A Technology Maturation Plan for the Development of Nuclear Electric Propulsion

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ABSTRACT

Over the last two years NASA's Space Nuclear Propulsion (SNP) Project formulated a Technology Maturation Plan (TMP) for development of the sub-systems needed for a MW-class Nuclear Electric Propulsion (NEP) system which, combined with a high thrust chemical propulsion stage, would be suitable for human missions to Mars. Two recent assessments, independently conducted by the National Academies for Science, Engineering, and Medicine and the NASA Engineering & Safety Center, concluded that the technologies required for a high-power NEP system are immature and the attendant risks insufficiently quantified to justify initiating a flight project. For NEP to be available as a viable option to meet flight opportunities in the late 2030s / 2040s time frame, development of the key sub-systems must begin now. SNP has subdivided the NEP system into five Critical Technology Elements (CTE): the nuclear reactor, power conversion, power management and distribution, electric propulsion sub-system, and the primary heat rejection system. Development plans for each of these CTEs have been drafted which will serve as the template for a focused milestone-driven research and development campaign intended to advance each CTE to Technology Readiness Level (TRL) 5. This will be accomplished by building and testing hardware at relevant power levels (~ 1 MW) and for relevant durations (2,500 hours, ~10% of the required operational lifetime) and conducting numerical modeling of the CTEs anchored by the accumulated test data to predict system performance and reliability. Concurrent with this work, high-level coupled system/mission modeling will be carried out to refine the key performance parameters that the various CTEs must achieve. Non-advocate reviews will be held at milestone points to assess progress and inform down-select decisions. The strategy for formulating the TMP was described previously; this paper describes ongoing progress on the drafting and baselining of the plan, including key specific details.

INTRODUCTION

Nuclear Electric Propulsion (NEP) systems use a fission reactor to power electric thrusters to propel the spacecraft. The high specific impulse of the electric thrusters (thousands of seconds) coupled with the large amounts of energy that can be extracted from a nuclear reactor offer the potential of significant spacecraft mass reductions compared with purely chemical propulsion systems for missions with large Δv requirements.

Although first proposed nearly 70 years ago[1], there have only been three NEP vehicles flown in all that time, all of which were essentially low power demonstration missions: SNAP-10A launched by the United States in 1965, and Kosmos 1818 and Kosmos 1867 launched by the U.S.S.R. in 1987. SNAP-10A, a collaboration of the AEC and the USAF, was the only nuclear reactor ever launched by the United States[2]. It had a 30 kW_{th} reactor fueled with $UZrH_x$ and cooled with a sodium-potassium eutectic alloy (NaK); it produced 0.5 kW_e using thermoelectric (TE) conversion, which powered an 8.5 mN Cs-Ion thruster.

A much higher power reactor (1 MW_{th}), the SNAP-8, was developed jointly by the AEC and NASA; it was ground tested though never flown[3]. The SP-100 program[4], a DoE / NASA collaboration lasting from 1983 to 1994, sought to develop a HEU-UN fueled, liquid metal (Li) cooled reactor, which would have produced 100 kW_e from 2.4 MW_{th} using TE power conversion. The SP-100 reactor did not advance beyond design studies with the exception of some limited hardware development that was insufficient to demonstrate the efficacy of the technology.

In 2003 NASA commissioned project Prometheus, an NEP flight project focused on a Jupiter Icy Moons Orbiter (JIMO) exploration mission[5]. JIMO was to have used a HEU-UO_2 fueled, direct gas cooled reactor with closed Brayton cycle power conversion, producing 200 kW_e to power Xenon thrusters (Hall and

Ion). Prometheus / JIMO ran through 2005 and mostly consisted of design work with some hardware development and testing (e.g., H_2O/titanium heat pipe based radiators).

Recent studies have explored the possibility of using an NEP system combined with a chemical propulsion stage for human missions to Mars[6,7,8]. The chemical stage (likely using LOx-CH_4 as the propellant) would perform the high-thrust required for climbing out of and dropping into planetary gravity wells with the NEP stage providing the balance of the Δv required to complete the mission. Results of analyses to date indicate that NEP-Chem hybrid vehicles can provide mission profiles comparable to Nuclear Thermal Propulsion (NTP) systems (i.e. comparable trip-times and launch mass requirements) with smaller, lower-temperature reactors. A comparison of some characteristic parameters for NTP and NEP are shown in Table 1.

