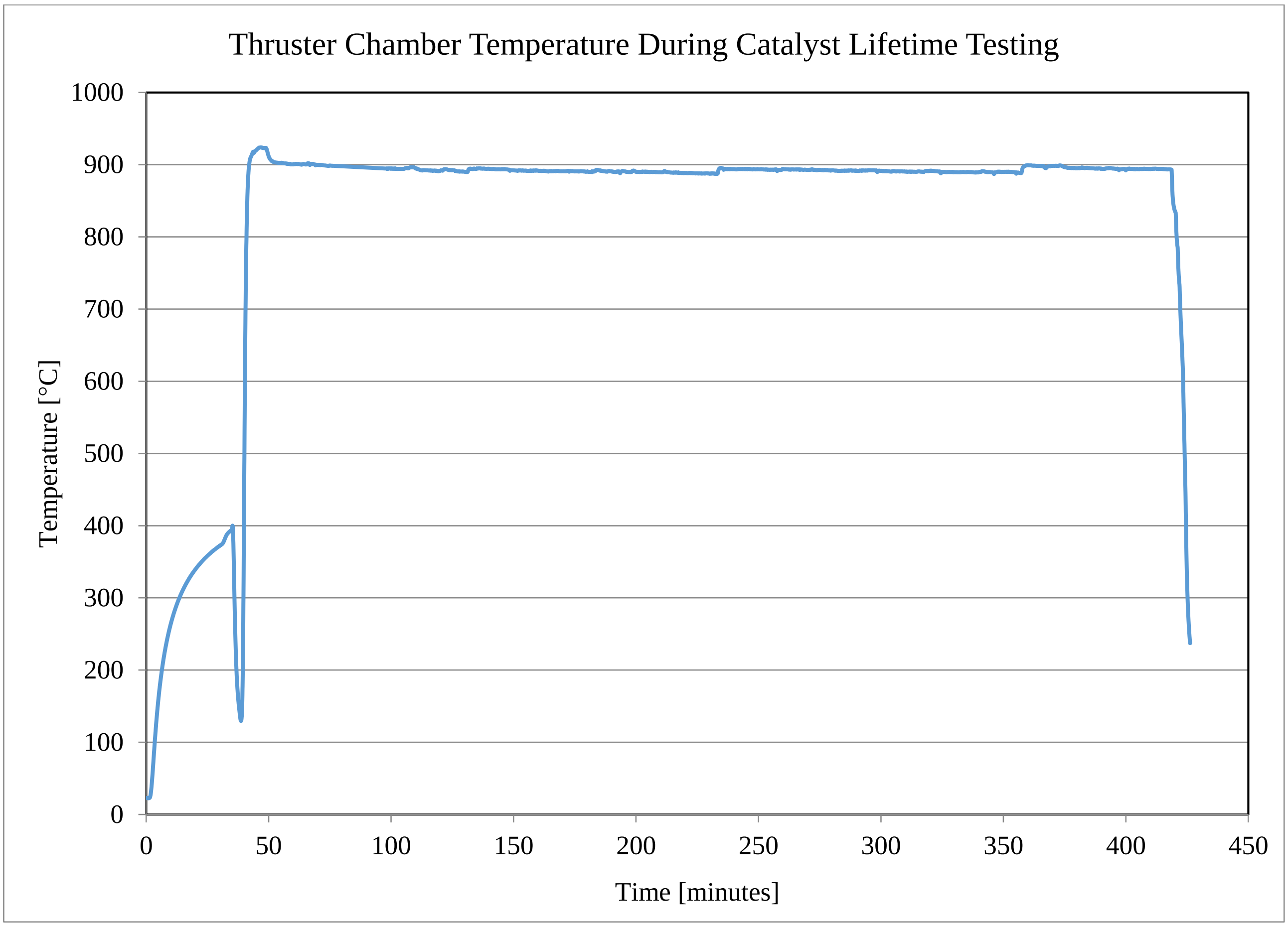

Figure 4: Chamber temperature results from the catalytic lifetime test. The flow of N_2O is started at approximately 38 minutes following the warm-up period. The flow is shut off at 420 minutes.

