

CubeSat High Impulse Propulsion System (CHIPS) Design and Performance

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ABSTRACT

The CubeSat High Impulse Propulsion System (CHIPS), under development by CU Aerospace with partner VACCO Industries, is a system targeted at CubeSat and micro-satellite platforms designed to enable mission operations beyond simple orbit maintenance, including significant altitude changes, formation flying, and proximity operations such as rendezvous and docking. CHIPS integrates primary propulsion, ACS and propellant storage into a single bolt-on module that is compatible with a variety of non-toxic, self-pressurizing liquid propellants. The primary propulsion system uses micro-resistojet technology developed by CU Aerospace to superheat the selected propellant before subsequent supersonic expansion through a micro-nozzle optimized for frozen-flow efficiency. A 1U design is estimated to be capable of providing 471 N-s total impulse at ~20 mN thrust using R236fa propellant, resulting in a volumetric impulse of 525 N-s/liter. The ACS is a cold gas, 4-thruster array to provide roll, pitch, yaw, and reverse thrust with a minimum impulse bit of 0.4 mN-s. A high-fidelity, fully-integrated engineering unit was extensively tested in cold and warm gas modes on the University of Illinois thrust stand under a range of conditions. This paper presents thrust and specific impulse data for the resistojet thruster using two different propellants. Resistojet data include cold and warm gas performance as a function of mass flow rate, plenum pressure, geometry, and input power. Presently the CHIPS prototype is TRL 5 as a result of a Phase II SBIR effort funded by NASA.

1. INTRODUCTION AND BACKGROUND

An emerging trend in the field of space exploration is the development and deployment of low mass satellites, CubeSats, as a low-cost alternative to more traditional large-scale spacecraft. CubeSats are typically designed for a life of 1-2 years. They often have body-mounted solar panels, which makes them severely power limited, with usable specific power P/m of 1-3 W/kg of satellite mass (note that the addition of deployable arrays is enhancing this power capability, but is not yet common). CubeSats are also volume limited (1 liter per cube), placing a severe volume constraint on the propulsion system. Since nanosats are a low-cost, easily replaced approach to satellite constellations, they need to be nimble. That is, orbital maneuvers need to be accomplished relatively quickly to minimize mission control costs and maximize the usable satellite duty cycle of 1-2 years. As discussed by Burton *et al.* [Burton, 2010] and Hejmanowski *et al.* [Hejmanowski, 2015], the “sweet spot” for responsive nanosat orbital maneuvers appears to be in the 70 – 400 s range of I_{sp} , a range favoring electrothermal or monopropellant thrusters.

It is anticipated that the market for nano/microsatellite propulsion will grow considerably over the coming decade as the capabilities and flexibility of nano/microsatellites grow. SpaceWorks Enterprises Inc. (SEI)

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Work funded by NASA Glenn on contract NNX13CC64P.

estimates that the number of worldwide 1-50 kg satellite launches will be 435 by the year 2022 [Doncaster, 2016], most of which could benefit from onboard propulsion. CU Aerospace's Cubesat High Impulse Propulsion System (CHIPS) is a highly compact, simple, and efficient propulsion system that provides an integrated solution for both primary propulsion and attitude control, enabling nano-, micro-, and even larger satellites to perform various mission tasks including orbit transfer, drag makeup, maneuvering, de-orbiting, station keeping, and position-attitude-acceleration control for satellites in formation.

CHIPS supports the NASA Roadmap for In-Space Propulsion Systems [Meyer, 2012]. The baseline CHIPS design is a 1U system containing 754 g of R236fa propellant having a total impulse is 471 N-s, and a max ΔV is 135 m/s for a 4 kg CubeSat. Total thrust time is 4.9 hours (< 5 orbits), thereby minimizing collision possibilities with other spacecraft during orbit change. The choice of R236fa and R134a as the best propellants for CHIPS is discussed in [Hejmanowski, 2015]. For an initial altitude of 400 km, CHIPS can bring a 4 kg CubeSat down to ~120 km for re-entry, or can raise the CubeSat by ~260 km to 660 km, enabling a number of different significant missions for initial orbits of 350 – 450 km. The drag makeup capability of CHIPS would allow extended lifetime for low altitude orbits, thereby preserving the satellite asset for extended mission duration. Herein we discuss the CHIPS design, testing, nozzle simulations, and performance estimates for different configurations.

2. CHIPS DESIGN

The CubeSat High Impulse Propulsion System, **Fig. 1**, is a complete nanosatellite propulsion solution offering a high-performance micro-resistojet for primary propulsion and 3-axis cold gas attitude control. Building on experience from prior nanosat propulsion product development, CHIPS integrates all necessary propulsion subsystems into a bolt-on unit, including control and power processing units, resistojet and ACS thrusters, frictionless micro-solenoid valves, tankage, maintenance systems and software. System set-points, status, and firing telemetry are accessible and configurable through an RS-422 serial interface. The CHIPS baseline propellant is R236fa: a self-pressurizing, non-toxic and inert refrigerant in widespread commercial use. R134a is a good alternate propellant option because it has slightly higher total performance, but has higher tank pressure and cannot be scrubbed by filters in the International Space Station (ISS); for these latter reasons related to range safety and deployment, R236fa was selected as the baseline propellant.

