Space Nuclear Propulsion for Human Mars Exploration

Bobby Braun and Roger Myers
Co-chairs

June 2021

Committee Members

ROBERT D. BRAUN, Jet Propulsion Laboratory, Co-Chair

ROGER M. MYERS, R Myers Consulting, LLC, Co-Chair

SHANNON M. BRAGG-SITTON, Idaho National Laboratory

JONATHAN W. CIRTAIN, BWX Technologies

TABITHA DODSON, Defense Advanced Research Projects Agency

ALEC D. GALLIMORE, University of Michigan

JAMES H. GILLAND, Ohio Aerospace Institute

BHAVYA LAL, IDA Science and Technology Policy Institute

PARVIZ MOIN, Stanford University

JOSEPH A. SHOLTIS, JR., Sholtis Engineering & Safety Consulting

STEVEN J. ZINKLE, University of Tennessee, Knoxville

Schedule

2/1/2020	Contract start
4/21/2020	Committee membership approved
4/22/2020	Committee membership posted to NAPAR
5/13/2020	Earliest possible date for a committee meeting
5/18/2020	First Meeting, virtual
9/21/2020	Last Meeting, virtual
10/20/2020	Development of Consensus Draft
11/20/2020	Report Sent to External Review
12/10/2020	Comments Back from All Reviewers
1/19/2021	Report Review Completed
2/4/2021	Report Delivered to Sponsor (Pre-publication copies)

~~Original Plan: 3 in-person committee meetings, several days each, two with open sessions~~

COVID Plan: 14 virtual committee meetings, 3 hours each, 5 with open sessions

Statement of Task

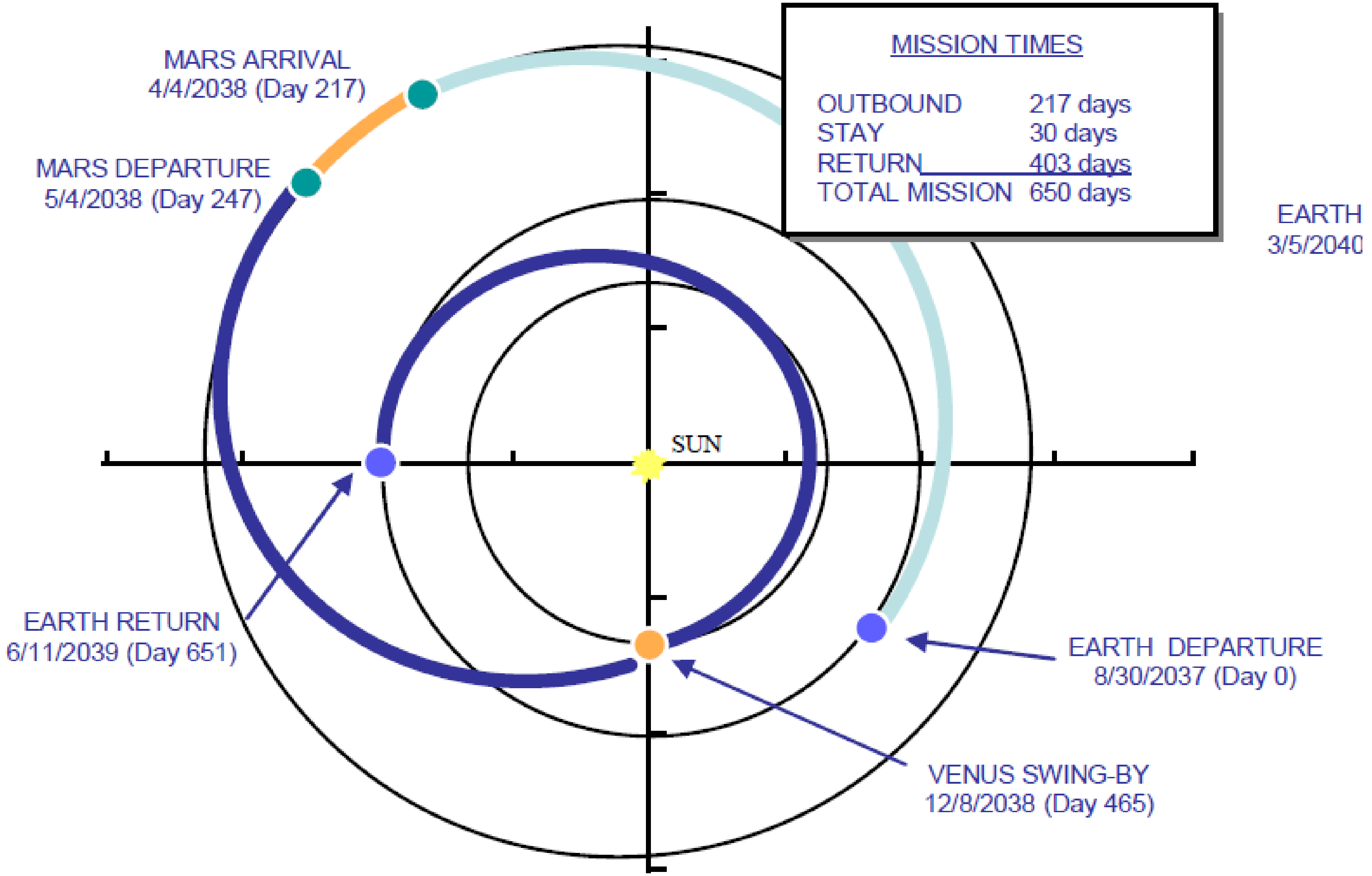
- Focus: Nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) systems for the human exploration of Mars
  - NTP
    - Specific impulse (Isp) of at least 900 s
    - Hydrogen propellant heated to at least 2500 K*
  - NEP
    - Power level of at least 1 MWe
    - Mass-to-power ratio (kg/kWe) substantially lower than the current state of the art

