National Aeronautics and Space Administration

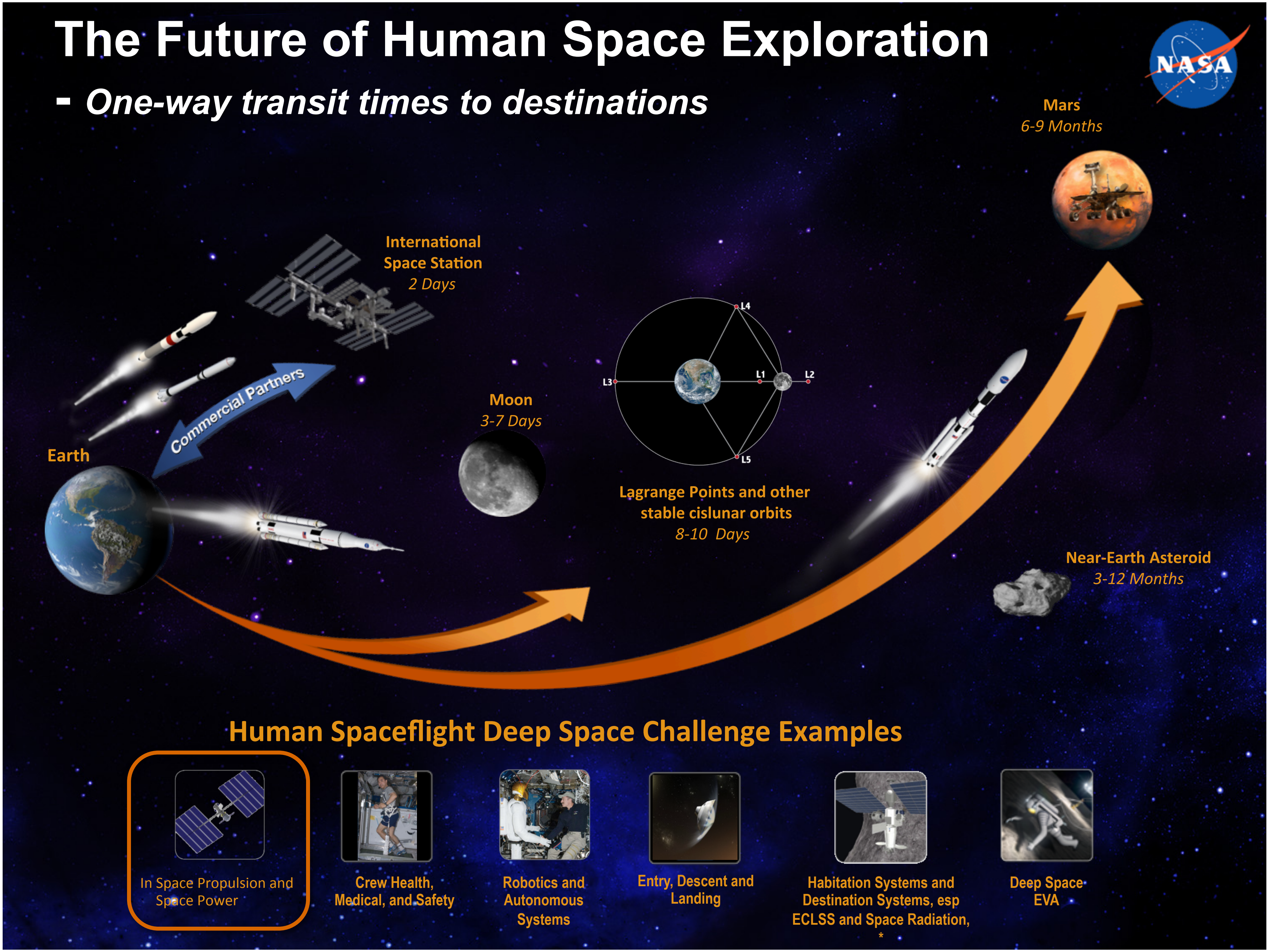
In-Space Propulsion and Power For Human Space Flight

Briefing to the National Research Council Committee on Human Spaceflight

Technical Panel

March 27, 2013

Les Johnson • NASA Marshall Space Flight Center

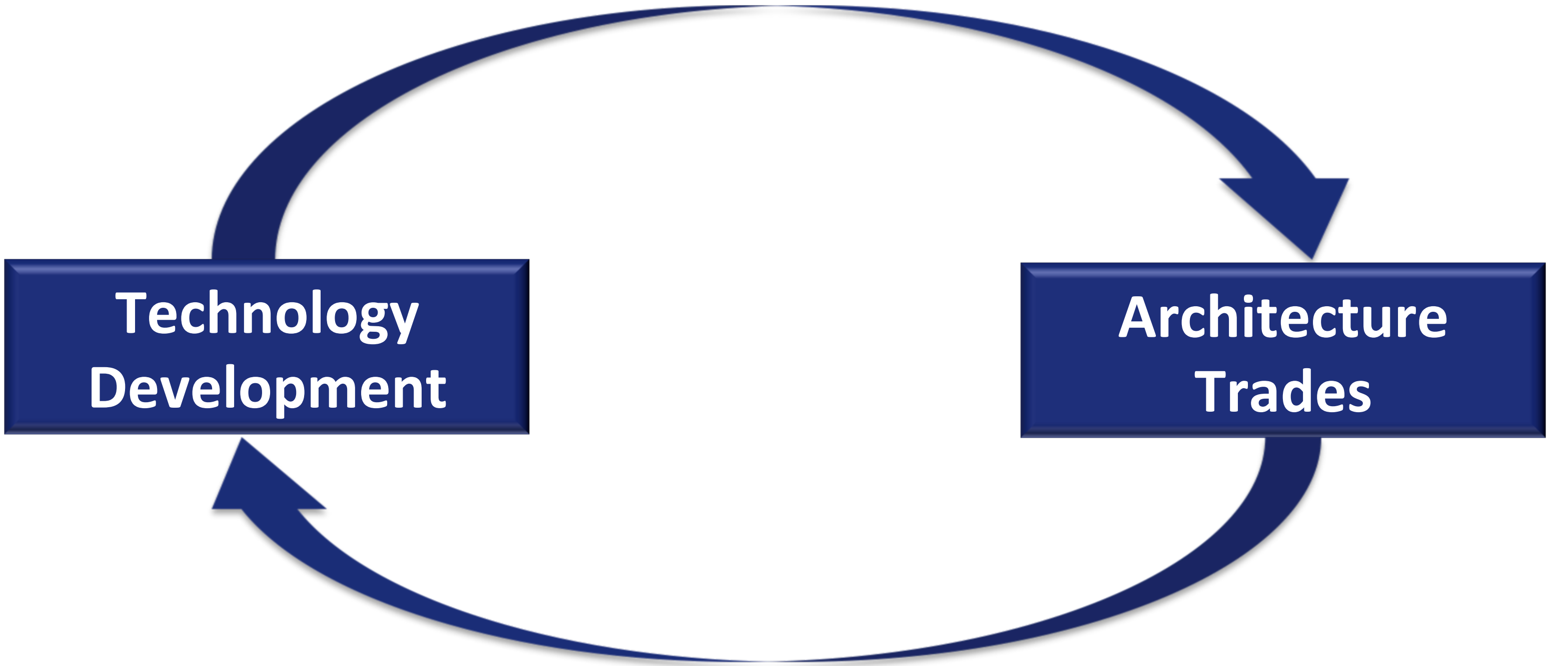

The Future of Human Space Exploration
- One-way transit times to destinations
NASA
Mars
6-9 Months
International
Space Station
2 Days
Commercial Partners
Earth
Moon
3-7 Days
L4
L3
L1
L2
L5
Lagrange Points and other
stable cislunar orbits
8-10 Days
Near-Earth Asteroid
3-12 Months
Human Spaceflight Deep Space Challenge Examples
In Space Propulsion and
Space Power
Crew Health,
Medical, and Safety
Robotics and
Autonomous
Systems
Entry, Descent and
Landing
Habitation Systems and
Destination Systems, esp
ECLSS and Space Radiation,
*
Deep Space
EVA

