NASA Marshall Space Flight Center
Tri-gas Thruster Performance Characterization

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Historically, spacecraft reaction control systems have primarily utilized cold gas thrusters because of their inherent simplicity and reliability. However, cold gas thrusters typically have a low specific impulse. It has been determined that a higher specific impulse can be achieved by passing a monopropellant fluid mixture through a catalyst bed prior to expulsion through the thruster nozzle. This research analyzes the potential efficiency improvements from using tri-gas, a mixture of hydrogen, oxygen, and an inert gas, which in this case is helium. Passing tri-gas through a catalyst causes the hydrogen and oxygen to react and form water vapor, ultimately heating the exiting fluid and generating a higher specific impulse. The goal of this project was to optimize the thruster performance by characterizing the effects of varying several system components including catalyst types, catalyst lengths, and initial catalyst temperatures.

Nomenclature

a_o = sonic velocity
A_e = exit area
A_t = throat area
c^* = characteristic velocity
d = chamber diameter
D = particle diameter
g_o = acceleration due to gravity
γ = ratio of specific heats
I_{sp} = specific impulse
k = conversion factor
k_m = MACOR thermal conductivity
k_s = stainless steel thermal conductivity
l = catalyst bed length
$\dot{m}_f$ = fluid mass flow rate
M_e = exit Mach number
μ_f = fluid viscosity
P_c = chamber pressure
P_e = exit pressure
Q = heat energy
Re = Reynolds number
ρ_f = fluid density
T_o = stagnation temperature
T_∞ = ambient temperature

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I. Introduction

REACTION control systems used for spacecraft maneuvering purposes are typically designed to be simple, safe, and reliable. These systems often utilize cold gas thrusters because they contain very few mechanisms and are historically consistent performers. Although they are logistically simple, cold gas thrusters usually have a relatively low specific impulse compared to other types of propulsion systems. The tri-gas thruster is configured similarly to a cold gas thruster, except that it passes the inert gas through a catalyst bed before expelling the gas through the nozzle. By inducing this catalytic reaction, the gas is heated prior to exiting the nozzle, which ultimately increases specific impulse. The design of the tri-gas thruster is only slightly more complicated, yet it maintains the consistency associated with cold gas thrusters. Furthermore, this propellant has been categorized as a “green” propellant due to its inherent non-toxicity.

II. Background

A. Tri-Gas

Tri-gas is a gaseous mixture of hydrogen and oxygen that is diluted with a large quantity of an inert gas. When the gas passes through a catalyst, the hydrogen and oxygen become reactive and the overall gas temperature is increased because the formation of water vapor is an exothermic reaction. The inert gas is considered a carrier gas because it is chemically unaffected through the catalytic reaction. It is the primary constituent of the gas mixture and is used to limit the relative amounts of hydrogen and oxygen such that the combination is not detonable. Helium was selected as the carrier gas for this testing in an attempt to reduce the molecular weight and obtain higher specific impulse. The tri-gas mixture was designed to contain a stoichiometric combination of hydrogen and oxygen with a final mixture of 92% helium, 5% hydrogen, and 3% oxygen. The gas was procured from an external supplier.

B. Catalyst Reactions

Traditionally, catalysts are used to lower the activation energy for chemical reactions. When the oxygen and hydrogen in tri-gas pass through a catalyst, the two elements react and produce heat. Because there is a positive correlation between temperature and specific impulse, it is desirable to maximize the energy generated from this reaction. Several catalyst configurations were investigated in an attempt to optimize the thruster performance.

One configuration variable that was investigated was the initial temperature of the catalyst prior to gas flow. Because the specific impulse of the thruster is directly related to the chamber temperature, reaching a steady state chamber temperature is highly desirable to have continuous performance from the thruster. Given a reactive catalyst and enough time, the tri-gas will eventually reach this steady state temperature at the chamber exit. However, if the thruster system is pre-heated, the energy generated from the reaction can be directly applied to the tri-gas itself because all other components are already at the steady state temperature. This lowers the thermal rise time for the system, which means that the optimal performance is achieved more quickly. The helium based mixture’s adiabatic flame temperature, or steady state temperature, was predicted to be 1200°F. This temperature is approximately 33% hotter than a nitrogen mixture, which also increases the specific impulse of the thruster. Operating at the steady state temperature is desirable for in-space applications because it provides the most efficient thruster performance and therefore requires the least amount of fuel. Shorter transients also provide more economical operation of the thruster, thus allowing for more accurate prediction of the propellant needed to maintain a spacecraft’s attitude.

Figure 1. Pelletized (left) and Substrate (right) catalysts.

The effects of varying the catalyst length were also examined. Determining the correlation between catalyst length and performance can provide insight into both the minimum amount of catalyst required to fully react the tri-gas at a given flow rate and the activity of the catalyst itself. During testing, the catalyst length was increased until the temperature profile along the thrust chamber suggested that equilibrium was reached, meaning the tri-gas was fully reacted. The change in thermal rise time was observed and provided an indication of the catalyst activity.

Lastly, two different types of catalysts were compared: a platinum-coated spherical pelletized catalyst produced by Engelhard Corporation and a platinum-coated substrate catalyst produced by Ultramet Corporation. The standard packed catalyst bed uses the spherical pellets, but because the substrate catalyst has an extremely high surface area due to its porous composition, it was predicted that it would have a higher activity than the standard pellets. Because more surface area would be in contact with the tri-gas, it was predicted that the amount of substrate catalyst required to fully react the tri-gas would be lower than that required for the spherical pellets.

