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Space Nuclear Propulsion: From Current Efforts to a Future Human Mars Campaign

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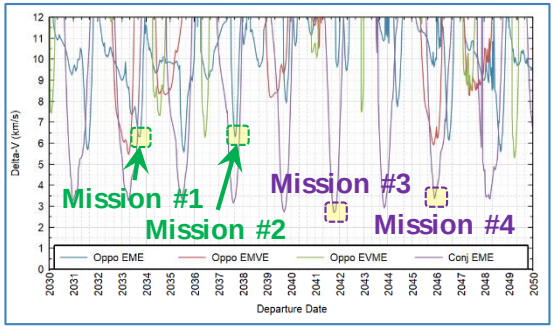
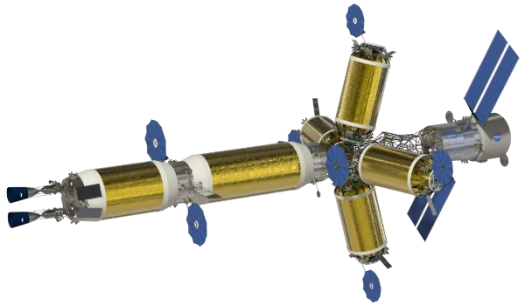
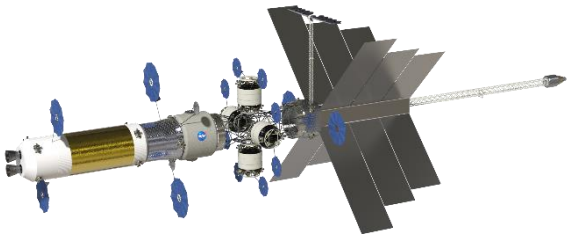
Future In-Space Operations (FISO) Briefing

Introduction

- Current Space Nuclear Propulsion Efforts
- Overview of Envisioned Human Mars Campaign
- Nuclear Thermal Propulsion (NTP) Human Mars Campaign
- Nuclear Electric Propulsion (NEP) / Chemical Propulsion Hybrid Human Mars Campaign
- Campaign Summary and Future Work

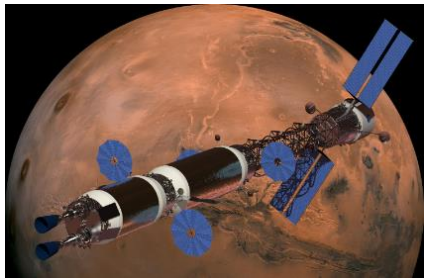


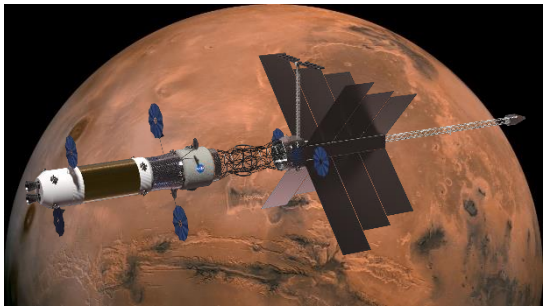




Current Space Nuclear Propulsion (SNP) Efforts

- In 2016, AR began supporting a NASA-led SNP effort to analyze and assess High-Assay Low Enriched Uranium (HALEU) for Nuclear Thermal Propulsion (NTP) with a goal to prove feasibility – proven
- Through 2019 and 2020, AR supported the NASA-led SNP team with the development of various Design Analysis Cycles providing increased fidelity for a NTP engine design leveraging the NASA-led work in fuels testing and reactor core design – provided confidence in Isp ≥ 900 sec
- Current NASA-led NTP efforts focused on: fuels and materials testing; subscale prototype reactor and engine design (subscale prototype to demonstrate fuel and component technologies and operational capability); ground and flight test options; regulatory issues and mitigation requirements; and cryofluid management (CFM) technology
- Current NASA-led NEP effort is focused on developing a technology maturation plan for several key tech areas: Megawatt space power production, power conversion, heat rejection, high power / high voltage power management, high power (≥100 kWe) electric propulsion

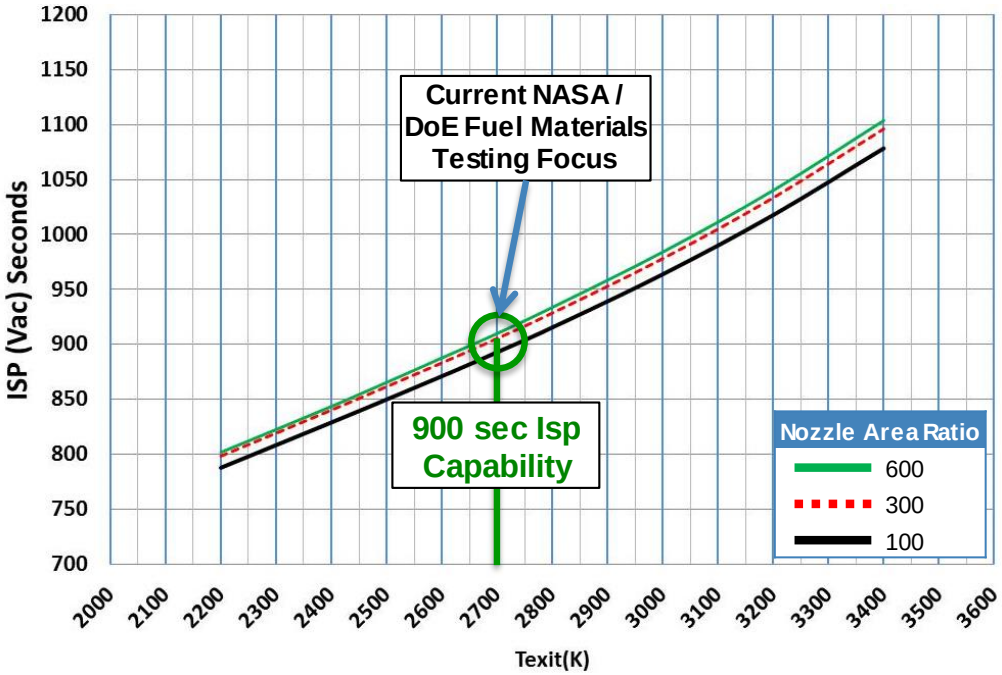




NTP Isp Performance Capability

NTP Engine Vacuum Isp vs. Reactor Exit Temperature

Reactor Exit Pressure = 500 psia, Nozzle Loss Correction = 0.97



Current NASA / DOE Fuel Materials Testing Focused on Achieving LEU NTP Performance > 900 Sec – Target for Human Mars Missions