The prototype 1.0U+ system that has been developed and fabricated on a NASA-funded Phase II SBIR, **Fig. 1**, targeted at 2U - 6U CubeSats, occupies 1020 cm³ of total volume and takes advantage of the "hockey puck" space available in the CubeSat PPOD. The 95 mm x 95 mm cross section maximizes propellant load while leaving clearance for other CubeSat subsystems such as solar panels. The CHIPS design allows for modifications based on customer-specific mission requirements. An optional energy reservoir (battery pack) can be added to allow the user to specify the bus power load (as little as 1 W) during propulsive maneuvers.

The CHIPS design allows any thruster in a VACCO Cold Gas Micro Propulsion System to be upgraded to a warm gas thruster in order to meet specific mission requirements while preserving their proven system-in-a-tank design. The resulting propulsion system is readily customizable to almost any desired height and width to meet mission and payload requirements. Depth may be as little as 5 cm. An example of this flexibility is our alternate design for the NASA NEA Scout mission propulsion system where two axial warm gas CHIPS thrusters are incorporated into a 23 x 10 x 6.7 cm volume that also includes four ACS thrusters, **Fig. 2**.



Figure 1: Photograph of prototype Phase II SBIR 1.0U+ CHIPS flight system (TRL 5) showing locations and orientation of the primary thruster and 2 of 4 ACS thrusters. The propellant tank is included in the structure.

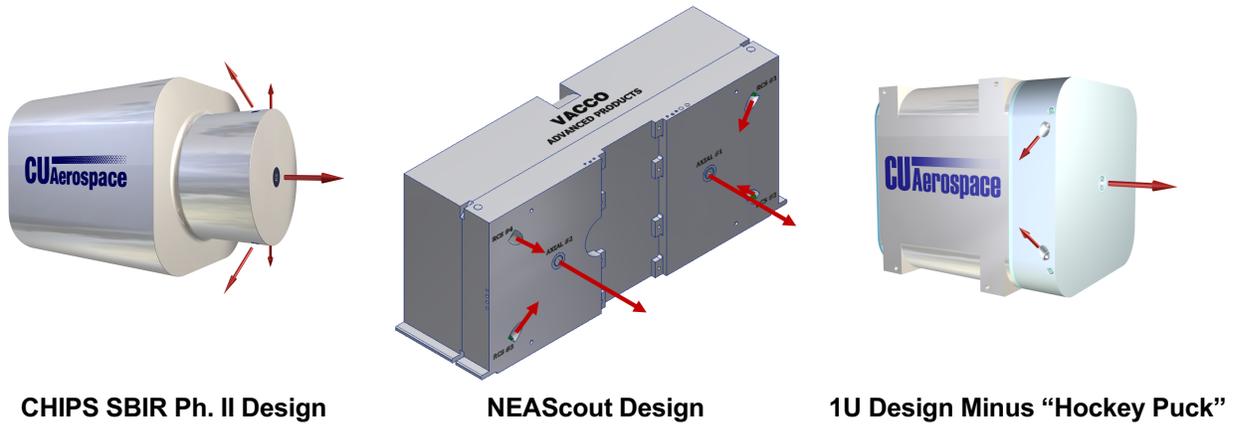


Fig. 3. Family of CHIPS thruster system designs with different propellant tank sizes: (from left to right) prototype 1U+ “hockey puck” volume for a 3U P-POD deployer (NASA SBIR Phase II), VACCO-CUA NASA NEA Scout alternate design (23 x 10 x 6.7 cm³), and 1U configuration without the hockey puck extension. For performance estimates, see Section 5.

CHIPS RESISTOJET

At the core of CHIPS is the high-efficiency micro-resistojet, the superheater cartridge (SHC), **Fig. 3**. Resistive heating is accomplished by passing current through the small-diameter, thin-walled “superheat” tube which feeds the supersonic micro-nozzle. The superheat tube has been optimized to minimize losses due to thermal conduction and radiation. A coaxial shroud further reduces radiation losses while protecting the superheat tube during handling and transportation. Extensive testing of the SHC has demonstrated a consistent performance in both warm-fire and cold-fire modes (see **Section 3** for experimental results).



Fig. 3. Superheater cartridge (SHC) prototype.

CHIPS ACS MODULE

The cold gas thrusters of the CHIPS ACS module are located to provide 3-axis stabilized control of satellite attitude when coasting and steering during ΔV maneuvers, **Fig. 4**. Four cold gas thrusters are symmetrically spaced on the manifold, providing a nominal 0.4 mN-s impulse bit. When fine adjustments are desired, the feed pressure can be lowered to provide a minimum impulse bit as low as 0.18 mN-sec.

ACS thruster pairs are fired to provide steering in yaw, roll, and pitch to correct for any finite mismatch between the satellite center-of-gravity (CG) and the primary thrust vector. The internal geometry of the storage volume aided by internal screens will naturally damp propellant slosh. For fine control in the primary thrust axis, the four ACS thrusters are oriented 15 degrees below the X-Y plane (**Fig. 4**), and are pulsed to provide +Z maneuvering, while the primary thruster is pulsed for -Z maneuvering.

