National Aeronautics and
Space Administration

Space Technology Mission Directorate

Propulsion and Power Technology Development Strategy

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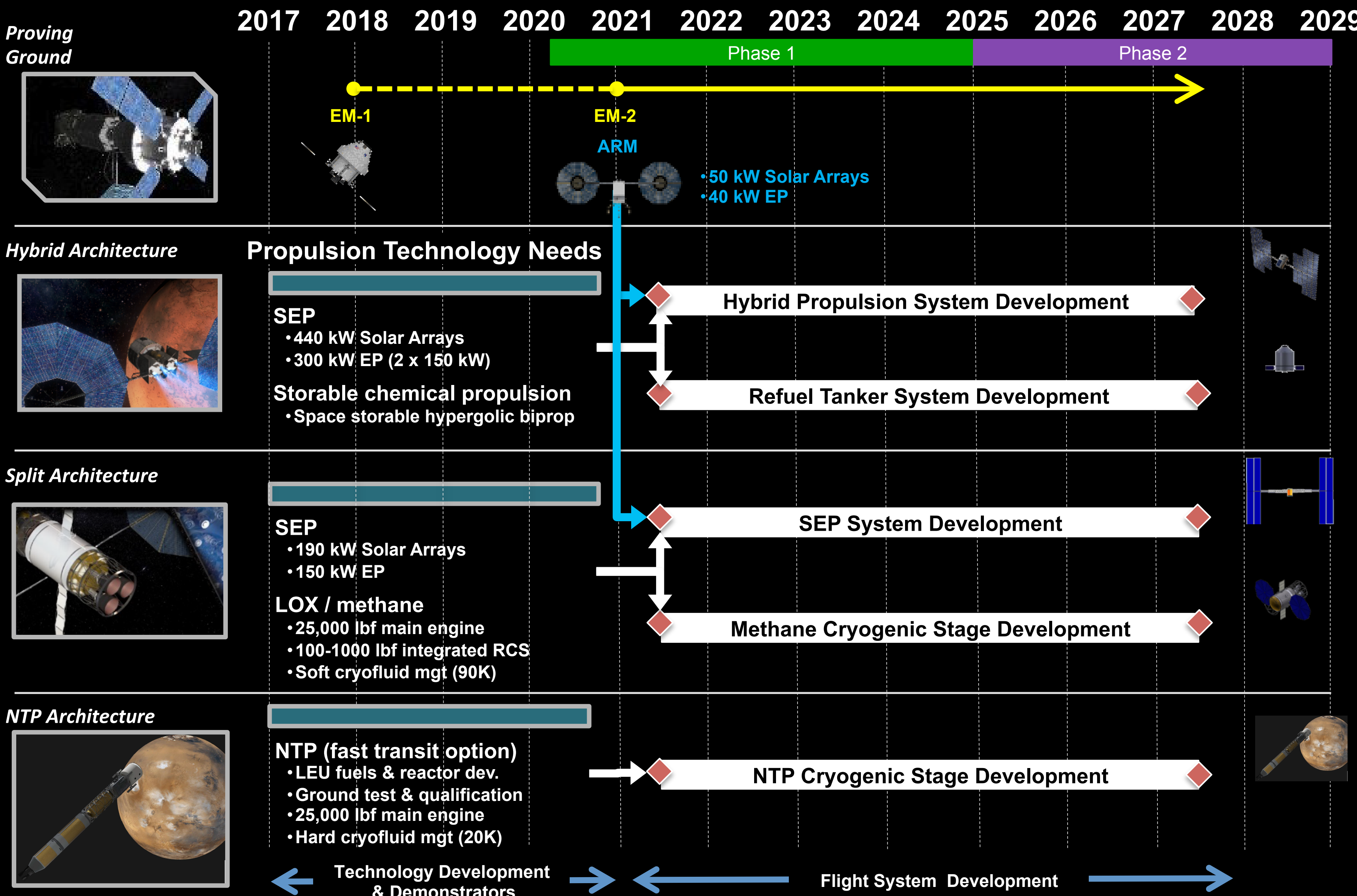
Investment Themes

- **Efficient deep space propulsion**
  - High-power solar electric propulsion flight demonstration (current project)
  - Nuclear thermal propulsion technology development (current & potential projects)
  - LOX / methane propulsion technology development (potential project)
- **Mission-enhancing space storable propulsion**
  - MON-25 / MMH engine technology development & flight demonstration (potential project)
  - 'Green' propellant thruster technology development & flight demonstration (current & potential projects)
- **Cubesat / smallsat propulsion technology development & flight demonstration** (current projects)
- **Advanced solar arrays**
  - Large deployable solar array technology development (past & current project)
  - Extreme environment solar array technology development (current project)
- **Planetary surface power**
  - Small nuclear fission power technology development (current & potential projects)
  - Ultra-low temperature battery technology development (current project)
- **Revolutionary propulsion research and technology development** (potential project)

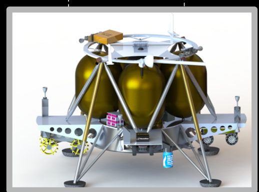
Propulsion Technology Drivers:
Candidate Options for Crewed Mars Exploration



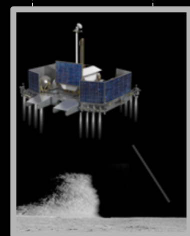
Propulsion Technology Drivers:
Potential Science & Commercial Missions

2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030

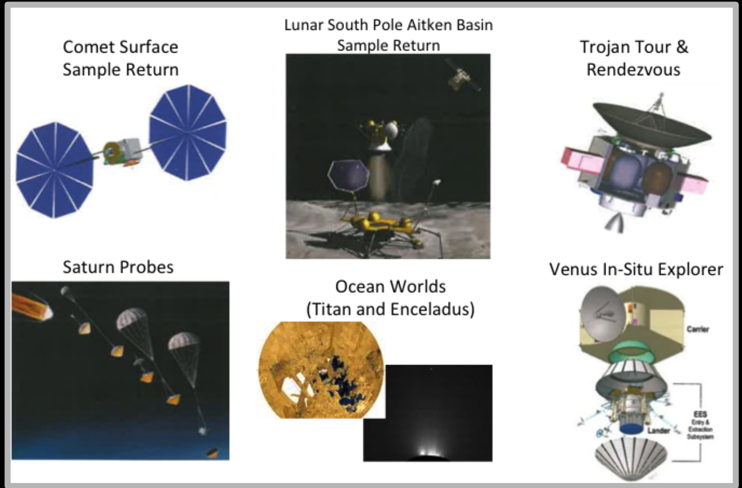
NF4 Tech Day — NF4 AO Release — NF4 Selection — NF4 Launch



Astrobotic Lunar Surface Mission



Resource Prospector Lunar Surface Mission



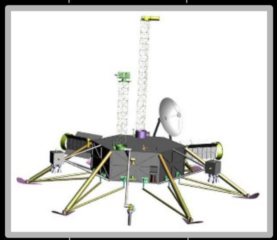
Propulsion Technology Needs

Planetary landing & ascent

Extreme environments
- Reduce SWaP
- Utilize ISRU
- Low temperatures
- Long duration deep storage

Small satellites & probes
- Expand CONOPS – science & commercial
- Micropropulsion / sails

Small launch vehicles
- Enhance commercial viability
- Solid & liquid boosters
- Upper stages & ACS



Europa Surface Mission

Mars Sample Return

High-Power Solar Electric Propulsion Flight Demonstration

(current project)

SEP Vehicle Evolution

500 kW

100 kW

50 kW

10 kW

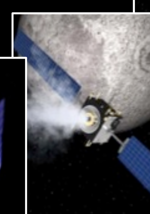
1 kW

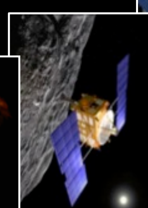
2030s: 200 - 500 kW Possibilities
Human missions to Mars
Hybrid Chem/SEP vehicle for crew
SEP vehicle for prepositioning assets

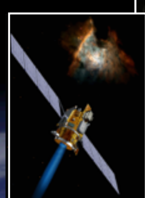
2025-2030: 80 - 200 kW Possibilities
- Proving Ground
- Logistics resupply
- Excursion mission capability

2020-2025: 50 kW Possibilities
- HEOMD – Asteroid Redirect Robotic Mission
- SMD – Mars orbiter & sample return
- DoD – space situational awareness
- Commercial – servicing & geo insertion

2010-2011 Advanced EHF (DoD comsat)
- Launched to GTO, apogee engine failure, 9kW EP system used for GEO transfer
- Over the course of a year ~ 500 maneuvers (from mins to >14 hrs) to reach GEO
- SEP saved $1.6 B asset with full function





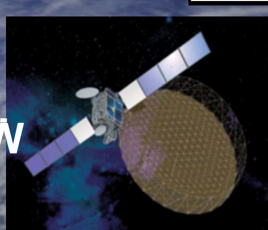


2007-2016 Dawn: 2 kW (10 kW @ 1AU) NASA SMD, asteroid rendezvous

2008 SMART-1: 1.5kW ESA Tech demo, lunar science

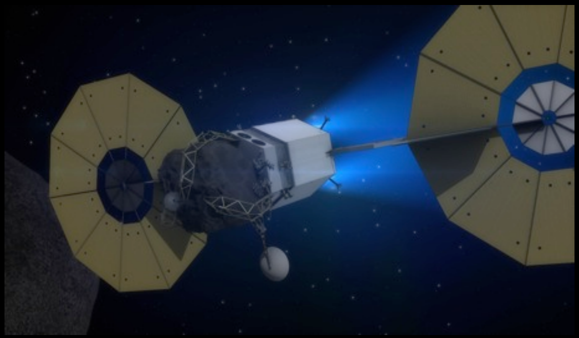
2003 Hayabusa: 2 kW JAXA Tech demo, asteroid sample/return

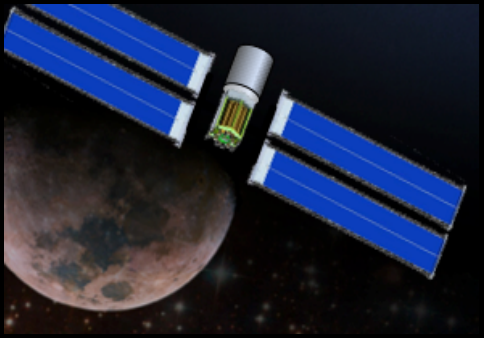
1998 Deep Space-1: 2 kW NASA Tech demo, asteroid comet flyby

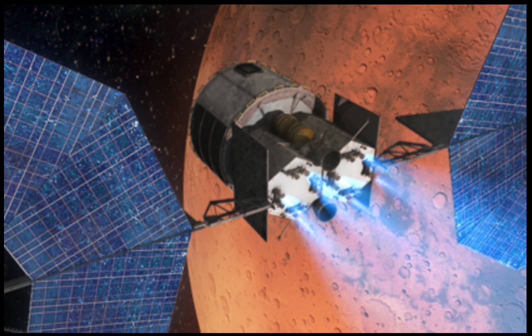


1990's – present: Geostationary comsats, kW-class solar electric propulsion used for station keeping
- Using SEP increased operational lifetimes up to 18 years
- Substantially increased payload capability
- 100s of spacecraft and tens of thousands hours of successful on-orbit operation

High-Power SEP Vehicle Notional Requirements

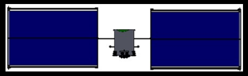






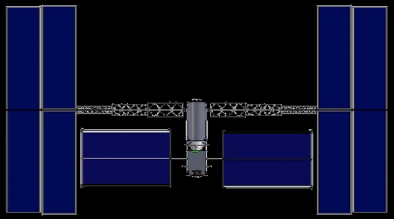
Initial SEP bus

- 50-kW Solar Array System
- 40-kW EP System
- 5-t class Xenon Capacity
  - Refueling Capability
- 13-kW EP strings



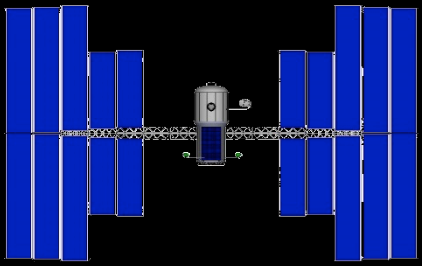
Proving ground or split Mars architecture

- 190-kW Solar Array
- 150-kW EP System
- 16-t class Xenon Capacity
- 13-kW EP strings

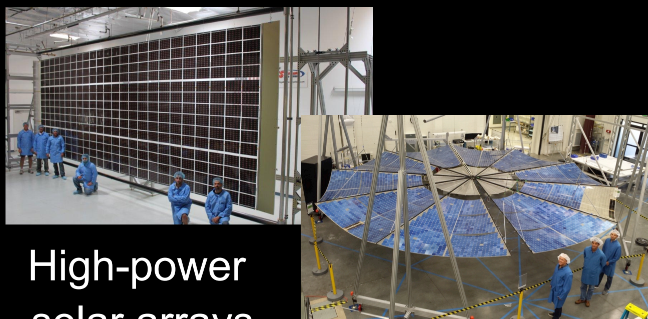


Hybrid Mars architecture

- 400-kW class Solar Array
- 300-kW class EP System
- 16-t class Xenon Capacity
- 30-kW class EP



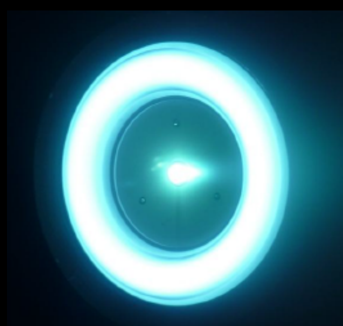
Key Technologies for High-Power SEP Demonstration