Overview of Envisioned Human Mars Campaign

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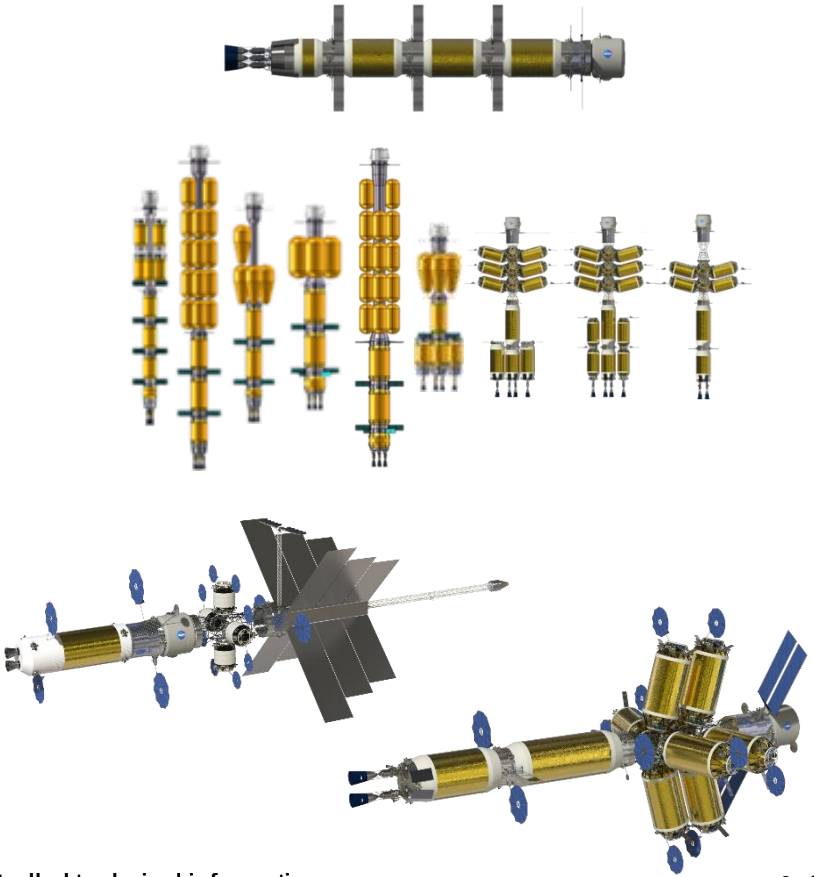
Campaign Background

- Since 2016, AR has supported the NASA Space Nuclear Propulsion project with an initial focus on Conjunction Class Mars mission and Nuclear Thermal Propulsion (NTP) engine risk reduction
- In late 2019, attention shifted within NASA to Opposition Class Mars missions and AR developed several NTP vehicle configurations to satisfy a mission in the late 2030s
- Since 2020, AR has examined options for a human Mars campaign: a series of missions, starting with initial sorties to Mars, and leading to the eventual permanent human presence on the surface of Mars
  - Examined both NTP and NEP / Chem Mars Transport Vehicle (MTV) options

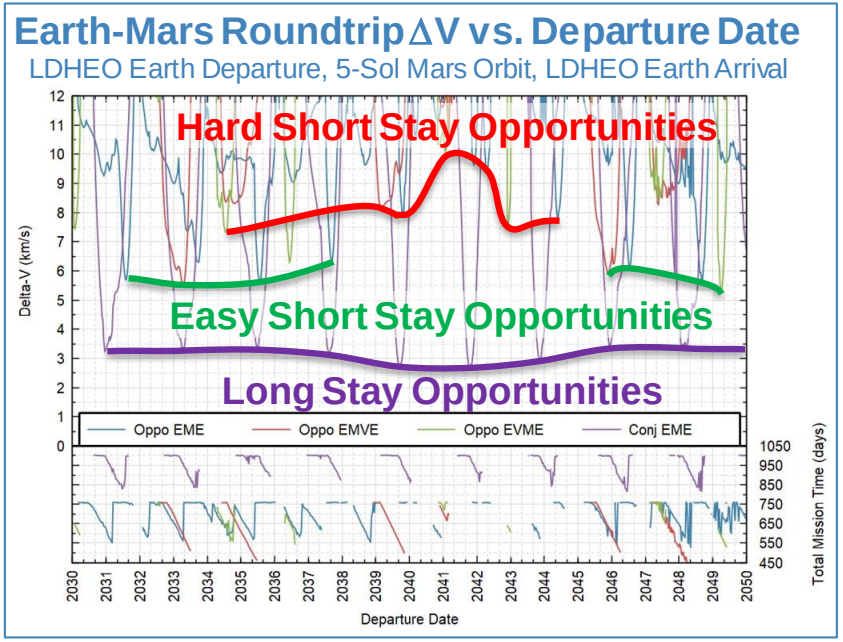


Campaign Goal and Key Assumptions

- **Campaign Goal:** The eventual human settlement of Mars, starting with crew on the surface of Mars in the late 2030's and the build-up of a surface outpost
- **Crew Size:** Four crew in Deep Space Habitat (DSH); Two crew to Mars surface for short stay missions; Four crew to Mars surface for long stay missions
- **Mars Surface Site:** Land at the same Mars surface site for initial missions to build up surface outpost
- **Reusability:** Deep Space Habitat is reusable; Crew and Cargo Mars Transport Vehicles (MTV), either NTP-based or NEP/Chem-based, are reusable and can be used for three missions; Mars surface habitats and surface power system are reusable
- **In-Situ Resource Utilization (ISRU):** ISRU of Mars atmospheric O_2 for Mars Ascent Vehicle (MAV) oxidizer (MAV fuel launched with MAV from Earth)
- **Launch Vehicles:** Leverage mixture of SLS B2 (Long 8.4m Fairing) and large commercial launch vehicles (Blue Origin New Glenn and SpaceX Starship)

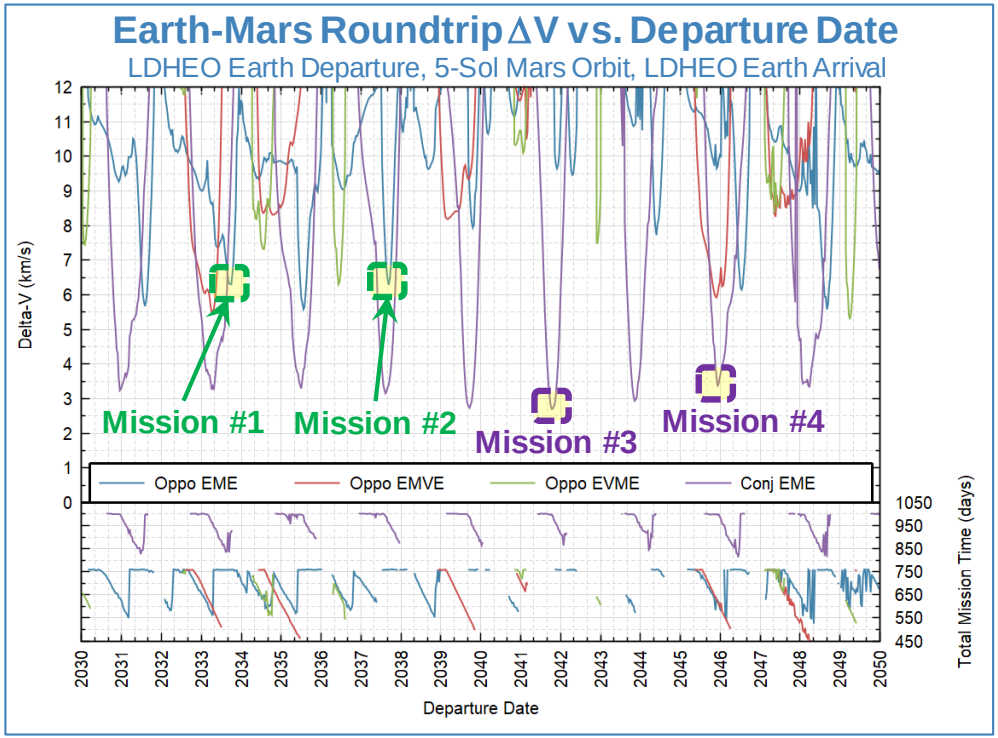
Campaign Mission Selection Rationale

- Start with an uncrewed mission to shake down in-space transportation system
- First crewed mission is **short stay** – minimizes required surface infrastructure, but challenge of more difficult interplanetary trajectories
  - Choose mission opportunity wisely: avoid **hard short stay opportunities** to limit in-space transportation system complexity
- Subsequent crewed missions are **long stay**
  - Enables more substantial surface science and exploration activities
  - Allows for development required for long duration surface infrastructure
  - Initially target the same surface location to build up surface outpost; eventually expand to other landing sites of interest



