# DEVELOPMENT OF
# $H_2O_2$-BASED MONOPROPELLANT PROPULSION UNIT FOR CUBESATS (MPUC)

D. King, C. Woodruff, R. Burton, and D. Carroll
CU Aerospace, LLC
Champaign, IL

## ABSTRACT

CU Aerospace recently completed an Air Force Phase I SBIR to test a proof-of-principle Monopropellant Propulsion Unit for CubeSats (MPUC), consisting of a thrust chamber and demonstrating complete catalyzed combustion of an $H_2O_2$-based propellant denoted as CMP-8. CMP-8 has zero toxicity and no special measures are required for its long-term storage. The propellant was subjected to a scaled UN Series 1 detonation test series and demonstrated no detonation propagation when confined under a charge of high explosive. Potentiometric titrations with standardized sodium bisulfite demonstrated no degradation in the CMP-8 over a four-month, room-temperature storage period. Thrust stand tests achieved a thrust level of >100mN at $I_{sp}$ >183 s with an average input power of ~3 W, for hot fire runs typically spanning >10 minutes. A single run of greater than one hour was also demonstrated. A trade study was performed of CMP-8 and its nearest competitors. A number of operational metrics and issues were examined, and while other propellants have a minor advantage in $I_{sp}$, the MPUC propellant has advantages in availability, cost, lower flame temperature (less thermal management and radiation losses), lower pre-heat temperature, lower viscosity, and low thruster materials costs. MPUC designs comprise a complete propulsion system technology for CubeSats and other small satellites, with a high performance, nontoxic monopropellant that possesses benign storage characteristics. The conceptual system also provides cold-gas attitude control and projects >1200 N-s/liter of volumetric impulse.

## INTRODUCTION

Commercial interest in very small satellites continues to grow. In the 1-50 kg satellite sector, launches have shifted from a fairly balanced distribution between civil, government, commercial, and defense (2009-2015) to a distribution dominated by commercial interests [Doncaster, 2016]. Moving forward, it is more important than ever that these satellites have access to propulsion systems to extend their asset time on orbit. Such a system must occupy minimal bus volume and carry a high product of propellant density times $I_{sp}$. Avoiding the use of toxic propellants such as hydrazine that significantly complicate the storage and handling of the propulsion system is also desirable [Hargus, 2010; Singleton, 2013]. While AF-M315E is a green monopropellant, it has a high flame temperature of 1800 ºC requiring a thrust chamber constructed from refractory materials, which adds further expense and complication. A survey of available propellants motivated the search for a less exotic and more easily sourced chemistry to be utilized in these small satellite propulsion systems.

The authors sought to develop a new monopropellant from non-toxic, readily available reagents. The candidate needed a flame temperature low enough to avoid refractory construction, while maintaining high enough specific impulse and density to be competitive with legacy propellants. The chosen propellant has heritage in bipropellant thrusters [Woschnak, 2013, Wieling, 2012] and as a US Navy Mark 16 torpedo propellant [Clark, 1972], but has not been developed for a thruster in the 100 mN class. A variant has even been used to drive a turbine-powered Volkswagen Beetle [Delchev, 1987].



Work funded by AFRL/RQRS on contract FA9300-15-M-1003, Public Affairs Clearance Number 16504.

Risk reduction (both in the laboratory and for the end product on the launch range) was paramount in the propellant development program. Desirable monopropellant safety properties were described by Hawkins, *et al.* [Hawkins, 2010] and include high thermal stability, low unconfined ignition explosive response, low impact sensitivity, low friction sensitivity, low detonability, insensitive adiabatic compression, low electrostatic discharge sensitivity, and low vapor toxicity. To that end, a considerable effort was undertaken to ensure that the propellant conformed to detonability, ignition, and storability behavior guidelines set to ensure user safety.

## RESULTS AND DISCUSSION

A search of potential fuel formulations yielded a mixture of 50% (w/w) hydrogen peroxide and one of several alcohols (tert-butyl alcohol (TBA), 2-propanol, ethanol, methanol and glycerol). Each of these systems requires a catalytic element to enable combustion. Glycerol was favored early in the program for its high product of density and maximum theoretical specific impulse. However, it soon became evident that detonation concerns would seriously reduce its utility. Ternary detonability plots were gathered (where available) for the candidate fuels, **Figs. 1a-d** [Shanley, 1947; Shreck, 2004].

