National Aeronautics and Space Administration

EXPLORE SPACE TECH

Nuclear Technology Portfolio Briefing

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SPACE TECHNOLOGY PORTFOLIO

EARLY STAGE INNOVATION
- NASA Innovative Advanced Concepts
- Space Tech Research Grants
- Center Innovation Fund/ Early Career Initiative

PARTNERSHIPS AND TECHNOLOGY TRANSFER
- Technology Transfer
- Prizes and Challenges
- iTech

SBIR/STTR PROGRAMS
- Small Business Innovation Research
- Small Business Technology Transfer

TECHNOLOGY MATURATION
- Game Changing Development
- Lunar Surface Innovation Initiative

TECHNOLOGY DEMONSTRATIONS
- Technology Demonstration Missions
- Small Spacecraft Technology
- Flight Opportunities

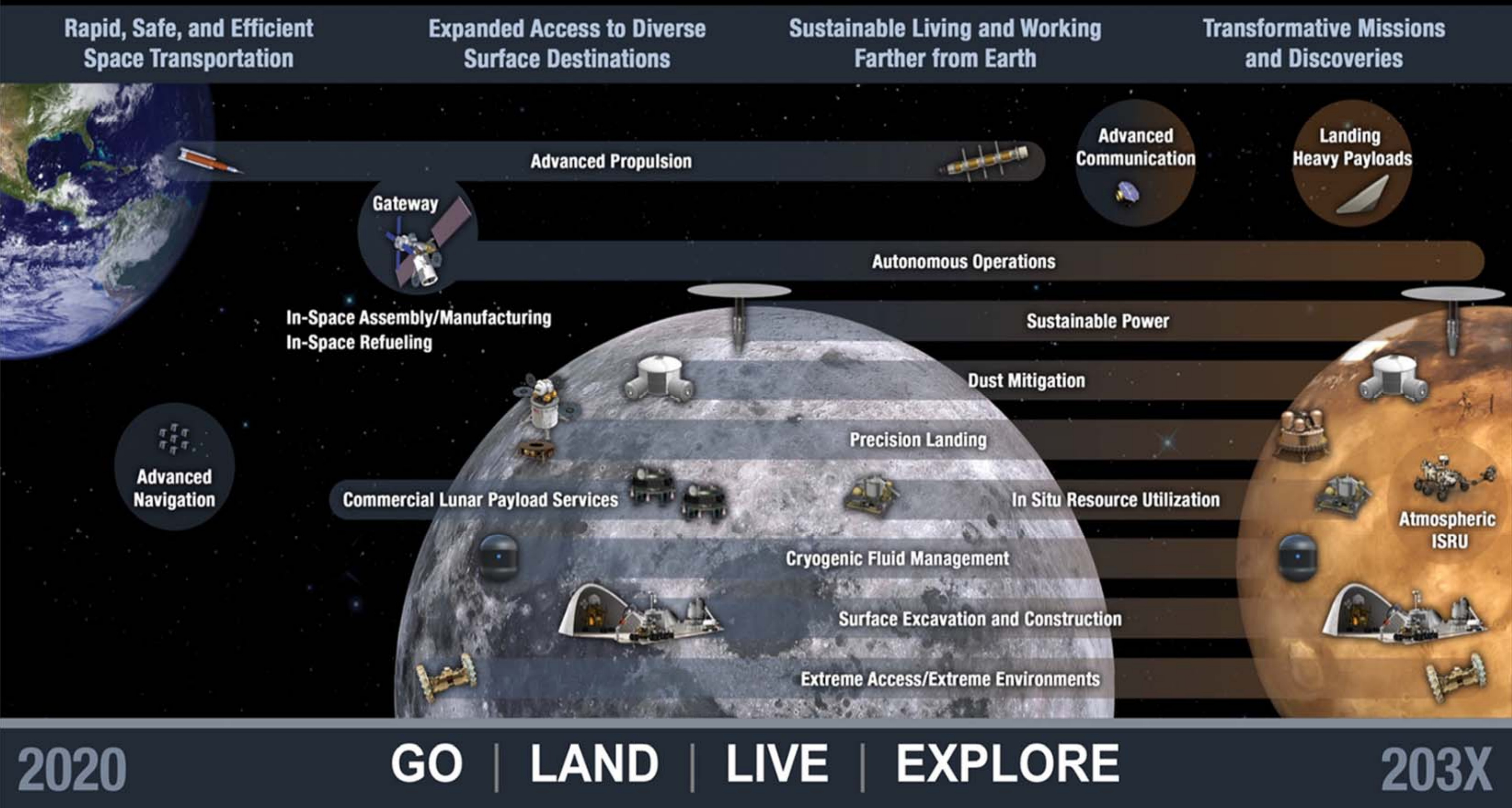
STMD Strategic Framework

LEAD	THRUSTS	OUTCOMES	CAPABILITIES
Ensuring American global leadership in Space Technology • **Lunar Exploration building to Mars and new discoveries at extreme locations** • **Robust national space technology engine to meet national needs** • **U.S. economic growth for space industry** • **Expanded commercial enterprise in space**	***Go*** ***Rapid, Safe, & Efficient Space Transportation***	• Enable Human Earth-to-Mars Round Trip mission durations less than 750 days. • Enable rapid, low cost delivery of robotic payloads to Moon, Mars and beyond. • Enable reusable, safe launch and in-space propulsion systems that reduce launch and operational costs/complexity and leverage potential destination based ISRU for propellants.	• Cryogenic Fluid Management & Propulsion • Advanced Propulsion
	Land ***Expanded Access to Diverse Surface Destinations***	• Enable Lunar and Mars Global Access with ~20t payloads to support human missions. • Land Payloads within 50 meters accuracy while also avoiding local landing hazards.	• Human & Robotic Entry, Descent and Landing • Precision Landing
	Live ***Sustainable Living and Working Farther from Earth***	• Conduct Human/Robotic Lunar Surface Missions in excess of 28 days without resupply. • Conduct Human Mars Missions in excess of 800 days including transit without resupply. • Provide greater than 75% of propellant and water/air consumables from local resources for Lunar and Mars missions. • Enable Surface habitats that utilize local construction resources. • Enable Intelligent robotic systems augmenting operations during crewed and un-crewed mission segments.	• Sustained human life support systems • Advanced Materials, Structures and Manufacturing • Sustainable Power • In-situ Propellant and Consumable Production • Autonomous Systems and Robotics
	Explore ***Transformative Missions and Discoveries***	• Enable new discoveries at the Moon, Mars and other extreme locations. • Enable new architectures that are more rapid, affordable, or capable than previously achievable. • Enable new approaches for in-space servicing, assembly and manufacturing. • Enable next generation space data processing with higher performance computing, communications and navigation in harsh deep space environments.	• On-orbit Servicing, Assembly and Manufacturing • Small Spacecraft Technologies • Advanced Avionics • Advanced Communications & Navigation

