Propulsion Solutions for CubeSats and Applications

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BUSEK
Advanced Space Propulsion

Distribution Statement A (Approved for Public Release)

Introduction

Satellites are becoming more capable due to willingness to accept less redundancy and miniaturization of devices and MEMS based systems – Moore's Law and microfab techniques.

Impact is dramatic since much of a satellite is electronic parts, typically electronics represents as much as 30% of dry mass, and other systems that can be reduced in size. This leads to smaller and smaller platforms with almost no loss of capability

Two areas where miniaturization has not kept pace because of physics limits - optical (or RF) aperture size determines observation resolution and propulsion systems or not easy to down size while preserving performance (surface-to-volume, very small nozzles, laminar flow losses etc). New approaches are needed (e.g. electrospray)

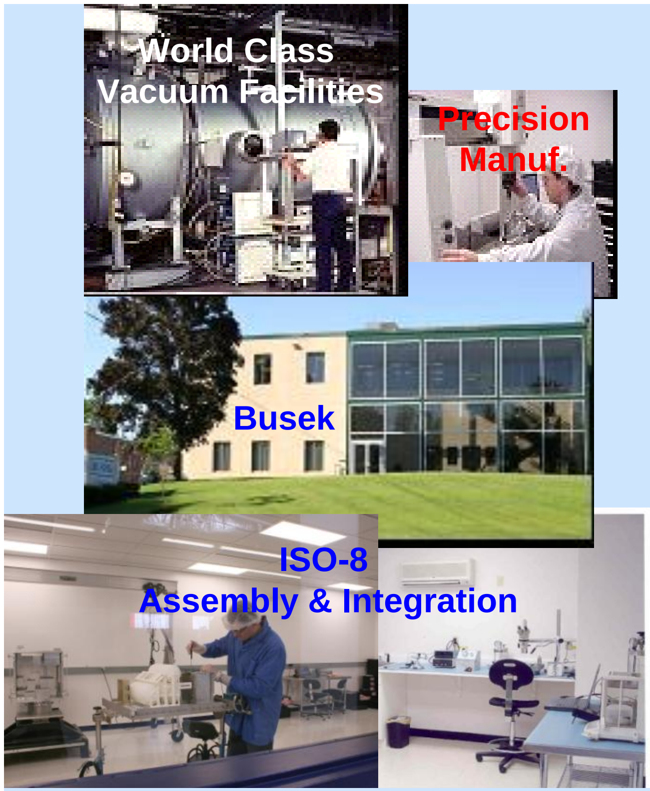
Busek will show seven CubeSat propulsion systems aimed at multiple missions using variety of approaches (electrothermal, electromagnetic, electrostatic, electrospray, green monoprops)

Busek will should possible missions with these smaller spacecraft.

Busek Co. Inc., A History of Innovation

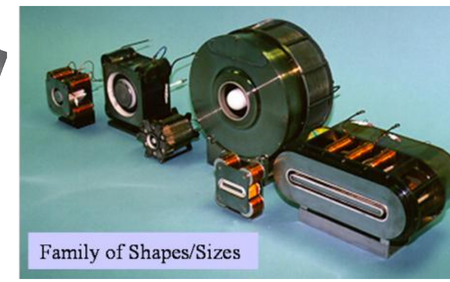
Incorporated in Massachusetts, 1985
- **Founder & president V. Hruby**

Engineering Offices and Facility
- **23,000 sq ft, Natick, MA**



Staffing: ~40 Employees
26 Degreed, 18 hold PhD/Masters

- **All US Hall thrusters flown to date (BHT-200 to BPT-4000) are based on Busek technology.**
- **Largest staff in industry dedicated to EP.**
- **Over 40 unique Hall thruster designs to understanding underlying physics.**



BPT-4000

BHT-200

Proven methodology transitioning from development to deliverable hardware.

Over 20 flight and deliverable thrusters: all met or exceeded performance

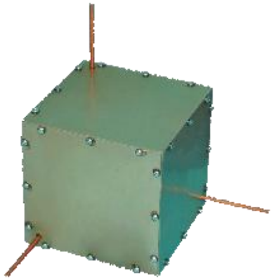
Busek Industry "Firsts"

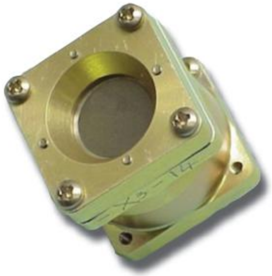
Busek is recognized as the leading innovator and supplier of advanced electric propulsion systems

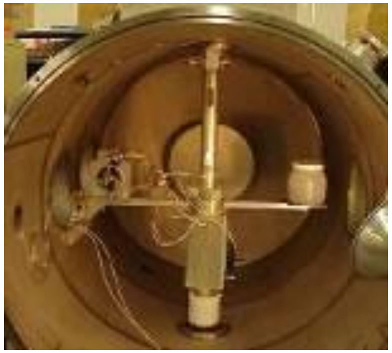
Busek developed:

- **the first US Hall thruster to operate in space**
- **the first co-axial Pulsed Plasma thruster operating in space, transitioned AFRL technology to flight**
- **world's first flight-qualified electrospray thruster**
- **the first flight-qualified Carbon Nano-tube Field Emission Neutralizer**
- **world's best micro-thrust measuring system (NASA JPL statement)**

All of our success started out as SBIR programs and transitioned into flight programs







Outline

Overview of Seven Propulsion Systems

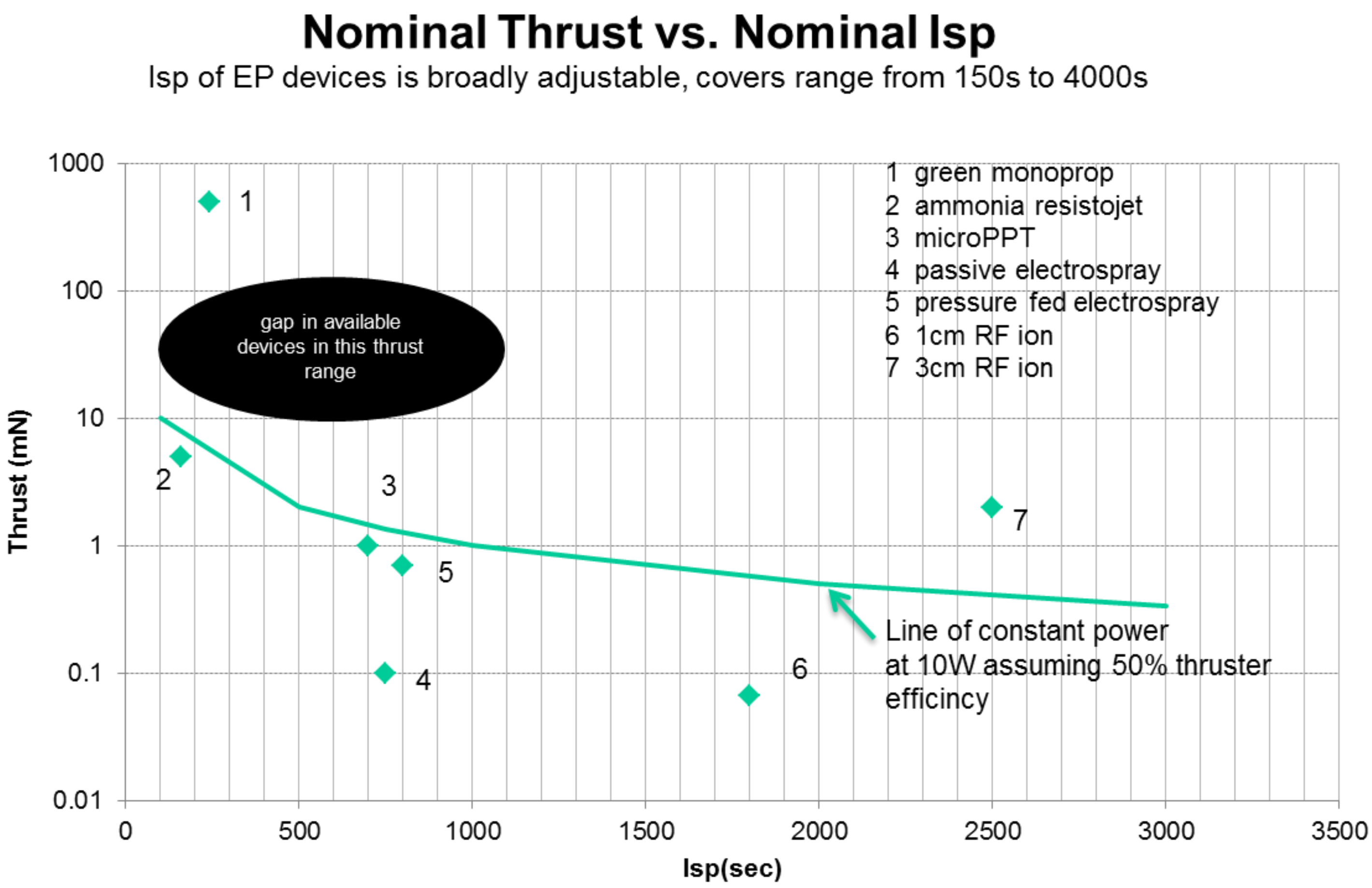
- **Range of Isp and thrust levels**
- **Description of propulsion systems**

