Committee Members

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STEVEN J. ZINKLE, University of Tennessee, Knoxville
## Schedule

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/1/2020</td>
<td>Contract start</td>
</tr>
<tr>
<td>4/21/2020</td>
<td>Committee membership approved</td>
</tr>
<tr>
<td>4/22/2020</td>
<td>Committee membership posted to NAPAR</td>
</tr>
<tr>
<td>5/13/2020</td>
<td>Earliest possible date for a committee meeting</td>
</tr>
<tr>
<td>5/18/2020</td>
<td>First Meeting, virtual</td>
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<tr>
<td>9/21/2020</td>
<td>Last Meeting, virtual</td>
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<tr>
<td>10/20/2020</td>
<td>Development of Consensus Draft</td>
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<tr>
<td>11/20/2020</td>
<td>Report Sent to External Review</td>
</tr>
<tr>
<td>12/10/2020</td>
<td>Comments Back from All Reviewers</td>
</tr>
<tr>
<td>1/19/2021</td>
<td>Report Review Completed</td>
</tr>
<tr>
<td>2/4/2021</td>
<td>Report Delivered to Sponsor (Pre-publication copies)</td>
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</tbody>
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**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
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
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.
## System Requirements and Characteristics

<table>
<thead>
<tr>
<th><strong>NTP</strong></th>
<th><strong>NEP</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Isp: 900 s</td>
<td>Isp $\geq$ 2,000 s</td>
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<tr>
<td>Thrust: up to 100,000 lbf with up to 25,000 lbf/engine</td>
<td>Electrical power: 1 to 2 Mwe</td>
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<tr>
<td>Total operational lifetime: 4 h (intermittent operation: 6 to 8 restarts)</td>
<td>Specific mass: $\leq$ 20 kg/kWe</td>
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<tr>
<td>Reactor thermal power: $\sim$500 MWth</td>
<td>Operational lifetime (continuous operation): 4 years for power generation, 1 to 2 years for thrust</td>
</tr>
<tr>
<td>Temperature of propellant at reactor exit: $\sim$2700 K</td>
<td>Reactor thermal power: $\sim$3 to 10 MWth</td>
</tr>
<tr>
<td>Propellant: LH$_2$ stored at 20 K</td>
<td>Reactor coolant outlet temperature: $\sim$1200 K</td>
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<tr>
<td><strong>Propellant options:</strong> argon (stored as a cryogen liquid at 90 K), xenon, krypton (gases), lithium (solid)</td>
<td><strong>Supplemental chemical propulsion system</strong></td>
</tr>
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</table>

- Fuel: Liquid methane (110 K) and liquid oxygen (90 K)
- Isp: 360 s
- Thrust: 25,000 lbf
Findings and Recommendations
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.
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.
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

years: 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
- Prototype Critical (Final) Design
- Prototype Fabrication, Integration

Cargo Mission Development and Launch
- Cargo Mission Flight Vehicle Development, Integration and Launch
- Cargo Mission Launch
- Safety Assessments and Nuclear Systems and Mission Launch Approval
  - PDR
  - CDR

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

Trade study HEU vs HALEU
- Reactor Design
- Fuel Technology Development
- Engine Technology Development
- Reactor fuel, moderator, and control systems manufacture
- Non-nuclear Separate Effects Testing
- Integrated Tests
- Ground Nuclear Tests
- Ground-based Test Facilities
- Safety Analyses
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.
**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.
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

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

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
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**

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

**MISSION TIMES**
- OUTBOUND: 210 days
- STAY: 496 days
- RETURN: 210 days
- TOTAL MISSION: 916 days

Conjunction Class: Long-Stay Mission
Propulsive Requirements: Conjunction Class Missions

Conjunction Class: Long-Stay Mission

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Delta-V (km/s)</th>
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<tbody>
<tr>
<td>Earth Departure</td>
<td></td>
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<tr>
<td>Mars Arrival</td>
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<tr>
<td>Mars Departure</td>
<td></td>
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<tr>
<td>Deep Space Maneuver</td>
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MISSION TIMES

- OUTBOUND: 210 Days
- STAY: 496 Days
- RETURN: 210 Days
- TOTAL MISSION: 916 Days

Earth Departure Year

- 2030
- 2032
- 2034
- 2036
- 2038
- 2040
- 2042
- 2044
- 2046
- 2048