High-power solar arrays

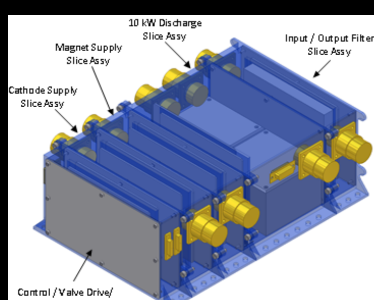
	State of the Art	Goal
Power	25 kW	50 kW (2 wings)
Power to Mass Ratio	60 W/kg	> 100 W/kg
Stowage Efficiency	10 kW/m^3	> 40 kW/m^3
Operating Voltage	70 - 160 V	150 -300 V

High-power Hall thruster



	State of the Art	Goal
Input Power/unit	4.5 kW	12.5 kW
Thrust/unit	0.235 N	0.68-0.48 N
Specific Impulse	2040 sec	2000-3000 sec
Propellant Throughput	450 kg	3400 kg

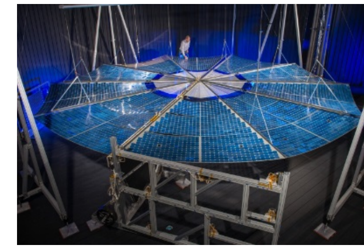
Advanced power processing unit

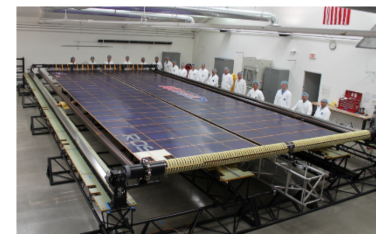


	State of the Art	Goal
Input Power	4.5 kW	13.3 kW
Input Voltage	70 - 100 V	300 V
Output Voltage	250 - 400 V	800 V
Efficiency	90 - 92%	≥ 92%

Completed High-Power SEP Technology Risk Reduction Projects

Solar array development contracts fully successful



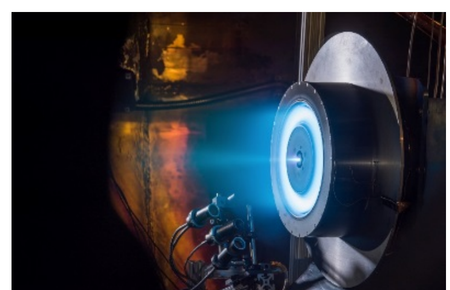


- MegaFlex engineering development unit (ATK)
- ROSA engineering development unit (Deployable Space Systems)
- Both arrays achieved all performance metrics including:
  - 4x rad tolerance
  - 1.7x power/mass (kW/kg)
  - 4x stowed volume efficiency
  - 20x deployed strength

Technology development thruster and PPU tests at GRC

- Confirmed thruster magnetic shielding (enables long-life operation)
- Power processing unit vacuum tests successfully completed
- Conducted 12.5 kW thruster integrated tests with 300 V and 120 V PPUs
- 400+ hours of testing completed

Demonstrated full performance compatibility between thruster and PPUs

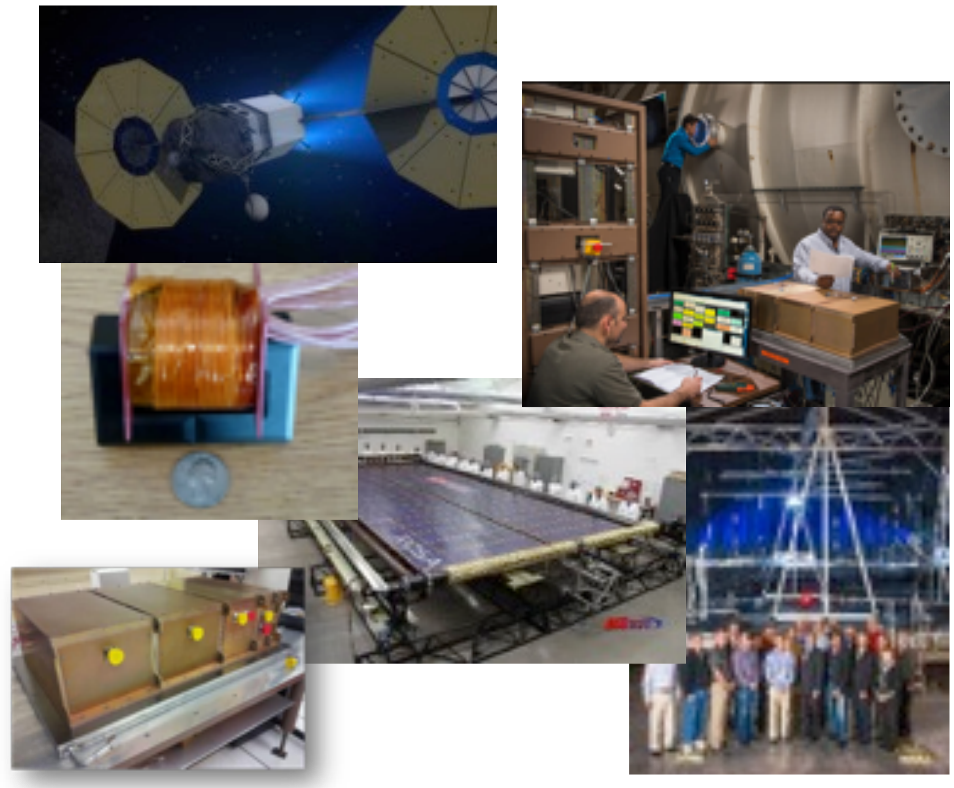


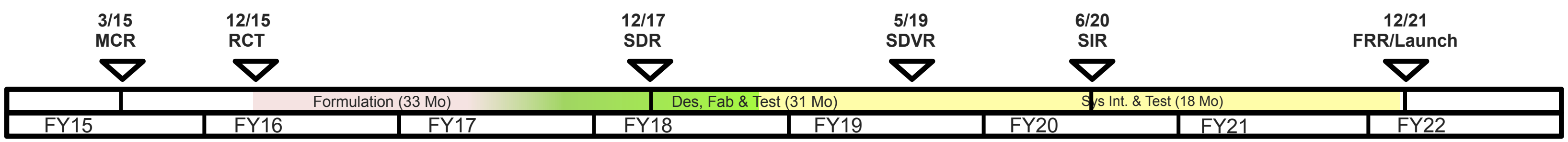
High-Power SEP Demonstration Project Overview

Develop and fly a 50-kW class spacecraft that uses flexible blanket solar arrays for power generation and EP for primary propulsion and is capable of delivering payload from LEO to higher orbits.

Objectives:

- Demonstrate high-power EP and solar array system technologies in relevant space environments
- Demonstrate orbit transfer with an integrated high-performance SEP spacecraft
- Demonstrate a SEP system that is extensible to next-generation, higher-power SEP systems
- Provide a cross-cutting high-performance orbit transfer capability





Nuclear Thermal Propulsion Technology Development

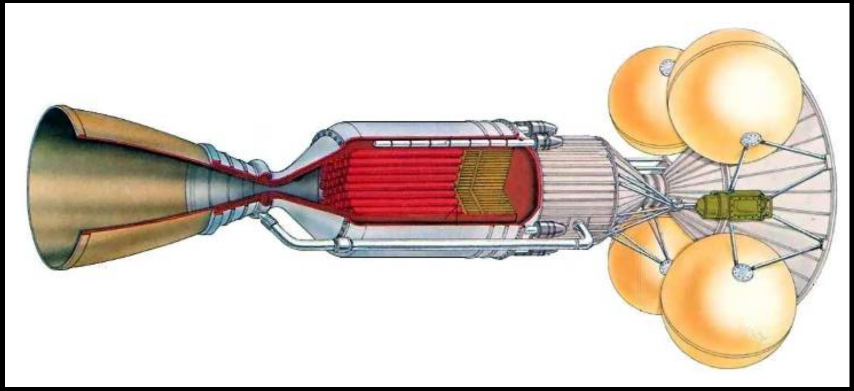
(current & potential projects)

Nuclear Thermal Propulsion

NTP vehicle concept from DRA 5.0

NTP key benefits:

- Faster transit times and reduced crew radiation hazards
- Reduced architectural mass and fewer SLS launches
- Decreased sensitivity to mission departure and return dates



Nuclear thermal rocket engine concept

Near-term project focus:

- Reactor fuel design that achieves higher temperature while minimizing erosion and fission product release
- NTP design based around low enriched uranium (LEU) fuel elements
- Mature critical technologies associated with LEU fuel element materials & manufacturing
- Evaluate the implications of using LEU fuel on NTP engine design

Congressional Direction on NTP

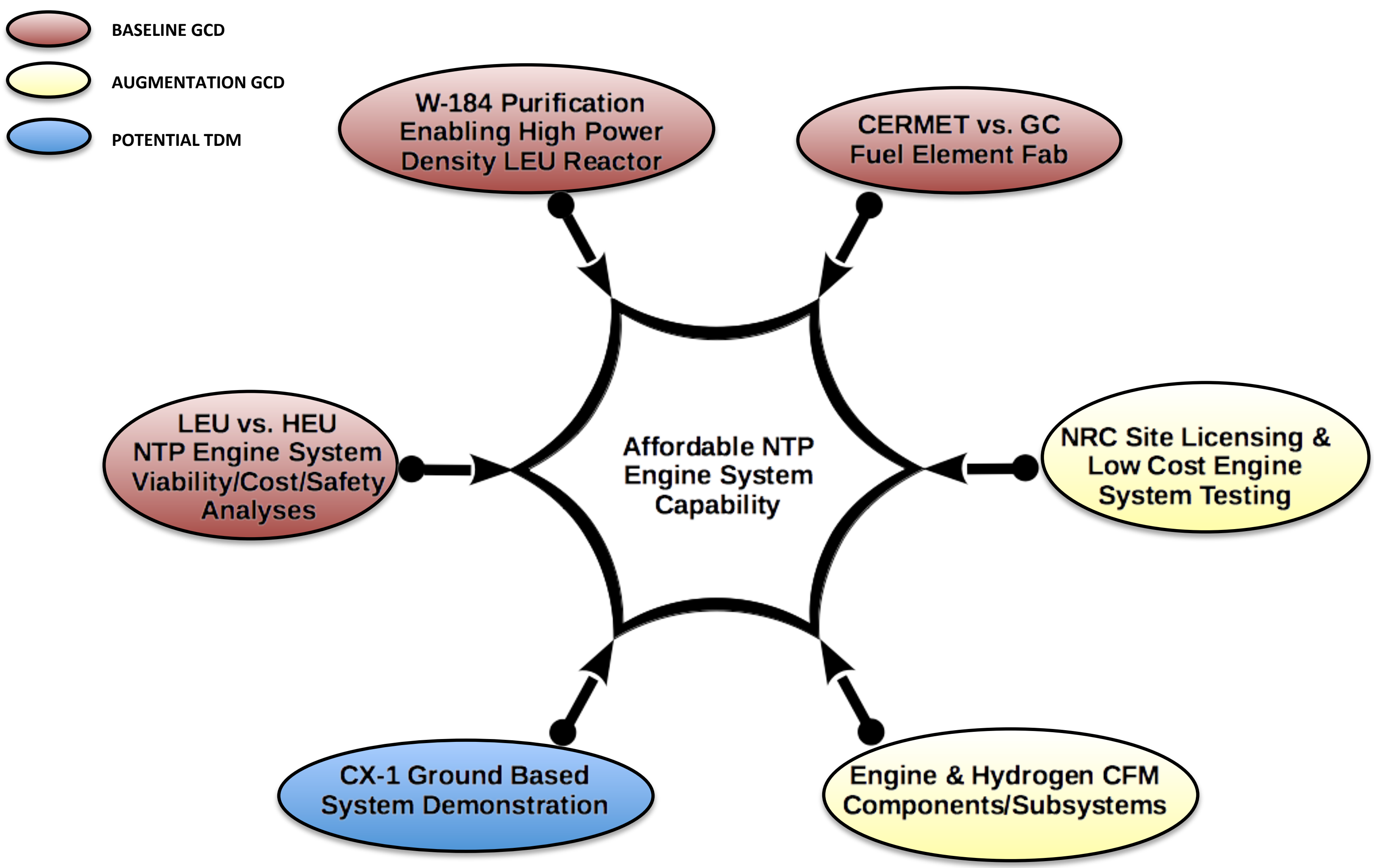
FY16

- **House**: The recommendation includes **no less than $20,000,000** for nuclear propulsion technologies for space transportation and exploration. NASA shall provide a report within 180 days of enactment of this Act on ongoing nuclear propulsion research and how NASA intends to employ this technology to support various exploration programs.
- **Senate:** No specific direction.
- **Final language:** In lieu of House language on nuclear propulsion technologies, the agreement provides **up to $20,000,000** for these activities.