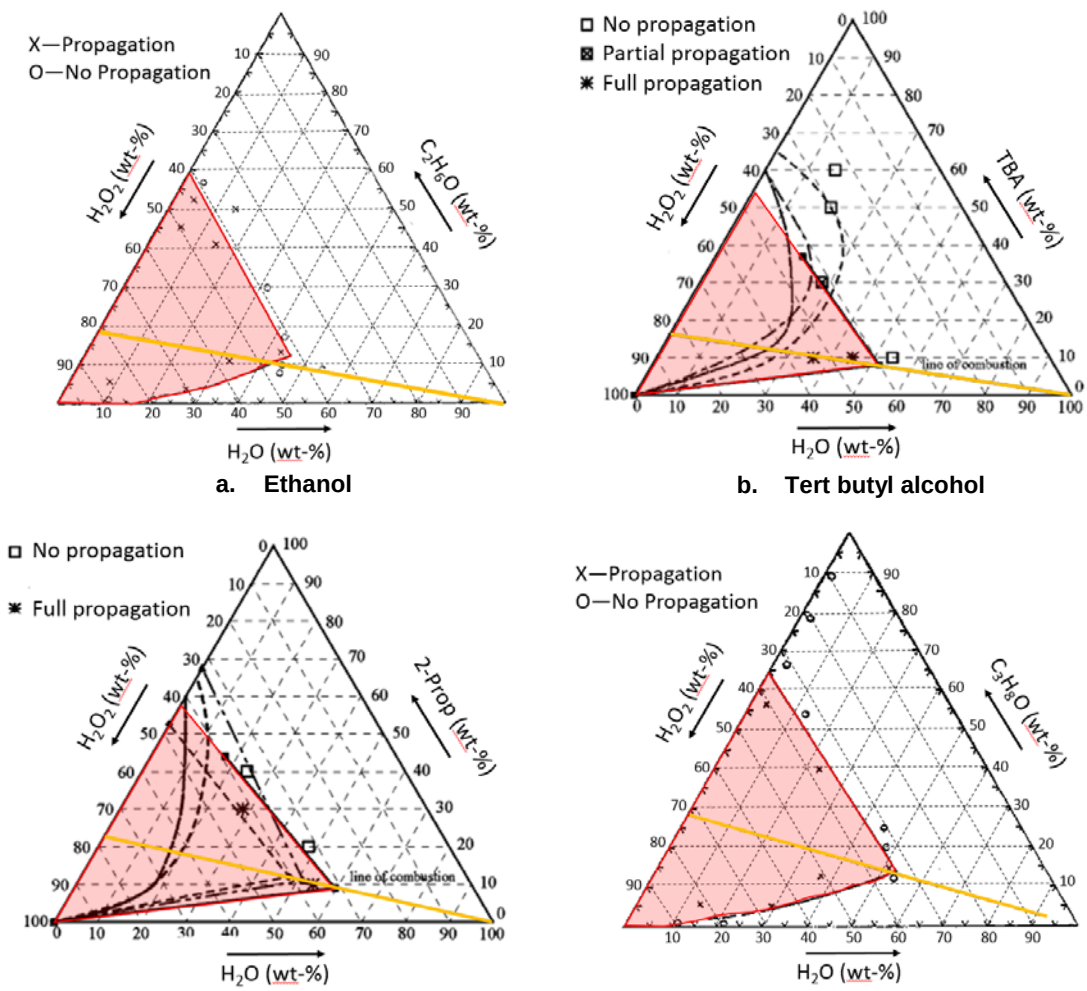



**Figure 1: Ternary plots for $H_2O_2$ / alcohol mixtures (the detonation region lies within the red shaded region). Note the stoichiometric mixture denoted as a yellow line.**

