



TFAWS
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Thermal Design and Analysis of Green Propulsion Dual Mode CubeSat

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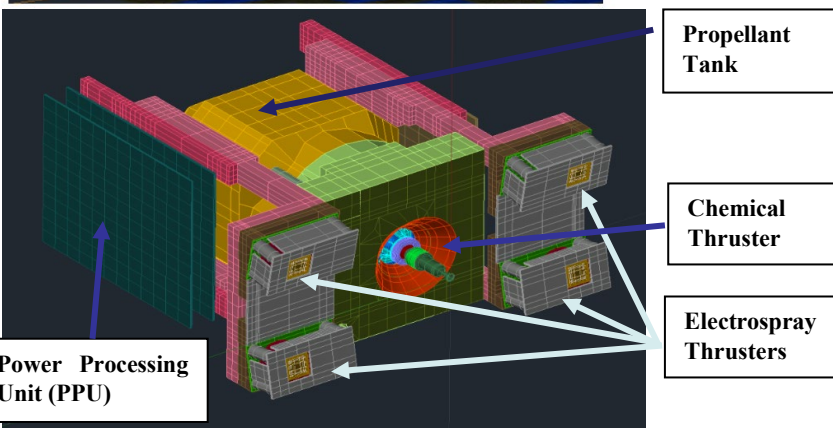
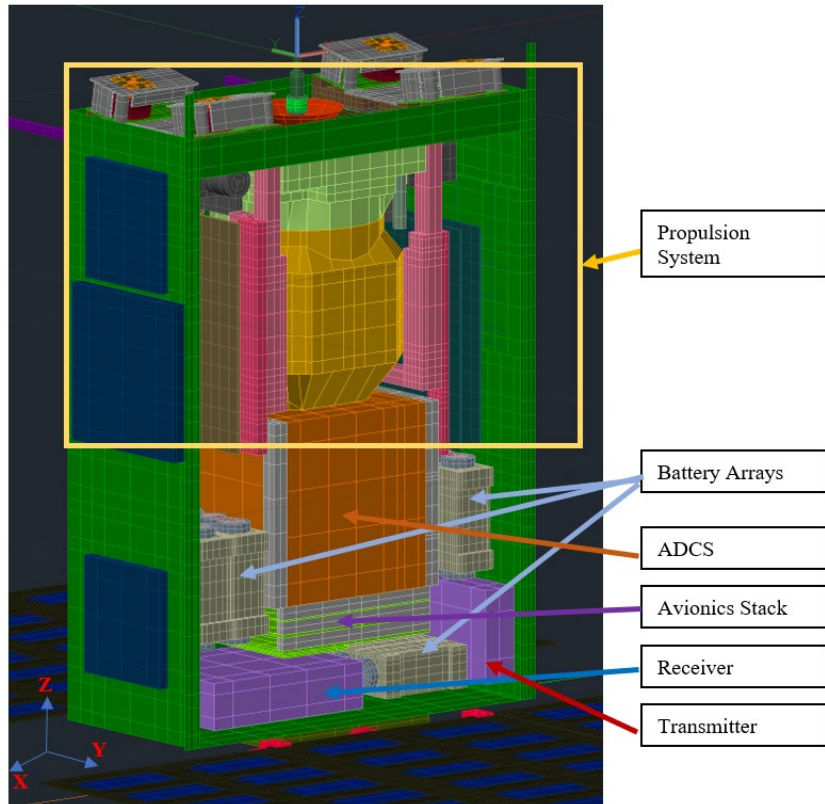
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Overview



- Green Propulsion Dual Mode (GPDM) is a collaboration between NASA MSFC and Georgia Tech to create a 6U CubeSat demonstrating the use of the green propellant Advanced Spacecraft Energetic Non-Toxic (ASCENT) in two propulsion systems:
 - A traditional chemical thruster
 - An electrospray thruster system
- Several driving thermal considerations
 - Chemical thruster reaches 1300°C during firing
 - Radio receiver heating issues during TVAC
- Analysis highlighted several issues common to experimental/academic satellites, which will be discussed



- Georgia Tech is the bus provider, avionics designer, environmental test group, and mission ops support
- MIT/E-Space provided the electrospray system and controllers
 - Ion thruster (electrical field charging particles used for thrust) that uses the same propellant as the chemical thruster
- Rubicon Space Systems (RSS) provided the Sprite propulsion unit with the propellant tank



GPDM Thermal Analysis Parameters



- Broken into two models, managed with XREF in Thermal Desktop
 - Propulsion model
 - Spacecraft and bus model, with XREF of propulsion model
- Orbit subject to change, so β angle from 0° to 90° analyzed with worst-case sun-facing sides

