Hydrogen Peroxide – Water – Ethanol Monopropellant Blend for CubeSat Propulsion

Steven J. Schneider[1]
NASA Glenn Research Center, Cleveland, OH 44135, USA

Monopropellant propulsion that provides high performance and low hazards compared to state-of-art hydrazine are being investigated under NASA, DOD and commercially sponsored green propellant research and development programs. This NASA effort looks at phosphate stabilized 50% hydrogen peroxide/water – ethanol blends to evaluate their stability and combustion behavior in submillimeter diameter microtube combustion apparatus for cubesat propulsion applications. Exploratory 7-day stability tests find no pressure rise in a sealed test tube environment at room temperature indicating at least short term stability of the mixture. Temperature rise during combustion testing in resistively heated nickel microtube apparatus shows that micro-combustion is achieved in the tube. Propellant density is approximately 1.2 g/cm^3 compared to 1.0 g/cm^3 for hydrazine. Theoretical specific impulse of the stoichiometric blend is 219 s at a chamber pressure of 20 psia and an area ratio of 30:1. Density-specific impulse of this blend is 263 s while hydrazine is only about 215-220 s in small reaction control system thrusters. This provides about 20-22% more density-specific impulse for the cubesat compared to hydrazine. The theoretical combustion temperature is 2168°F, which is thermally compatible with stainless steel materials of construction and the nickel catalyst used in the tests. Combustion test results are given for stoichiometric, as well as fuel-lean and fuel-rich propellant formulations. These tests focus on thermally and catalytically supported combustion in the microtube, which requires a microtube preheat temperature of about 900°F and sufficient residence time to achieve combustion that is stable and anchored in the tube without blowing through the tube unreacted. Thrust class is expected to be in the 10 mN range based on flow rate and estimated specific impulse. Power requirements are generally below 25 W to heat the tube. Steady state combustion testing is typically conducted for 3 minutes and shows little degradation of the hardware over multiple test cycles indicating that there is little catalyst degradation over time and little catalyst deactivation due to the phosphate stabilizer in the hydrogen peroxide.

I. Introduction

The NASA Green Propulsion Roadmap[1] focuses on the development of ionic liquid propellants, which can be direct or near-direct replacements for hydrazine. This paper takes a step back from this development and looks at other possible direct replacements for hydrazine based on hydrogen peroxide. In a review of Green Propulsion[2], it was noted that a direct comparison of the flight performance of hydrazine and high-test hydrogen peroxide in 1967 lead to the common use of hydrazine as the propellant of choice based on its performance. The 90% hydrogen peroxide/water blend only had a specific impulse of 148 s compared to 240 s for hydrazine and the hydrogen peroxide underwent a gradual dilution over time due to exothermic decomposition and the continuous evolution of oxygen gas by the propellant. Stabilizers[3] for hydrogen peroxide were explored and a stabilized 50% hydrogen peroxide/water solution containing less than 200 ppm of a phosphate added as a stabilizer can now be procured. This stabilized solution is mixed with pure biological grade ethanol for this research effort. The Safety Data Sheet (SDS) for the peroxide warns against mixing the peroxide with combustibles, but such mixtures as the proposed blend were not detonable with the impact of a fuse-ignited No. 6 blasting cap lowered into 10 cc of mixture about half immersed[4]. Exposure limits defined as an employee's average airborne exposure in any 8-hour work shift of a 40-hour work week or 8-hour Total Weight Average (TWA) permissible for hydrogen peroxide are TWA of 1.0 ppm compared to hydrazine’s TWA of 0.1 ppm for an order of magnitude less toxicity. The freezing point of 50% hydrogen peroxide/water is -62ºF compared to hydrazine’s 36ºF. The first part of this study provides short term exploratory data on whether the stabilized 50% hydrogen peroxide/water remains stable with the addition of the ethanol to the blend.

---

[1] Aerospace Research Engineer, Chemical and Thermal Propulsion Systems Branch, Associate Fellow AIAA.

Since the mixture may pose a detonation hazard, safety protocol requires that only small quantities (less than 10 cc) of mixture be on hand. Research on small quantities is programmatically compatible with addressing cubesat propulsion needs as a path forward in development of the propellant. After some record of safety is established with cubesats, then scale up to larger propulsion systems with larger quantities of propellant can be pursued. Cubesat missions have been on the increase by NASA, DOD, and commercial industries in recent years. The desire for attitude and orbit control, extended life, and deorbit on command is driving the development of propulsion technologies for these vehicles. Current propulsion systems for cubesats are either low performing cold gas, toxic hydrazine, or power consuming electrical discharge type systems. Combustion type systems with Green Propellants have very limited flight heritage. The chemical propulsion combustion process in very small combustors is known to be quenched by heat loss through the walls of the combustor. This is addressed by a surface combustion process relying on surface catalysis in microtube combustors[5]. Adapting this work to the current effort, nickel is chosen as the catalyst material because it is used extensively as a catalyst in fuel cells for the steam reformation process of methane[6]. Hence, this catalyzed combustion process uses the resistively heated nickel microtube to first thermally vaporize the stoichiometric propellant blend, promote exothermic decomposition of hydrogen peroxide, and with surface catalysis promote possible steam reformation of the ethanol. Finally, the nickel promotes the exothermic oxidation of the reformed ethanol to raise the temperature of the predominately water mixture toward the theoretical combustion temperature of 2168°F. Nickel has a compatible melting point of 2625°F and has lower molecular weight and cost than other catalysts such as platinum or palladium. The second part of this study provides data on exploratory combustion tests with the peroxide-water-ethanol blends conducted in submillimeter diameter microtubes resistively heated to about 900°F as determined by the required catalyst preheat temperature used in the fuel cell steam reformation process[6].

II. Analysis

The review criteria for Green Propulsion Advancement[2] noted that history has shown that green monopropellants that offer no performance advantage over hydrazine face difficulty being adopted. Theoretical performance[7] analysis of the stoichiometric (Stoic) blend of 50% hydrogen peroxide/water – ethanol predicts a specific impulse of 219 s at 20 psia chamber pressure and 30:1 area ratio along with a combustion temperature of 2168°F. This is shown as the 50% hydrogen peroxide/water point on Fig. 1. This performance measure is in the range of the 215-220 s of hydrazine in small reaction control system thrusters and the specific gravity of this solution is near 1.2 giving a density specific impulse of 263 s exceeding the 215-220 s density specific impulse of hydrazine with its specific gravity of 1.0 by almost 20-22%.

