National Aeronautics and
Space Administration

Technology, Innovation & Engineering Committee Report NASA Advisory Council

Presented by:
Dr. Bill Ballhaus, Chair

July 29, 2016

TI&E Committee Meeting Attendees
July 26, 2016

- Dr. William Ballhaus, Chair
- Dr. Kathleen Howell, Purdue University
- Mr. Michael Johns, Southern Research Institute
- Mr. Matt Mountain, Association of Universities for Research in Astronomy
- Mr. David Neyland, Consultant
- Mr. Jim Oschmann, Ball Aerospace & Technologies Corp.
- Dr. Mary Ellen Weber, Stellar Strategies, LLC

TI&E Committee Meeting Presentations July 26, 2016

- Welcome to Glenn Research Center (GRC) and remarks
  - Dr. Marla Perez-Davis, GRC Deputy Director
- Space Technology Mission Directorate Update
  - Mr. Stephen Jurczyk, Associate Administrator, STMD
- Space Propulsion and Power Overview
  - Dr. Jeff Sheehy, STMD Chief Engineer
- SpaceX Red Dragon Partnership Overview
  - Mr. Jim Reuter, Deputy AA for Programs, STMD
- Chief Technologist Update
  - Dr. David Miller, NASA Chief Technologist
- Tours of STMD Projects at GRC

GRC STMD Tour Stops

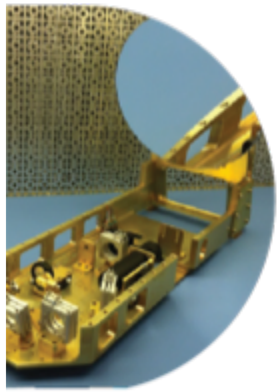
- Small Multipurpose Research Facility (SMiRF) – eCryo
- Electric Propulsion Laboratory – High-power Solar Electric Propulsion
- Radioisotope Power Systems and Small Nuclear Fission Power technology development
- Energy Conversion Laboratory - Large Deployable Solar Array technology development

Committee was impressed with the quality of the research and the people.

STMD Thrust Areas

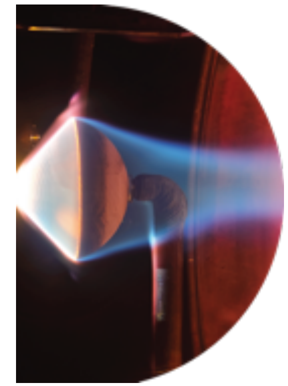
Space Technology focus investments in 7 thrust areas that are key to future NASA missions and enhance national space capabilities.

Space Power and Propulsion



High-Bandwidth Comm, Deep Space Navigation, Avionics

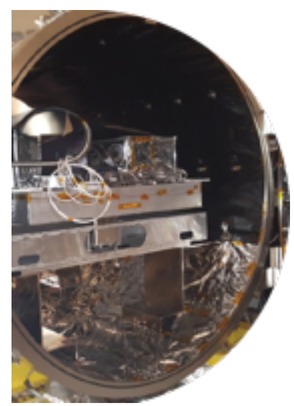
Advanced Life Support & Resource Utilization



Entry Descent and Landing Systems

Autonomy & Space Robotic Systems

Lightweight Structures & Manufacturing



Space Observatory Systems

National Aeronautics and Space Administration

Space Technology Mission Directorate

Propulsion and Power Technology Development Strategy

Jeffrey Sheehy, PhD
Chief Engineer

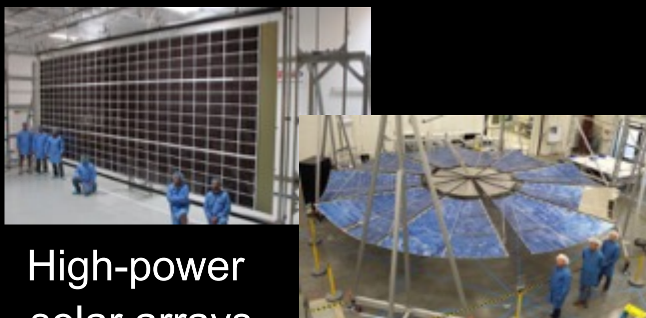
26 Jul 2016

www.nasa.gov/spacetech

Investment Themes

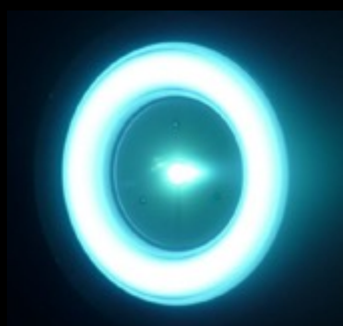
- **Efficient deep space propulsion**
  - High-power solar electric propulsion flight demonstration (current project)
  - Nuclear thermal propulsion technology development (current & potential projects)
  - LOX / methane propulsion technology development (potential project)
- **Mission-enhancing space 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)