Case Title	Beta Angle	Solar Flux (W/m ²)	Albedo	Planetshine	Sun-Facing Side
Hot Orbit Positive X Sun Facing Transient Burn	90°	1414	0.35	Blackbody model with value of -23.15°C	+X
Hot Orbit Negative X Sun Facing Transient Burn	90°	1414	0.35	Blackbody model with value of -23.15°C	-X
Hot Orbit Negative Z Sun Facing Transient Burn	90°	1414	0.35	Blackbody model with value of -23.15°C	-Z
Hot Orbit Positive Z Sun Facing Transient Burn	90°	1414	0.35	Blackbody model with value of -23.15°C	+Z
Cold Orbit Negative Z Low Power	0°	1322	0.11	Blackbody model with value of -23.15°C	-Z



Temperature Constraints and Power Values



Spacecraft Bus Sub-System:

Component	Minimum Temperature Limit (°C)	Maximum Temperature Limit (°C)
EPS Board	-5	70
Interface Board	-5	70
Flight Computer	-20	85
XACT-50 (ADCS)	-20	60
Battery Pack	-20	75
Transmitter	-40	85
Receiver	-20	70

Component	Worst-Case Hot Power (W)	Worst-Case Cold Power (W)
X-ACT 50	9.13	6.8
Battery	1.5	1.5
EPS Board	1.5	1.5
Interface Board	2.45	1.45
Flight Computer	7.28	5
Receiver	16.7	0.5
Transmitter	21 when transmitting, 0 otherwise	0

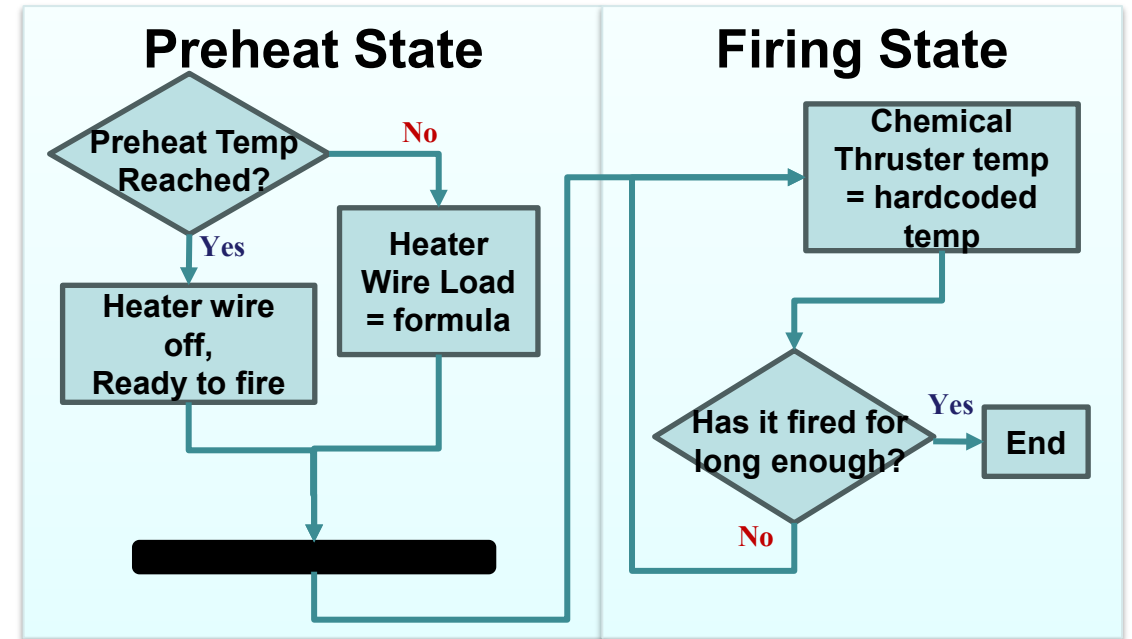
Propulsion Sub-System:

Component	Minimum Temperature Limit (°C)	Maximum Temperature Limit (°C)
Sprite Structure	0	250
Sprite Propellant	-65	90
Sprite Thruster/Isolation Valves	-5	60
CPRS Valves	-5	60
Foxglove Model 1	5	70
Foxglove Model 2	5	70
Power Processing Unit (PPU)	-10	50
Electrospray Thrusters	10	40

Component	Worst-Case Hot Power (W)	Worst-Case Cold Power (W)
Sprite Thruster/Isolation Valves	1.8	0
Foxglove Model 1	3.17	0
Foxglove Model 2	0.26, distributed 0.0025 applied to Chips U9 and U13 while firing 0.08 applied to Chip U15 during preheat and firing Resistance heating equation for Chip U11 during preheat (slide 8)	0
PPU	1.7	0
Sprite Thruster	Boundary condition (slide 6)	0