FY17

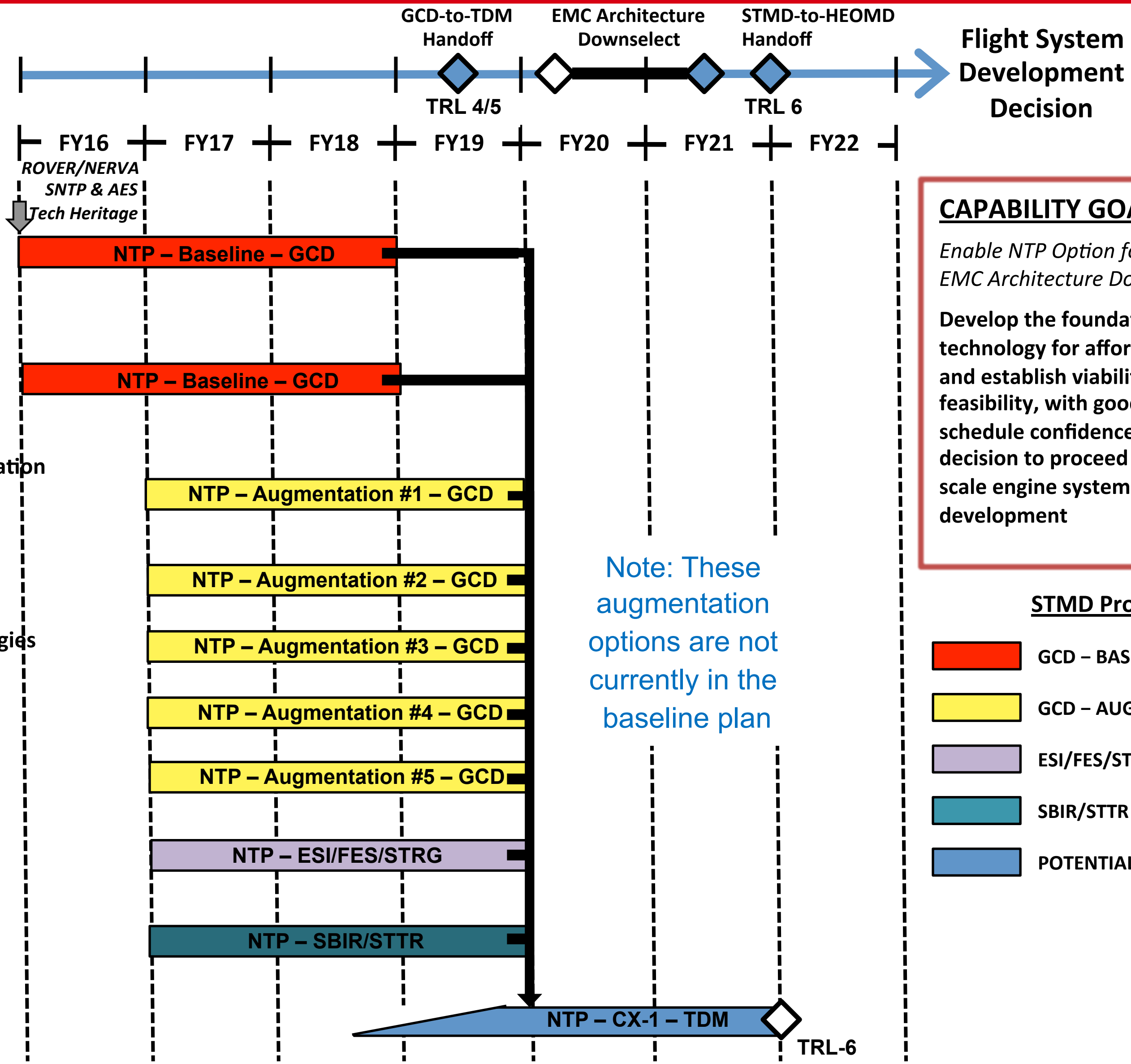
- **House**: The recommendation includes **no less than $35,000,000** for nuclear propulsion technologies for space transportation and exploration. NASA shall provide a report to the Committee within 180 days of enactment of this Act on ongoing nuclear propulsion research, how NASA intends to employ this technology to support various exploration programs, and a comparison of nuclear propulsion and use to other forms of propulsion, in terms of speed and ease of construction.
- **Senate:** NASA is continuing its work to develop the foundational technologies and advance low enriched uranium nuclear thermal propulsion systems that can provide significantly faster trip times for crewed missions than non-nuclear options. The Committee **provides $28,900,000** above the request for ongoing nuclear thermal propulsion technologies for space transportation and exploration. NASA shall update its report to the Committee within 180 days of enactment of this act on ongoing nuclear thermal propulsion research and how the research into this technology supports NASA's exploration programs.
- **Final language:** **TBD**.

NTP Technology Development:
Project Elements



NTP Project Elements & Timeline

KDP Timeline



Technology Elements

GCD – Fuels/Reactor Design & Fabrication
- Isotopically Pure ^{184}W Production
- CERMET FE Fabrication
- Graphite Composite FE Fabrication
- Non-Nuclear FE Testing (NTREES)

GCD – System Assessment
- Engine System Design Maturation
- LEU (preferred) vs. HEU Reactor Trades
- Engine System Testing Trades
- Viability, Affordability, & Cost Element Analysis

GCD – Ground Test Technology & Qualification
- Sub-Scale Fully Contained Exhaust Demo
- Site-Selection | EIS & NRC Licensing

GCD – Fuel Risk Reduction
- Materials/Process/Fabrication R&D
- Specimen Fab (DU) & CFEET Testing

GCD – Component & Subsystem Technologies
- Cryogenic MIPS Performance & CONOPS

GCD – Active CFM Technology
- Liquefaction & Zero Boil-Off

GCD – Passive CFM Technology
- High Performance Insulation

ESI/FES/STRG – Academic Support
- Fuels Risk Reduction
- Advanced Modeling & Simulation

SBIR/STTR – Cross-Cutting Technologies
- Commercial Technology Infusion
- Complimentary DOE-NE75 Topic (External)

TDM – Critical Ground Demonstration
- Critical Experiment (CX-1)

CAPABILITY GOAL

Enable NTP Option for FY20/21 EMC Architecture Downselect

Develop the foundational technology for affordable NTP and establish viability & feasibility, with good cost & schedule confidence, prior a decision to proceed with full-scale engine system development

STMD Programs

- GCD – BASELINE
- GCD – AUGMENTATION
- ESI/FES/STRG
- SBIR/STTR (+ DOE Aug)
- POTENTIAL TDM

SBIR/STTR Projects Supporting Propulsion & Power Technology Development

FY15 NASA SBIR/STTR NTP awards ($500 K Phase I / $3 M Phase II)

- **Representative Phase I awards**
  - 15-1-H2.02-9101: "*Advanced Zirconium Carbide Tie-Tubes for NTP*" (Plasma Processes)
  - 15-1-H2.02-9127: "*Passive Technology to Improve Criticality Control of NTP Reactors*" (Ultra Safe Nuclear Corp)
- **Representative Phase II awards**
  - 14-1-H2.03-9718: "*Superconducting Electric Boost Pump for Nuclear Thermal Propulsion*" (Florida Turbine Technologies)
  - 14-1-H2.04-9121: "*Hydrogen Wave Heater for Nuclear Thermal Propulsion Component Testing*" (ACENT Laboratories)

FY16 NASA SBIR/STTR propulsion & power awards ($3 M Phase I / $3 M Phase II)

- **Representative Phase I awards**
  - 16-1-A1.07-7705: *"Injector-Integrated Fuel-Air Heat Exchanger Module"* (Micro Cooling Concepts)
  - 16-1-H2.01-7120: *"Additive Manufacturing Technology for a 25,000 lbf LOX/Methane Mars Ascent Engine"* (Masten Space Systems)
  - 16-1-H2.02-7555: *"Joining of Tungsten Cermet Nuclear Fuel"* (Plasma Processes)
  - 16-1-H8.03-8031: *"Affordable, Lightweight, Compactly Stowable, High Strength / Stiffness Lander Solar Array"* (Deployable Space Systems)
  - 16-1-H8.03-8153: *"38% Efficient Low-Cost Six-Junction GaAs/InP Solar Cells Using Double Epitaxial Lift-Off"* (MicroLink Devices)
- **Representative Phase II awards**
  - 15-II-H2.01-9296: *"Additively Manufactured Monolithic LOx/Methane Vortex RCS Thruster"* (Parabilis Space Technologies)
  - 15-II-H8.02-9587: *"Efficient, High Power Density Hydrocarbon-Fueled Solid Oxide Stack System"* (Precision Combustion)

LOX / Methane Engine Technology Development

(potential project)

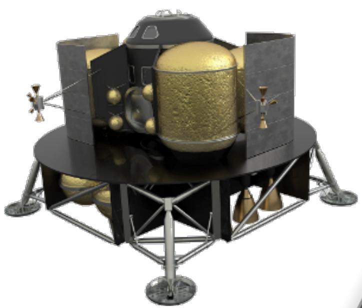
LOX / Methane Engine

- **Needed to inform Mars exploration architecture downselect in the FY20-21 time frame**
  - LOX / methane is suitable for all propulsion architecture options: "split" – "hybrid" – all-chemical
  - Increased mission flexibility due as part of an ISRU-based implementation approach
  - Increased specific impulse compared to conventional space storable propellants
  - Relaxed cryofluid management requirements compared to LH2

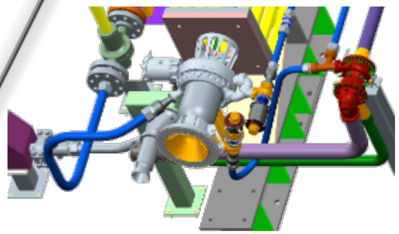
- **Performance characteristics**
  - Common propellant & engine infrastructure
    - Cryogenic propulsion stage main propulsion / SLS kick stage – 22,000 lbf engines
    - Cryogenic propulsion stage RCS – 100 to 1000 lbf thrusters with integrated feed systems
    - Baseline Mars ascent – 22,000 lbf engines utilizing ISRU-generated oxygen
  - Desired performance metrics:
    - Regeneratively cooled pump- or pressure-fed engines
    - 5:1 throttling
    - Isp > 360 sec
    - Lifetime > 300 hours

LOX / Methane Engine:
Architecture & Technology Development Needs

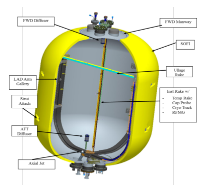
Mars descent vehicle



TECHNOLOGY DEVELOPMENT NEEDS (TRL 4-6)

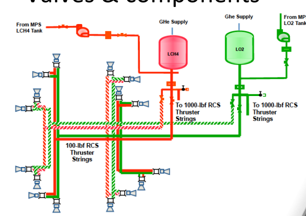


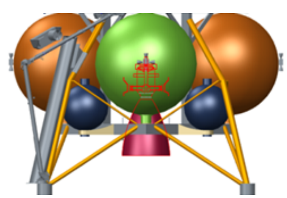
Main propulsion system
- Combustion chamber
- Injectors
- Main valves
- turbopumps



Cryofluid management
- Passive CFM (cryocooler/BAC)
- Active CFM (TVS/MLI/foam)
- Low leak valves
- Helium storage
- Thermal conditioning

Reaction control system
- Thrusters (100 lbf & 1000 lbf)
- Electric pump
- Feed systems
- Valves & components

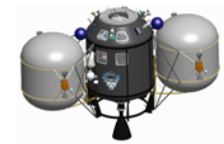




Integrated ground demonstration

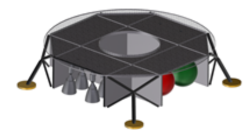
Risk Reduction

Mars Ascent Vehicle

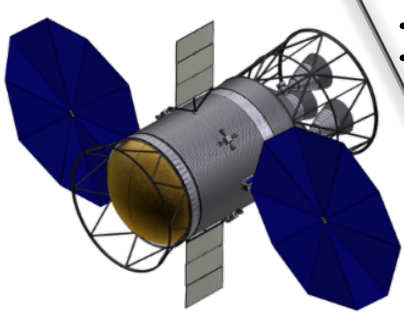


2nd stage

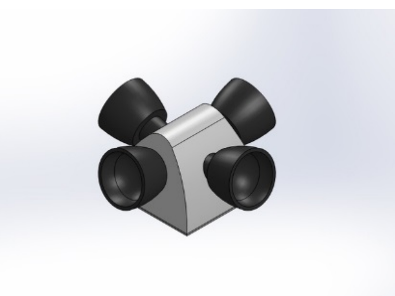
1st stage



Mars Descent Module

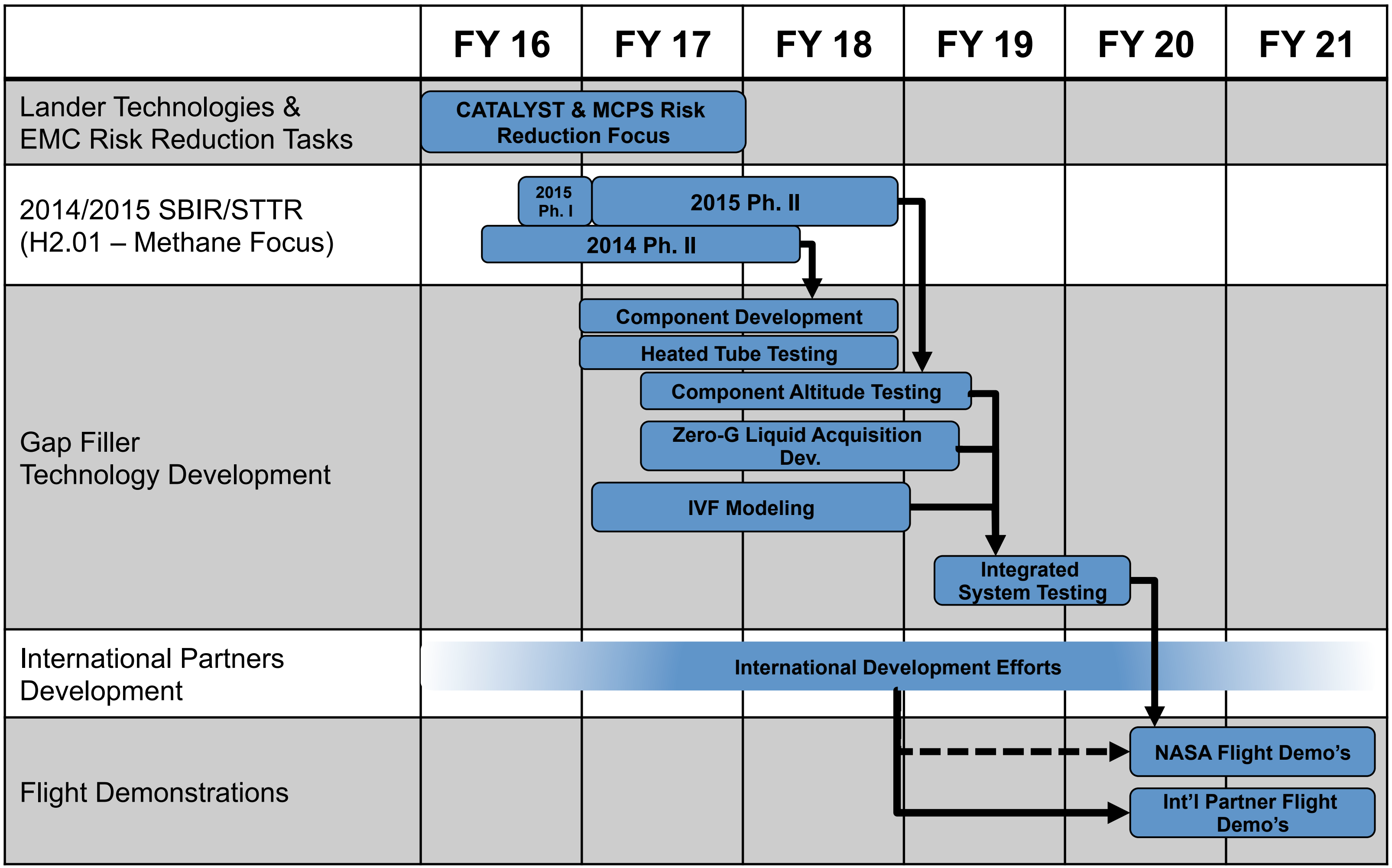


Methane cryogenic propulsion stage



Reaction control system

LOX / Methane Engine:
Notional Technology Development Timeline



*** Notional development plan.**

MON-25 / MMH Engine Technology Development & Flight Demonstration

(potential project)