Examples of possible applications

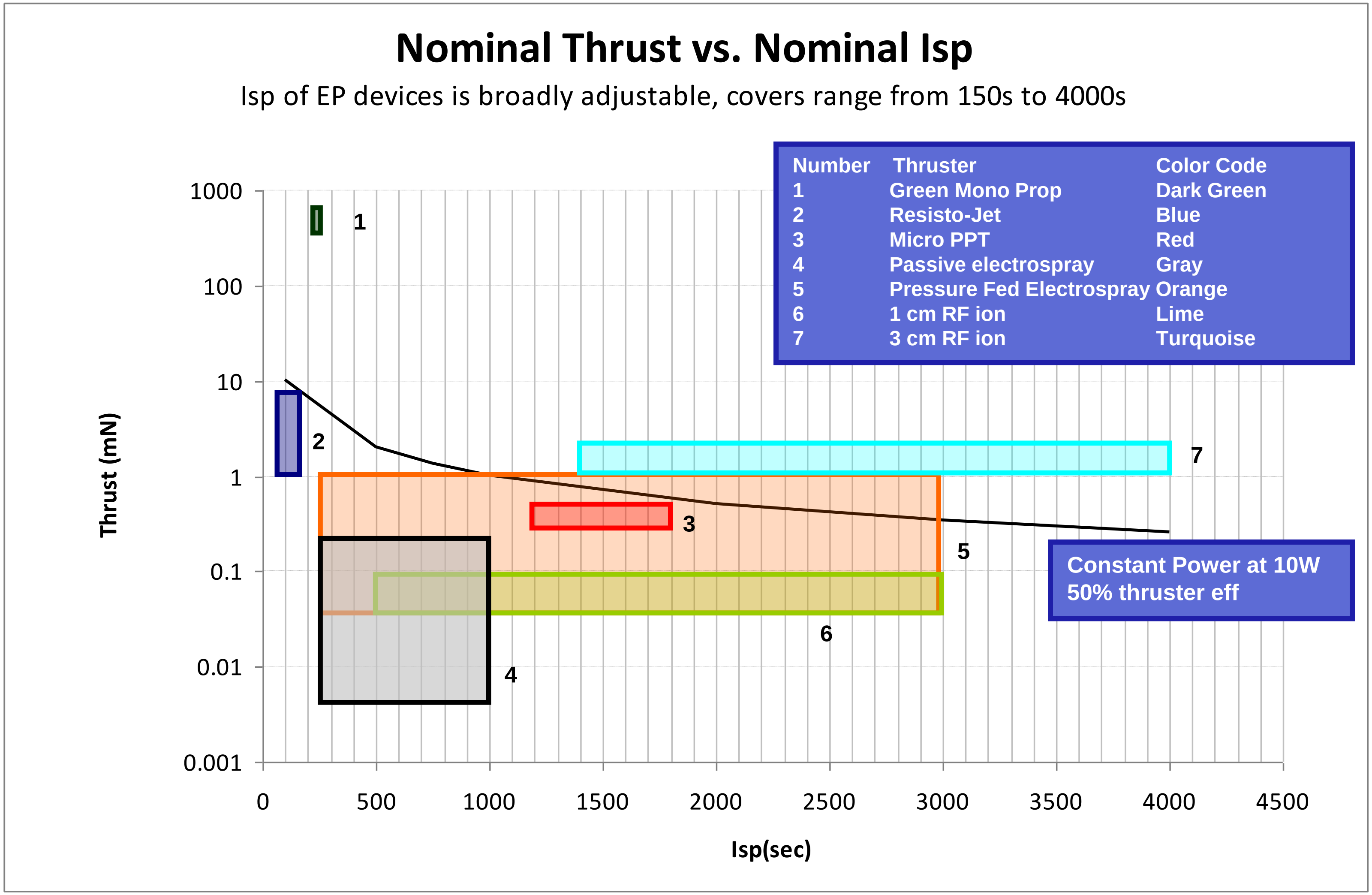
- **CubeSats to the moon**
- **Servicing and repurposing spacecraft**

Busek Strives to Fill all Mission Needs

over a broad thrust and Isp range

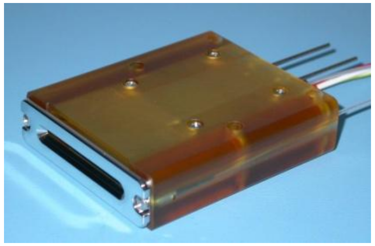


Thrust vs Isp



Busek CubeSat Propulsion Portfolio Summary

Electrospray Thruster
- ✓ High Efficiency
- ✓ Multi-emitter
- ✓ Low Risk / Technically Mature

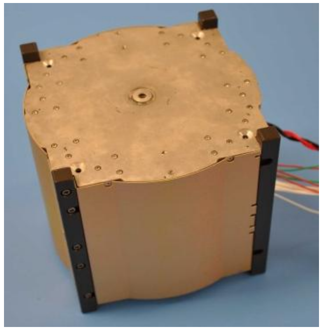


Passive Electrospray Thruster
- ✓ No moving parts, valves
- ✓ No pressure vessel
- ✓ Low Power
- ✓ High ISP