Table 1. Comparison of characteristic NTP and NEP parameters.

Parameter or Configuration	NTP	NEP
Reactor Temperature (K)	~ 3,000	1,200 – 1,500
Reactor Power (MW_{th})	250 - 500	5 - 16
Reactor Power Ramp Duration	Minutes	Hours - Days
Required Operational Lifetime	Hours	Years
Reactor Cooling	Open-Cycle	Closed-Cycle
Chemical stage required	No	Yes

In 2020, an independent review of the state of nuclear propulsion for spaceflight was conducted by the NASA Engineering and Safety Center (NESC)[9]. Another major review, also commissioned by NASA, was conducted by the National Academies of Science, Engineering, and Medicine[10] in 2021. These reviews considered the state-of-the-art (SOA) of both NTP and NEP specifically in the context of a human mission to Mars and concluded that the Technology Readiness Level (TRL) of both NEP and NTP is too low to support the initiation of a flight project and that extensive technology research and development efforts will be required before technology selections for a preliminary vehicle design could be credibly considered.

NASA, through the Space Nuclear Propulsion (SNP) Project within the Space Technology Mission Directorate (STMD), has been conducting technology maturation work on NTP over the last decade. Beginning two years ago SNP embarked on the development of a comprehensive Technology Maturation Plan (TMP) to advance the technologies required for NEP from their current SOA to TRL 5. The rest of this paper describes the process and rationale leading to the current draft TMP and plans for its implementation.

DESCRIPTION OF THE NEP SYSTEM

The NEP system can be subcategorized into five subsystems, or Critical Technology Elements (CTE):

- CTE-1: Reactor and Coolant Subsystem (RXS)
- CTE-2: Power Conversion Subsystem (PCS)
- CTE-3: Power Management and Distribution (PMAD) Subsystem
- CTE-4: Electric Propulsion Subsystem (EPS)
- CTE-5: Primary Heat Rejection Subsystem (PHRS)

Each CTE can be broken down into Major Assemblies (MA) that in turn consist of subassemblies and components. For example, the power conversion subsystem (CTE-2, PCS) is based on a closed cycle Brayton unit MA in which an individual turbine blade is a component.

These five subsystems (CTEs) work in concert as an NEP propulsion system that, together with a LOx-CH_4 chemical propulsion stage for high-thrust maneuvers, constitute the NEP-Chem propulsion system under consideration for human missions to Mars. A notional NEP-Chem vehicle is shown in Figure 1. Figure 2 shows a block diagram of a representative NEP system showing the relationship of the five CTEs. Note that this is a representative diagram only; the specific selection and arrangement of MAs and/or components will change with different design choices.

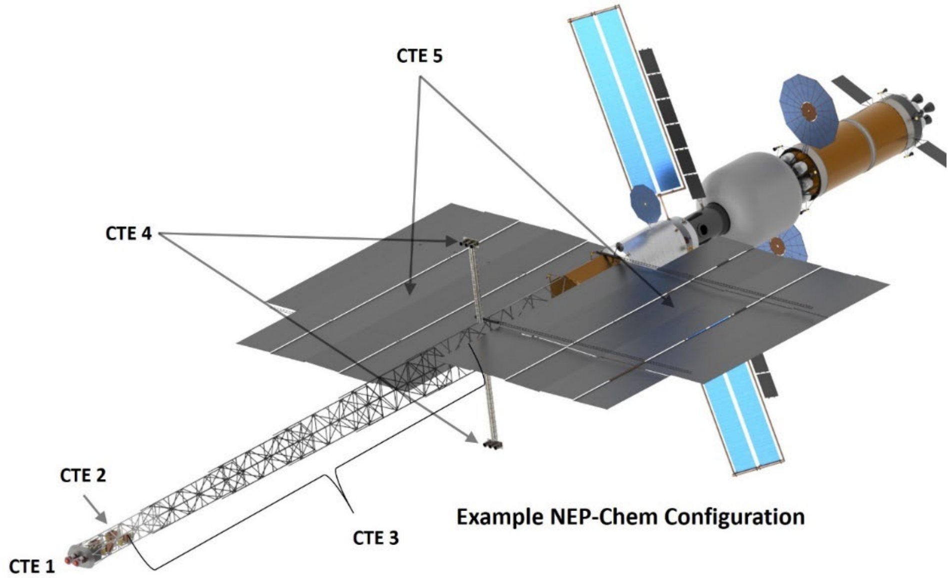

Figure 1. A notional NEP-Chem vehicle showing the five Critical Technology Elements (CTEs) of the NEP stage.