Key Technologies for High-Power SEP Demonstration



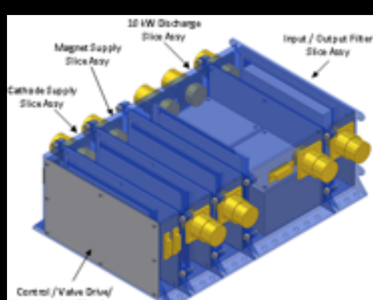
High-power solar arrays

	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



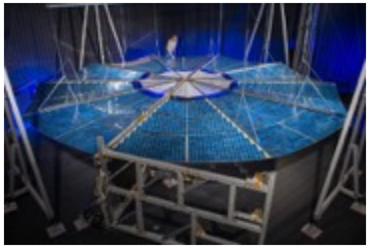
Advanced power processing unit

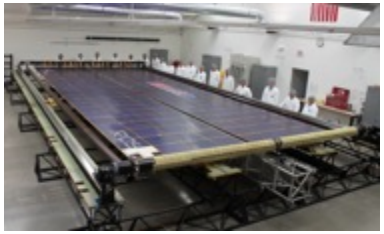
	State of the Art	Goal
Input Power	4.5 kW	13.3 kW
Input Voltage	70 - 100 V	300 V
Output Voltage	250 - 400 V	800 V
Efficiency	90 - 92%	$\geq$ 92%

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

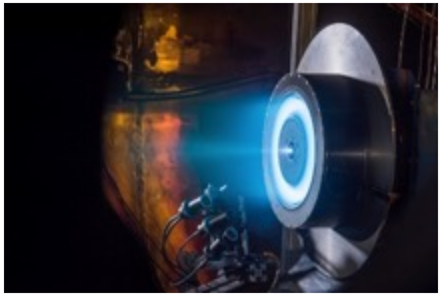




Technology development thruster and PPU tests at GRC

- 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

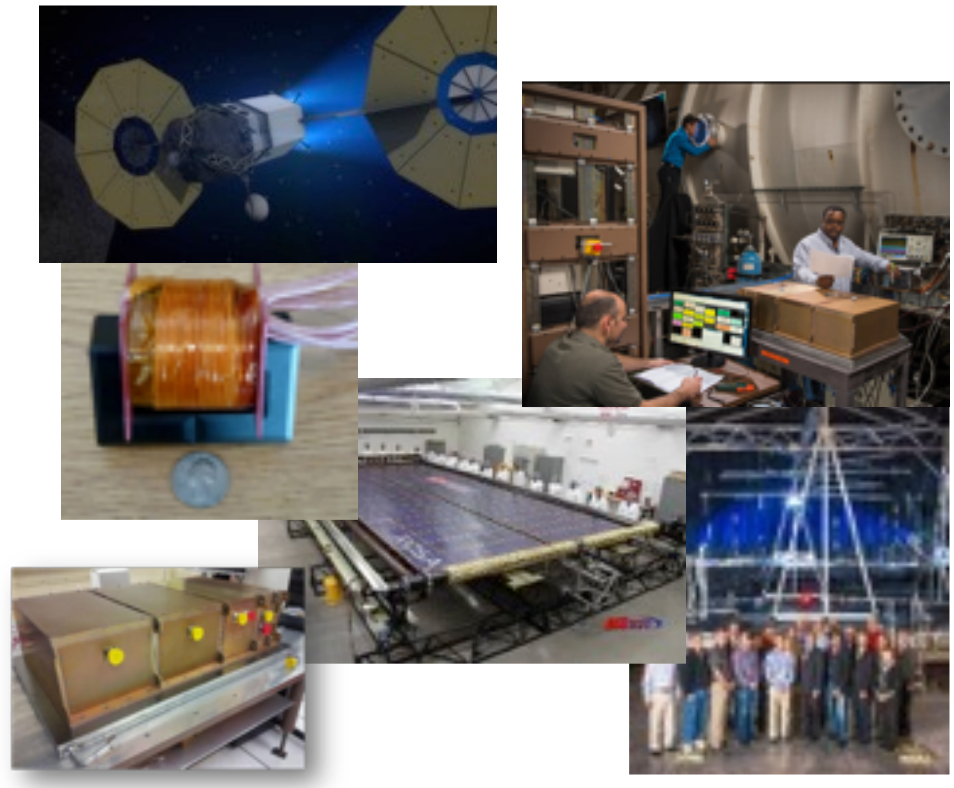


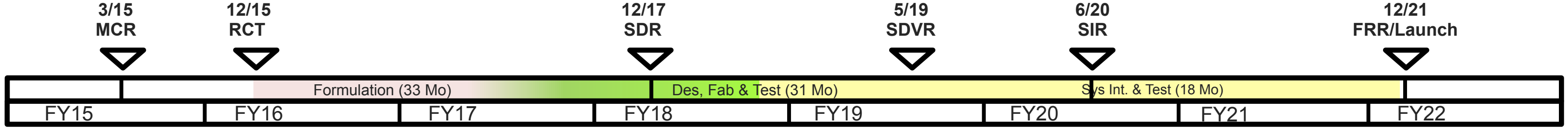
High-Power SEP Demonstration Project Overview