Regimes, Needs, and Potential Technologies

	Beyond GEO	NEA	Mars
Propulsion			
Needs	• Mod. ΔV – Mod. Mass Propulsive Maneuvers	• Mod. ΔV – Mod. Mass Propulsive Maneuvers • High Payload Fraction	• Mod. ΔV – High Mass Propulsive Maneuvers • High Payload Fraction
Potential Technologies	***Cryogenic Fluid Management*** ***Advanced Cryogenic Propulsion*** ***Advanced EP***	***Long-Duration Cryogenic Propulsion*** ***Nuclear Thermal Propulsion*** ***High Power Electric Propulsion (EP)***	
Power			
Needs	• High-efficiency energy storage	• Large solar array deployment and control • Variable solar power accommodation for EP	• Scalability of solar and nuclear power sources for EP
Potential Technologies	***High Strength/Stiffness Deployable 10-100 km Solar Arrays***	***Moderate Fission Power*** ***Autonomously Deployable 300 kw Solar Arrays***	***Multi-MWe Fission Power***

Architecture Trade – Technology Development Linkage

Architectures Drive Tech & Tech Drives Architectures

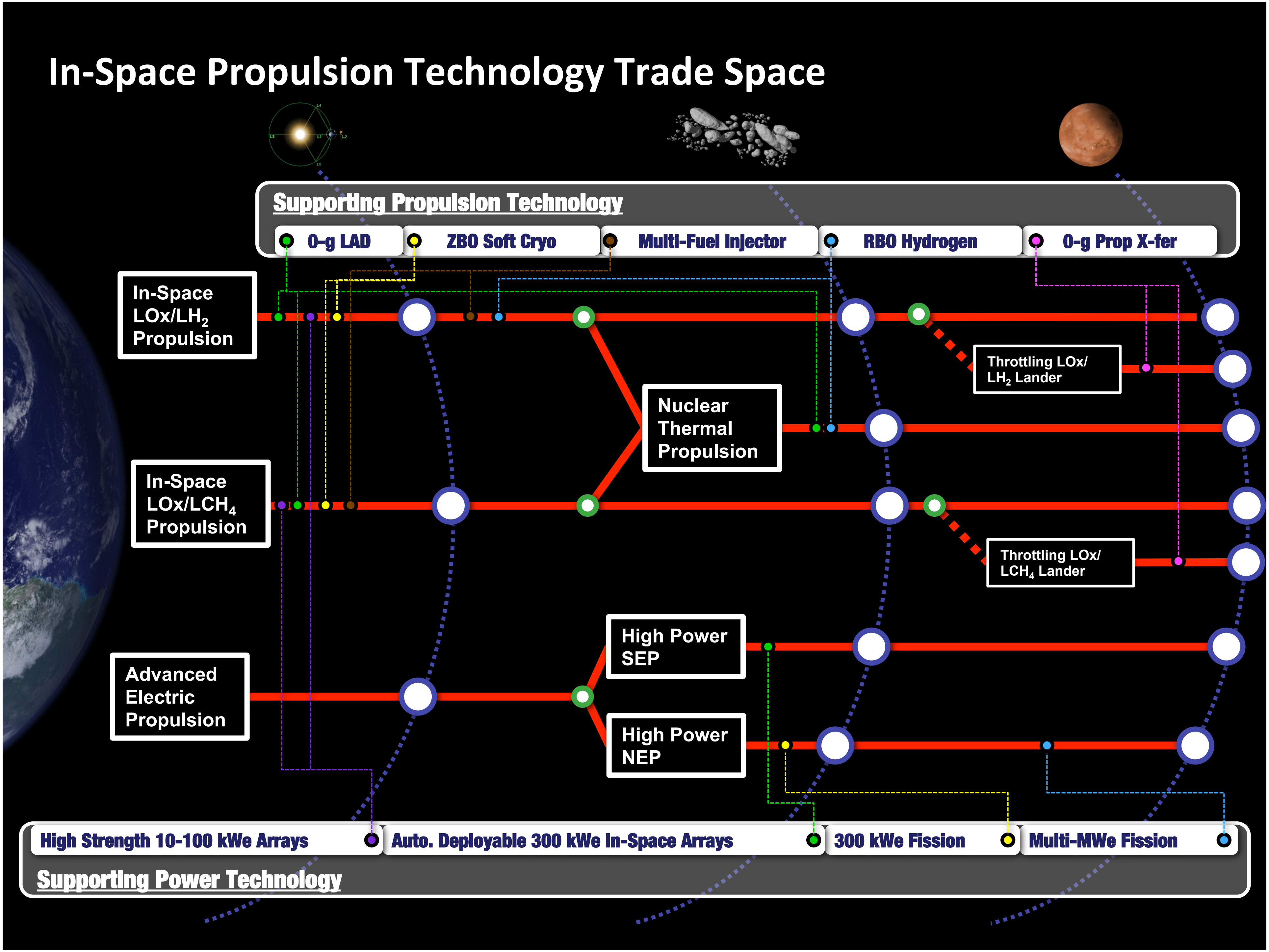


Today's technology investments can drive tomorrow's architecture solutions

- Investment in high-power nuclear fission reactors could drive us to NEP vs. high power SEP

The approach we take to performing a mission drives technology need

- Stage refueling would require development of 0-g propellant transfer, but low-cost modular propulsion would not



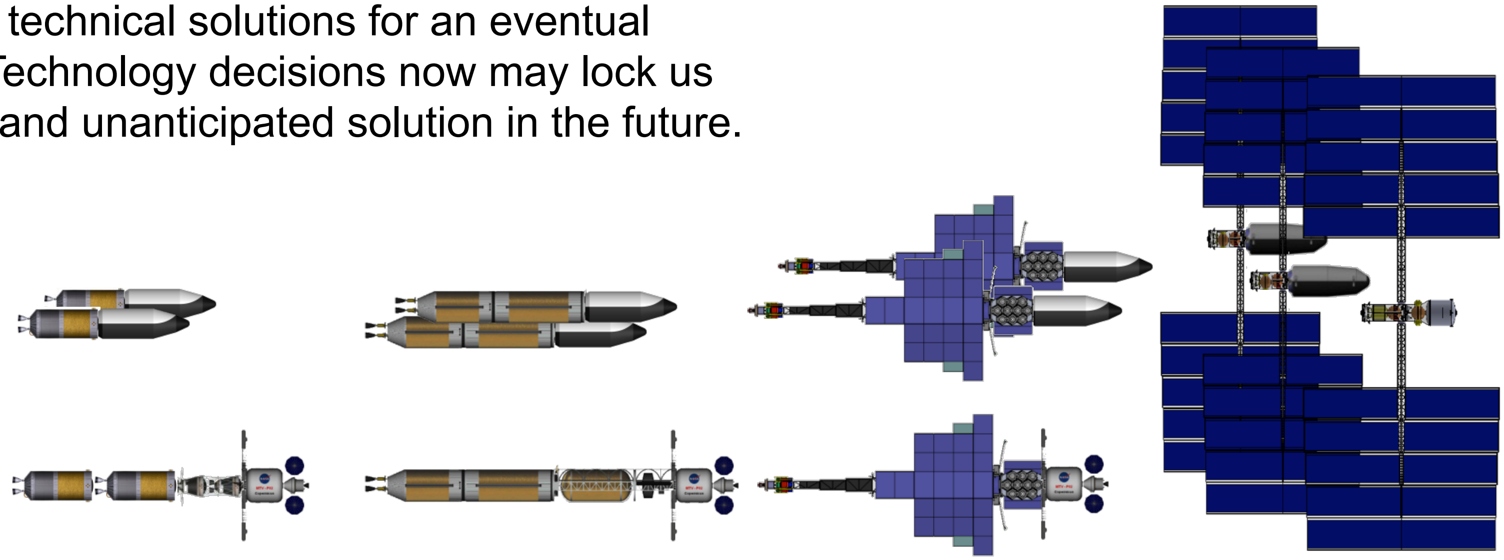
In-Space Propulsion Technology Trade Space
Supporting Propulsion Technology
0-g LAD
ZBO Soft Cryo
Multi-Fuel Injector
RBO Hydrogen
0-g Prop X-fer
In-Space LOx/LH2 Propulsion
Throttling LOx/ LH2 Lander
Nuclear Thermal Propulsion
In-Space LOx/LCH4 Propulsion
Throttling LOx/ LCH4 Lander
High Power SEP
Advanced Electric Propulsion
High Power NEP
High Strength 10-100 kWe Arrays
Auto. Deployable 300 kWe In-Space Arrays
300 kWe Fission
Multi-MWe Fission
Supporting Power Technology

Early Decisions Impact Later Capabilities/Campaigns

There are many technical solutions for an eventual Mars mission. Technology decisions now may lock us into a particular and unanticipated solution in the future.