Note: Multiple Capabilities are cross cutting and support multiple Thrusts. Primary emphasis is shown

Revision date: : April 24, 2020

Reaching the Moon and Mars Faster With NASA Technology



Go

Rapid, Safe, & Efficient Space Transportation

Solar Electric Propulsion (SEP)

Nuclear Propulsion Technologies

Thruster Advancement for Low-temperature Operations in Space (TALOS)

Cryogenic Fluid Management

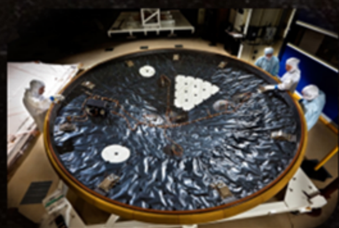
Green Propellant Infusion Mission (GPIM)

Rapid Analysis and Manufacturing Propulsion Technology

- Enable Human Earth-to-Mars Round Trip mission durations less than 750 days.
- Enable rapid, low cost delivery of robotic payloads to Moon, Mars and beyond.
- Enable reusable, safe launch and in-space propulsion systems that reduce launch and operational costs/complexity and leverage potential destination based ISRU for propellants.

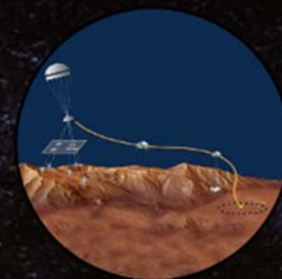
Land

Expanded Access to Diverse Surface Destinations



Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI 2)

Navigation Doppler LIDAR



Terrain Relative Navigation

Mars Entry Descent and Landing

Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID)

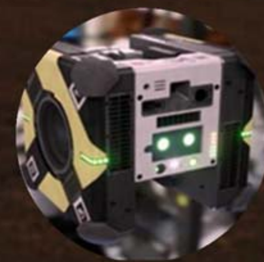
Safe and Precise Landing – Integrated Capabilities Evolution (SPLICE)

- Enable Lunar and Mars Global Access to land large (on the order of 20 metric tons) payloads to support human missions.
- Land Payloads within 50 meters accuracy while also avoiding local landing hazards.

Live

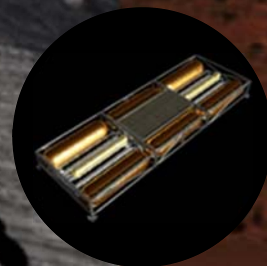
Sustainable Living and Working Farther from Earth

Surface Power



In Space Manufacturing

Regenerative Fuel Cells



Astrobee

In-situ Resource Utilization (ISRU)

Synthetic Biology

Integrated Systems for Autonomous Adaptive Caretaking

- Conduct Human/Robotic Lunar Surface Missions in excess of 28 days without resupply.
- Conduct Human Mars Missions in excess of 800 days including transit without resupply.
- Provide greater than 75% of propellant and water/air consumables from local resources for Lunar and Mars missions.
- Enable Surface habitats that utilize local construction resources.
- Enable Intelligent robotic systems augmenting operations during crewed and un-crewed mission segments.

Note: Mid TRL and High TRL Technology Development for Life Support and EVA suits are HEOMD Responsibility

Explore

Transformative Missions and Discoveries

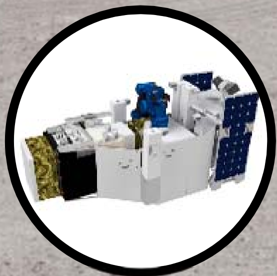
- Enable new discoveries at the Moon, Mars and other extreme locations.
- Enable new architectures that are more rapid, affordable, or capable than previously achievable.
- Enable new approaches for in-space servicing, assembly and manufacturing.
- Enable next generation space data processing with higher performance computing, communications and navigation in harsh deep space environments.