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



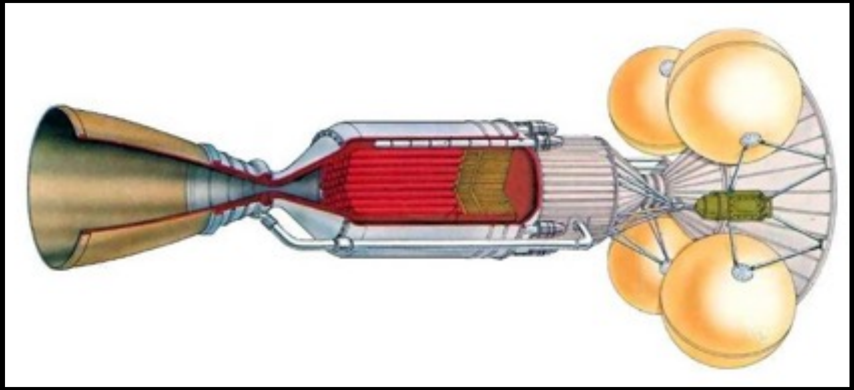


Nuclear Thermal Propulsion

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

MON-25 / MMH Engine

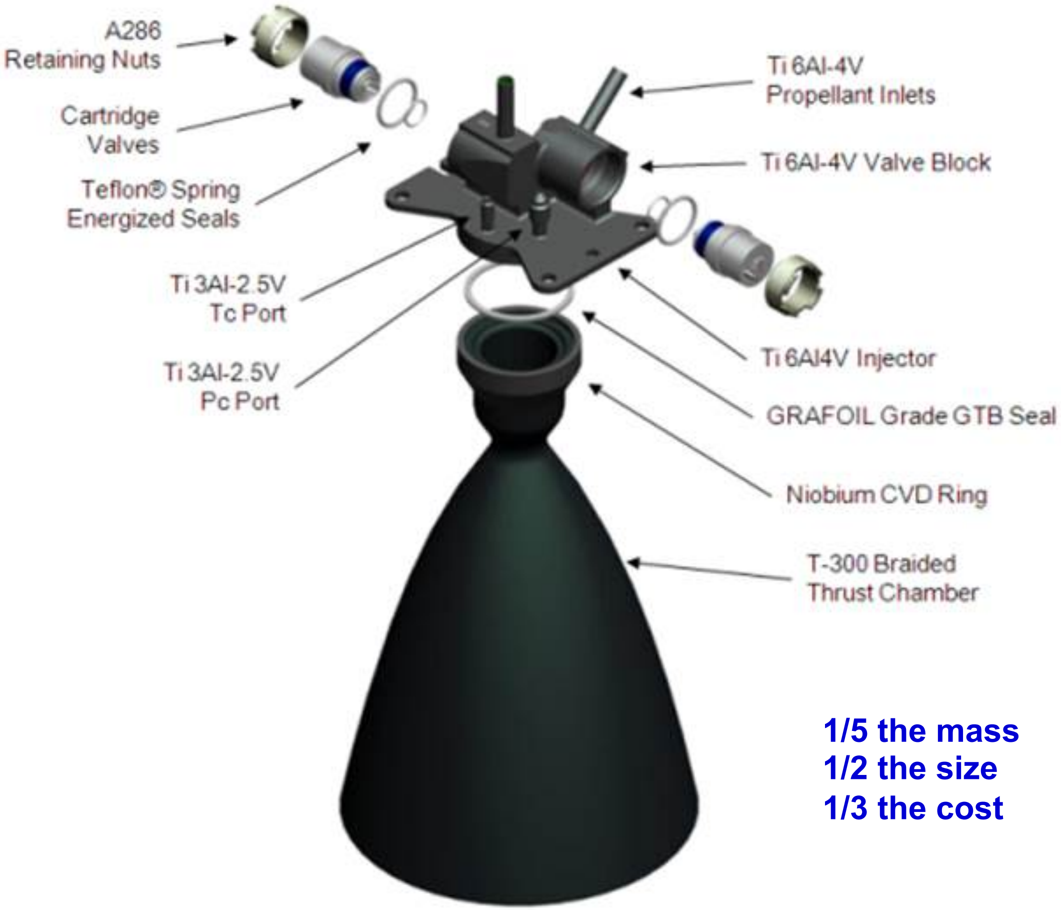
- **Provides more efficient solar system access for science missions**
  - Compact, lightweight, low-cost chemical propulsion reduces burden on spacecraft
  - Low-temperature capability facilitates operation in extreme environments
  - Adaptable to main propulsion, reaction control systems, and lander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