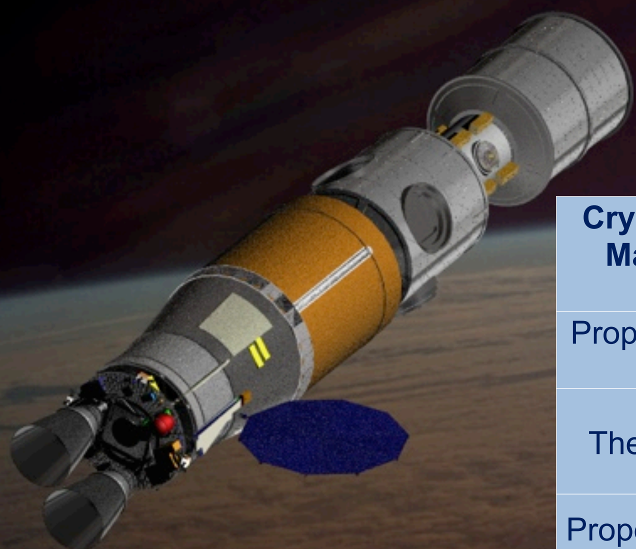
Cargo Missions

Crew Mission



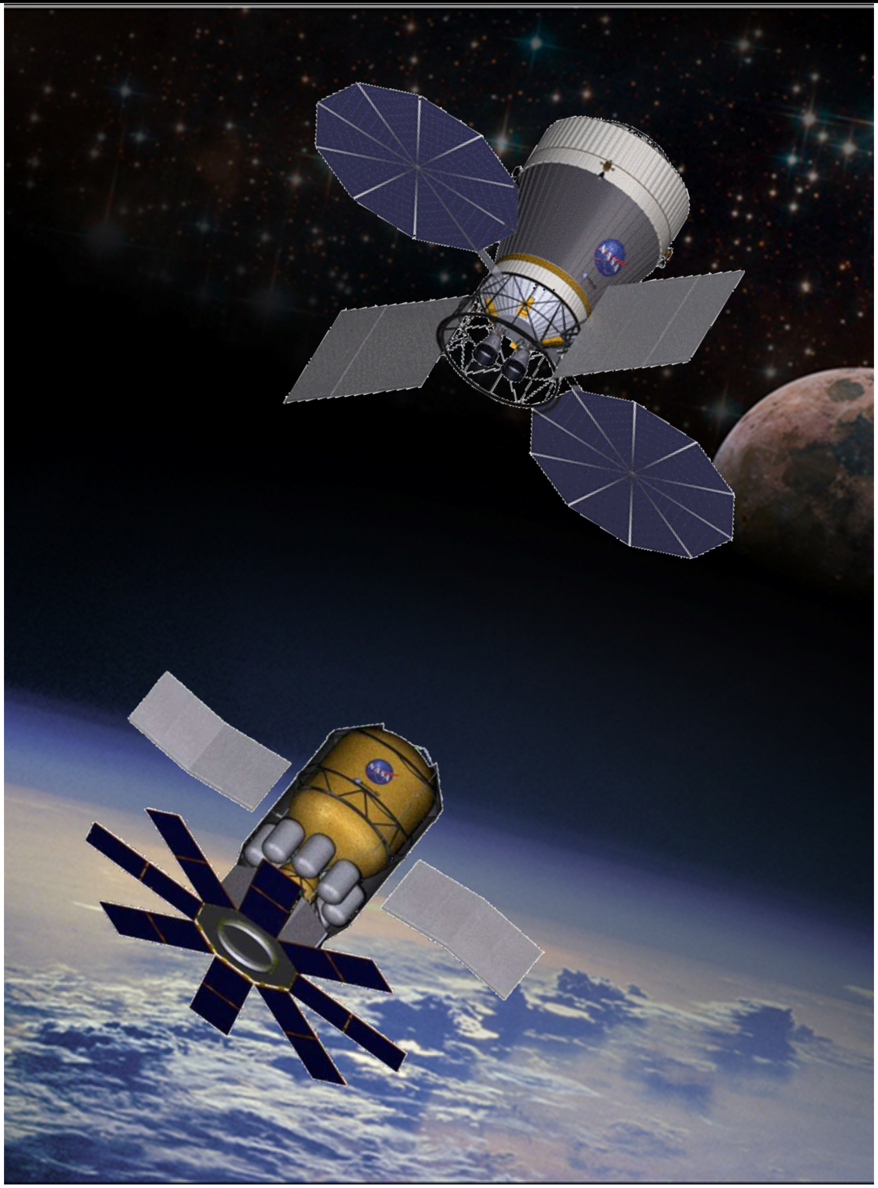
	Chemical Propulsion		Nuclear Thermal		Nuclear Electric		Solar/Chem	
Parameter	**“Hard” Long-Stay (500d)**	**“Easy” Short-Stay**	**“Hard” Long-Stay (500d)**	**“Easy” Short-Stay**	**“Hard” Long-Stay (400d)**	**“Easy” Short-Stay**	**“Hard” Long-Stay (300d)**	**“Easy” Short-Stay**
Total Mass (t)	~1,200	~1,450	~600	~700	~550	~700	~490t	n/a
Launch Spacing (days)*	50-100	45-90+	70-120	70-120+	90-150	70-120+	90-150	n/a

Chemical (Cryogenic) In-Space Propulsion



Cryogenic Fluid Management Needs	Near-Term T Demo Mission (2017)	Medium-Term Exploration Missions (ca. 2020's)	Far-Term Exploration Missions (ca 2030's)
Propellant Storage Duration	Days	Weeks	Months to Years
Thermal Control	• Reduced Boil-off Oxygen • Reduced Boil-off H2	• Zero Boil-off Oxygen • Zero Boil-off Methane • Reduced Boil-off H2	• Zero Boil-off Oxygen • Zero Boil-off Methane • Zero Boil-off Hydrogen
Propellant Gauging Strategy	• Settled Gauge • Attempt Unsettled Gauge	• Settled Gauge • Unsettled Gauge	• Settled Gauge • Unsettled Gauge
Propellant Acquisition Strategy	• Settled Expulsion • Attempt Surface Tension Devices	• Settled Expulsion • Liquid Acquisition Devices	• Settled Expulsion • Liquid Acquisition Devices
Resupply Capability	• Intra-vehicular Subscale Demo	• Inter-vehicular transfer Demo	• Operational Capability

Long-Duration Cryogenic Propellant Storage



Capability Description:

- State of the art is 9 hours of subcritical oxygen/hydrogen storage in LEO
- Need ability to store subcritical oxygen, methane and hydrogen for months to years
- Requires both passive and active technologies