Laser and Optical Communications

CAPSTONE

SPIDER

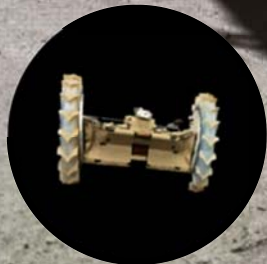
Restore-L



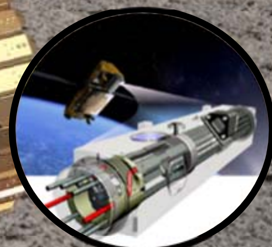
Archinaut

Bulk Metallic Glass Gears

In Space Manufacturing



Surface Robotic Scouts



Atomic Clock

STMD NAS Statement of Task

The National Academies of Sciences, Engineering, and Medicine will convene an ad hoc committee to identify primary technical and programmatic challenges, merits, and risks for developing and demonstrating space nuclear propulsion technologies of interest to future exploration missions. Nuclear propulsion has been shown to offer the potential for rapid human transit to Mars with one-way transit times less than 9 months and total roundtrip times including Mars surface stays less than 3 years. The committee will also determine the key milestones and a top-level development and demonstration roadmap for each technology. Additionally, the committee will identify missions that could be enabled by successful development of each technology.

The space nuclear propulsion technologies of specific interest are:

1. High-performance nuclear thermal propulsion (NTP) that heats hydrogen propellant to 2500K or more and produces specific thrust of at least 900 seconds.

2. Nuclear electric propulsion (NEP) that converts thermal energy to electricity to power plasma thrusters for highly efficient and rapid transport of large payloads (e.g., a propulsion system with a power level of at least 1 MWe and a mass-to-power ratio (kg/kWe) that is substantially lower than the current state of the art).

STMD NAS Statement of Task – Plan of Action

This study should examine the merits and challenges of developing and demonstrating NTP and NEP systems as described in the statement of task. This examination should consider the following factors:

- The key technical and programmatic challenges and risks;
- The options for full-scale system-level ground demonstration testing;
- The benefits and drawbacks of foregoing ground demonstration testing in favor of flight demonstration testing;
- The prospects for developing a fuel element form or other reactor subsystems that could be common to at least two of NTP, NEP, and the mobile 1-10 MW power reactors being considered for development by the Department of Defense Strategic Capabilities Office;
- The technical, programmatic, and policy considerations associated with selecting highly enriched uranium (HEU) rather than high assay low enriched uranium (HALEU) as the fissile material;
- The capability of NASA, the Department of Energy, and industry to develop the key subsystem technologies to readiness for mission infusion (i.e., to technology readiness level 6); and
- Key milestones and a top-level development and demonstration roadmap.

Space Nuclear Technology Portfolio

The Space Nuclear Technologies Portfolio will mature technologies and demonstrate system capabilities to meet Artemis power and propulsion needs

- Nuclear surface power activities will focus on design / fabrication / test of a 10 kW fission power system leading to a capability demonstration on Moon in the late 2020s
- Nuclear propulsion activities will focus on maturing critical technologies, developing the required test capabilities, and designing major subsystems for flight demonstration / mission implementation

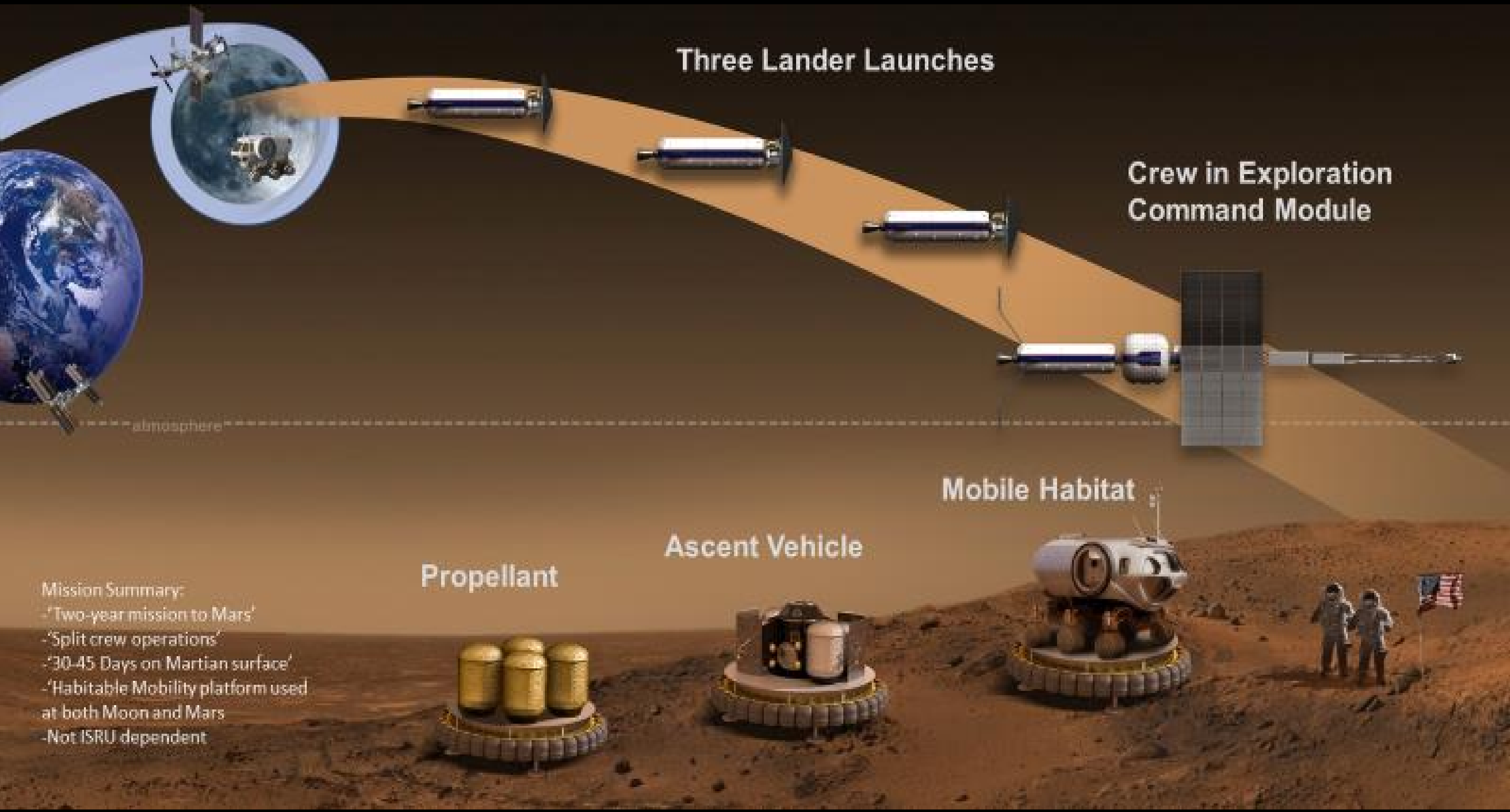
Detailed Mars transportation architecture studies include both nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) as options