Campaign Initial Missions

- **Mission #1: 2033** – Uncrewed short stay or flyby mission – dress rehearsal for first crewed mission
- **Mission #2: 2037 Crew (2035 Cargo)** – Crewed short stay mission – first humans on the surface of Mars
- **Mission #3: 2041 Crew (2039 Cargo)** – Crewed long stay mission – first human extended Mars surface stay
- **Mission #4+: 2045 Crew (2043 Cargo)** – Series of crewed long stay missions with extended Mars surface stays, building up surface infrastructure



Common Campaign Elements Between NTP and NEP / Chem Human Mars Campaigns

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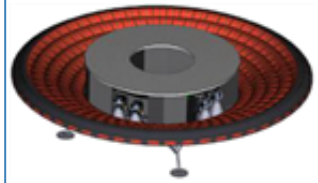
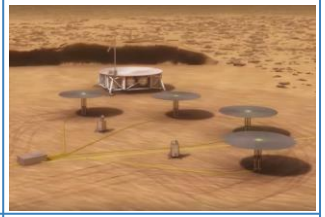
Launch Vehicles

NASA SLS B2 Crew	NASA SLS B2 Cargo	Blue Origin New Glenn	SpaceX Starship
 Carries Orion, crew, and logistics	 Carries large, high value, nuclear and chemical main propulsion and power elements, and Mars surface elements	 Carries Drop Tank truss elements	 Carries propellant tankers (LH2, Xe, LOX/CH4, depending on architecture)

Images Credit: NASA, Blue Origin, SpaceX

Mars Surface Elements

Mars Descent Stage	Mars Ascent Vehicle	Mars Surface Habitat / Pressurized Rover	Long Duration Surface Habitat	Surface Logistics Module	Mars Surface Power System
					
Function: Transport Mars surface elements from Mars intercept trajectory to surface of Mars. One Mars Descent Stage is used for each lander. **Mass:** 45 t fully fueled	**Function:** Transport crew from surface of Mars to Crew MTV in Mars orbit. **Mass:** 20 t during EDL (incl ISRU systems); 39 t at launch (not incl ISRU systems)	**Function:** Provide habitation and logistics for Mars crew for descent from Mars orbit to the surface of Mars, and while on the surface for 30 days **Mass:** 20 t	**Function:** Provide habitation for the Mars crew for descent from Mars orbit to the surface of Mars, and while on the surface for >400 days **Mass:** 20 t, with no logistics	**Function:** Provide logistics (food, water, other supplies) for the Mars crew while on the surface for >400 days **Mass:** 20 t	**Function:** Provide power to Mars Ascent Vehicle, LOX ISRU system, and Mars Surface Habitat systems while on the surface of Mars **Mass:** 20 t

Images Credit: NASA

NTP Human Mars Campaign

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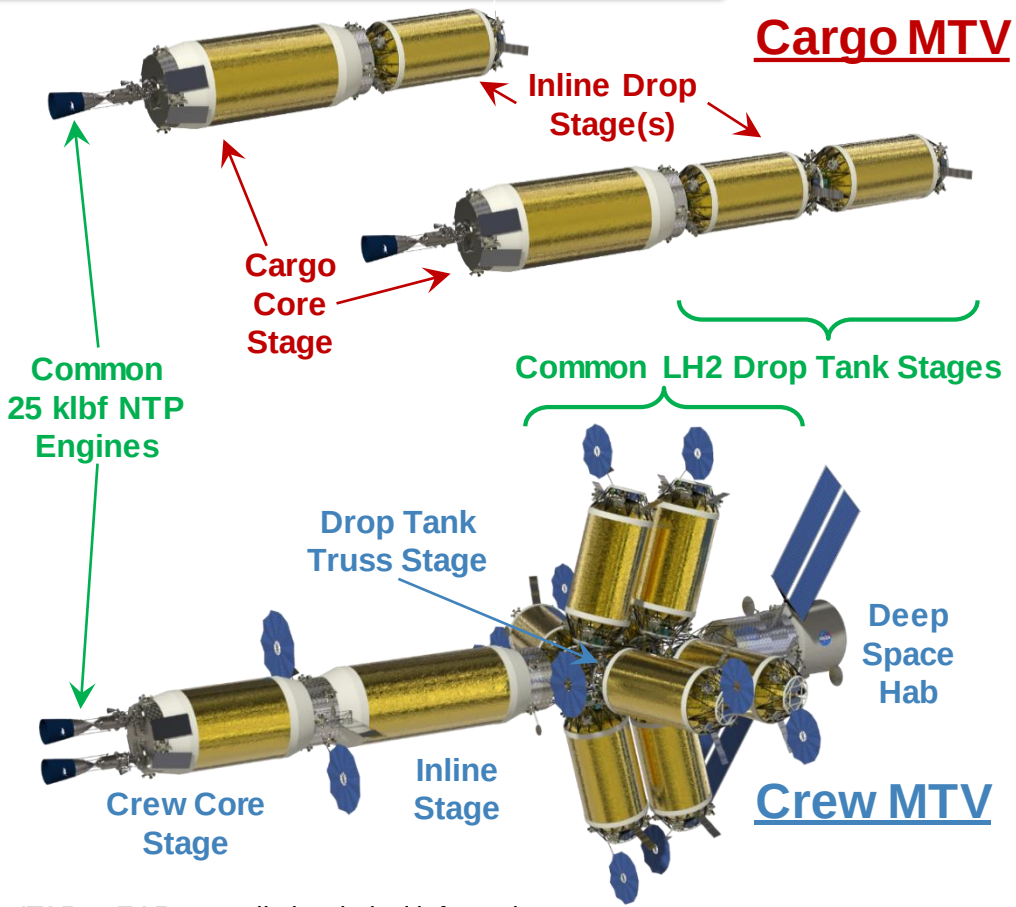
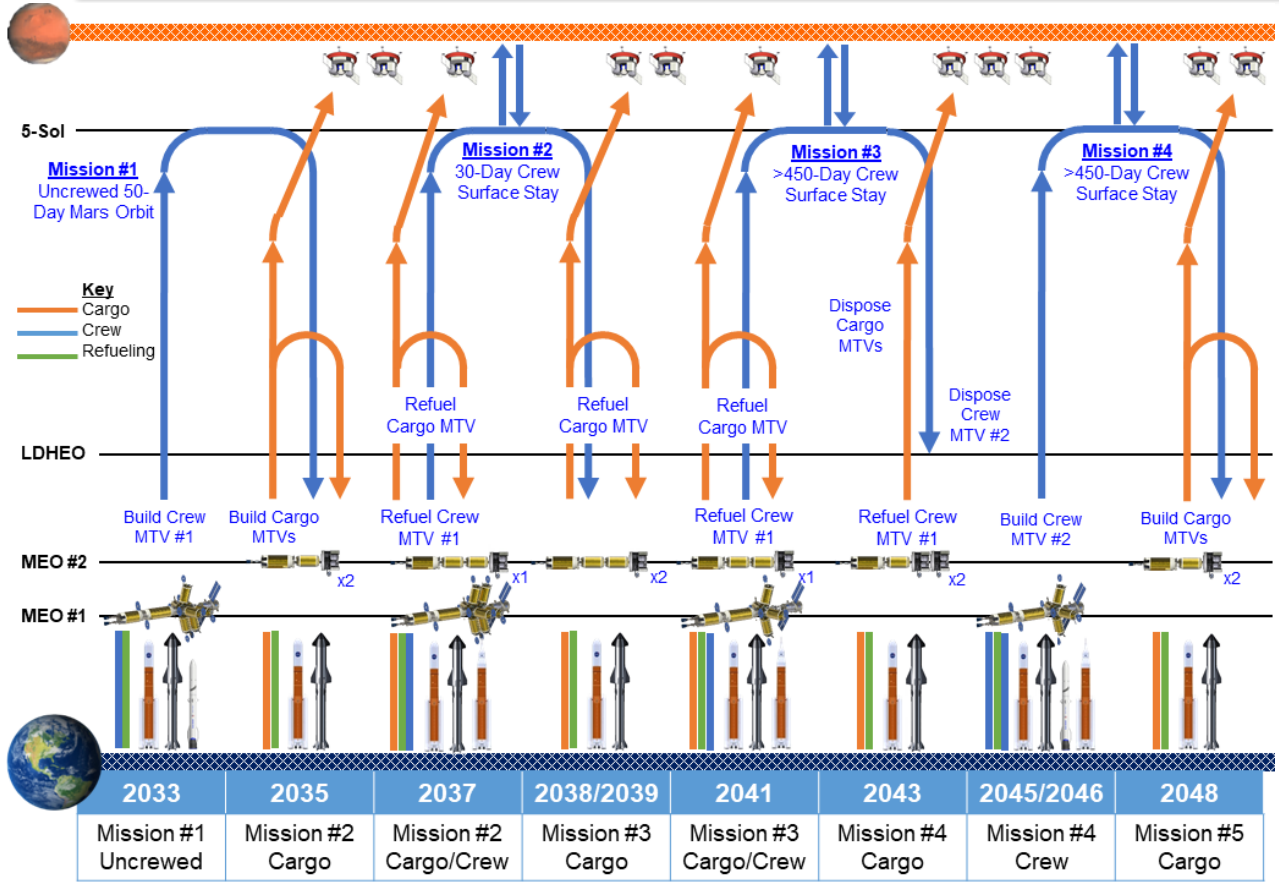
Cargo and Crew NTP Mars Transport Vehicles