MON-25 / MMH Engine

- **Provides more efficient solar system access for science missions**
  - Compact, lightweight, low-cost chemical propulsion reduces burden on spacecraft
  - Low-temperature capability facilitates operation in extreme environments
  - Adaptable to main propulsion, reaction control systems, and lander ascent / descent propulsion

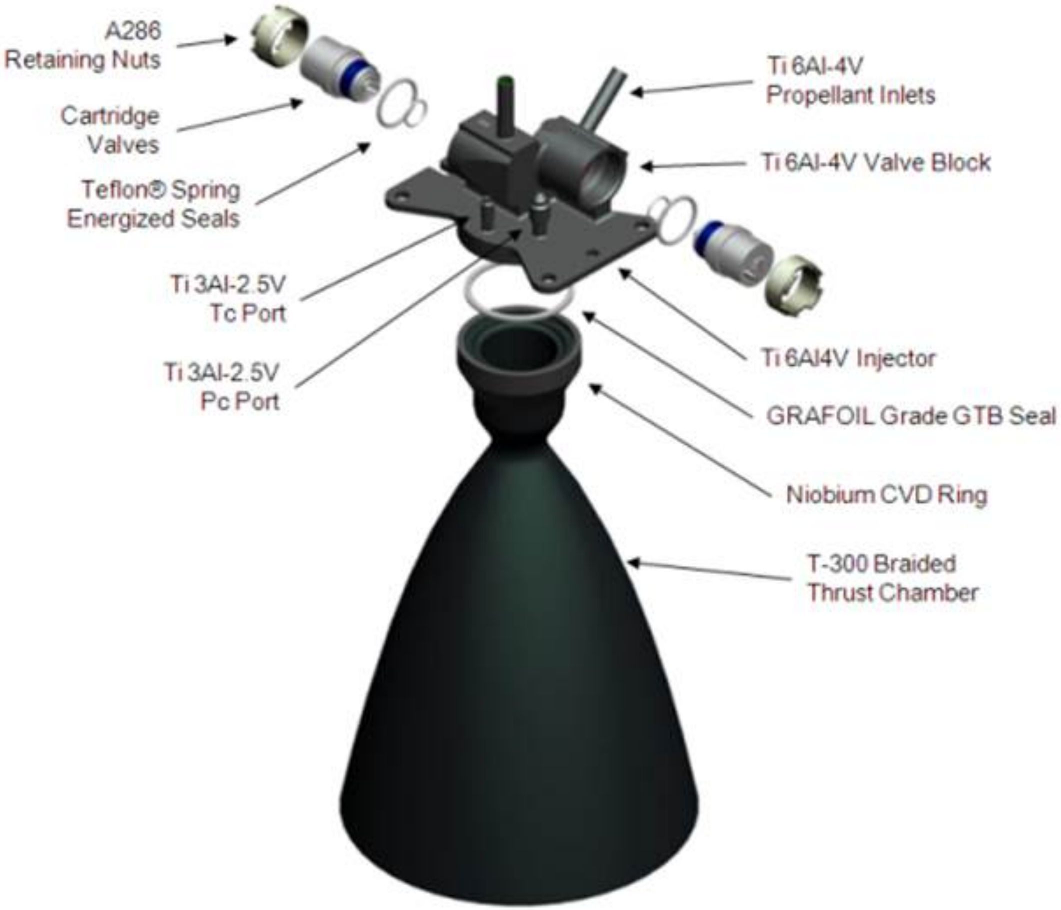
- **Performance characteristics of 100 lbf class engine**
  - Substantially reduced propulsion system SWaP:
    - Reduce propulsion system volume by at least 50%
    - Reduce propulsion system mass by at least 80%
    - Reduced spacecraft power draw for propellant thermal conditioning due to substantially lower freezing point
  - Enhanced affordability
    - Utilize integrated design, composite materials, and advanced manufacturing to reduce propulsion system costs by at least 50%

Current and Future MON / MMH Engines

R-4D-11
Aerojet Rocketdyne
MON-3 / MMH

HiPAT
Aerojet Rocketdyne
MON-3 / MMH

LEROS 2B
Moog
MON-1 / MMH



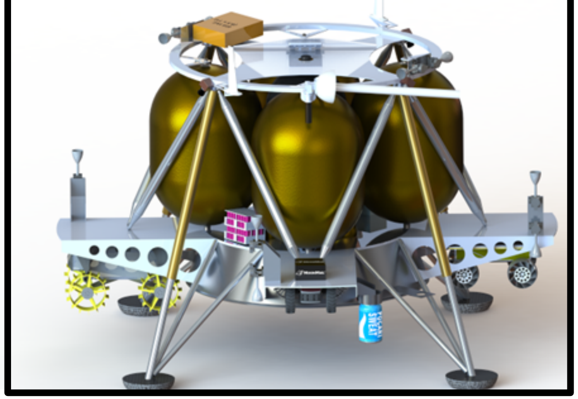
ISE-100

MON-25 / MMH bipropellant thruster
(Aerojet Rocketdyne & NASA)

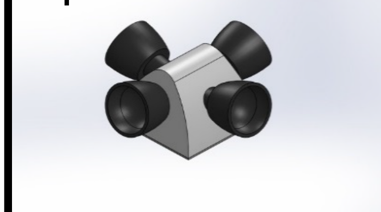
MON-25 / MMH Engine:
Mission Infusion Potential

HEOMD ⟷ SMD

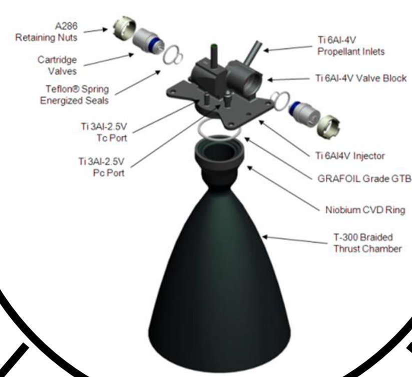
CATALYST Astrobotic Lunar Lander



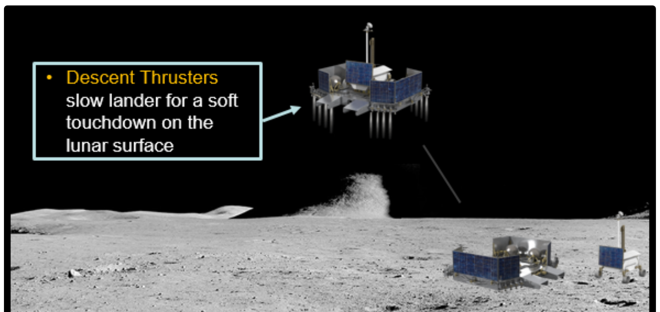
Exploration-class RCS



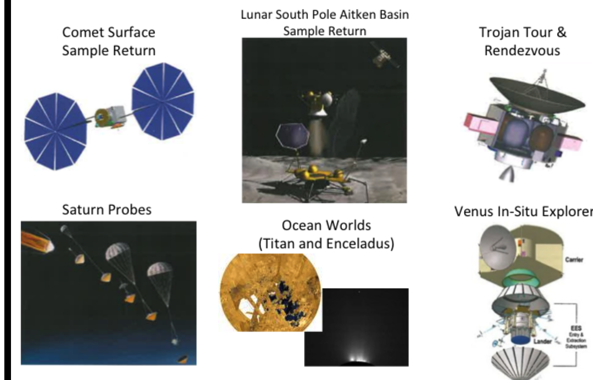
ISE-100
MON-25/MMH Biprop Thruster



Resource Prospector

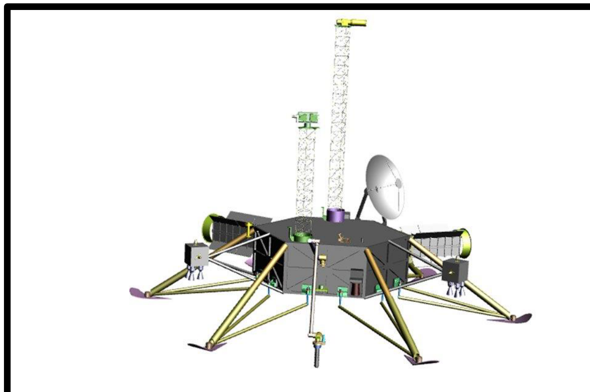


New Frontiers AO



Mars Sample Return

Europa Lander



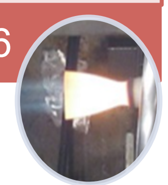
MON-25 / MMH Engine:
Past & Near-Term Technology Maturation Timeline

TRL 1/2
- **Concept Studies**
- Lunar landing mission
  - ✧ Light weight
  - ✧ Low cost
  - ✧ Deep chilled prop.

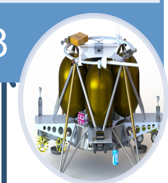
TRL 3/4
- **MDA/MSFC/WSTF**
- 100-lbf DACS Test at Room Temp (2009)
- 5-lbf class Thruster (2010)
- Lessons Learned
- ISE-100 Development

TRL 5
- **AES/SMD Partnership**
- *Design Verification* Test Campaign at AMPT

TRL 6
- **GCD project**
- *Flight Qualification* Test Campaign at AMPT or WSTF



TRL 8
- **Potential Follow-on effort**
- *Flight Demo* ISE-100 on Astrobotic Lunar Lander Mission
- 2018 Launch



TRL 9
- **Flight Proven HW**
- Engine for Multiple Science & Exploration Missions Beyond 2018

2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018

Thruster Development — SMD
Aerojet Rocketdyne contributed 50% of development costs

Prototype Fabrication — SMD
Fabrication & Test Tooling Development Cost

Design Verification Test — SMD & AES
ISE-100 Design Verification Test Campaign at AMPT

Flight Qualification Test — GCD & AES
ISE-100 Flight Qualification Test Campaign at AMPT or WSTF

Fabrication / Flight Demo — Potential follow-on effort
Propulsion System Integration & Flight Demonstration
(Astrobotic $30M Lunar Lander Flight)

Beyond 2018

Flight Proven Propulsion System — Mission Infusion
- Resource Prospector
- New Frontiers AO
- Europa Clipper
- Mars Sample Return
- Exploration-Class RCS
- Multiple other exploration missions

Green Propellant Thruster Technology Development & Flight Demonstration

(current & potential projects)

What Does ‘Green’ Mean In This Context?

- **Significantly easier to transport, store, and transfer than hydrazine**
  - Anyone can acquire the propellant and load it in their own spacecraft
- **Biologically more benign than hydrazine (reduced toxicity)**
- **Environmentally more benign than hydrazine (reduced contamination hazard)**
- **Lower total operations cost than hydrazine**

Other desirable characteristics (if you can get them):

- Higher specific impulse than hydrazine
- Higher bulk density than hydrazine
- Lower freezing point than hydrazine
- Not too difficult to ignite and sustain
- Lower propellant cost than hydrazine

Green Propellant Infusion Mission (GPIM):
An STMD Flight Demonstration Project

Ball Aerospace (PM and PI)
- Program lead
- Outreach
- Project system engineering
- Mission requirements
- Flight thruster performance verification
- Ground and flight data review
- BCP-100
- AI&T
- Launch support
- Flight experiments operations lead
- Responsibility for secondary payloads

Aerojet Redmond (Co-I)
- Green propulsion payload
- 1N and 22N thruster development
- Payload integration
- Ground and flight data review

NASA GRC (Co-I)
- Plume modeling
- Thruster independent testing
- Experimental plume diagnostics
- Ground and flight data review
- NASGRO fatigue analysis

AFRL Edwards (Co-I)
- Propellant (contribution)
- Propellant loading cart (contribution)
- Propellant loading
- Ground and flight data review

NASA GSFC (Co-I)
- Propulsion subsystem peer review
- Propellant slosh test oversight
- Subsystem flow testing

Air Force SMC
- Mission operations
- Ground segment support
- STP-SIV GSE

NASA KSC (Co-I)
- Green propellant handling, loading processes
- Tank material fatigue characterization
- Propellant assay analysis
- IMLI for flight experiment