The Agency has not yet selected a propulsion architecture for crewed Mars missions

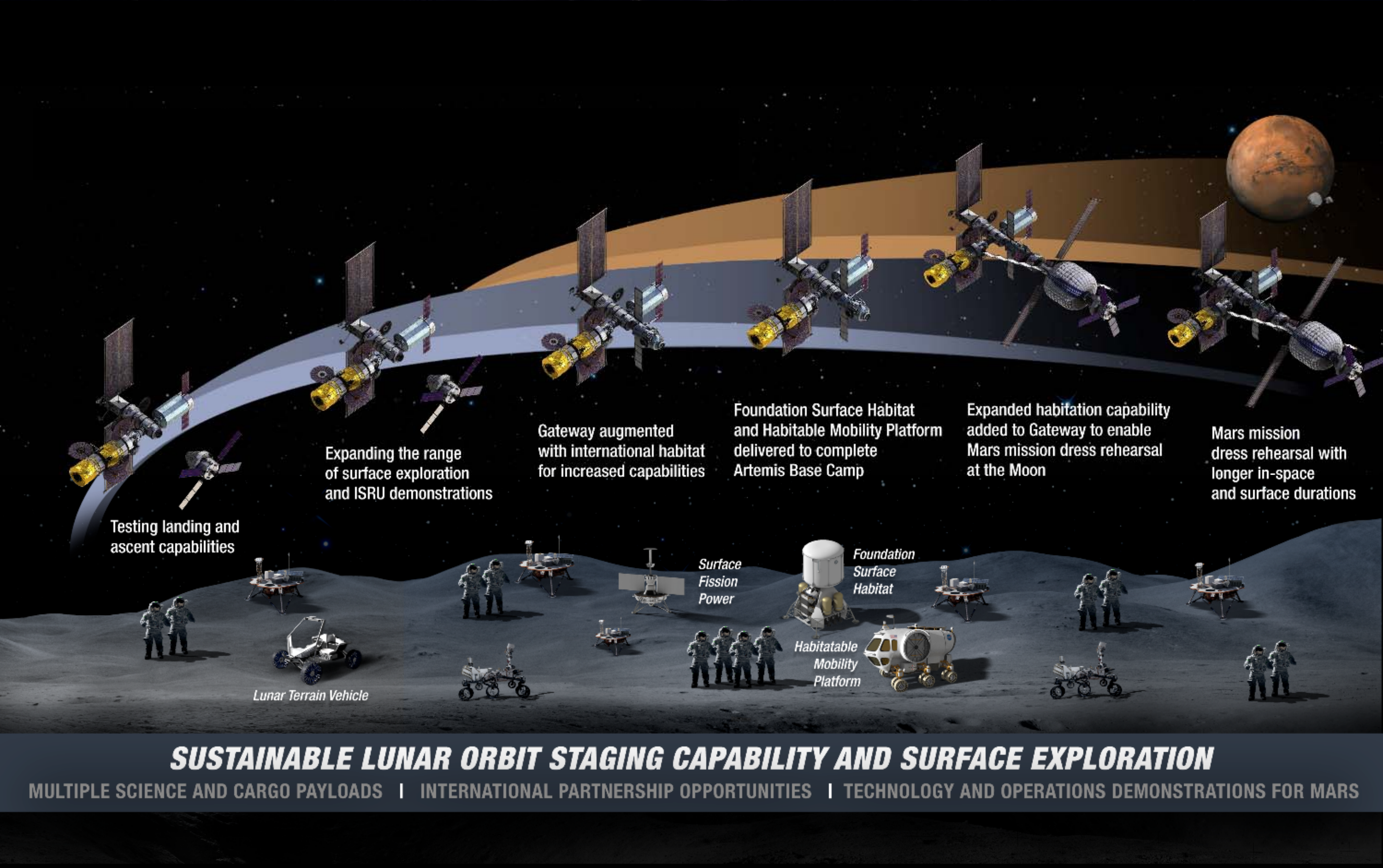
MSFC will lead the nuclear propulsion project regardless of the option selected