III. The Tri-Gas Thruster

A. Thruster Chamber

This experiment utilized a heritage 304 stainless steel thruster that was previously designed and manufactured for a different tri-gas research project conducted in 2010, entitled “Tri-gas Thruster Analysis.” The thruster used MACOR sleeves to insulate the catalyst in the chamber to minimize heat loss during the thruster firing. MACOR is an alumina, a glass-ceramic with excellent insulating properties. In order to adequately protect the delicate substrate catalysts for this project, new MACOR sleeves were machined to specifically fit each of the three catalysts. Each sleeve was machined to the length of its respective catalyst, so the thruster was capable of testing different catalyst length configurations for both the pelletized and substrate catalysts. To test different length configurations, catalyst was simply added or removed from the thrust chamber. For the pelletized catalyst tests, the catalyst was poured into the sleeves to the desired length. Once the desired length was reached, the catalyst was secured into the chamber using a stainless steel screen. For the purpose of consistency in this report, the shortest catalyst length will be referred to as configuration A, the intermediate length as configuration B, and the longest as configuration C. The short substrate catalyst will be referred to as configuration D, and the long substrate catalyst will be referred to as configuration E.

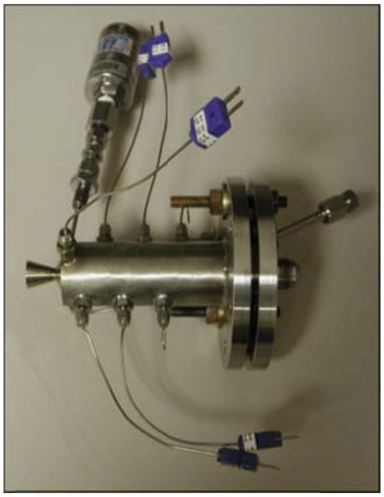

Figure 2. 304 SS Tri-gas thruster.

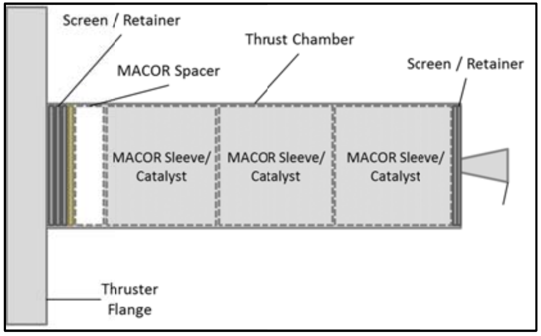

Figure 3. Thruster schematic.

The thruster was outfitted with eight thermocouples to accurately measure the catalyst bed temperature distribution, as well as two pressure ports to provide static pressure measurements before and after the catalyst bed. The two ports allowed a differential pressure drop to be measured across the catalyst bed, which provides insight into catalyst bed performance versus reactivity. Additional surface mount thermocouples were used to measure the rate of heat loss through the chamber walls; these measurements would be important in predicting in-space surface temperatures and rate of thermal radiation away from the thruster.

IV. Analysis

A. Method of Heating/Heat Transfer through the Catalyst Bed

As previously described, to obtain optimal catalyst performance, the catalyst should be pre-heated. Many methods were considered for pre-heating the catalyst, such as a heated probe that would be inserted at the nozzle, an external heater to encompass the thrust chamber, tri-gas pulsing, and pulsing with a separate heated gas. It was determined that any sort of pulsing with either tri-gas or another gas would not be a viable option because for true in-space conditions, as pulsing would physically be thrusting the spacecraft while just attempting to pre-heat the catalyst bed. The probe heater would also be unfavorable, despite its direct contact with the catalyst, because it would have required an additional mechanism to both retract it during flow so the flow would not be inhibited and re-insert it for additional pre-heats. Additionally, a heating probe would take much longer than other feasible methods of pre-heating. Ultimately, it was determined that an electrically powered external heater was the most realistic option for this application. A commercially available, thermally and electrically insulated, flexible heater tape was purchased for the testing. The main difficulty with using an external heater, however, is overcoming the thermal resistance separating the surface from the catalyst. The heater is required to not only heat the catalyst, but also the MACOR insulation and the thruster wall itself, while simultaneously convectively cooling in the air surrounding the heater. In order to determine the feasibility of using a radially conducting process and its impact on the testing schedule, a calculation of the total time to elevate the catalyst temperature to the adiabatic flame temperature was performed. The total thermal resistance in the path of heat conduction was obtained by the equation below.

$$R_{th} = \left(\frac{1}{h_{\infty}A_s}\right)_{air} + \left(\frac{\ln({}^{r_2}/_{r_1})}{2\pi lk}\right)_{\substack{stainless\\steel}} + \left(\frac{\ln({}^{r_3}/_{r_2})}{2\pi lk}\right)_{macor} \tag{1}$$

The total energy required to heat each material present in the thruster chamber was calculated by the equation below.

$$q = \sum mCp\Delta T \tag{2}$$

The rate of heat transfer between the external surface of the thruster chamber and the catalyst is defined below.

$$\dot{q} = \frac{T_{catalyst} - T_{surface}}{R_{th}} \tag{3}$$

Using this model, it was necessary to complete a series of iterations using small time increments to determine the point at which the thermal equilibrium was reached in the system. For the purposes of this calculation, it was assumed that the heating process was to begin at an ambient temperature of 300 K. The external heater was assumed to be capable of holding a temperature of 1400 °F (1030 K) as per the specification of the chosen heater. This analysis suggested that the catalyst bed could be electrically preheated to the adiabatic flame temperature in a matter of minutes and that the impact on the turnaround time for testing would be minimal.

B. Pressure Drop through the Catalyst Bed

The following analysis was performed with the assistance of several technical resources. In addition to the use of multiple textbooks, software called REFPROP was used to determine the state of the gas at various points in the system. REFPROP was developed for use as part of the National Institute of Standards and Technology's (NIST) standard reference database. REFPROP provides thermodynamic and transport properties of any gas when given two input parameters; in this case, temperature and pressure are input into the software, and additional properties of interest are calculated for analytical use.