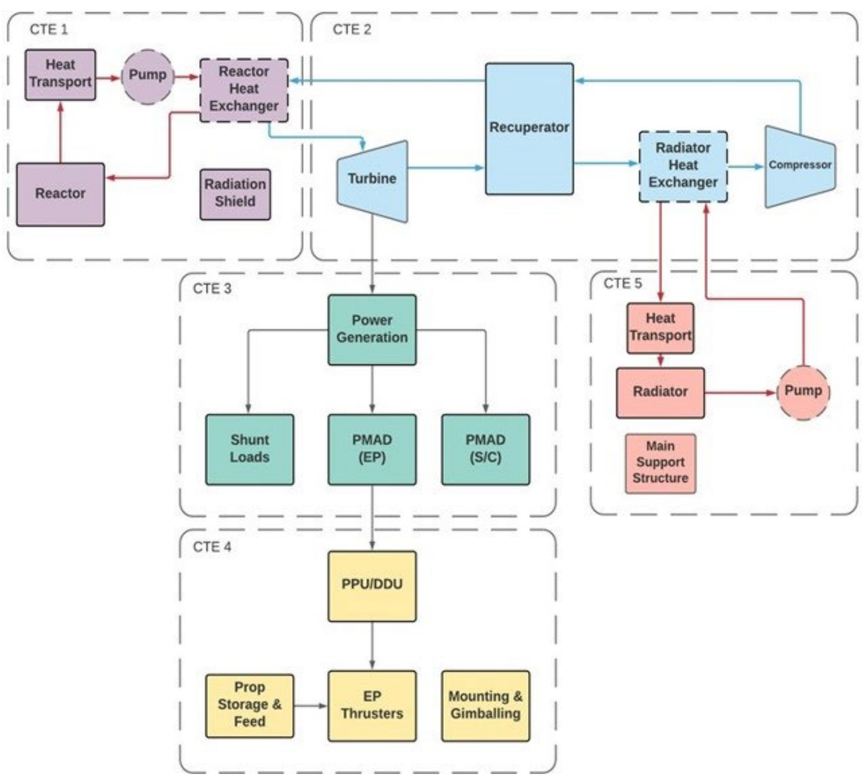

Figure 2. Block diagram of a representative NEP system.

This design configuration is extensible to essentially all NEP spacecraft – a low power NEP-Chem vehicle for a robotic outer solar-system exploration mission, for example, would have the same basic arrangement of CTEs as shown in Figure 1 but with technology choices specific to the lower power mission requirements.

FORMULATION OF THE TECHNOLOGY MATURATION PLAN (TMP)

In direct response to the aforementioned NESC and National Academies reviews, SNP was charged with the task of creating a TMP for the development of NEP technologies sufficient to bring them to TRL 5, at which point a decision about their suitability for a human Mars mission could be made with high confidence[11].

Beginning in FY21 and continuing into FY22 a comprehensive review of the SOA of relevant NEP technologies was conducted. From December 2020 through April 2021, SNP sponsored Technical Interchange Meetings (TIMs) with numerous government and industry Subject Matter Experts (SMEs) to assess the state of development of NEP technologies, identify specific, high-confidence, viable NEP system design options, and develop an understanding of the tasks required to mature critical technologies[12]. TIMs were held on the following topics:

- Nuclear Reactor Design
- Power Conversion
- Power Generation, Management, and Distribution
- Electric Propulsion
- Thermal Management
- In-Space Assembly

These topics covered all of the CTEs and the last was included to evaluate advancements in in-space assembly that could have a major impact on mission architecture. SNP personnel also met individually with many SMEs over the subsequent year to further clarify and better assess the state of NEP technologies. These deliberations provided the technical background for the formulation and writing of the TMP.

