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

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A strategy for maturing the technologies required for a megawatt-class nuclear electric propulsion (NEP) system is presented. The effort is responsive to recent non-advocate reviews stating high-power NEP technologies were relatively immature and significant maturation was required before contemplating the use of NEP on a flight mission. The maturation strategy presented accomplishes this through hardware test and evaluation at the sizes, scales, and conditions expected during high-power NEP missions. The development effort is accompanied by modeling of such a system to demonstrate thorough understanding and verification of the performance, lifetime, and failure modes. The proposed effort uses a building-block approach, maturing technologies for a 1 $MW_e$ block under the assumption that a future high-power NEP mission will have requirements that can be met either through straightforward scaling of this building block to the levels required or through the use of multiple blocks to meet the overall power needs. The plan is outlined for maturation to technology readiness level 5, characterized by test and evaluation using brassboard-fidelity hardware in a relevant environment and by demonstration of agreement between test data and analytical predictions.

## I. Introduction

In late fiscal year 2020, the Space Nuclear Propulsion (SNP) project began the process of formulating a 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. Over the course of the past six decades, NASA made multiple large investments in the NEP arena. Major examples include the Systems for Nuclear Auxiliary Power (SNAP) program of the 1960s,[1,2] the Space Exploration Initiative (SEI) effort that was conducted in parallel with the Space reactor Prototype (SP-100) effort to develop a 100 kW-class NEP system in the early to mid-1990s,[3-6] and the Jupiter Icy Moons Orbiter (JIMO)/Project Prometheus effort in the early 2000s that targeted a 100 kW-class system.[7,8]

There have also been several recent architecture studies concerning human-rated Mars missions.[9-18] The most recent of these examined opposition-class human Mars missions to occur in the late 2030s timeframe. The mission architecture for these studies assumed a hybrid NEP/chemical-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 entering and exiting gravity wells. The use of a high thrust chemical system in combination with the NEP system enables a reduction in required NEP power while still meeting the trip time requirement. Trajectory analyses performed in this

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study showed that such a mission could be performed with 2-6 $MW_e$ 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.

Despite these extensive efforts, two recent, independent reviews found that essentially all the major NEP subsystems needed for a human-rated Mars mission are well-below the stage of technology readiness required to make informed technology down-selections. 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.[19] 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 ($AD^2$ > 4) for maturation, requiring a dual development approach"
- "The proper assessment of baseline TRL and $AD^2$ 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, a panel of the National Academies of Science, Engineering, and Medicine issued a separate report[20] 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 report contained several important findings, including:

- "Developing a $MW_e$-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."

Based on these finding, the SNP project has formulated a technology maturation strategy that would realize TRL advancement through milestone-based hardware development and testing supported by modeling and simulation activities. The goals of the modeling and simulation efforts are to demonstrate understanding of the important and controlling physical phenomena in the system and to aid in the prediction of lifetime capability for a full-duration mission. The project aims to perform work at the sizes and scales necessary to bring all key NEP technologies to readiness levels where they can be credibly considered for a range of human Mars missions.

The SNP project NEP technology maturation plan (TMP) is not based upon a specific architecture or vehicle design. Dating back to the late 1950's there have been scores of architecture studies on the efficacy of NEP, including, for example, SEI, JIMO/Project Prometheus, and recent studies referenced above. These studies yield sets of missions that 'close' for a given set of ground rules and assumptions, but the long-standing issue with this approach is that the uncertainties regarding inputs on mass and performance for a $MW_e$-class NEP system are quite large because most of the key subsystems are still at a low TRL and high $AD^2$. In addition, NEP-class mission opportunity selection has been a moving target for six decades and the propulsive requirements can be significantly different depending on the opportunity. For this reason, choosing capabilities that enable a large fraction of potential mission opportunities is advantageous.

Despite uncertainties in the results of various mission studies, we can use the general results of those studies to state that the required power for an electric propulsion system on an opposition-class human-rated Mars mission for the 2039 mission opportunity, when used in combination with a chemical system, is between 2 to 6 $MW_e$. This is a propulsively-intense mission opportunity, so development of a propulsion system that could meet these requirements would also be enabling for a wide range of less intense mission opportunities. SNP's intent is to focus on the development and demonstration of hardware that will provide confidence in NEP technologies that can accomplish a wide range of missions. For this, SNP has chosen an approach demonstrating 1 $MW_e$ building blocks for the key power conversion, power management and distribution, and electric propulsion subsystems. Validated hardware (supported by significant modeling and simulation activities) is expected to be adaptable to any human-rated architecture once a mission target is selected. That is, successful execution of SNP TMP will enable the flexibility to address final mission power requirements through straightforward engineering efforts accomplished either by scaling the power capabilities of each subsystem or by using multiple $MW_e$-class building blocks working in concert.