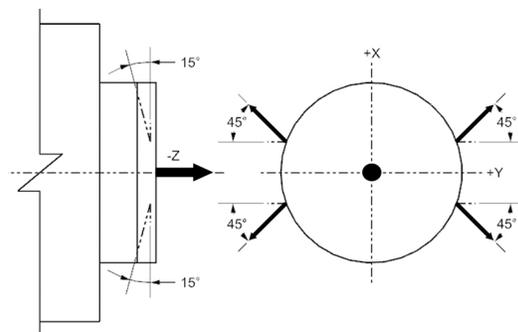


Fig. 4. Thrust vector diagram depicting both primary and ACS thrusters on the CHIPS prototype (Fig. 1). A similar arrangement can be machined around a rectangular perimeter (Fig. 2).

CHIPS FUNCTIONAL DESCRIPTION

The schematic shown in **Fig. 5** illustrates CHIPS functionality. The self-pressurizing propellant is stored as a liquid in the integral storage tank, which includes a heater to maintain supply pressure when CHIPS is near the lower operational temperature limit. When a firing sequence is initiated, the shutoff valve is opened and propellant is drawn from the tank through a micro-heat exchanger feed dryer designed to ensure no liquid reaches the vapor plenum. The in-situ CHIPS controller board actively regulates plenum pressure via closed-loop control of the pressure control valve. Feed valves located in the plenum control gas flow to their respective thrusters. All 7 valves in the CHIPS feed system are normally-closed, *frictionless* soft-seat solenoid micro-valves from VACCO Industries. The propellant tank and vapor plenum are welded against external leakage, and the feed system topology is designed to be *dual-fault tolerant* against leakage to satisfy Air Force Space Command range safety user requirements [AFSPCMAN 91-710].

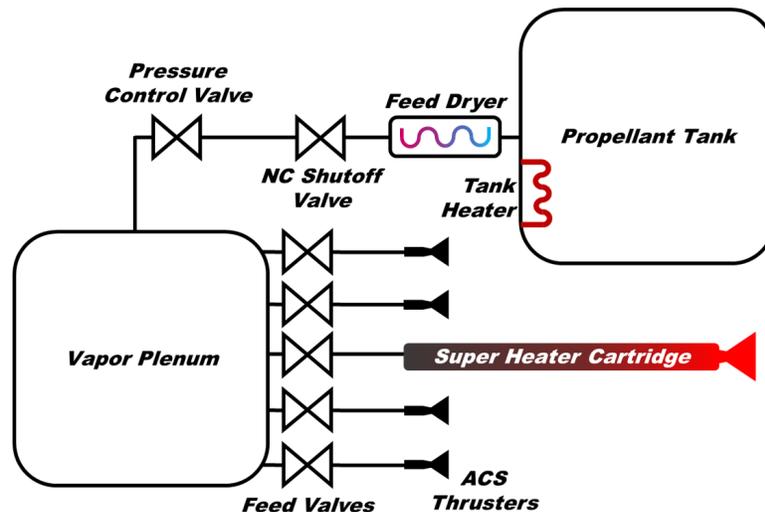


Fig. 5. CHIPS schematic. Electronics boards can be enclosed inside the vapor plenum or propellant tank when using non-corrosive and electrically non-conducting R236fa or R134a to maximize propellant volume.

An optional battery pack can be mounted in an enclosure on the rear bulkhead of the propellant tank. Charger, maintenance, and survival electronics are integrated into existing electronics which interface with the CHIPS controller board. In order for the battery pack to supply power to CHIPS, the satellite bus must first activate CHIPS; this ensures that CHIPS will remain powered off unless intentionally activated in order to satisfy common launch service requirements. For CubeSats without deployable solar panels (that is, low power CubeSats), the battery pack enables high-performance ΔV maneuvers while allowing the mission to decide how much power is supplied by the satellite bus via software (e.g. if bus power draw is set to 1 W, CHIPS can fire at full power for 20 min before the pack must be recharged, giving ~ 9 m/s ΔV). Charge rate and timing is also configured via software, allowing the customer to schedule charging around payload operations.

INTEGRATION AND SYSTEM FEATURES

Figure 6 shows an illustration of a CHIPS unit without the hockey puck extension integrated into a standard 3U CubeSat frame. As noted earlier, CHIPS is highly adaptable to a wide range of specific

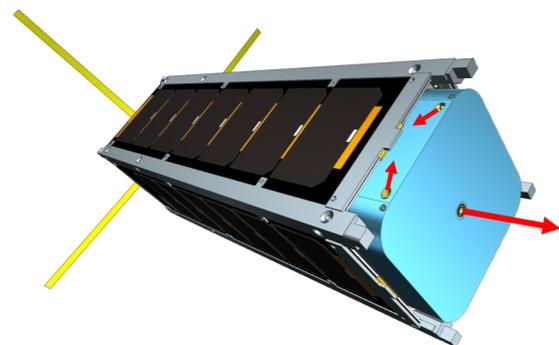


Figure 6: Illustration of CHIPS (without “hockey puck”) in a 3U CubeSat frame. Arrows show locations and orientation of the primary thruster and 2 of 4 ACS thrusters.

