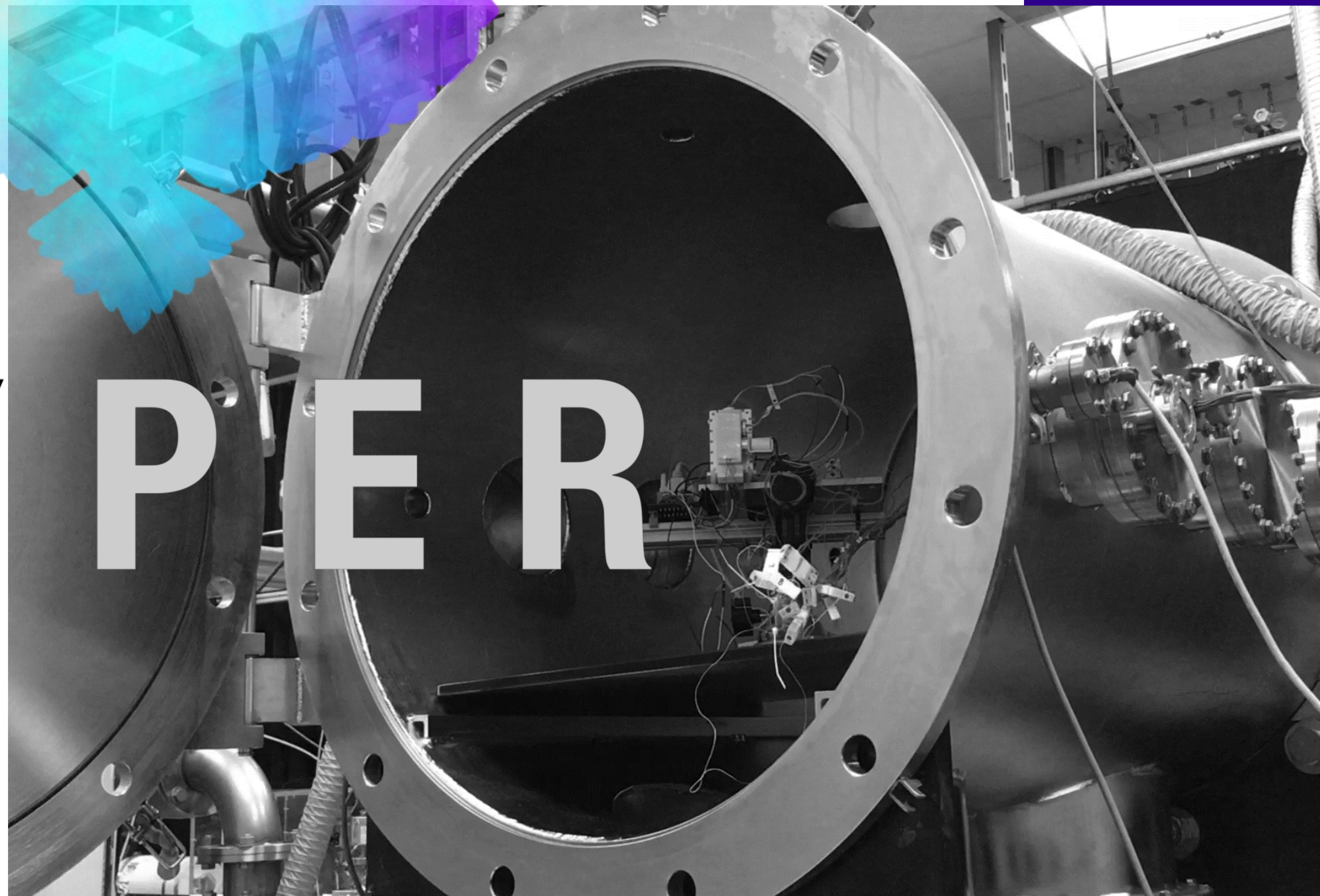
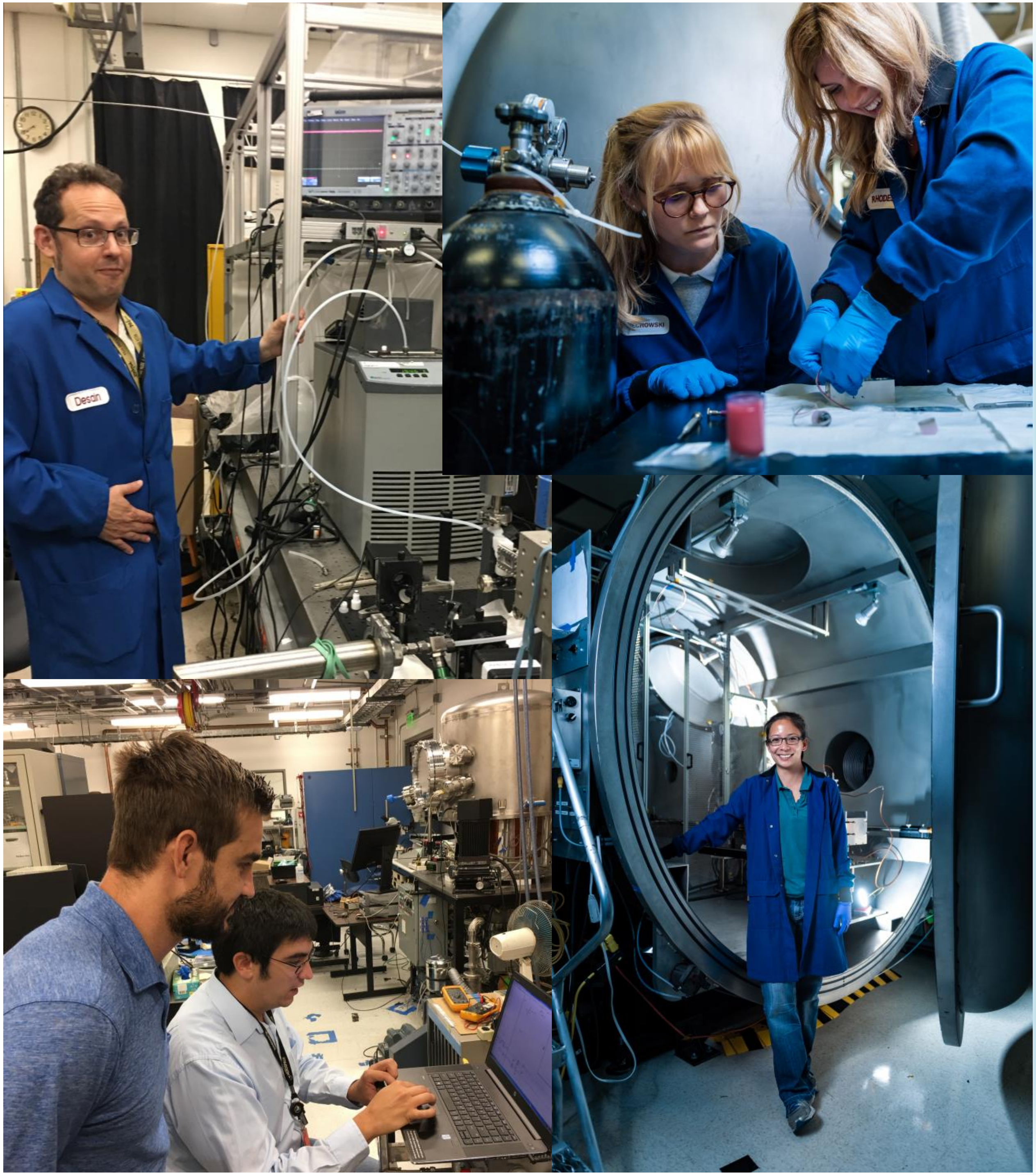
NASA S3VI Webinar

Brandie Rhodes

April 15, 2019

HYPER

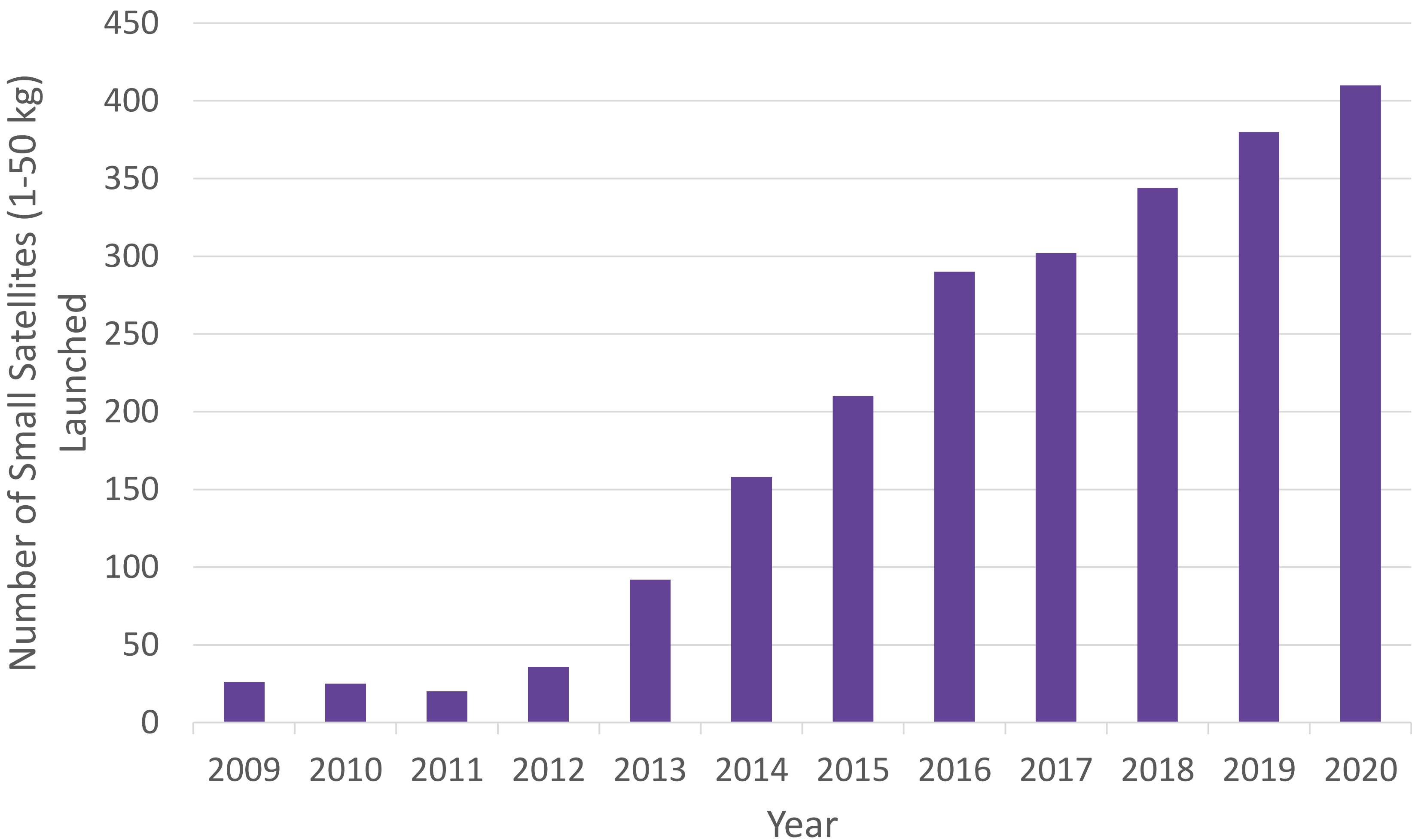




Collaborators:

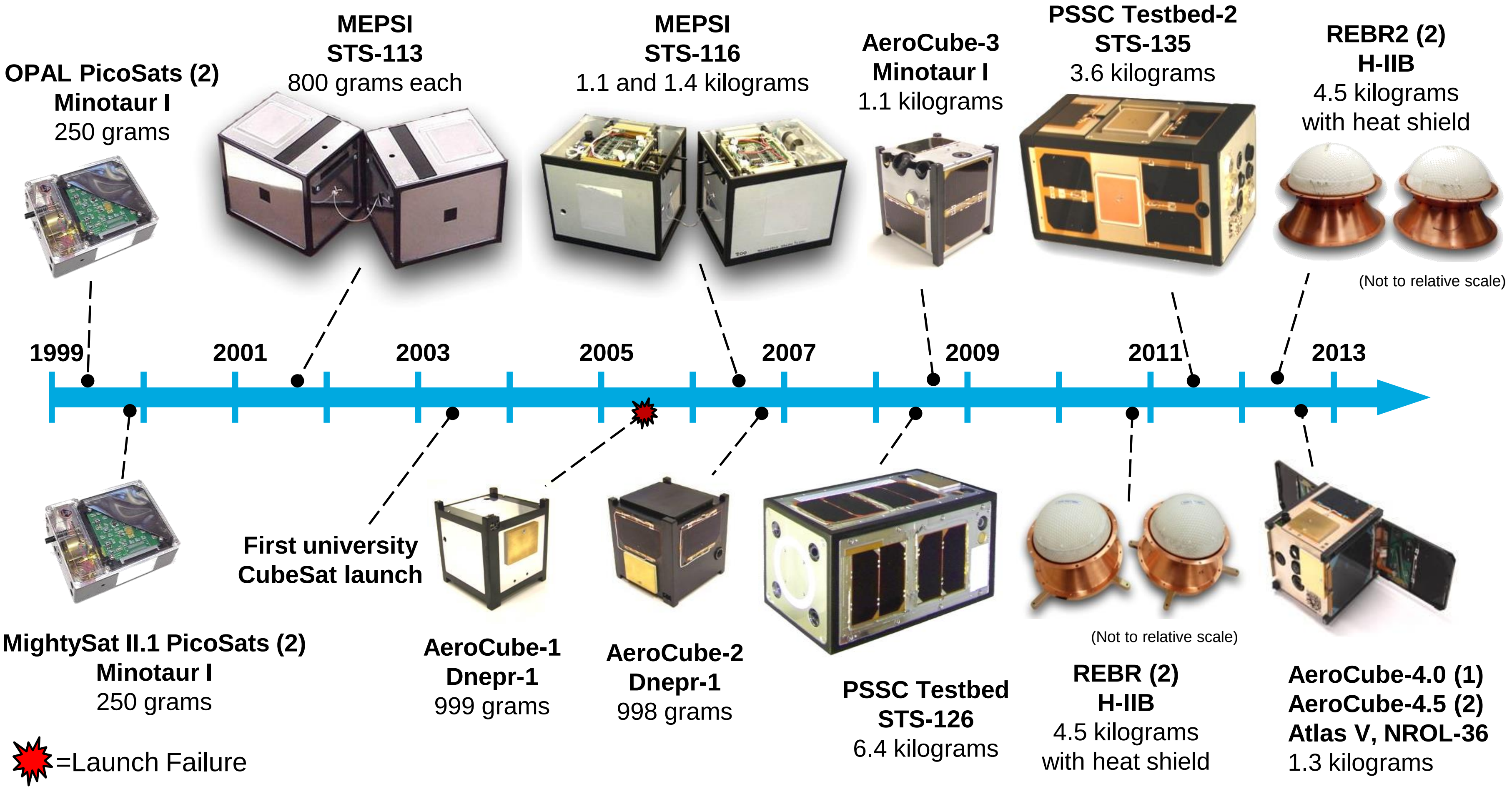
Dr. Paul Ronney (USC)
Dr. Evan Ulrich (Embedded Control Systems, VSD)
Dr. John DeSain (Propulsion Sciences, Tech & Lab Ops)
Dr. Brian Brady (Propulsion Sciences, Tech & Lab Ops)
Summer Intern [2] (Propulsion Sciences, Tech & Lab Ops)
Dave Hinkley (Small Satellite, xLab)
Andrew Blackney (Electromechanical Control, VSD)
Dr. Dan Erwin (USC)
Dr. Mike Gruntman (USC)
Dr. GP Purohit (Propulsion, VSD)
Lee Steffeney (Space Materials, Tech & Lab Ops)
Hannah Weiher (Control Analysis, VSD)
Jessica Byington (Embedded Control Systems, VSD)
Dr. Andrea Hsu-Schouten (Propulsion Sciences, Tech & Lab Ops)
Madison Piechowski (Computer Aided Engineering, Information Systems)
Aerospace Machine Shop