To date, the project has performed a detailed assessment over the past two years of the technologies available for an NEP system. This included a deep dive into the literature summarizing past NEP efforts, the hosting of several technical interchange meetings focused on the various subsystems comprising an NEP system (primarily from Dec. 2020-Apr. 2021), and an even larger number of individual technical discussions with institutions, partners, and subject matter experts. The project cast a wide net to investigate available technologies, including those developed for applications outside of NEP (e.g., electric aircraft propulsion, gas turbine technologies for aircraft and power generation applications).

Based on this assessment process, the project has made certain choices on the 'most likely' technology choices for each NEP subsystem, with 'most likely' being a qualitative evaluation weighing several factors. These include, for example, the relative maturity of the system at the scales of interest, successes and difficulties encountered in past efforts, likely scalability to the range of interest for NEP systems, the ability to ground-test units at scales of interest (either as a subsystem or as part of a larger, integrated system), and a general judgement by SNP-selected subject matter experts (SME) on the ability of the selected technologies to meet project-specified system and subsystem key performance parameters (KPPs). The specific target NEP KPPs will be discussed in the next section as the NEP subsystems and functions are discussed.

Specific NEP subsystems selected by the project will not be discussed in this paper as these selections are undergoing final review. After all reviews are completed, these selections will be published as part of SNP's comprehensive and baselined TMP.

## II. The NEP System

In general, an NEP system can be subdivided into five top-level subsystems or critical technology elements (CTEs). These are given in schematic form in Figure 1, which shows how power (thermal or electric) moves between the various CTEs. The schematic is somewhat general, and we note that some of the items are given with dashed lines because those elements may or may not be present, depending upon the specific design configuration.

Briefly, each specific CTE in the NEP system accomplishes the following:

1. Nuclear Reactor and Coolant Subsystem (RXS – CTE 1) – The thermal power source for the system, using high-assay low enriched uranium (HALEU) as the nuclear fuel. The internal reactor radiation shielding is also included in this CTE.
2. Power Conversion Subsystem (PCS – CTE 2)– Operates as a thermodynamic cycle, accepting nuclear reactor thermal power as an input and converting it to mechanical power. The schematic in Fig. 1 has been customized to show this CTE as a closed-cycle Brayton power conversion system.