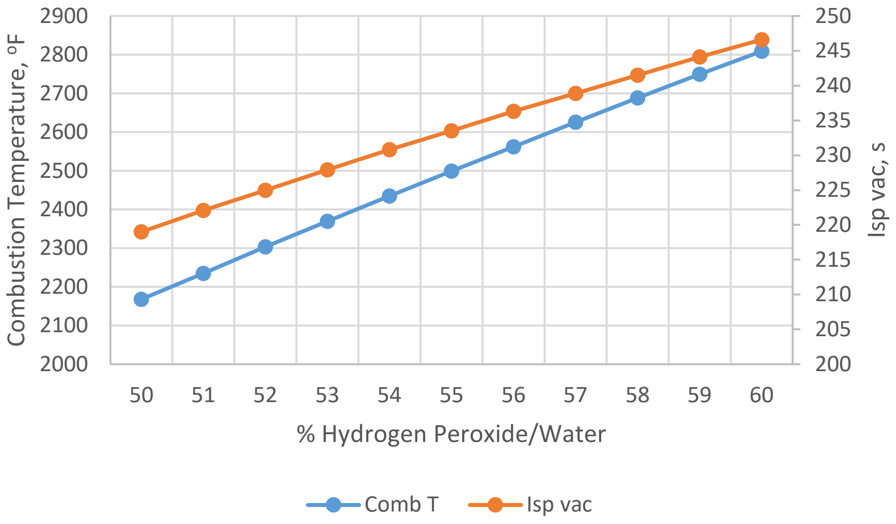


Fig. 1. Stoichiometric performance of peroxide-water-ethanol mixtures

If this performance still proves to be an issue in gaining acceptance, it should be noted that more performance can be obtained by developing Stoic blends using higher concentrations of hydrogen peroxide/water with the ethanol. Performance numbers for these Stoic blends up to 60% hydrogen peroxide/water – ethanol are also shown in Fig. 1.

The Stoic 60% hydrogen peroxide/water – ethanol blend gives a theoretical specific impulse of 246 s at a combustion temperature of 2809°F. The specific gravity of this solution, also near 1.2, gives a density specific impulse of 295 s exceeding the 215-220 s of hydrazine by almost 34-37%.

The Safety Data Sheet (SDS) for the peroxide warns against mixing the peroxide with combustibles, however, such tri-mixtures were tested[4] in the past for detonability as shown in Fig. 2 reproduced from the Reference 4.

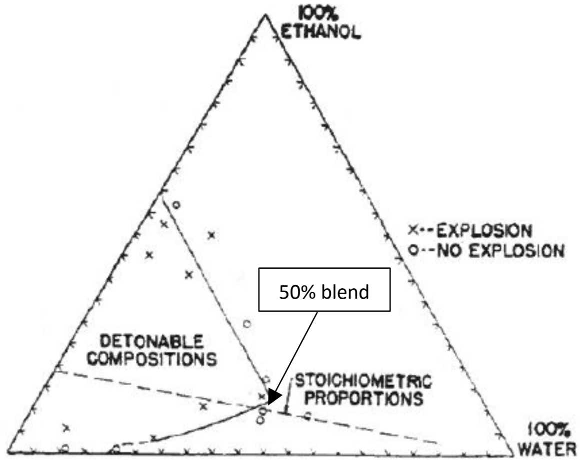


Fig. 2. Range of Explosive Compositions for Peroxide-Water-Ethanol Mixtures showing stoichiometric proportions (dashed line) (Reference 4).

Detonable compositions are marked with an “x”. The boundary between detonable and non-detonable compositions is not rigorously established as noted by the detonable mixture outside of the boundary at 60% hydrogen peroxide/water. The dashed line shows the Stoic proportions and the proposed Stoic blend of 50% hydrogen peroxide/water – ethanol pointed to by the arrow is shown to have an open circle “o” on the dashed line in Fig. 2 indicating that it is not detonable, however, care must be taken since it is close to the detonable boundary. These tests were conducted with the impact of a fuse-ignited No. 6 blasting cap lowered into 10 cc of mixture about half immersed. If more performance is needed to gain propellant acceptance, the Stoic blend of 60% hydrogen peroxide/water – ethanol could be explored, however, this blend is well within the detonable composition range as shown in Fig. 2 making this composition a more challenging development. Also, if higher concentrations of hydrogen peroxide/water are desired for performance, this would entail accommodating higher combustion temperatures as shown in Fig. 1. Stoic blends above 57% hydrogen peroxide/water – ethanol exceed the melting point of Nickel at 2625°F. Higher temperature catalysts such as platinum which melts at 3215ºF would have to be used for that development and if eventual scale up to larger propulsion systems is a desirable goal, then the use of higher concentrations of hydrogen peroxide would preclude the use of stainless steel materials and drive the thruster fabrication to higher temperature materials.

The chosen microtube geometry for this cubesat thruster development consists of a 0.8 mm I.D. tube, 200 mm long and was previously analyzed and tested with gaseous oxygen and methane[8]. Gasdynamic area relations that avoid choking using the equilibrium properties[7] of the propellant combustion products are used to calculate subsonic flow requirements throughout the tube. Fanno Line friction pressure drop is used to estimate flow rates of propellant for experimental design purposes. The Reynolds Number of the flow is well within the laminar range. Thrust class is expected to be in the 10 mN range based on flow rate and estimated specific impulse.

III. Stability Tests

Exploratory stability test apparatus consists of circular chart recorders for measuring pressure and temperature of the propellant sealed in a Teflon test tube with a pressure transducer and relief valve as shown in Fig. 3. Safety precautions require the tests to be conducted under a fume hood with small quantities of mixed solution. These tests are conducted on 8 cc of solution in the test tube monitored for gage pressure and environmental temperature by the circular chart recorders for 7 days.

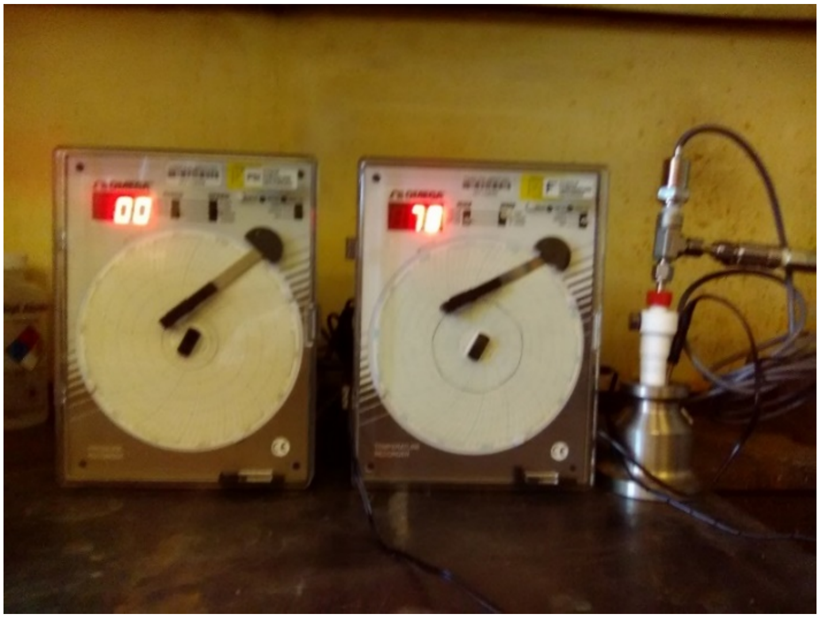


Fig. 3. Seven day test tube stability test apparatus which recorded gage pressure in a Teflon test tube and environmental temperature on circular charts.