In order to predict the pressure in the thruster chamber, P_c, the pressure across the catalyst bed must be predicted in a reliable way. One way this has been done in the past is to employ Ergun's equation for pressure drop through porous media. Ergun's equation was developed for use with packed particle beds of a specific geometry, and works well when applied to spherical particles. Ergun's equation is defined as:

$$\frac{\Delta P}{L} = \frac{150\mu V}{kgD^2}\frac{(1-\epsilon)^2}{\epsilon^3} + \frac{1.75\rho V^2}{kgD}\frac{(1-\epsilon)}{\epsilon^3} \tag{4}$$

The Ultramet catalyst used a platinum infused alumina substrate, which has the consistency of a very porous charcoal, and is cylindrical in shape. Each substrate catalyst was friction fit to a custom MACOR sleeve. The geometry of these substrate catalysts allows for a great amount of reactive surface area in smaller volumes. While this design is ideal for space and weight savings, it leaves the catalyst fragile and brittle, with very low compressive strength (approximately 10 psi). An additional goal of this research was to address the utility of such substrate catalysts in tri-gas thruster applications, as well as verify the accuracy and versatility of the Ergun equation in predicting the pressure drop through such a medium.

C. Orifice Sizing

Orifices are very useful in limiting mass flow rates and provide a measure of safety in case of system failure. When flow through an orifice is choked, or sonic, the system mass flow rate is limited by upstream pressure only. Therefore, orifice sizes can be chosen to satisfy requirements of different parts of the system. The tri-gas system uses three separate orifices, all of which are implemented to satisfy different requirements. Figure 4 shows the system flow schematic including the various orifices and their locations. Orifice 5 (OR 5) was sized and located to limit the system supply flow rate in case of a failure in the regulator. Because the relief valve can only accommodate a certain amount of flow, a limiting orifice must be implemented to ensure that the relief valve flow rate limit is never breached. In a failure scenario, the high upstream pressure forces sonic flow through the orifice. The equation for mass flow through an orifice under these conditions is:

$$\dot{m} = C_d A_2 p_1 \sqrt{\frac{g_c}{RT_1} \gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{5}$$

Using this equation, OR 5 can be appropriately sized to limit the supply flow. The diameter of OR 13 was selected in a similar manner; however, it was sized to limit the flow rate through the flow meter in the event of increased upstream pressure in order to prevent damage to the instrument. Depending on the mass flow rate for each test, the orifice was chosen and integrated into the system accordingly.

The diameter of OR 16 was determined in the same manner as OR 5, but was sized to limit the flow of the nitrogen purge line. The purge line is regulated per the standards set in place by the Component Development Area (CDA) at MSFC and therefore its operational limits were predefined.

D. Sizing the Relief Valve

The system relief valve (RV 9) is utilized as a safety measure to prevent overpressure in the lines in the event of a system failure. In the tri-gas system, it was determined that the worst-case failure scenario was that in which the regulator failed, causing a direct flow from the K-bottles through OR 6 and out of the relief valve. The K-bottles had a max pressure of 2200 psig, and thus failure was analyzed at this pressure. Most relief valve manufacturers provide an empirical formula for the amount of flow that can be accommodated by their relief valves. An Anderson Greenwood model 81-6 (AG 81-6) was utilized in this system. Volumetric flow rate through the relief valve can be determined by the following equation:

$$V = \frac{6.32 A_2 C K P_1}{\sqrt{MTZ}} \tag{6}$$

where V is the volumetric flow rate through the relief valve in standard cubic feet per minute (SCFM), A_2 is the area of the orifice in in^2, C is the gas constant, K is the valve discharge coefficient, P_1 is the upstream pressure in psi, M is the molecular weight of the fluid in lbm/lbmol, T is the temperature of the fluid in R, and Z is the compressibility factor of the fluid. REFPROP was used to find the compressibility factor of the fluid. With these parameters, the AG 81-6 relief valve is rated to accommodate 2357 SCFM tri-gas, which is equivalent to 0.47 lbm/s mass flow rate. Compared to the 0.40 lbm/s available flow from the K-bottles, it is evident that the relief valve is sized correctly to provide hazard mitigation in the event of a failure.

E. Determining Regulator Pressures

After an estimate for the chamber pressure has been determined, it is necessary to calculate the pressure setting of the regulator for each test. The regulator pressure is essentially the only controllable variable in the tri-gas system, and will determine the mass flow rate of the system. The regulator pressure must be chosen such that the volumetric flow rate through the flow meter does not exceed the operating ranges of the meter, as outlined in section C. In addition to providing a limited flow through the flow meter, the regulator pressure also determines the mass flow rate through the thrust chamber. Due to the coupling between mass flow rate through the thruster and volumetric flow through the turbine flow meter, the regulator pressure must be solved iteratively to ensure satisfactory operation throughout the entire system. Each unique configuration for length and type of catalyst shares a common regulator setting regardless of heater status; this is to ensure that mass flow rate is constant between separate tests.