The Small Satellite Market is Booming

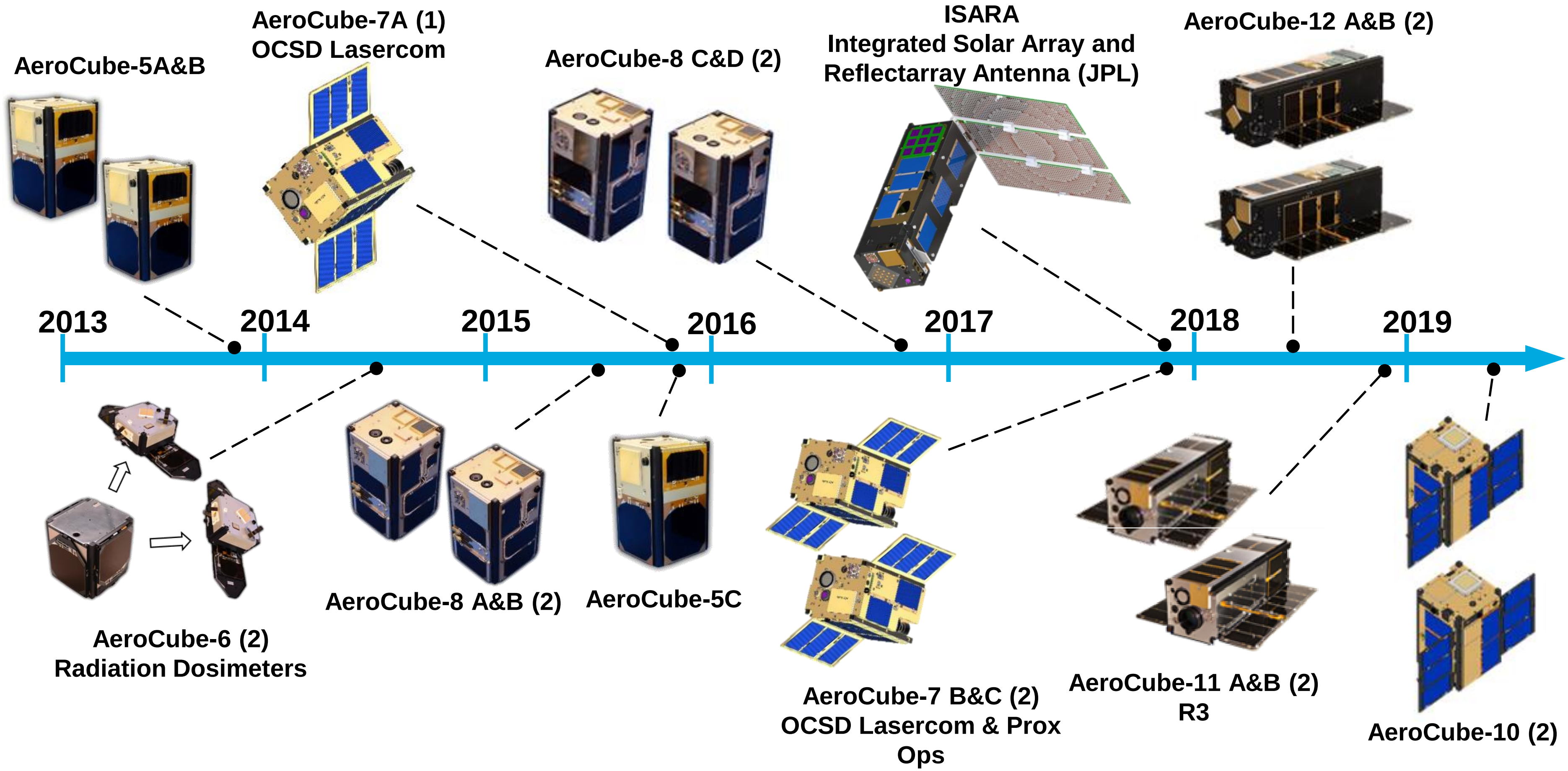


2015 Small Satellite Market Observations, StratSpace

The Small Satellite Market is Booming



The Small Satellite Market is Booming



Most smallsats fly with no propulsion at all

You cannot maintain a set orbit

You cannot increase altitude or change inclination

Limits flexibility and capabilities

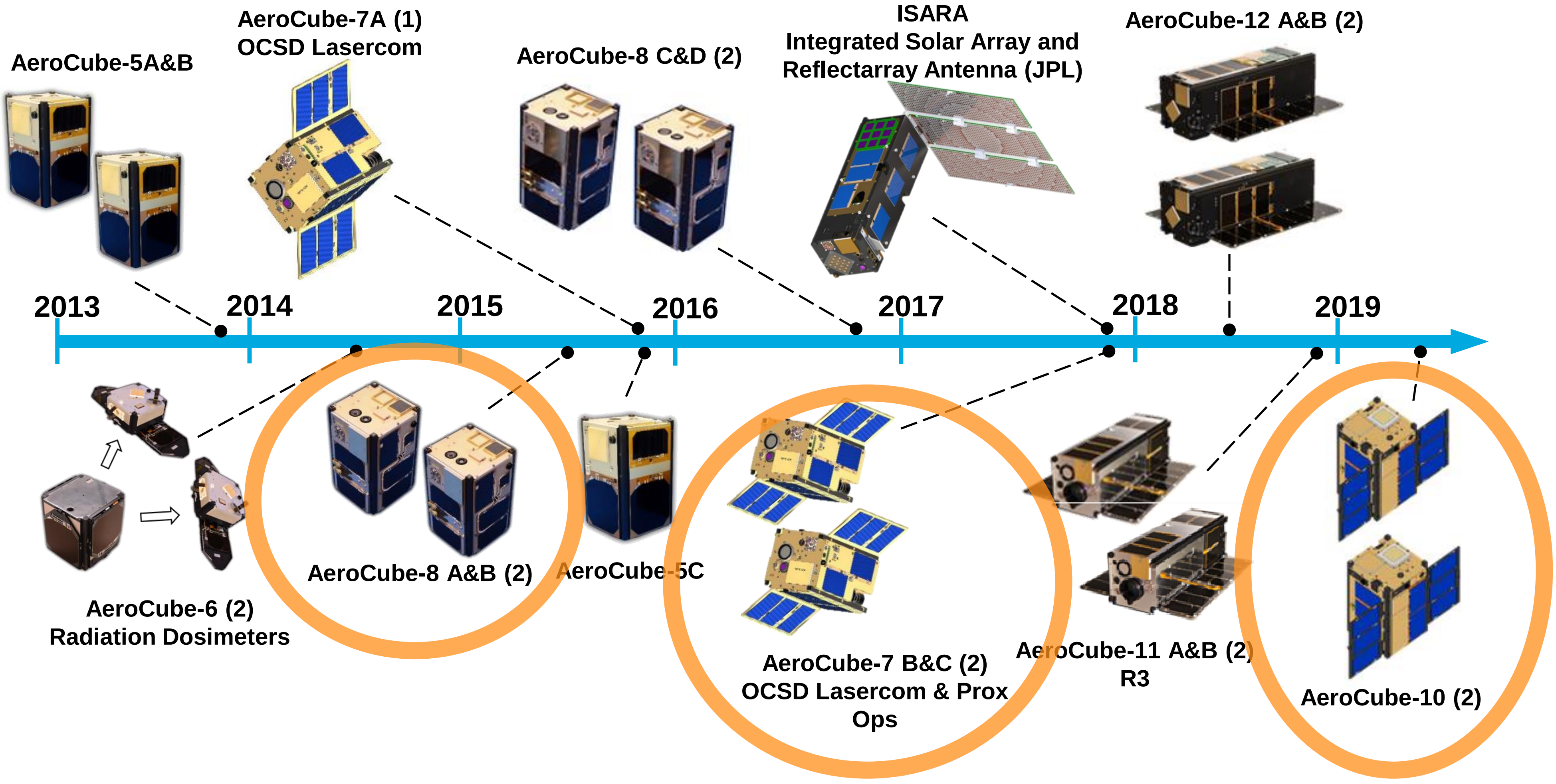
https://www.planet.com/flock1/

If we want to replace large, expensive satellites

We need to develop new propulsion systems

that work on a small scale

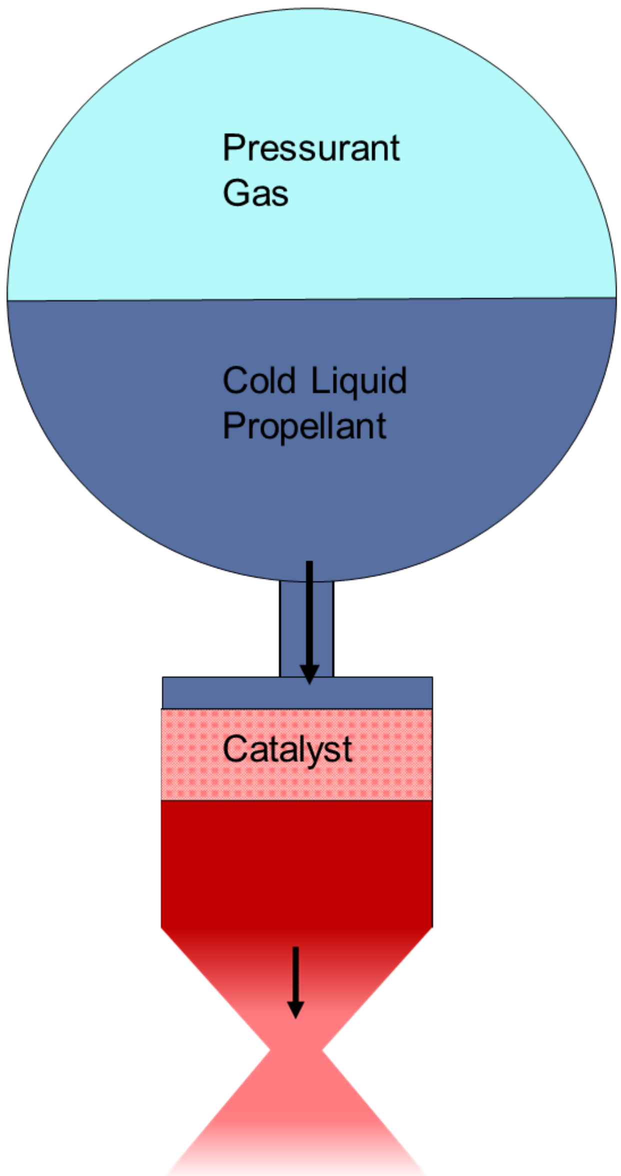
The Small Satellite Market is Booming



Flight Tested Small Satellite Propulsion Systems

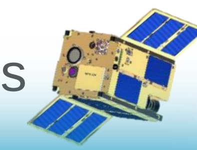
	Prop. Type / Manufacturer	Propellant	Thrust	I_{sp}	Satellite
Cold Gas	Cold Gas / SFL	Sulfur hexafluoride	12.5-50 mN	45 s	CanX-2 & 5
Cold Gas	Cold Gas / Aerospace Corp	Xenon	100 mN	30 s	MEPSI-3
Cold Gas	Cold Gas / Microspace	Argon	1mN/nozzle	32 s	POPSAT-HIP1
Cold Gas	Cold Gas / TNO	Nitrogen	6 mN	69 s	Delfi-n3xt
Cold Gas	Cold Gas / Marotta	Nitrogen	2.4 N at 154 bar	70 s	NASA ST-5
Cold Gas	Warm Gas / Nanospace	Butane	1mN/nozzle	50-75 s	TW-1
Cold Gas	Warm Gas / SSTL	Butane	100 mN	45 s	SNAP-1
Cold Gas	Warm Gas / Aerospace Corp.	Water	3-5 mN	Not Reported	AeroCube OCSD
Solid	Solid Motor / Pacific Scientific	Not Reported	>1N	210 s	PacSciSat
Electric	Pulsed Plasma / Busek [4]	PTFE	500 μN	700 s	Falcon-Sat 3
Electric	Ion + Cold Gas / Univ. of Tokyo	Xenon	300 μN	1000 s	PROCYON & HODOYOSHI-4
Electric	Vacuum Arc / GWU	Metal	1-20 μN	3000 s	BRICSat-P
Electric	FEEP / Enpulsion	Indium	250 μN	4000 s	Not Reported
Monopropellant	Monoprop / ECAPS	LMP-103S	1 N	225 s	SkySat

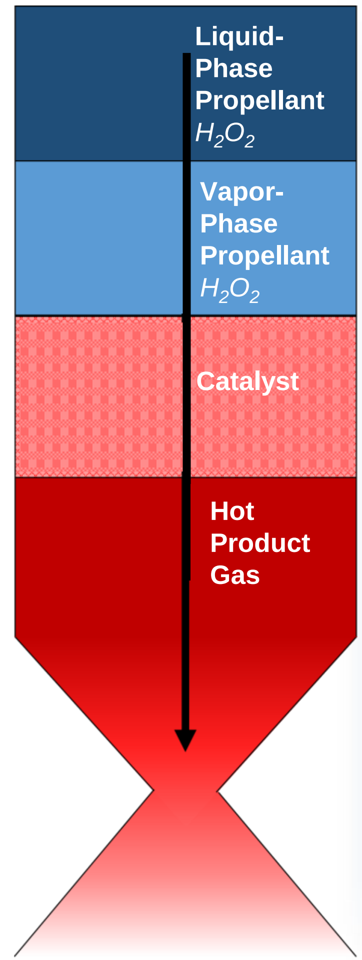
References on last slide



Hydrogen Peroxide Vapor Thruster

For Small Satellites





Controllable low thrust

Green propellant

Low pressure

Low power

Continuous thrust and pulse options

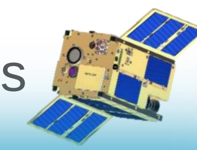
Small overall package

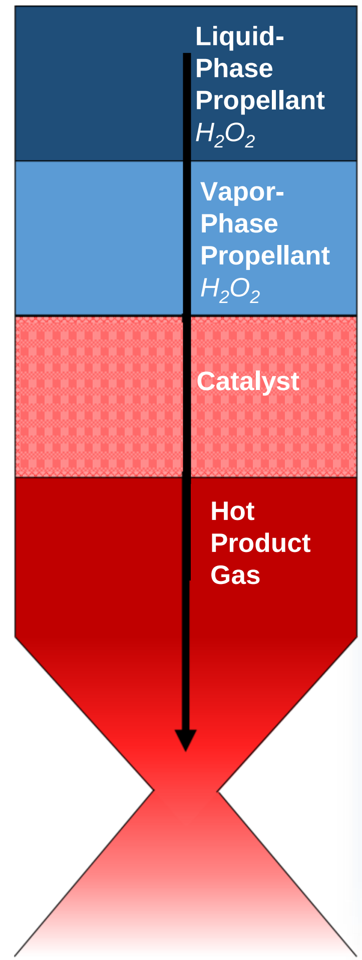
Requirements:

1. No phase separation
2. Liquid phase at ambient conditions
3. Low vapor pressure
4. Low health hazard
5. Low volatility in storage