Also during this time, an extensive campaign of coupled system and mission modeling was conducted using a suite of numerical modeling tools developed for this purpose. The detailed results of this NEP System Integration Model (NEP-SIM) are described elsewhere[13-18]. Using the NEP-SIM results[16] and the engineering judgement of the SMEs consulted during the TIMs, SNP developed a set of preliminary Key Performance Parameters (KPP) for the overall NEP system and for each CTE, shown in Table 2. Note that the term “threshold” in Table 2 does not indicate a boundary in the associated parameter space where the mission fails to close, rather it indicates a KPP value that, in the estimation of the SMEs, should be achievable with straight-forward extrapolation of existing technology.

These KPPs represent the developmental goals being targeted during the initial execution of the TMP. They will be updated as the technology development program advances and test data is used to refine system models and remove uncertainty from the overall design.

Table 2. Preliminary KPP values for a MW-Class NEP Human Mars Mission (taken from reference 16).

Parameter	KPP value
Power system α (kg/kW$_e$) (consists of CTEs 1, 2, 3, and 5)	24 (threshold), 13 (target)
Total electric propulsion thrust (N)	65 - 120
Electric propulsion efficiency and I_{sp} (s)	Efficiency and I_{sp} required to close mission: dependent on electric propulsion system choice
Nominal mission duration (hours)	25,000
CTE-1 power output (MW$_{th}$)	5 - 16
CTE-1 outlet/CTE-2 power conversion inlet temp (K)	1200 (threshold), 1400 (target)
CTE-2 power output (MW$_e$)	2 - 4
CTE-4 Thruster life-time (hours)	21,000 - 35,000 (depends on electric propulsion system choice)
CTE-2 outlet/CTE-5 inlet temp (K)	550 - 750
CTE-5 outlet/CTE-2 compressor inlet temp (K)	325 - 500

The TMP lays out a plan, with detailed milestones and schedules, for advancing the key technologies for all five CTEs by stages, first to TRL 4 and then to TRL 5, at which point a technical assessment of the suitability of NEP for human Mars missions could be made with high confidence. Based on the recommendations of the above-mentioned NESC and National Academies reviews, SNP has set as the primary task of this development effort the building and testing of hardware at the relevant parameters (power levels, temperatures, etc.) to demonstrate the performance required for an NEP vehicle and to provide test data that will permit informed decisions regarding further development. These data will also be used to anchor modeling and simulation efforts and constrain performance assumptions to those that are realistic and achievable. The goals of the TMP were designed to ensure that all the CTEs would be ready for a flight program decision upon completion of the development effort.

The maturation plans for each CTE were written to be modular with high fidelity emulator interfaces at the CTE boundaries, to permit development of any one CTE independent of the others. The project will maintain strict control of these interfaces to ensure that the individual CTEs meet overall system requirements. At SNP's discretion, integrated testing of two or more CTEs may be attempted if it yields advantages in meeting cost and schedule requirements, but it is not necessary to the overall plan. The plan envisions a four year development schedule from project start if fully funded and implemented; funding at a lower level would still permit progress, albeit at a slower pace. Based on lessons learned from past programs, the TMP stipulates that Non-Advocate Reviews (NAR) are to be conducted at all key decision points. In particular, final determination as to whether TRL advancement has occurred will be made by NAR panels.

Based on SME consensus, some down-selections were made in advance of the drafting of the TMP. Examples include:

CTE-1: Liquid-metal cooled reactors were excluded as being too difficult to develop in the required time frame, based on past experience with the SP-100 program.

CTE-2: A closed-cycle Brayton converter (CBC) with He-Xe working fluid was the consensus choice of the SMEs for power conversion. Use of super-critical carbon dioxide (sCO_2) as the CBC working fluid was also investigated, however based on system modeling that showed it offered no significant advantage for the NEP application[19] and accounting for the technical risk associated with corrosion in high temperature sCO_2 systems, it was excluded from further consideration.

CTE-4: A variety of thruster technologies were evaluated, including Hall thrusters, MPD thrusters, gridded ion thrusters, and the VASIMR concept. All but Hall and MPD were excluded as being either too low in technological maturity or technically infeasible.