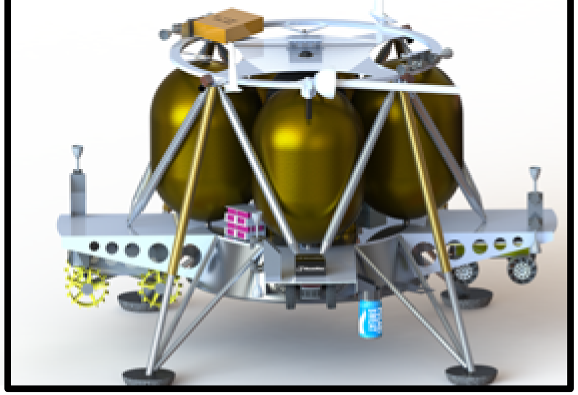
1/5 the mass
1/2 the size
1/3 the cost

ISE-100
MON-25 / MMH bipropellant thruster
(Aerojet Rocketdyne & NASA)

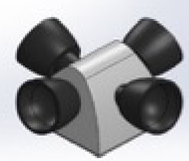
MON-25 / MMH Engine:
Mission Infusion Potential

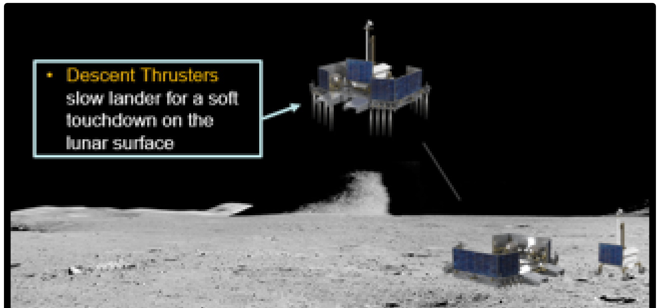
HEOMD ↔ SMD

CATALYST
Astrobotic Lunar Lander



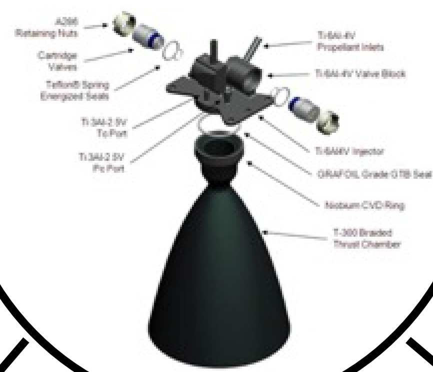
Exploration-class RCS



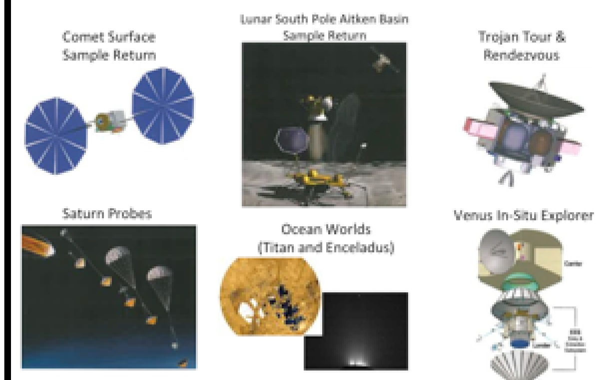


Resource Prospector

ISE-100
MON-25/MMH Biprop Thruster



New Frontiers AO

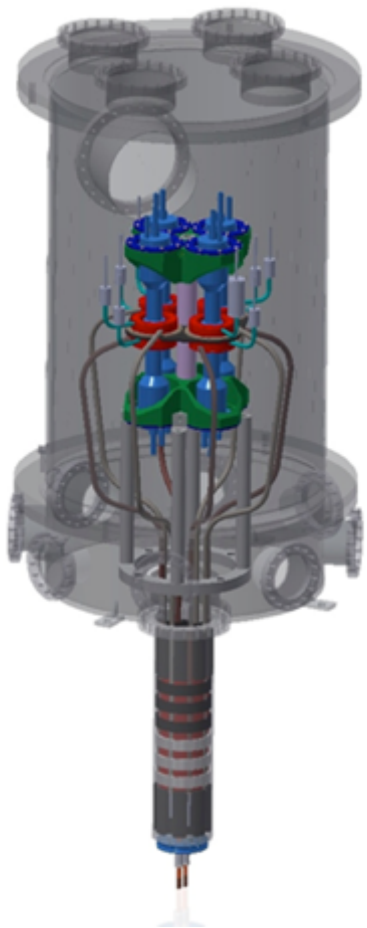


Mars Sample Return

Europa Lander

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



NASA Collaboration with SpaceX’s Red Dragon Mission

House Committee on Science, Space, and Technology

July 11, 2016

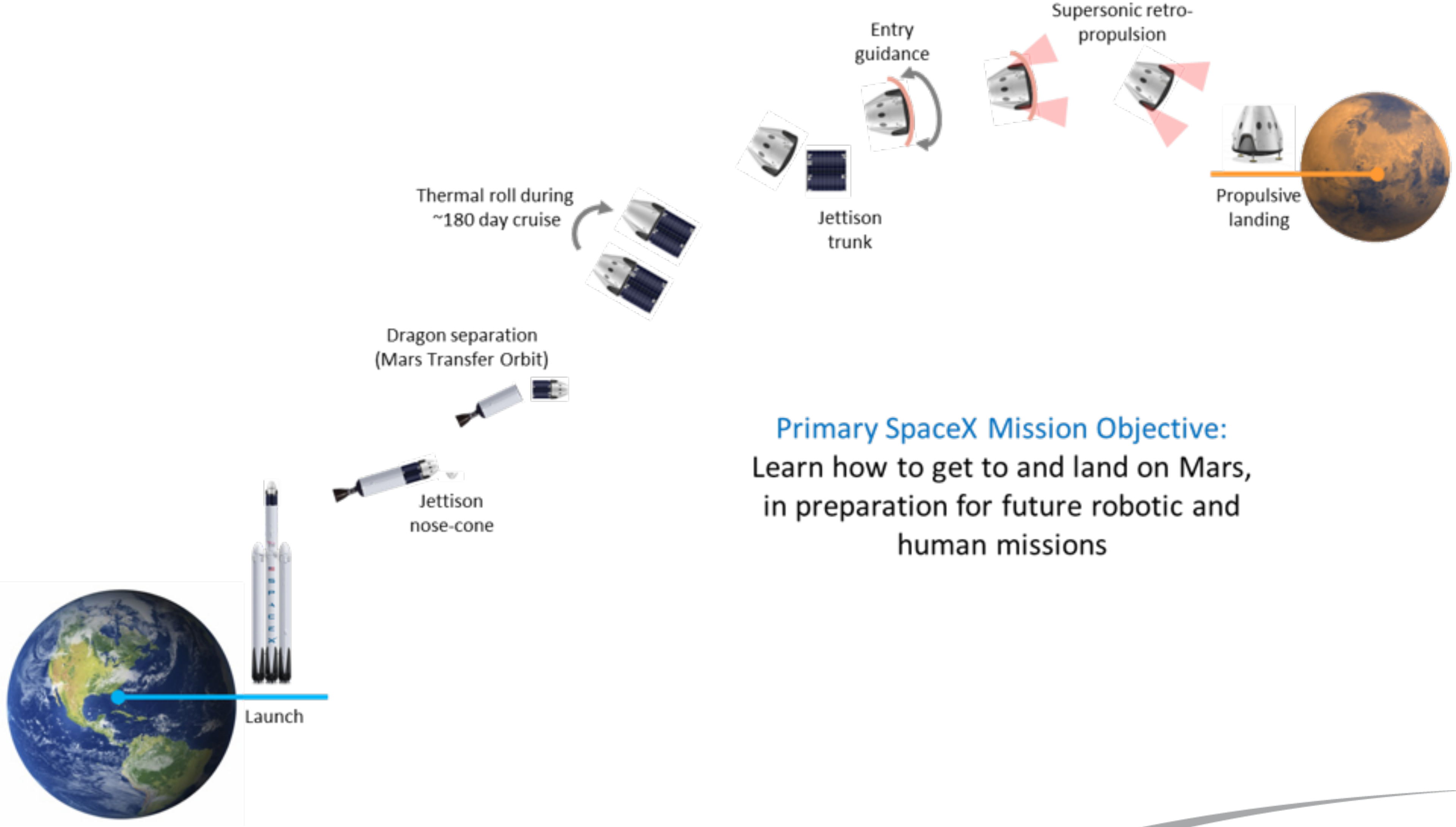
Agreement and Approach

- SpaceX is responsible for and will maintain control over Red Dragon design, hardware, and operations. NASA is only providing specific technical support in several technical areas.
- The modification to the CCSC SAA with SpaceX establishes NASA support as defined in six Technical Exchange Documents (TEDs):
  - TED 1. Deep space communications, data relay, and tracking
  - TED 2. Deep space trajectory design and navigation support
  - TED 3. Entry, descent, and landing (EDL) system engineering and analysis
  - TED 4. Aerosciences activities
  - TED 5. Flight system technical review and advice
  - TED 6. Planetary protection consultation and advice
- In return, NASA obtains EDL flight data for a critical technology in the Mars environment

Agreement and Approach *(cont.)*

- NASA's support is coordinated across three Mission Directorates:
  - **Human Exploration and Operations Mission Directorate (HEOMD):** (a) manage the overall SpaceX CCSC agreement, and (b) provide communications and tracking support to the mission (TED 1)
  - **Space Technology Mission Directorate (STMD):** lead the Red Dragon technology demonstrator mission design and EDL (entry, descent, and landing) support (TEDs 2-5)
  - **Science Mission Directorate (SMD):** provide planetary protection support (TED 6)
  - An Executive Committee has been established to ensure cross-directorate coordination
- This will be a SpaceX-funded mission:
  - NASA's support is primarily from existing Civil Service and JPL workforce, employed as needed depending on the requested support.
  - Generally will not be full-time activities.
  - Preliminary estimated cost of NASA's workforce support is ~$32M over 4 years with ~$6M in FY16