Hydrogen Peroxide Vapor Thruster

For Small Satellites





Controllable low thrust

Green propellant

Low pressure

Low power

Continuous thrust and pulse options

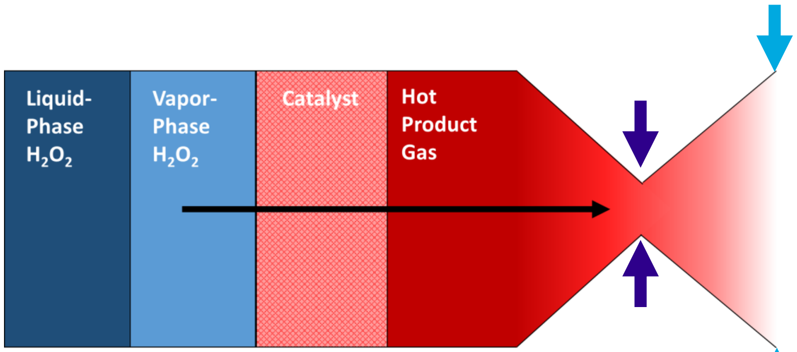
Small overall package

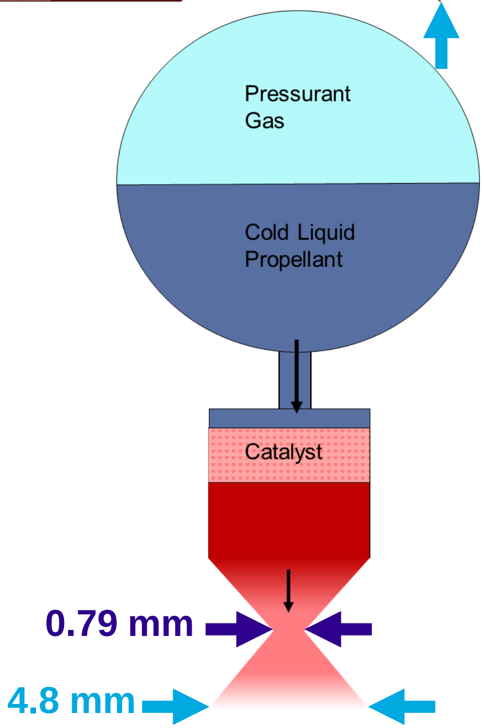
Objectives

1. **Prove the concept.**
2. **Understand propellant and catalyst behavior.**
3. **Investigate the performance and its application as a small satellite propulsion system.**

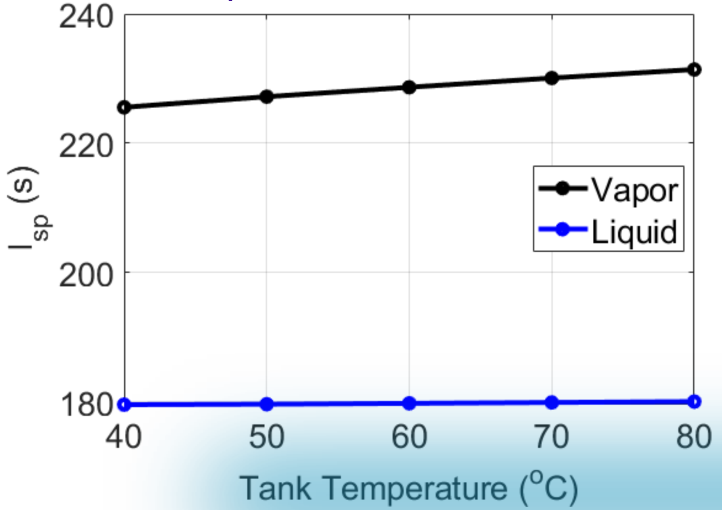
Introduction to the H_2O_2 Vapor Thruster

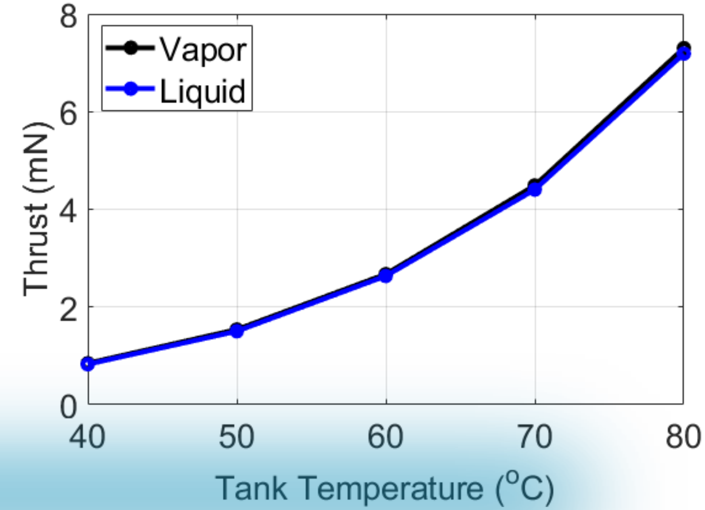
Theoretical Performance



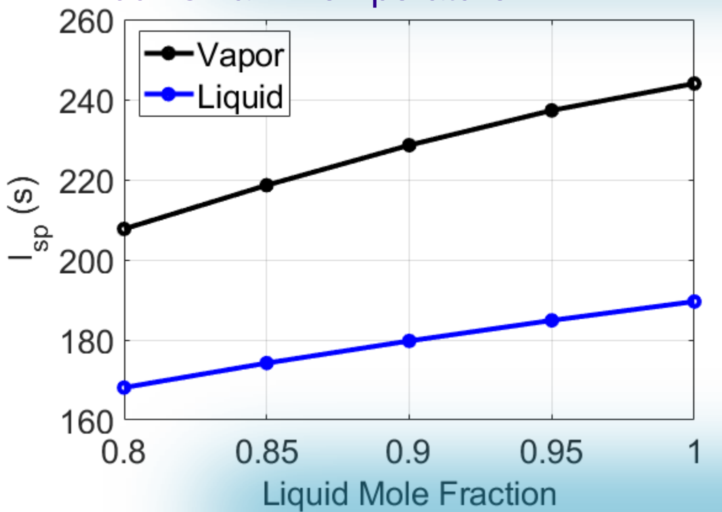


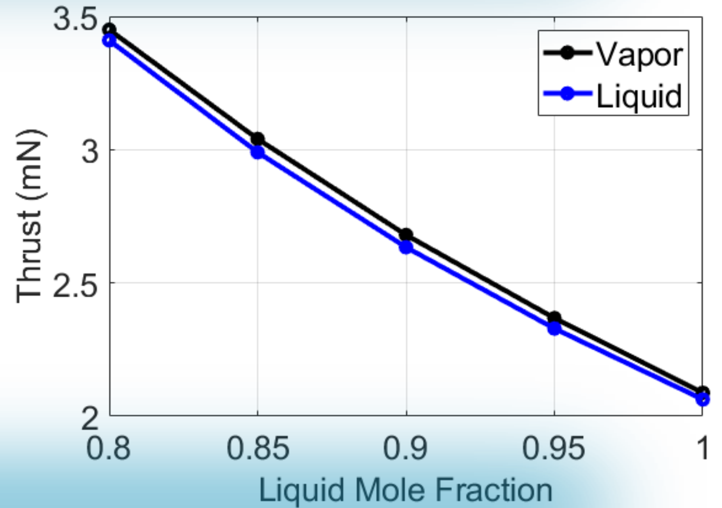
0.9 Liquid Mole Fraction





60 °C Tank Temperature



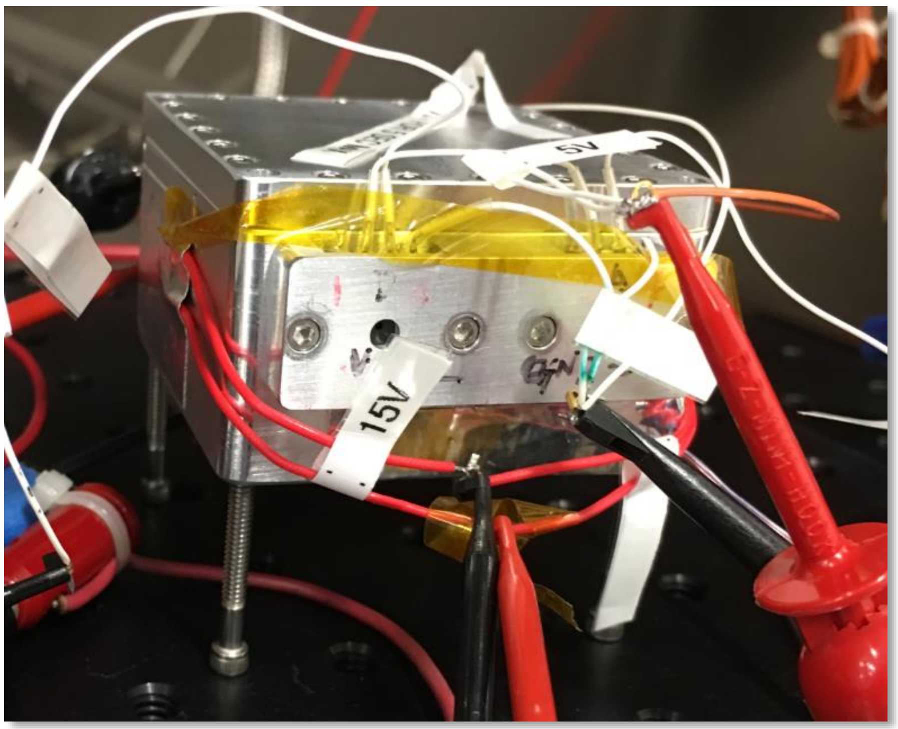


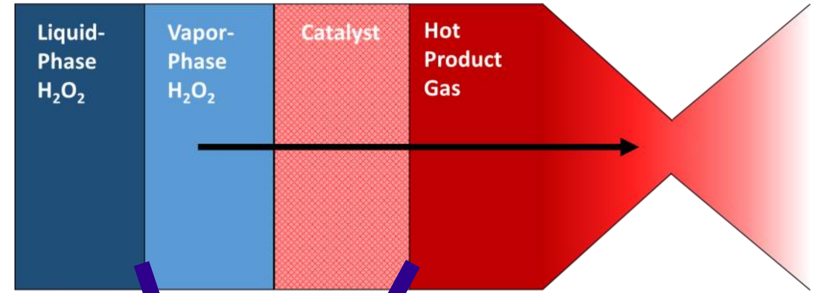
Assumptions

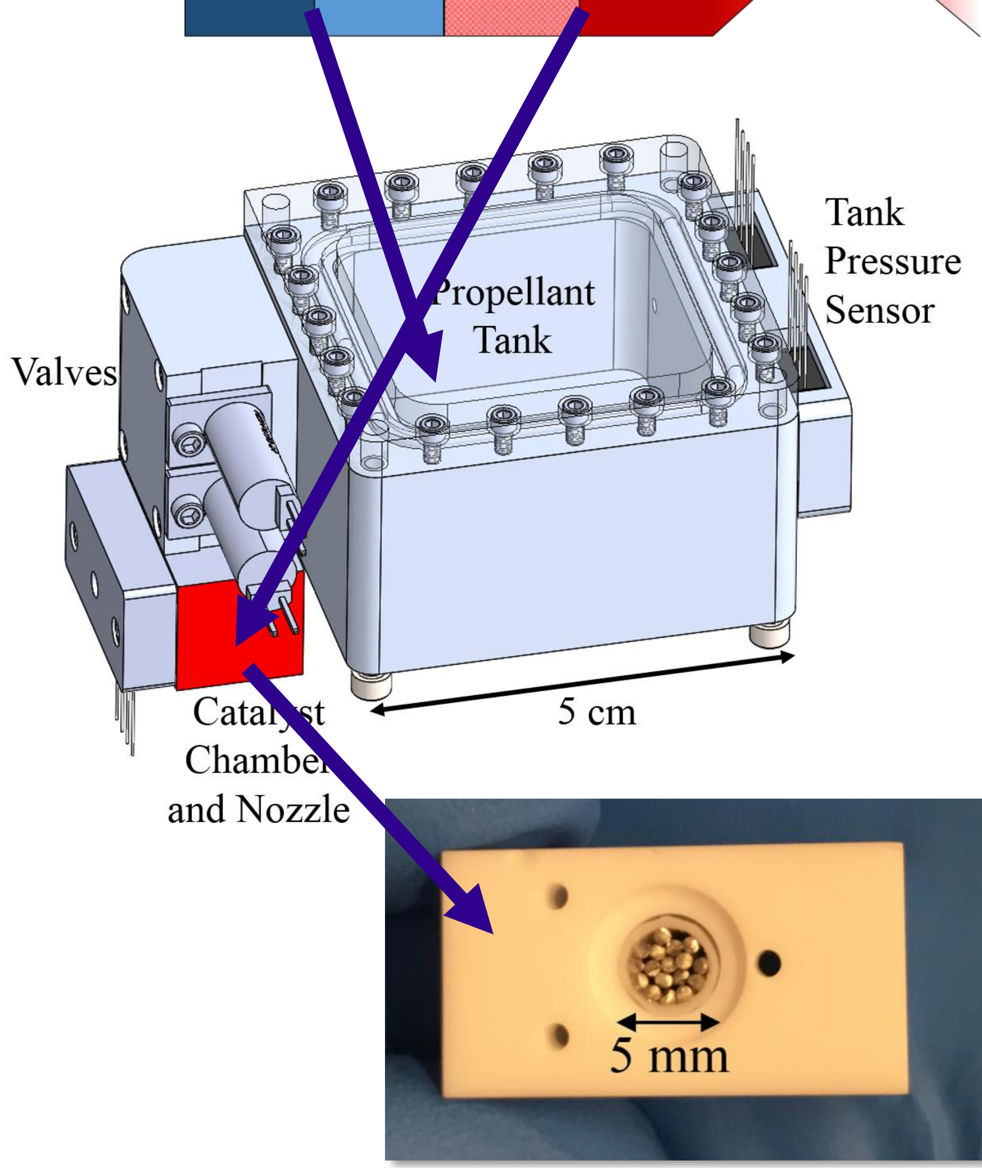
- Catalyst chamber pressure = H_2O_2 vapor pressure
- Steady flow
- Constant pressure decomposition
- Isentropic expansion
- Choked flow
- Negligible boundary layer