- Identify:
  - Primary technical and programmatic challenges, merits, and risks
  - Key milestones and a top-level development and demonstration roadmap
  - Missions that could be enabled by each technology

*Committee determined that 2700 K required for Isp of 900 s

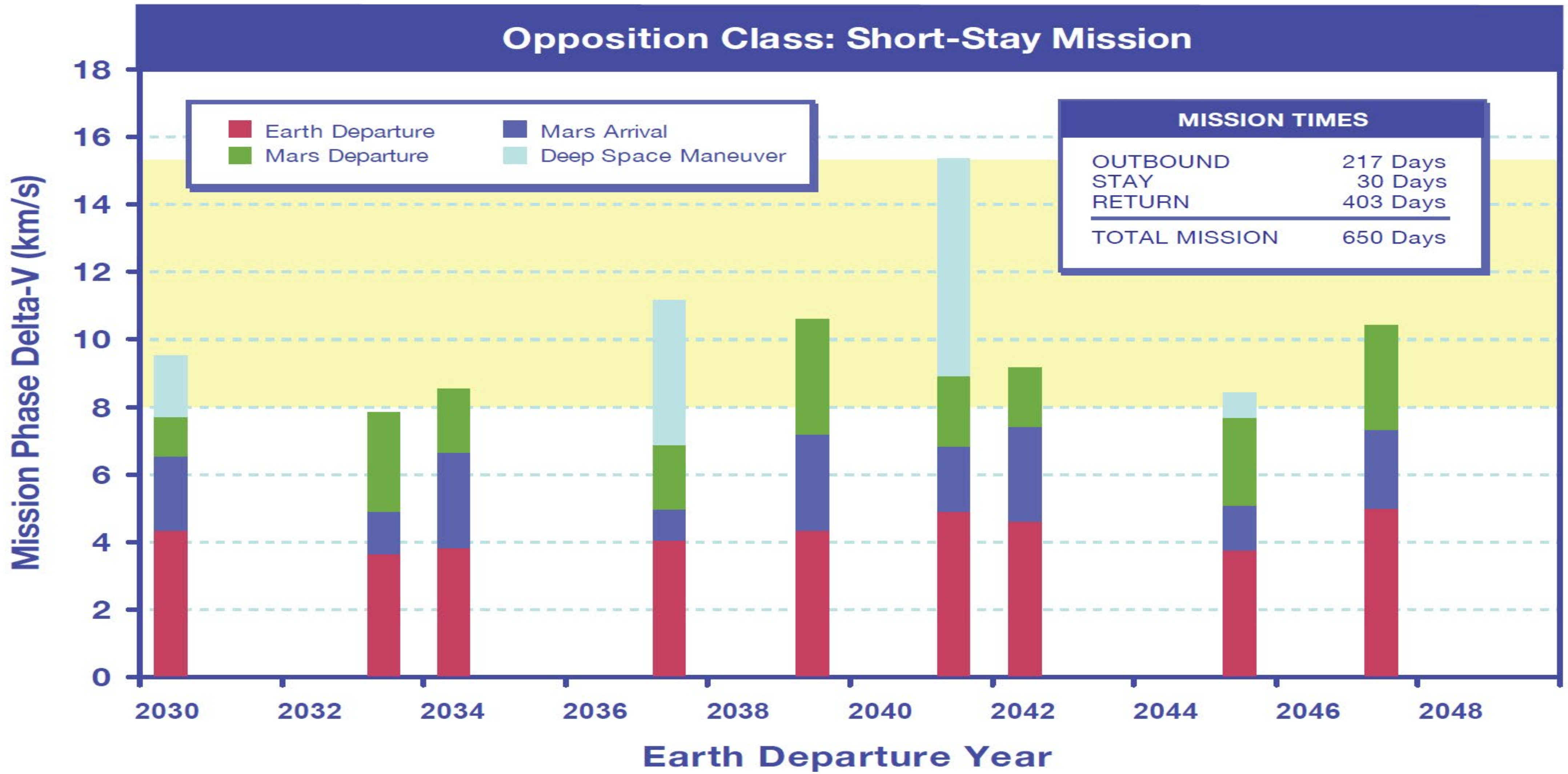
Baseline Mission: Opposition Class

- **2039 Launch**
- **≤ 750 days mission time**
- **Separate cargo and crewed vehicles**
- **Assembly orbit in LEO or cislunar space**