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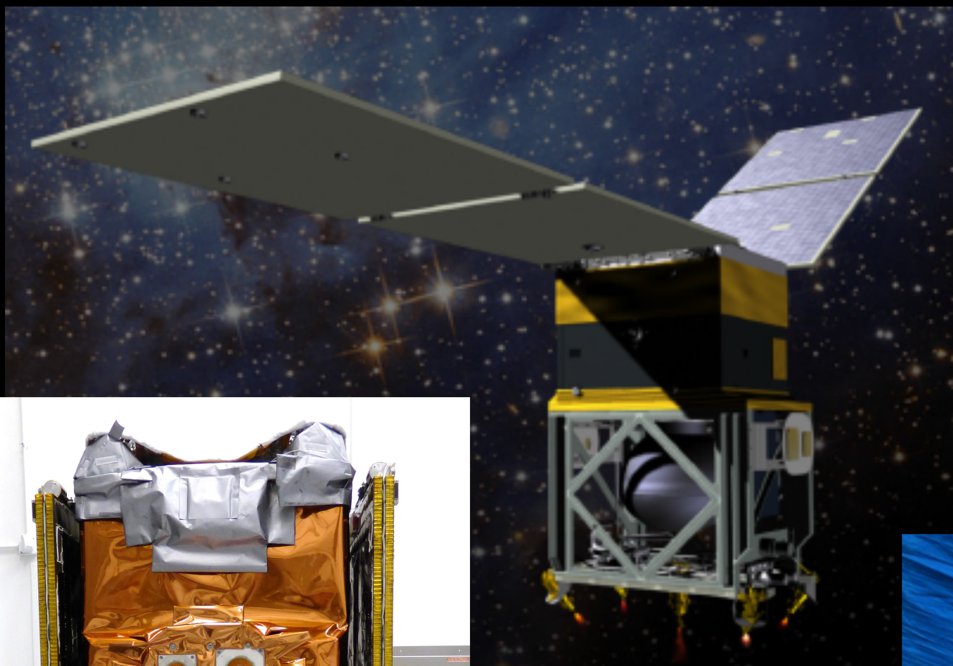
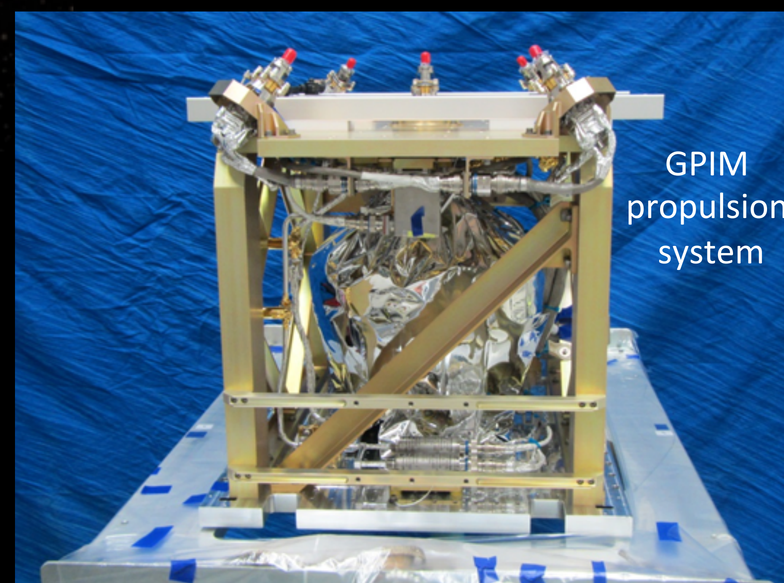
GPIM Flight Hardware



GPIM spacecraft

1 N thrusters



GPIM propulsion system

GPIM Flight Demonstration Objectives

- **Demonstrate on-orbit performance of a complete green propellant propulsion system suitable for an ESPA-class spacecraft**
  - Demonstrate attitude control and fine pointing, orbit inclination change, orbit raising/lowering
- **Demonstrate that AF-M315E delivers a volumetric impulse of at least 40% greater than hydrazine**
- **Bring AF-M315E and compatible tanks, valves, and thrusters to an operational level suitable for NASA and commercial spaceflight missions**
- **Demonstrate that green propellants offer shorter launch processing time and lower processing costs**
- **Produce a detailed report comparing all aspects of ground and on-orbit propellant operations for AF-M315E and hydrazine**

GPIM Concept of Operations

- **Launched as an ESPA secondary payload aboard the USAF STP-2 mission on a Falcon Heavy in Mar 2017 (or later)**
- **USAF operates the spacecraft from Multi-Mission Satellite Operations Center using AF Satellite Control Network ground stations**

	Number of Days	ΔV (m/sec)	AF-315 (kg)	Comment
Commissioning	21	-	-	Bus commissioning
Thruster Checkout	7	-	0.7	Open latch valve, verify telemetry, heater operations. Brief functional verification, validate control logic for 22N steady-state, 4 x 1N duty cycled
Orbit Lowering	3	50.65	4.094	Lower from 720 km drop-off orbit to 625 km to meet 25 year re-entry requirement
ACS Demonstration, Thruster Performance 1	10	-	0.1	Verify ACS: three axis control, min prop consumption with hold, Measurement of I-bit, repeatability, thrust, thermal performance
Insertion Point for Secondary	105			Option for secondary payload operations (625 km/24 deg inclination)
Inclination Change	7	32.91	2.68	Demonstrate long term firing, change inclination +0.25 deg
ACS Demonstration, Thruster Performance 2	10	-	0.1	Measurement of I-bit, repeatability, thrust, thermal performance
Insertion Point for Secondary	105			Option for secondary payload operations (625 km/24.5 deg inclin)
Orbit Lowering	5	54.45	4.579	Lower orbit from 625 to 525 km
ACS Demonstration, Thruster Performance 3	10	-	0.1	Measurement of I-bit, repeatability, thrust, thermal performance
Insertion Point for Secondary	105			Option for secondary payload operations (525 km/24.5 deg inclin)
Final Orbit Lowering	3	22.11	1.795	Lower orbit from 525 to <500 km, deplete propellant tank

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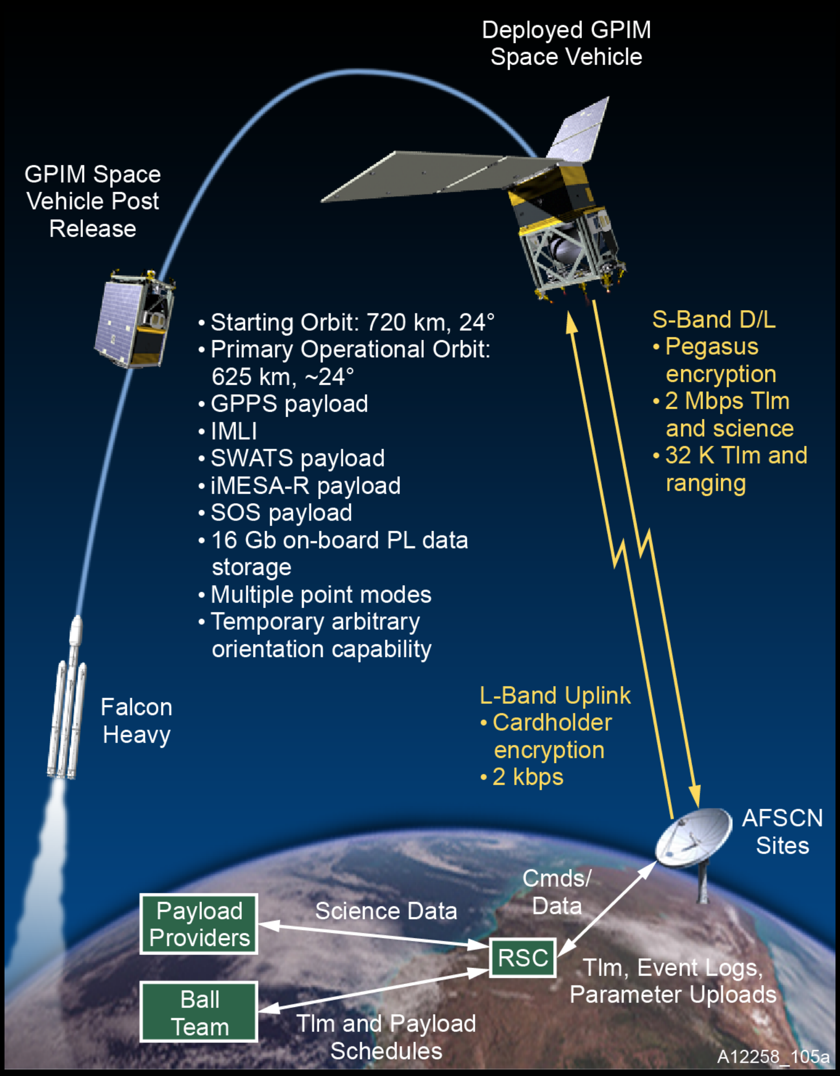


Where Do We Go After GPIM?

- Update design of 1 N AF-M315E thruster to improve manufacturability and reduce cost
- Development and qualification of larger (5 N, 22 N, 220 N, 445 N) green propellant thrusters
- Continued development of efficient catalyst systems (or noncatalytic ignition methods?) for green propellants
- Investigate the viability of green propellants with lower flame temperatures even at the expense of performance benefits
- Infuse green propellant propulsion systems into actual missions; repeatedly demonstrate that there are total mission cost benefits to green propellants

Green Propellant 1 N Thruster Technology Maturation Project

ACO Topic 4: Green Propellant Thruster Technology Qualification

Title: GR-1 ARGG Collaboration

Company Overview

Aerojet Rocketdyne (AR) is a $1.5B U.S. company specializing in advanced aerospace propulsion technologies. AR is the only domestic provider of all four propulsion types (liquid, solid, air-breathing and electric).

Project Overview

This effort will revise the GR-1 thruster design to implement design improvements that were uncovered during the NASA STMD GPIM program. This project includes initial heavyweight thruster testing at GRC to improve injector design and optimize catalyst bed diameter. After manufacturing the improved GR-1 thruster, it will be taken through qualification testing again at GRC. In support of NASA infusion, GSFC will lead all test planning.

Technology Overview

The GR-1 thruster operates on the green propellant, AF-M315E, developed by AFRL. Under the NASA STMD GPIM program this thruster will be matured to TRL=7.

The GR-1 thruster is the first design iteration. To enhance infusion, it is recommended that potential improvements for manufacturability and cost that were uncovered throughout the GPIM thruster design and manufacturing process, be implemented to improve competitiveness.

Commercialization Overview

The GR-1 thruster is the first in a new green propulsion product line for NASA, DoD, and commercial companies for space propulsion applications.

AR is experiencing strong demand for a non-toxic propellant replacement to hydrazine for a wide range of applications. The green propulsion technology is estimated to become a >$50M/year business within the US alone by 2021.

Green Propellant 5 N Thruster Technology Maturation Project

ACO- Emerging Space Technology

5N Green Monopropellant Thruster Maturation

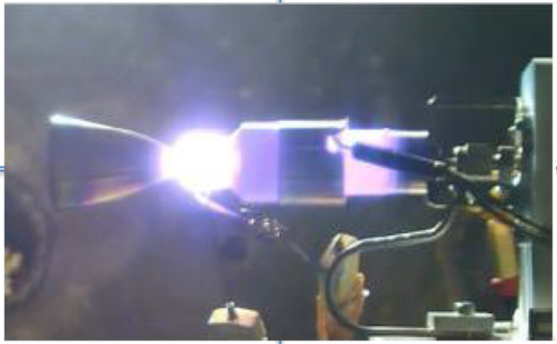
Company Overview

Busek Company Inc.
11 Tech Circle
Natick, MA 01760

#Employees: 46

Busek is a small business focused on the development of both electric and chemical in space propulsion.

Busek is teamed with the chemical propulsion branches at NASA Glenn and NASA Marshall



Technology Overview

Busek has developed an unique catalyst for AF-M315E thrusters, most recently with a 5N thruster BGT-5. The thruster requires performance verification, life test, and additional understanding of operational characteristics.

Thruster will be validated in lab environment by the start of this program, and completed life test and operation validation at the end.

Beginning TRL:5 End TRL:6

Project Overview

The team proposes to test two engineering model (EM) BGT-5 thrusters with AF-M315E to confirm Busek's measured performance, gain significant additional run times including a life test, and plume characterization.

Price: ~$1M
Schedule: 22 months
Major Milestones:

- Plume diagnostics
- Thrust/Isp Verified
- Life Test Completed

Commercialization Overview

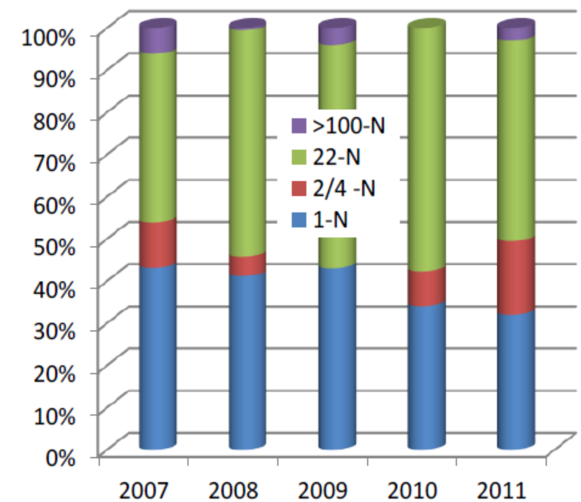
Three paths of commercialization exist for Busek products and technologies. 1) Fabrication of complete thruster Systems 2) Fabrication of Thrusters 3) Thruster licensing

Market size: 24 shipsets (5N) per year – indicating a $3-4M market

The addition of commercial, flight-ready GMTs would be of large significance to Busek, satellite integrators (primes), as well as NASA and the DoD, enabling new missions and lowering costs as a non-toxic option.