Introduction to the H_2O_2 Vapor Thruster

Prototype 1 (of 3): Proof of Concept



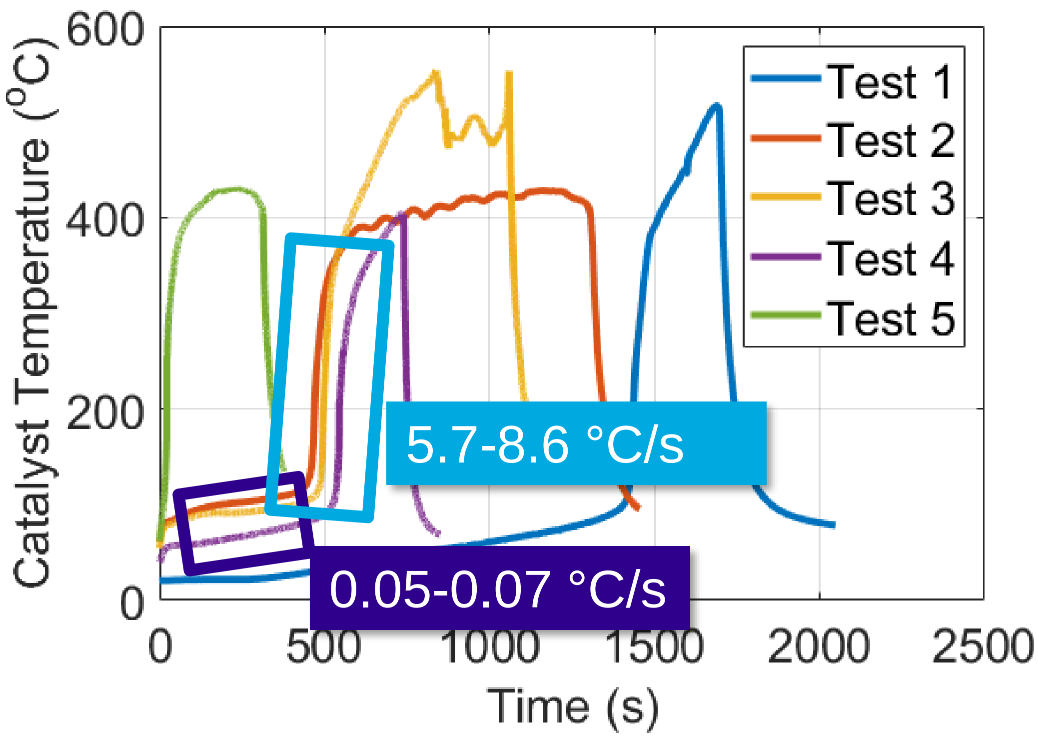


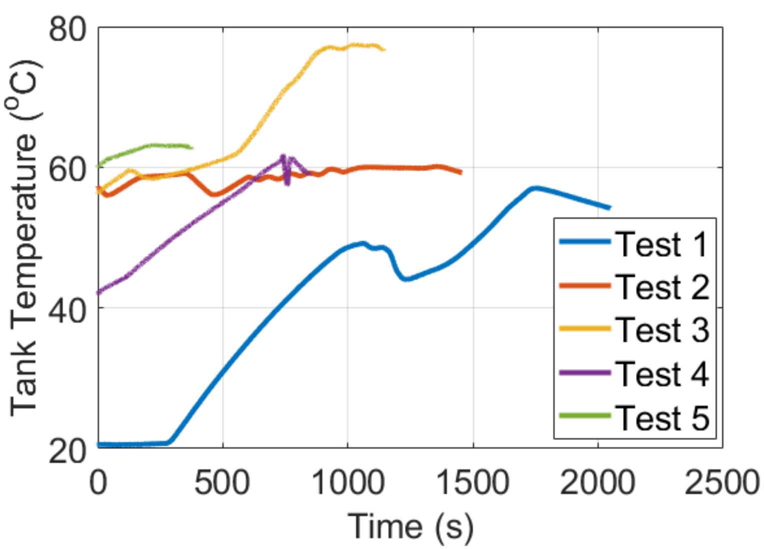


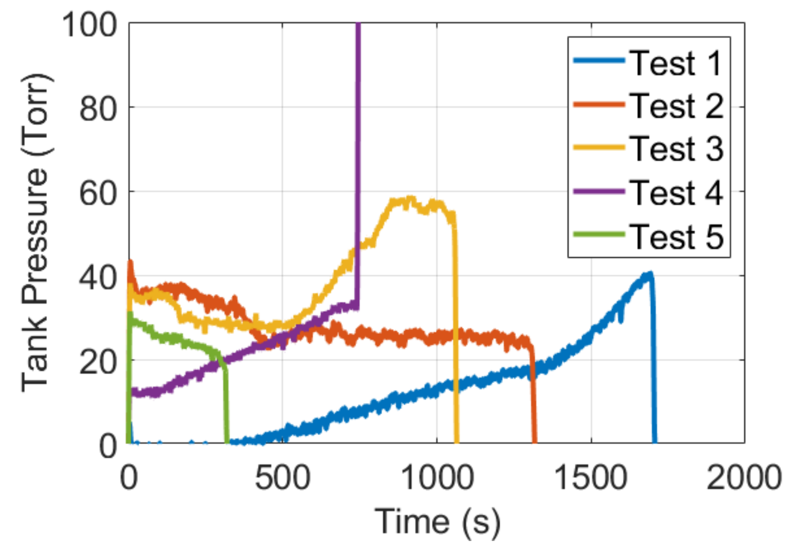
Introduction to the H_2O_2 Vapor Thruster

Prototype 1: Test Results

Test	H2O2 Conc. (by mass)
1	79%
2	79%
3	79%
4	79%
5	90%

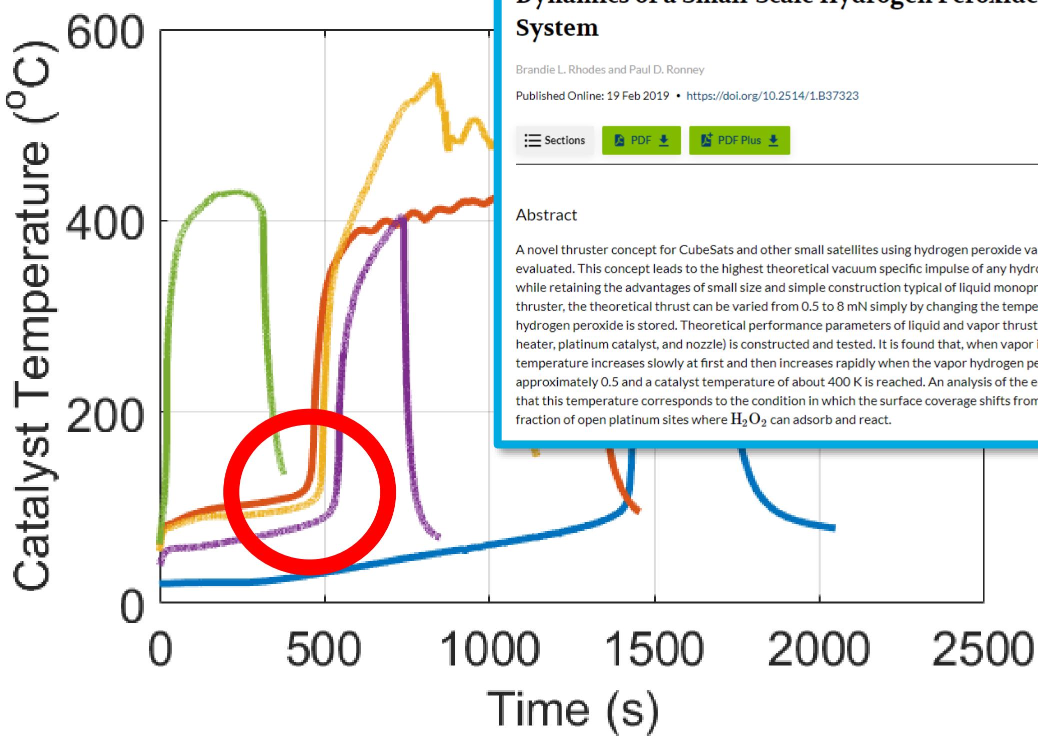


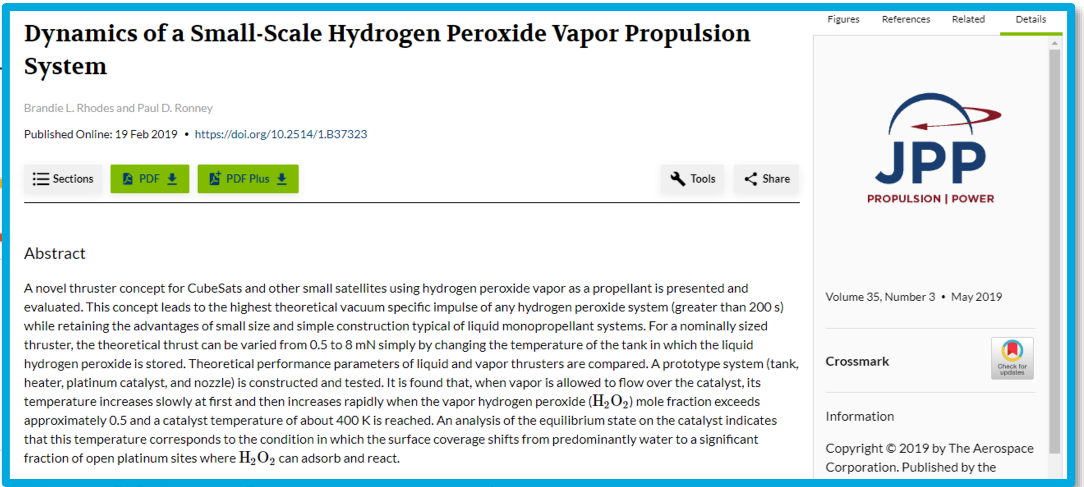




Introduction to the H_2O_2 Vapor Thruster

Prototype 1: Test Results





Figures References Related Details

Dynamics of a Small-Scale Hydrogen Peroxide Vapor Propulsion System

Brandie L. Rhodes and Paul D. Ronney

Published Online: 19 Feb 2019 • https://doi.org/10.2514/1.B37323

Sections PDF PDF Plus Tools Share

Abstract

A novel thruster concept for CubeSats and other small satellites using hydrogen peroxide vapor as a propellant is presented and evaluated. This concept leads to the highest theoretical vacuum specific impulse of any hydrogen peroxide system (greater than 200 s) while retaining the advantages of small size and simple construction typical of liquid monopropellant systems. For a nominally sized thruster, the theoretical thrust can be varied from 0.5 to 8 mN simply by changing the temperature of the tank in which the liquid hydrogen peroxide is stored. Theoretical performance parameters of liquid and vapor thrusters are compared. A prototype system (tank, heater, platinum catalyst, and nozzle) is constructed and tested. It is found that, when vapor is allowed to flow over the catalyst, its temperature increases slowly at first and then increases rapidly when the vapor hydrogen peroxide (H_2O_2) mole fraction exceeds approximately 0.5 and a catalyst temperature of about 400 K is reached. An analysis of the equilibrium state on the catalyst indicates that this temperature corresponds to the condition in which the surface coverage shifts from predominantly water to a significant fraction of open platinum sites where H_2O_2 can adsorb and react.