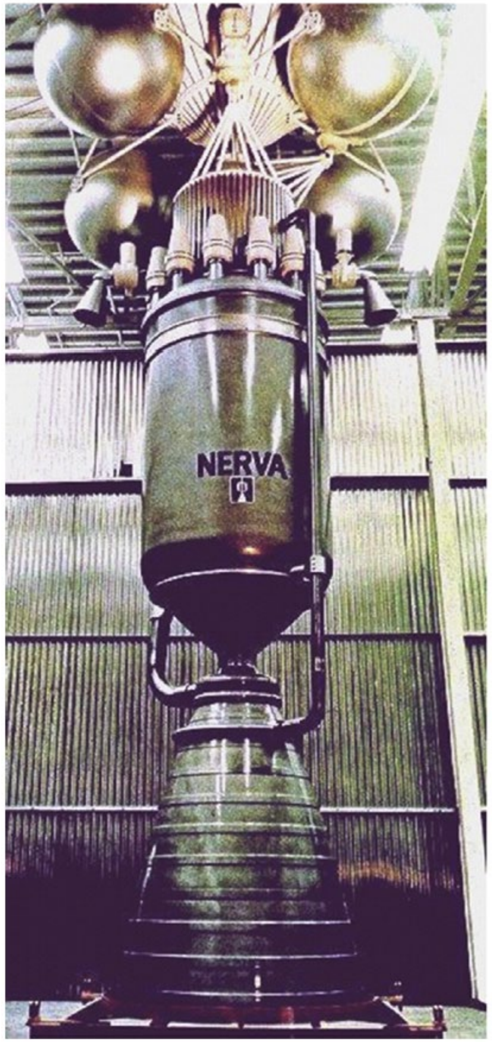
Opposition Class: Short-Stay Mission

Propulsive Requirements: Baseline Mission

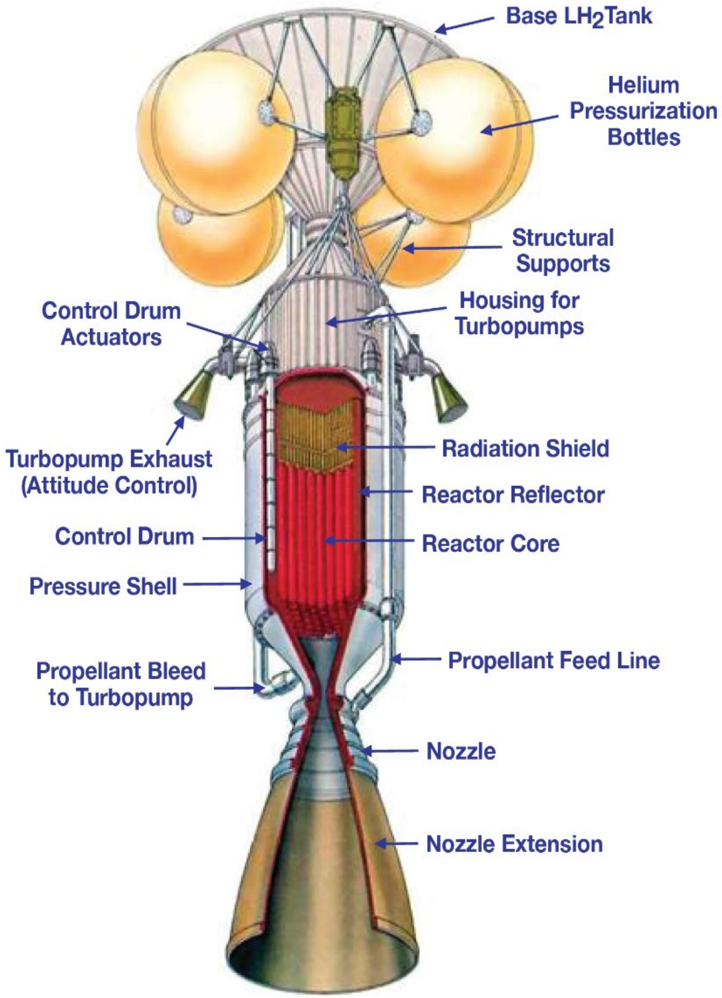


- Many Earth-departure opportunities are feasible within the propulsive capability of a SNP system sized for the 2039 opportunity; 2042, 2045 and 2047 provide fallback potential and schedule mitigation for the chosen path