V. Tri-gas Thruster Testing

A. Test Schematic

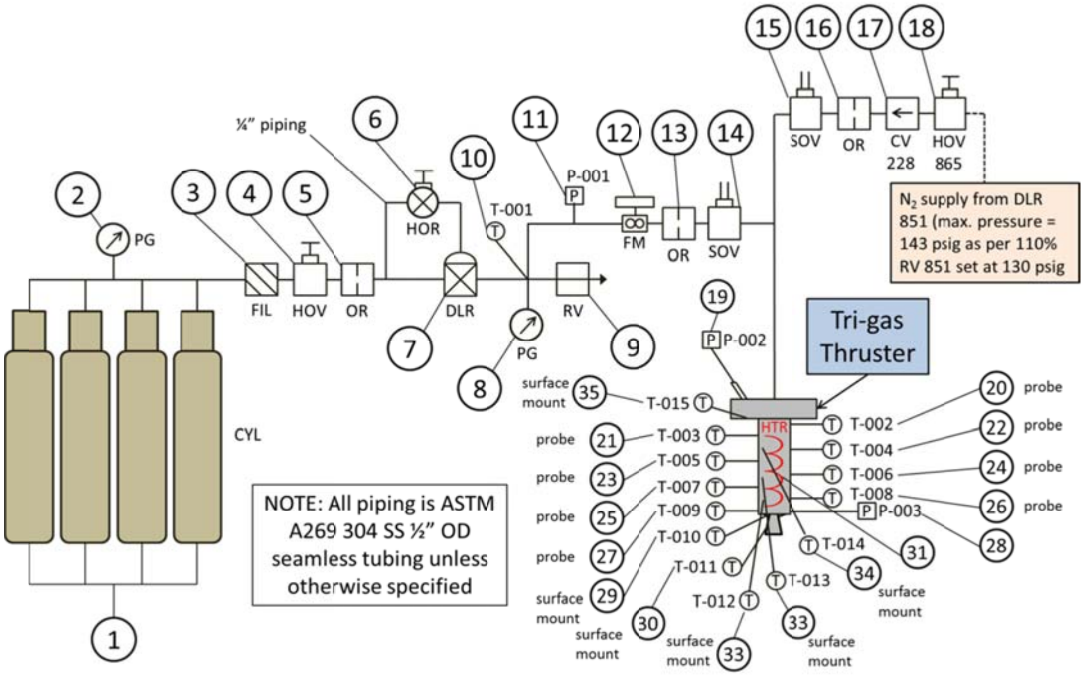

Figure 4. Test Schematic.

B. Test Instrumentation

A total of 15 E-type thermocouples, three pressure transducers, and one flow meter were used to obtain the test data during the thruster firing. In addition, an electronic heater controller was implemented that used a dedicated K-type thermocouple for the feedback system. It was mounted on the surface of the thruster chamber directly in contact with the heater tape. P-001 and T-001 were implemented to determine the state of the tri-gas as it entered the flow meter. The flow meter and calculated fluid density were used to measure the mass flow rate for thrust and specific impulse calculations. Thermocouples 2-9 were staggered probes that were spread out along the length of the chamber. All were inserted into the center of the chamber except thermocouple 8, which was a little bit closer to the wall. Thermocouples 10 and 11 were surface mounts that measured the temperature of both the convergent and divergent sections of the nozzle. Thermocouples 12-14 were surface mounts that monitored the temperature of the heater during pre-heating to ensure its maximum allowable temperature was not exceeded. Thermocouple 15 was a surface mount that was placed on the thruster flange to see if any heat conduction traveled that far upstream during long duration tests. Pressure transducer 2 measured the chamber inlet pressure, which was upstream of the catalyst bed and pressure transducer 3 measured the effective chamber pressure just before the nozzle, which was downstream of the catalyst bed. The difference in these two measurements was also used as an empirical measurement of pressure drop across the catalyst. No load cells were available to directly measure the thrust generated by the system, but the combination of chamber pressure, nozzle expansion ratio, and chamber temperature was used to analytically determine an estimate for the thrust. This thrust estimate was used in conjunction with the turbine flow meter output to arrive at the specific impulse for the thruster. Pressure and flow meter data was taken at a 5 kHz sampling rate with a 1 kHz filter.

d.

C. Test Matrix

The following table lists 13 tests that were performed using the tri-gas thruster.

Table 1. Test Matrix.

Test	Configuration	Regulator Pressure (psi)	Initial Temperature (°F)
1	C – Pelletized long	410	Ambient
2	C – Pelletized long	410	1100
3	E – Substrate long	213	Ambient
4	E – Substrate long, second test	213	Ambient
5	E – Substrate long, third test (two pulses)	213	Ambient
6	B – Pelletized intermediate	410	Ambient
7	B – Pelletized intermediate	410	1100
8	D – Substrate short	160	Ambient
9-12	D – Substrate short, pulses	160	Ambient
13	D – Substrate short, long duration	160	Ambient

D. Test Procedure

Test procedures were developed in an effort to both ensure that all of the necessary data was captured and that all personnel and hardware remain safe during operations. A hazards analysis was performed prior to testing that outlined the potential safety issues for this testing and the mitigations in place to handle those issues. Procedurally, the testing operations were essentially identical for each catalyst configuration, so one governing test procedure was created in conjunction with multiple data recording sheets for each test case. In addition, both the pelletized and substrate catalysts were baked in a nitrogen purged furnace at 450°C for 1 hour to remove any oxidation from the surface of the catalyst. After baking was completed, great care was taken to ensure that the catalyst had limited access to the atmosphere as it traveled from the oven to the test stand. Once the test preparations were complete, a leak check of the system plumbing was performed and the regulator pressure was set for the specific test. All personnel then returned to the control room, and testing was clear to commence. Once the personnel in the control room were satisfied that the system had reached steady state, the flow of tri-gas was stopped and a nitrogen purge was introduced. This was used both to cool the thruster after firing and to limit the oxygen exposure for the catalyst. Once the thruster had cooled enough to handle, it was inspected, disassembled, reassembled for the following configuration, and then re-installed on the test stand for another cycle of testing.

VI. Results

A. Catalyst Results

As mentioned earlier, the pressure drop across the catalyst bed was predicted for given regulator pressures by using the Ergun equation. The Ergun equation is typically used to estimate pressure drops through packed beds of spherical catalysts. It was determined that the Ergun equation approximated the pressure drop through the pelletized catalyst to within 1-2 psi, but may not have been appropriate for use with the substrate catalyst. For both substrate configurations shown in Table 4, the actual pressure drop seen during testing far exceeded the predicted value. Upon disassembly of the thruster after testing the substrate catalyst, it was found that the catalyst had structurally failed and compressed about 25% in length, which is believed to be the primary cause of the large pressure drop encountered. Because the substrate did not prove to be strong enough to survive already minimized flow rates, the majority of the testing was performed using the spherical pelletized catalyst.