geometries and can be designed to accommodate different propellant tanks and configurations, **Fig. 2**. A list of system features is provided below:

- Two operational modes:
 - Warm gas mode for high specific impulse, large total impulse
 - Cold gas mode for minimum or small total impulse maneuvers
- Control authority: roll, pitch, yaw, +/- Z
- On-orbit update of system parameters, including:
 - Thrust duration
 - Plenum pressure (thrust)
 - Superheater power level (specific impulse)
 - Temperature & fault set-points
- Telemetry and status packets for system monitoring
- Dedicated propellant heater for continuous operation below +0°C ambient temperature.
- Propellant pressure sensor for closed-loop propellant temperature regulation.
- Propellant vaporizer ensuring 100% vapor delivered from liquid storage.
- High-reliability, frictionless valve propellant feed system
 - VACCO micro-valves tested to 200,000+ cold gas firings
 - Double-fault tolerant against leakage
- High-density, self-pressurizing R236fa baseline propellant:
 - Green, non-toxic, non-flammable & inert
 - Chemically stable, high critical temperature, low freezing point & vapor pressure
- Possibly able to be refueled in space through primary nozzle and latching mechanism

3. EXPERIMENTAL RESULTS WITH CHIPS PROTOTYPE HARDWARE

EXPERIMENTAL SETUP

CHIPS thrust testing was performed in the University of Illinois at Urbana-Champaign (UIUC) Electric Propulsion (EP) laboratory. Within the facility's 1.5 m³ vacuum tank is an advanced Watt pendulum thrust stand with 8 μN resolution [Wilson, 1997]. Thrust stand measurements were taken with a background pressure of approximately 400 milli-Torr. Windage effects [Whalen, 1987] artificially lower thrust readings, but the correction is within experimental error and is not applied. A CHIPS support board uses an onboard pressure sensor to measure and control the vapor plenum pressure by operating the pressure control valve. In addition, the board provides a specified amount of power to the superheater cartridge. Power and pressure measurements are recorded by the board via a telemetry stream from the device. Conditions are controlled precisely enough to repeat flow conditions, which has been a useful gauge on system health. Example pressure, power, and thrust stand voltage profiles for a typical thrust stand test were presented previously in [Hejmanowski, 2015]. The CHIPS test apparatus and earlier thrust stand measurements are diagrammed and described in more detail in [Hejmanowski, 2015].

EXPERIMENTAL DATA

Throughout the CHIPS program, there have been several design iterations on both the superheater and its nozzle. Many of these configurations were tested without the superheater cartridge, which neatly packages the superheater, nozzle, electrical connections, and gas feed. The performance of the CHIPS micro-resistojet with R236fa is compared with that of R134a in **Figs. 7 and 8**, showing that R236fa nearly matches R134a in terms of the product of density and specific impulse ($\rho * I_{sp}$). With a higher molecular weight, the I_{sp} of R236fa is lower than R134a (**Fig. 7**), but its increased liquid storage density largely makes up for the disparity (**Fig. 8**). More detailed performance data using R134a can be found in [Hejmanowski, 2015].

Figure 9 shows the R236fa thrust vs. mass flow rate performance at 25 W of power to the SHC. **Figure 10** shows data from a 15-hour superheater life test indicating relatively constant CHIPS performance after a small pressure rise during an initial burn-in time. Because a 1U CHIPS has ~ 5 hours

of propellant available at nominal operating flow rate conditions, this represents approximately a 300% life test for a 1U tank size. This 300% superheater life test is highly encouraging and shows the capability for scaling to larger tank sizes without performance degradation.

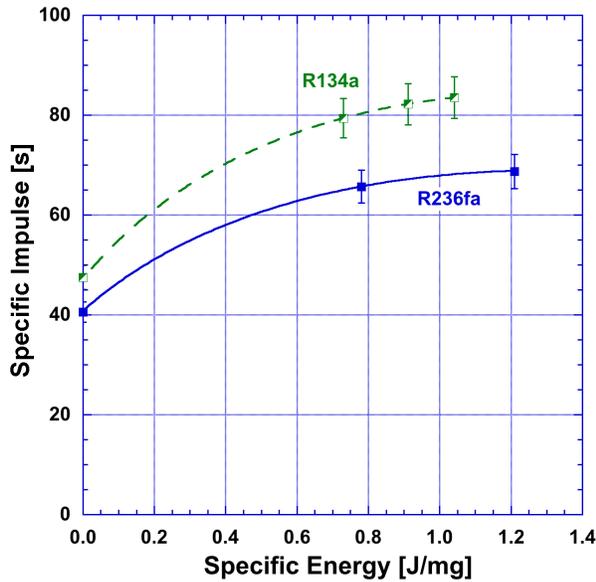


Fig. 7. I_{sp} vs. specific energy for 25-30 mg/s R236fa and R134a using 10 cm superheater tubes.