- Cargo and Crew MTV's provide in-space transportation for Mars landers and Crew in Deep Space Hab
- MTV's are reusable for up to three missions
- MTV's use common NTP engine for primary propulsion and common Drop Tank Stages
- Modular design enables MTV's to support a wide variety of missions throughout the campaign



Human Mars Exploration Campaign Using NTP



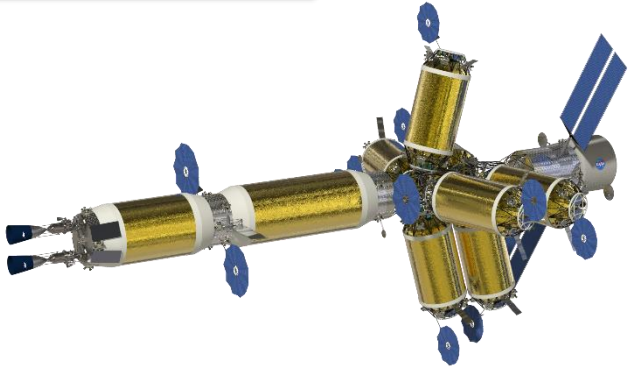
2033	2035	2037	2038/2039	2041	2043	2045/2046	2048
Mission #1 Uncrewed	Mission #2 Cargo	Mission #2 Cargo/Crew	Mission #3 Cargo	Mission #3 Cargo/Crew	Mission #4 Cargo	Mission #4 Crew	Mission #5 Cargo

Images Credit: NASA, SpaceX, Blue Origin

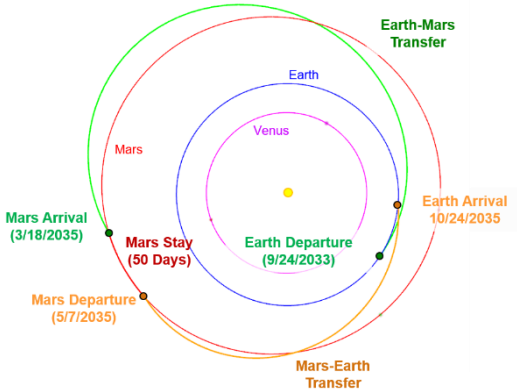
- **Mission #1: 2033** Uncrewed short stay mission – dress rehearsal for first crewed mission
  - Mars analog of Artemis I
- **Mission #2: 2037** Crewed short stay mission – first humans on the surface of Mars
  - Mars analog of Artemis III
- **Mission #3: 2041** Crewed long stay mission – buildup of surface infrastructure through multiple missions
- **Mission #4: 2045** Sustained long stay missions – series of extended Mars surface stays
  - Mars analog of follow-on Sustainable Artemis Missions

Mission #1: Uncrewed Opposition Class Mission

- **Mission #1:** Uncrewed short stay demonstration mission
- First mission in envisioned campaign, demonstrating vehicle performance and allowing additional development time for surface elements
- NTP Crew MTV (uncrewed) flies on 2033 EME Opposition trajectory
  - Time away from Earth limited to 760 days; Mars orbit for 50 days
  - Core Stage, Inline Stage, Drop Tank Truss, 7x Drop Tank Stages
  - 2x NTP engines operating at 848 sec (900 sec nominal)
  - MTV mass at final assembly: 391 t; mass at Earth departure: 208 t
- Upon return to Earth, Crew MTV is returned to Medium Earth Orbit (MEO) maintenance orbit and prepped for Mission #2
- Launches: 2 SLS Cargo, 2 New Glenn, 11 Starship



Mission #1 Crew MTV

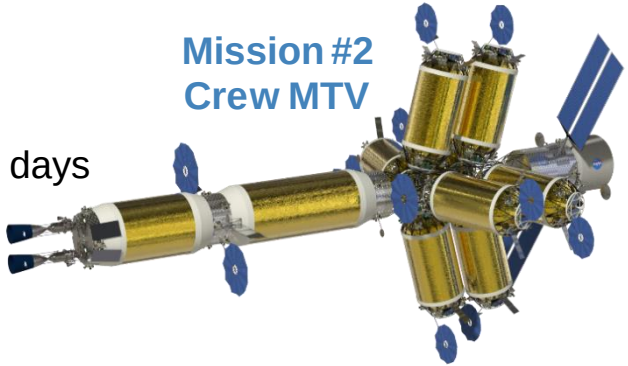


Mission #1 Trajectory

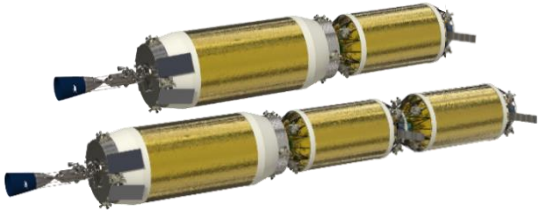
Mission #2: Crewed 30-Day Surface Stay

- **Mission #2:** Crewed short stay mission to surface of Mars
- NTP Crew MTV on 2037 EME Opposition trajectory
  - Time away from Earth limited to 760 days; 2 Crew on surface for 30 days
  - 8 Drop Tank Stages required
  - 2x NTP engines operating at 888 sec (900 sec nominal)
  - MTV mass at final assembly: 471 t; mass at Earth departure: 301 t
- Two Cargo MTVs used to deliver three Mars landers on Mars intercept trajectories – two in 2035, one in 2037
  - 65 t Mars Lander (45 t Mars Descent Stage + 20 t Cargo)
  - After payload separation, Cargo MTVs return to Earth orbit for reuse on later missions
- Upon return to Earth, Mission #2 Crew MTV prepped for Mission #3
- Launches: 2 SLS Crew, 5 SLS Cargo, 22 Starship