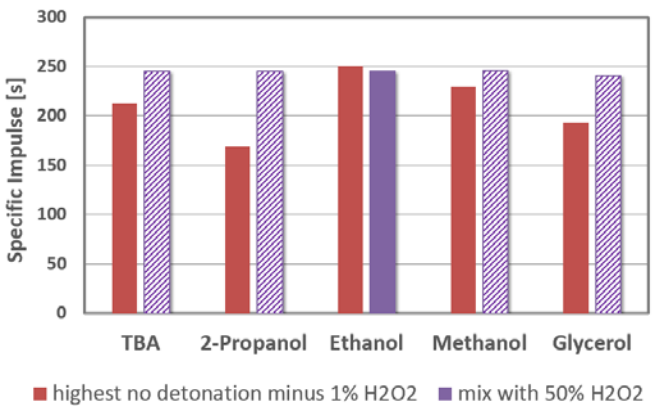



**Figure 2: Theoretical maximum specific impulse of candidate MPUC fuels. *All fuels except ethanol were eliminated because their stoichiometric mixtures are detonable when mixed with 50% H2O2, denoted here by diagonal striped columns.***

Adiabatic flame temperatures were computed for each of the candidate mixtures, assuming complete stoichiometric combustion with all reactions going to water and carbon dioxide. Performance estimates were then made for theoretical maximum thruster specific impulse Isp, **Fig. 2**. Safety concerns, reagent availability, and performance levels led to the ultimate choice of CMP-8, a mixture of 10.2% ethanol, 45% $H_2O_2$, and 44.8% $H_2O$. With its flame temperature of just 1220 ºC, CMP-8 allows MPUC to be constructed from common stainless steels.

A sodium bisulfite potentiometric titration [Gimeno, 2013] was used for determination of the peroxide content in CMP-8 mixtures, and proved to be a robust technique for all of the candidate alcohols. Long-term storage samples were prepared into polyethylene storage vials and kept at room temperature. The samples were titrated at regular intervals throughout a 123 day study period, maintaining their initial peroxide concentration to within experimental error, **Table 1**.

**Table 1: Long term storage titration results**

| **target $H_2O_2$ % by initial mixture mass** | 43.5% |
|---|---|
| $H_2O_2$ % by titration - 1hr | 43.3% |
| $H_2O_2$ % by titration - 36d | 43.6% |
| $H_2O_2$ % by titration - 75d | 43.5% |
| $H_2O_2$ % by titration - 123d | 43.1% |

Detonation tests were performed to confirm the detonability of the candidate propellants. Due to a 400 kJ facility total energy limit in the 1800-liter blast chamber (University of Illinois Energetic Materials Laboratory), we employed a ~1/6 scaled version of the UN Series 1(a) apparatus [TB 700.2, 2012]. This featured a 1.25" OD, 0.874" ID (0.188" wall), 6.62" long, drawn over mandrel steel tubing as the pressure vessel and housed ~65 ml of propellant, topped by a 1" OD x ~0.5" tall booster charge of PBXN9, initiated with an RP-81 detonator. Control runs were performed with water and a known-detonable glycerol mixture before testing CMP-8. The tests resulted in a no-propagation finding for CMP-8 via witness plate inspection, **Figs. 3 and 4**.

**Figure 3: Detonation test setup: (left) before testing, (middle) after water control test, and (right) after positive propagation glycerol test.**


**Water** **Glycerol** **Ethanol**

***(negative propagation)*** ***(positive propagation)*** ***(negative propagation)***

**Figure 4: Detonation test steel witness plates**

Following the validation of the anticipated detonation limits, a series of ignition studies were conducted. Each candidate fuel was tested with various ignition sources (butane flame, platinum glow plug, Tesla coil, and piezoelectric spark) in a simple spot plate setup. It was observed that although CMP-8 was not ignitable in air without the presence of a catalyst, it readily lit in the presence of several common granular and metallic catalysts, **Fig. 5**.