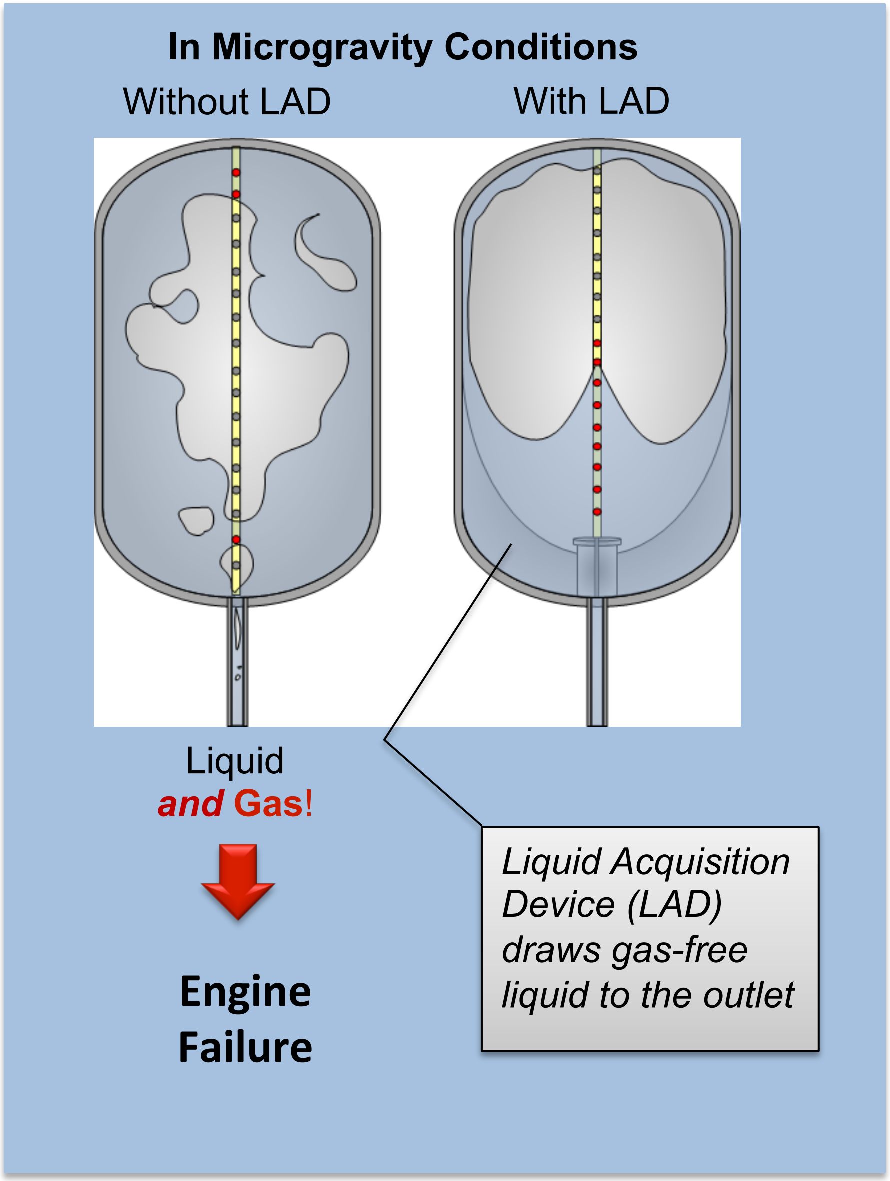
Performance Characteristics:

- Zero Boil Off for > 400 days
- LO2 Storage: < 8W per W of heat removal at 90K.
- LH2 Storage: < 120W per W of heat removal at 20K
- Cryocooler mass < mass of propellant saved

Potential Destinations Supported: NEA and Mars. Required for both chemical and nuclear thermal missions.

Current TRL Estimate: 3-4

In-Space Cryogenic Liquid Acquisition



Capability Description: Liquid Acquisition Devices (LADs) are needed for expelling gas-free liquid from tanks under unsettled conditions

- Technologies for LO2/LCH4 and LO2/LH2 are needed

Performance Characteristics:

- Ratio of LAD system pressure drop to bubble point pressure at max outflow rate < 0.75

Potential Destinations Supported: Anywhere cryogenic RCS is used or in-space resupply is required

Current TRL Estimate: 3-4

Unsettled Cryogenic Propellant Transfer

Capability Description: Unsettled cryogenic fluid transfer is required for in-space propellant resupply to cryogenic propulsion stage

- Technologies for LOX/CH4 and LOX/H2 are needed
- Includes need for 2-phase tolerant pump and automated cryo fluid coupling

Performance Characteristics:

- Mass Gauging <2% uncertainty
- 2 Phase Fluid Transfer Pump
- Leakage < 10^{-3} sccs gHe after 1000 cycles

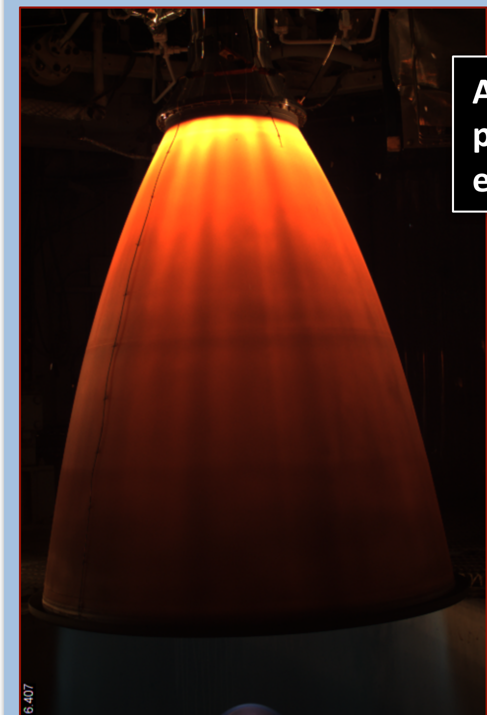
Potential Destinations Supported: NEA & Mars missions; Mars surface missions involving ISRU propellant production & loading

Current TRL Estimate: 3-4

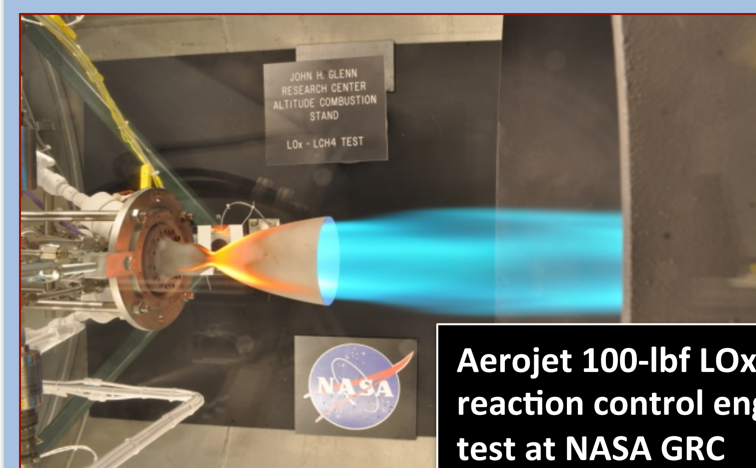
Cryogenic In-Space Engine Needs

Chemical (Cryogenic) In-Space Engine Needs	Near-Term	Medium-Term Exploration Missions (ca. 2020's)	Far-Term Exploration Missions (ca. 2030's)
Mission Challenges	• Interim CPS	• CPS	• CPS
Primary Propulsion	• Oxygen / Methane / Hydrogen	• Oxygen / Hydrogen • Oxygen / Methane	• Oxygen / Hydrogen • Oxygen / Methane
Non-Toxic RCS Engines	• Tech Demo Missions	• Oxygen / Methane RCS • Non-Toxic Storables	• Oxygen / Methane • Advanced Non-Toxic Storables
Cost Reductions	Low-Cost Advanced Manufacturing Technologies		

In-Space Liquid Oxygen / Liquid Methane Engines



Aerojet LOx/LCH4 5,500-lbf pressure-fed workhorse engine in test at NASA WSTF



Aerojet 100-lbf LOx/LCH_4 reaction control engine in test at NASA GRC

Capability Description: In-Space delta-V and Reaction Control Engines propulsion capability based on oxygen/ methane propellants

Performance Characteristics:

- Improves ground operations compared to conventional storables, due to low toxicity
- Approximately 10% increase in performance (specific impulse) compared to conventional storables

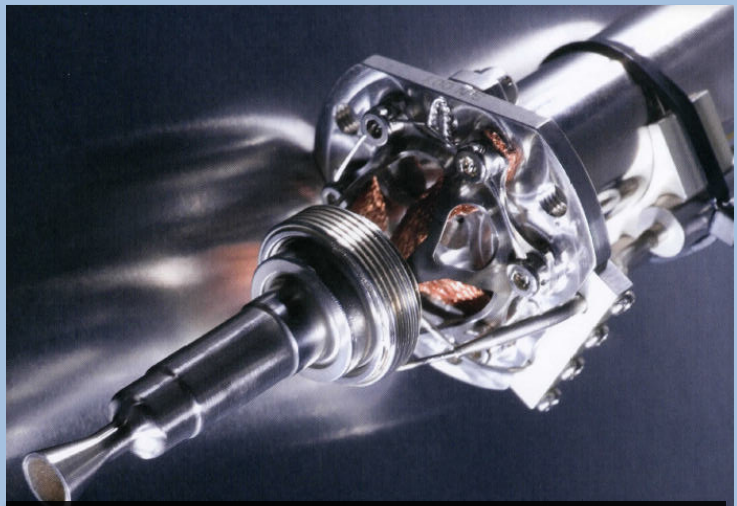
Potential Destinations Supported: Mars, NEA

Current TRL Estimate:

- Pump-fed Main Engine - TRL 4
- Pressure-fed Main Engine - TRL 5
- Reaction Control Engine – TRL 6

Advanced, Non-Toxic Reaction Control Systems

Thermographic image of Mighty Eagle robotic lander demonstration flight



European (ECAPS) 1-N green propellant thruster

Capability Description: Reaction Control Systems Based on Advanced, Storable, Non-Toxic Propellants such as ionic liquids, or nitrous oxide combinations, etc.