Table 2. Catalyst Pressure Drop Summary

Catalyst Type	Configuration	Estimated Pressure Drop (psi)	Actual Pressure Drop (psi)
Pelletized	C	16.5	14
Pelletized	B	11.54	10
Substrate	E	11	23-65
Substrate	D	5	9-11

B. Thruster Testing Thermal Profiles

The temperature profile along the thruster chamber was of particular interest for this testing since it was necessary to obtain insight into catalyst activity, rise time, and ultimately specific impulse. The four figures below show the temperature profiles for each of the tests of interest selected for drawing the comparisons between catalyst type, catalyst length, and initial catalyst temperature. Figure 6 outlines the results from the first test conducted, which served as the baseline performance test. These results were also compared to previous thruster research in 2010, which utilized a nitrogen tri-gas and a palladium catalyst. The maximum temperature reached with helium tri-gas was 1101 degrees F, which was reasonably close to the predicted adiabatic flame temperature of 1200 degrees F. The rise time, which was defined as the time required for the system to achieve 90% of the maximum temperature, was determined to be roughly 10.5 seconds for this configuration. These values stand in comparison to a maximum temperature of 760 degrees F and a rise time of roughly 25 seconds obtained during previous nitrogen tri-gas and palladium catalyst testing. It was therefore determined that the overall performance of the platinum catalyst / helium tri-gas combination was superior to the palladium catalyst / nitrogen tri-gas combination.

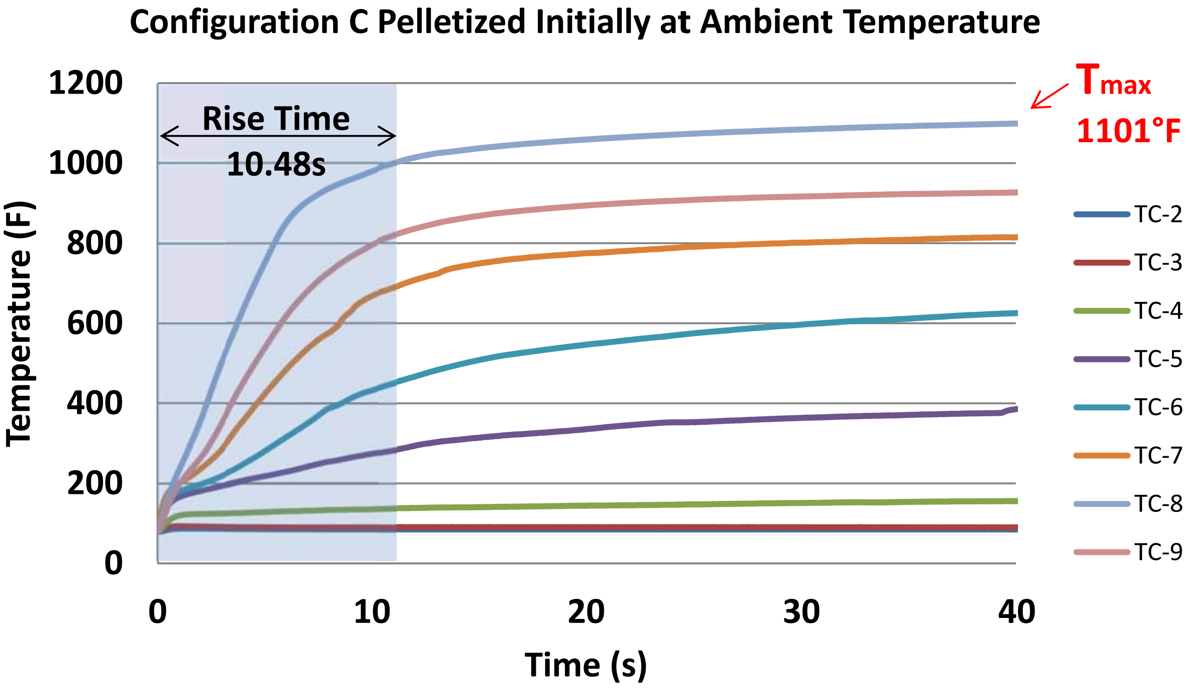

Figure 6. Baseline Test.

Figure 7 shows the results from a similar test that changed the catalyst configuration from C to B. This test confirmed the hypothesis that less catalyst would take longer to achieve steady state temperature, and it was also determined that the maximum temperature from the reaction was not as high as configuration C. The rise time was just under 30 seconds and the maximum temperature was found to be 1073 degrees F. Based on these results, it was determined that a longer catalyst length improved performance.