1 cm Micro RF Ion Thruster
- ✓ No internal cathode
- ✓ >2000s Isp
- ✓ FE Neutralizer is space qualified

3 cm Micro RF Ion Thruster
- ✓ No internal cathode
- ✓ Tested up to 3,000s Isp
- ✓Thermionic Neutralizer is space qualified

Micro Pulsed Plasma Thruster
- ✓ No moving parts, valves
- ✓ No pressure vessel
- ✓ Low Power
- ✓ Integrated Primary / ACS
- ✓Prior version flying on FalconSat3



Micro Resistojet
- ✓ Simple, ideal for prox-ops
- ✓ Higher thrust (scales with power)
- ✓ Integrated Primary / ACS

Green Monoprop
- ✓ High thrust (high Cubesat acceleration)
- ✓ High density Isp
- ✓Low-toxicity propellant

Busek PUC Electrospray Thruster

PUC Electrospray Thruster

✓ Low Risk

- ✓ leverages $20M NASA ST7 Technology flight development
- ✓ Leverages SBIR work on micro-valves and power management
- ✓ Phase I risk reduction successfully completed

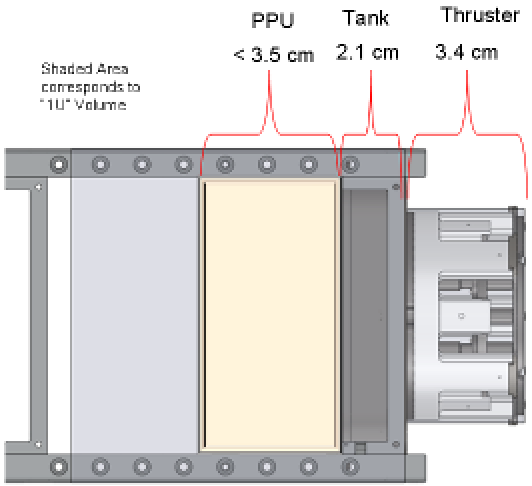
✓151 m/s ΔV for 4.0kg spacecraft

✓ Safe, Non-Toxic, Non-Volatile Propellant

✓ Up to 1mN thrust output

✓ 452 hours of life in Busek's lab

✓ ICD, all Manufacturing Drawings completed



Remaining Development to Flight

✓ Package Design of the PPU

✓ Construct

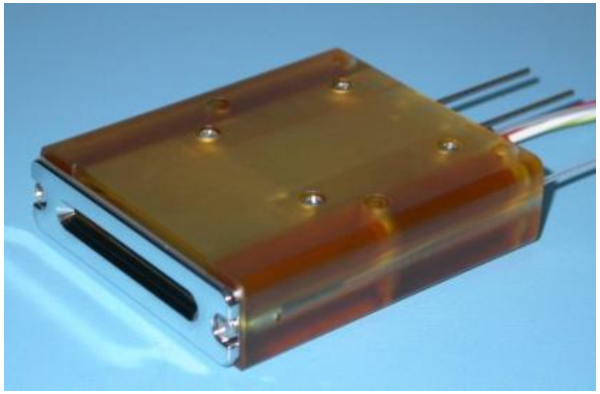
✓ Shock / Vibe / Thermal cycle

Key Performance Characteristics, Busek PUC Electrospray Thruster

System Volume	0.5 U
System Mass	< 1.15 kg
System Power	< 9 W
Thrust	0.70 mN (range 0.1 – 1.0 mN)
ISP	800 s (range 625 - 1,300 s)
Delta V (for 4kg spacecraft)	151 m/s
TRL	5

Busek HARPS Thruster

HARPS Thruster
- ✓ Leverages NASA ST7 Technology flight development
- ✓ Life limiting elements well known
- ✓ Modular
- ✓ Phase II under development
- ✓ Safe, Non-Toxic, Non-Volatile Propellant
- ✓ Features Low Power operation (~0.57W)



Thruster including fuel storage, PPU not shown

Remaining Development to Flight
- ✓ Package Design of the PPU
- ✓ Construct
- ✓ Shock / Vibe / Thermal cycle

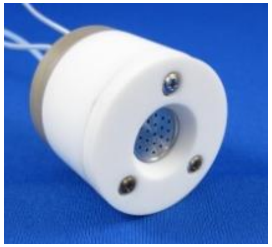
Key Performance Characteristics, Busek HARPS Thruster

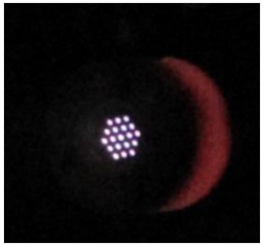
System Volume	< 0.4 U
System Mass	< 0.4 kg
System Power	< 1 W
Thrust	0.1 mN
ISP	750 s
Delta V (for 4kg spacecraft)	76 m/s
TRL	3-4