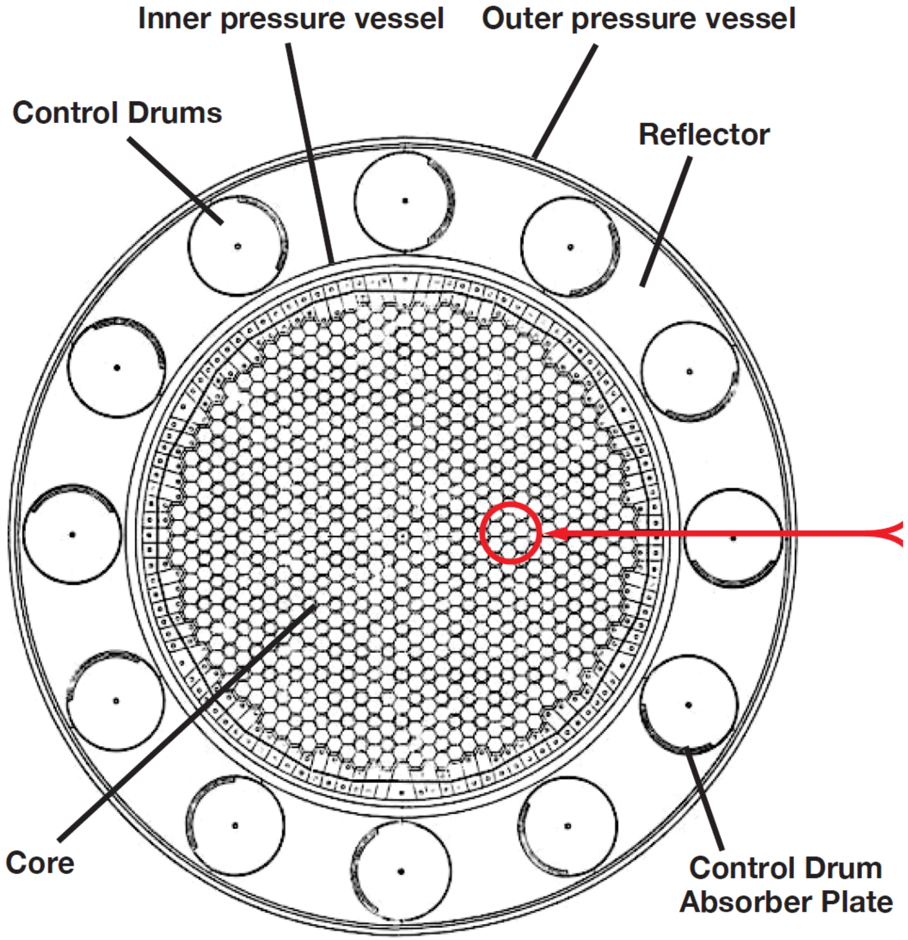
NTP System



NERVA

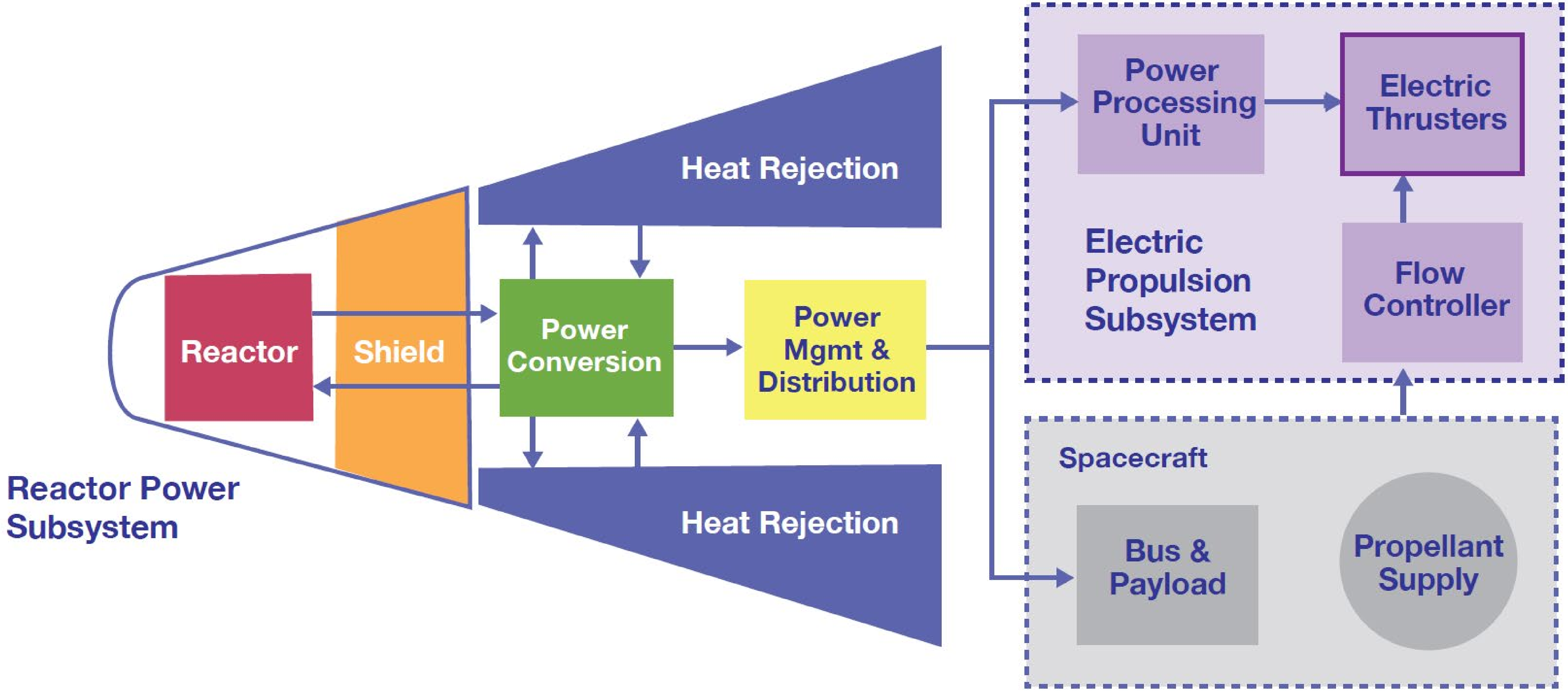


Base LH_2 Tank
Helium Pressurization Bottles
Structural Supports
Housing for Turbopumps
Control Drum Actuators
Turbopump Exhaust (Attitude Control)
Radiation Shield
Reactor Reflector
Control Drum
Reactor Core
Pressure Shell
Propellant Feed Line
Propellant Bleed to Turbopump
Nozzle
Nozzle Extension



Inner pressure vessel
Outer pressure vessel
Control Drums
Reflector
Core
Control Drum Absorber Plate