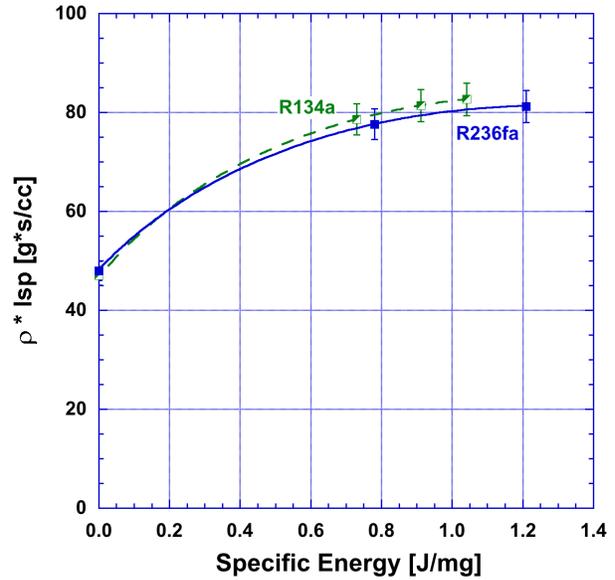


Fig. 8. Density * I_{sp} product vs. specific energy for 25-30 mg/s R236fa and R134a using 10 cm superheater tubes.

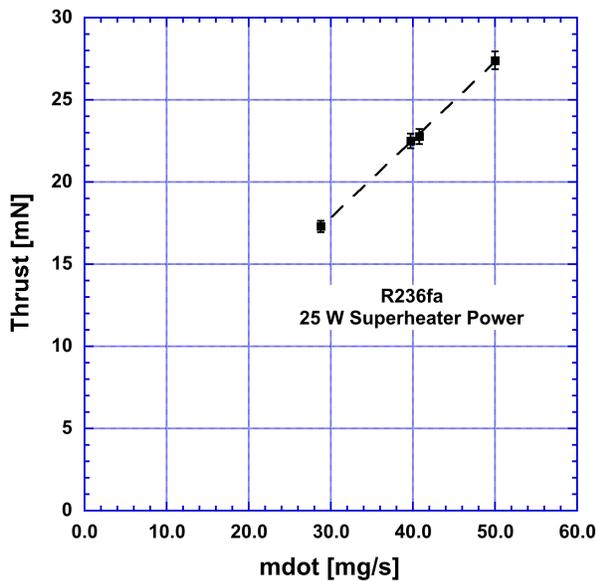


Figure 9. Thrust stand measurements of thrust vs. mass flow rate for R236fa with a power input of 25W to the SHC.

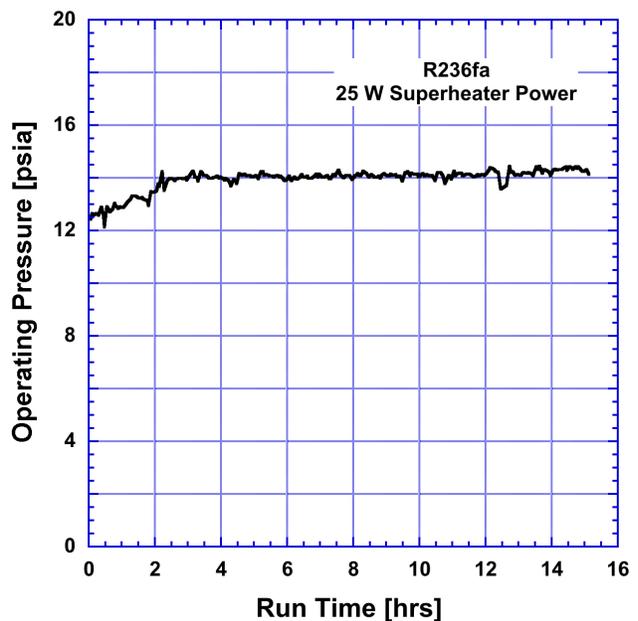


Fig. 10. Operating pressure vs. powered run time for R236fa life test (40 mg/s, 25 W) showing \approx constant pressure (data taken in 10-min burns followed by \sim 6 min cool down periods).

RISK ASSESSMENT AND MITIGATION

Overall technical risk of the CHIPS thruster unit is low and has been substantially mitigated through testing on the NASA-funded Phase II SBIR project. Additionally, the TRL 7 PUC thruster systems [Carroll, 2015] already delivered to the Air Force by the CU Aerospace-VACCO team have validated many of the proposed technologies (valves, welds, materials compatibility, control boards, pressure vessel testing, etc.) through testing.

The CHIPS superheater cartridge and associated drive electronics are a primary focus of the ongoing SBIR effort and have been validated through testing to TRL 5 at this time. Resistojet thrusters as a class are at TRL 9. Liquid propellant resistojets have been extensively ground and flight tested [Morren, 1988; Sweeting, 1999]. Micronozzle performance has been well-characterized as a function of Reynolds number, and the CHIPS nozzle ($Re = 1600$) will be operating at a demonstrated high efficiency [Whalen, 1987]. Superheater performance is based on extremely well-known heat transfer performance for internal turbulent convective flow ($Re = 7500$, Nusselt No. = 25.8) to a constant temperature wall. Evaporator performance is based on the effect of microgravity on pool boiling [Kim, 2002; Lee, 1997], and on the strong absorption by liquid R134a of infrared radiation [Pikkula, 2004]; R236fa should be similar.