Based on the requirements of the reference mission and the NMT design point, as summarized in Table 1 and Table 2, the total thrust duration is 41.7 hr during which 11.1 kg of N_2O is exhausted. Preliminary testing of an initial catalyst indicated that it did not last the required lifetime, completely deactivating within 8 hours of operation at the nominal mass flow rate. A second catalyst was identified which contained significantly more rhodium by weight. A dedicated test was performed with this new catalyst. The objective of the lifetime testing was to determine how the proposed catalyst performs over the thruster lifetime. The catalyst lifetime test was divided into 8 sub-tests during which the prototype thruster was run for approximately 7.5 hours continuously. Figure 4 shows the temperature results from one of the sub-tests. During the warm-up period, the catalyst bed is pre-heated to 400 °C. The nitrous oxide is then allowed to flow at the nominal rate over the catalyst. Decomposition occurs immediately as indicated by the steep increase in temperature. The system reaches steady state with an internal temperature of about 900 °C. The propellant flow is shut off after about 6.5 hours and the thruster is allowed to cool down.

In total, the system ran for 50.4 hours on a single catalyst cartridge successfully decomposing 13.4 kg of N_2O. The temperatures inside the decomposition chamber ranged between 890 °C and 1040 °C. The results indicate that the catalyst is able to last for the required lifetime (41.7 hours and 11.1 kg) of the thruster system. However, there is evidence of degradation of the catalyst beginning around 20 hours. Degradation of the catalyst is manifested as an increased amount of time required to obtain the steadystate temperature as shown in Figure 5. Additional testing indicated that the increased heat-up time can be avoided by increasing the pre-heat temperature. For example, after the completion of sub-test 7 the pre-heat temperature was increased from 350 °C to 500 °C in an effort to reduce the time required to reach. Because it was believed that the deactivation of the catalyst was related to the high temperatures experienced by the catalyst, the NMT prototype design was modified to reduce the chamber temperature to 700 °C from the nominal 1000 °C. This change comes with a cost in specific impulse as demonstrated by Figure 1. Research into the causes of catalyst deactivation, deactivation mitigation approaches, and alternative catalysts are ongoing in an effort to increase the overall lifetime of the system. If an alternative catalyst solution is adopted the decomposition chamber temperature may be increased again to improve the system's efficiency.