Initial Assumptions

- All bus components thermally well-connected to the external structure (bolted aluminum-aluminum contact)
- Sprite thruster firing heat loads provided by RSS, based on empirical test data collected in NASA/RSS partnership
 - Propellant preheat behavior controlled with logic blocks
 - Sprite chemical thruster modeled via boundary node logic





Thermal Control Design



- Initial analysis revealed need for a low α/ε to best radiate the heat produced by the spacecraft during operations
 - Elimstat paint chosen for outer coating ($\alpha = 0.4$, $\varepsilon = 0.9$)
- Radio receiver behaved unexpectedly during thermal vacuum testing, pulling more power and heating up more rapidly than predicted
 - Flight software modified to duty cycle the receiver, rather than being powered 100% of the time
 - TVAC testing proceeded with the receiver at 20% duty cycle
- Flight rule proposed to not have the thruster side (+Z) in sun-facing position
 - Electropray thrusters must keep their propellant reservoirs within a narrow temperature range to operate
 - Coating or tape would have been a cost and/or schedule impact, since it would need to be electrostatically conductive if applied to the electropray structure cover



Areas of Thermal Interest

- The thruster requires the propellant to be preheated to 440° C before firing
- Preheating is done by a heater wire controlled by the Sprite Foxglove board, specifically Chip U11 which controls the heater wire
- This heat load is modeled as a function of heater wire temperature, due to the change in electrical resistance with change in temperature
 - Maintaining this thermostatic control of the heater wire therefore raises the board temperature until the preheat heater is turned off
- Focal area of propulsion system thermal analysis was the maximum duration the system could hold a preheated state

$$Q_{U11} = \left(\frac{0.76 * \text{Heater_Wire_Voltage}}{0.5 + (0.0063 * (\text{heater wire node temperature}) + 4.8522)} \right)^2 * 0.5$$

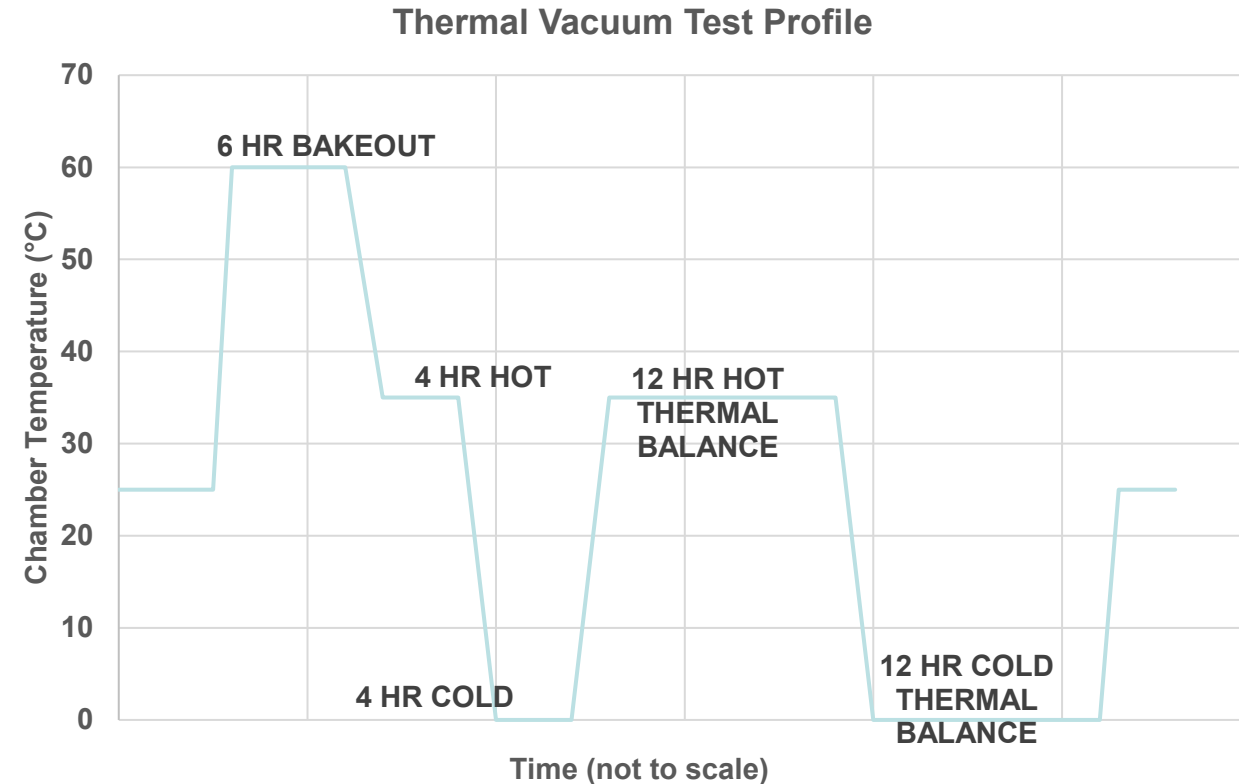
where: Heater_Wire_Voltage is the incoming voltage