JPP PROPULSION | POWER

Volume 35, Number 3 • May 2019

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Information

H_2O_2 Vapor Mole Fraction > 0.5

Catalyst temperature > 130 °C

Hydrogen Peroxide Vapor Reaction Rates

$$H_2O_2 \xrightarrow{k} H_2O + \frac{1}{2}O_2$$

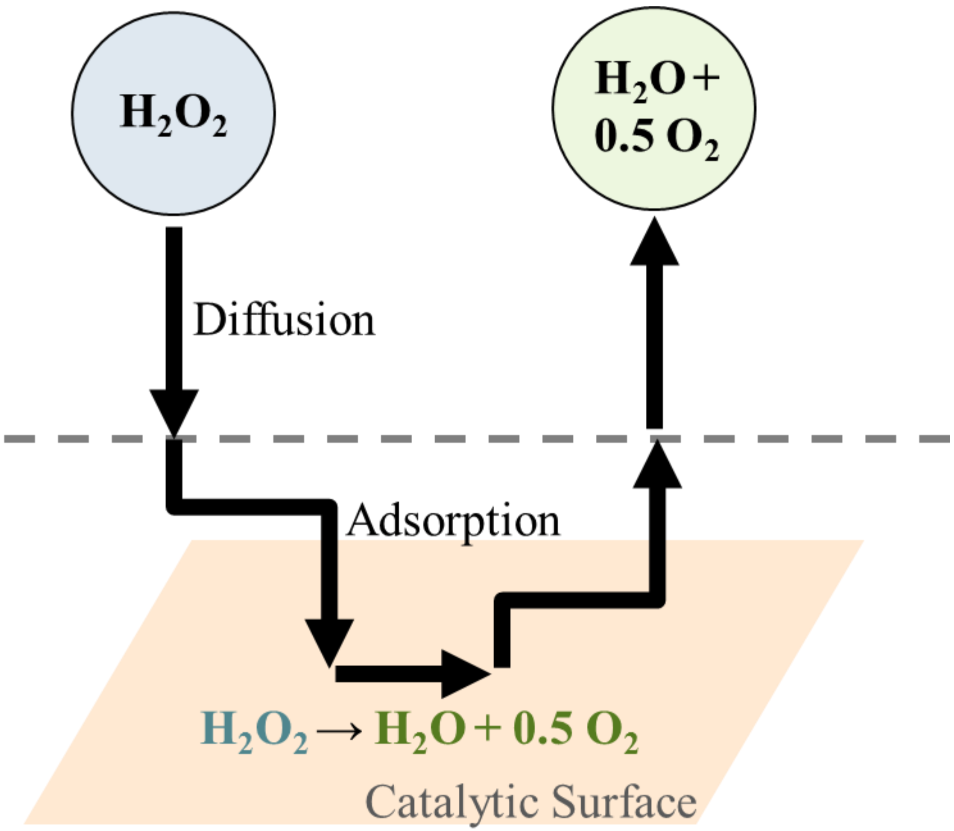
Catalytic (Surface) Decomposition

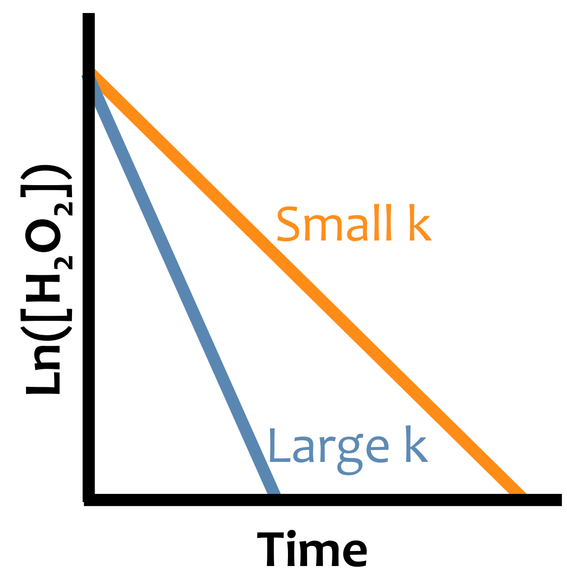
Ga

Catalysts

- Platinum
- Silver
- Palladium
- Manganese dioxide
- Copper

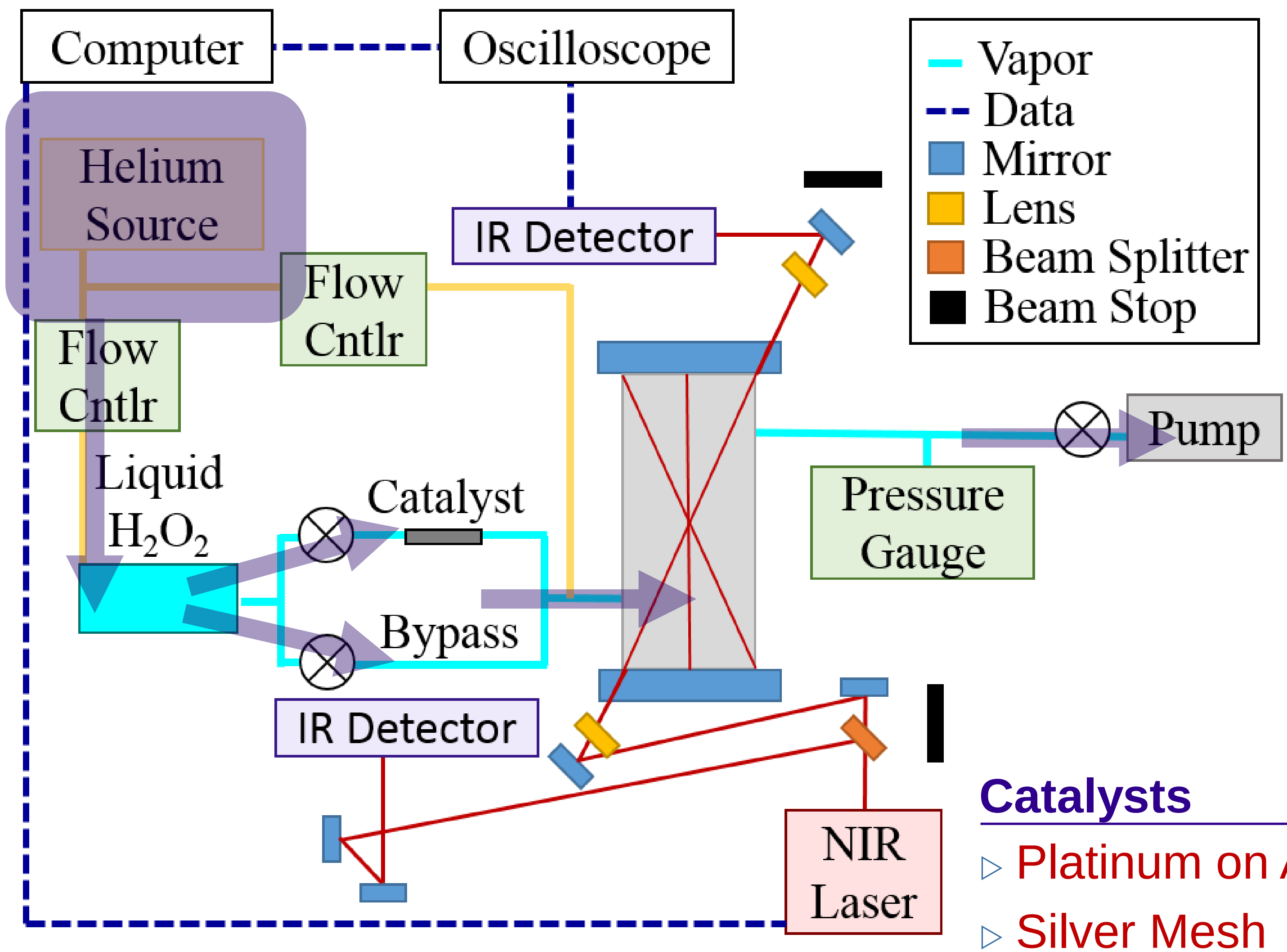
- Wire
- Mesh
- Powder
- Pellets





Hydrogen Peroxide Vapor Diagnostic - Reprise

Reaction Rate Experiment

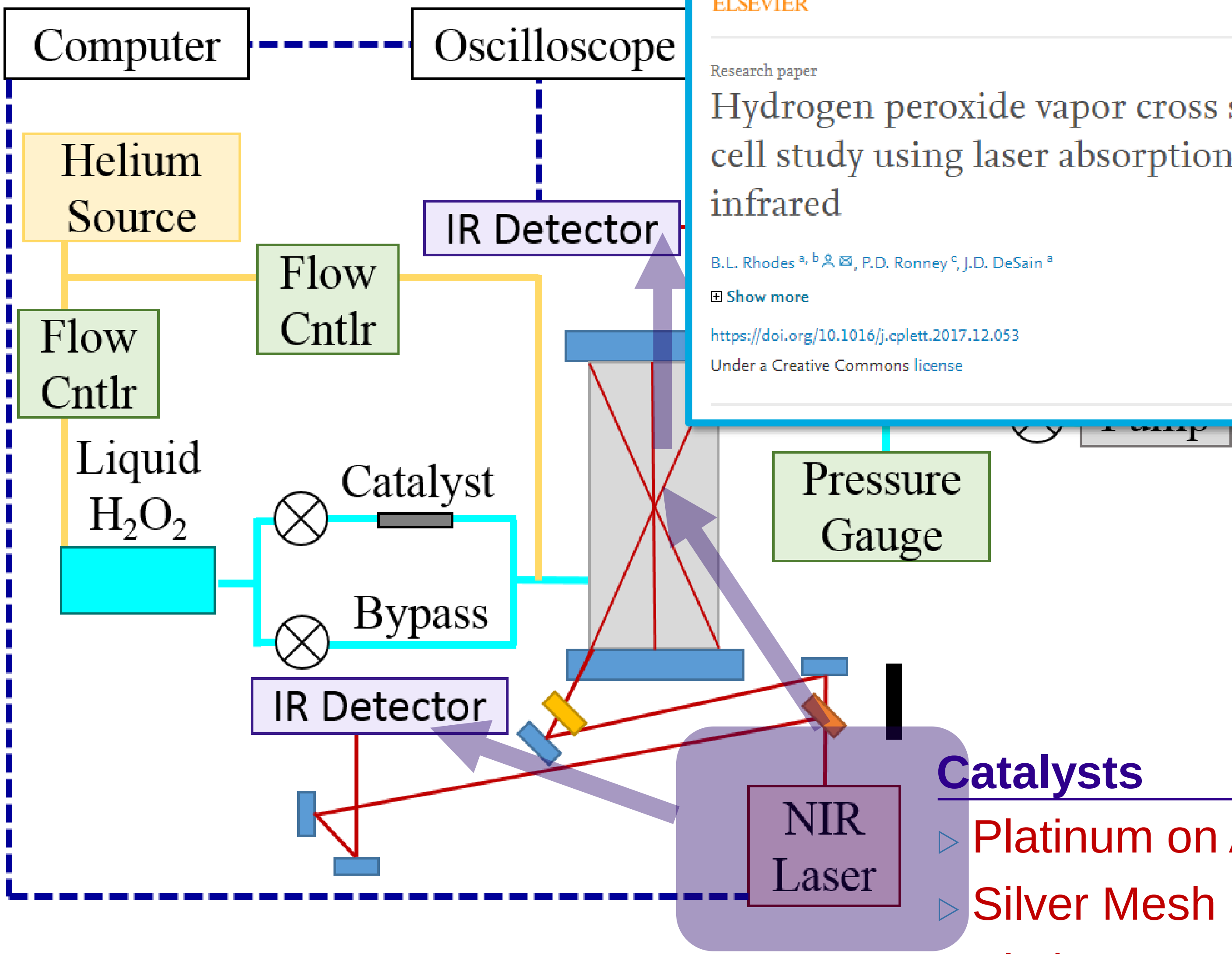


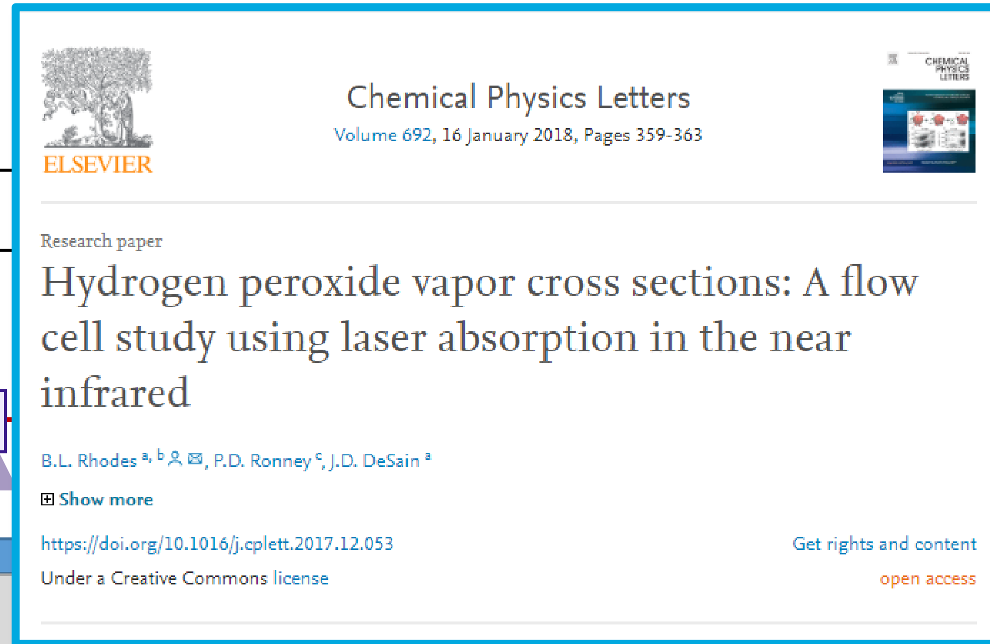
Catalysts

- Platinum on Alumina Spheres
- Silver Mesh
- Platinum Mesh

Hydrogen Peroxide Vapor Diagnostic - Reprise

Reaction Rate Experiment





ELSEVIER

Chemical Physics Letters
Volume 692, 16 January 2018, Pages 359-363

Research paper

Hydrogen peroxide vapor cross sections: A flow cell study using laser absorption in the near infrared

B.L. Rhodes [a, b], P.D. Ronney [c], J.D. DeSain [a]

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https://doi.org/10.1016/j.cplett.2017.12.053

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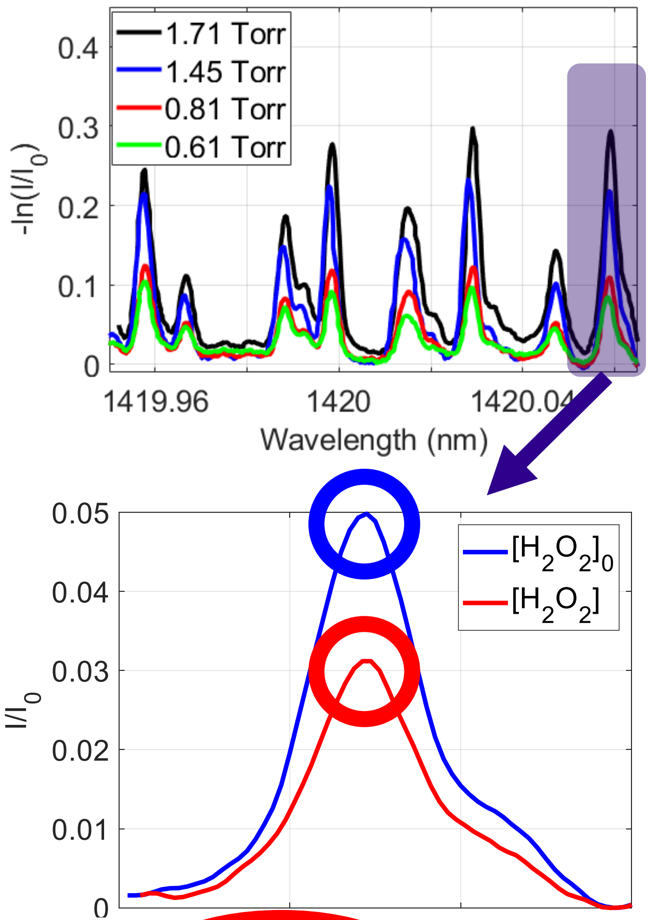
Catalysts

- Platinum on Alumina Spheres
- Silver Mesh
- Platinum Mesh

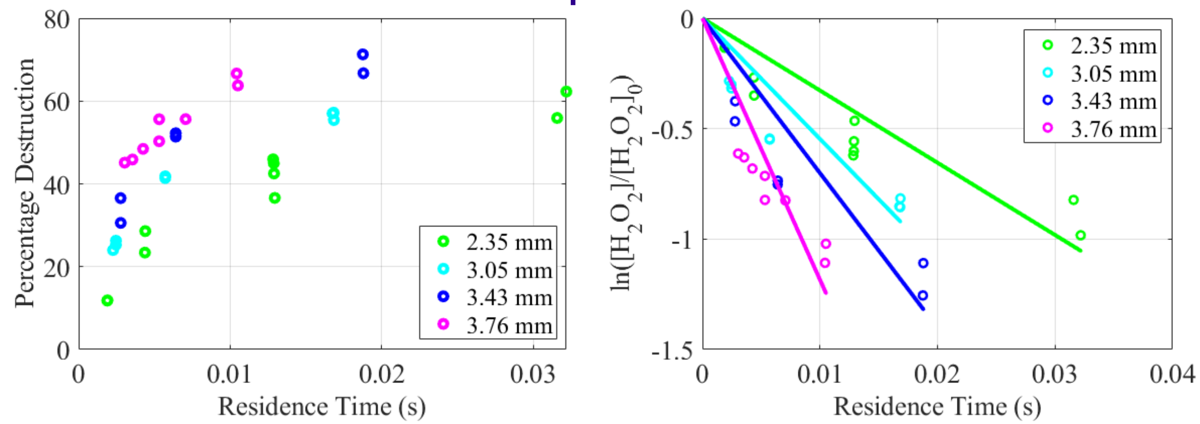
Hydrogen Peroxide Vapor Reaction Rates

Experiment

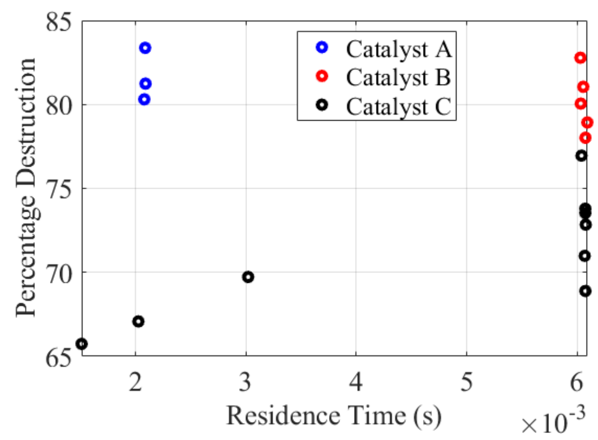


$$ln\frac{[H_2O_2]}{[H_2O_2]_0} = -kt$$

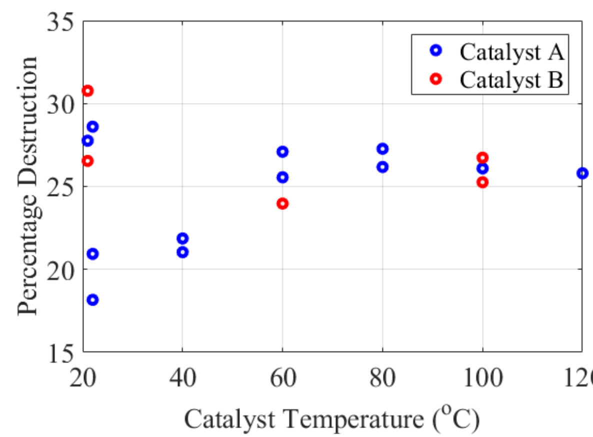
Platinum on Alumina Spheres



Silver Mesh



Platinum Mesh



Hydrogen Peroxide Vapor Reaction Rates

Multiphysics model

Model Assumptions

- ▷ Gas-only
- ▷ Axisymmetric

Catalyst	Destruction	BR* Rate	COMSOL Rate	
Platinum on Alumina Sphere (3.05 mm)	56.5%	55 s^{-1}	1.74 s^{-1}	3
Silver Mesh	73.7%	398 s^{-1}	10.7 s^{-1}	4.0 x 10^{-3} m/s
Platinum Mesh	25.3%	26.8 s^{-1}	1.42 s^{-1}	3

Catalytic Decomposition of Low Pressure Hydrogen Peroxide Vapor on Platinum and Silver: Kinetics and Implications

Brandie L. Rhodes, Paul Ronney and John DeSain

AIAA 2019-1237
Session: Heterogeneous Combustion
Published Online: 6 Jan 2019 • https://doi.org/10.2514/6.2019-1237

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Figures References Related Details

SCITECH FORUM

AIAA Scitech 2019 Forum
7-11 January 2019
San Diego, California
https://doi.org/10.2514/6.2019-1237

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Topics

Catalytic Decomposition of Low Pressure Hydrogen Peroxide Vapor on Platinum and Silver: Kinetics and Implications

Brandie L. Rhodes
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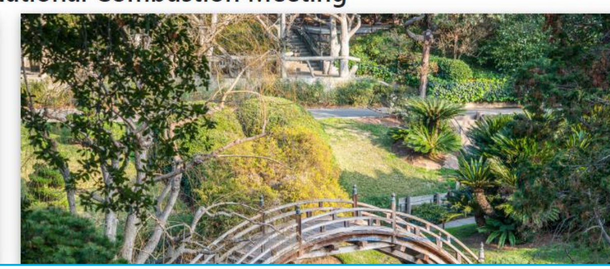
John D. DeSain
The Aerospace Corporation, El Segundo, CA, 90245

11th US National Combustion Meeting

WSSCI
Western States Section Combustion Institute

March 24-27, 2019
Pasadena, CA, USA



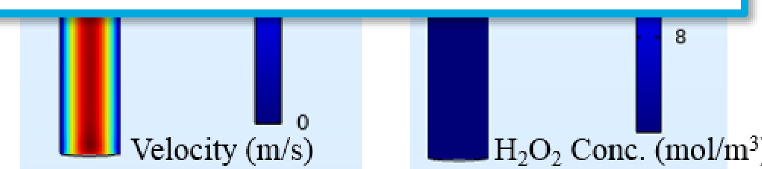
Heterogeneous Catalysis of Hydrogen Peroxide Vapor on Platinum

Brandie L. Rhodes[1,2,*], *Paul D. Ronney*[2], *and John D. DeSain*[1]