Mission #2 Crew MTV



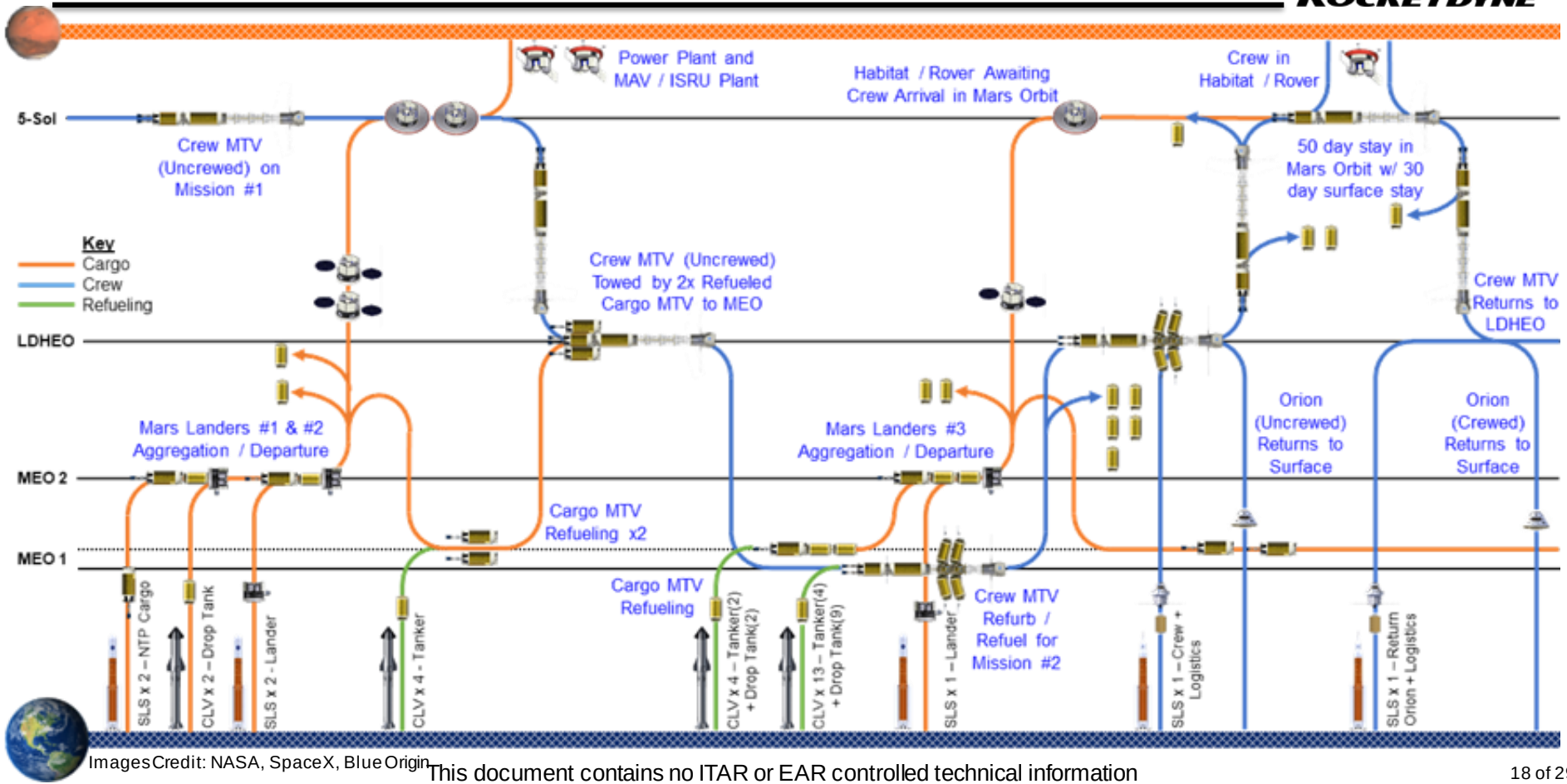
Mission #2 Cargo MTVs



Mission #2 Surface Elements

Lander Images Credit: NASA

Mission Concept of Operations Example: Mission #2



Images Credit: NASA, SpaceX, Blue Origin

Missions #3 and #4: Long Duration Surface Stay

Building Towards Sustainable Surface Ops and Long-term Exploration

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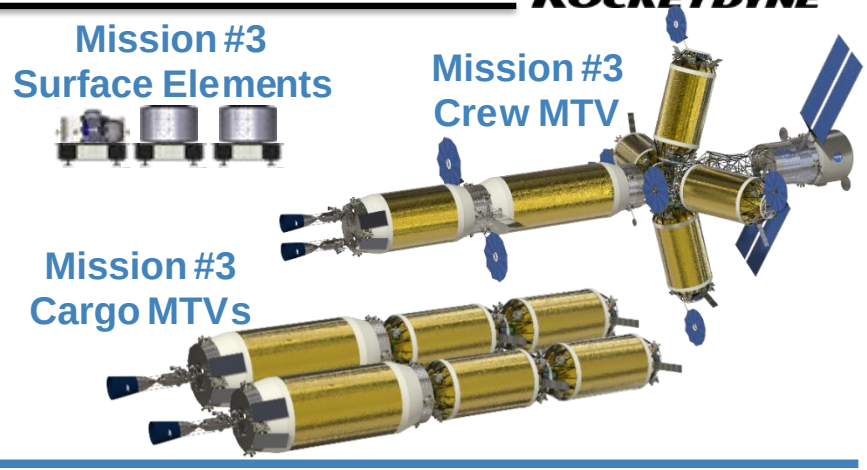
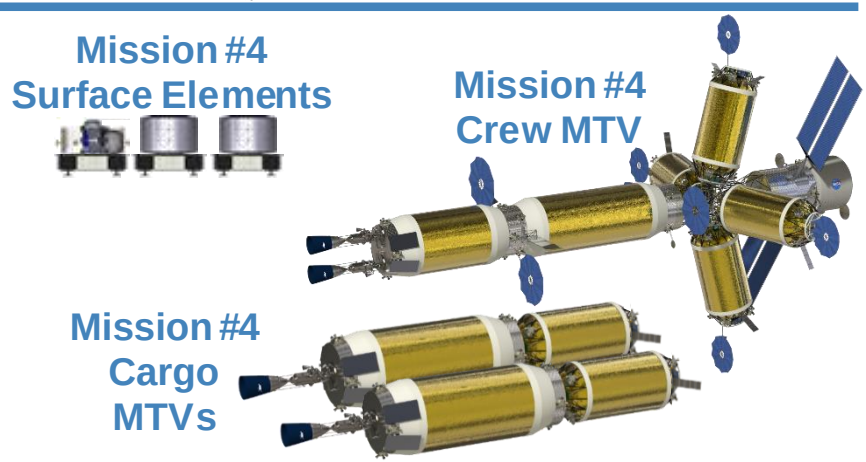
- **Mission #3:** First Long Surface Stay Mission
  - Crew MTV on 2041 Conjunction trajectory with 4 Drop Tank Stages, heliocentric disposal after Earth orbit insertion and crew departure
  - Cargo MTVs used to send two landers to Mars during 2038/2039 opportunity and one lander to Mars during 2041 opportunity; brought back to Earth for reuse
  - 4 Crew on surface for 448 days
  - Launches: 2 SLS Crew, 3 SLS Cargo, 20 Starship