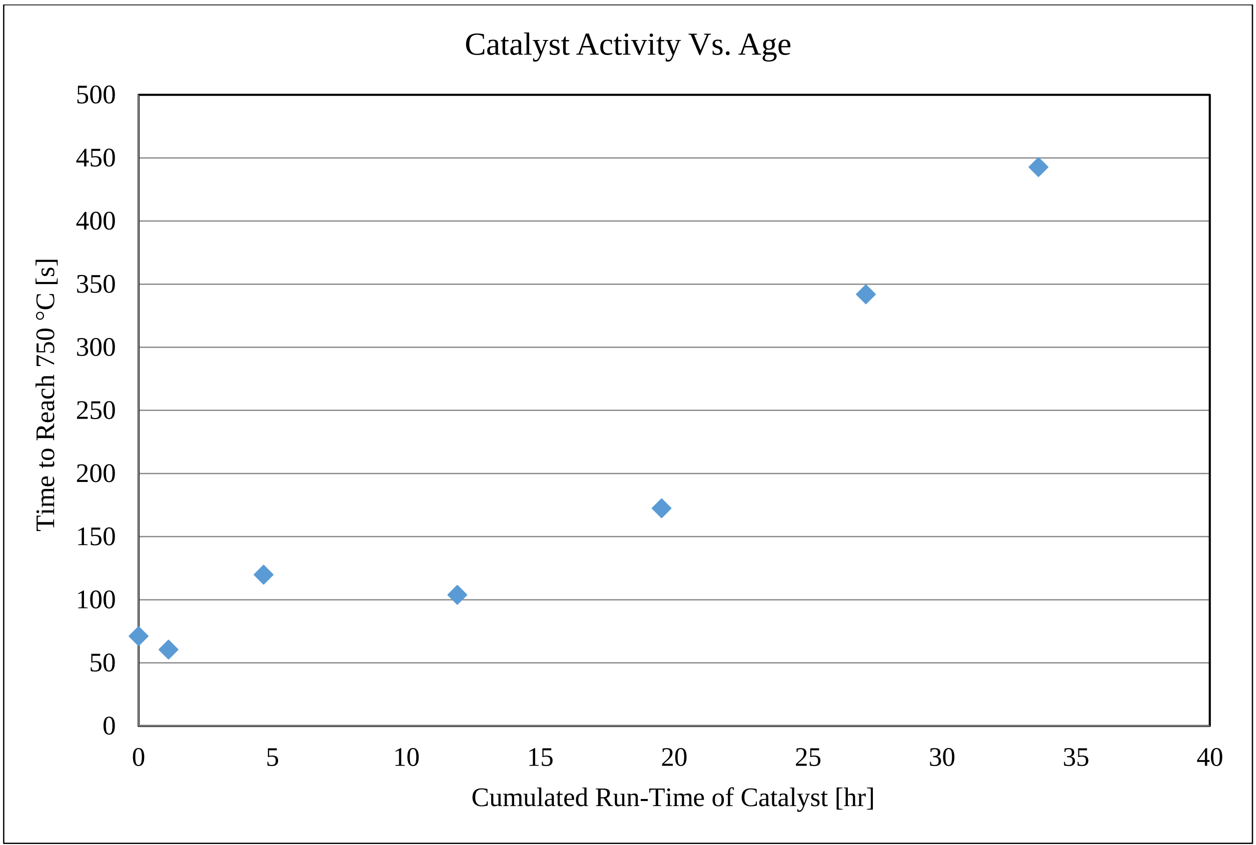

Figure 5: Time for decomposition reaction to heat up as a function of catalyst life.

5.2 Performance Characterization

The purpose of the vacuum operation test is to validate that the performance requirements are met with the proposed system. The objectives of the vacuum operation test is to confirm the specific impulse and thrust of the system as summarized in Table 2. The NMT prototype was tested in vacuum using a precision mass balance to measure the thrust. K-type thermocouples were used for internal temperature measurement. A calibrated mass flow meter was used to control the propellant flow rate into the thruster. Figure 6 shows the NMT prototype mounted inside the vacuum chamber.

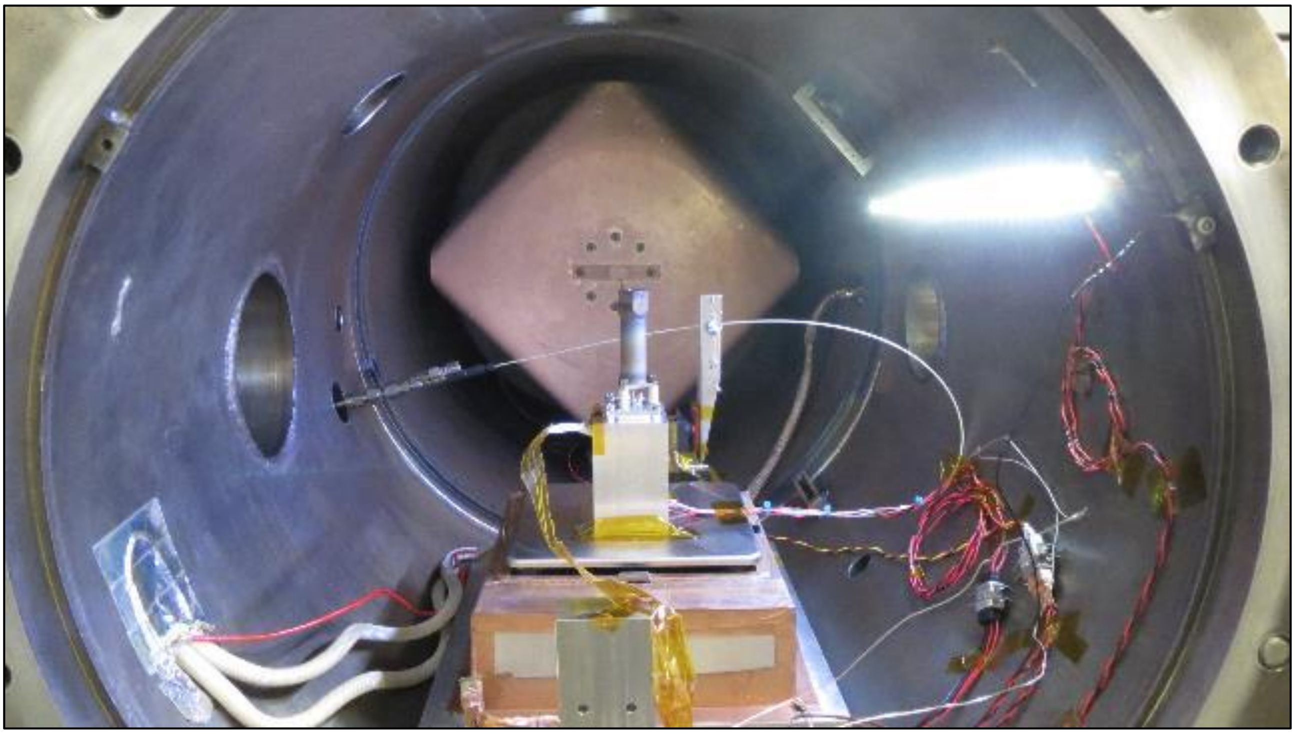

Figure 6: The NMT prototype mounted on the precision mass balance in the vacuum chamber.