[1]*The Aerospace Corporation, El Segundo, CA, 90245*
[2]*Viterbi School of Engineering, University of Southern California, Los Angeles, California, 90089*
[*]*Corresponding author:* brandie.l.rhodes@aero.org

$$ln\frac{[H_2O_2]}{[H_2O_2]_0} = -kt$$

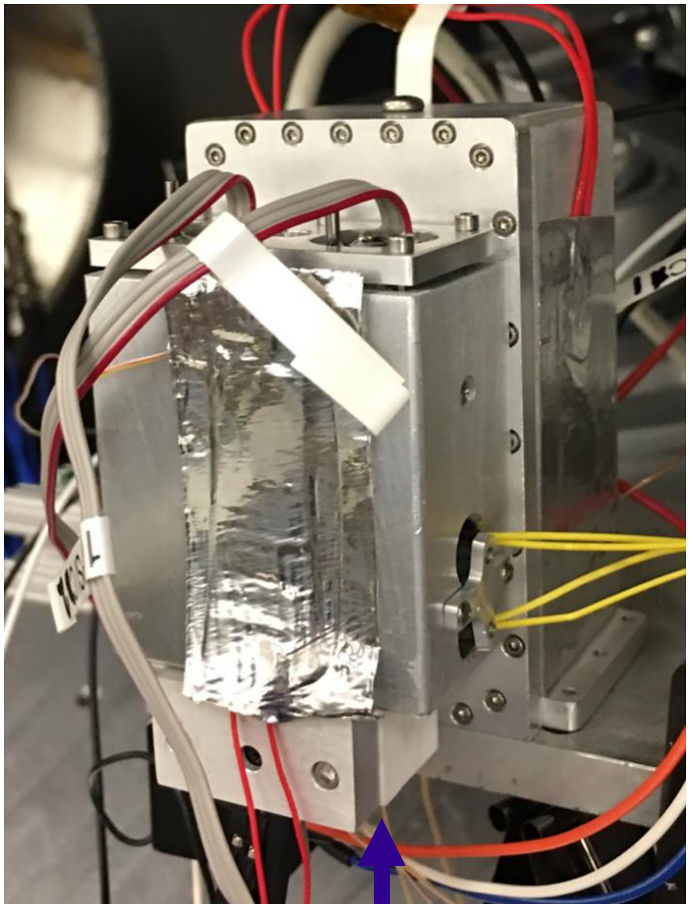
$$ERC = k\left(\frac{V}{SA}\right)$$

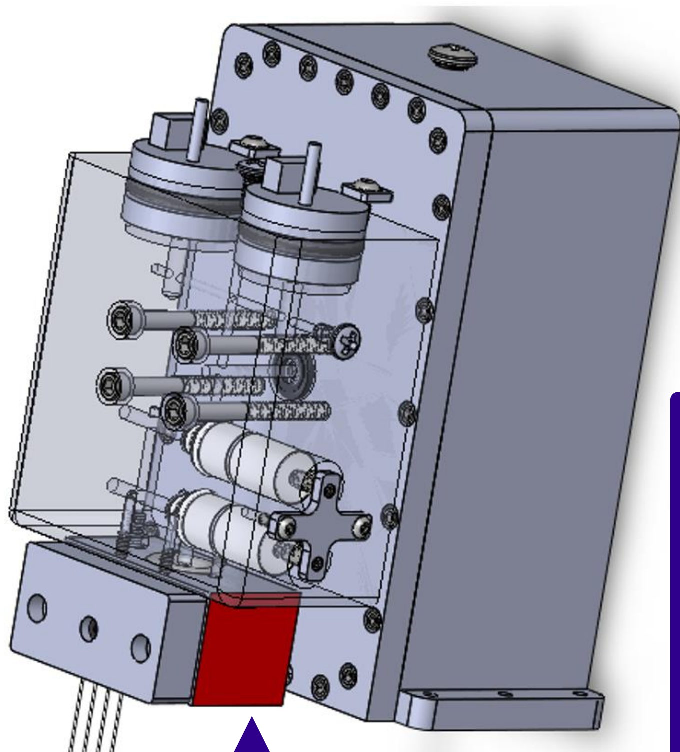


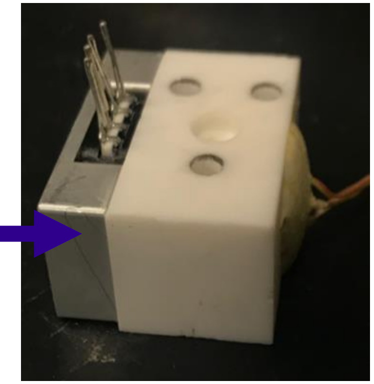
* BR = Batch Reactor
** ERC = Engineering Rate Constant

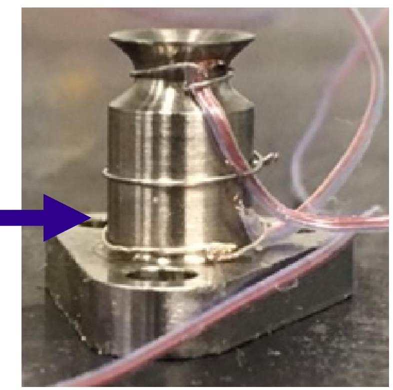
Performance Optimization

Prototype 2 (of 3): Focus on Catalyst and Chamber Construction







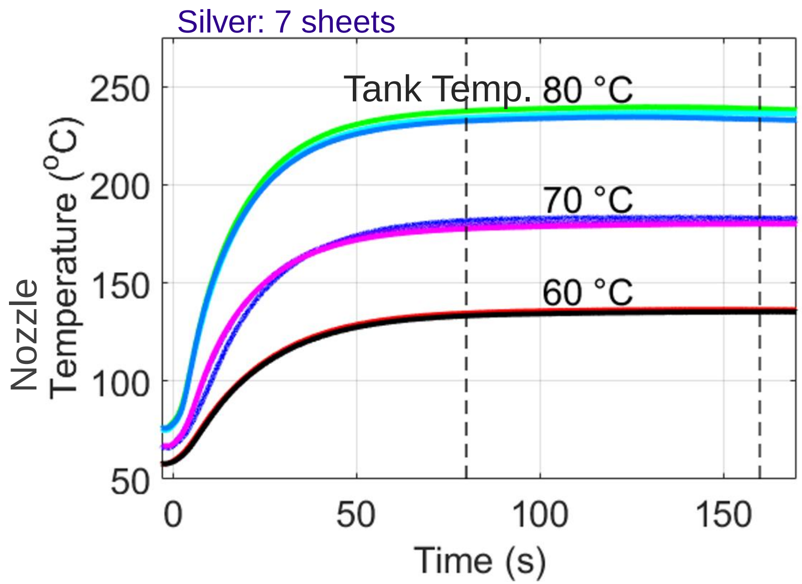


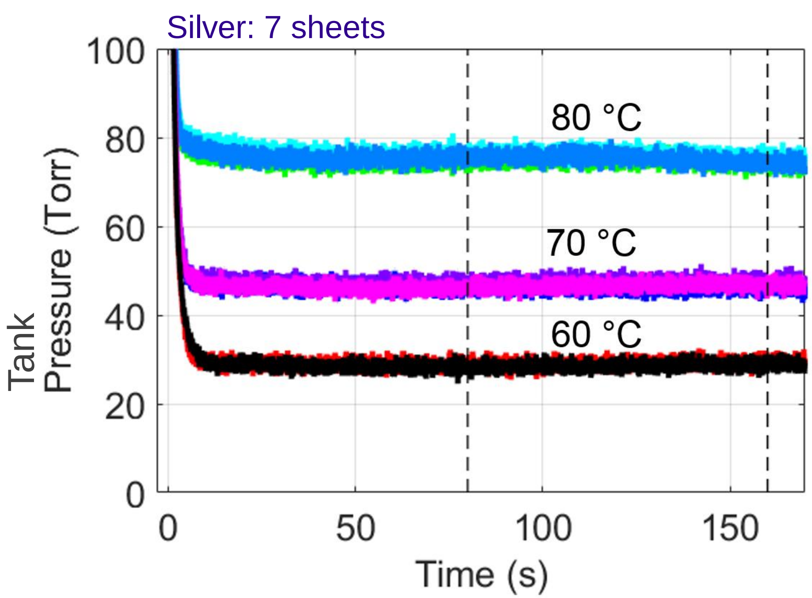
Catalysts

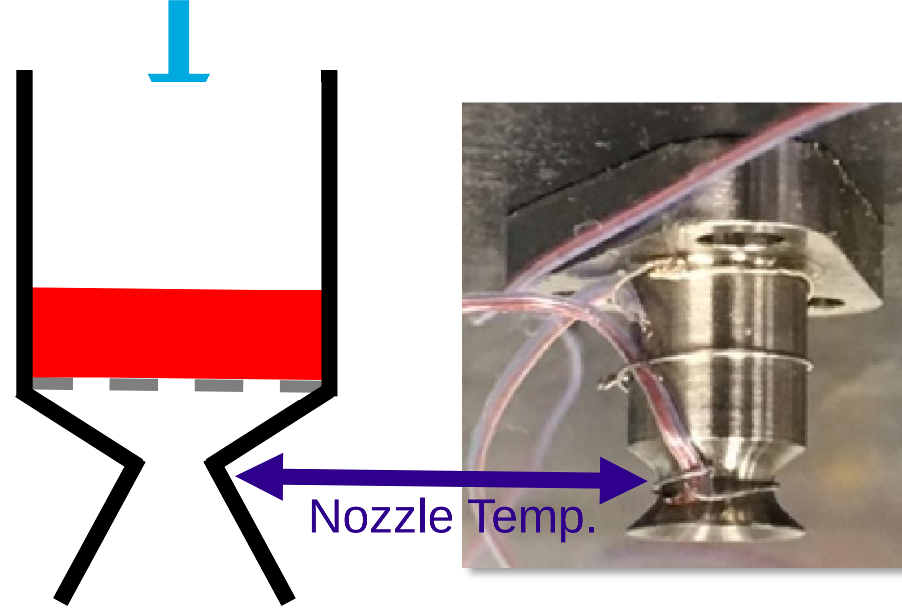
- Silver Mesh
- Platinum Mesh
- Platinum on Alumina Spheres

Performance Optimization

Prototype 2: Stainless CD* Nozzle





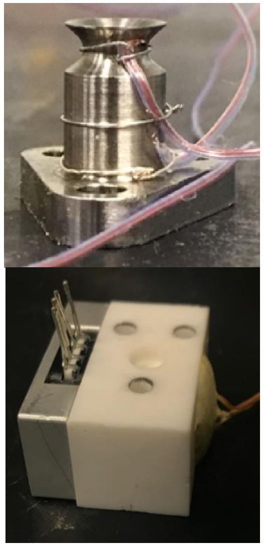


	3 Sheets	7 Sheets	14 Sheets	Spheres
60 °C Tank Temperature				
Silver	139 °C	135 °C	98 °C	
Platinum	124 °C	131 °C		114 °C
70 °C Tank Temperature				
Silver	182 °C	181 °C	130 °C	
Platinum	169 °C	176 °C		154 °C
80 °C Tank Temperature				
Silver	231 °C	236 °C	170 °C	
Platinum	220 °C	224 °C		203 °C

* CD = Converging Diverging

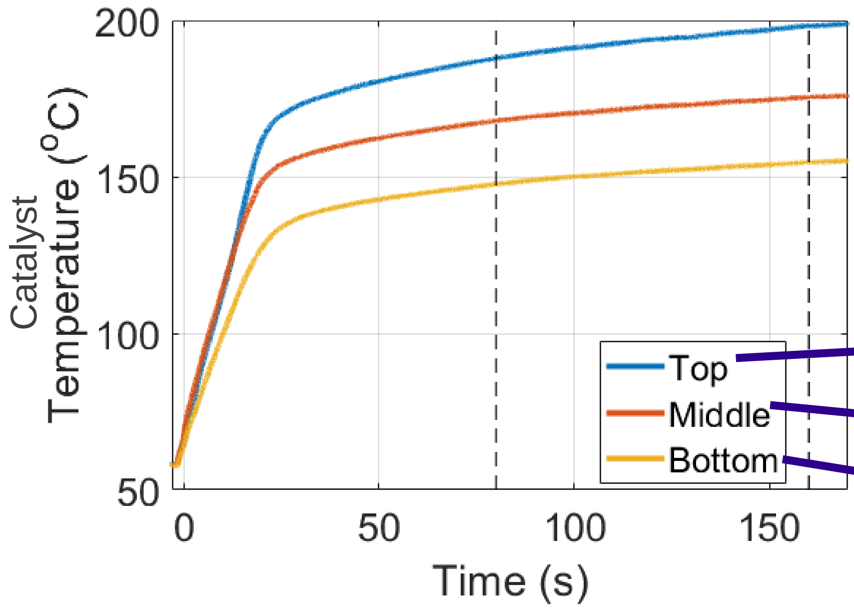
Performance Optimization

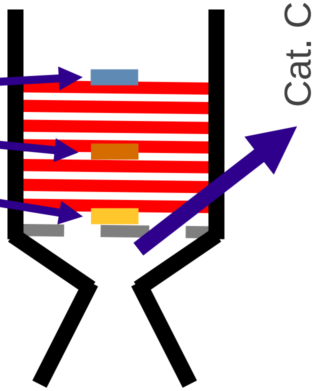
Prototype 2: Nozzle Construction

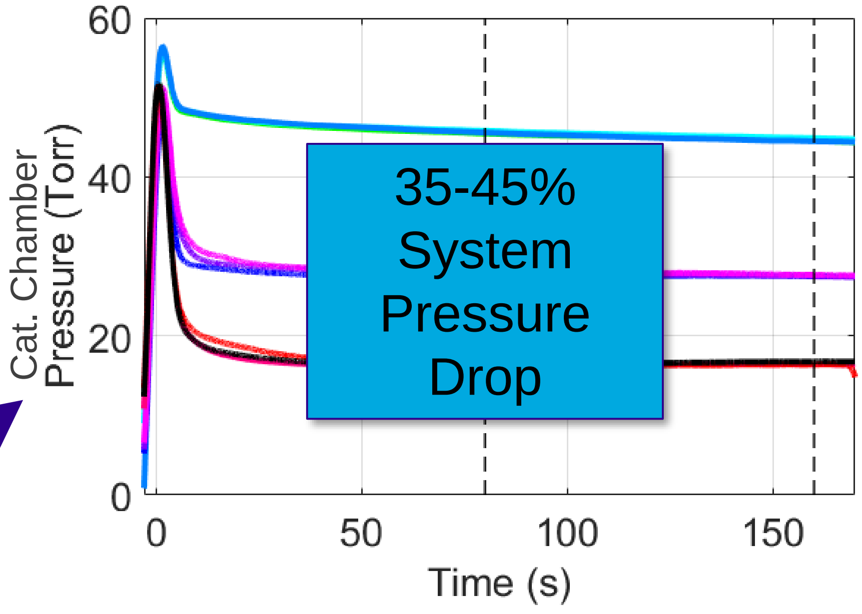


Silver: 7 sheets

Nozzle	60 °C Tank	70 °C Tank	80 °C Tank
Stainless	135 °C	181 °C	236 °C
Macor	174 °C	239 °C	304 °C

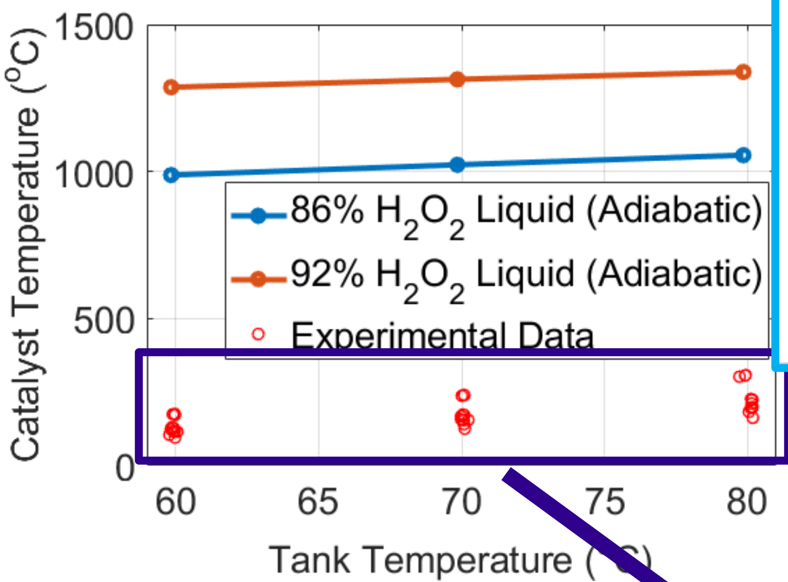






Performance Optimization

Prototype 2: Characterization of Heat Loss



Small-Scale Hydrogen Peroxide Vapor Propulsion System: Catalyst Performance and Heat Transfer