	FY21	FY22	FY23	FY24	FY25
Space Nuclear Technology Portfolio	**100.0**	**142.4**	**168.1**	**190.0**	**256.8**
Nuclear Surface Power	62.1	107.4	118.1	125.0	149.8
Nuclear Propulsion	37.9	35.0	50.0	65.0	107.0
Cryogenic Fluid Management	**104.2**	**137.0**	**160.1**	**137.3**	**145.5**

Concept of Operations for Future Mars Mission



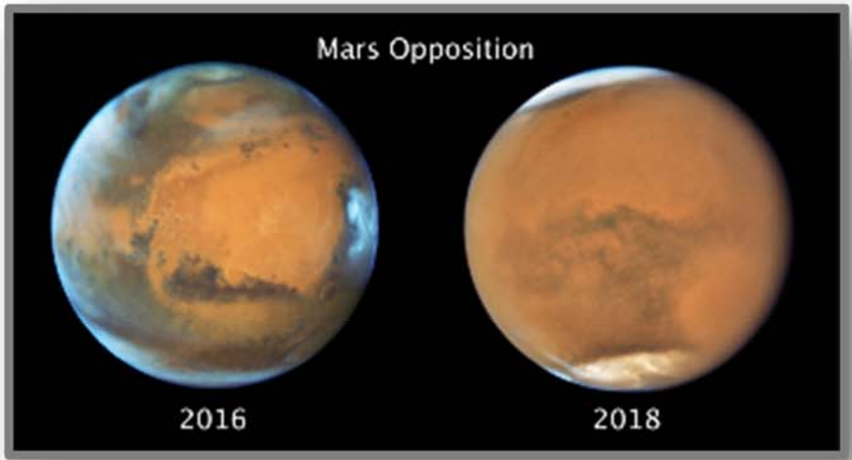
ARTEMIS Prepares for Mars



Nuclear Power for Moon and Mars

Nuclear power systems can enable robust exploration of Moon and Mars.

- Fission power systems can provide abundant and continuous surface power in all environmental conditions on Moon and Mars:
  - Lunar night is 14.5 Earth days long and permanently shadowed regions may contain water ice, thus surface nuclear power is required for a sustainable lunar presence
  - Mars has recurring planet-wide dust storms that can last for weeks or months
- A fission system designed for a capability demonstration on the Moon will be directly applicable to human Mars exploration
- Recent analyses indicate that a Mars fission surface power system is likely to enable 2-3x less mass to be flown to space and be significantly more reliable than a comparable solar power system



Nuclear Fission Power Project Overview

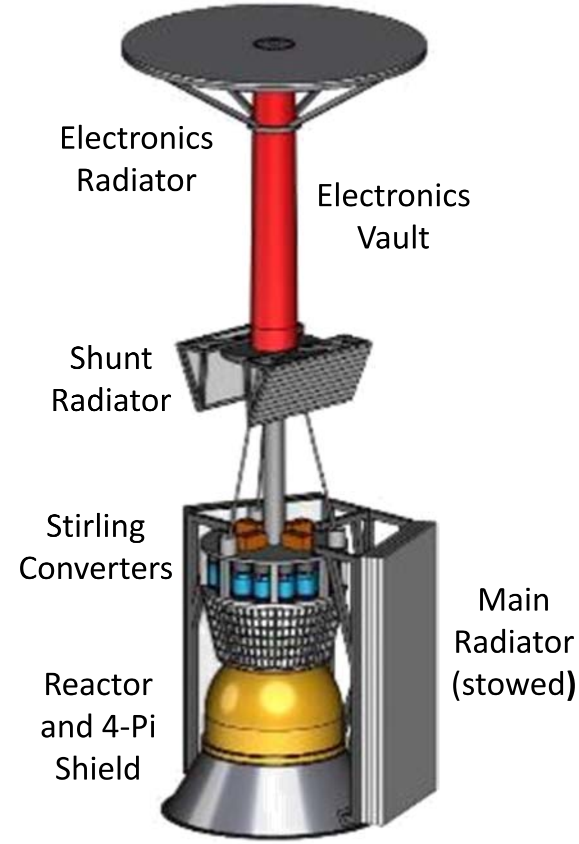
The Nuclear Fission Power project will design a fission power system for the Moon that is extensible to Mars and execute a lunar capability demonstration of the system

Project status:

- Formulating a capability demonstration concept and establishing design requirements
- Developing a solicitation for preliminary designs from industry with subsequent down selection to a final design
- Established an Interagency Agreement whereby NASA and DOE are working as a blended team

DOE has completed a six-month reactor conceptual design study

- Concluded that moderated HALEU-fueled reactors are competitive in mass with HEU-based designs but have greater complexity



Fission reactor lunar demonstration concept

Fission surface power is the Agency’s top nuclear priority

- Enabling capability for lunar sustainable presence and crewed Mars exploration
- Provides a near-term opportunity for fabrication, testing, and flight of a space fission system
- Will serve as a pathfinder for launching and operating other space fission systems