Performance Characteristics:

- Improved safety and ground operations
- Improved performance compared to conventional storables
- Elimination of cryogenic storage and delivery challenges

Potential Destinations Supported: All

Current TRL Estimate: 3-4 (for large scale)

Advanced, Low-Cost Engine Manufacturing

Capability Description: Significantly decrease recurring manufacturing cost to achieve affordability and sustainability goals by replacing slow, labor-intensive methods with:

- Metal stereo-lithography
- Chemical etching
- Advanced welding/joining techniques

Performance Characteristics:

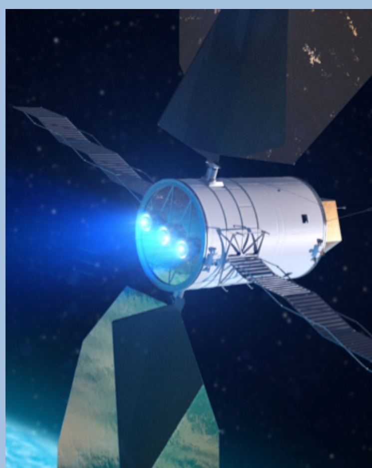
- Support low-rate production
- Reduce overall touch labor & schedule
- Target 50% recurring cost reduction

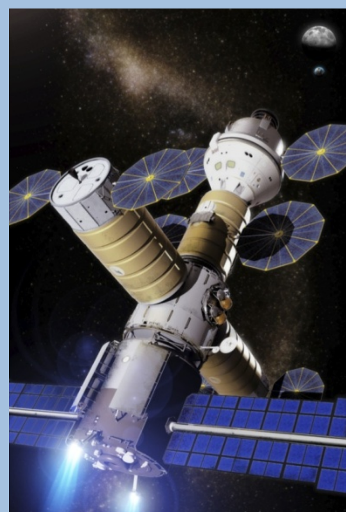
Potential Destinations Supported:

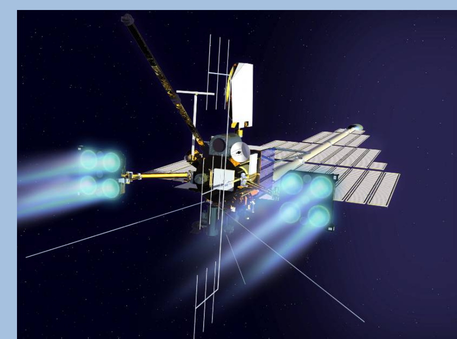
- NEA, Mars
- Applicable to both launch and in-space engine systems and components

Current TRL Estimate: 3-5

Electric Propulsion Options







30kw-class SEP
~ 2017

Operational mission with advanced technology

~30kW-class power
~20kW-class EP

ΔV > 10km/s

Med-term Exploration Missions circa 2020's

Crewed mission to cis-lunar space

30kW-class power system
20kW-class EP

ΔV ≈ 3 km/s

Far-term Exploration Missions circa 2030's

Crewed mission beyond Earth space

350kW-class power system
300kW-class EP

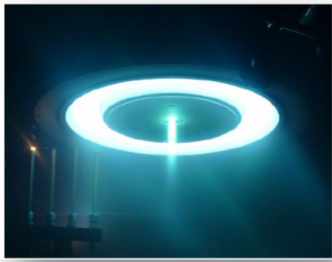
ΔV ≈ 8 km/s

Far-term Exploration Missions circa 2030's

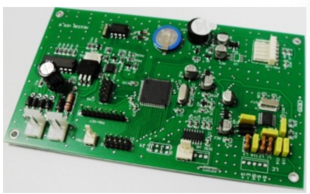
Crewed mission beyond Earth space

MW-class nuclear power
MW-class EP

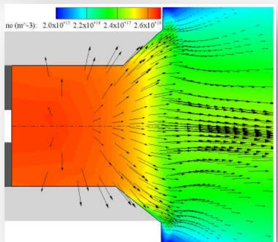
Electric Propulsion and Power Processing



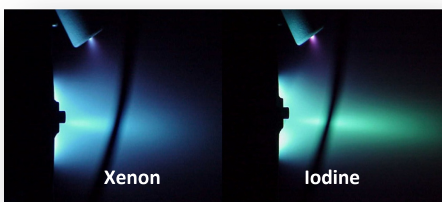
High Power Hall Thruster



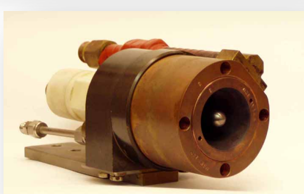
High Voltage Power Processing



Advanced modeling and diagnostics



Alternate Propellants



Advance Electric Propulsion

Capability Description: Electric propulsion vehicles may significantly reduce the number of launches required and can decrease sensitivity to mass growth of other in-space elements.

- Minimum of 3X current state-of-the-art lifetime improvements required for new EP systems
- A propulsion systems requiring nominally from 10’s kW to megawatts of electrical power is required for these missions; technology development is required because the state-of-the-art is 5 kW thrusters.
- Advanced technologies such as alternate propellants, magnetoplasmadynamic (MPD) Thruster, pulsed thrusters, field reverse configurations, and nested configurations required for the very high power class missions

Performance characteristics

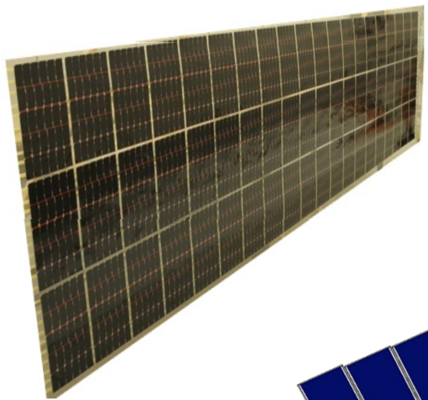
- High power (from 10-100’s kW power at beginning of life)
- High specific impulse (2000 – 3000+ seconds)
- Long life (20,000+hrs)
- High voltage (>300V), high efficiency power processing systems
- Note: these characteristics requires up to a 200x increase in thrust and 100x increase in power to the propulsion subsystem compared to the state-of-the-art.

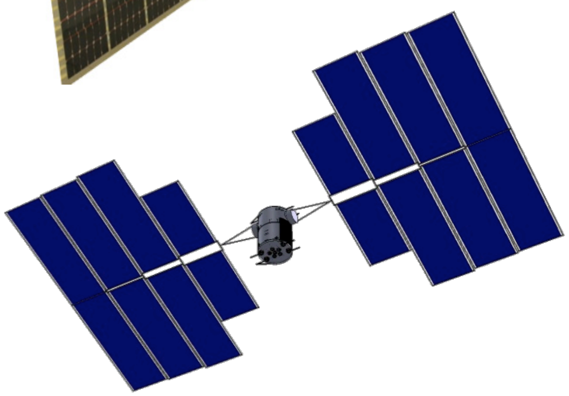
Potential Destinations Supported

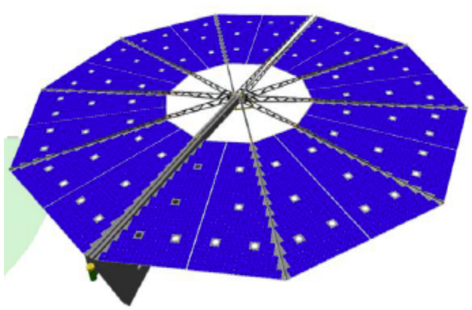
- NEA, Mars

Current TRL Estimate: 3-5

Evolution of Solar Power for Propulsion Application







Capability Description: Autonomously deployable arrays with high strength/stiffness and high power per mass and stowed volume

- Enabling features include compact stowage, reliable deployment, sufficient deployed strength and robust performance through the mission end-of-life. Leading options include large, dual-wing structures and modular, sub-wing structures employing advanced photovoltaic cells on flexible substrates.