- **Mission #4:** Beginning of Steady-State Long Surface Stay Missions
  - Newly constructed Crew MTV on 2045 Conjunction trajectory with 4 Drop Tank Stages
  - Cargo MTVs deliver three landers to Mars on 2043 opportunity, expended after payload separation
  - 4 Crew on surface for 526 days
  - Launches: 2 SLS Crew, 5 SLS Cargo, 1 New Glenn, 14 Starship



Lander Images Credit: NASA

NEP / Chemical Hybrid Human Mars Campaign

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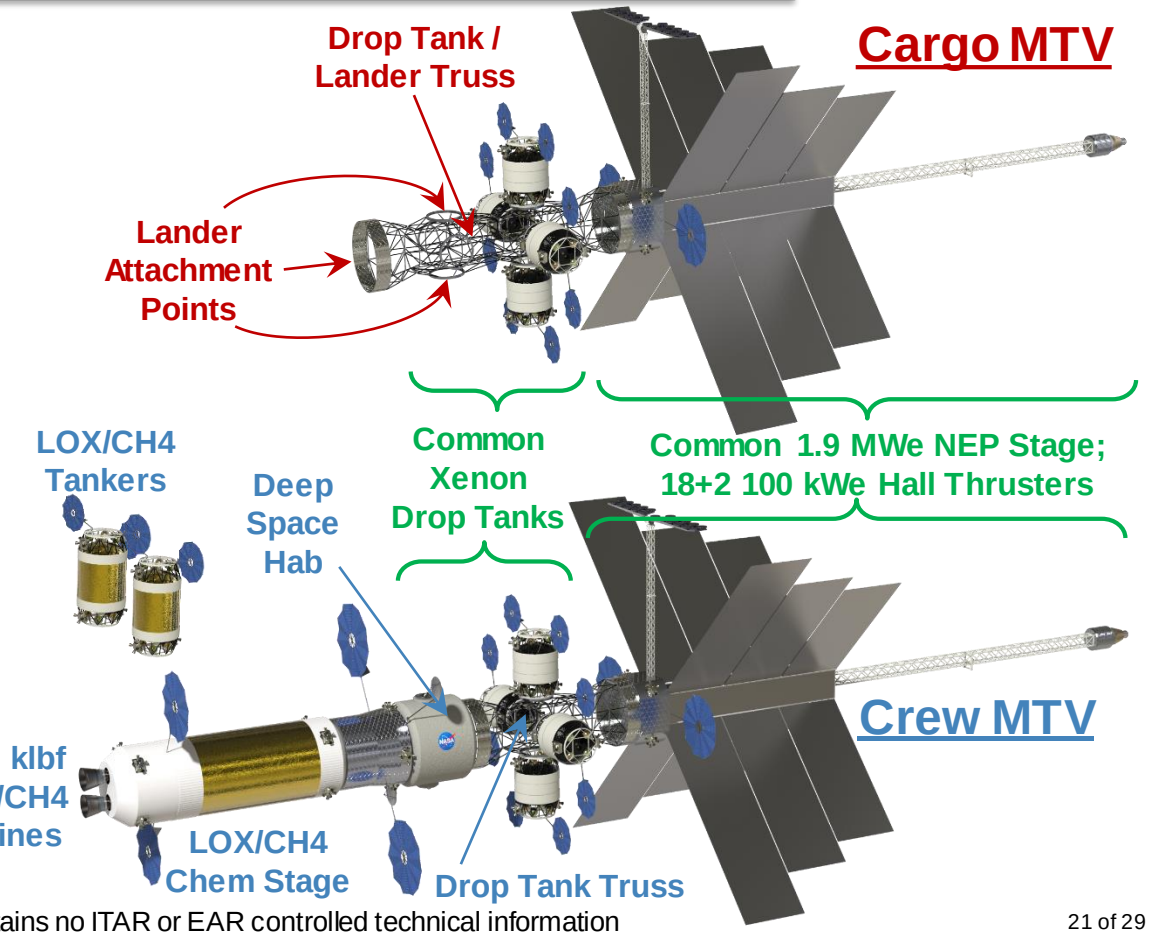
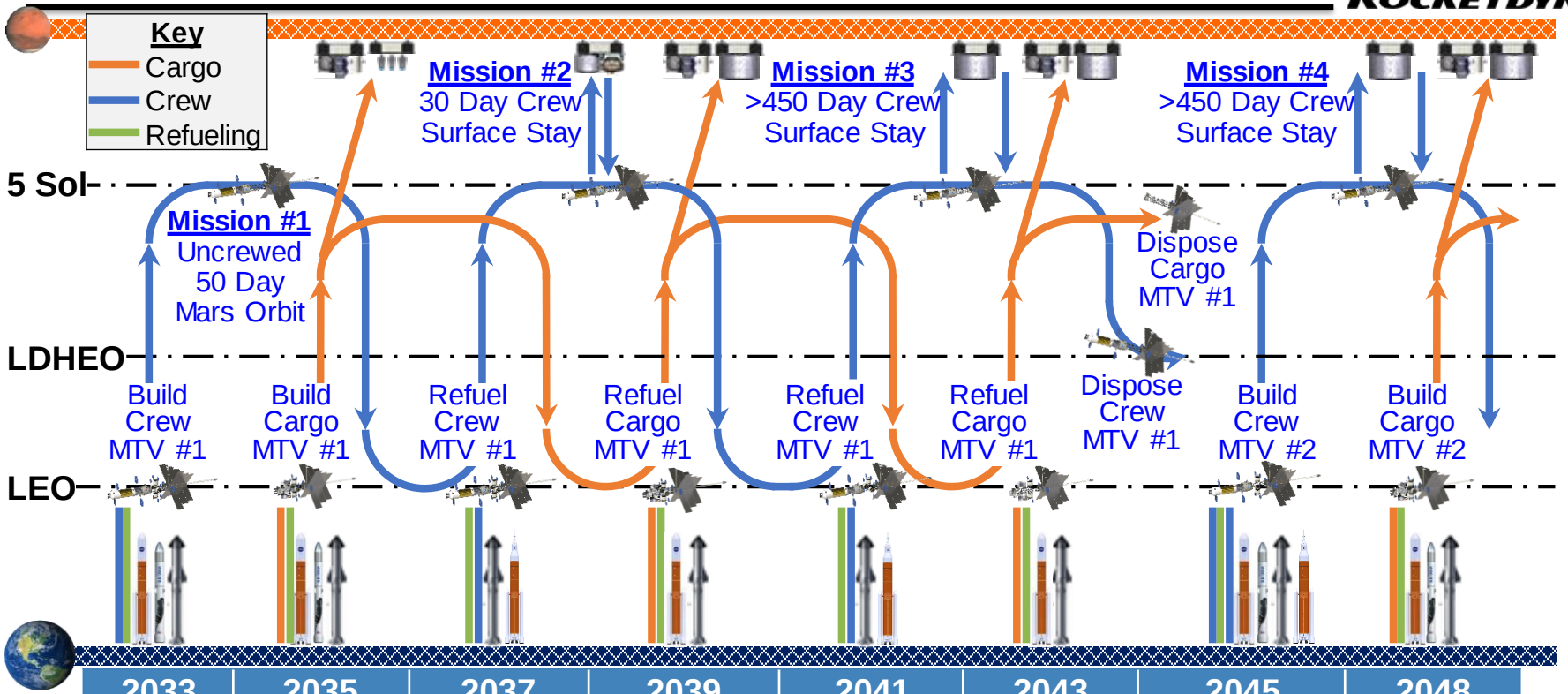
Cargo and Crew NEP/Chem Mars Transport Vehicles