The stability of the as received stabilized 50% hydrogen peroxide/water is shown in Fig. 4a and Fig. 4b. The gage pressure as measured on a 0-50 psig transducer is steady at zero for the 7 days on Fig.4a, while there is a slightly varying room temperature of 72-74°F on Fig.4b. This shows that spontaneous decomposition is not occurring.

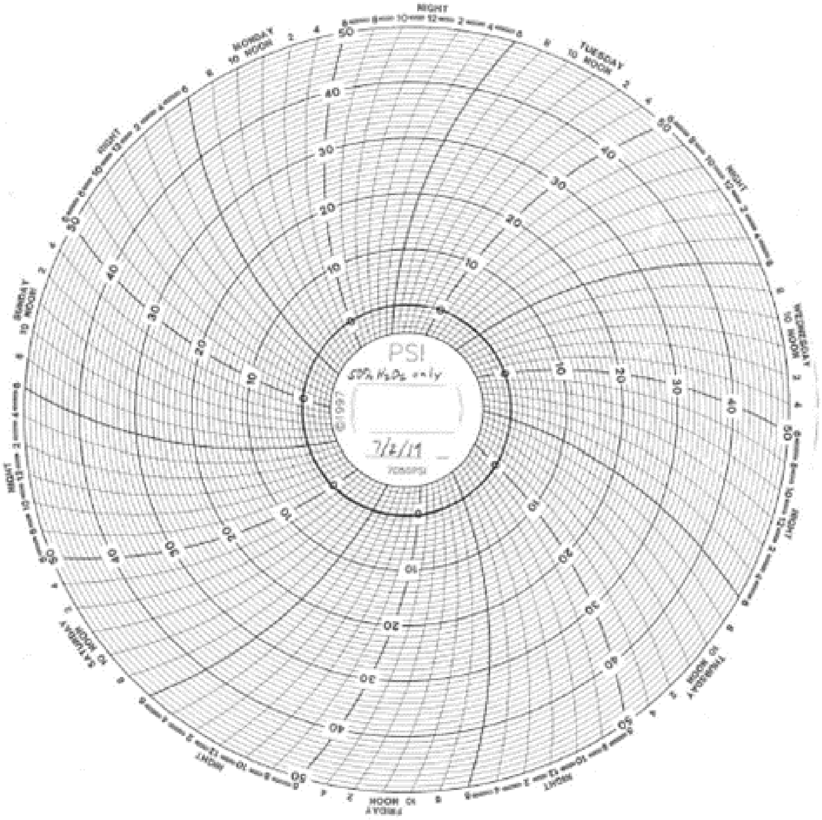


Fig. 4a. Seven day gage pressure trace of the as received stabilized 50% hydrogen peroxide/water showing no pressure rise during the test cycle.

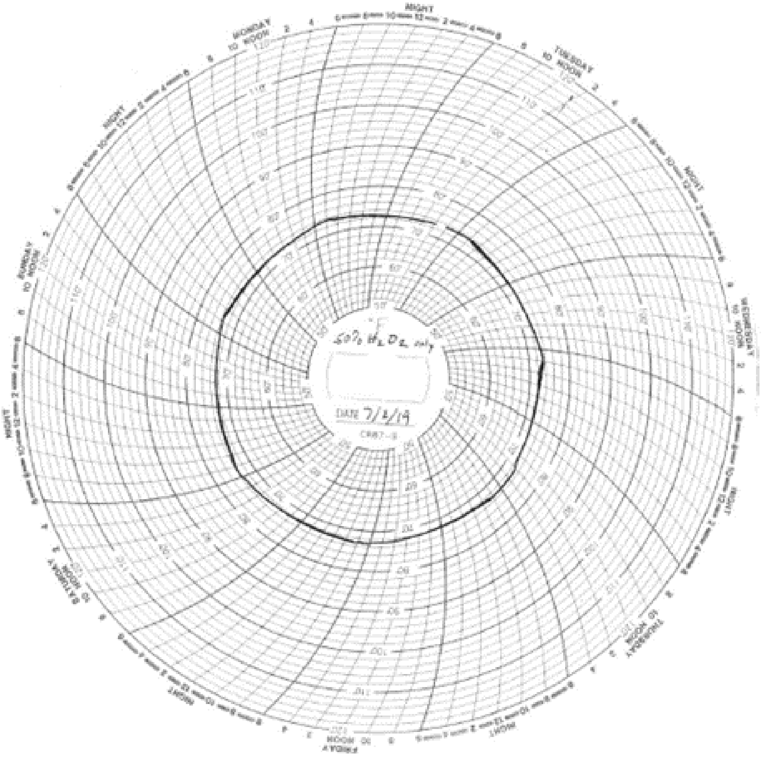


Fig. 4b. Seven day room temperature trace of the as received stabilized 50% hydrogen peroxide/water showing a slight temperature variation between 72-74ºF during the test cycle.

Subsequent gage pressure measurements with different blends of stabilized 50% hydrogen peroxide/water – ethanol propellant are shown in Fig. 5a, Fig.5b, and Fig.5c.

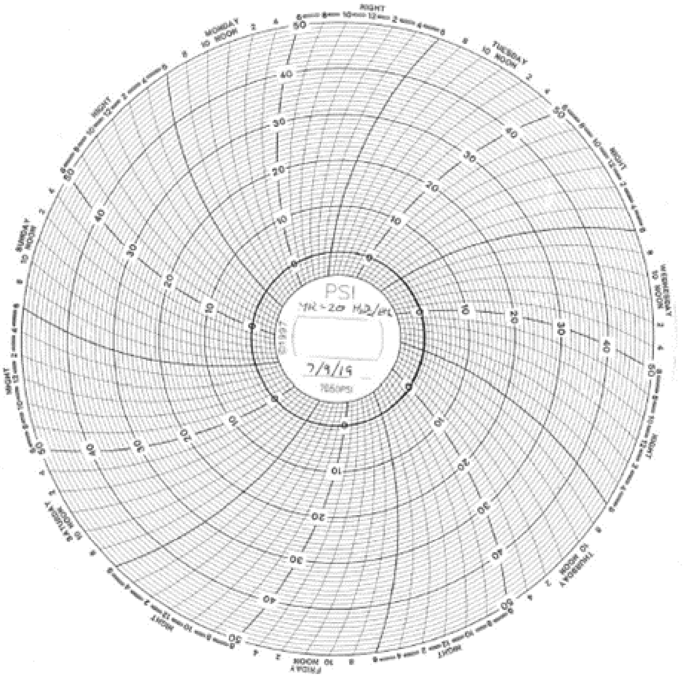


Fig. 5a. Seven day gage pressure trace of the fuel lean MR=20 blend of stabilized 50% hydrogen peroxide/water – ethanol showing no pressure rise.