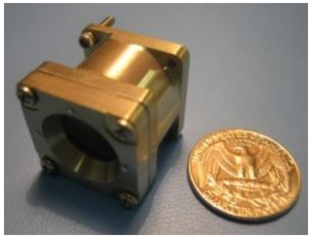
Busek 1cm RF Ion Thruster

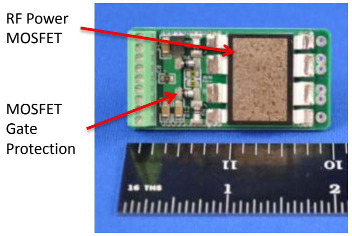
Micro RF Ion Thruster

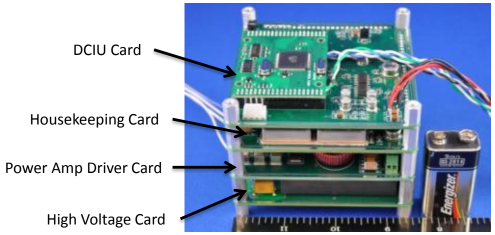
- ✓ Low Risk
  - ✓ Leverages NASA ST7 Technology flight development (cathode, valves)
  - ✓ Leverages NASA SBIR funding on a 400W RF ion thruster development
  - ✓ Leverages SBIR work on micro-valves and power management
  - ✓ Phase II risk reduction successfully completed
  - ✓ ICD Complete
- ✓ Innovative, patent-pending micro RF power generator
- ✓ Up to 150µN thrust and 4000sec Isp output











Remaining Development to Flight

- ✓ Additional performance point optimization
- ✓ Additional performance characterization
- ✓ Miniaturization of Electronics
- ✓ Package Design of the PPU and RF power generator
- ✓ Construct
- ✓ Shock / Vibe / Thermal cycle

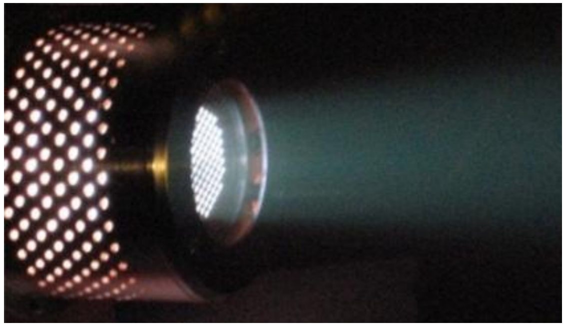
Key Performance Characteristics, Busek RF Ion Thruster

System Volume	**< 1.25 U**
System Mass	**~ 1.25 kg**
System Power	**10 W**
Thrust	**0.67 mN (0.150 mN, max)**
Isp	**1800 s (4,200 s, max)**
Delta V (for 4kg spacecraft)	**244 m/s**
TRL	**5**

Busek 3cm RF Ion Thruster

Micro RF Ion Thruster

- ✓ Low Risk
  - ✓ Leverages NASA ST7 Technology flight development (cathode, valves)
  - ✓ Leverages NASA SBIR funding on a 400W RF ion thruster development
  - ✓ Leverages SBIR work on micro-valves and power management
- ✓ Innovative, patent-pending micro RF power generator
- ✓ Up to 2.5mN thrust and >3000sec Isp output
- ✓ Can deliver 6U Cubesat to Moon orbit



Remaining Development to Flight

- ✓ Additional performance point optimization
- ✓ Additional performance characterization
- ✓ Miniaturization of Electronics
- ✓ Package Design of the PPU and RF power generator
- ✓ Shock / Vibe / Thermal cycle
- ✓ Neutralizer position optimization (neutralizer is space qualified)

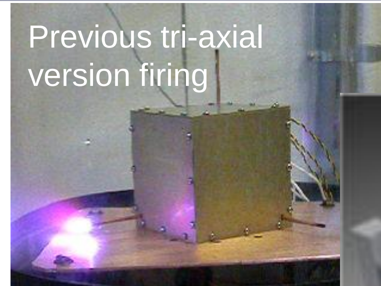
Key Performance Characteristics, Busek 3cm RF Ion Thruster

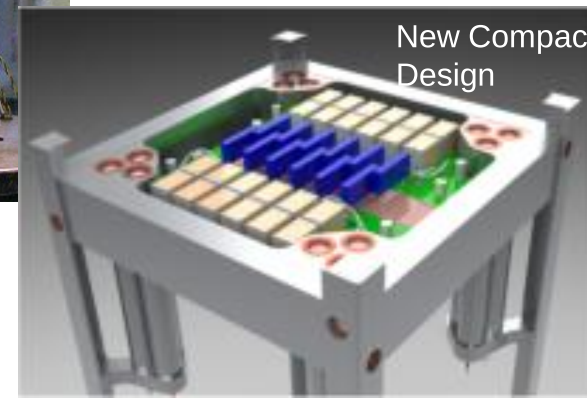
System Volume	< 1.25 U
System Mass	~ 1.25 kg
System Power	< 100 W
Thrust	1.9 mN (range 1 to2.5 mN)
Isp	2,460 s (range 1,500 to3,000 s)
Delta V (for 4kg spacecraft)	~4,000 m/s on 0.5 kg Xenon
TRL	5