In-house testing at CUA has effectively mitigated the risk in propellant selection on materials compatibility. These propellants are well known and benign, and thus inherently carry very low risk. R236fa and R134a are benign, non-toxic, non-hazardous refrigerants, so they are not hazardous materials. The CHIPS hardware also contains no hazardous materials. Further, R236fa can be removed from the air by the International Space Station (ISS) filtration system, making it a candidate for deployment from ISS (whereas R134a cannot be so filtered on ISS).

The primary safety risk with CHIPS is pressure, but this is predominantly mitigated by the use of R236fa propellant rather than R134a. R236fa requires more preheating because of its lower vapor pressure, and its I_{sp} performance is worse than R134a. However, with R236fa, the overall total impulse will be similar (**Fig. 8**) and more importantly, the propellant tank will be below 100 psig at the CHIPS maximum expected operating pressure (MEOP) under worst-case temperature conditions of 65°C, so it is not a hazardous pressure system [AFSPCMAN 91-710, Vol. 3 Chap. 12]. This is extremely low compared with pressures routinely encountered in the space industry and does not present a serious safety issue. As such, R236fa is now considered as the baseline propellant choice (R134a was the original baseline propellant). The primary pressure hazard occurs if the system is erroneously over-filled with liquid R236fa, sealed, then raised in temperature. Liquid refrigerant is relatively incompressible and pressure will increase rapidly potentially exceeding burst pressure causing external leakage. This safety issue is mitigated by using fill methods that leave a prescribed minimum amount of vapor in the system. The correct propellant load is easily verified by simply measuring the mass of the system. To address a filling error, the aluminum alloy system will be designed to plastically deform then leak before burst. The maximum temperature limit will be determined for a system inadvertently filled with 100% liquid. This information will be incorporated into ground handling and storage procedures for a fueled system. Should a larger structural margin be desired, the all-welded titanium propellant tank design for CHIPS has already been validated in our PUC thruster system.

Failure of the warm-gas functionality of the primary thruster is mitigated by operating the system in cold-gas mode, which is still capable of satellite maneuvering and limited de-orbiting using solar warming of the propellant.

The thruster system will have triple physical and electronic timer inhibits and can only be activated via ground command, to guarantee the CHIPS unit cannot have extended uncontrolled firing in case of failure. For example, one option to limit thrust duration on any flight unit design is to include real time clock (RTC) electrical inhibits on the primary propellant feed valve.

4. NOZZLE SIMULATIONS USING BLAZE MULTIPHYSICS

BLAZE Multiphysics™ [<http://blazemultiphysics.com>] simulations were performed for cold and warm gas nozzle cases with R134a; such simulations will be used as a baseline for future calculations to help optimize the nozzle design. A fully developed parabolic mass flow profile was assumed at the nozzle inlet. The R134a flow was modeled using the BLAZE Pressure-Based Coupled Navier-Stokes and

Material Properties models where heat capacity, enthalpy, specific gas constant, gamma, thermal conductivity, and molecular dynamic viscosity were modeled as a function of gas temperature using user input fits in the Material Properties model. All scalar fluxes were modeled using 2nd order schemes with a Barth-Jespersen flux gradient limiter applied only to the second order upwind flux scheme applied to axial momentum flux in order to limit numerical dispersion and non-physical extrema at finite volume cell boundaries. A grid study was performed (not shown for brevity) in order to determine the rectilinear grid density required to limit discretation errors in calculated thrusts to less than 1%. A grid with 440 cells in the axial dimension (with a relatively finer mesh near the nozzle throat) and 40 cells in the radial dimension was derived. The nozzle walls were modeled as thermally non-conducting. As the simulations utilized a “mass inlet” compressible inlet boundary condition, the total mass flux is user specified and the inlet total pressure is calculated by the model. All calculations were run to have < 0.25% mass error between the inlet and outlet mass flows.

For the cold flow cases, the temperature at the inlet to the nozzle was 300 K. For the warm gas cases, the temperature at the inlet to the nozzle was 953.3 K for 30 W of additional thermal energy added from the superheater tube, and 861.2 K for 25 W of additional thermal energy added from the superheater tube. Further, for the warm gas cases, the geometry of the nozzle was increased by 7% to reflect the increase in size of the nozzle due to thermal expansion. Multiple flow rates were modeled for comparison to experimental data. A comparison between experimental data and BLAZE calculations is made in **Tables 1** and **2** for cold and warm gas, respectively.

Table 1. Comparison of cold gas R134a experimental and modeled thrusts and specific impulses.

Case	Mass Flux, mg/s	Power, W	Thrust, mN	I _{sp} , s
Exp. Cold	40.4	0	19.0	47.9
Exp. Cold	37.1	0	17.5	48.1
BLAZE Cold	40.4	0	18.0	45.5
BLAZE Cold	37.8	0	16.5	44.6
BLAZE Cold	39.7	0	17.7	45.5

Table 2. Comparison of warm gas R134a experimental and modeled thrusts and specific impulses.