22 N Class Green Propellant Thruster

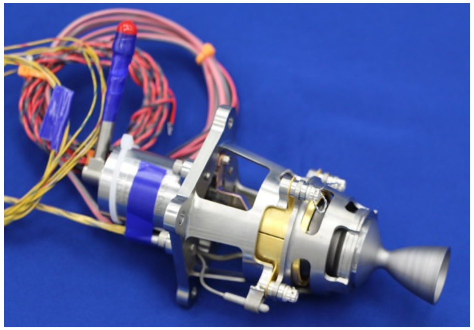
- Developing the 22 N thrust class will facilitate adoption of green propellant technology by NASA & commercial missions
  - 22 N thrust class is 40-50% of the hydrazine thruster market
  - Green propellants deliver improved monopropellant performance for increased mission capability
  - Green propellants provide safer handling and reduced ground operations burden and costs



Aerojet Rocketdyne market share by thrust class (AIAA-2013-3849)

- **Performance characteristics**
  - Increase density specific impulse by at least 25%
  - Reduce propellant freezing point by up to 40 C
  - Enhanced affordability
    - > Eliminate necessity for SCAPE suit loading operations
    - > Reduce ground operations costs by at least 65%

Aerojet Rocketdyne GR-22 AF-M315E monopropellant thruster



ECAPS family of LMP-103S monopropellant thrusters

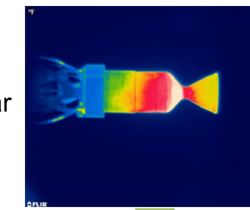
Green Propellant Thrusters:
Interagency Simplified Technology Maturation Roadmap

U.S. AIR FORCE

HIGH PRIORITY

<u>Over the next 3 years</u>, concentrate on the high priority tasks which helps to enable larger scale thrusters with focus on maturing up to the 22-N class

- Propellant Throughput (duty cycles, catalyst/thruster life)
- Plume Measurements (anchor models, effects on optical systems & solar array)
- Transient Thermal Analysis (non-CFD, effects on soak back)
- Valve work (configuration, seals, operation)
- Decomposition Chemistry (sooting, corrosion, modeling & testing)
- Power Consumption (catbed heating and ops impact for human missions)



MEDIUM PRIORITY

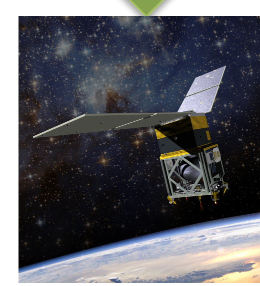
Over the next 3-7 years, focus on the medium priority tasks and deliver a 110-N thruster that has mutual benefit to both NASA and DoD

- M&P Investigations (bladder/material compatibility)
- Performance Trades (propellant variation, scaling effects)
- Loading Demonstrations (at launch facilities)
- System Modeling (influenced by CFD and plume data)
- CFD (kinetics)
- Storage & Transport (of loaded prop)

LOW PRIORITY

Over the next 7-10 years, deliver a 440-N thruster for NASA and commercial satellite providers & develop alternate applications

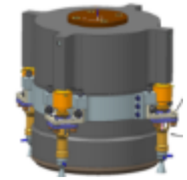
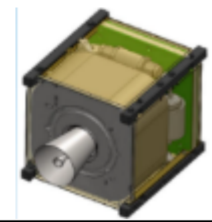
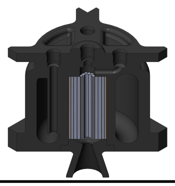
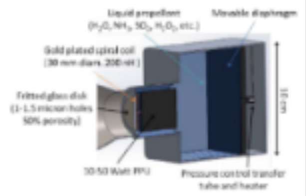
- Contamination (purity/quality impacts)
- High Radiation Flux (material selection)
- Alternate Applications (APU/EPU, etc.)



Cubesat / Smallsat Propulsion Technology Development & Flight Demonstration

(current projects)

Summary of Recent Cubesat Propulsion Technology Maturation Projects

Propulsion System	TRL Start	Design	TRL Finish	Flight Demo Readiness
Aerojet (MPS-120) -- CHAMPS Module - $249K **Description**: Provides a 1U high impulse propulsion module using hydrazine (high impulse), used for orbit transfer/de-orbit in LEO. Requires Hydrazine waiver.	3		6	Now
Busek (RF Ion thruster) – $150K **Description**: 3 cm thruster shown that can run both Iodine or Xenon. Provides for 3 cm dia. RF-Ion thruster using solar electric propulsion, and Iodine (initially solid) as propellant, low pressure, high impulse, and low thrust. Thruster using Xenon is at TRL 5	2 Iodin e Feed		3 Iodin e Feed	Xenon in 1 Year Iodine in 4 Years
Busek (Green Propulsion) - $233K **Description:** Development of a CubeSat level green propellant (alternate to Hydrazine), uses a bellows tank thermally activated solid gas generator for pressurization	3		4	3 Years
Aerospace (Hybrid Rocket Motor) - $200K **Description:** Development of a CubeSat level Hybrid rocket motor using N_2O and a solid propellant in a 1U tank configuration	2		5	2.5 Years
MSNW, LLC (ICE Thruster) - $125K **Description:** Development of an Inductively coupled electromagnetic thruster (ICE) for CubeSat propulsion	2		3	1 - 2 years

Small Spacecraft Propulsion Technology Maturation Project

Tipping Point Technologies

HYDROS Thruster

Company Overview

Tethers Unlimited, Inc.

Address: 11711 N. Creek Pkwy S., D113
Bothell, WA 98011

 # Employees: 30

Description: TUI develops transformative technologies for space and defense missions:

- Propulsion
- Power
- Communications
- Additive manufacturing

Teaming Partners:

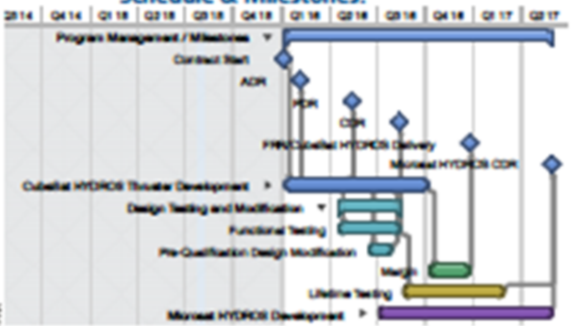
- Millennium Space Systems (cost-share customer)
- Air Force Institute of Technology

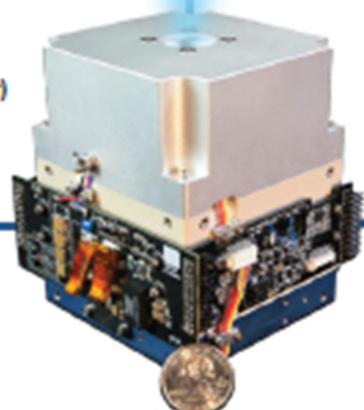
Project Overview

Price

$970K NASA Investment
+ $573K Customer & Corporate Cost Share

Schedule & Milestones:





HYDROS Technology Overview:

- Hybrid chemical/EP technology to provide safe, high-performance propulsion for secondary payloads
- Uses electrolysis cell to split water propellant into gaseous hydrogen and oxygen, pressurizing separate gas storage volumes
- Burns hydrogen and oxygen in simple bipropellant thruster to provide up to 1N @ 258s

Required Development:

- Optimize system designs for CubeSat and Microsat applications
- Integrate flight-configuration control electronics
- Functional, Environmental, & Lifetime testing to establish TRL necessary for commercial sales

TRL:

Start: SBIR & post-SBIR testing in vacuum established TRL-5

End: Functional, Qual, & Lifetime testing will establish TRL-6

Technology Overview

High-Thrust, High-Isp Propulsion with Non-Toxic, Non-Explosive, Non-Pressurized, ISRU-Compatible Propellant: WATER

Commercialization Overview

Market Value:

Unit cost ≤$100K

10-50 units/yr

~1-5M/yr

Commercial Applications:

- Orbit raising, deorbit, & stationkeeping of LEO constellations –
- HYDROS baselined for 1 government-funded multi-satellite system
- Multiple commercial & government SATCOM and EO constellations are evaluating HYDROS (RFQ's)

NASA Applications:

- Science & Exploration missions conducted using ride-share secondaries and requiring orbit maneuvering, stationkeeping, or drag makeup

Tipping Point

Enabling High Thrust High Delta-V Green Propulsion for CubeSats

Company Overview

Employees: 5,000
2014 Sales: $1.6B

AEROJET ROCKETDYNE *The Rocket Company*
11411 139th PL NE
Redmond, WA 98052

Aerojet Rocketdyne (AR) is a leader in satellite propulsion systems
- Provides currently 80% in-space propulsion
- Provides approximately five propulsion systems per year
- Provided propulsion systems for spacecraft to every planet
- Develops wide range of propulsion systems –mono-, bi-, and solid propellant as well as electric propulsion

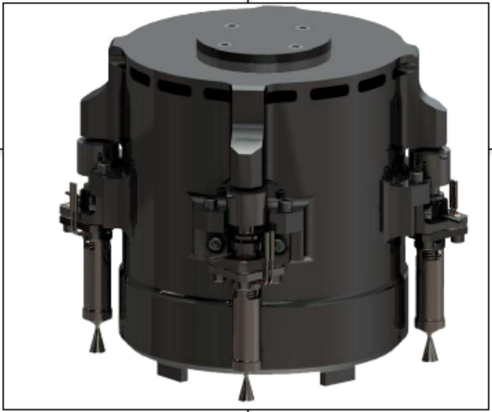
US Leader in investment in green propellant
Leader in additive manufacturing-named #1 most innovative space company
-Fast Company Magazine

Project Overview

High thrust, high delta-V, green propellant propulsion system for CubSats and SmallSats
- Deliver within 18 month the MPS-130 (1U green propulsion system) for flight
- MPS-130 is highly integrated to reduce cost, and highly scalable to maximize applications
- Transform the mission capabilities of CubeSats and SmallSats
- Remove the NRE barrier to commercial use

Schedule: 18 mos Kickoff to delivery
- 1.5 mos schedule reserve
- Hotfire: at 11 mos
- CDR: at 12 mos
- Flight hardware delivery: at 18 mos

Price: NASA - $1,941K, AR - $647K



Technology Overview

High thrust, high delta-V, green propellant propulsion system for CubSats and SmallSats

Key Development:
- Miniaturization of rocket engines
- Scalable additive manufactured piston tank
- Refine design of
  - Catalyst bed heater
  - Catalyst chamber
  - Thermal actuated burst disk

Transformative performance for CubeSats and SmallSats
- 30x cold gas delta-V capability
- 1.5x density I_{sp} and impulse of hydrazine

Move technology from TRL 5 to TRL 7 flight demonstration
- Key technologies Additive Manufacturing and Green Propulsion
- Both technologies demonstrated
- Successfully hot fired MPS-120 AM CubeSat System
- Delivered GPIM propulsion system flight hardware

Commercialization Overview

Market: by 2016 CubeSat market expected to see >80% CAGR:
- 300 CubeSats forecasted to be launched in 2016
- Over 1,700 satellites from 1-50 kg expected over next five years

AR has been working with satellite operators for over 3 years on CubeSat/SmallSat propulsion solutions

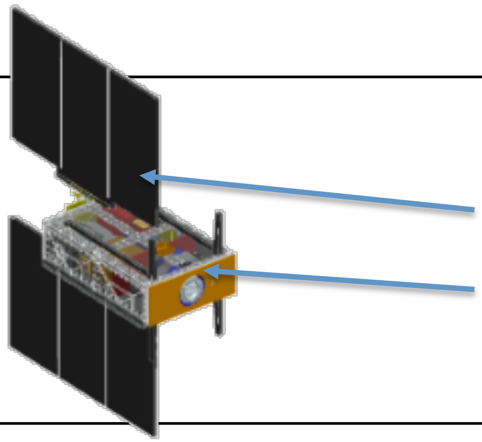
Potential NASA application:
- Highly capability propulsion systems for NASA lunar or inter planetary CubeSat missions proposed by JPL and ARC
- CubeSats and SmallSats launched from ISS-AR is working with Surrey Satellite and NanoRacks on SmallSats from ISS

Potential commercial application/market:
- CubeSat remote sensing constellations and telecom constellations
- PlanetLabs, Skybox other operators only use green propellant

Potential other USG or non-USG application:
- Multiple civil and defense agencies considering, comm, debris removal, SA, remote sensing

Pathfinder Technology Demonstrator Project

The Pathfinder Technology Demonstrator project will conduct a rapid cadence of technology demonstration missions



Spacecraft Specifications

- Mass: 10-12kg
- Quantity: One 6U CubeSat
- Orbit: 350-800 km, 51°, 98° incl.
- Size: 50 x 9.1 x 13.5 (*inches*)
- Communication: via Globalstar

Mission Description

The Pathfinder Technology Demonstrator project will demonstrate novel spacecraft technologies in Low Earth Orbit. The cubesat will be operated by NASA, in partnership with the spacecraft and technology payload vendors using either a NASA or vendor ground data system.

Status

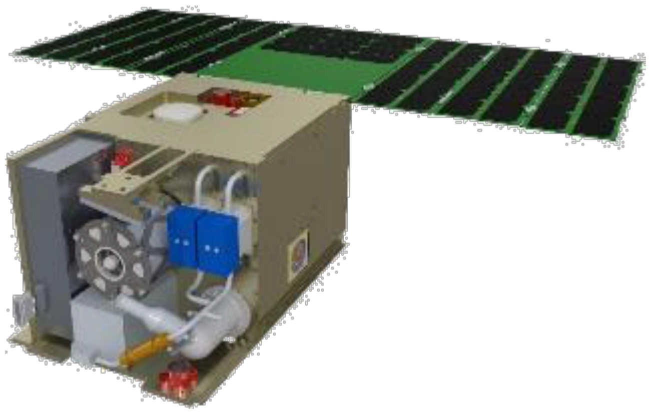
Selection Evaluation Committee completed spacecraft vendor evaluations and submitted findings for review to Ames Legal/Policy. Awaiting completion of that review.