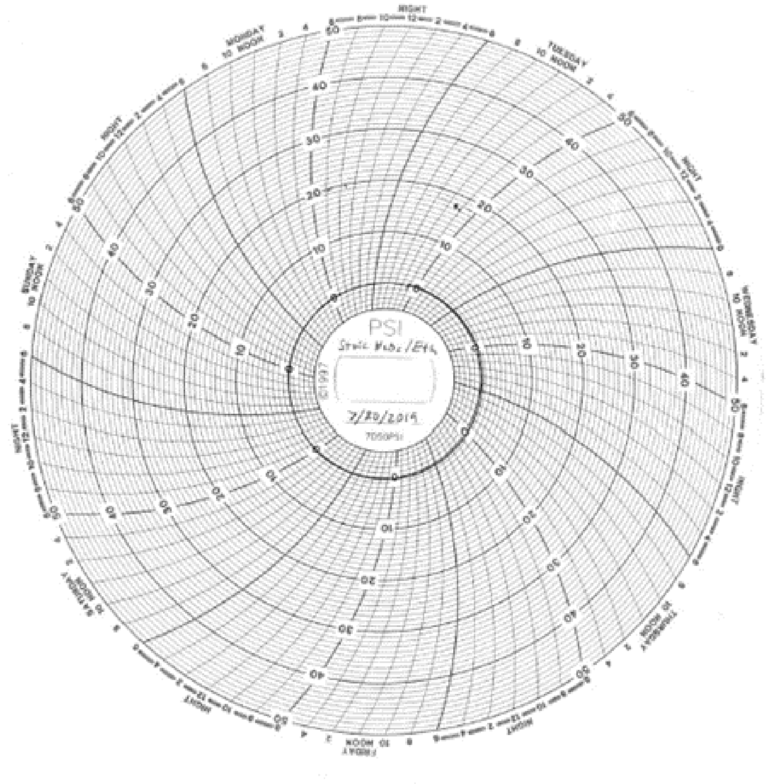


Fig. 5b. Seven day gage pressure trace of the stoichiometric MR=8.86 blend of stabilized 50% hydrogen peroxide/water – ethanol showing no pressure rise.

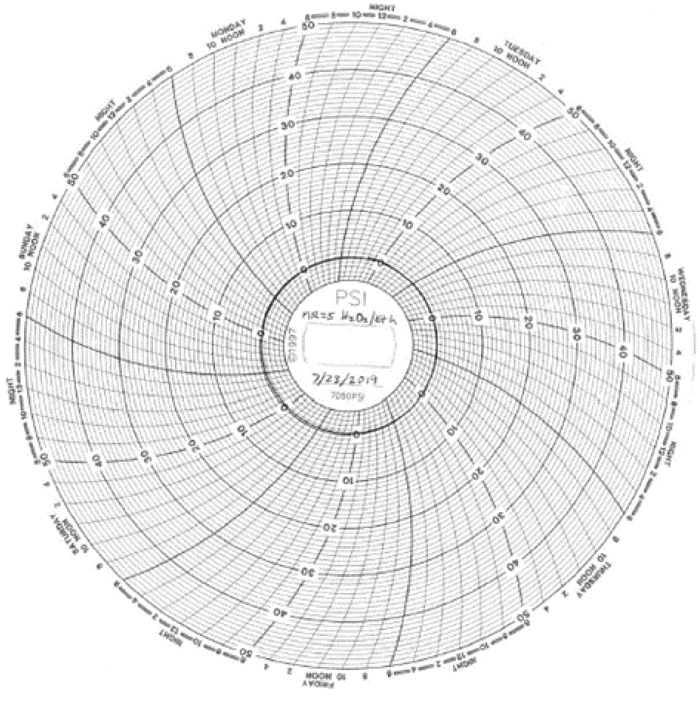


Fig. 5c. Seven day gage pressure trace of the fuel rich MR=5 blend of stabilized 50% hydrogen peroxide/water – ethanol showing no pressure rise.

These tests have similar temperature traces to the as received stabilized 50% hydrogen peroxide/water that are not reproduced here. According to Fig. 2, fuel lean is the safest blend to test and a 7 day gage pressure trace is shown for the MR=20 blend showing no pressure rise on Fig. 5a. Next, the 7 day gage pressure trace of the stoichiometric MR=8.86 blend is given showing no pressure rise on Fig. 5b. Finally, the fuel rich MR=5 blend is tested and the result is given also showing no pressure rise on Fig. 5c. No stability issue was found in any of the compositions as indicated by this lack of gage pressure rise in the sealed test tube environment at room temperature over a 7-day period. More and longer term stability tests are recommended, however.

IV. Micro-tube Combustion Tests

Exploratory combustion tests are conducted in this part of the study with the stabilized hydrogen peroxide-water-ethanol blends using resistively heated submillimeter diameter micro-tubes. The micro-tube is fabricated from nickel which is a catalyst used in fuel cell reformers in which the nickel is heated to a preheat temperature[6] of about 900°F. The resistively heated micro-tube vaporizes the propellant blend, thermally decomposes the hydrogen peroxide, promotes steam reformation[6] of the ethanol, and the evolved oxygen from the peroxide catalytically reacts with the reformed ethanol in the submillimeter diameter tube. The micro-tube combustion test setup is shown in Fig. 6.