NEP System



Reactor
Shield
Power Conversion
Power Mgmt & Distribution
Heat Rejection
Heat Rejection
Reactor Power Subsystem
Power Processing Unit
Electric Thrusters
Electric Propulsion Subsystem
Flow Controller
Spacecraft
Bus & Payload
Propellant Supply

System Requirements and Characteristics

NTP

Isp: 900 s

Thrust: up to 100,000 lbf with up to 25,000lbf/engine

Total operational lifetime: 4 h (intermittent operation: 6 to 8 restarts)

Reactor thermal power: ~500 MWth

Temperature of propellant at reactor exit: ~2700 K

Propellant

LH_2 stored at 20 K

NEP

Isp ≥ 2,000 s

Electrical power: 1 to 2 MWe

Specific mass: ≤ 20 kg/kWe

Operational lifetime (continuous operation): 4 years for power generation, 1 to 2 years for thrust

Reactor thermal power: ~3 to 10 MWth

Reactor coolant outlet temperature: ~1200 K

Propellant options:

- argon (stored as a cryogen liquid at 90 K), xenon, krypton (gases), lithium (solid)

Supplemental chemical propulsion system

Fuel: Liquid methane (110 K) and liquid oxygen (90 K)

Isp: 360 s

Thrust: 25,000 lbf

Findings and Recommendations

Highly Enriched Uranium (HEU) vs.
High Assay Low Enriched Uranium (HALEU)

FINDING. Enrichment of Nuclear Fuels. A comprehensive assessment of HALEU vs HEU for NTP and NEP systems that weighs the key considerations is not available. These considerations include technical feasibility and difficulty, performance, proliferation and security, safety, fuel availability, cost, schedule, and supply chain as applied to the baseline mission.

RECOMMENDATION. Enrichment of Nuclear Fuels. In the near term, NASA and DOE, with inputs from other key stakeholders, including commercial industry and academia, should conduct a comprehensive assessment of the relative merits and challenges of HEU and HALEU fuels for NTP and NEP systems as applied to the baseline mission.

Trade Studies

FINDING. Recent, apples-to-apples trade studies comparing NEP and NTP systems for a crewed mission to Mars in general and the baseline mission in particular do not exist.

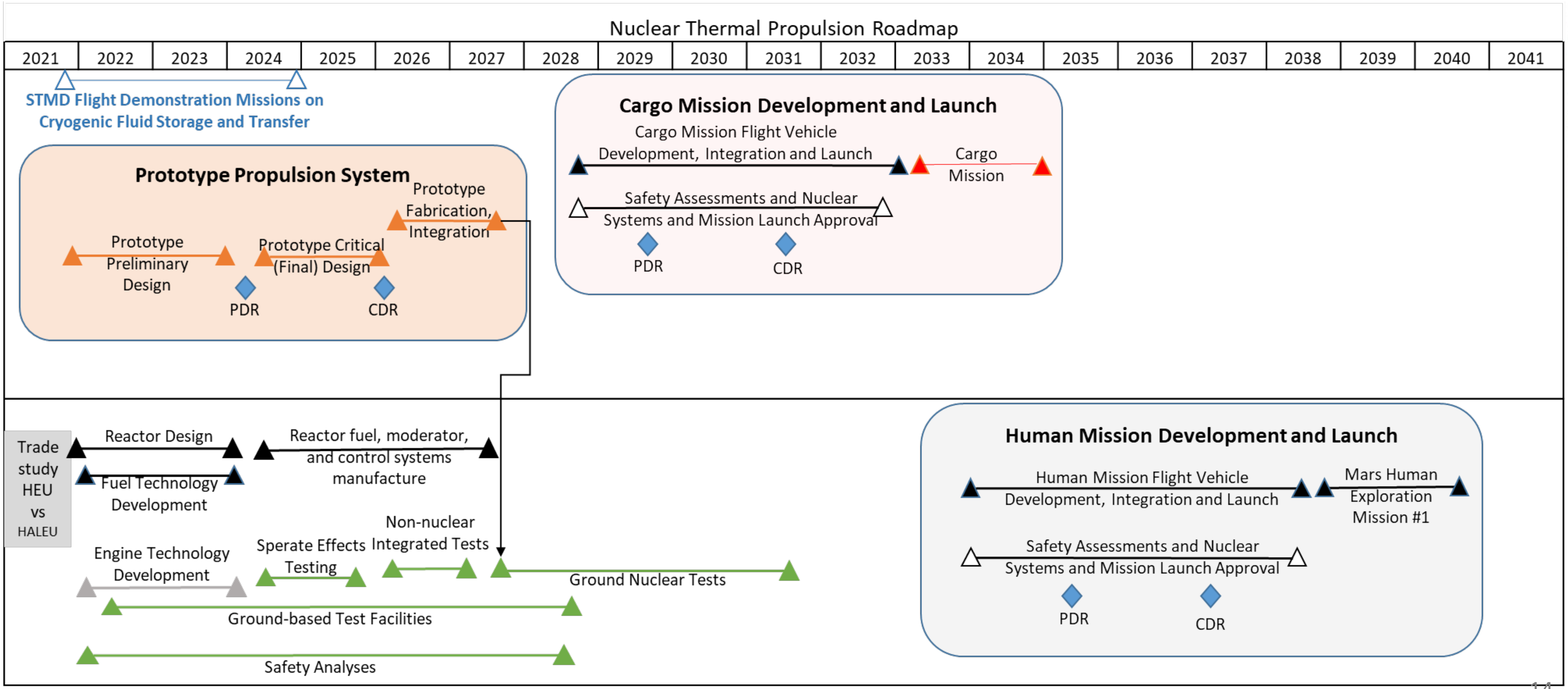
RECOMMENDATION. NASA should develop consistent figures of merit and technical expertise to allow for an objective comparison of the ability of NEP and NTP systems to meet requirements for a 2039 launch of the baseline mission.