Busek Micro Pulsed Plasma Thruster

Micro-Pulsed Plasma Thruster

- ✓ Integrated Primary & ACS Propulsion System
- ✓ Leverages MPACS, FalconSat-3 flight technology
- ✓ Leverages SBIR work on continued development and miniaturization
- ✓ Safe, Non-Toxic, Solid Propellant
- ✓ No moving parts
- ✓ Long storage shelf-life, wide operational temperature range





Remaining Development to Flight

- ✓ Direct thrust measurements to aid in stick geometry propellant optimization
- ✓ Final Electrical Design of PPU
- ✓ Final Package Design of the PPU
- ✓ Construct
- ✓ Shock / Vibe / Thermal cycle

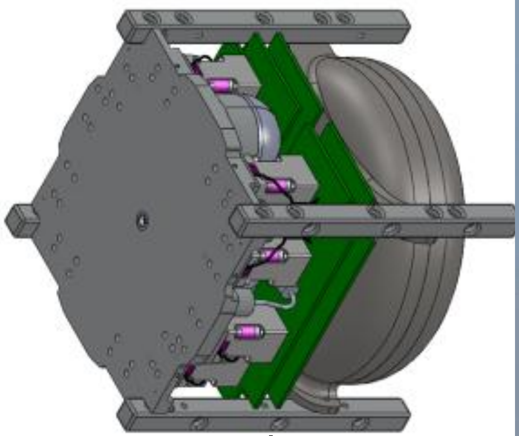
Key Performance Characteristics, Busek Micro-Pulsed Plasma Thruster

System Volume	**< 0.5 U**
System Mass	**< 0.55 kg**
System Power	**2 W (at 2 Hz firing rate)**
Thrust	**0.5 mN, primary 0.13 mN, ACS**
ISP	**700 s**
Delta V (for 4kg spacecraft)	**63 m/s, primary 65 m/s, ACS**
TRL	**5**

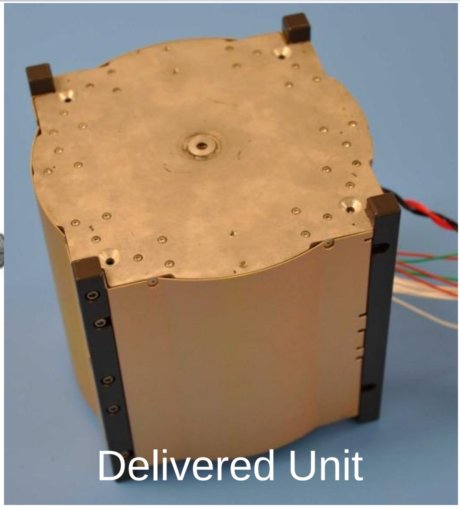
Busek Micro Resistojet Thruster

Micro Resistojet Thruster

- ✓ Integrated Primary & ACS Propulsion System
- ✓ Resistojet is simplest electric propulsion
- ✓ Leverages SBIR work on micro-valves and power management
- ✓ Safe, Non-Toxic propellant
- ✓ Up to 10mN thrust output
- ✓ Life limit constrained by propellant storage
- ✓ Flight Prototype in final stages
- ✓ Can operate from <3 watts to >15 watts
- ✓ Isp and/or thrust increases with power
- ✓ Precise maneuvering possible
- ✓ Delivered integrated system prototype to USAF



Design



Remaining Development to Flight

- ✓ Trade PPU design/components for cost versus rad hard
- ✓ Test complete system
- ✓ Shock / Vibe / Thermal cycle

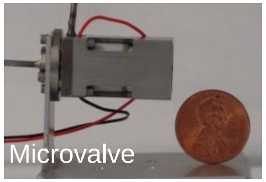
Key Performance Characteristics, Busek MRJ Thruster (Primary Propulsion Unit)

System Volume	1.0 U
System Mass	< 1.25 kg
System Power	3-15 W
Thrust	2-10 mN, primary 0.5 mN, ACS
ISP	150 s, primary 80 s, ACS
Delta V (for 4kg spacecraft)	60 m/s, primary 6 m/s, ACS
TRL	5

Busek Green Monopropellant Thruster

0.5N AF-315 Green Monopropellant Thruster

- ✓ Integrated piezo microvalve, catalyst igniter and high temeprature thruster body
- ✓ Busek's microvalve fills the void of low-flow, low power, material compatible thruster valve
- ✓ Can be packaged into a 0.5U CubeSat system, including a fuel tank
- ✓ AF-315 is highly stable and non-toxic, yet performs better than SOA monoprop
- ✓ Leverages two concurrent SBIR Phase II work on microvalves and monopropellant thruster
- ✓ Precise firing and short impulse possible
- ✓ Stable operation demonstrated