Performance Characteristics:

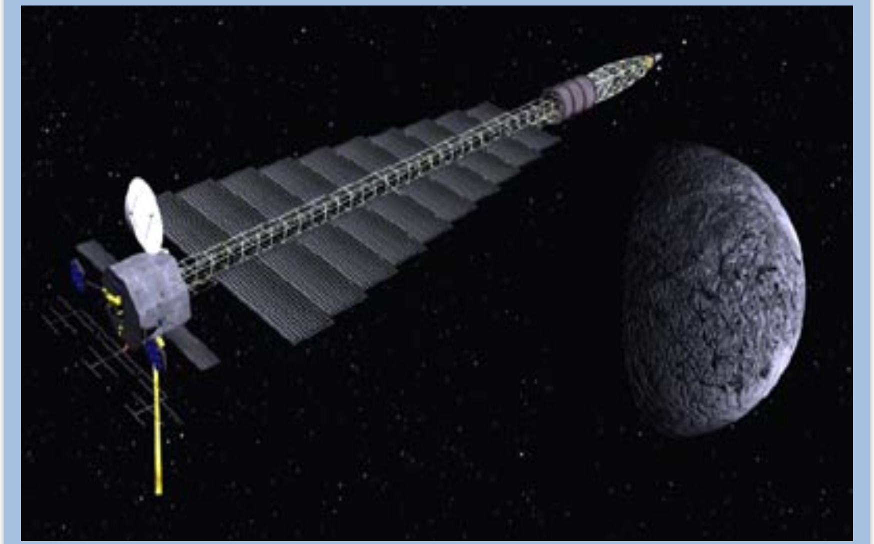
- For SEP:
  - ~50kW for asteroid retrieval mission; ~300kW for piloted NEA mission; ~800kW for piloted Mars mission
  - High voltage for high power missions
  - Low mass and low stowed volume
  - Lower cost (2x reduction)
  - ~0.1g deployed strength; tolerant to the deep space environment
- For other vehicles applications:
  - 10 - 100kW autonomously deployable and operational under propulsive accelerations (0.1g) and high voltage

Potential Destinations Supported:

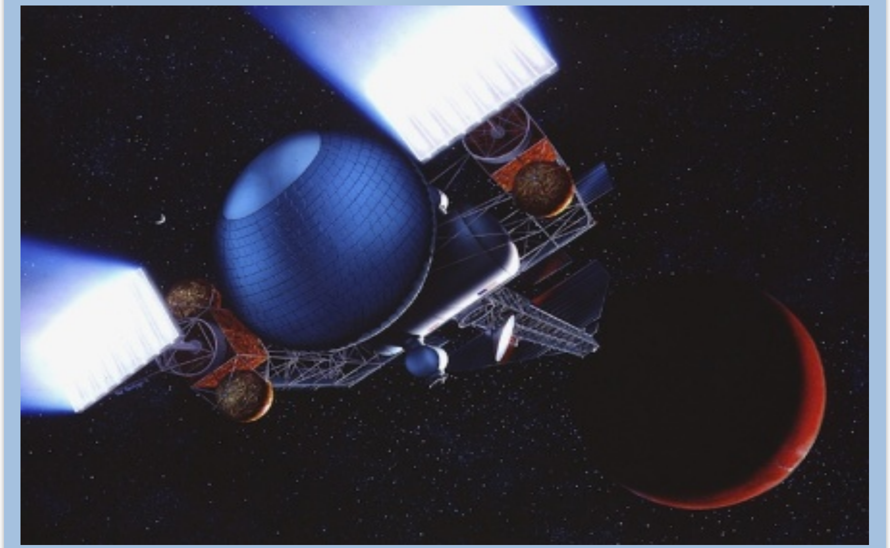
- NEA, Mars
- Also benefits: Landers and habitats

Current TRL Estimate: 3-5

Evolution of Power for Nuclear Electric Propulsion

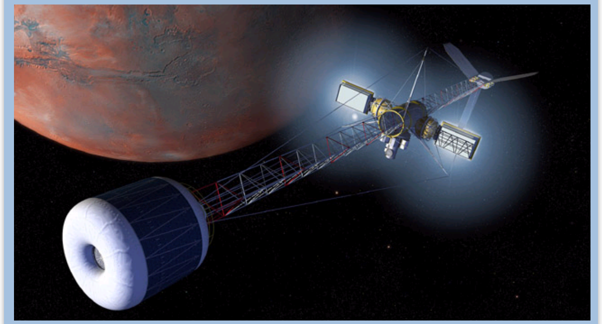


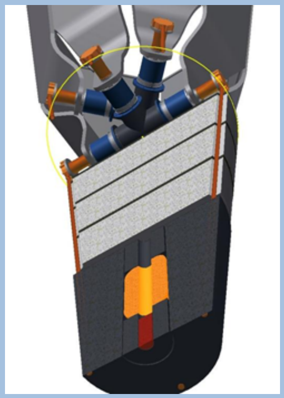
Moderate Power NEP-Near Term
- 100 kWe to 1 MWe
- 1200 K reactor outlet – direct gas Brayton or pumped liquid metal coolant.
- Brayton or Stirling power conversion
- 500 K composite radiators with H_2O heat pipes

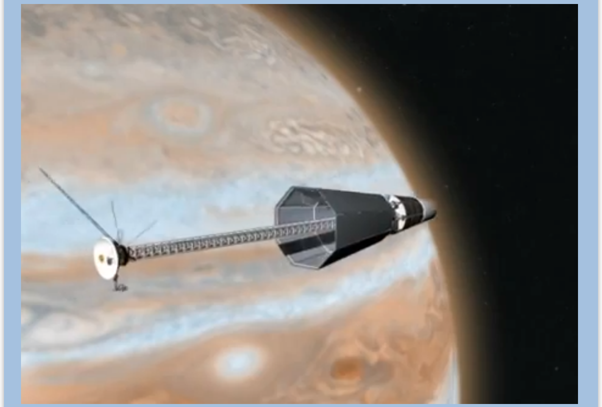


High Power NEP-Far Term
- Multi-Megawatt
- 1500 K Liquid metal (Li) cooled reactor with UN or other advanced fuel and refractory alloy structure
- Brayton or Rankine power conversion
- 800 K composite radiators with Na or K heat pipes

Nuclear Electric Propulsion Power







Capability Description

Space fission power systems can provide safe, abundant energy anywhere in the solar system, independent of available sunlight. Fission systems are typically considered for missions very close to the sun (thermal management), and for missions to Mars and beyond. Uranium fueled, variable power, essentially non-radioactive at launch, over 70 years of related terrestrial experience.