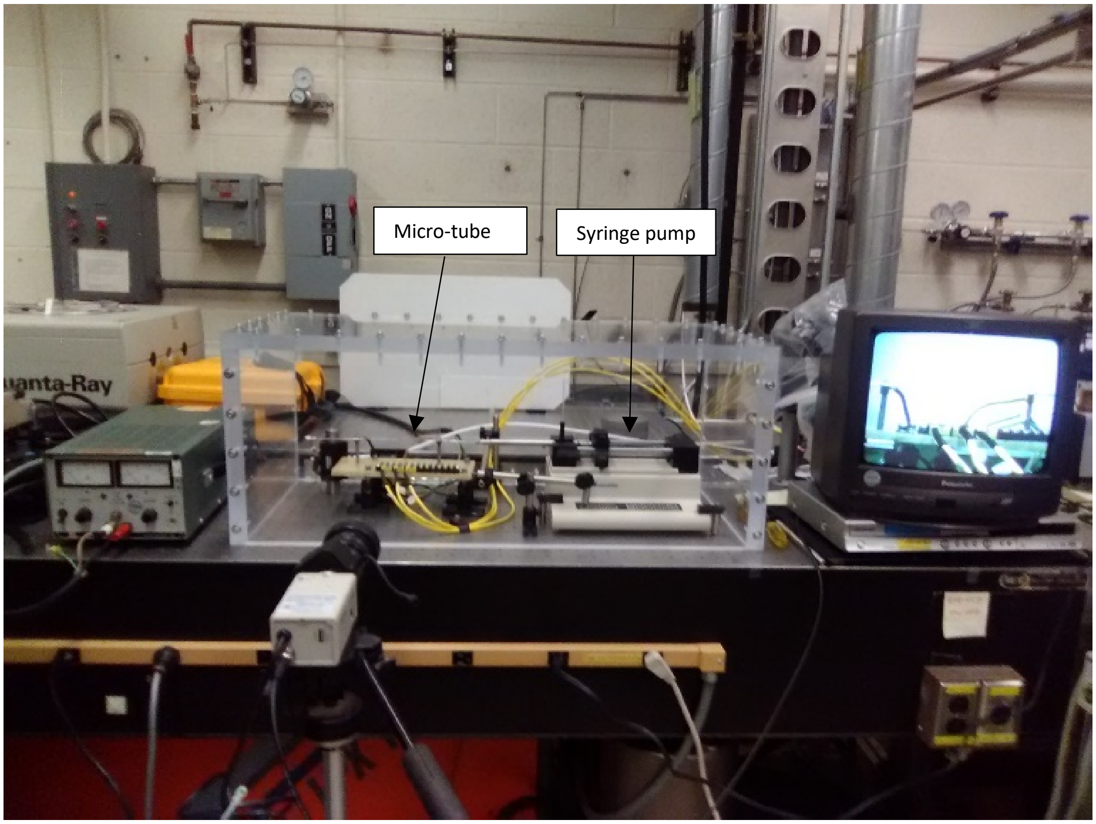


Fig. 6. Micro-tube combustion test apparatus with video and thermocouple temperature recording.

The micro-tube combustor identified in Fig.6 is a 200 mm long, 0.8 mm I.D., resistively heated, nickel capillary tube fed by a variable speed, armored syringe pump also identified in Fig.6. The micro-tube is instrumented with three type K thermocouples. Also shown in the picture are the DC power supply, camera, and video recording apparatus. DC power requirements were generally below 25 watts. Steady state combustion was typically from 3 to 6 minutes depending on the test. The addition of a possible ignition source to the testing requires the safety precaution of an explosive barrier consisting of 1-inch thick plexiglass enclosure around the combustion apparatus with the quantity of mixed propellant kept to less than 10 cc.

After a series of checkout tests at fuel lean conditions (MR=20), stoichiometric (MR=8.873) combustion tests are conducted showing that the tube can support a flow rate of about 0.14 ml/min, which is enough flow to heat the tube but not blow through the tube without reacting. At 219 s of specific impulse this flowrate would give about 6 mN of thrust. Thermocouple (TC) data from the stoichiometric (MR=8.873) combustion test is given in Fig. 7 for this flow rate of 0.14 ml/min.

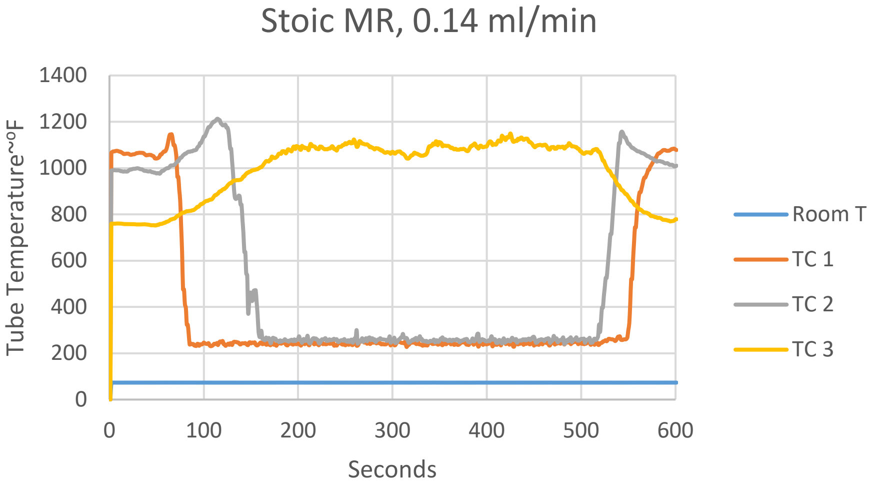


Fig. 7. Thermocouple data on stoichiometric combustion in the 200 mm long, 0.8 mm I.D. nickel tube at a flow rate of 0.14 ml/min and a preheat of approximately 1100°F on TC1.

The thermocouple locations from the entrance of the tube are TC1 at 52 mm, TC2 at 100 mm, and TC3 at 148 mm on the 200 mm long tube. The data reveal that micro-combustion was achieved in the tube. Preheat temperature on the tube varies with thermocouple location, but for test characterization the first temperature that the propellant sees is at TC1 which is at about 1100°F. Flow rate was not measured but was set on the calibrated syringe feed system which was activated at about 1 minute into the 10 minute recording. When flow is initiated, TC1 rapidly drops from 1100°F to about 250°F as the flow of propellant is heated by the tube resulting in vaporization of the propellant constituents of water, ethanol, and hydrogen peroxide. Nickel, the known steam reformation[6] catalyst for hydrogen production in steam-hydrocarbon reactions possibly produces hydrogen at this point in the tube. Nickel is also known as an incompatible material[3] for hydrogen peroxide possibly causing it to evolve oxygen. TC2 initially shows a temperature rise due to exothermic reactions of these decomposition products and then falls in temperature as the flowrate exceeds the capacity of the catalyst in the tube to promote the reactions. TC3 shows a slow temperature rise from 750°F to around 1100°F as the reaction is slowly driven toward the end of the tube aided by heat conduction in the tube material. The flow is turned off at around 8.5 minutes into the run giving the TCs enough time to return to their preheat temperature set at the beginning of the run.

To demonstrate the effect of flowrate on this combustion process, the flow was reduced from 0.14 ml/min to 0.11 ml/min at the same preheat condition of TC1 at 1100°F. The thermocouple data for the 0.11 ml/min flowrate are shown in Fig. 8. Comparing Fig. 7 and Fig. 8, one notes that flow initiation at 2.5 minutes into the recording causes TC1 to again rapidly drops from 1100°F to about 250°F. However, there is now an unsteady exothermic reaction near the middle of the tube at TC2 which now shows a temperature rise to around 1200°F while the downstream TC3 is lower at around 950°F. The lower flowrate at the same preheat temperature allows the flame front to move upstream to the middle of the tube. As the flow is turned off at about 9.5 minutes into the recording, the reactions die out and the tube temperatures return to the initial preheat temperatures as shown.