- Cargo and Crew MTV's provide in-space transportation for Mars landers and Crew in Deep Space Hab
- MTV's are reusable for up to three missions
- MTV's use common NEP Stage design with Xenon Drop Tanks
- Modular design enables MTV's to support a wide variety of missions throughout the campaign



Human Mars Campaign Using NEP / Chem

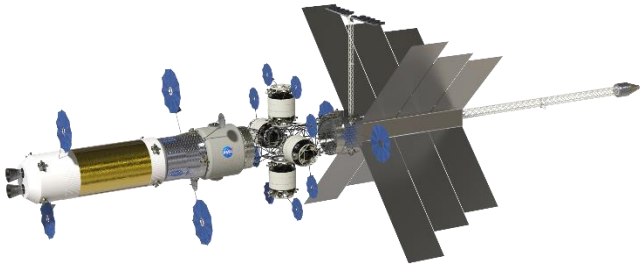


2033	2035	2037	2039	2041	2043	2045	2048
Mission #1 Uncrewed	Mission #2 Cargo	Mission #2 Crew	Mission #3 Cargo	Mission #3 Crew	Mission #4 Cargo	Mission #4 Crew	Mission #5 Cargo

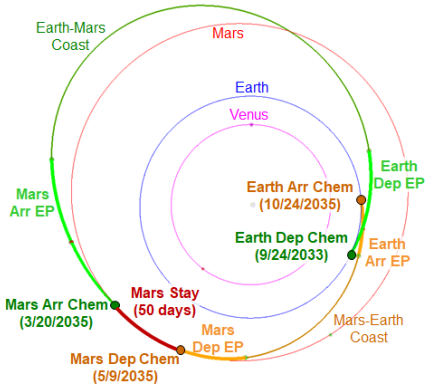
Images Credit: NASA, SpaceX, Blue Origin

Mission #1: Uncrewed Opposition Class Mission

- **Mission #1:** Uncrewed short stay demonstration mission
- First mission in envisioned campaign, demonstrating vehicle performance and allowing additional development time for surface elements
- NEP/Chem Crew MTV (uncrewed) flies on 2033 EME Opposition trajectory
  - Time away from Earth limited to 760 days; Mars orbit for 50 days
  - NEP Stage, Chem Stage, Drop Tank Truss, 4x Drop Tank Stages
  - 18+2 100 kWe EP thrusters operating at 2500 sec
  - 2x 25 klbf LOX/CH4 chemical engines operating at 360 sec
  - MTV mass at final assembly: 500 t; mass at Earth departure: 290 t
- Upon return to Earth, Crew MTV is returned to Low Earth Orbit (LEO) maintenance orbit and prepped for Mission #2
- Launches: 3 SLS Cargo, 1 New Glenn, 8 Starship



Mission #1 Crew MTV

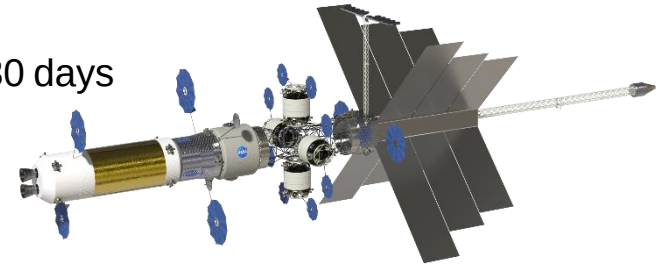


Mission #1 Trajectory

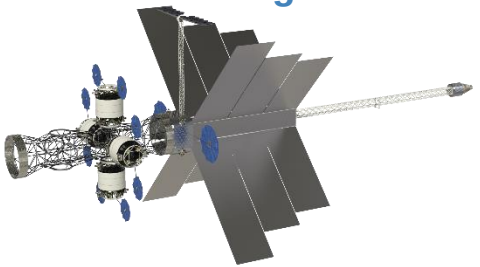
Mission #2: Crewed 30-Day Surface Stay

- **Mission #2:** Crewed short stay mission to surface of Mars
- NEP/Chem Crew MTV on 2037 EME Opposition trajectory
  - Time away from Earth limited to 760 days; 2 Crew on surface for 30 days
  - 4 Drop Tank Stages required
  - 18+2 100 kWe EP thrusters operating at 2500 sec
  - 2x 25 klbf LOX/CH4 chemical engines operating at 360 sec
  - MTV mass at final assembly: 519 t; mass at Earth departure: 297 t
- NEP Cargo MTV with 4 Drop Tank Stages used to deliver three Mars landers on Mars intercept trajectories – 2035 Earth SOI departure
  - 65 t Mars Lander (45 t Mars Descent Stage + 20 t Cargo)
  - After payload separation, Cargo MTVs return to Earth orbit for reuse on later missions
- Upon return to Earth, Mission #2 Crew MTV prepped for Mission #3
- Launches: 2 SLS Crew, 5 SLS Cargo, 2 New Glenn, 12 Starship