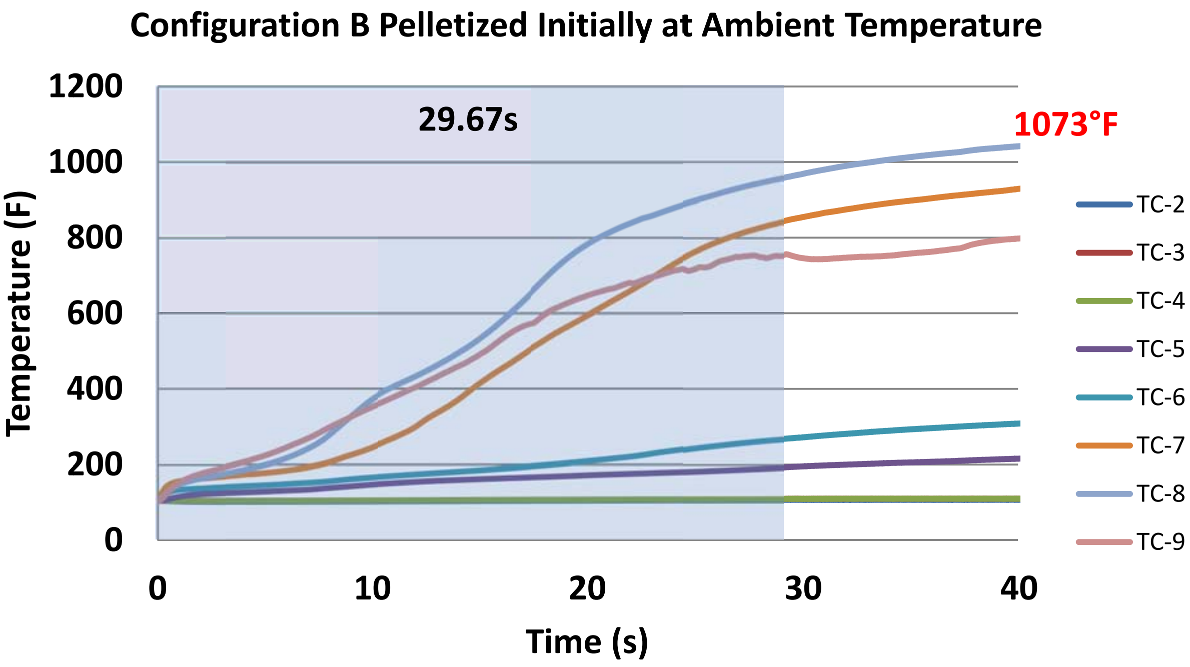

Figure 7. Comparing Catalyst Lengths.

The next test uses the substrate catalyst in configuration E. Ideally, this test would have been in configuration C to directly compare with the pelletized catalyst, but because the structural integrity of the substrate catalyst had not been tested, only configuration E, a smaller length, was used. This was ultimately a good decision because even though a significantly reduced chamber pressure and mass flow rate was used for the test, the substrate still failed in compression. The vendor suggested that the compressive strength of the catalyst was 10-15 psi and that tests had been performed that encountered a 20 psi drop across the catalyst. The regulator pressure was set such that the anticipated pressure drop across the substrate was 11 psi, which was thought to be in the safe region. However, the substrate still failed and experienced a pressure drop of up to 65 psi after compressing. Figure 8 shows the results from the configuration E substrate test, which despite having the catalyst structurally fail, had an improved rise time over the pelletized catalyst, which was anticipated based on the increased surface area of the substrate. Ultimately, this configuration had a 7.25 second rise time, whereas the pelletized catalyst in configuration C had a rise time of 10.48 seconds. Based on this, it can be said with certainty that the substrate had a higher activity than the pelletized catalyst. However, due to its inability to handle the necessary flow rates to achieve the desired thrust the substrate was deemed impractical for this application.

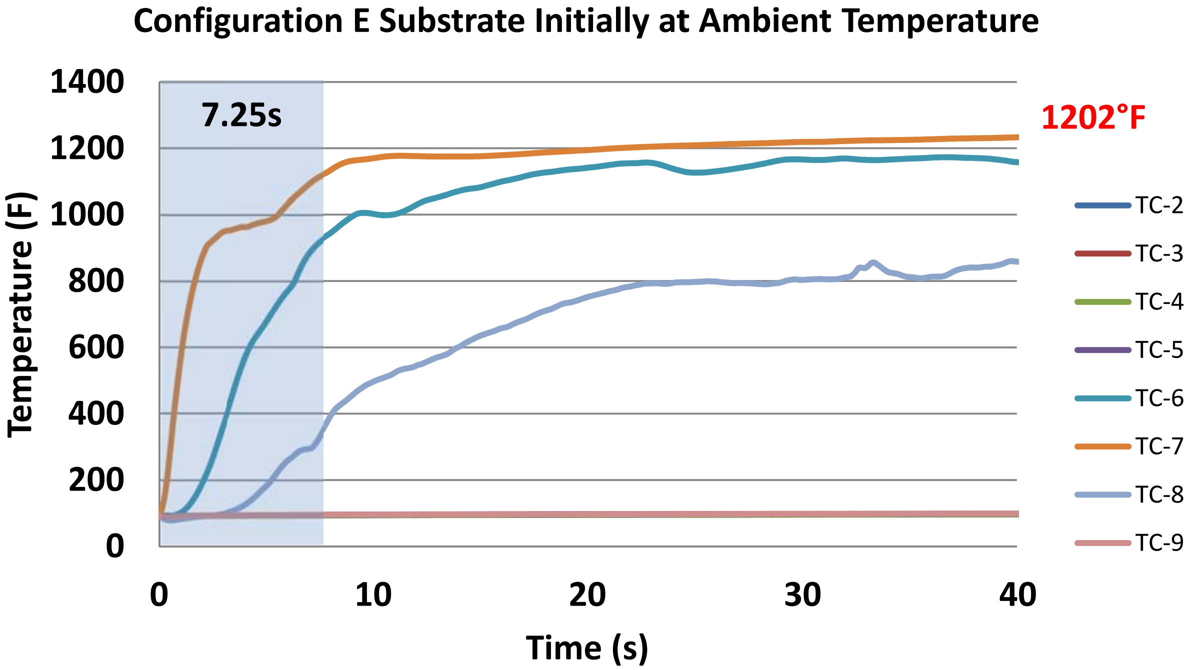

Figure 8. Comparing Catalyst Type.

The pelletized catalyst in configuration C was also preheated to see if the rise time could be reduced to compete with the higher activity of the substrate. A heater controller was used to drive a flexible heater tape to 1100 degrees F. Thermocouples were placed on the surface of the thruster to monitor the surface temperature to ensure the heater was not exceeding its maximum temperature of 1400 degrees F. In addition the catalyst probe thermocouples were monitored during heating to determine when the catalyst reached the 1100 degrees F preheat temperature. Once the internal temperature was achieved, the heater was turned off and the tri-gas began to flow. Figure 9 shows that the maximum temperature was increased to 1250 degrees F and that the rise time for that temperature was 0.52 seconds. This reflects a 95% decrease in rise time and a 13.5% increase in maximum temperature. This configuration was determined to be optimal for the variables that were being analyzed. It maximized specific impulse and reached a steady state thrust and temperature the quickest.