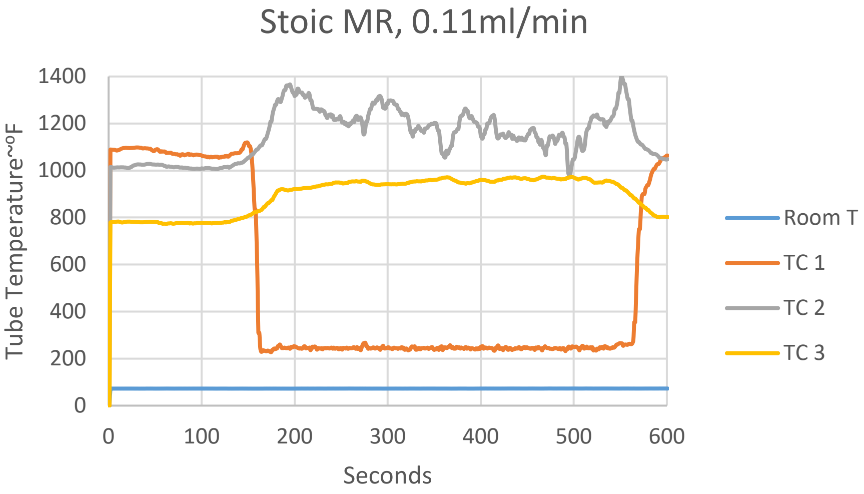


Fig. 8. Thermocouple data on stoichiometric combustion in the 200 mm long, 0.8 mm I.D. nickel tube at a flow rate of 0.11 ml/min and a preheat of approximately 1100ºF on TC1.

To demonstrate the effect of preheat temperature at the flowrate of 0.11 ml/min, the DC power to the tube is reduced such that TC1 is reduced from 1100ºF at the start of the recording to 850ºF at about 1 minute into the recording and held there until the propellant flow is started at about 2 minutes into the recording. This thermocouple data is shown in Fig. 9.

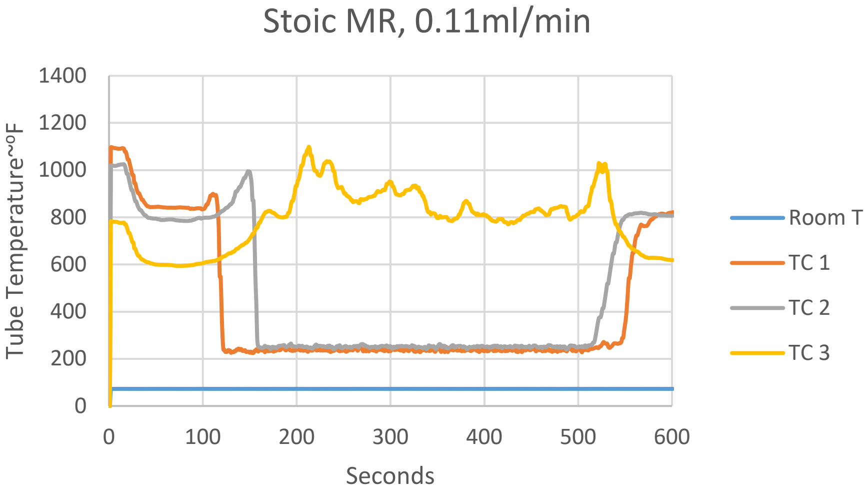


Fig. 9. Thermocouple data on stoichiometric combustion in the 200 mm long, 0.8 mm I.D. nickel tube at a flow rate of 0.11 ml/min and a preheat of approximately 850ºF on TC1.

In comparing Fig. 8 and Fig. 9, one notes that at flow initiation TC1 immediately drops from 850ºF to 250ºF as before, but there is not enough evaporative energy at the entrance of the tube and TC1 is now followed by TC2 to 250ºF indicating that vaporization of the propellant constituents has moved downstream of TC2 due to the lower resistive heating of the tube. Now the catalytic combustion is occurring downstream of TC3, but TC3 shows a temperature rise that fluctuates between 800ºF and 1000ºF probably affected by axial conduction along the tube and out through the electrical lead. The combustion process is now an unsteady exothermic reaction at a lower temperature indicating that the lower preheat temperature/energy input has caused the reaction to move downstream toward the end of the tube. Again, the flow is turned off at about 9 minutes into the recording and as the reactions die out the tube temperatures return to the initial preheat temperatures.

To demonstrate the effect of lower flowrate at the lower preheat temperature of 850ºF, the stoichiometric blend flowrate is reduced from 0.11 ml/min to 0.08 ml/min. This thermocouple data is shown in Fig.10.

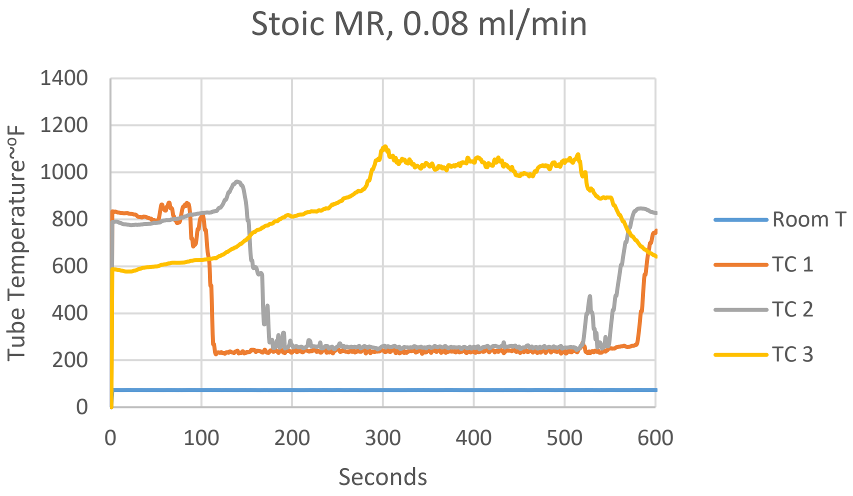


Fig. 10. Thermocouple data on stoichiometric combustion in the 200 mm long, 0.8 mm I.D. nickel tube at a flow rate of 0.08 ml/min and a preheat of approximately 850ºF on TC1.

In comparing Fig. 9 and Fig. 10, one notes that again TC1 immediately drops to 250ºF as the mixture is vaporized and is followed with a slight lag by TC2 to 250ºF. An exothermic reaction starts between TC1 and TC2 that temporarily raises the temperature at TC2 but the flame front is pushed past TC2 at about 3 minutes into the recording. The flame front, probably aided by heat conduction along the tube slowly moves toward TC3 which registers its maximum temperature of about 1050ºF at about 5 minutes into the recording. The temperature oscillation is much less than shown in Fig. 9 and is at a higher average temperature indicating that at this flowrate and preheat temperature, the catalysis occurring in the tube is able to more fully react this flowrate and conduction out of the tube through the electrical lead is lower. Again, the flow is turned off at about 9 minutes into the recording and as the reactions die out, the tube temperatures return to the initial preheat temperatures.

To demonstrate the effect of fuel rich mixture at the lower preheat temperature of 850ºF, combustion of the fuel rich blend of MR=7 at the flowrate of 0.08 ml/min is given in Fig. 11 for comparison with the stoichiometric blend given in Fig. 10.