Case	Mass Flux, mg/s	Power, W	Thrust, mN	I _{sp} , s
Exp. Warm	37.9	25	28.4	76.3
Exp. Warm	37.4	30	29.3	79.9
Exp. Warm	41.5	25	32.3	79.1
BLAZE Warm	37.3	25	27.2	74.4
BLAZE Warm	37.3	30	28.5	77.9
BLAZE Warm	37.4	25	27.7	75.7
BLAZE Warm	41.5	25	30.6	75.4

These BLAZE calculations for thrust and specific impulse values are at worst within 8% of experimental values, **Tables 1 and 2**. The source of difference is likely some combination of: (i) a 5% uncertainty in the actual throat diameter, (ii) a 5% uncertainty in the experimental mass flow rate, (iii) that radiative losses from the superheater tube were not accounted for in the calculations, therefore all of the superheater energy was being pumped into the gas flow, and/or (iv) that nozzle heating from mechanical connection to the superheater tube was not accounted for in the simulations (thermally non-conductive nozzle walls were modeled). Regardless, the BLAZE calculations are relatively close to measurements and predict reasonably accurate quantitative results. Therefore, we have confidence that future simulations can be performed to guide the optimization of the nozzle design for enhanced Isp and thrust.

5. PERFORMANCE ESTIMATES FOR DIFFERENT CONFIGURATIONS

Performance estimates for the three different CHIPS configurations shown in **Fig. 2** are presented in **Table 3**. As can be seen, the warm gas performance numbers are ~ 60% higher than for cold gas, **Table 3**. Volumetric impulse (also known as impulse density) has been shown to be a good metric (figure of merit) for propulsion system capability and degree of system integration in nanosatellite-class spacecraft that are also volume limited.

Table 3. Performance specifications of CHIPS primary propulsion in warm and cold-fire modes for different volume configurations (see Figure 2). Note that thrust can be adjusted as desired with flow rate. Propellant load estimates assume a fill fraction of 0.876 at MEOP of 100 psi at 65°C.

Parameter	1U without Hockey Puck Warm (Cold) Gas	1U+ with Hockey Puck Warm (Cold) Gas	NEAScout Warm (Cold) Gas	Units
Thruster System Package Volume	865	979	1,590	cm ³
Available Tank Volume	627	721	1,083	cm ³
Propellant Mass (R236fa)	754	867	1,302	g
Dry Mass	758	798	1,179	g
Wet Mass	1,512	1,665	2,481	g
Satellite Total Wet Mass (assumed)	4,000	4,000	14,000	g
Specific impulse	66 (40)	66 (40)	66 (40)	sec
Mass Flow Rate	40 (64)	40 (64)	40 (64)	mg/s
Thrust	25	25	25	mN
Total impulse	471 (296)	542 (340)	814 (511)	N-s
Vol. Impulse (total impulse / sys. volume)	545 (342)	553 (393)	512 (321)	N-s/liter
Delta-V capability (for Sat. Total Wet Mass)	135 (82)	158 (96)	63 (38)	m/s
Maximum continuous thrust time	10 (unlim.)	10 (unlim.)	10 (unlim.)	min

CU AEROSPACE – VACCO TEAM THRUSTER CHOICES

A variety of CubeSat propulsion systems are advertised as available today, though very few are actually fully functional, deliverable units. **Table 4** lists two mature CU Aerospace – VACCO team warm gas CubeSat propulsion systems and compares how the different systems perform based upon the metric of “Impulse Density” (also called “Volumetric Impulse”), and an estimated total impulse density per unit cost. Impulse Density is approximately the total impulse for a 1U system, and helps indicate the scaling potential. Pricing of other warm gas systems is not readily available (so they are not listed here), but we estimate that CHIPS is the best value available in terms of total impulse density per unit cost, **Table 4**, and CHIPS utilizes the completely non-toxic green propellants R236fa/R134a. The primary advantage of the PUC system [Carroll, 2015] is the use of an extremely compact micro-cavity discharge (MCD) thruster that enables a large impulse density in a small 0.25U package, which would be unachievable with most other technologies; the downside of the MCD discharge is that it is not compatible with the hydrocarbon-based self-pressurizing refrigerants such as R236fa, so PUC could only be used in a cold-gas mode with such a refrigerant.

Table 4: CU Aerospace – VACCO team state-of-the-art warm gas CubeSat propulsion systems.

Manufacturer	Model	Propellant	Volumetric Impulse [N-s / liter]	Cost Value: Estimated Total Impulse Density per \$K [N-s / L / \$K]	Comments
CU Aerospace /VACCO	PUC	SO ₂ (low-toxicity)	526	2.9	8 flight units delivered (0.25U), TRL 7, low-toxicity
CU Aerospace /VACCO	CHIPS	R236fa / R134a	545	4.0	ACS included, green propellant. Prototype being testing, TRL 5

* Volumetric Impulse (or Impulse Density) = total impulse of the system divided by the volume of the propulsion system. For 1U systems, this number is approximately the total impulse.