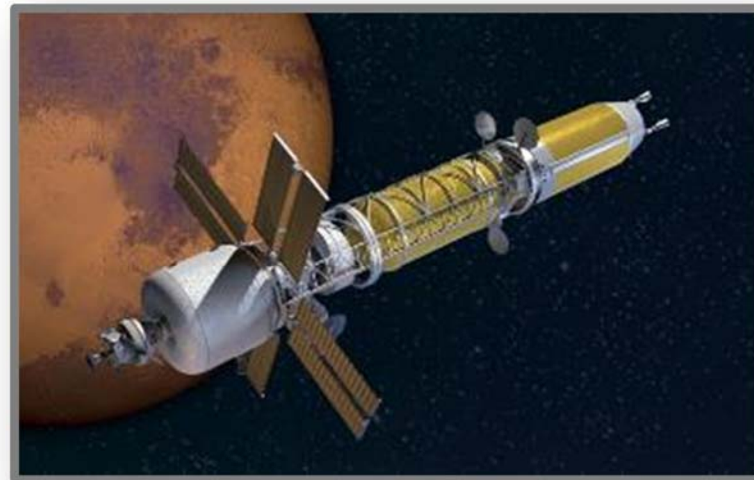
Nuclear Propulsion for Mars

In the longer-term, Nuclear propulsion systems can enable robust exploration of Mars

- **There are two basic categories of round-trip Mars missions:**
  - **Conjunction-class missions** with **long stays** at Mars (500+ d); **longer mission** times (~975 d); similar times (~210 d) for outbound & return trips; and lower demands on the propulsion system
  - **Opposition-class missions** with **short stays** at Mars (30-50 d); **shorter mission** times (~675 d); dissimilar transit times (~210 d & ~400 d); and higher demands on the propulsion system
- **NASA is conducting detailed analyses of high-performance options – nuclear thermal propulsion (NTP) & nuclear electric propulsion (NEP) – to enable opposition-class missions**
  - NEP vehicle configurations being assessed, which include a chemical propulsion system for high-thrust maneuvers, can meet opposition-class mission performance requirements
  - NTP configurations require specific impulse (Isp) ~900 s to close conjunction-class missions; current architecture studies indicate that opposition-class missions would require Isp >1100 s
- **Key technology activities to bring nuclear propulsion to maturity in the 2030s:**
  - **NTP key technologies** include nuclear fuel/element design & manufacturing; advanced reactor design; long-term liquid hydrogen storage; and fuel element & engine test capabilities/facilities
  - **NEP key technologies** include nuclear fuel/element design & manufacturing; thermal-to-electric power conversion; very large deployable composite radiators; high-power electric propulsion thrusters; and long-term oxygen/methane storage for the associated chemical propulsion system

Space Nuclear Propulsion: MSFC Project Overview

The Space Nuclear Propulsion (SNP) project will develop & validate the performance of key technologies needed for an NTP engine for Mars human exploration



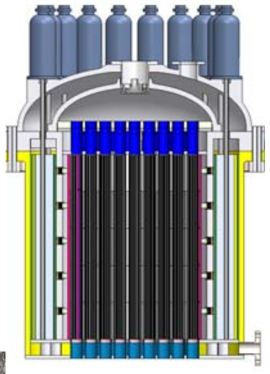
Key NTP benefits include faster transit times, robust mission abort capability, and increased mission flexibility

Major project elements:

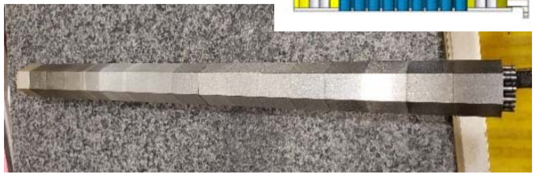
- **Fission fuel technology maturation and reactor design**
  - Develop fuel form and fuel element manufacturing technologies; establish HALEU-based reactor design for an NTP Mars transportation system
  - Leverage DOD and DOE common fuel development interests and production capabilities
- **Subscale system design**
  - Design a subscale 12,500 lbf system with Isp $\geq$900 s and assess ground & flight-testing options
  - Potential for collaboration with DARPA on their Demonstration Rocket for Agile Cislunar Operations (DRACO) program, which aims to develop and demonstrate a HALEU-based NTP system
- **Mars mission performance requirements**
  - Establish NTP engine and cryogenic fluid management performance requirements; support analyses of full-scale Mars exploration system

Space Nuclear Propulsion: MSFC Fuel and Reactor Development

- **SNP project identified an alternate fuel element and reactor design strategy in early FY20**
  - Two sub-element tests showed that fuel elements using ceramic powder fuel packed into a refractory metal canister were not sufficiently robust to survive reactor operational environment
- **Transitioned to a moderator block reactor design with fused solid-core fuel elements**
  - Ceramic fuel kernels that are clad with a refractory ceramic are sintered together to form solid fuel sub-elements
  - Ceramic cladded fuel production partnership with DOD/DOE will enable production of higher-temperature ceramic-ceramic fuel forms that offer increased NTP performance capability
  - Moderator block reactor design approach can accommodate advanced higher-temperature fuels
- **Initial fuel element development is showing good progress**
  - Solid core segment survived reactor thermal transient testing at INL in Dec 2019; fuel sub-element combined thermal and hydrogen environments testing at MSFC in Mar 2020
- **Developing test capability and procedures for increasing sample size and adding flowing hydrogen to INL reactor**
  - Current test facilities cannot accommodate a sufficiently large fuel element sample that is simultaneously subjected to all the relevant effects (thermal, radiation, flowing hydrogen)