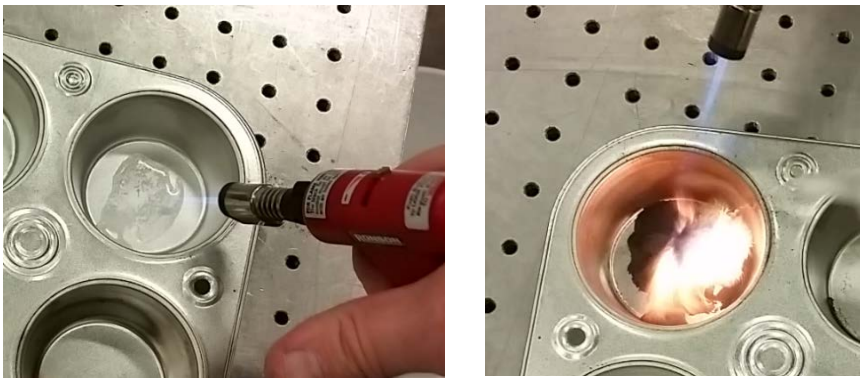


**Figure 5: Ignition tests with CMP-8 showing no ignition (left) without catalyst and successful ignition (right) in the presence of catalyst.**

A variety of combustion test fixtures were designed and manufactured. Common between all fixtures were the following elements: inlet flow control orifice, catalyst bed (with resistive preheat), internal ignition source (platinum hot wire or miniature spark plug), and nozzle. The geometry of each was varied considerably, yielding a rapid increase in measured temperature after the first several modifications were tested, **Fig. 6**.

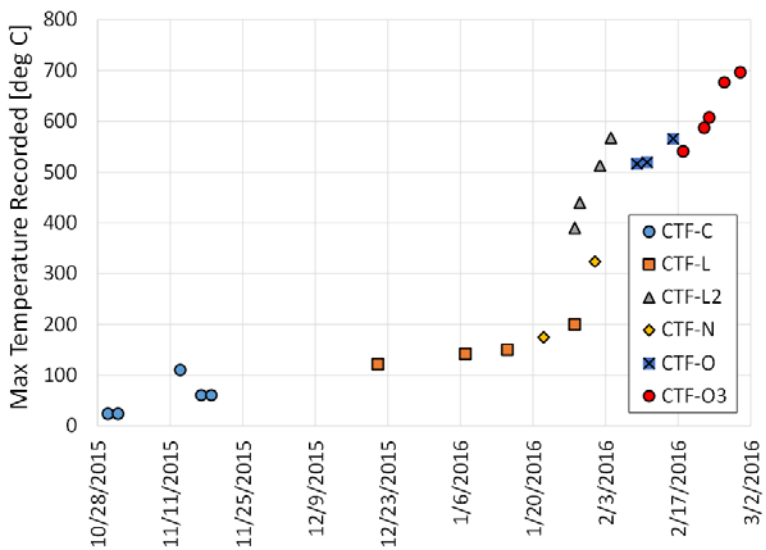
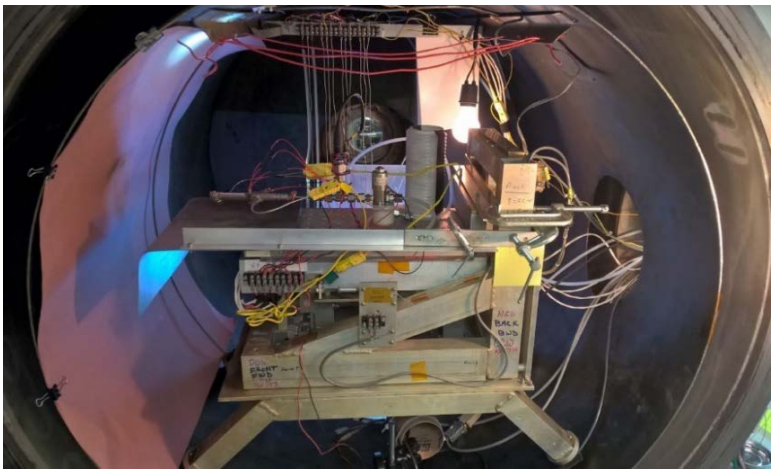



**Figure 6: Chronological time history of measured system temperature as hardware was modified.**

Performance increases were realized mostly from geometric variation, thermal management, and catalyst bed design. Once the "CTF-O" series hardware showed promise in the bench tests (a simple vacuum chamber with electrical and fluid feedthroughs), the assembly was brought to the UIUC Electric Propulsion Laboratory for thrust performance measurements. Propellant feed rate was monitored via a spiral pressurized-tube feed system (with nitrogen pressurant) whose internal volume was calibrated with a precision graduated cylinder. Propellant density was also carefully measured via the same graduated cylinder and a precision laboratory balance. As seen in **Fig. 7**, the propellant was dyed green (<0.1% w/w) for visibility. No degradation in performance was noted for dyed vs. non-dyed propellant.