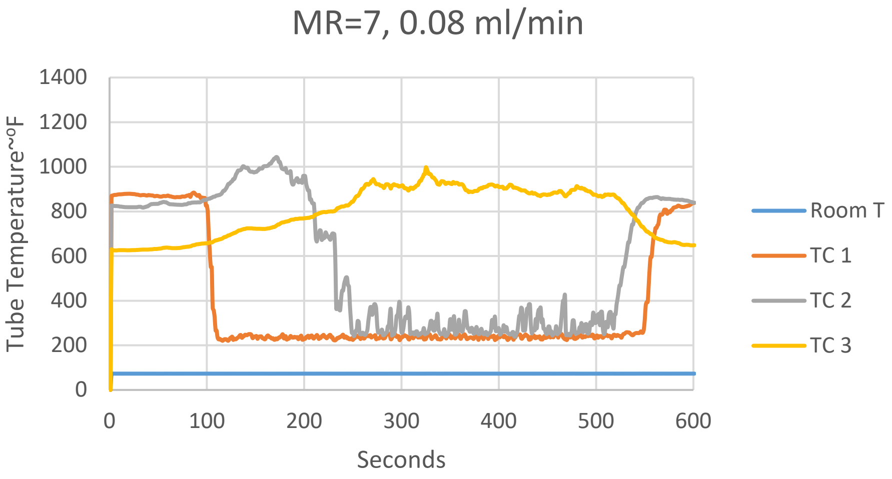


Fig. 11. Thermocouple data on the fuel rich mixture ratio MR=7 in the 200 mm long, 0.8 mm I.D. nickel tube at a flow rate of 0.08 ml/min and a preheat of approximately 850ºF on TC1.

One notes that again TC1 immediately drops to 250ºF as the mixture is vaporized and is followed by a combustion process that propagates past TC2 which follows TC1 down to 250ºF. Again, the flame front probably aided by heat conduction along the tube slowly moves toward TC3 which registers its maximum temperature of only about 900ºF at about 5 minutes into the recording. The maximum combustion temperature at TC3 is about 150ºF less than the stoichiometric case due to the lower energy content of the mixture. Again, the flow is turned off at about 9 minutes into the recording and as the reactions die out the tube temperatures return to the initial preheat temperatures.

To demonstrate the effect of fuel lean mixture at the lower preheat temperature of 850ºF, combustion of the fuel lean blend of MR=10 at the flowrate of 0.08 ml/min is given in Fig. 12 for comparison with the fuel rich mixture at MR=7 given in Fig. 11. The preheat is stepped up to about 850ºF at about 5 minutes into this 20 minute run. The flow is turned on about 6 minutes into the run and TC1 immediately drops to 250ºF followed shortly after by TC2. TC3 starts a steady climb to 900ºF and is fairly constant until the flow is turned off at 17 minutes into the run. This maximum combustion temperature is comparable to that of the fuel rich blend at MR=7 indicating that it also is a lower energy content mixture compared to the stoichiometric blend.

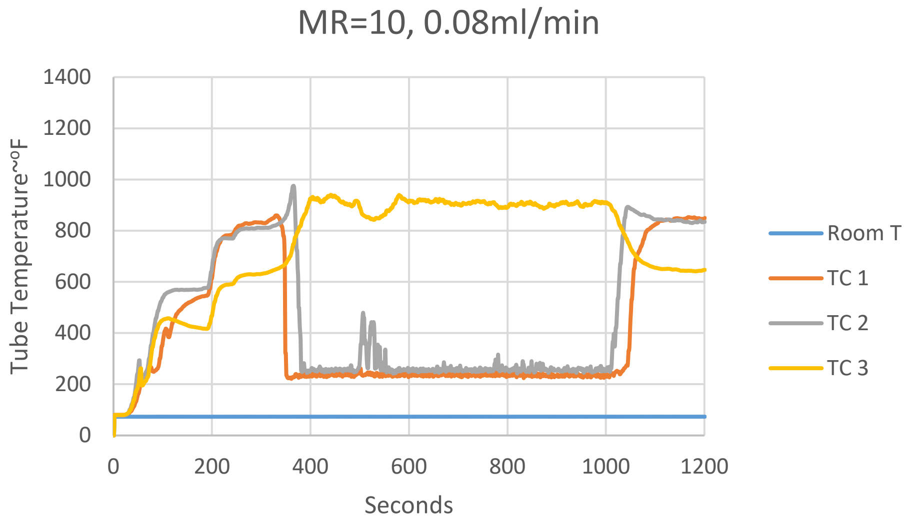
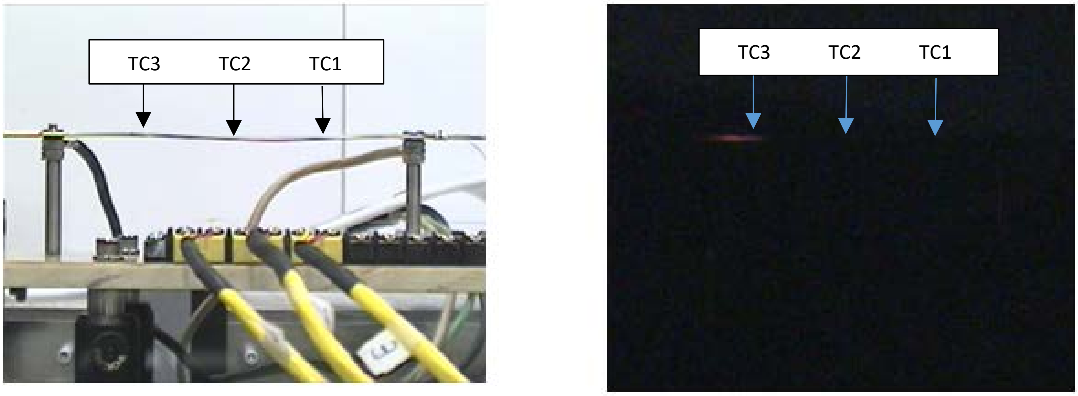


Fig. 12. Thermocouple data on the fuel lean mixture ratio MR=10 in the 200 mm long, 0.8 mm I.D. nickel tube at a flow rate of 0.08 ml/min and a preheat of approximately 850ºF on TC1.

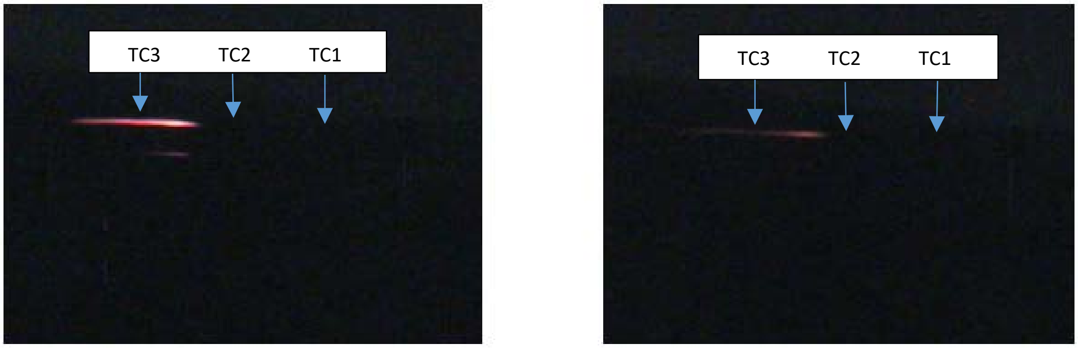
Video test results were obtained for all of the runs. Examples of frames from the tests are shown in Fig. 13, which includes a close-up of the microtube setup. After the lights are turned off so that the glow is visible, a frame is shown from the fuel rich MR=7 test with thermocouple data shown in Fig. 11 and TC3 at about 900ºF. A frame is also shown from the stoichiometric MR=8.873 test with thermocouple data shown in Fig. 7 and TC3 at about 1100ºF. Finally, a frame is shown from the fuel lean MR=10 test with thermocouple data shown in Fig. 12 and TC3 at about 900ºF. Frames from the videos of these tests show the tube visibly glows downstream at TC3, but is less energetic at the rich and lean mixtures.