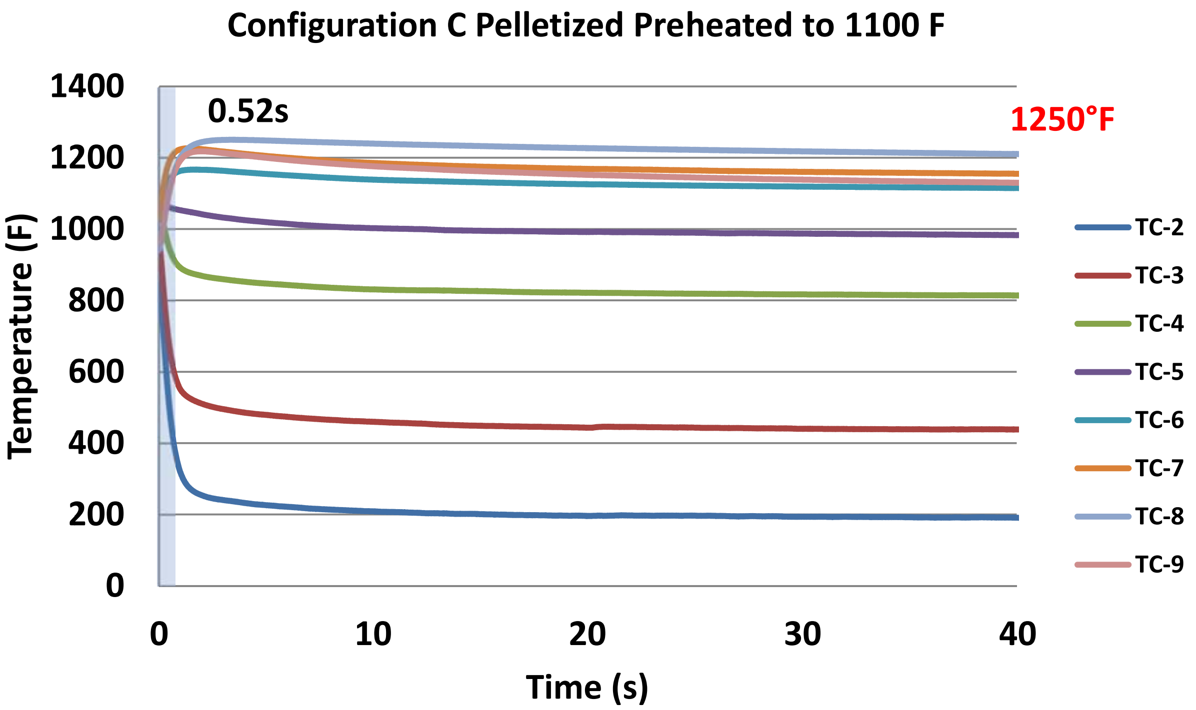

Figure 9. Comparing Initial Catalyst Temperature.

C. Thrust and Specific Impulse Calculations

Thrust and specific impulse were calculated using the equations outlined below. First, the exit Mach number at the nozzle exit was calculated using the ratio of the nozzle throat and the exit area, where nozzle throat Mach number is 1 (choked flow).

$$\frac{A_t}{A_e} = M_e \sqrt{\left(\frac{1+\frac{\gamma-1}{2}}{1+\frac{\gamma-1}{2}M_e^2}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{7}$$

Next, the exit Mach number was used to find the pressure ratio between the exit and the chamber.

$$\frac{P_e}{P_c} = \left(1+\frac{\gamma-1}{2}M_e^2\right)^{\frac{\gamma}{1-\gamma}} \tag{8}$$

Finally, the thrust was calculated with the following.

$$F = A_t P_c \gamma \left[\left(\frac{2}{\gamma-1}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left\{1-\left(\frac{P_e}{P_c}\right)^{\frac{(\gamma-1)}{\gamma}}\right\}\right]^{\frac{1}{2}} + (P_e - P_a)A_e \tag{9}$$

The specific impulse was calculated with the below equation.

$$I_{sp} = \frac{F}{\dot{m} g_o} \tag{10}$$

Because of dimensional analysis, the gravity term can be neglected when using English units. It should be noted that due to the reduction of mass flow rate for the substrate catalyst tests, a correction to Eq. (9) had to be implemented in order to obtain an accurate thrust measurement. The expansion ratio of the nozzle was too large, and greatly over-expanded the exhaust gases, thus causing flow separation in the nozzle. In order to account for this, it was determined that the flow separates at approximately 30% of the way through the nozzle and the exit area and pressure terms must be adjusted accordingly.

Additional configurations were tested and a summary of tri-gas test performance data can be seen in Table 5 below. The highest performing test (Configuration C, pelletized, preheated), is highlighted. This configuration resulted in a maximum catalyst temperature of 1202 deg F, and an I_{sp} of 221 s, which met the thrust output desired for the 5lbf class thruster and provided a 35-40% increase in I_{sp} in comparison to a traditional helium cold gas thruster. This I_{sp} is also comparable to a hydrazine monopropellant system (typically near 230 s), proving that similar performance can be attained while using a non-toxic propellant.

Table 3. Thruster Performance Summary.