Mission #2 Crew MTV



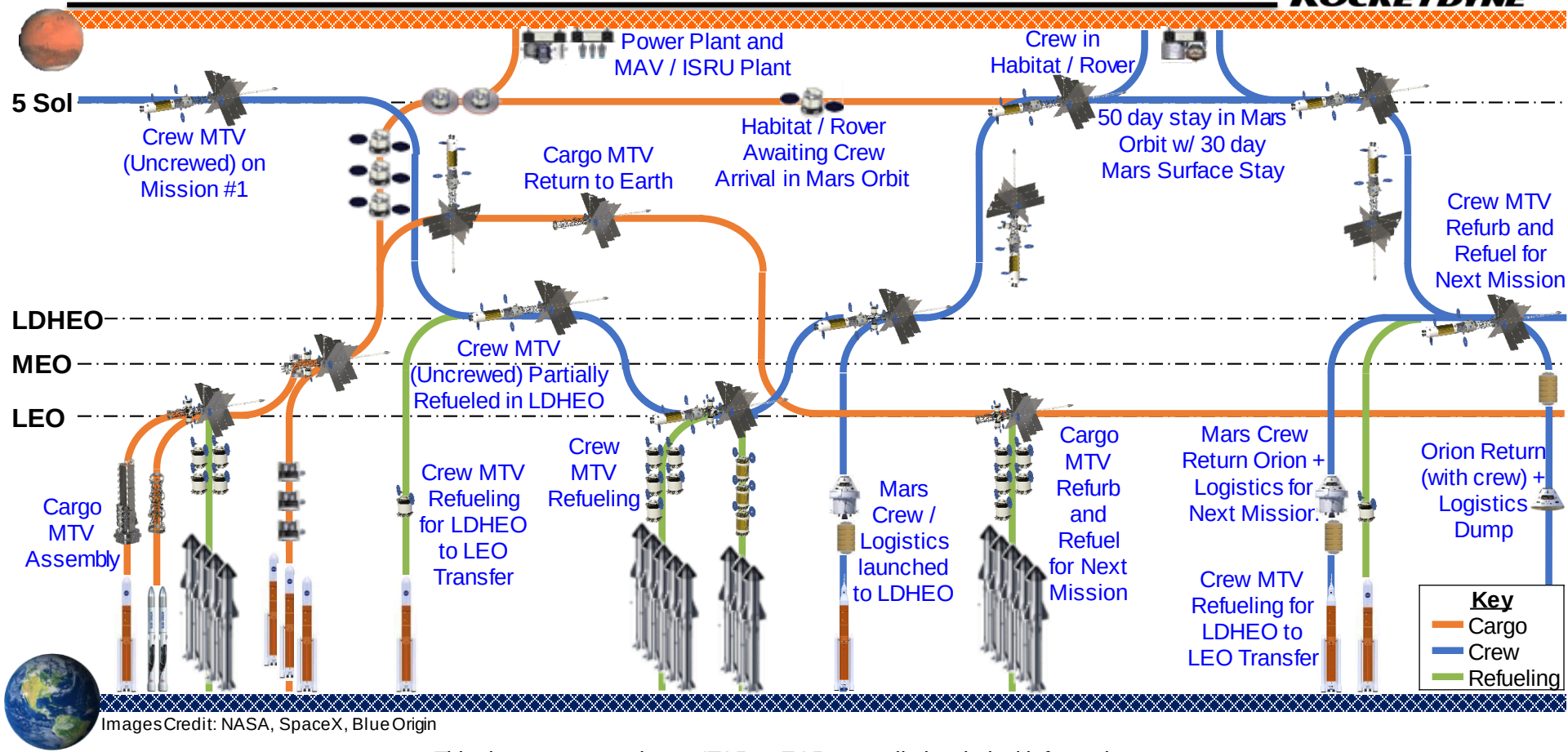
Mission #2 Cargo MTV



Mission #2 Surface Elements

Lander Images Credit: NASA

Mission Concept of Operations Example: Mission #2



Images Credit: NASA, SpaceX, Blue Origin

Missions #3 and #4: Long Duration Surface Stay

Building Towards Sustainable Surface Ops and Long-term Exploration

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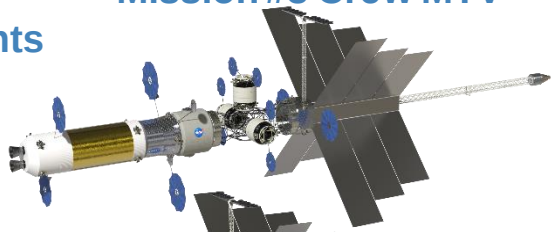
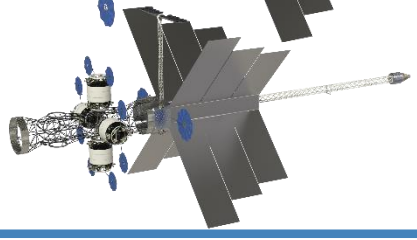
- **Mission #3:** First Long Surface Stay Mission
  - Crew MTV on 2041 Conjunction trajectory with 3 Drop Tank Stages, heliocentric disposal after Earth orbit insertion and crew departure
  - Cargo MTV, with 4 Drop Tank Stages, used to send three landers to Mars during 2039 opportunity; brought back to Earth for reuse
  - 4 Crew on surface for 460 days
  - Launches: 2 SLS Crew, 3 SLS Cargo, 12 Starship

Mission #3 Surface Elements

Mission #3 Crew MTV



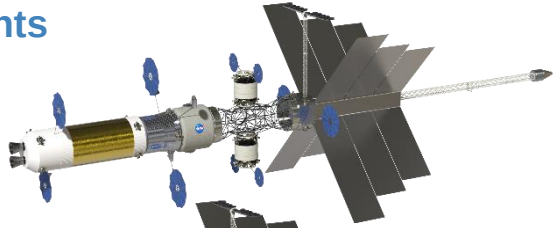
Mission #3 Cargo MTV



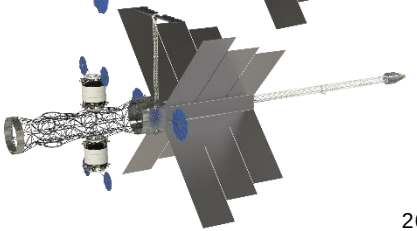
- **Mission #4:** Beginning of Steady-State Long Surface Stay Missions
  - Newly constructed Crew MTV on 2045 / 2046 Conjunction trajectory with 2 Drop Tank Stages
  - Cargo MTV, with 2 Drop Tank Stages delivers three landers to Mars on 2043 opportunity, expended after payload separation
  - 4 Crew on surface for 460 days
  - Launches: 2 SLS Crew, 6 SLS Cargo, 1 New Glenn, 6 Starship

Mission #4 Surface Elements

Mission #4 Crew MTV



Mission #4 Cargo MTV



Lander Images Credit: NASA

Campaign Summary and Future Work

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Campaign Summary: 2032-2048

- Four Mars missions
  - Three missions with crew to the surface of Mars
  - Total of 12 crew with 10 crew to the surface (2 for 30 days, 8 for 450+ days)
  - Nearly 3,750-4,000 person-days available for Mars surface science, exploration, and ops
- 9 Mars landers: 3 MAV's, 1 Pressurized Rover, 1 Fission Surface Power System, 2 Long Duration Surface Habs, 2 Surface Logistics Modules
- NTP-based Campaign:
  - 2 Reusable Crew MTV's, 4 Reusable Cargo MTV's
  - 1.2 SLS launches / yr, 4.1 CLV launches / yr
- NEP/Chem-based Campaign:
  - 2 Reusable Crew MTV's, 2 Reusable Cargo MTV's
  - 1.4 SLS launches / yr, 2.5 CLV launches / yr
- Established Mars surface outpost for continued / expanded future use

Future Architecture Work

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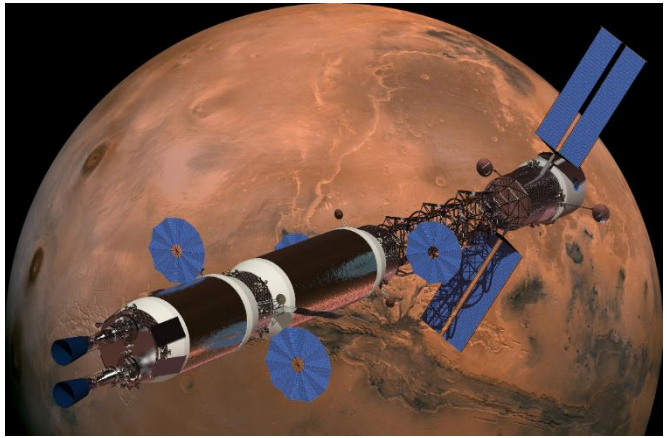
NTP

- Further refine NTP vehicle architecture and campaign analysis, working toward architecture optimization
- Evaluate alternative mission concepts, surface and transportation elements, and NTP vehicle configurations
- Perform MAV optimization by trading propellant combinations, design configuration, insertion orbit, and ISRU technology



NEP / Chem

- MTV subsystem trades with a particular focus on NEP Stage subsystem design attributes: reactor/shield, power conversion, heat rejection, power management & distribution, structures
- Campaign refinement: mission duration trades, Mars orbit option trades, Chem Stage staging trades, all-NEP Crew MTV option for Conjunction missions, alternative NEP Stage uses at end-of-life, abort capabilities