Moderator block reactor design



Fuel element test specimen

NTP Flight Demonstration Studies: Approach

Two distinct flight demonstration strategies were assessed:

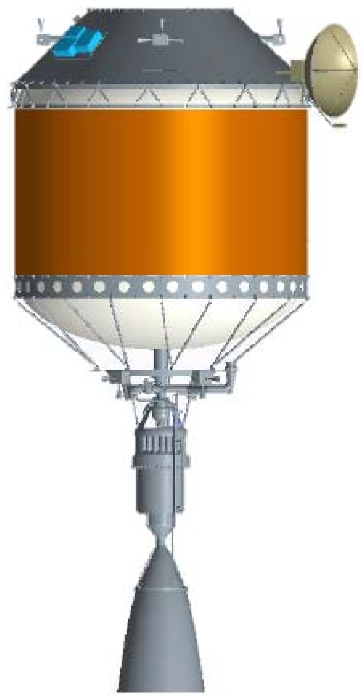
- **Schedule-driven** approach assessed what could be accomplished by 2024-2025
  - MSFC-led team with DOE support for the reactor design
  - It had been planned to have an industry team study the schedule-driven approach, but that was deemed unnecessary based on the results of the NASA study

- **Performance-driven** approach assessed the development schedules and costs for flight demonstration of systems extensible to **conjunction-class Mars missions**
  - **Industry study team** led by Analytical Mechanics Associates and including Aerospace Corporation, Aerojet Rocketdyne, Blue Origin, Boeing, BWX Technologies, General Atomics, Ultra Safe Nuclear Corporation, United Launch Alliance, Ursa Major, and Xenergy
  - Performance assumptions included Isp of at least 700 s with a goal of 900 s; thrust between 5000 and 25,000 lbf; and at least two engine burns
  - Conceptual designs developed for nine reactors and six engines (non-nuclear components); selected elements were combined into four demo flight system concepts
  - Assumed no ground test facilities would be needed
  - An MSFC-led team also independently developed a performance-driven demonstration concept

NTP Flight Demonstration Industry Studies: Key Findings

- **Schedule-driven approach (flight demonstration in 2024-2025):**
  - A flight demonstration that might be achievable by 2024-2025 would necessarily rely on existing technologies and be executed at a non-representative scale (Isp ~500 s with very low thrust)
  - **It would retire essentially no technical risk and have no extensibility to the Mars architecture** despite an estimated cost of $900+ M

- **Performance-driven approach (four demonstration concepts with varying levels of relevance to a conjunction-class Mars system):**
  - Specific impulse (Isp) between 766 and 957 s (Note: Current architecture assessments indicate that this performance could accomplish conjunction-class but not opposition-class missions.)
  - **Cost estimates between $1.2 and $2.3 B (70% confidence level); schedule estimates between 5.5 and 10.5 years.** Higher-performing concepts that are more representative of a Mars system require more technology development.
  - **Fuel development should include multiple options due to the relatively low TRL of all candidates**
  - **Moderate-to-high risk must be accepted** mainly due to the lack of full-scale ground testing for the fuel element and the NTP engine



NTP flight demonstration vehicle concept (one of four studied)

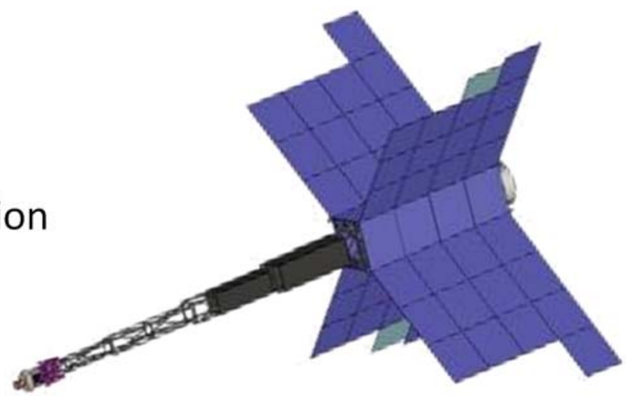
Nuclear Electric Propulsion

The Agency is currently performing detailed analyses of nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) suitability for opposition-class missions

- **Analysis indicates that an NEP system paired with a LOX/LCH4 chemical propulsion stage can perform a two-year round trip, opposition-class Mars mission**

- **Although both rely on nuclear reactors, an NEP system is fundamentally different from NTP:**
  - NTP system is high Isp and high thrust; NEP system is very high Isp and extremely low thrust
  - NTP system runs for a few short bursts (~10 min each) per mission; NEP system runs for months or years
  - NTP reactor is ~500 MW (thermal) and runs at ~2500+ K; NEP reactor is ~10 MWt and ~1200-1500 K

- **NEP technology development needs include:**
  - Reactor fuel capable of withstanding 1200-1500 K
  - Pumped liquid metal (Li) heat transport from reactor to power conversion
  - Brayton cycle power conversion system
  - Pumped liquid metal (NaK) heat rejection system with very large deployable composite radiators
  - High-power (~100 kW) electric propulsion thrusters



NEP power module concept for opposition-class Mars missions

- **Can leverage STMD-funded investments on Hall thrusters for Gateway PPE and surface power reactors; also potential synergies with DOD/DOE common fuel development and production**

Cryogenic Fluid Management (CFM) Technologies

Demonstrate technologies enabling autonomous transfer and storage of cryogenic hydrogen, capable of scaling to tens of metric tons, with negligible losses for long duration in space and on the lunar surface.