NTP Prospects for Program Success

Finding: An aggressive program could develop an NTP system capable of executing the baseline mission in 2039.

RECOMMENDATION. NASA should invigorate technology development associated with the fundamental NTP challenge, which is to develop an NTP system that can heat its propellant to approximately 2700 K at the reactor exit for the duration of each burn. NASA should also invigorate technology development associated with the long-term storage of liquid hydrogen in space with minimal loss, the lack of adequate ground-based test facilities, and the need to rapidly bring an NTP system to full operating temperature (preferably in 1 min or less).

NTP Roadmap



Nuclear Thermal Propulsion Roadmap
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
STMD Flight Demonstration Missions on Cryogenic Fluid Storage and Transfer
Prototype Propulsion System
Prototype Preliminary Design
PDR
Prototype Critical (Final) Design
CDR
Prototype Fabrication, Integration
Cargo Mission Development and Launch
Cargo Mission Flight Vehicle Development, Integration and Launch
Cargo Mission
Safety Assessments and Nuclear Systems and Mission Launch Approval
PDR
CDR
Trade study HEU vs HALEU
Reactor Design
Fuel Technology Development
Reactor fuel, moderator, and control systems manufacture
Engine Technology Development
Sperate Effects Testing
Non-nuclear Integrated Tests
Ground Nuclear Tests
Ground-based Test Facilities
Safety Analyses
Human Mission Development and Launch
Human Mission Flight Vehicle Development, Integration and Launch
Mars Human Exploration Mission #1
Safety Assessments and Nuclear Systems and Mission Launch Approval
PDR
CDR

Fuel Development (for NTP)

FINDING. NTP Fuel Characterization. A significant amount of characterization of reactor core materials, including fuels, remains to be done before NASA and DOE will have sufficient information for a reactor core design.

RECOMMENDATION. NTP Fuel Architecture. If NASA plans to apply NTP technology to a 2039 launch of the baseline mission, NASA should expeditiously select and validate a fuel architecture for an NTP system that is capable of achieving a propellant reactor exit temperature of approximately 2700 K or higher (which is the temperature that corresponds to the required Isp of 900 sec) without significant fuel deterioration during the mission lifetime. The selection process should consider whether the appropriate fuel feedstock production capabilities will be sufficient.

Storage of Liquid Hydrogen (for NTP)

FINDING. NTP systems for the baseline mission will require long-duration storage of LH_2 at 20 K with minimal boiloff in the vehicle assembly orbit and for the duration of the mission.

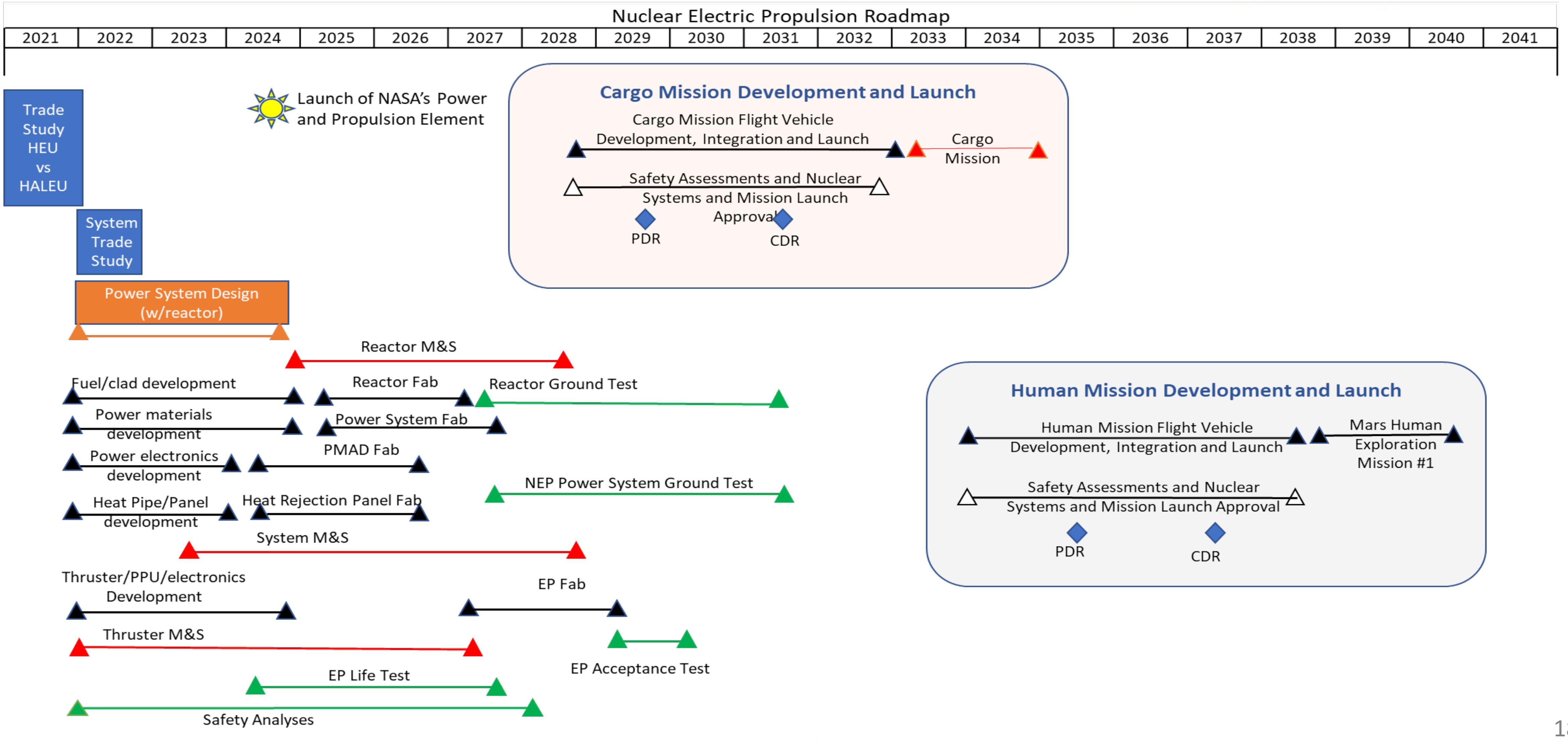
RECOMMENDATION. If NASA plans to apply NTP technology to the baseline mission, NASA should develop high-capacity tank systems capable of storing LH_2 at 20K with minimal boiloff in the vehicle assembly orbit and for the duration of the mission.