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Hydrogen peroxide vapor can be utilized as a monopropellant for low thrust, reliable propulsion. In this manuscript, a prototype system specifically designed for small satellites is detailed, with specific focus on catalyst performance and heat transfer. Three catalyst materials are evaluated: silver mesh, platinum mesh, and 0.5% platinum on alumina spheres. Silver mesh resulted in the highest catalyst chamber temperatures, specifically when 3 - 7 sheets were compacted into the chamber. Sheet numbers outside this range resulted in lower temperatures. Heat transfer proved to be the primary concern in the system, with substantial effects on catalyst temperature and overall system performance. Finite element modeling was used to identify heat paths in

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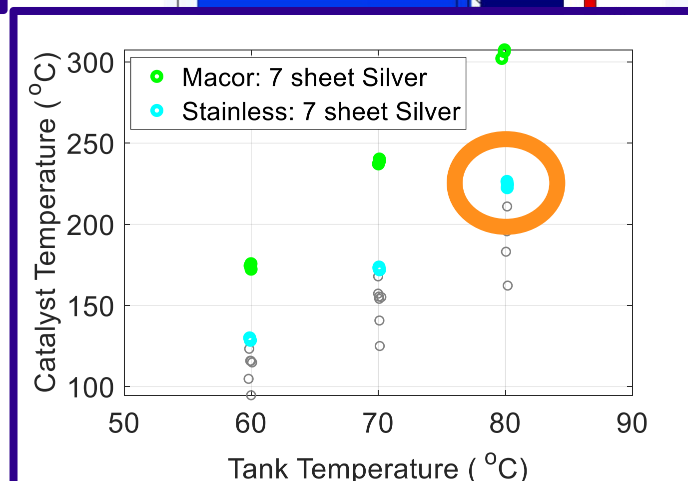
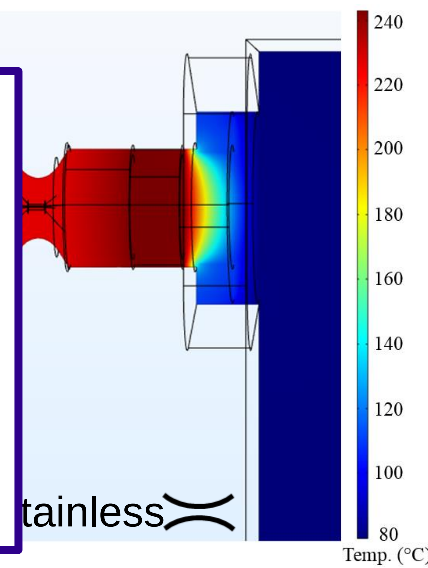
Topics

Gas Turbine Engines





Model Simplifications

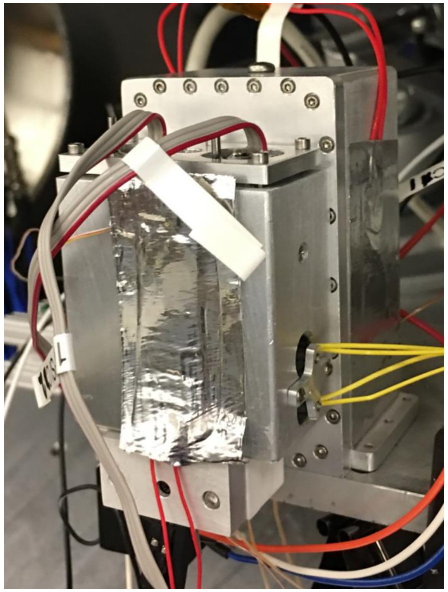
- Only heat transfer, no flow or chemical reaction
  - Reaction modeled as heat flux
- Simplified geometry with perfect thermal connection

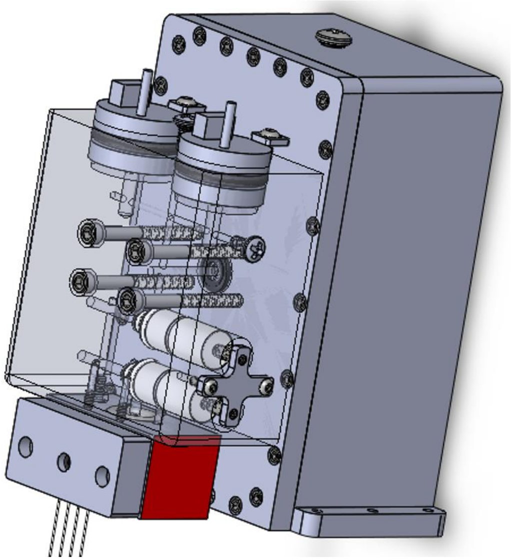
Model matches experimental data closely

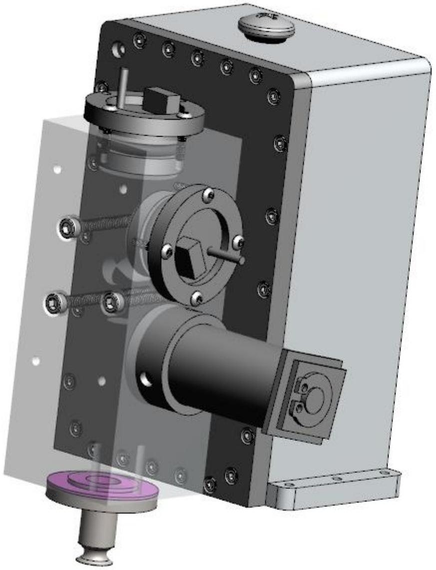
Heat Transfer Assumption	Complete	No Conduction to Manifold	No Radiation
Macor ⌣ Catalyst Temp.	199 °C	369 °C	206 °C
Stainless ⌣ Catalyst Temp.	224 °C	527 °C	233 °C