**Figure 7: CMP-8, dyed green for visibility: (left) in spiral feed system, and (right) polyethylene storage cylinders.**

The UIUC compact thrust stand [Wilson, 1997], **Fig. 8**, was used to make thrust measurements. Test runs comprised a thrust stand calibration, a pre-heat of the catalyst bed, a propellant flow and CTF burn of between 1 – 10 minutes, and finally another calibration run. Pre- and post-run calibrations are necessary to account for the effects of changing thrust stand platform center of gravity and its resultant influence on period and responsivity. Sample calibration and experimental measurements are shown below in **Fig. 9**. During testing, the stainless steel CTF body glowed red hot, **Fig. 10**. The external body temperature measured 690 ºC in this test.



| # | Description |
|---|---|
| 1 | spiral feed system |
| 2 | electric inlet valve |
| 3 | Internal thermocouple |
| 4 | MPUC combustor |
| 5 | nozzle |
| 6 | external thermocouple and clamp |
| 7 | glow plug |
| 8 | pressure transducer |

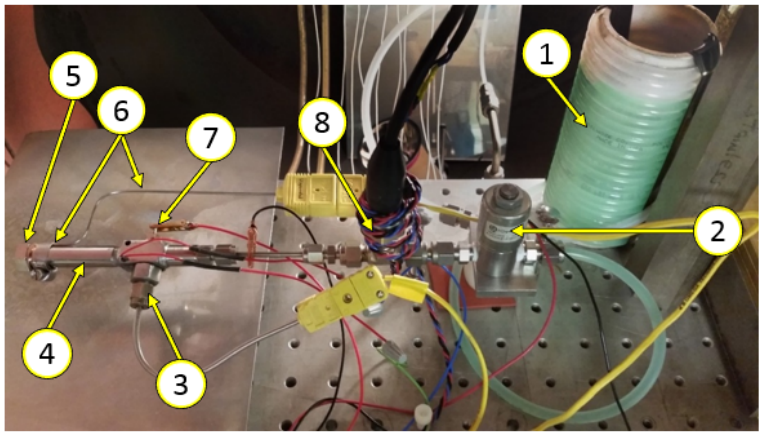



**Figure 8: MPUC CTF mounted on top of UIUC compact thrust stand in the Electric Propulsion Laboratory 1.5 m$^3$ vacuum chamber. Gas flow is right to left.**

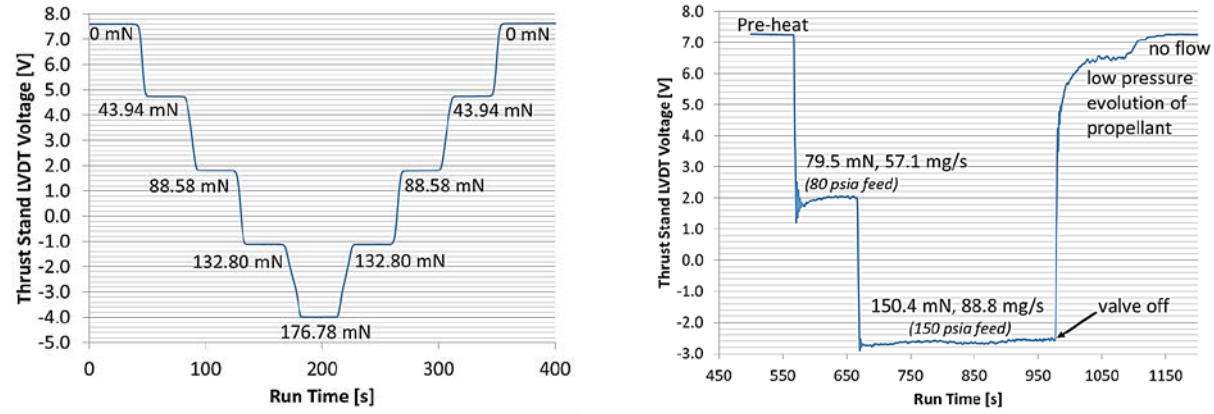



**Figure 9: Thrust calibration (left) and measurement (right) for a typical MPUC thrust test. This test measured a specific impulse of 173 s.**