6. SUMMARY AND CONCLUSION

Nanosatellites are a cost-effective alternative to large-scale spacecraft; the CubeSat form factor in particular is increasingly utilized for a number of academic, commercial and government missions, but the nature of the platform imposes severe power, mass and volume constraints which often force users to forgo primary propulsion, limiting mission duration and on-orbit operations. CHIPS provides an attractive solution to this problem by integrating 3-axis attitude control with a high-impulse micro-resistojet primary propulsion system and supporting subsystems into a bolt-on package. System volume is in line with typical reaction wheel + magnetorquer combinations for nanosats, and the optional battery pack allows CHIPS to operate in power-limited systems.

R236fa was selected as the baseline propellant for CHIPS because of its appealing characteristics as a propellant and benign nature in comparison to other options such as hydrazine or sulfur hexafluoride. A 1U design is estimated to be capable of providing 471 N-s total impulse at ~20 mN thrust using R236fa propellant, resulting in a volumetric impulse of 545 N-s/liter. The CHIPS design allows for modifications based on customer-specific mission requirements: the propellant tank may be reduced to as little as 0.5U or expanded to any desired length, tank width is readily customizable, and the thrusters can be repackaged should the hockey puck volume be unavailable. An optional energy reservoir (battery pack) can be added to allow the user to specify the bus power load (as little as 1 W) during propulsive maneuvers. Presently the CHIPS prototype is TRL 5 as a result of a Phase II SBIR effort funded by NASA.

7. ACKNOWLEDGEMENTS

This work has been sponsored by the NASA Glenn Research Center under SBIR contract NNX14CC04C. Heather Hickman served as the technical monitor, and Eric Pencil and Tim Smith served as technical advisors. Our thanks also to Kevin Bassett, Darren King, Jonathan Igartua, Jason Lee, and Scott Robbins for their assistance with different technical aspects of the program.

REFERENCES

- Burton, R. L., Eden, J. G., Park, S.-J., de Chadenedes, M., Garrett, S., Raja, L. L., Sitaraman, H., Laystrom-Woodard, J., Benavides, G., and Carroll, D., "Development of the MCD Thruster for Nanosat Propulsion," JANNAF Conf., Colorado Springs, CO, Paper 1387 (2010).
- Burton, R. L., Benavides, G.F., and Carroll, D.L., "Space Thruster Using Robust Microcavity Discharge," U.S. Patent Application No. 13/680,484 (2012).

- Carroll, D. L., et al., "Propulsion Unit for CubeSats (PUC)," *62nd JANNAF Propulsion Meeting*, Nashville, TN, 1-5 June 2015, Paper Tracking # 4059 (2015)
- Doncaster, B. and Shulman, J., "2016 Nano/Microsatellite Market Forecast", SpaceWorks Enterprises Inc. (SEI) website publication, accessed on 9/28/2016. <http://tinyurl.com/SEIreport2016>
- Ghosh, A, Coverstone, V. "Study of Low-Thrust Trajectories for Low Orbit Multiple CubeSat Missions," AAS conference, paper no. 10-174 (2010).
- Hejmanowski, N. J., et al., "CubeSat High Impulse Propulsion System (CHIPS)," 62nd JANNAF Propulsion Meeting (7th Spacecraft Propulsion), Nashville, 2015, Paper Tracking # 4032 (2015).
- Kim, J., et al., "Pool Boiling Heat Transfer on Small Heaters: Effect of Gravity and Subcooling," *Int. J. Heat and Mass Transfer*, **45**, pp. 3919-3932, 2002.
- Lee, H.S., Merte, H., Jr. and Chiaramonte, F., "The Pool Boiling Curve in Microgravity", *Journal of Thermophysics and Heat Transfer*, Vol.11, No. 2, 216-222, April-June 1997.
- Laystrom, J.K., Burton, R.L., and Benavides, G.F., "Geometric Optimization of a Coaxial Pulsed Plasma Thruster," AIAA Paper 2003-5025 (2003).
- London, A. P., and Droppers, L. J., "High-Performance Liquid Propulsion For CubeSats: Requirements and Approaches," JANNAF Conf., Colorado Springs, CO, Paper 1428 (2010).
- Morren, W. E. and Stone, J. R., "Development of a Liquid-Fed Water Resistojet," AIAA Paper No 88-3288, NASA TM100927, 1988.
- Morren, W. E. et al., "Performance Characteristics of an Engineering Model Multipropellant Resistojet," *J. Propulsion and Power*, Vol. 5, No. 2, pp 197-203, 1989.
- Pikkula, B. M., et al., "Infrared absorption spectrum of liquid cryogen R-134a," *Lasers in Surgery XIV*, Bartels, et al. Eds., Proc. of SPIE, Vol. 5312, 18-23, 2004.
- Sweeting, M. N., et al., "Low-Cost Orbit Manoeuvres for Minisatellites Using Novel Resistojet Thrusters," *Proc. of the Inst. Of Mech. Engr. Part G*, **213**, 4, pp. 223-231, 1999.
- Whalen, M.V., "Low Reynolds Number Nozzle Flow Study," NASA-TM-100130 (1987).
- Wilson, M.J., Bushman, S.S., and Burton, R.L., "A Compact Thrust Stand for Pulsed Plasma Thrusters," 25th International Electric Propulsion Conf., IEPC Paper 97-122, Cleveland, OH (1997).