The results from the vacuum operation test are shown in Figure 7. Once the propellant feed begins, the internal temperature and thrust measurements rise accordingly. After 400 seconds, the system has effectively reached steadystate at an internal temperature of approximately 700 °C. The system is operated continually for approximately 8 minutes at which point the propellant flow is cut off and the system is allowed to cool.

The results indicate that an average specific impulse of 131 s was achieved with an average thrust of 96.1 mN at a mass flow rate of 75 mg/s. The thrust peaked at 100 mN with an instantaneous specific impulse of 134 s thereafter the temperature continued to increase while the thrust decreased. The likely cause of this seemingly contradictory trend is the location of the thermocouple within the decomposition chamber. The thermocouple is located slightly upstream of the nozzle. It is believed that during the test the decomposition front is shifting upstream such that the peak temperature shifts from just before the exhaust closer to the middle of the catalyst pack. As the propellant moves through the chamber its temperature rises to a maximum, it then cools down slightly before being exhausted through the nozzle, resulting in a lower thrust and specific impulse.

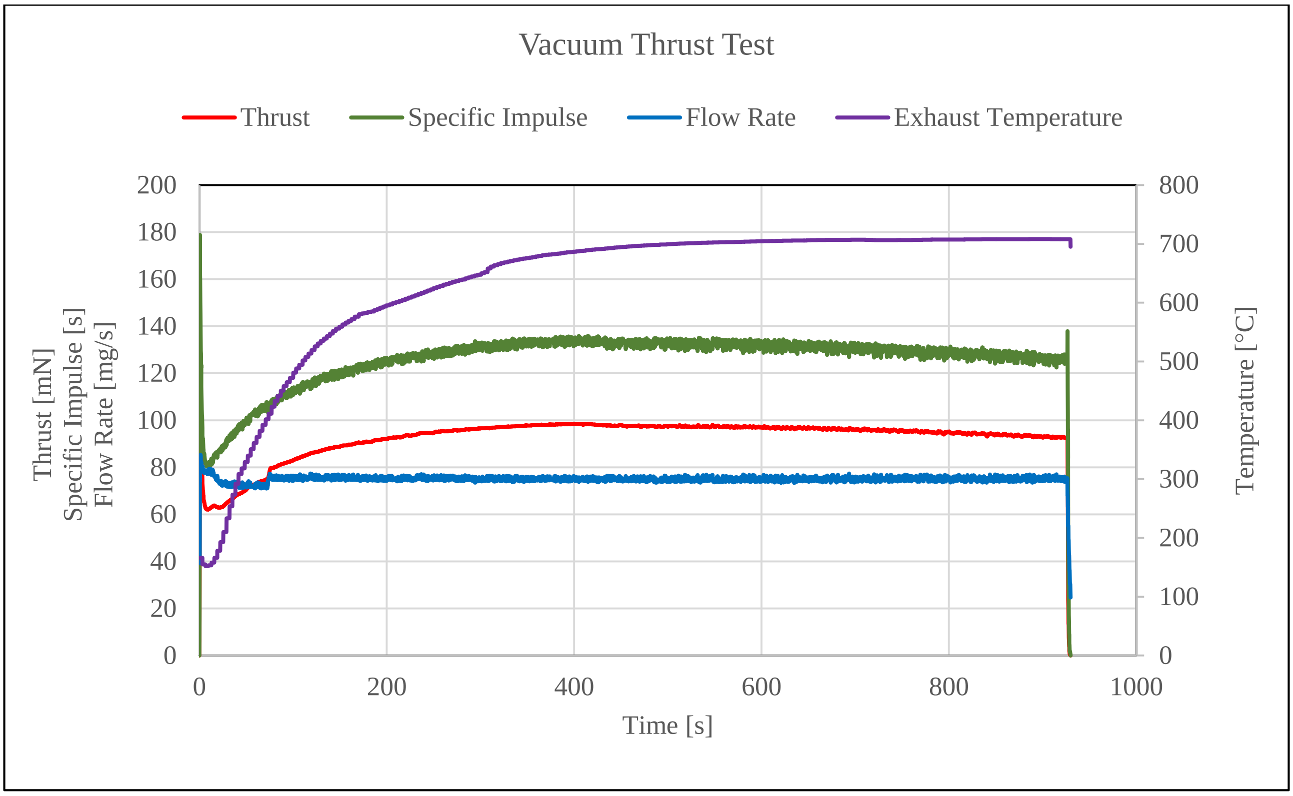

Figure 7: Vacuum operation test results.