The nominal technologies selected in this TMP for each CTE are as follows:

- **CTE-1: Reactor and Coolant Subsystem (RXS)**
  - Fuel: UN or UO_2, with clad pellet fuel form
  - Moderator: YH_2 and BeO, or BeO
  - Reactor heat transfer options (to be developed in parallel)
    - Direct Gas Cooled with He-Xe coolant
    - Li Heat Pipe Cooled
  - Power level: 5 – 16 MW_{th}
- **CTE-2: Power Conversion Subsystem (PCS)**
  - Closed cycle Brayton
    - Working fluid: Helium-Xenon (He-Xe)
    - Inlet Temperature
      - 1,200 K (threshold)
      - 1,400 K (target)
    - Power level per unit: 500 kW_e – 1 MW_e
    - Power level per unit: 2 - 4 MW_e
    - Recuperated (likely)
- **CTE-3: Power Management and Distribution (PMAD) Subsystem**
  - AC Power Transmission
  - Transmission Voltage, Frequency: 1 kV, 2 kHz
- **CTE-4: Electric Propulsion Subsystem (EPS)**
  - Thruster options:
    - Hall thrusters
      - Propellant: Xenon
      - Power per thruster: 100 – 250 kW_e
    - Magnetoplasmadynamic (MPD) thrusters
      - Propellant: Lithium
      - Power per thruster: 500 kW_e – 1 MW_e
- **CTE-5: Primary Heat Rejection Subsystem (PHRS)**
  - Pumped-loop thermal trunkline
    - Working fluid: liquid metal
  - Finned C-C radiator panels with embedded heat-pipes
    - Working fluid: water

For many of the technologies considered in this TMP, the Advancement Degree of Difficulty (AD^2) is greater than 4, which warrants parallel development paths according to accepted NASA project management guidelines. In these cases, at least two options are carried for further development, until such time as one of them emerges as the clear choice for further maturation. As an example, while MPD and Hall thruster subsystem technologies are clearly at a higher maturity level than the alternatives, neither has a TRL/AD2 level that permits making a discrimination between them. The TMP details plans for developing both with a potential down selection at TRL 4. Similarly, two reactor cooling options are carried at the CTE level and multiple alternatives for MAs, sub-MAs, and components are carried in all CTEs.

Although the TMP reflects technology choices made by SNP, specifically choices that have been deemed as the most likely to result in successful near-term technology maturation to the point of application in an NEP system design, an offeror may propose technologies not covered in the TMP if they believe that the proposed options can meet the required KPPs during the time frame of interest. However, as the project progresses and funded requests for development are made, the offeror must justify their proposal both to the SNP project and to a NAR or source-selection panel with their own thorough technology maturation plan written at the same level of detail as found in this TMP.

The system modeling effort undertaken over the last two years to develop the system- and subsystem-level KPPs and inform the writing of this TMP will continue in parallel with the hardware development effort. Test-data will be fed back into the computational effort to reduce modeling uncertainties, refine the KPPs, and provide further guidance to the project. Overall, the combination of hardware development and system models is necessary to enable informed technology selections required to realize operational NEP systems.

As of the date of this paper, the TMP will have undergone a review by NASA and DOE personnel and will be sent out via NSPIRES to the wider technical community[20]. Following that, it will be submitted to a Non-Advocate Review (NAR) conducted by the NESC in early 2023, before being formally adopted by SNP.

SUMMARY AND CONCLUSIONS

At the direction of NASA STMD, and in response to the findings of recent reviews by the NESC and the National Academies on the state of nuclear propulsion technology for human Mars missions, SNP has developed a TMP to guide the advancement of MW-class NEP technology to TRL 5. The TMP contains milestone-driven schedules for the advancement of all critical technologies required for a MW-class human Mars mission. Technical milestones are hardware focused and set at relevant parameter values (power levels, temperatures, etc.) to insure that real technology advancement is demonstrated. The milestones will be confirmed (or modified if necessary) by non-advocate review panels and all advancement claims will be accepted only after full non-advocate review.

FUTURE WORK

Upon adoption of the TMP in early 2023, we anticipate initiating NEP development efforts according to the plan contained in the TMP, should funding become available. SNP is also pursuing cost-sharing partnerships with other government agencies to advance NEP technology.

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