NEP Prospects for Program Success

Finding: As a result of low and intermittent investment over the past several decades, it is unclear if even an aggressive program would be able to develop an NEP system capable of executing the baseline mission in 2039.

RECOMMENDATION. NASA should invigorate technology development associated with the fundamental NEP challenge, which is to scale up the operating power of each NEP subsystem and to develop an integrated NEP system suitable for the baseline mission. In addition, NASA should put in place plans for (1) demonstrating the operational reliability of an integrated NEP system over its multi-year lifetime and (2) developing a large-scale chemical propulsion system that is compatible with NEP.

NEP Roadmap



Nuclear Electric Propulsion Roadmap
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
2036
2037
2038
2039
2040
2041
Trade Study HEU vs HALEU
System Trade Study
Power System Design (w/reactor)
Launch of NASA's Power and Propulsion Element
Cargo Mission Development and Launch
Cargo Mission Flight Vehicle Development, Integration and Launch
Cargo Mission
Safety Assessments and Nuclear Systems and Mission Launch Approval
PDR
CDR
Reactor M&S
Fuel/clad development
Reactor Fab
Reactor Ground Test
Power materials development
Power System Fab
Power electronics development
PMAD Fab
NEP Power System Ground Test
Heat Pipe/Panel development
Heat Rejection Panel Fab
System M&S
Thruster/PPU/electronics Development
EP Fab
Thruster M&S
EP Acceptance Test
EP Life Test
Safety Analyses
Human Mission Development and Launch
Human Mission Flight Vehicle Development, Integration and Launch
Mars Human Exploration Mission #1
Safety Assessments and Nuclear Systems and Mission Launch Approval
PDR
CDR

Pace of Technology Development (for NEP)

FINDING. Developing a MWe-class NEP system for the baseline mission would require increasing power by orders of magnitude relative to NEP system flight- or ground-based technology demonstrations.

RECOMMENDATION. If NASA plans to apply NEP technology to a 2039 launch of the baseline mission, NASA should immediately accelerate NEP technology development.

Major Development Challenges for NTP and NEP

Category	NTP	NEP
Reactor Core Fuel and Materials	• High reactor fuel operating temperature (more than 2700 K)	
System Operational Parameters	• Rapid system startup to full operating temperature (preferably in 1 min or less)	• Long system operational reliability (4 years for power generation, 1 to 2 years for thrust)
Scale		• Power conversion and thermal subsystem tests conducted to date have been at power levels orders of magnitude below that required for baseline mission • Limited full scale, short duration electric propulsion subsystem testing at power levels an order of magnitude below that required for baseline mission
Ground-Based Testing	• Need to capture and process engine exhaust (resulting in high cost) • Facility preparation time (stresses baseline schedule) • Little integrated system testing experience; none of it recent • Last relevant-scale tests were nearly 50 years ago	• No fully integrated system testing experience
In-space Propulsion Technology Needs	• Long-term storage of liquid hydrogen in space at 20 K with minimal loss	• Parallel development of a chemical propulsion systems
System Complexity		• Highly complex: six NEP subsystems and a chemical propulsion system

NEP and NTP Commonalities

FINDING. NEP and NTP systems require, albeit to different levels, significant maturation in areas such as nuclear reactor fuels, materials, and additional reactor technologies; cryogenic fluid management; modeling and simulation; testing; safety; and regulatory approvals. Given these commonalities, some development work in these areas can proceed independently of the selection of a particular space nuclear propulsion system.

Findings and Recommendations: Modeling and Simulation, Ground Testing, and Flight Testing

- The development of operational NTP and NEP systems should include extensive investments in modeling and simulation.
- Ground and flight qualification testing will also be required.
- For NTP systems, ground testing should include integrated system tests at full scale and thrust.
- For NEP systems, ground testing should include modular subsystem tests at full scale and power.
- Given the need to send multiple cargo missions to Mars prior to the flight of the first crewed mission, NASA should use these cargo missions as a means of flight qualification of the space nuclear propulsion system that will be incorporated into the first crewed mission.