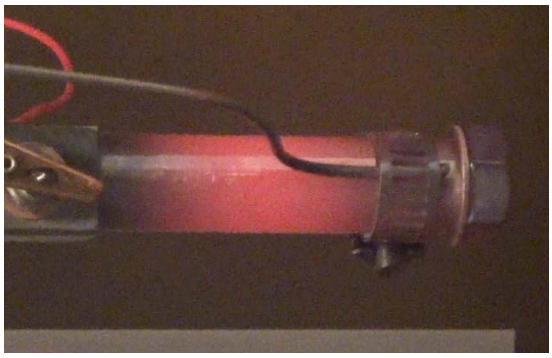


**Figure 10: MPUC CTF glowing hot during combustion testing. Gas flow is left to right.**

By varying the pressure of the feed system pressurant, propellant flow rate could be varied at any time during the run, enabling throttling of the thruster to desired thrust levels. More than 2000 ml of propellant was burned in various developmental test series. One long-duration test consumed a total of 315 ml (with ~20 s pauses to refill the spiral feed system).

Thruster performance was repeatable and steady at ~180 seconds of specific impulse. Selected data are presented below in **Table 2**, which lists the conditions recorded during a thrust stand test that achieved one of the highest recorded temperatures for the program. Note that the exhaust gas temperature will exceed the measured external temperature, due to radial heat flow in the combustion chamber.

**Table 2: MPUC performance data.**

| **Source Pressure [psia]** | **140** | **170** |
|---|---|---|
| External Temperature [°C] | 678 | 694 |
| Mass Flow Rate [mg/s] | 76.4 | 87.2 |
| Thrust [mN] | 137 | 160 |
| Specific Impulse [s] | 183 | 187 |

Propellant viscosity was identified as a feed system risk factor for MPUC. The room temperature kinematic viscosity of CMP-8 was measured to be 1.39 cSt with a Zahn Cup #1 efflux technique, **Table 3**. Note that the Zahn Cup #1 method is less accurate for values below 5 cSt, however by measuring efflux times for liquids of known viscosities (water and kerosene), we can interpolate a reasonable estimated viscosity for CMP-8, which we believe to be accurate to within ±10%. Note that this kinematic viscosity of 1.39 cSt is similar to water and well below the kinematic viscosity of AF-M315E propellant at room temperature. AF-M315E can have very small Re numbers in small flow channels which can create a propellant feed problem, but this will not be an issue with CMP-8 propellant.

**Table 3: Measurement of CMP-8 kinematic viscosity**

| Test # | **Efflux Time [s]** | | | |
|---|---|---|---|---|
| | **Kerosene** | **Water** | **CMP-8** | **AF-M315E** |
| 1 | 30.25 | 25.87 | 26.50 | |
| 2 | 27.98 | 25.55 | 26.62 | |
| 3 | 27.54 | 25.73 | 26.57 | |
| 4 | 30.10 | 25.68 | 26.57 | |
| 5 | 32.75 | 25.70 | 26.65 | |
| **Average** | 29.59 | 25.71 | 26.58 | N/A |
| Kinematic Viscosity [cSt] | 2.71 | 1.0038 | **1.39** | **≈ 25** |

CMP-8 is compared with AF-M315E and hydrazine in **Table 4**. Its advantages include low viscosity, high availability, low cost, and low toxicity. Although the demonstrated specific impulse to date is lower than AF-M315E and hydrazine, further development will close that gap. Compared to AF-M315E, considerably lower thermal soak-back rates into the satellite are achievable with CMP-8 due to the lower reaction temperature.