Technology Gaps

- LOX/Methane CFM - Zero Boil Off and Liquefaction at Low Power (100's Watts @ 90K)
- Zero-g Cryo Storage & Transfer (LOX, LCH4, LH2)
- Advanced Cryocoolers
- Improved Vacuum Insulation Systems
- Transfer Operations
- Zero-g Fluid Modeling

Current CFM component development work:

- HLS BAA Refueling Studies
- Cryogenic thermal coatings
- Automatic Cryo-couplers
- Low Conductivity Structures (SHIIVER tank)
- Propellant Densification
- High Vacuum MLI (IFUSI and CELSUIS)
- Vapor Cooling (eCryo)
- Unsettled liquid mass gauging (RRM-3)
- Low Leak Valves
- High Capacity Cryocooler (20K 20W)
- 90K Cryocooler development

Ongoing: 2020 Tipping Point Solicitation focuses on CFM Flight Demonstration

Future Mission Planning:

Demonstrate enabling technology for a propellant refueling and storage needed for both lunar sustainability and Mars Transit Integrated demo, including, but not limited to the following technologies:

- Autogenous pressurization
- Multilayer Insulation
- 90 K Cryocoolers
- Tube-on-tank heat transfer
- Unsettled Mass Gauge
- Thermodynamic Vent
- Transfer Operations
- Line-chilldown & 2 phase flow meter
- Automated Cryo-coupler

Cryogenic Fluid Management

HLS Refueling Studies

NORTHROP GRUMMAN

Masten

SSL A MAXAR COMPANY

Dynetics

SPACEX

BOEING

LOCKHEED MARTIN

Cryogenic Fluid Transfer Technology Demo Con-ops development with SpaceX

The Evolvable Cryogenics (eCryo) project

ULA United Launch Alliance

ULA H2/O2 Thruster development

Lunar CFM Studies and Cryocooler Development with Lockheed Martin

Creare

BLUE ORIGIN

AEROSPACE

Intuitive Machines: “Utilize NASA’s Radio Frequency Mass Gaging System for first flight”

ASTROBOTIC

Cryocooler Development enabling zero boil-off with Creare

MOOG

PARAGON SPACE DEVELOPMENT CORPORATION

Paragon Space Development Corp.: Cryogenic Encapsulating Launch Shroud and Insulated Upper Stage (CELSIUS)

NESC Assessment of NTP & NEP Technology Maturity

- **The NASA Engineering & Safety Center was recently asked to perform an independent assessment of the technical maturity of NTP and NEP components and subsystems**

- **The assessment team is comprised of current and retired experts from NASA (including Technical Fellows), DOE, industry, and academia**

- **Technology maturity is evaluated based on published data using four discriminators:**
  - Technology readiness level (TRL)
  - Advancement degree of difficulty (AD2)
  - Technology Stoplights based on system/component readiness for a 2035 mission
  - Coarse categorization of approximate funding needed to reach flight readiness

- **Approximately 25 technologies have been evaluated; a final report is being peer reviewed and will be presented to the NESC Review Board and stakeholders in June.**

Summary of Key Points

Space nuclear power and propulsion can enable robust exploration of Moon and Mars

- Fission surface power systems can provide abundant and continuous power in all environmental conditions
- Fission propulsion systems can enable human Mars exploration with the shortest total mission times
- Surface power is NASA's most pressing power need

Surface power: NASA will collaborate with DOE & industry to design, fabricate, and test a fission power system that will be operating on the Moon by the late 2020s

- The project can serve as the pathfinder for launching and operating other space fission systems

Propulsion: The Agency is performing detailed analyses of NTP and NEP systems and has not yet selected a propulsion architecture for crewed Mars missions

- NASA MSFC will lead the nuclear propulsion project regardless of the option selected

Propulsion: Key technologies need substantial development and demonstration prior to initiating detailed design of flight systems

NASA will mature technologies and demonstrate system capabilities to meet the power and propulsion needs for Artemis

NASA Inputs for FY21 Appropriations Language

FY20 Bill Language:
Provided further, That $110,000,000 shall be for the development and demonstration of a nuclear thermal propulsion system, of which $80,000,000 shall be for the design of a flight demonstration system: Provided further, That, not later than 180 days after the enactment of this Act, the National Aeronautics and Space Administration (NASA) shall provide a plan for the design of a flight demonstration.

FY20 Report Language:
Nuclear Thermal Propulsion.-The agreement provides $110,000,000 for the development of nuclear thermal propulsion, of which not less than $80,000,000 shall be for the design of a flight demonstration by 2024 for which a multi-year plan is required by both the House and the Senate, within 180 days of enactment of this Act.

The Agency understands emphasizing the maturation of nuclear propulsion technologies in preparation for developing flight systems, but notes that:

- Nuclear Fission Surface Power is Agency highest priority for the near term, is needed for both Moon and Mars applications, and a lunar capability demonstration is a major emphasis in the Agency FY21 budget proposal
- Adopting the term “Nuclear Propulsion” allows the Agency flexibility to pursue the best option (NTP or NEP) for Mars mission performance requirements
- Proposed plan in development for a late-2020s nuclear propulsion flight technology demonstration
- Nuclear propulsion appropriations should be scaled to technology maturation funding needs in the near term


NASA
EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION