Strategy for Developing Technologies for Megawatt-class Nuclear Electric Propulsion Systems

Kurt A. Polzin and Adam K. Martin
NASA Marshall Space Flight Center, Huntsville, AL, 35812, USA

Francis M. Curran
MZNBLUE, LLC, New Market, AL, 35761, USA

Roger M. Myers
R Myers Consulting, Woodinville, WA, 98072, USA

Mitchell A. Rodriguez
Jacobs Space Exploration Group, Huntsville, AL, 35806, USA

I. Introduction

In late fiscal year 2020, the Space Nuclear Propulsion (SNP) project began the process of formulating an investment strategy to support development of the technologies required for a high-power (megawatt-class) nuclear electric propulsion (NEP) system capable of performing human-scale missions. This activity was initiated concurrent with several high-level studies and assessments were either under way or had just concluded.

Studies of human-scale Mars missions have been performed several times over the past two decades. One of the most recent studies examined opposition-class human Mars missions to occur in the late 2030s timeframe [1,2]. The mission architecture assumed a hybrid NEP/chem-propelled vehicle that used a high specific impulse (I_{sp}) NEP-system and a liquid oxygen (LOx)-liquid methane high thrust chemical stage (two 110 kN (25 klb$_f$) thrust, 365 s I_{sp} engines) for maneuvers performed to enter and exit gravity wells. Trajectory analyses performed in this study showed that such a mission could be performed with 2-4 MW$_e$ directed into the electric propulsion system (operating for 20,000+ hours), with the large range representing different opposition-class Mars mission opportunities and permutations on the trajectory design, concept of operations, and technology choices.

In 2020, the NASA Engineering and Safety Center (NESC) performed a study to evaluate the maturity of the different technologies required for nuclear propulsion systems [3]. The executive summary of this report provided the following top-level conclusions:

- "The majority of critical technologies for… NEP/Chem… systems are relatively immature"
- "TRLs [technology readiness levels] in the literature are often overestimated"
- "The majority of critical technologies… for NEP/Chem… systems are at a relatively high level of advancement degree of difficulty (AD2 > 4) for maturation, requiring a dual development approach"
- "The proper assessment of baseline TRL and AD2 values and the estimation of requirements and resources required for advancement have been consistent issues for NEP,"
- "Non-advocate reviews should occur at the start of a technology program and at all key milestones."

In 2021, the National Academies of Science, Engineering, and Medicine (NASEM) issued a separate report [4] identifying the "primary technical and programmatic challenges, merits, and risks for maturing space nuclear propulsion technologies of interest to a future human Mars exploration mission." That work contained several important findings, including:

- "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 completed to date."
- "Subscale in-space flight testing of NEP systems cannot address many of the risks and potential failure modes associated with the baseline mission NEP system. With sufficient M&S [modeling & simulation] and ground testing, including modular subsystem tests at full scale and power, flight qualification requirements can be met by the cargo missions that will precede the first crewed mission to Mars. Fully integrated ground testing may not be required."

- “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.”

These efforts motivated the SNP project to investigate the technologies available for a megawatt-class high power nuclear electric propulsion system. That system is illustrated schematically in Figure 1 and is comprised of five separate top-level critical technology elements (CTEs).

1. Nuclear Reactor – Thermal power source for the system, utilizing high-assay low enriched uranium (HALEU) as the nuclear fuel. Reactor radiation shielding is also included in this CTE.
2. Power Conversion – Operates as a thermodynamic cycle, accepting nuclear reactor thermal power as an input and converting it to mechanical power.
3. Power Management and Distribution (PMAD) – Accepts as an input mechanical power from the power conversion system, which is used to generate electrical power. The PMAD system also distributes the generated electrical power to all other parts of the spacecraft, including the high-power EP system. The PMAD system may also perform duties such as isolation, fault detection, and power transformation/rectification for different spacecraft systems, including the thrusters.
4. Electric Propulsion (EP) – Accepts as an input electrical power, which is used to accelerate a propellant to high speeds to produce thrust. This system includes the power processing unit (PPU), which converts the power it receives to the correct current and voltage required by the thrusters, and the propellant storage and feed systems, which contain and meter the flow of propellant to the thrusters.
5. Thermal Management (Radiators/Heat Rejection) – The cold side of the thermodynamic power conversion cycle, accepts thermal power from the power conversion system and radiatively rejects that heat to space.

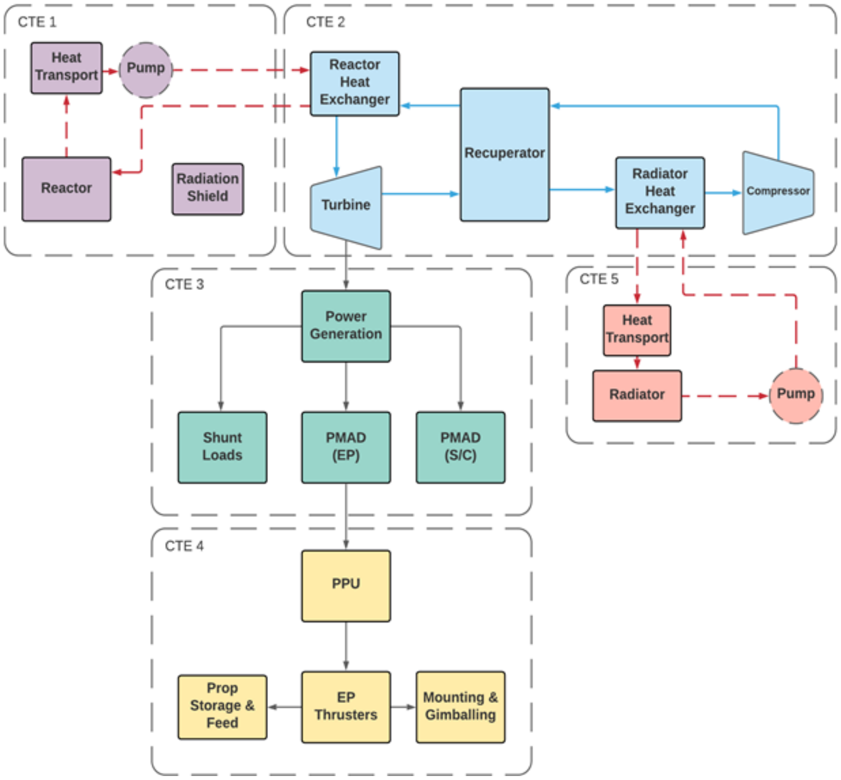

Figure 1: Critical technology elements (CTEs) of a nuclear electric propulsion system based upon a closed-cycle Brayton power conversion system (CTE 2).

In this paper, we describe the SNP project formulation and investment strategy that aims to accomplish the research and development required to advance the technology readiness for each CTE. The strategy relies heavily upon experimental testing supported by modeling and simulation to yield realistic assessments of the technologies, which in turn will be used to inform future NEP system-level design decisions and any potential technology downselects.

Acknowledgements

This work was supported by NASA's Space Technology Mission Directorate (STMD) through the Space Nuclear Propulsion (SNP) project.

References

[1] Compass Team, "Combined Nuclear Electric and Chemical Propulsion Vehicle Concepts for Piloted Mars Opposition Class Missions (presentation only)," in Joint Army-Navy-NASA-Air Force (JANNAF) Spacecraft Propulsion Subcommittee meeting, 2021. Abstract 2021-0001BW.

[2] S.R. Oleson, L. Burke, L. Dudzinski, J. Fittje, L.S. Mason, T. Packard, P. Schmitz, J. Gyekenyesi, and B. Faller, "A Combined Nuclear Electric and Chemical Propulsion Vehicle Concept for Piloted Mars Opposition Class Missions," in ASCEND Meeting, Nov. 16-18, 2020. AIAA paper 2020-4055. https://doi.org/10.2514/6.2020-4055

[3] "Independent Assessment of the Technical Maturity of Nuclear Electric Propulsion (NEP) and Nuclear Thermal Propulsion (NTP) Systems," NASA Engineering & Safety Center, 2020.

[4] National Academies of Sciences, Engineering, and Medicine, *Space Nuclear Propulsion for Human Mars Exploration*, The National Academies Press, Washington, DC, 2021. https://doi.org/10.17226/25977