**Table 4: Fuel comparison**

| Issue | CUA CMP-08 | AF-M315E | Hydrazine |
|---|---|---|---|
| Detonability | not detonable by blasting cap, ESD, or impact, UN Class 1 classification antic. | UN 1.4C classification | high |
| Vapor Pressure | very low | very low | high |
| Exhaust Product Toxicity | non-toxic | non-toxic | Class 8 - highly toxic |
| PPE required | Spill protection - gloves / goggles | Spill protection - gloves / goggles | Full SCAPE suit |
| Availability | >2M metric tons annually from COTS reagents (low cost) | 10000 lbs to date, 8000 lbs additional capacity | >14000 metric tons annually [1984] |
| Reaction Temperature [°C] | 1200-1300 | 1700-1800 | 800 |
| Necessary Catalyst Pre-heat Temp [°C] | ≤200 | 400-450 | 25-250 |
| Kinematic Viscosity [cSt at 25 °C] | 1.4 | 25 | 0.9 |
| Thruster materials necessitated | stainless steels | refractory metals | stainless steels |
| Demonstrated $I_{sp}$ at 100 mN class | 183 [CUA MPUC] | 214 [Busek BGT-X1] | 219 [Aerojet MPS-120] |
| Demonstrated $I_{sp}$ at 500 mN class | n/a | 220 [Busek BGT-X5] | 227 [Airbus 0.5N] |
| Demonstrated $I_{sp}$ at 1 N class | n/a | 235 [Aerojet GR-1] | 224 [Aerojet MR-103D] |

## FUTURE WORK

The MPUC combustor has been integrated into a complete CubeSat thruster design including 3-axis ACS, using a self-pressurizing pressurant for both primary thruster fuel feed and ACS propellant. The design philosophy of future MPUC systems is simple: maximize the $H_2O_2$/ethanol propellant load by using as much of the available envelope as possible for propellant storage. By selecting pressurants with a several-atmosphere vapor pressure over 0 to 60ºC (standard CubeSat temperature range requirement) the system will self-pressurize, yet still retain a pressure low enough to allow a rectangular pressure boundary. Conceptual models of a 1U MPUC with ACS are shown in **Fig. 11**. Notional internal schematics have also been developed (not shown for brevity).

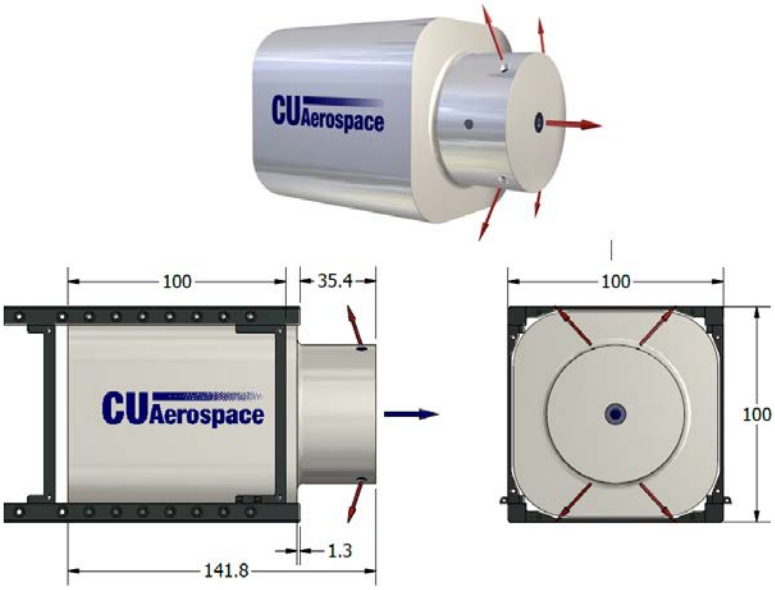



**Figure 11: MPUC 1U concept.**

## SUMMARY AND CONCLUSIONS

CU Aerospace (CUA) demonstrated a proof-of-principle Monopropellant Propulsion Unit for CubeSats (MPUC) thruster during a recent Air Force Phase I SBIR. During this 6-month program, we took the MPUC concept (TRL 2) to successful demonstration and performance testing as well as initial system design (TRL 4). A specific impulse of 187 s was demonstrated during thrust stand testing. MPUC uses a nontoxic propellant, with no special measures required for long-term storage. With its lower operational temperature (and therefore, lower thermal soak back rate), the MPUC system provides longer duration impulse capability for given thrust levels than higher-temperature propellants.

A principle program objective was to retire a significant amount of MPUC risk, which was achieved in the areas of propellant toxicity, cost, detonability, viscosity, low flame temperature, storability and combustion efficiency. Other primary technical objectives of the program were to prove stable, reliable operation of a breadboard MPUC system and obtain preliminary thruster performance. Additional risk reduction tasks that were accomplished included: (i) demonstration of reliable storage, (ii) detonation limits, and (iii) experimental demonstration of specific impulse and thrust capabilities in a simulated space environment. The conceptual system provides cold-gas attitude control and is estimated to have >1200 N-s/liter of volumetric impulse.