Test	**Configuration**	**Maximum Temperature (°F)**	**I_{sp}**
1	C – Pelletized long	1101	195
2	C – Pelletized long	1202	221
3	E – Substrate long	1230	134
4	E – Substrate long, second test	1215	81.4
5	A – Substrate long, third test (two pulses)	880	-
6	B – Pelletized intermediate	1073	180
7	B – Pelletized intermediate		202
8	D – Substrate short	1081	83.3
9-12	D – Substrate short, pulses	1082	-
13	D – Substrate short, long duration	999	81.3

Figure 10 shows that the specific impulse for each of the tests followed a similar profile to that of the temperature, which was the expected behavior. The baseline test using configuration C had a rise time of approximately 10.5 seconds and asymptotically approached a maximum specific impulse of 195 seconds. The unheated catalyst using configuration B specific impulse profile was seen to be steadily increasing and peaked at approximately 180 seconds when the flow of tri-gas was cut off. The configuration E substrate test showed a slightly longer rise time for the specific impulse than the temperature profile and only approached a specific impulse of approximately 134 seconds. The preheated pelletized catalyst configuration C was seen to deliver a nearly constant specific impulse over the entire duration of the burn. It provided approximately 221 seconds of specific impulse, which was the highest of all configurations. This attribute lends itself to more easily predicted burn times and propellant masses required for short duration in-space maneuvers, which can help to trim mass contingencies in design and ultimately aid in spacecraft development. Based on these findings, it was clear that the pre-heated, pelletized catalyst configuration C was the optimal alternative for this type of application.

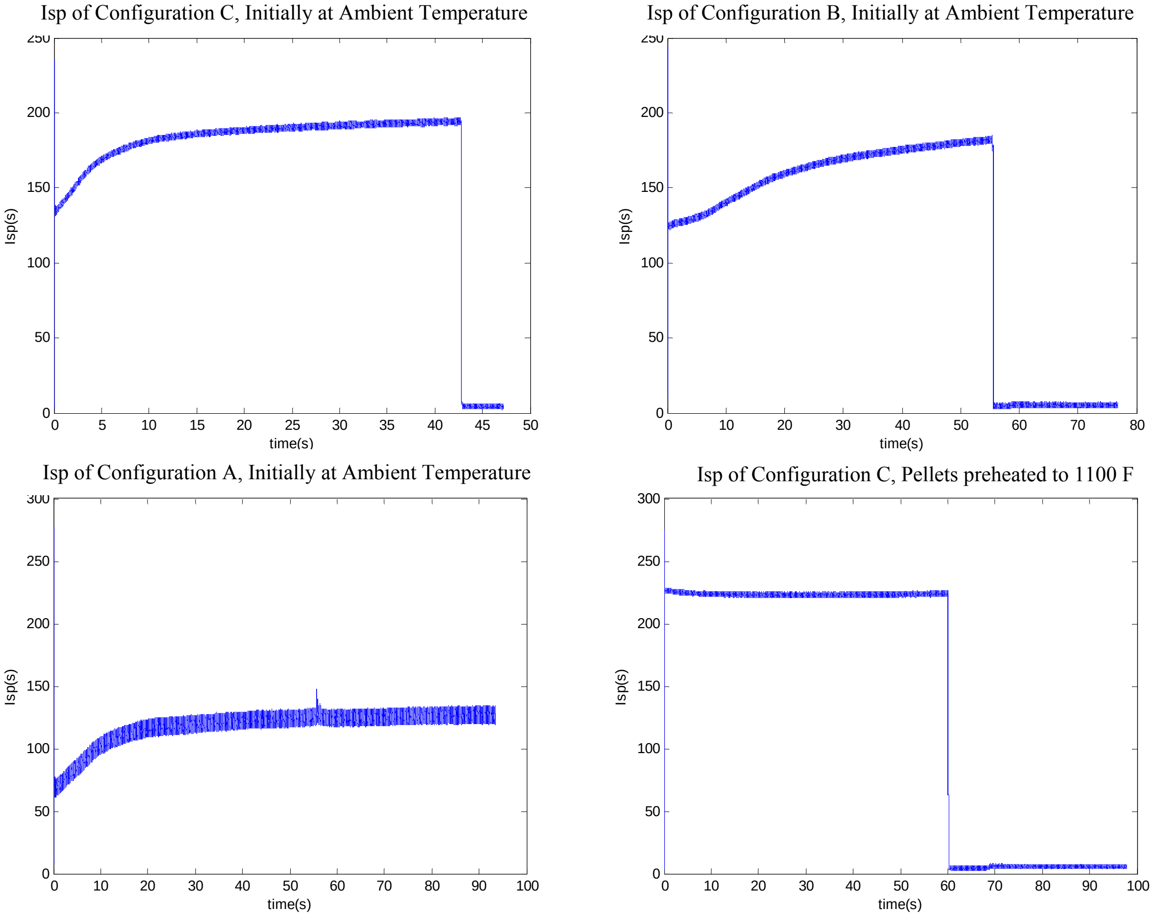

Figure 10. Specific Impulse during firing for all configurations.

VII. Conclusion

Analysis of test results for both catalyst types suggests that the pelletized catalyst provides better performance when optimizing thrust and I_{sp}. Although the substrate catalyst demonstrated a shorter rise time, its low compressive strength required more than a 78% decrease in mass flow to avoid structural failure, and was not tested empirically to the point at which it did not fail. It was determined that longer pelletized catalyst beds had a shorter rise time, which could be further minimized by pre-heating the catalyst bed. The optimal configuration was finalized to be the pre-heated, pelletized catalyst configuration C. This does come with the tradeoff of requiring electrical power to drive the heater device. Additional trade studies would be necessary to determine the mass savings or penalties of the additional heater system versus the additional propellant required.

Ongoing experiments seek to continue exploring reaction transients and study the substrate's structural integrity. Future experiments that might further this project's goals include testing of the following conditions:

- *Optimized catalyst bed length – gradual length increase*
- *Hydrogen (fuel) rich tri-gas mixture*
- *Performance in simulated high altitudes*

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