Pathfinder Technology Demonstration:
Expected and Potential Payloads

- **Propulsion technologies:**
  - Busek microelectrospray propulsion – SBIR Commercialization Readiness Program effort in progress
  - Busek RF ion thruster – SBIR Select Phase 2 award approved
  - Tethers Unlimited Hydros thruster – STMD Tipping Point project in progress
  - Aerojet 1 N green propellant thruster – STMD Tipping Point project in progress
  - And many other candidates …

- **Other technologies:**
  - Blue Canyon HyperXACT star tracker – STMD Tipping Point project in progress
  - Northrop Grumman Reaction Sphere – STMD Tipping Point project in progress
  - Laser Communications – possible SCaN partnership
  - Raincube – possible SMD partnership
  - Optical Communications – Fibertek
  - And many other candidates …

iSat: Iodine Hall Thruster Flight Demonstration



Spacecraft Specifications

- Mass: 24kg
- Quantity: One 12U CubeSat
- Orbit: 700km initial orbit (SSO), 98.1880° incl.
- Size: 20cm x 20cm x 30cm
- Communication: S-Band

Mission Description

The iSAT Project is the maturation of iodine Hall technology to enable high ΔV primary propulsion for NanoSats (1-10kg), MicroSats (10-100kg) and MiniSats (100-500kg) with the culmination of a technology flight demonstration. The iSAT project has three major elements: iodine Hall technology development support, the iSAT flight demonstration and future technology risk reduction. In addition to the iodine Hall focus, this project recognizes the market growth potential for SmallSats and the gap in commercially off the shelf (COTS) options for higher capable spacecraft: higher power systems, additional thermal control, higher data rates, improved stability and attitude control, etc.

Status

The iSAT project completed acceptance testing of the Busek 200W thruster. The team is preparing for an Interim Design Review in December 2015 with a final Critical Design Review in Fall 2016.

iSAT
Iodine Satellite

Critical Milestones

ATP	SRR	PDR	CDR	FHR	FRR/ORR	Launch	Mission Ops	Mission Duration	Project Closure
7/18/14	7/28/14	12/9/14	Fall 2016	02/28/17	03/15/17	12/1/2017	12/15/2017	6 Months	06/15/2018

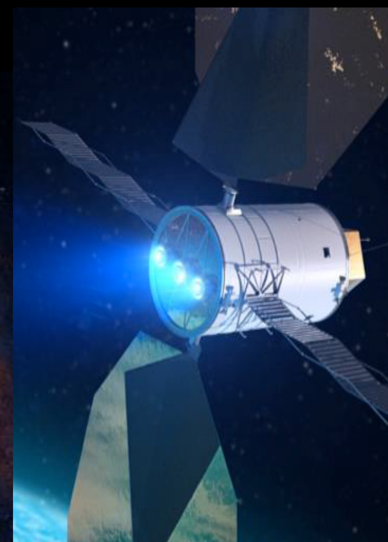
Large Deployable Solar Array Technology Development

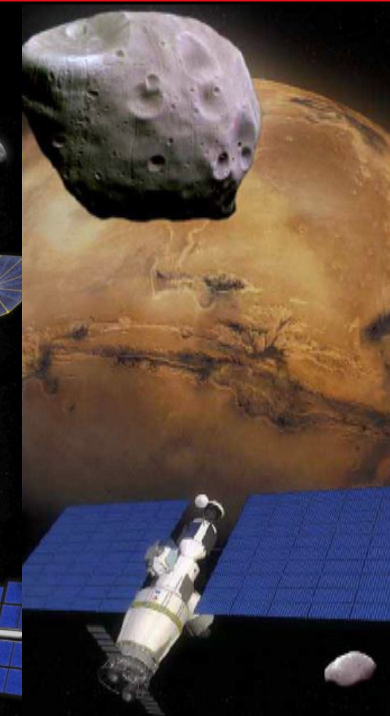
(past & current projects)

Large Deployable Solar Arrays:
Synergy of Power & Propulsion

Solar electric propulsion provides a mission pull for the development of large deployable solar arrays





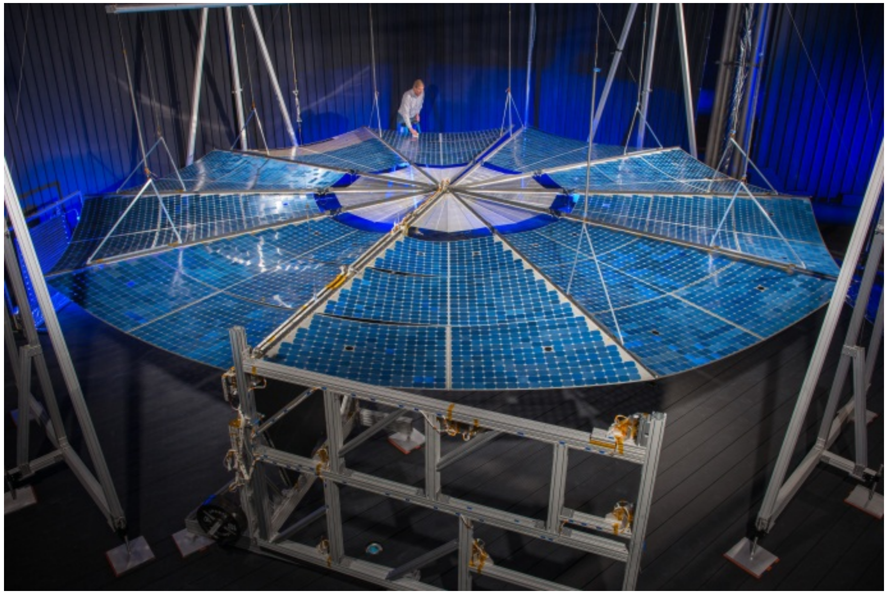


Deep Space-1 1998	Dawn 2007	SEP TDM 2018	Mid-term Exploration 2020s	Far-term Exploration 2030s
Technology Demonstration	Deep-Space Science Mission	Operational mission with adv. technology	Crewed mission to cis-lunar space	Crewed mission beyond Earth space
490 kg	1220 kg	~2000 kg	~30,000 kg	~70,000 kg
2.5 kW power 2 kW EP	10 kW power 2.5 kW EP	~30 kW power ~20 kW EP	~30 kW power ~20 kW EP	~350 kW power ~300 kW EP
ΔV 2.7 km/s	ΔV 10 km/s	ΔV >10 km/s	ΔV ~ 3 km/s	ΔV ~ 8 km/s

Large Deployable Solar Arrays:
Technology Maturation Results

- Novel 20 kW class solar arrays designed and built to advance TRL from 4 to 5+ for SEP missions; extensible to 300 kW class
- Improvements over state of the art in power, voltage, mass, stowed volume, deployed strength/stiffness, and radiation hardness
- Testing included stowed acoustic/random vibration; thermal extreme vacuum deployments; deployed strength/stiffness; deployed structural dynamics in ambient & vacuum; and photovoltaic coupon plasma interactions up to 600 V in ambient and EP plasma plume

ATK MegaFlex



DSS Roll Out Solar Array (ROSA)

Large Deployable Solar Arrays: Key Performance Parameters

Parameter	SOA (Large GEO Satellite)	Goal	Goal / SOA	DSS ROSA	ATK MegaFlex
Power	<20 kW	30 kW – 50 kW, extensibility to >250 kW	2x–10x	38 kW BOL Ext to 1 MW	34 kW BOL Ext to 440 kW
Operating Voltage	32 V – 105 V	160 V – 300 V	1.5x–3x	✔	✔
Specific Mass	60 W/kg	>100 W/kg	1.7x	164 W/kg BOL 117 W/kg EOL	150 W/kg BOL 104 W/kg EOL
Specific Stowed Volume	10 kW/m^3	>40 kW/m^3	4x	42 kW/m^3 BOL	41 kW/m^3 BOL
Deployed Frequency	>0.05 Hz	>0.1 Hz	2x	✔	✔
Deployed Strength	0.005 g	>0.1 g	20x	✔	✔
Radiation	5×10^{14} e/cm^2 DENI	2×10^{15} e/cm^2 DENI	4x	✔	✔

Extreme Environment Solar Array Technology Development

(current project)

Extreme Environment Solar Power Project

- The Extreme Environment Solar Power Project seeks to develop solar cell / solar array technologies for mission applications in high radiation and low solar flux environments
  - Project objectives will be accomplished by industry partners selected through competitive solicitation
  - Addresses NASA outer planet missions subjected to intense radiation (such as at Jupiter) while experiencing less than 10% of the solar flux at Earth

- **Expected Technology Advancements**
  - Develop photovoltaic cell chemistry improvements for higher performance in low intensity, low temperature environments
  - Develop array configuration options that improve performance in extreme environments
  - Increase array efficiency and life
  - Decrease system mass & cost

Key Performance Parameters

Performance Parameter	State of the Art	Threshold Value	Project Goal
Beginning of Life (BOL) Cell Efficiency (%)	30	33	35
End of Life (EOL) Cell Efficiency (%)	21	25	28
Specific Power (W/kg)	70	100	120
Stowed Volume (kW/m^3)	15-30	45	60

Extreme Environment Solar Power Project:
Status

- Four proposals were selected for contract negotiations in March
  - "Solar Array for Low-intensity Low Temperature and High-Radiation Environments" (JPL)
  - "Transformational Solar Array for Extreme Environments (JHU-APL)
  - "Micro-Concentrator Solar Array Technology for Extreme Environments" (Boeing)
  - "Concentrator Solar Power Systems for Low-intensity Low Temperature and High Radiation Game Changing Technology Development" (ATK)

- Awards are expected in July or August

- Option I (12 mo duration, $1.25M each) is for development of component test hardware

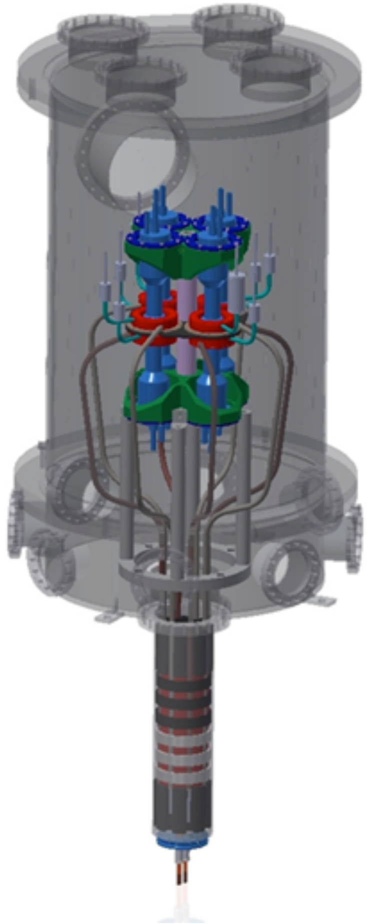
- Option II (15 mo duration, $2.0 M each) is for development of scalable system hardware

Small Nuclear Fission Power Technology Development

(current & potential projects)

Small Nuclear Fission Power Project: Overview

- Innovation:
  - A compact, low cost, fission reactor for exploration and science, scalable from 1 kW to 10 kW electric
  - Novel integration of available U-235 fuel form, passive sodium heat pipes, and flight-ready Stirling convertors
- Impact:
  - Provides modular option for HEOMD Mars surface missions
  - Potentially enables SMD Decadal Survey missions without reliance on Pu-238
- Goals:
  - Full 1 kW-scale nuclear test at prototypic operating conditions of prototype U-235 reactor core coupled to flight-like Stirling convertors with sodium heat pipes
  - Detailed design concept that verifies scalability to 10 kW electric
- Leveraging:
  - Leverages existing DOE/NNSA nuclear materials, manufacturing capabilities, test facilities, and nuclear safety expertise
  - U235 provided free-of-charge to NASA from large stockpile surplus
  - DOE/NNSA co-funding (~$5M) to complete nuclear prototype test



Small Nuclear Fission Power Project:
Major Elements

- **KRUSTY – Kilowatt Reactor Using Stirling Technology – a 1 kWe reactor prototype test**
  - **Materials testing** to fill gaps in UMo fuel data (e.g., temperature dependent creep) and evaluate interactions/diffusion at heat pipe interface
  - Design, build, and **test a reactor thermal prototype** using an electrically-heated stainless-steel core mockup and a full array of experimental Na heat pipes to demonstrate thermal performance
  - Conduct a **non-nuclear system test** using an electrically-heated DU core with prototypic Na heat pipes coupled to a flight-like Stirling power module with 2 functional convertors and 6 calorimetric simulators
  - Complete a **nuclear system demonstration** with a prototype HEU core and a flight-like neutron reflector to achieve sustained nuclear criticality at representative space system operating conditions