## ACKNOWLEDGMENTS

This work was sponsored by USAF under SBIR contract FA9300-15-M-1003. The authors would like to thank Dr. William Hargus (who served as our technical monitor), Professors Herman Krier and Nick Glumac at the University of Illinois at Urbana-Champaign, as well as their students, for conducting the detonation testing. The JANNAF Green Monopropellant Alternatives to Hydrazine Technical Interchange Meeting was found to be a critically important resource for this MPUC project. Finally, special thanks go to Dr. Mike Tsay of Busek Co., Inc., for constructive discussions.

## REFERENCES


Clark, J., **Ignition!**, Rutgers University Press (1972).

Delchev, N., **US Patent 4,698,965** (1987).

**Department of Defense Ammunition and Explosives Hazard Classification Procedures**, TB 700-20, NAVSEAINT 8020.8C, TO 11A-1-47 (July 2012).

Doncaster, B. and Shulman, J., **2016 Nano/Microsatellite Market Forecast**, SEI website publication, accessed on 9/28/2016. http://tinyurl.com/SEIreport2016

Gimeno, M P, M C C Mayoral, and J M M Andrés. **A potentiometric titration for $H_2O_2$ determination in the presence of organic compounds**, Analytical Methods 5.6 (Jan 2013)

Hargus, W., Singleton, J., and Holmes, M., **An Analysis of Cubesat Propulsion Options**, 53rd JANNAF Joint Propulsion Meeting, Colorado Springs, CO (May 2010).

Hawkins, T.W, Brand, A.J., McKay, M.B., and Tinirello, M., **Reduced Toxicity, High Performance Monopropellant at the U.S. Air Force Research Laboratory**, AFRL Report AFRL-RZ-ED-TP-2010-219 (2010).

King, S., Marx, P., and Taylor, D., **The Aerospace Corporation Shell 405 Catalyst Evaluation Program**, AF Report #SAMSO-TR-69-271.VOL1 (August 1969).

Schreck, A, *et al*, **Investigation of the explosive hazard of mixtures containing hydrogen peroxide and different alcohols**, Journal of Hazardous Materials, Volume 108, Issues 1–2, (April 2004).

Shanley, E.S., **Prediction of the Explosive Behavior of Mixtures Containing Hydrogen Peroxide**, Journal of Jet Propulsion, Vol. 28, No. 6 (1958)

Singleton, J., Hargus, W., Carroll, D.L., Burton, R.L., Benavides, G.F., Hejmanowski, N., Laystrom-Woodard, J., King, D.M., Day, C., Bhandari, R., Hageman, K., and Cardin, J.M., **Propulsion for Cubesats (PUC) – A Smart, Robust Propulsion System for CubeSats**, JANNAF 2013-3243, Colorado Springs, CO (May 2013).

Tsay, M. Feng, C., Paritsky, L., Zwahlen, J., Lafko, D., and Robin, M., **Complete EM System Development for Busek's 1U CubeSat Green Propulsion Module**, 52nd AIAA/SAE/ASEE Joint Propulsion Conference, Propulsion and Energy Forum, (AIAA 2016-4905).

Vierea, R., Pham-Huu, C., Keller, N., and Ledoux M.J., **New carbon nanofiber / graphite felt composite for use as a catalyst support for hydrazine catalytic decomposition**, Chemical Communications (2002).

Wieling, Zandbergen, Mayer, and Schrijer, **Development of a Hydrogen Peroxide Ethanol Thruster for the Advanced Re-Entry Vehicle**, Space Propulsion, Bordeaux, France (May 2012).

Wilson, M.J., Bushman, S.S., and Burton, R.L., **A Compact Thrust Stand for Pulsed Plasma Thrusters,** IEPC 97-122 (August 1997).

Woschnak, *et al*, **Development of a Green Bipropellant Hydrogen Peroxide Thruster for Attitude Control on Satellites**, Progress in Propulsion Physics, 4 (2013).