6 FUTURE of NITROUS OXIDE MONOPROPELLANT

6.1 Catalytic (Heterogeneous) Decomposition

The challenges involved with the development of a nitrous oxide monopropellant are almost entirely related to the catalyst. Initiating and sustaining the catalytic decomposition of nitrous oxide over the rhodium on alumina catalyst was straightforward. Integrating the catalyst bed into a simple thruster and validation of the performance was also achieved with minimal complications. In order to increase the catalyst lifetime the decomposition temperature was reduced from over 1100 °C to 700 °C having a significant negative impact on the resulting specific impulse and thus reducing some of the advantage that the monopropellant system has over the simpler resistojet system. The resulting system achieved a specific impulse 131 s which is significantly less than the 160 s specific impulse that is possible with exhaust temperatures of 1200 °C.

While the system meets the project requirements as summarized in Table 1, SFL is continuing research into the catalyst deactivation issues in order to expand the system's capabilities. An effort is being made to identify the mechanisms of deactivation of the baseline catalyst. A good review of mechanisms of catalyst deactivation is given in [7]. Depending on the causes there may be different mitigation approaches including improving the configuration of the catalyst within the decomposition chamber to mitigate tunneling and a further reduction in decomposition chamber temperature to eliminate the temperature dependent mechanisms of failure. However, it may turn out that the selected catalyst is may have an inherent weakness. For example, it is possible that the most dominant mechanism of failure is the formation of inactive oxides on the catalyst surface. There is a high concentration of energetic oxygen within the decomposition chamber making the formation of rhodium oxide (Rh_2O_3) very likely. SFL will also be testing different catalyst materials to identify alternatives.

6.2 Homogeneous Decomposition

Another potential area of research is the homogeneous decomposition of nitrous oxide. Given the appropriate conditions, nitrous oxide can be decomposed without a catalyst. Reference [8] documents an investigation into the stability of nitrous oxide from a safety point of view. In the research, Rhodes investigates the ability to initiate homogeneous decomposition of nitrous oxide in tubes of different diameters. The results show that decomposition can be sustained in a 2 inch and 1 inch pipe at moderate temperatures and pressures. However, in a ½ inch pipe (similar to the design point in this paper) decomposition could only be initiated at pressures of 55.1 bar (800 psia) and above. A very relevant example of homogeneous decomposition occurred during the testing of a 500 mN nitrous oxide resistojet by Timothy Sweeting et al. [9]. During that development, sustainable homogeneous decomposition was unintentionally achieved in a resistojet with a 60 mm chamber diameter, a mass flow rate of 4000 mg/s, chamber pressure of 10 bar (145 psi), and chamber temperature of 678 °C. The thruster is somewhat larger than the design point in this paper, however, it may be worth investigating to understand what the required conditions for sustainable homogeneous decomposition are. Developing a thruster that implements homogeneous decomposition has the overwhelming advantage of eliminating the longevity issues that catalysts seem to have. Furthermore, in such a system, the chamber temperature will be limited only by the material properties of the decomposition chamber and the thermal design rather than catalyst survivability. With high temperature materials, the efficiency can be significantly improved with a theoretical maximum temperature of 1640 °C [5] and specific impulse of greater than 180 s.

7 CONCLUSIONS

Using SFL's nitrous oxide resistojet thruster as a starting point, a research project was undertaken to improve the efficiency of the system. This was accomplished by implementing an exothermic decomposer and achieving a monopropellant system. Compared to the nitrous oxide resistojet, the monopropellant system offers a 25 % increase in specific impulse while consuming minimal power. The system was shown to meet the project requirements set out by the Canadian Space Agency, namely offering a delta v of 100 m/s for a 150 kg spacecraft at a nominal thrust of 100 mN. The propulsion system enables several exciting propulsive capabilities to small spacecraft including orbit acquisition, station-keeping, collision avoidance, and de-orbiting.

8 ACKNOWLEDGEMENTS

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