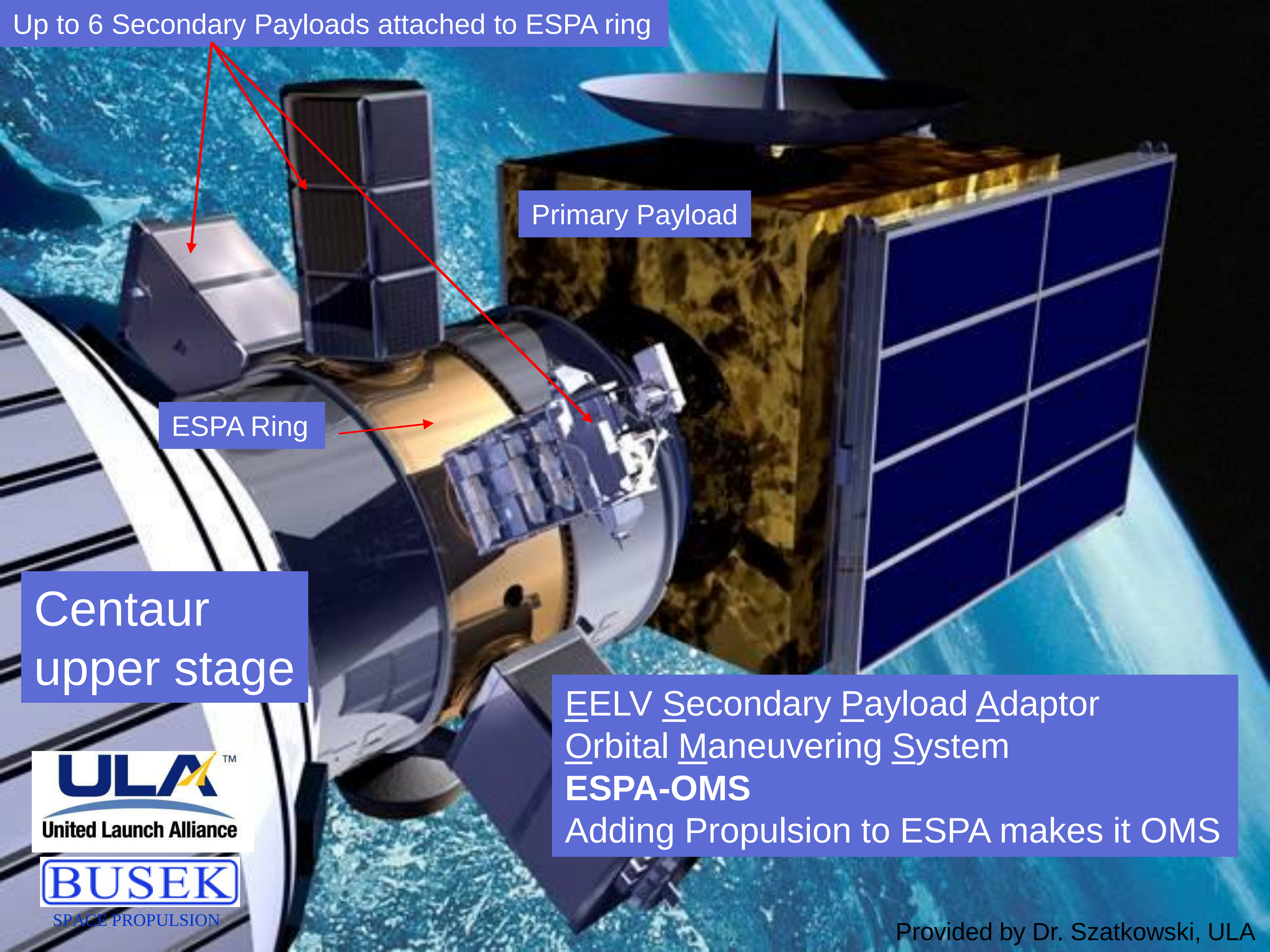


Remaining Development to Flight

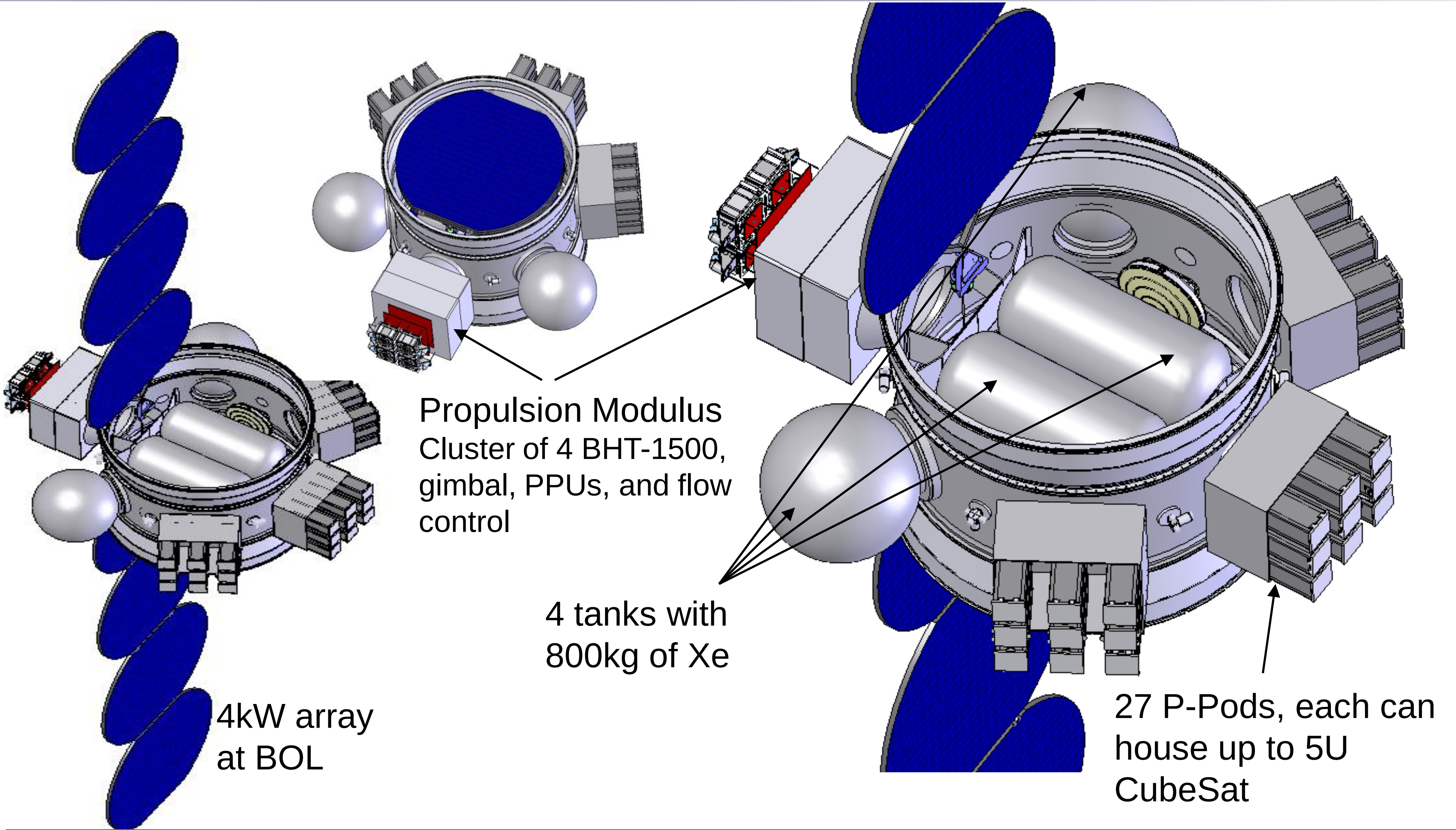
- ✓ System thermal management desi gn
- ✓ Integrated system testing
- ✓ Maximum life testing and minimum impulse testing
- ✓ Environmental testing Shock / Vibe / Thermal cycle

Key Performance Characteristics, Busek AF315 Green Monoprop Thruster

System Volume	**< 1.5 U**
System Mass	**< 1 kg**
Power	**< 30 W**
Thrust	**500 mN**
Isp	**250 s nominalat 300 psi**
Delta V (for 4kg spacecraft)	**100 m/s**
TRL	**5**


Up to 6 Secondary Payloads attached to ESPA ring
Primary Payload
ESPA Ring
Centaur upper stage
EELV Secondary Payload Adaptor
Orbital Maneuvering System
ESPA-OMS
Adding Propulsion to ESPA makes it OMS
ULA
United Launch Alliance
BUSEK
SPACE PROPULSION
Provided by Dr. Szatkowski, ULA

ESPA OMS Concept, Delivers ~27 of 3U Cubesats to Mars and then serves as a communications relay back to earth



Potentially stimulating broad international participation, nations fly their own Cubesats to Mars

DARPA Phoenix Project

- ✓ Service and Repurpose used and dead spacecraft
- ✓ Major role for very small satellites - Satlets
- ✓ Videos:

  DAPRA video website (8 min.)

  http://www.youtube.com/watch?v=uvkhWIlmHEg

  YouTube version (1 min.)

  http://www.youtube.com/watch?v=aPjXfXFGpjA

- ✓ Busek was awarded a Phase 1 effort for satlet propulsion development

Summary

✓ Recognized industry leader in advanced space propulsion R&D for over 25 years

✓ Delivered flight qualified propulsion payloads to government customers.

✓ Leader in EP solutions for CubeSat and NanoSat Propulsion

✓ Eager to fulfill your CubeSat needs

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