Red Dragon Mission Architecture



Primary SpaceX Mission Objective:

Learn how to get to and land on Mars, in preparation for future robotic and human missions

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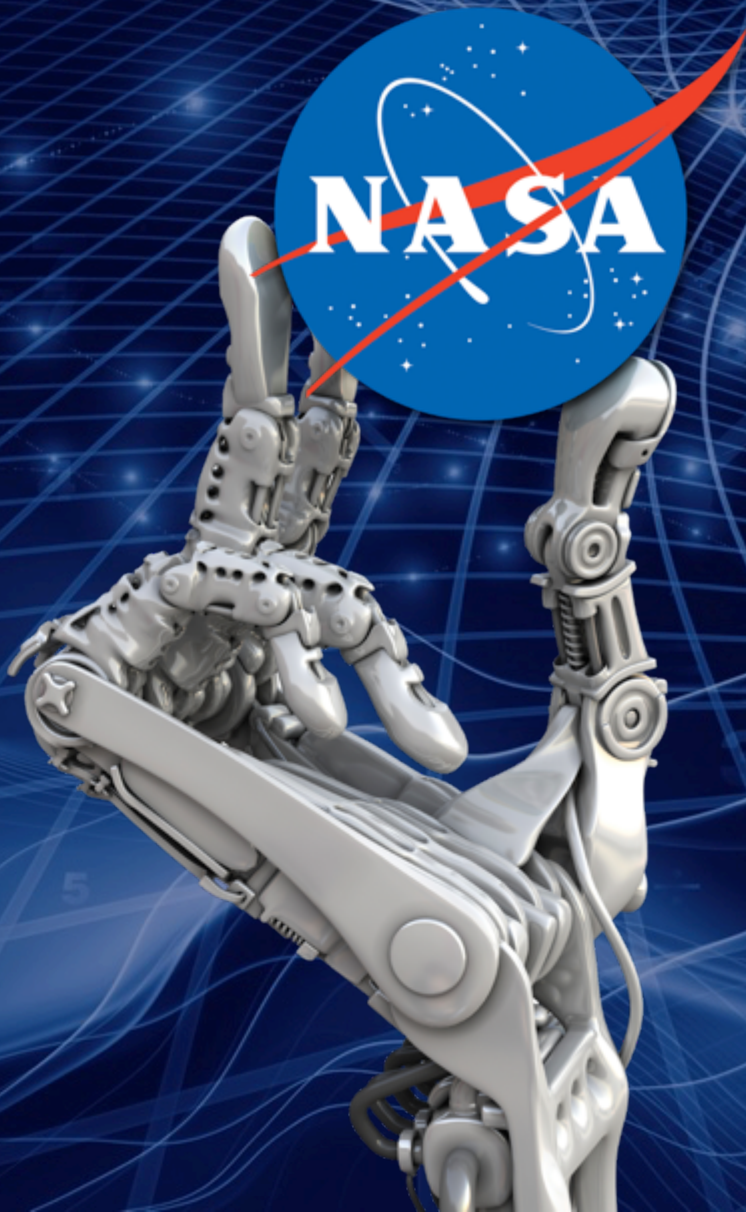
Red Dragon Participation - Benefits to NASA

- **Supports NASA's authorization to help enable the commercial space industry**
- **Offers flight technology demonstration of critical EDL technologies needed for human exploration (particularly supersonic retro-propulsion) in the Mars atmosphere about a decade sooner and at a fraction of the cost to NASA for a future technology demonstrator mission**
  - All candidate EDL architectures for Mars human exploration rely on supersonic retro-propulsion
- **Provides EDL flight data for supersonic retro-propulsion in Mars atmosphere to improve models**
- **Enhances NASA's EDL capability development/sustainment – preparing the workforce for challenges of landing greater mass on Mars**
  - Aero/aeroheating/trajectory performance data on the largest mass and largest ballistic coefficient ever flown at Mars
  - Entry surface heating and pressures
  - Entry guidance performance
  - Supersonic retro-propulsion performance and guidance during power-on flight
  - Ground surface interaction insight for large rocket plumes
- **Industry is focusing effort that will aid the long term challenge of heavy mass Mars landings**

Status and Next Steps

- **NASA conducted a fairly high-level technical feasibility assessment and determined there is a reasonable likelihood of mission success that would be enhanced with the addition of NASA's technical expertise**
- **First NASA/SpaceX quarterly review (with the expanded level of assistance) was held on April 13, 2016**
  - Work underway on all TEDs
- **2016: Focus on system design, based heavily on Dragon 2 version used for ISS crew and cargo transportation**
- **Commitment on flight date will be after system design progresses**
  - – First launch opportunity is May 2018 for favorable Earth/Mars alignment
  - – Additional opportunities every 26 months