Performance Characteristics

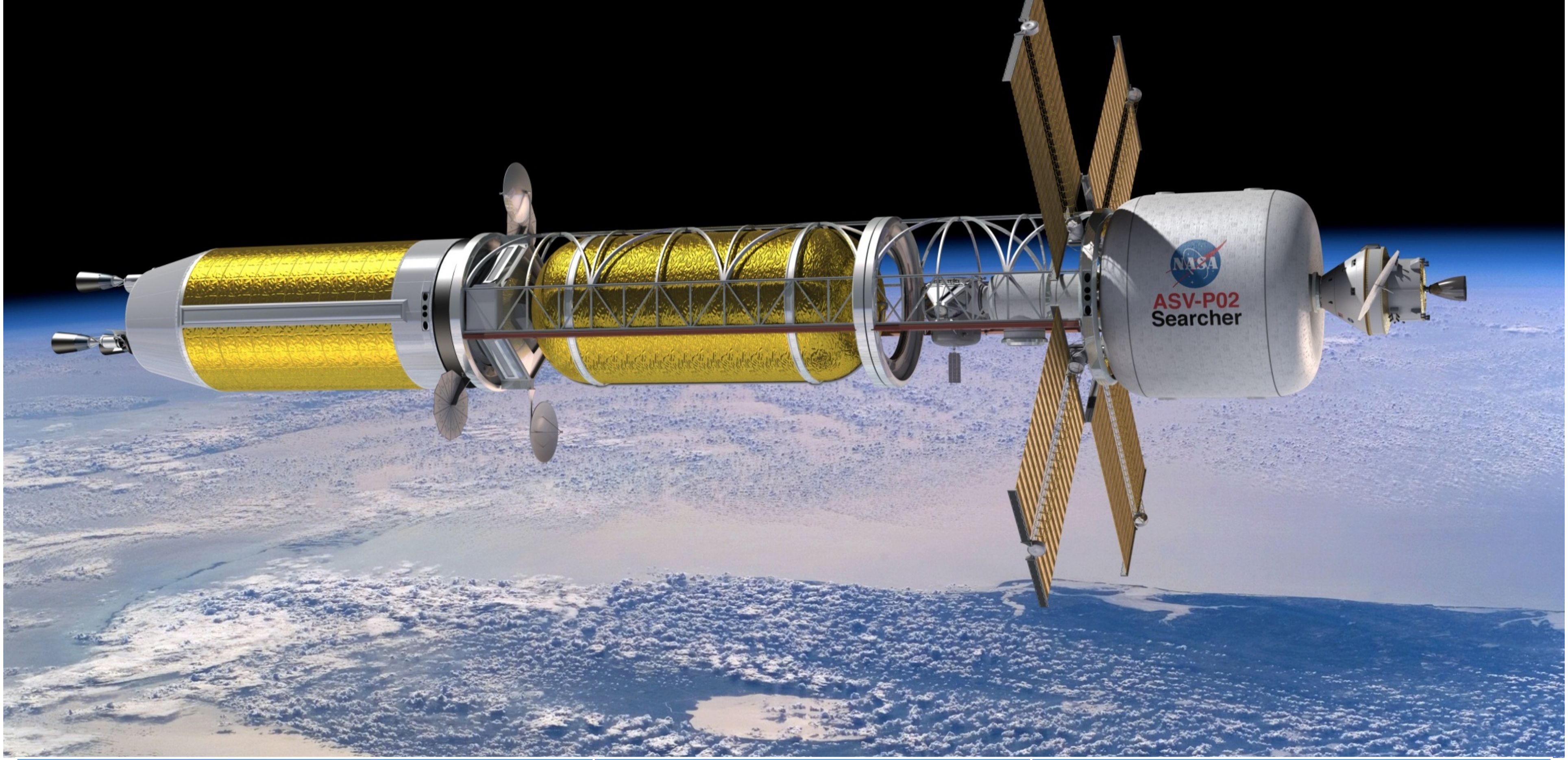
- 300kWe Class Systems:
  - Moderate power, low mass (<30 kg/kWe)
  - Current Technology Recommendation: Li-cooled UN-fueled reactor, multi-kWe-level Brayton power conversion, high voltage power management and distribution
  - Brayton power conversion technology
  - Large, deployable radiators
- MultiMWe Class Systems:
  - High (>1 MWe) power, low mass (<15 kg/kWe)
  - High temperature / high burnup fuel elements
  - High temperature heat transfer and structure
  - Advanced Power conversion (high temperature Brayton, Rankine, Magnetohydrodynamic)
  - Light weight, high temperature radiators

Potential Destinations Supported

- NEA, Mars
- Also benefit for surface power generation

Current TRL Estimate: 3-5

Nuclear Thermal Propulsion



Prototype Flight/Science Missions-2020's	Human/Cargo Missions- 2030's	Far Term Exploration- Beyond 2030's
Isp ~ 875 seconds with Hydrogen	Isp ~ 900 seconds with Hydrogen	Isp ~ 1000 seconds with Hydrogen
Thrust ~ 7,500 lbf with single engine	Thrust ~ 25,000 lbf per engine	Thrust ~25,000 lbf per engine
Power ~ 150 MW with single engine	Power ~ 550 MW per engine	Power ~ 575 MW per engine

Nuclear Thermal Propulsion (NTP) Engine

Capability Description

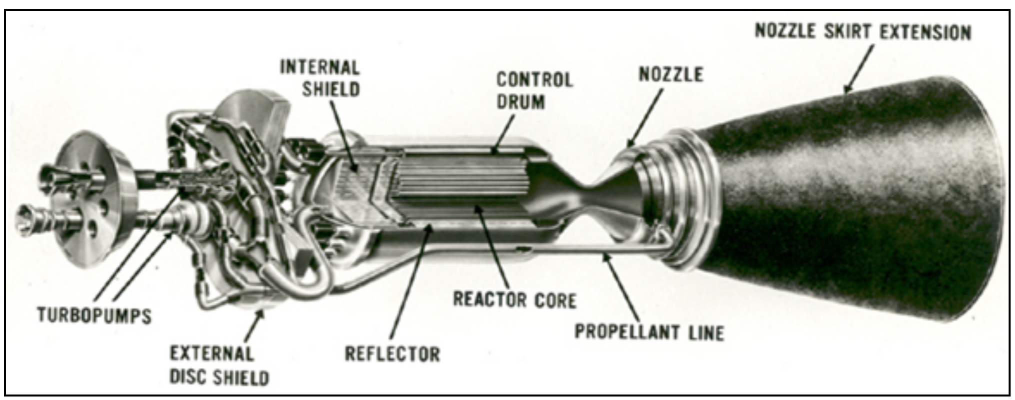
Nuclear thermal propulsion (NTP) uses ~500MW reactor to heat a propellant to extremely high temperatures without combustion. NTP has strong synergy with chemical rocket technologies (e.g., CFM, Propellant feed system, Nozzle, TVC). Evolves from Rover/NERVA NTP technologies in the 1960's.

Fuels

Prototypic Fuel Testing in non-nuclear simulators

Performance Characteristics

- Develop a high temperature and high power density reactor fuel
- Develop engine design with minimum amount of highly enriched uranium
- Cryogenic Fluid Management-Long duration storage and tank coupling for liquid hydrogen
- Ground test facilities to demonstrate reactor and propulsion system operation and performance
- Prototype flight test to demonstrate operation in space
- High thrust (10's of klbf) per engine
- High Isp (~900 s) propulsion with either NERVA-derived or ceramic-metallic (cermet) reactor fuel. Highest
- Isp (~1000 s) with advanced tri-carbide reactor fuel



Potential Destinations Supported

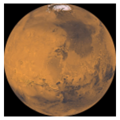
- NEA, Mars
- Also benefit for surface power generation

Current TRL Estimate: 3-5

National Environmental Policy Act (NEPA) must be addressed

Propulsion and Power Technologies Mapped to Destinations (Summary)





	Technology	Capability	For Destinations		
			NEA	Mars Orbit / Moons	Mars Surface
Transportation Options	**Cryo Propulsion Stage (CPS)**	High Thrust/Near Earth	**X**	Option	Option
	Nuclear Thermal Propulsion (NTP)	High Thrust/Beyond LEO	Option	Option	Option
	Nuclear Electric Propulsion (NEP)	Low Thrust/Beyond LEO	Option	Option	Option
	Solar Electric Propulsion (SEP)	Low Thrust/Near Earth	Option	Option	Option