Performance Optimization

Prototype 3 (of 3): Thrust Measurement

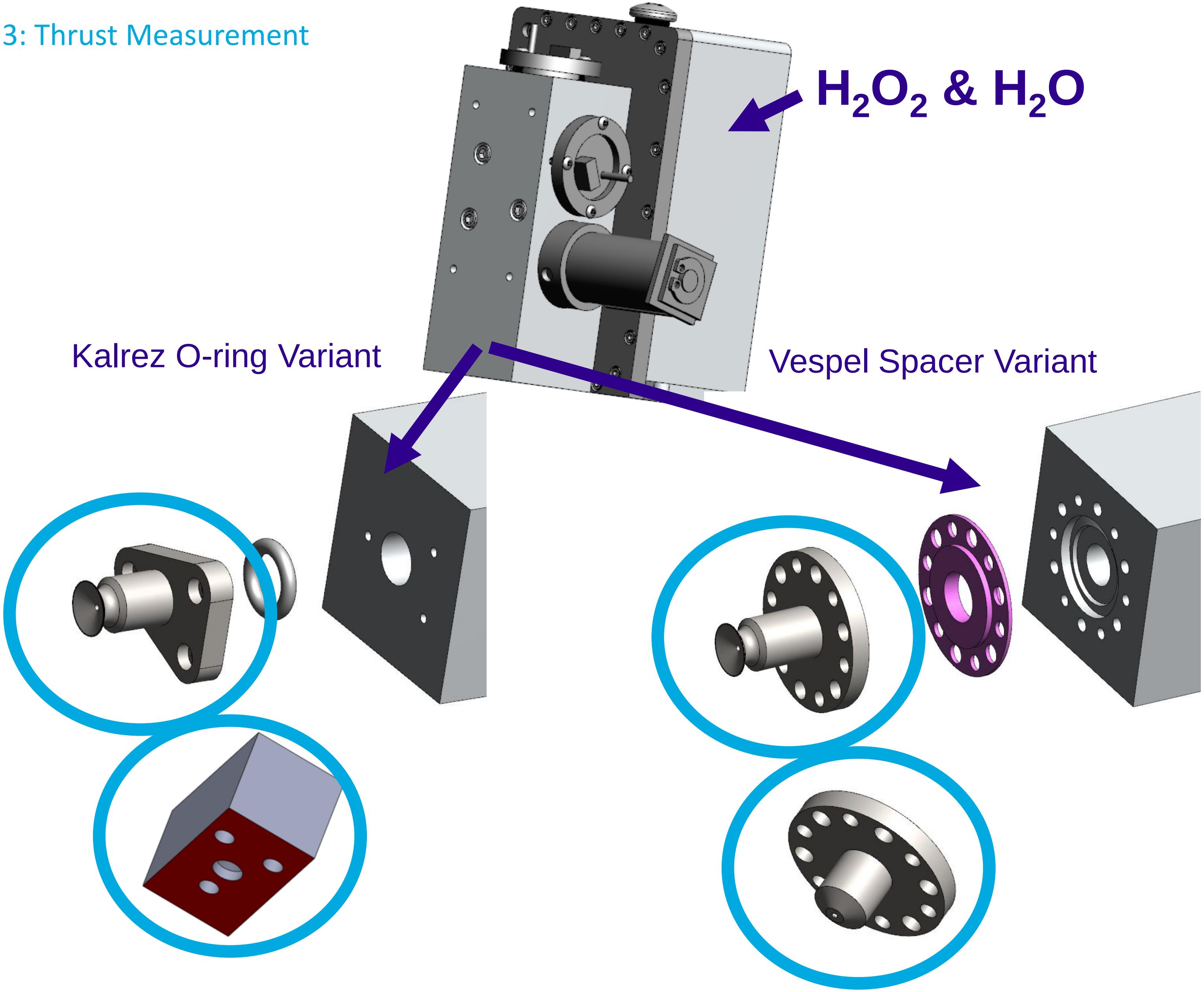






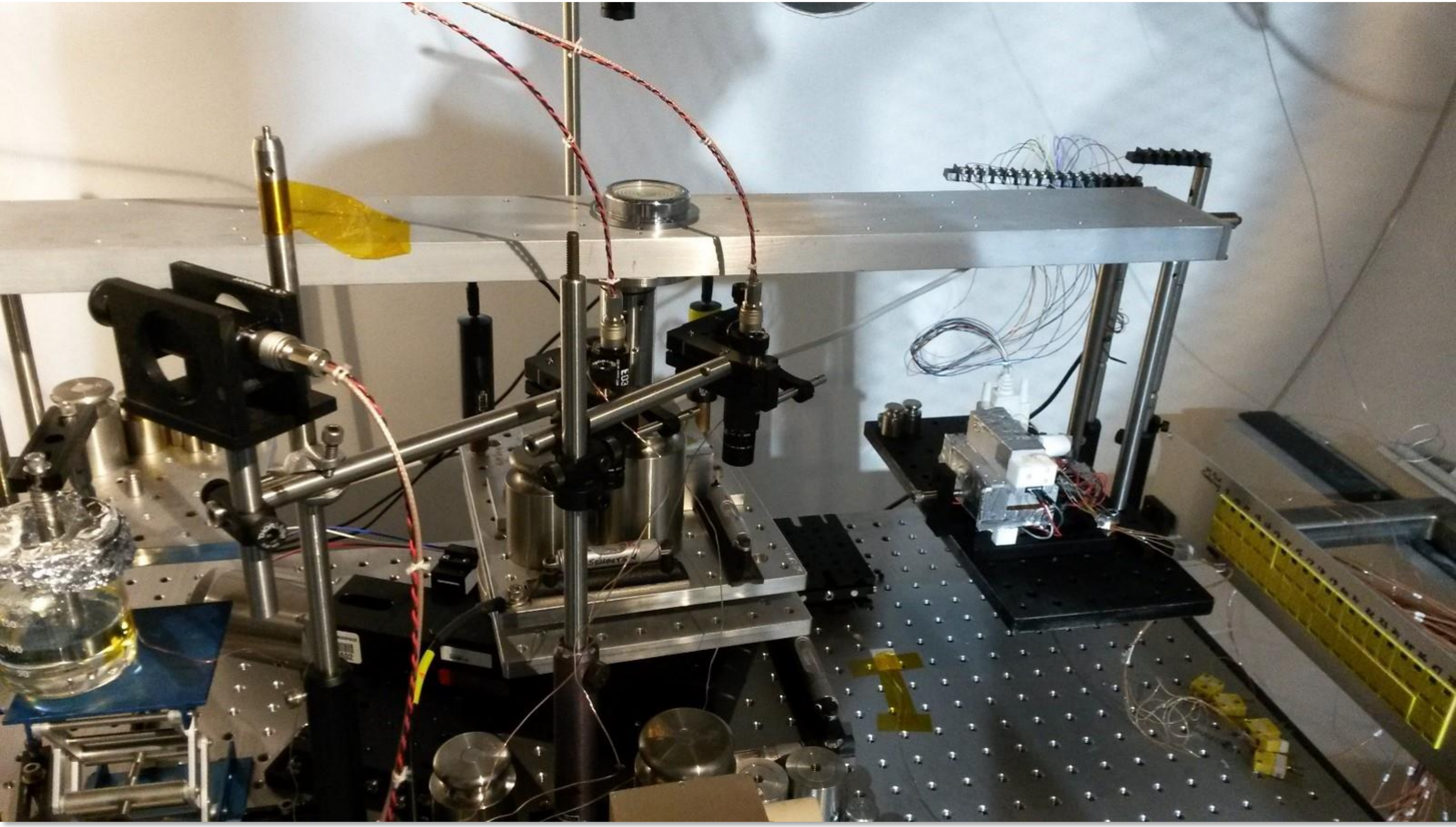
Performance Optimization

Prototype 3: Thrust Measurement



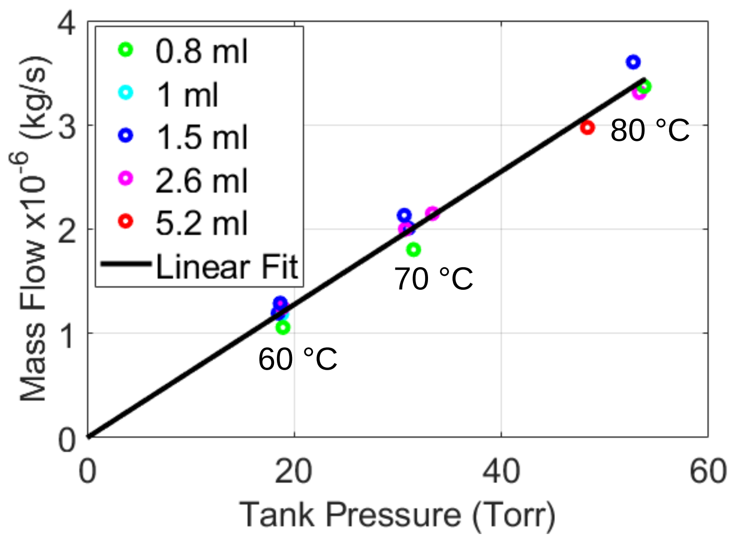
Performance Optimization

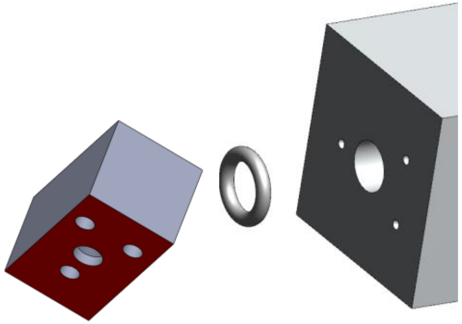
Prototype 3: Thrust Measurement

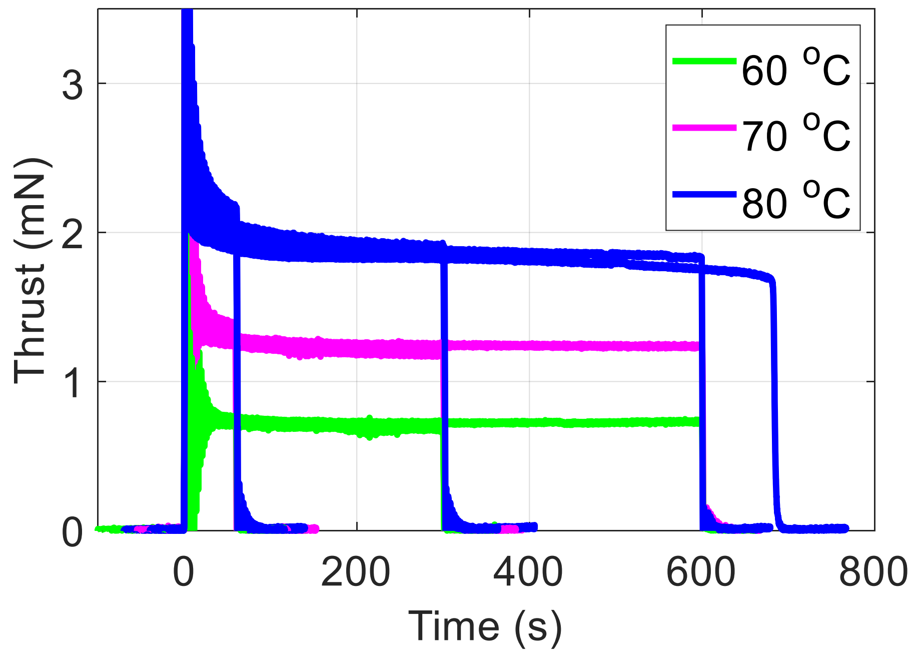


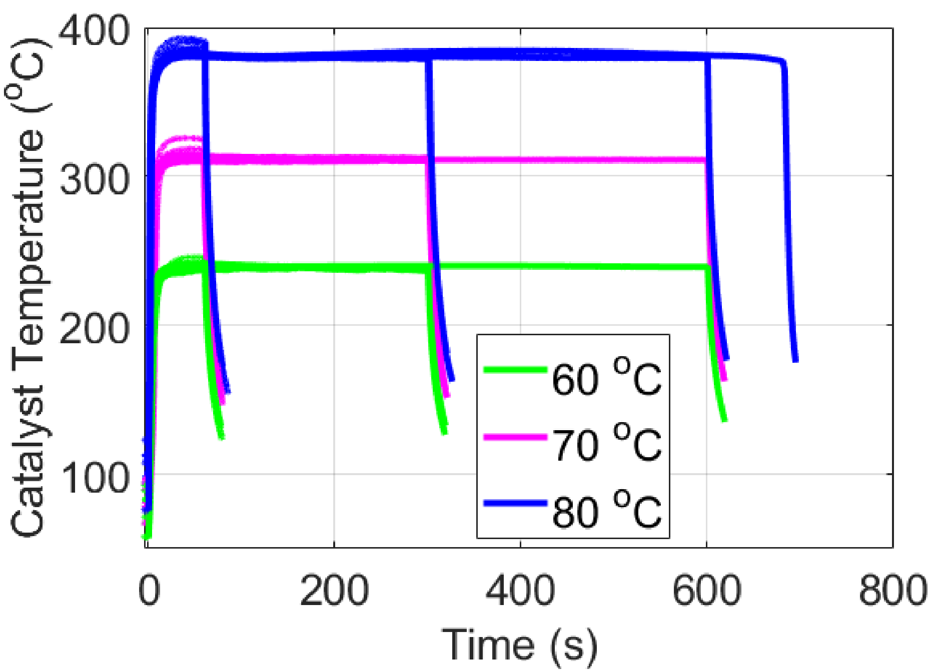
Performance Optimization

Prototype 3: Thrust Measurement



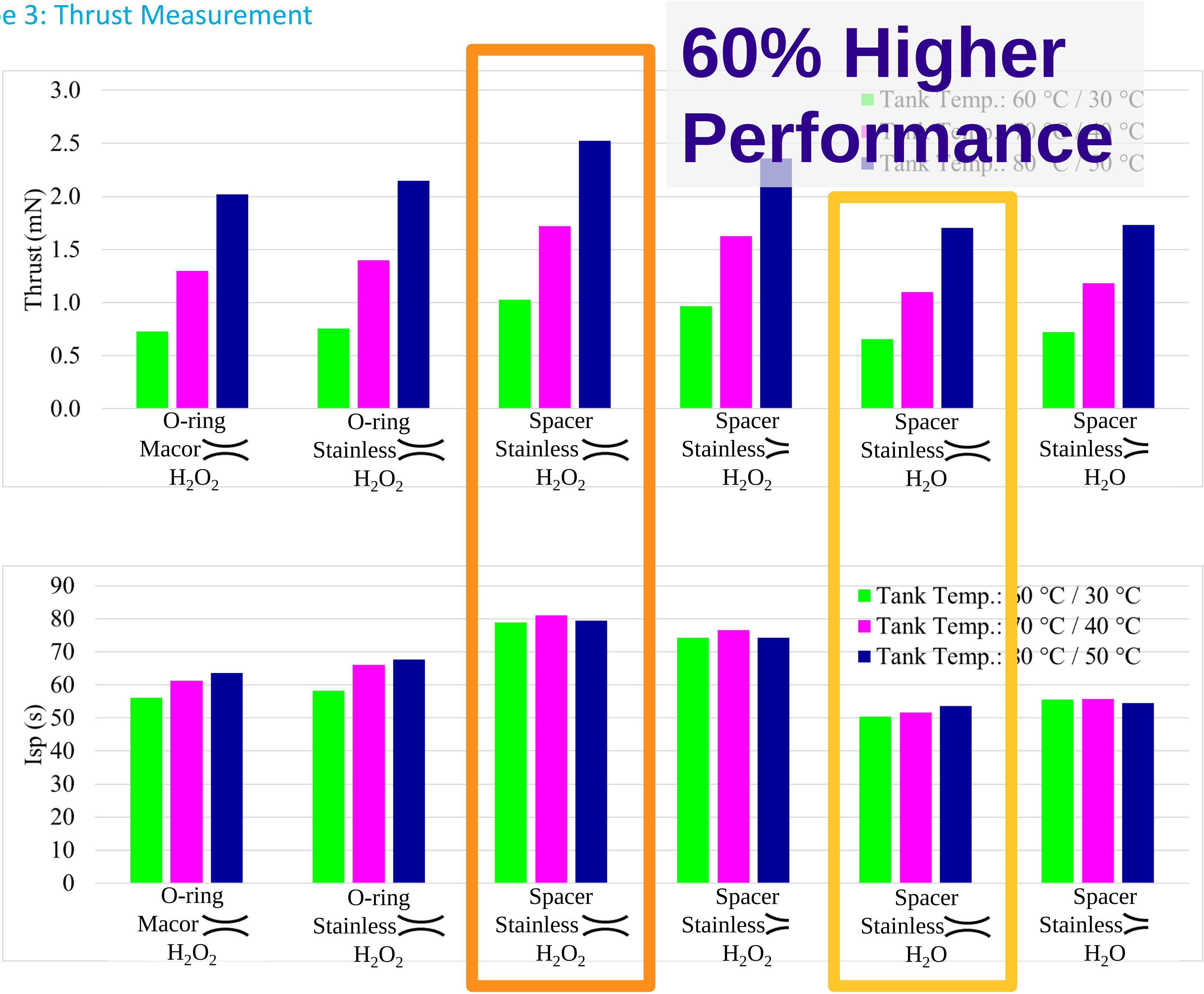






Performance Optimization

Prototype 3: Thrust Measurement



Performance Optimization

Comparison to Theoretical Nozzle

Stainless Nozzle	Prop.	Tank Temp.	Reynolds Number	$\dot{m}$ (Ex./Th.)	Thrust (Ex./Th.)	I_{sp} (Ex./Th.)
	H_2O_2	60 °C	171	0.77	0.51	0.67
	H_2O_2	70 °C	245	0.83	0.53	0.64
	H_2O_2	80 °C	344	0.87	0.52	0.60
	H_2O_2	60 °C	176	0.78	0.70	0.90
	H_2O_2	70 °C	240	0.83	0.73	0.87
	H_2O_2	80 °C	343	0.86	0.70	0.82
	H_2O	30 °C	553	0.97	0.49	0.51
	H_2O	40 °C	955	0.99	0.51	0.51
	H_2O	50 °C	1479	1.00	0.52	0.52

H_2O_2

H_2O

Viscosity “Stickiness”

Re $\uparrow$

$\dot{m}$ (Ex./Th.) $\uparrow$

Performance Optimization

Comparison to Theoretical Nozzle

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H_2O_2

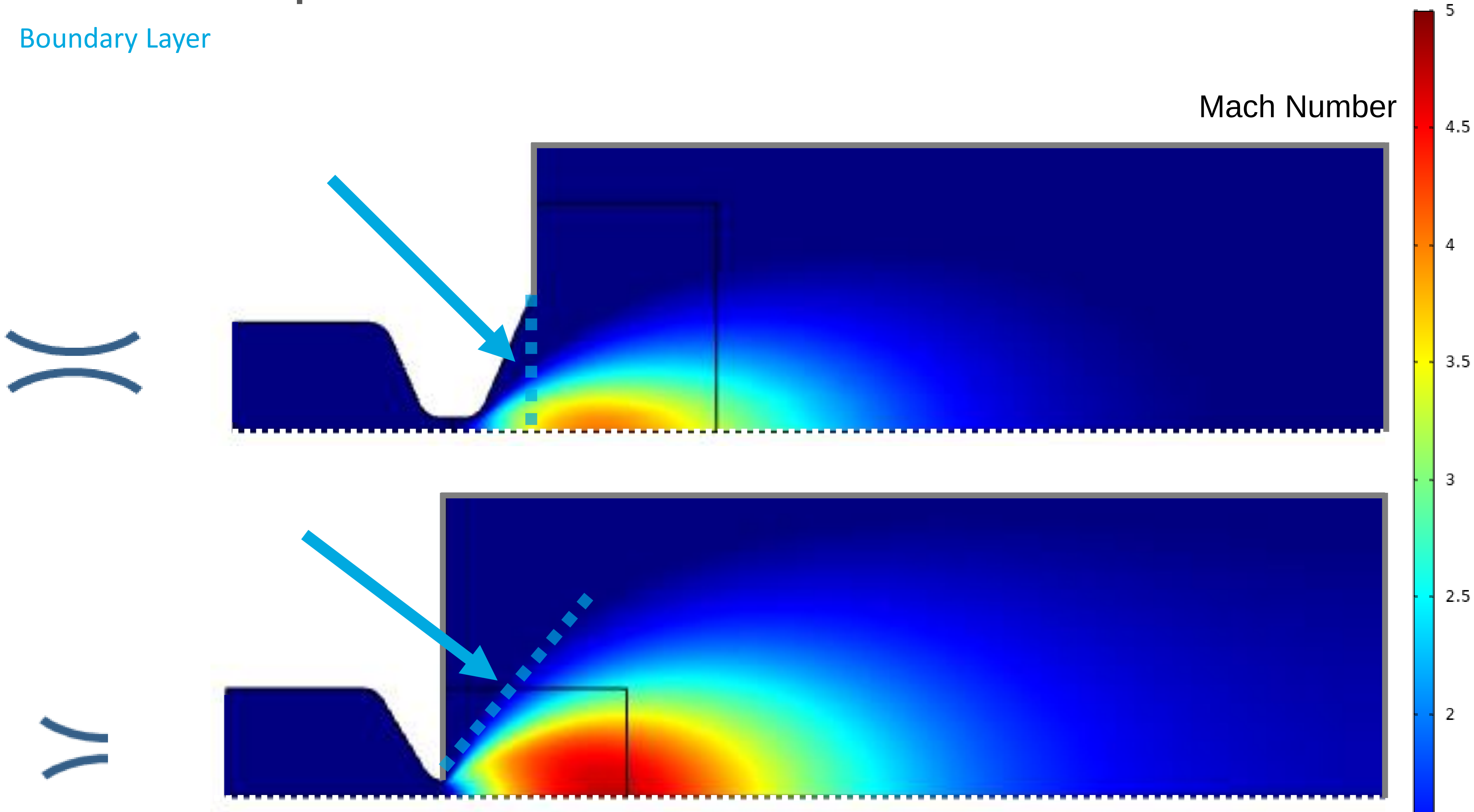
H_2O

Viscosity "Stickiness"

Thrust and I_{sp} (Ex./Th.)

Performance Optimization

Boundary Layer

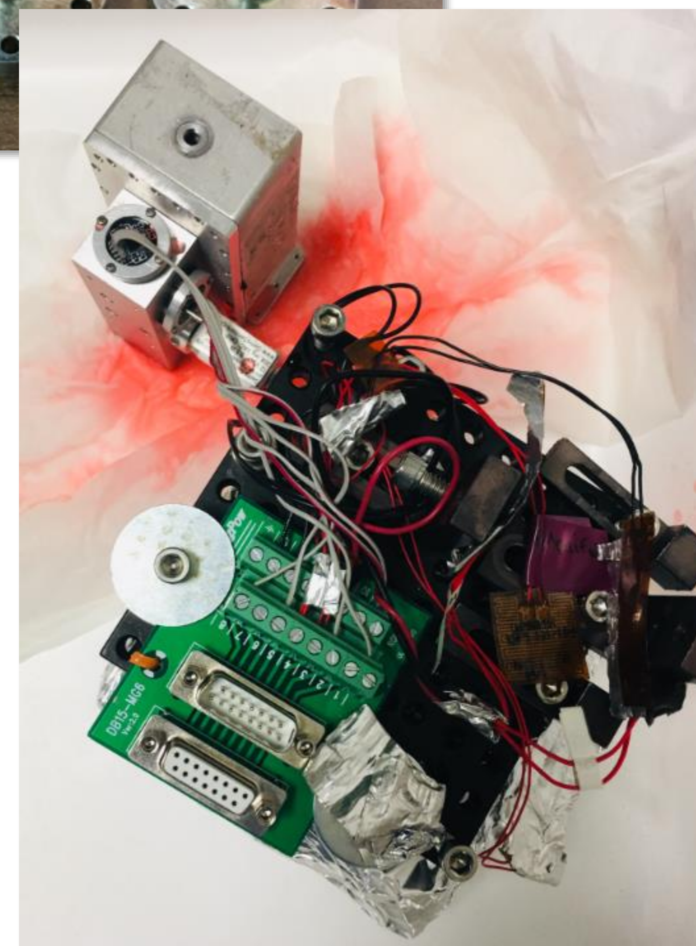


Model Conditions:
80 °C Tank Temperature
Flow only
Adiabatic, no-slip walls
Axisymmetric

Next Steps

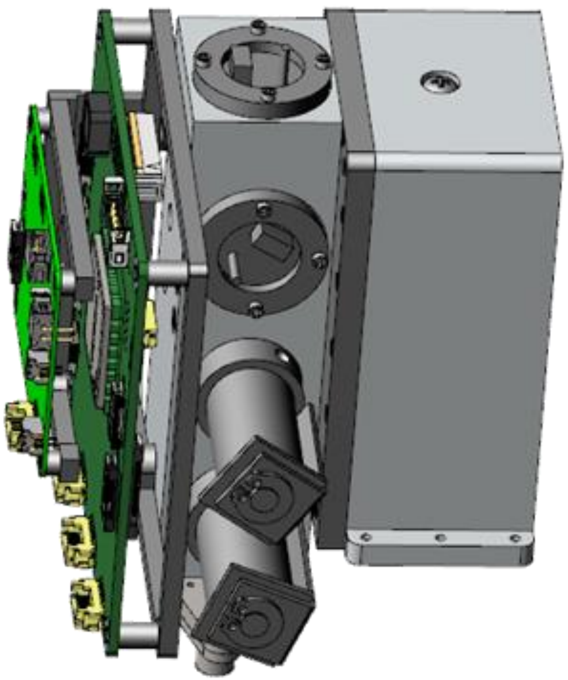
Further performance improvements to the H_2O_2 vapor thruster design

a. Thermal isolation
b. Nozzle design



Flight!

a. Safety testing
b. Electronics and control
c. Final packaging



Thank you for attending!

Questions?

Slide 9 References

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