Roles and Responsibilities of OCT and STMD

NAC Technology, Innovation and Engineering Subcommittee

David W. Miller
NASA Chief Technologist

July 26, 2016

Changes

a. Streamline Technology Roadmap Process and NRC Assessment
   - Use STIP to communicate strategy internal and external to NASA

b. OCT/STMD to more effectively utilize existing NAC TI&E advisory capability to review the Agency technology portfolio

c. Re-charter NTEC with support from Agency Council Staff

d. Move management of Emerging Space Grants to STMD

e. Conduct independent assessment of Centennial Challenges Program to improve alignment with Agency goals and objectives

f. Conduct independent assessment of TechPort

g. Implementation of the NASA Innovation Framework will be the responsibility of OCT under the direction of the Deputy Administrator
   - This decision does not reflect a change in OCT or STMD operations

h. Move Technology Transfer and Prizes & Challenges to STMD
   - Maintain strategic nature of P&C distinct from Centennial Challenges

i. Move TechPort management to STMD for cross-agency data gathering, archiving and reporting

TI&E Committee April 2016 Recommendation to STMD AA

Recommendation: STMD conduct an independent study of current small satellite technology developments to determine the appropriate focus for NASA's small spacecraft technology investments.

Reasons:

- NASA is at risk for having STMD's small satellite technology investments duplicated in commoditized capabilities. (consequence of no action)
- Given this, what is the appropriate, discriminating role for STMD vis-à-vis all the other organizations that are developing small satellite technology?

TI&E Observations

- **NASA needs cutting edge technologies to undertake its missions.**
  - Current missions are based on technologies developed through investments made over several decades.
  - In the timeframe FY2005-FY2009, technology budgets (basic research -$500M; applied research -$900M) were drastically reduced.
- **Current Administrator has established STMD and made an effort to rebuild the crosscutting technology program. OCT/STMD management has done an excellent job of formulating the technology program and executing it, within annual budget constraints.**
  - Example accomplishments: SEP, Green Propellant demo, composite cryotank, small spacecraft technologies, EDL including inflatable decelerator and TPS technologies. And more to come: laser comm, in-space robotic manufacture & assembly, ISRU demo, coronagraph.
  - STMD reengaged the academic community in engineering research and technology development and rekindling interest in NASA among students, especially at the graduate level.
  - STMD has effectively used internal and external partnerships to mature and develop technologies, for example, NASA is beginning to incentivize technology demonstrations on competitively selected science missions (e.g. deep space optical communications on Discovery).

TI&E Concerns

The Agency has increased external and internal appreciation for the importance of funding crosscutting technologies in STMD. However:

- **Technology budget priorities have been increasingly driven by factors external to STMD.**
  - NASA priorities
  - Congressional direction
  - Increasing SBIR/STTR mandate
- **The consequence of this is canceled projects (EDL, CPST, LDSD, CEUS) and an inability to start high priority new activities that would give NASA technology options required for future missions *(see next chart).***
- **If NASA wishes to have a sustainable, crosscutting technology program, it has to find a more effective way of funding STMD working with its stakeholders.**
  - e.g. NASA could develop an agency-wide policy for accommodating SBIR/STTR mandates and top line increases.

Thrust Areas Requiring Additional Investment

- **Lightweight Structures and Manufacturing**
  - Additional investment in materials, large space structures and manufacturing technology
  - Required to meet goals of reducing both mass and cost by 50%
- **Space Power and Propulsion**
  - Need to advance solar and nuclear power systems technology
  - Required for advanced propulsion systems (SEP and NTP) as well as surface power for Mars and deep space missions (e.g. Europa lander)
  - Also need continued investment in chemical propulsion/cryogenic fluids management (CFM)
- **Autonomy and Space Robotics Systems**
  - Need investments focused on human-robotic collaboration
  - Also should leverage external R&T for highly reliable, autonomous robotic/surface systems
- **Advanced Life Support and Resource Utilization**
  - Need to develop more comprehensive ISRU technology strategy/portfolio driven by architecture
  - STMD focusing on atmospheric ISRU and in-space/surface manufacturing
  - STMD will continue to deliver ECLSS component technologies to HEOMD/AES for system demonstration
  - Focus on next-generation, higher risk, higher payoff technologies
- **Maintain Early Stage** investment at ~10% of total STMD portfolio

Back-Up

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**.

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

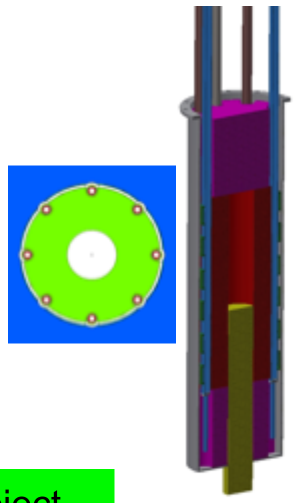
4.3 kW_t / 1 kW_e

28.4 kg U235

0.09% fuel burnup

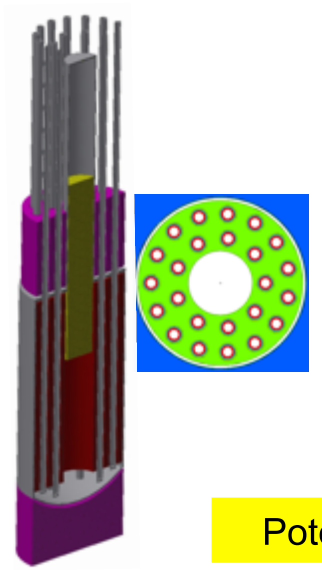
8X 3/8” heat pipes

~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

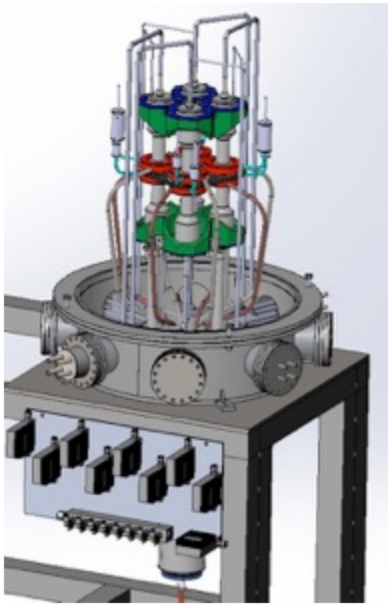
24X 5/8” heat pipes

~6” dia x 11” tall

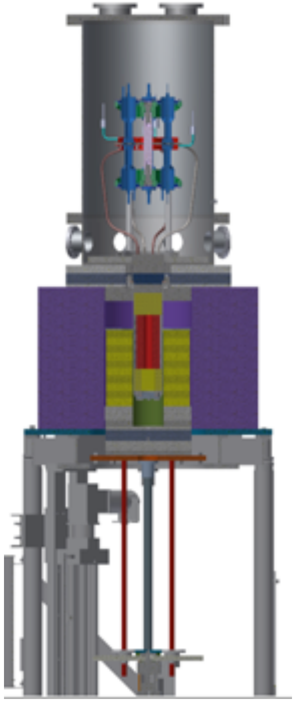
Potential project

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

Background

- **December 2014:** NASA's HEOMD competitively awarded Collaborations for Commercial Space Capabilities (CCSC) Space Act Agreements to four firms, agreeing to provide them with NASA's technical insight and assistance on a **no-exchange-of-funds basis:**
  - SpaceX – develop Mars cargo transportation system
  - ATK Space Systems - develop space logistics, hosted payload and other space transportation capabilities
  - Final Frontier Design - develop intra-vehicular activity space suits
  - United Launch Alliance - develop new launch vehicle capabilities to reduce cost and enhance performance
- **Late 2015:** SpaceX requested an expanded level of assistance from NASA under this existing agreement to support a planned **uncrewed technology demonstration mission** to Mars with its Dragon spacecraft
- **October 7, 2015:** NASA Agency leadership briefed on this concept
  - Directed STMD Associate Administrator to form a small team, led by senior leaders throughout the Agency, to conduct a preliminary concept feasibility study.
  - Feasibility study analyzed the technical areas of expanded assistance, identified benefits to NASA, and developed initial cost estimates for NASA's expanded level of assistance.
- **January 26, 2016:** NASA Agency leadership approved additional areas of assistance to the existing collaboration and directed the CCSC agreement be modified to accommodate
- **April 26, 2016:** NASA and SpaceX finalized modification to the CCSC agreement (SAA-QA-14-18883)

Summary of NASA Technical Support

- **Deep-Space Communications, Data Relay and Tracking**
  - Support the SpaceX mission operations team to develop and execute a concept of operations for deep-space communications, data relay and tracking. Includes providing support and advice on developing deep-space communications and tracking approach, frequency channel assignment and spectrum coordination, and provision of Deep Space Network use.
- **Deep-Space Navigation and Trajectory**
  - Support mission design and navigation including launch/arrival space analysis and trades, cruise trajectory assessments, mission strategies and navigation design assessments, navigation training and certification for operations, and participation in operational readiness tests.
- **Entry, Descent, and Landing System Engineering and Analysis**
  - Provide Mars EDL lessons learned, review and advice.
  - Support simulation development and model validation.
  - Provide landing site selection advice and engineering support.
- **Aerosciences Activities**
  - Coordinate with SpaceX to develop analysis plans for development of engineering source data and perform certain analysis related to EDL.
- **Flight System Technical Review and Advice**
  - Review end-to-end flight system, esp. autonomy, fault tolerance, operability, and qualification approaches.
  - Provide assessment of technical risks associated with flight system design, development, and testing.
- **Planetary Protection Consultation and Advice**
  - Advise SpaceX in the development and implementation of their Planetary Protection Plan (PPP).