Tests and Demonstrations Needed and Candidate Test Options

Ground *(Lab, Vacuum Chamber, Sea-Level)*	Simulated Altitude	Suborbital	Orbital	ISS Payload Candidates
Nuclear Fuel Element Samples in Lab	LOX/LCH4 Engine hot fire	Short-Duration Cryo Liquid Acquisition Demo (A low-cost risk mitigation Option)	LOX/LCH4 System Demo	Cryo Liquid Acquisition Device Subsystem demo (could include chill-down)
Nuclear Engine Component & System Tests at Sea Level	LOX/LCH4 System Hot Fire	High-Temperature Heat Pipes for Nuclear Systems	Solar Electric Propulsion Demo	Cryo Leak Detection Subsystem Demo
Cryogenic Integrated System Test in Vacuum Chamber	Non-Toxic RCS Pod Hot Fire	Simulated Nuclear Power System Demo	LOX/LH2 Cryogenic Propellant Storage and Transfer Demo	Cryo Mass Gauge Demo
Advanced Mfg Components (incorporated in engine tests)	Electric Propulsion System Test		NTP System Demo	Automated Cryo Fluid Coupling Demo
Solar Array Thermal / Vacuum Deployment	Engine hot fires with advanced mfg components		NEP System Demo	Fission Power Simulated Reactor Demo
			Large Solar Array Deployment and G-Force Loading	High Temperature Radiators for Nuclear Systems
				EP Feed System Demo

Technology Color Code:

- LOX-LCH4
- Non-Toxic RCS
- Advanced, Low-Cost Manufacturing
- Electric Propulsion
- Solar Power
- Nuclear Thermal Propulsion
- Fission Power For Nuclear Electric Propulsion
- Long-Duration Cryogenic Fluid Management

Comments on New Technology Development (Propulsion and Power)

- **Design the space propulsion and power system to be as safe, affordable, and reliable as feasibly possible**

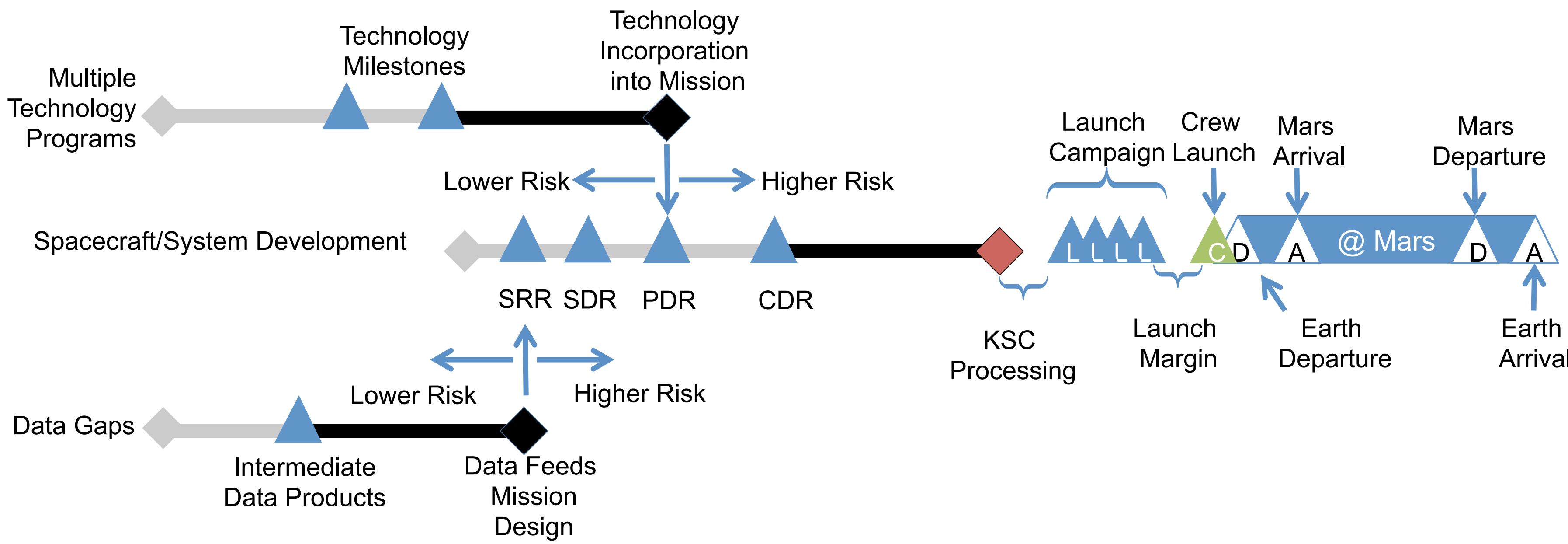
- **Achieve the highest thrust and/or Specific Impulse propulsion to shorten the trip time and/or reduce the spacecraft initial mass in low earth orbit**

- **Achieve a TRL 6 on all technologies needed for systems' operation before the preliminary design review associated with full system development**

Note - Even when a concept reaches TRL 6, it will take many more years to develop and qualify for flight.

Integrated Schedule Anatomy – Mars Example

- In this schedule-driven example, flight systems must arrive at KSC to support a launch date (which may be set by planetary physics)
- Flight system development for large human systems is 5-8 years
- New technologies incorporated into spacecraft design at PDR if TRL 6 or >
- Data gaps may need to be resolved in order to begin flight system design (e.g., choice of an asteroid target, planetary surface characteristics), or can be incorporated later in the design process (e.g., narrowing a landing site)
- Early incorporation of new technologies and data sets reduces mission risk
- The timeline varies for each destination, for different flight system developments, for different technology programs, and for the acquisition of different data sets



Status of NASA's Capabilities

- **An underpinning assumption is that this nation has a healthy propulsion industrial base ready to provide propulsion solutions as decisions are made**
  - That is not a good assumption
  - Limited development of new propulsion systems in this country for decades has left the propulsion industrial base much more fragile than it once was
  - The "propulsion industrial base" includes the propulsion related skills, capabilities and facilities of Government, industry and academia
- **This problem is larger than NASA … in reality, there is a single propulsion industrial base that supports civil, military and national security needs**
  - NASA, DoD, NRO, etc. do not each have their own propulsion industrial bases
  - In most instances, we are all pulling on the same skills, capabilities and facilities
  - Significant decisions by any one agency with respect to the industrial base impact all agencies
  - For this reason, Government agencies must inform each other and look for collaborative opportunities to "pool" resources to address this critical need…a healthy propulsion industrial base
- **The National Institute for Rocket Propulsion Systems (NIRPS) is being formulated as a collaborative, multi-agency entity to address these issues**
  - Support the competitiveness and resilience of the industrial base
  - Invigorate the STEM pipeline
  - Develop and integrate a science & technology plan for propulsion systems
  - Reduce development and sustainment costs for missile and rocket systems
  - Collaborate across agencies for missile and rocket propulsion system development
  - Foster access to facilities and expertise across Government, industry and academia

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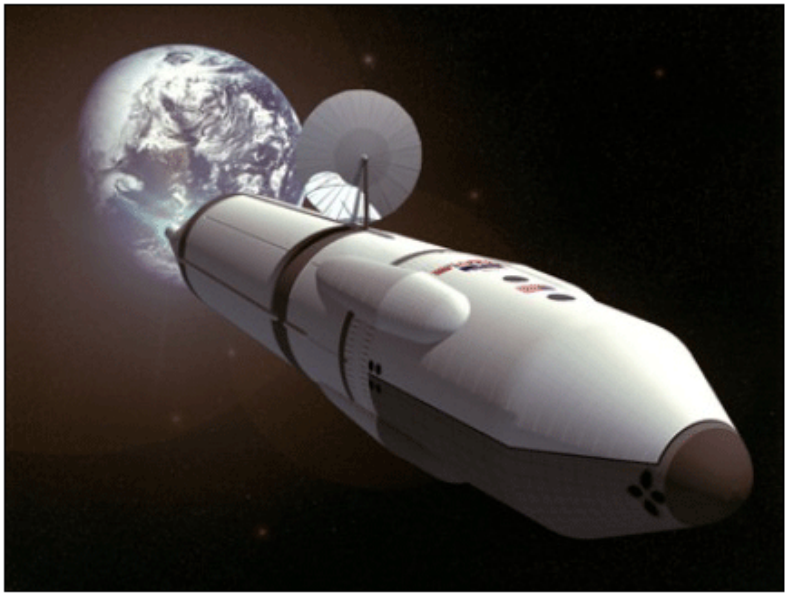

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- **And the many members of the NASA Design Reference Mission Study Teams**

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