No catalyst poisoning from the 200 ppm phosphate stabilizer commercially added to the hydrogen peroxide was noted as evidenced by no degradation in performance of the hardware over the multiple test period.



Closeup of micro-tube and TCs

Fuel rich MR=7



Stoichiometric MR=8.873

Fuel lean MR=10

Fig. 13 Frames from videos showing a close-up of the microtube and the combustion process at fuel rich MR=7, stoichiometric MR=8.873, and fuel lean MR=10 conditions.

V. Summary

This effort looked at phosphate stabilized 50% hydrogen peroxide/water – ethanol blends to evaluate their stability and combustion behavior in microtube combustion apparatus for cubesat propulsion applications. Theoretical specific impulse of the stoichiometric blend is 219 s at a chamber pressure of 20 psia and an area ratio of 30:1. Propellant density is approximately 1.2 g/cm^3 compared to 1.0 g/cm^3 for hydrazine giving a density-specific impulse of 263 s while hydrazine is only about 215-220 s in small reaction control system thrusters. This stoichiometric 50% hydrogen peroxide/water - ethanol blend provides about 20-22% more density-specific impulse for the cubesat compared to hydrazine and could go even higher if 60% hydrogen peroxide is used. The theoretical combustion temperature of the stoichiometric 50% hydrogen peroxide/water - ethanol blend is only 2168°F, which is thermally compatible with stainless steel materials of construction and the nickel catalyst used in these tests.

The exploratory stability test apparatus found no stability issues with the 50% hydrogen peroxide blends as indicated by a lack of off gassing and pressure rise in a sealed test tube environment at room temperature over a 7-day period. Mixture ratios tested included stoichiometric at 8.873, fuel rich at 7, and fuel lean at 10.

Tube size and flow rate for the micro-combustion apparatus are estimated using gasdynamic area relations that avoid choking using the equilibrium properties of the propellant combustion products. Fanno Line friction pressure drop is used to estimate flow rates of propellant for experimental design purposes. The Reynolds Number of the flow is well within the laminar range. Thrust class is expected to be in the 10 mN range based on flow rate and estimated specific impulse. The micro-combustion apparatus, consists of a 200 mm long, 0.8 mm I.D., resistively heated, nickel capillary tube fed by a variable speed, armored syringe pump. The test setup includes a DC power supply for heating the tube, video recording apparatus, and a data logger for recording thermocouple data. Power requirements are generally below 25 watts. Safety precautions required an explosive barrier, consisting of 1-inch thick plexiglass enclosure surrounding the combustion apparatus, but no safety issue was encountered during the tests.

These combustion tests focus on thermally and catalytically supported reactions in the microtube, which requires a microtube preheat temperature of about 900°F and sufficient residence time to achieve combustion that is stable and anchored in the tube without blowing through the tube unreacted. Steady state combustion in the resistively heated microtube apparatus was typically for 3 to 6 minutes in each test. These tests reveal that micro-combustion is achieved at various mixture ratios and preheat temperatures, but is very flow rate dependent. The thermocouple locations are at 52 mm, 100 mm, and 148 mm on the 200 mm long tube. Preheat on the tube is between 800ºF and 1120ºF. A typical 10 minute recording with the flow rate initiated at between 1 to 3 minutes into the recording shows that the first thermocouple immediately drops to about 250ºF as the flow of mixture is heated by the tube. The next thermocouple initially shows a slight temperature rise and then also falls in temperature to about 250ºF. The final thermocouple registers a slow temperature rise to between 900ºF and 1100ºF depending on mixture ratio, flowrate, and preheat temperature. Combustion test results are given for stoichiometric at MR=8.873, as well as fuel-rich at MR=7 and lean at MR=10 propellant formulations. Frames from the videos of these tests show the tube visibly glows downstream near the third thermocouple, but is less energetic at the rich and lean mixtures. The steady state combustion testing typically conducted for 3 minutes shows little degradation of the hardware over multiple test cycles. This indicates there is little catalyst degradation over time and little catalyst deactivation due to the 200 ppm phosphate stabilizer in the hydrogen peroxide.

Exposure limits for hydrogen peroxide are TWA of 1.0 ppm compared to hydrazine’s TWA of 0.1 ppm for an order of magnitude less toxicity. The freezing point of 50% hydrogen peroxide/water is -62ºF compared to hydrazine’s 36ºF. These characteristics and performance make stoichiometric 50% hydrogen peroxide/water – ethanol a comparable performance and a safer alternative to the current hydrazine systems.

References

[1] Cavender, D., Marshall, W. M., and Maynard, A., “NASA Green Propulsion Roadmap”, AIAA Paper 2018-4750, July 2018.

[2] Sackheim, R. L. and Masse, R. K., "Green Propulsion Advancement: Challenging the Maturity of Monopropellant Hydrazine," Journal of Propulsion and Power, Vol. 30, No. 2, March-April 2014, pp. 265-276.

[3] Schumb, W. C., Satterfield, C. N., and Wentworth, R. L., *Hydrogen Peroxide*, Reinhold Publishing Corporation, 1955.

[4] Shanley, E. S. and Greenspan, F. P., “Highly Concentrated Hydrogen Peroxide, Physical and Chemical Properties”, Industrial and Engineering Chemistry, Vol. 39, No. 12, 1947, pp. 1536-1543.

[5] Schneider, S. J., Boyarko, G. A., and Sung, C. J., “Catalyzed Ignition of Bipropellants in Microtubes”, AIAA Paper 2003-0674, January 2003.

[6] Dicks, A. L., “Hydrogen Generation from Natural Gas for Fuel Cell Systems of Tomorrow”, Journal of Power Sources, Vol. 61, 1996, pp. 113-124.

[7] McBride, B. J. and Gordon, S., “Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications”, NASA RP-1311, June 1996.

[8] Volchko, S. J., Sung, C. J., Huang, Y., and Schneider, S. J., “Catalytic Combustion of Methane/Oxygen Mixtures for Micropropulsion Applications”, AIAA Paper 2005-3924, July 2005