Synergies with Terrestrial and National Defense Nuclear Systems

FINDING. Terrestrial microreactors, which operate at a power level comparable to NEP reactors, are on a faster development and demonstration timeline than current plans for space nuclear propulsion systems. Development of microreactors may provide technology advances and lessons learned relevant to the development of NEP systems. Similarly, technology advances within the DARPA DRACO program could potentially contribute to the development of NTP systems for the baseline mission.

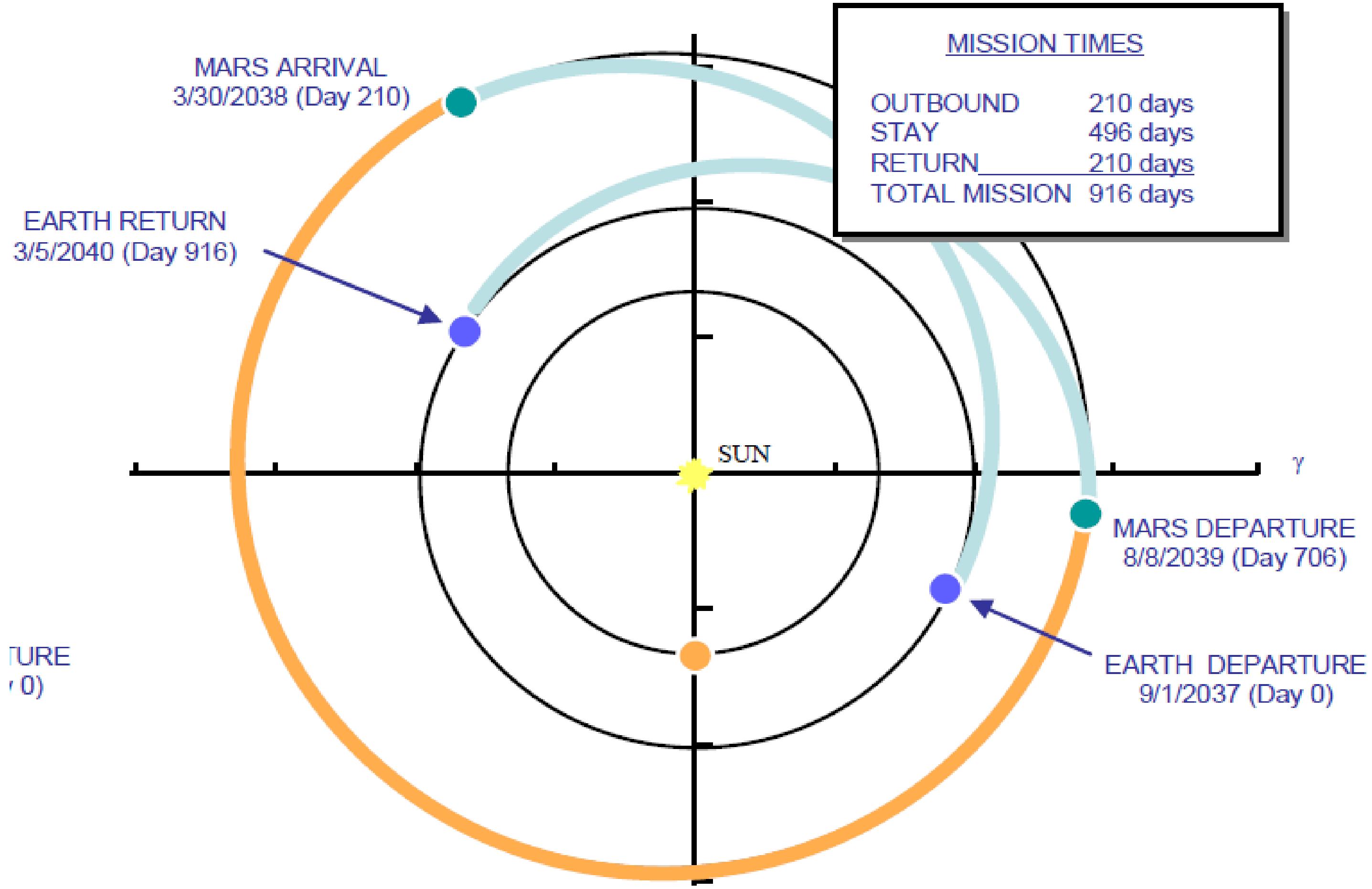
RECOMMENDATION. NASA should seek opportunities for collaboration with the DOE and DoD terrestrial microreactor programs and the DARPA DRACO program to identify synergies with NASA space nuclear propulsion programs.

Next Steps

- NEP and NTP systems show great potential to facilitate the human exploration of Mars.
- Using either system to execute the baseline mission by 2039 will require an aggressive research and development program.
- Such a program would need to begin with NASA completing an extensive and objective architecture assessment in the coming year and making a significant set of technology investments in the present decade.
- Such a program should include subsystem development, prototype systems, ground testing and cargo missions as a means of flight qualification prior to first crewed use.

Backup Slides

Alternate Orbital Profile: Conjunction Class



Conjunction Class: Long-Stay Mission

Propulsive Requirements: Conjunction Class Missions