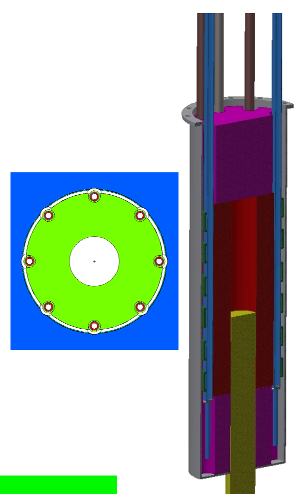
4.3 kW$_t$ / 1 kW$_e$

28.4 kg U235

0.09% fuel burnup

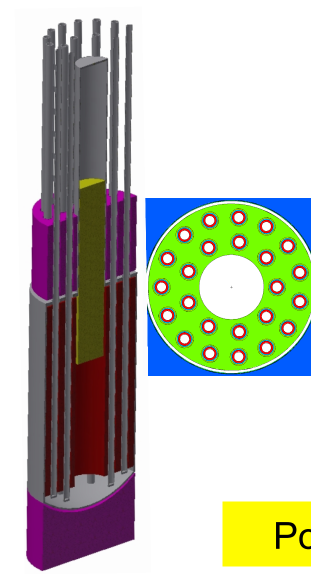
8X 3/8" heat pipes

~4.5" dia x 9.5" tall



Current project

KRUSTY experiment design is scalable from 1 kWe to 10 kWe



43.3 kW$_t$ / 10 kW$_e$

43.7 kg U235

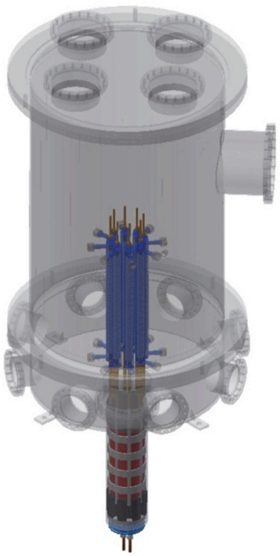
0.56% fuel burnup

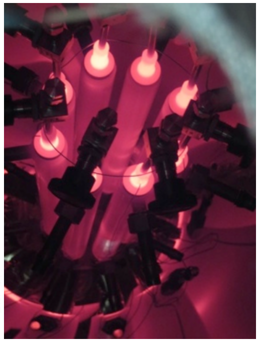
24X 5/8" heat pipes

~6" dia x 11" tall

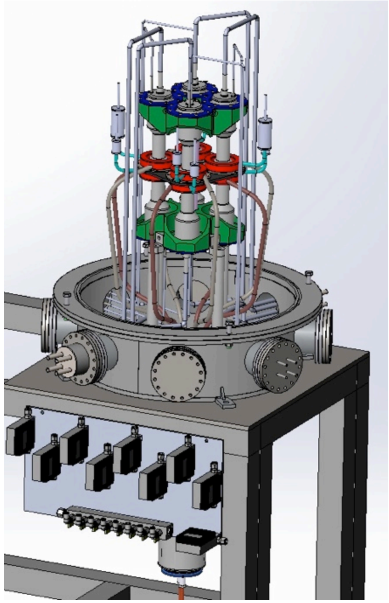
Potential project

Small Nuclear Fission Power Project:
Project Timeline

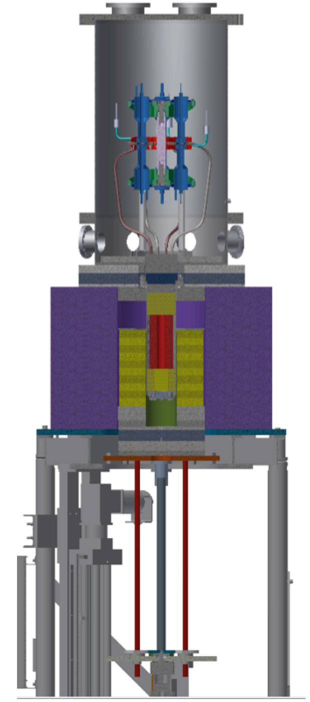




2015:
Thermal prototype & materials testing at GRC and NNSA/Y-12



2016:
Thermal vacuum system test with DU core and Stirling convertors at GRC



2017:
Reactor critical experiment with HEU Core at NNSS

NASA · NNSA National Nuclear Security Administration · Los Alamos National Laboratory EST.1943 · Y-12 National Security Complex · NNSA Nevada National Security Site

Commonality of Technical Challenges in 1 kWe and 10 kWe systems

- Existing Comet test stand at NNSS
- External heat pipe channels
- 8 perimeter, clamped heat pipes
- Single HP-to-Stirling thermal interface
- Existing Stirling units from RPS

TRL 5 for 1 kW_e

- Prototypic reactor core
- Material properties & compatibility
- UMo fuel casting, machining & inspection
- BeO reflector material & configuration
- Facility controlled reactivity insertion/removal
- Reactivity feedback control
- System performance – start, run, stop, restart
- Nuclear test safety and contingencies
- Nuclear performance code validation

Common Elements

TRL 5 for 10 kW_e

10 kWe specific

- New test stand at NNSS
- Internal heat pipe channels
- 24 brazed or liquid-metal bonded heat pipes
- Shared HP-to-Stirling thermal bus
- Larger, commercial-adapted power conversion units

Need Mission specific reqmts

- Fuel irradiation studies
- Prototypic reactor control/shielding
- End-to-end system operations
- Subsystem life testing
- Environmental testing
- Nuclear launch safety

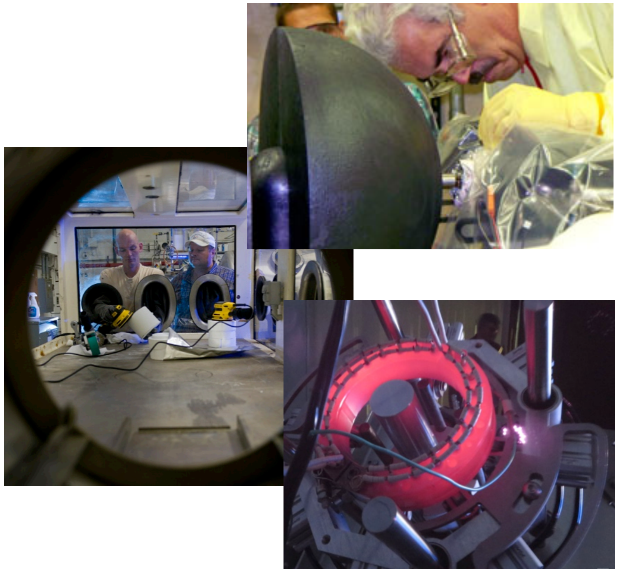
TRL 6

Technology Development Synergies Between NTP and Nuclear Surface Power

- **Common infrastructure:**
  - DOE / National Nuclear Security Administration – planning and executing nuclear tests; criticality safety relevant to space reactor ground handling and launch
  - National Criticality Experiments Research Center at Nevada National Security Site – testing of nuclear systems (Device Assembly Facility, U1A Complex, P-Tunnel, Jackass Flats)
  - Uranium storage, processing, manufacturing & shipping (Y-12 National Security Complex)
  - Nuclear fuel production with benchmarked quality control (BWXT)
  - Non-nuclear system testing and high-fidelity reactor thermal simulators (NASA)

- **Common engineering:**
  - Modeling & simulation: Integrated, multi-physics, nuclear performance codes (LANL); computational fluid dynamic and thermal hydraulic modeling (NASA & DOE)
  - High-temperature materials performance under irradiation (ORNL)
  - Nuclear criticality testing and neutron cross section data
  - Nuclear materials handling and radiation contingencies
  - Reactor core assembly procedures; reactor testing procedures
  - Nuclear launch safety analysis and destructive testing (SNL)
  - Nuclear launch processing facilities and security/safeguards (KSC)

- **Common components:**
  - Enriched uranium fuels / fuel alloys designed for high strength at temperature
  - Beryllium or beryllium oxide neutron reflectors
  - Boron-carbide reactor control elements
  - Radiation tolerant instrumentation sensors and drive motors
  - Tungsten and lithium hydride shielding materials



Ultra-Low Temperature Battery Technology Development

(current project)

Ultra-Low Temperature Batteries Project

Develop low temperature batteries that enable an extended Europa Lander Mission architecture:

① **Enable and increase the landed mission lifetime (relative to commercially available primary batteries) allowing science operations to proceed until an additional Europa Orbiter pass**

② **Reduces the mass and power consumption to enable an additional science instrument and operations**

③ **Greatly enhances power margins, mass margins, and lifetime of the baseline mission**

Integration with other projects/programs and partnerships

- SMD Planetary Science: Europa Lander Mission Study

Technology Infusion Plan:

- Europa Lander Mission is potential customer
- For use in low-temperature environments with high specific energy requirements

Key Personnel:

Program Element Manager: Wade May

Project Manager: Erik Brandon

Lead Center: JPL

Supporting Centers:

NASA NPR: 7120.8

Guided or Competed: Guided

Type of Technology: Pull

Key Facts:

Technology Start Date: October, 2015

Technology End Date: February, 2017

Technology TRL Start: 3

Technology TRL End: 5

Ultra-Low Temperature Battery Project:
Technology Maturation

- Technology Advancements
  - Develop electrolytes for low temperature Li-CFx/MnO_2 hybrid chemistry
  - Build on previous JPL low temperature electrolyte development efforts, focused on improving ionic conductivity at low temperature
  - Work with vendors on new cell designs
  - Test campaign underway to evaluate influence of electrolyte formulation, separator type and electrode thickness on performance at low temperature

- Technology advances enable a Europa Lander mission (battery only) that can survive through additional passes of the orbiter

Key Performance Parameters

Performance Parameter	State of the Art	Threshold Value	Project Goal	Estimated Value
KPP-01: Primary Battery Specific Energy	150-200 Wh/kg at -40 ˚C (rate dependent)	240 Wh/kg at -40˚C	300 Wh/kg at -40˚C	Available Q4 FY16 (based on measurement)
KPP-02: Rechargeable Battery Specific Energy	95-115 Wh/kg at -20 ˚C discharge, with charging limited to -30 ˚C	100 Wh/kg charging / discharging at -40 ˚C	200 Wh/kg charging / discharging at -40 ˚C	Available Q4 FY16 (based on measurement)

Revolutionary Propulsion Research and Development

(potential project)

Revolutionary Propulsion:
Rationale and Notional Approach

- **There will always be a desire for propulsion systems that offer faster trip times, more payload, and deeper reach into space**
  - Fundamental technologies are unproven & poorly characterized; requires emphasis on proof-of-principle demonstrations
  - Research and development is complex and costly with long learning curves and high failure rates
  - A sustained research and technology development focus is needed that maintains a diversified portfolio and emphasizes tangible action to remove barriers to the emergence of revolutionary capabilities

- **Notional approach:**
  - FY17-18: Encourage bridging investments by NIAC – STRG – SBIR/STTR – CIF programs
  - FY19: Begin Revolutionary Space Propulsion project in GCD with potential for FY19-21 competitive solicitations
    - > FY19 start aligns with relevant OGA technology investment timelines (e.g., FY16-18 ARPA-E Alpha Program in disruptive fusion energy technology)

- **Proposed objectives / criteria:**
  - Exploration-class specific power of at least 0.2 kW_{jet}/kg (or specific mass of no more than 5 kg/kW_{jet})
  - Entrance criterion: TRL 3 proof of principle
  - Exit criterion: TRL 5 functional validation

A Vision For Advanced Propulsion Technology Maturation Investment

IN-SPACE PROPULSION – Near term focus (TRL 3-6)

Technology investments in key areas enable evolved capability and modest gains in capability – *PROGRESS IS PREDICTABLE*

Advanced Chemical Propulsion

Key Technologies:
- Advanced Propellants
- Long-term CFM
- ISRU (LOX/Methane)

Capability Goals:
- Reduced SWaP
- Low Freezing Point
- Non-Toxic

Key Challenges:
- *Extreme Environments*
- *Propellant Handling*
- *Performance Plateau*

Combined Chemical-Electric Propulsion

Solar Electric Propulsion

Key Technologies:
- Light Weight Deployable Arrays
- Extreme Environment Arrays
- High-Power/Isp Thrusters

Capability Goals:
- Flight Demonstration
- Robust Array Ops
- High Power Scaling

Key Challenges:
- *Power Scalability Limit*
- *Array Degradation*
- *Efficiency/Specific Mass*

Bimodal Nuclear Thermal-Electric Propulsion

Nuclear Thermal Propulsion

Key Technologies:
- Robust High-Temperature Fuels
- High Power Density LEU Reactor
- Affordable Development & Testing

Capability Goals:
- LEU FE Prototype
- NTP Design/Costing
- Affordable Dev/Test

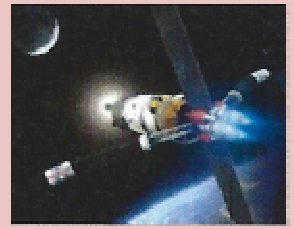
Key Challenges:
- *Affordability & Viability*

Revolutionary Unproven Energetic Propulsion Concepts
High Power NEP, Advanced Fission, Fusion, etc

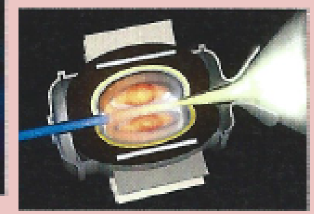
Key Challenges:
- *Complex & Costly*
- *Long Learning Curves*
- *High Failure Rates*

ADV PROPULSION – Far term focus (TRL < 3)

Sustained research investment enables possibility for revolutionary technologies – *PROGRESS IS NOT PREDICTABLE*

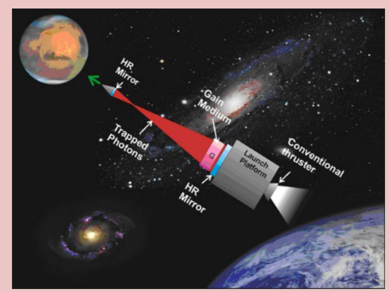


Multi-MW NEP



Fission Gas Core or Enhanced Solid Core

Pulsed Fission



Photonic Laser Thruster

Pulsed Fusion

Antimatter

Breakthrough Science

Sustained Low-Level Research Investment

Research on Advanced Energetic Processes & Concepts

Tangible Action to Remove Barriers to Innovation

Capability Goal:
α < 5 kg/kW

Congressional Direction on Interstellar Propulsion Research

FY17

- **House**: Current NASA propulsion investments include advancements in chemical, solar electric, and nuclear thermal propulsion. However, even in their ultimate theoretically achievable implementations, none of these could approach cruise velocities of one-tenth the speed of light (0.1c), nor could any other fission-based approach (including nuclear electric or pulsed fission). The Committee encourages NASA to study and develop propulsion concepts that could enable an interstellar scientific probe with the capability of achieving a cruise velocity of 0.1c. These efforts shall be centered on enabling such a mission to Alpha Centauri, which can be launched by the one-hundredth anniversary, 2069, of the Apollo 11 moon landing. Propulsion concepts may include, but are not limited to fusion-based implementations (including antimatter-catalyzed fusion and the Bussard interstellar ramjet); matter-antimatter annihilation reactions; multiple forms of beamed energy approaches; and immense ‘sails’ that intercept solar photons or the solar wind. At the present time, none of these are beyond technology readiness level (TRL) 1 or 2. The NASA Innovative Advanced Concepts (NIAC) program is currently funding concept studies of directed energy propulsion for wafer-sized spacecraft that in principle could achieve velocities exceeding 0.1c and an electric sail that intercepts solar wind protons. Over the past few years NIAC has also funded mission-level concept studies of two fusion-based propulsion concepts. Therefore, within one year of enactment of this Act, **NASA shall submit an interstellar propulsion technology assessment report with a draft conceptual roadmap**, which may include an overview of potential advanced propulsion concepts for such an interstellar mission, including technical challenges, technology readiness level assessments, risks, and potential near-term milestones and funding requirements.
- **Senate:** No specific direction.
- **Final language:** TBD.