Thermal Vacuum Testing and Model Correlation



- TVAC testing performed at Georgia Tech of integrated spacecraft prior to solar panel integration
 - Bakeout performed prior to two cycles of hot and cold dwells
 - Chamber temperatures chosen to represent the predicted external spacecraft temperature
 - 10 TCs were available to measure external spacecraft temperature, distributed on the five sides
 - TCs also internal to the spacecraft on the batteries, and from software interface to the radio, avionics boards, ADCS
 - Only battery TC locations known, other internal TCs part of telemetry data transmitted to flight software





Thermal Vacuum Testing and Model Correlation

- When powering on after bakeout, the radio receiver temperature was higher than expected and climbing at a fast rate ($>10^{\circ}\text{C}$ over 10 minutes)
- Test paused until consensus was reached to modify the operation of the receiver to 20% power duty cycling (1 minute on, 4 minutes off)
- Thermal balance conditions reached for 12 hour hot and cold dwells of $<0.5^{\circ}\text{C/hr}$ for external TCs
- Model correlation was difficult due to several factors
 - Emissivity of the chamber was unknown (eventually tested by MSFC to reduce correlation uncertainty)
 - Spacecraft not thermally isolated from test fixture attachment
 - Thermal conductivity between bolted external panels of the spacecraft roughly 100x lower than initially calculated
 - Inconsistent bolt torque, coating applied to mated surfaces



Retrospective



- Why was it so difficult to bound the thermal behavior?
 - High heat, short transient behavior (chemical thruster, radio receiver and transmitter)
 - Wide range of possible operations (β of any value, any face of spacecraft pointed towards sun or space)
 - Limited temperature constraint data
 - Bus COTS components included temperature limits from the manufacturers, but not detailed internal designs so lumped capacitance simplifications had to be used
 - Propulsion custom components had high design fidelity, but temperature limits had to be determined from the subsystem design leads
 - No component or sub-system thermal vacuum testing performed on bus components
 - Long lead time components began procurement prior to thermal analysis support for spacecraft bus
- Many of these issues are common on low-cost, high-risk tolerance missions
 - Tolerance of wide range of launch vehicle rideshare opportunities desired
 - Using components with limited or no flight heritage, limited test data
 - Relatively short schedule timelines



Low-Cost, High-Risk Tolerance Missions



- NPR 8705.4B, “Risk Classification for NASA Payloads”, sorts payloads into risk tolerance categories from lowest tolerance to highest, designated by Class A, B, C, and D
 - Flexible designations, meant to assist in defining the programmatic rigor necessary for the mission (Ex. Class A/B missions expected to monitor and downlink to ground station and record telemetry coverage during potential failure events, versus Class C/D expected to only record telemetry coverage during potential failure events)
- GPDM is a Research and Technology (R&T) mission as per the categorization in NPR 7120.8, which means it's not subject to NPR 8705.4B
 - Colloquially called “sub-class D” or “do no harm”
- CubeSats have a design specification maintained by Cal Poly which is a standard set of design requirements for all known launch providers
 - Not required to use for verification, CubeSats only required to meet the specific launch provider's interface document for deployer compatibility



Thermal Design and Analysis Approach



- This is a net benefit for low-budget missions, keeping resources flexible for focus on known mission-critical areas
 - Can cause issues when encountering “unknown unknowns”
- Excellent additional guidance in “Thermal Test Tailoring Guidelines for Class C and D Space Programs” by John W. Welch from The Aerospace Corporation
 - Test recommendations for class C and D
 - Subdivides class D into “high success expectations” and “lower success expectations” primarily based on development cost



Lessons Learned



- Changes in project scope should be carefully reviewed for potential issues
 - Initial thermal analysis only included propulsion, project intended to use modular spacecraft bus
 - When spacecraft bus thermal analysis need occurred, many bus components were already undergoing procurement
- Can't always rely on space-rated COTS hardware to perform as reported
 - Best practice to perform component/sub-system vacuum test to identify issues earlier on
- System with relatively low thermal mass and high-powered, short duration operations are inherently harder to characterize
 - Transient analysis more difficult to predict accurately, requires greater model fidelity



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