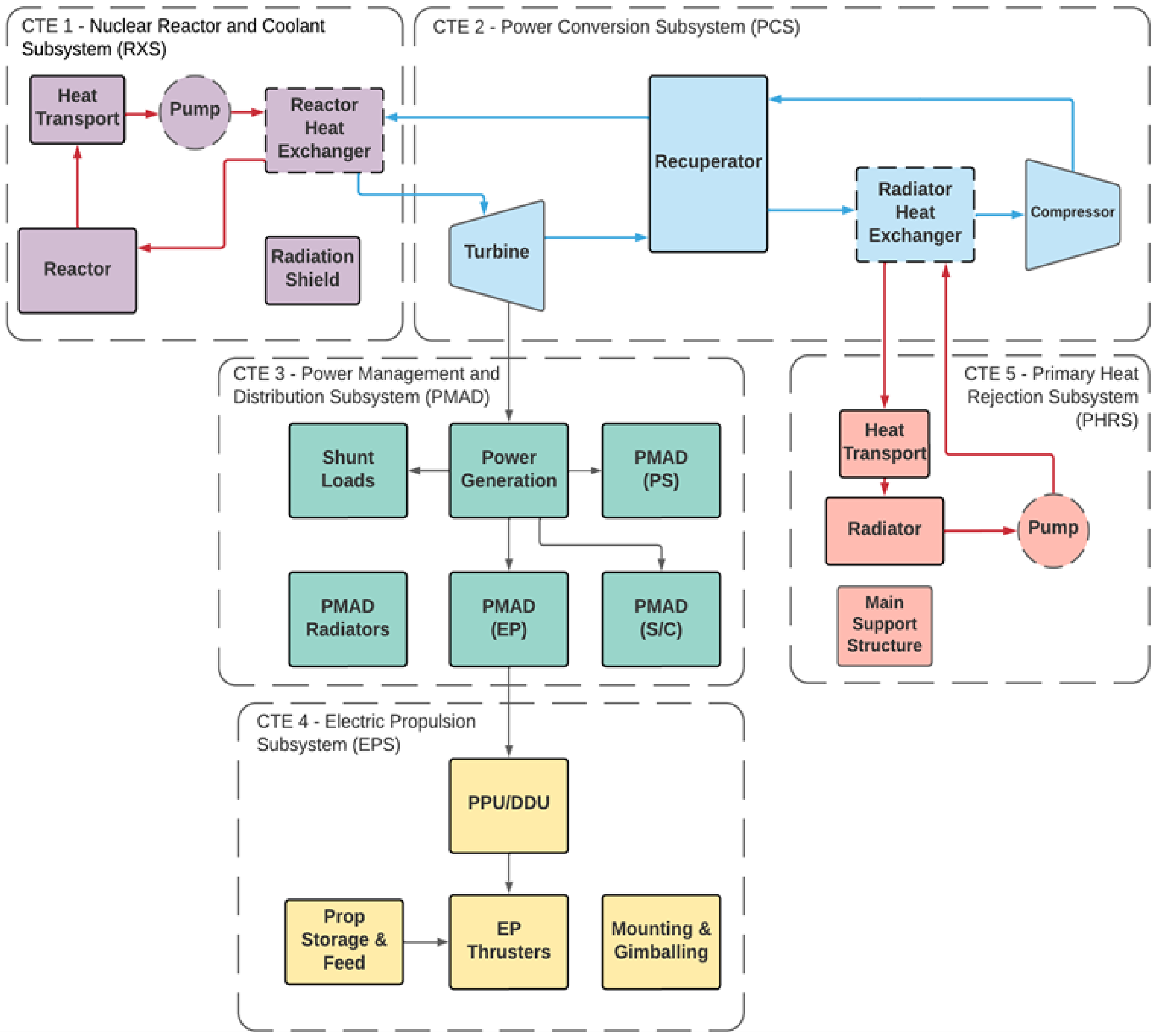


**Figure 1**: Schematic diagram of the critical technology elements (CTEs) comprising an NEP system, assuming the power conversion element (CTE 2) is a closed-cycle Brayton system.

3. Power Management and Distribution Subsystem (PMAD – CTE 3) – Accepts as an input mechanical power from the power conversion subsystem, which is subsequently used by the generator in the PMAD subsystem to produce electrical power. That power is then distributed by the PMAD subsystem to all other parts of the spacecraft, including the high-power EP system. The PMAD subsystem may also perform duties such as isolation, fault detection, and power transformation/rectification for different spacecraft systems, including the thrusters.
4. Electric Propulsion Subsystem (EPS – CTE 4) – Accepts as an input electrical power, which is used to accelerate a propellant to high exhaust velocities to produce thrust. This system includes the propellant storage and feed systems, which contain and meter the flow of propellant to the thrusters, and the power processing unit (PPU), which converts the power it receives to the correct current and voltage required by the thrusters and is the primary thruster control system. Alternatively, if the PMAD bus voltage is approximately equal to the voltage required by the thruster, the latter could be powered directly from the bus and controlled using a direct-drive unit (DDU).

5. Primary Heat Rejection Subsystem (PHRS – CTE 5) – The cold side of the thermodynamic power conversion cycle, this subsystem accepts thermal power from the power conversion system and radiatively rejects that heat to space.

Modeling of the power flow in this system and the mass associated with those components comprising each CTE, coupled with a mission model have allowed the project to set KPPs for the overall system and for each subsystem.[10,12,13] A few of the major KPPs for the overall system are given in Table 1. Mission and system modeling have shown that for an end-to-end nuclear power supply (CTEs 1, 2, 3, and 5) with a specific mass ($\alpha$) of ~20 kg/kW$_e$ and a nominal electrical power output of 2 MW$_e$, an opposition-class human Mars mission will close.[12] The "Threshold" values shown in Table 1 labeled 'Threshold' represent technology capabilities at which mission analysis shows closure with little margin The 'Target' values are associated with higher performance technologies that provide additional margin on mission closure.

**Table 1**: Major system and key subsystem KPPs for a human Mars NEP-powered mission.

| Parameter | KPP value |
|---|---|
| Power system $\alpha$ (kg/kW$_e$)<br>[consists of CTEs 1, 2, 3, and 5] | 20 (threshold), 13 (target) |
| Total electric propulsion thrust (N) | 80-100 |
| Electric propulsion efficiency and $I_{sp}$ (s) | Efficiency and $I_{sp}$ required to close mission – dependent on electric propulsion system choice |
| Mission duration (hours) | 25,000 |
| | |
| CTE 1 power output (MW$_{th}$) | 8-10 |
| CTE 1 outlet/CTE 2 power conversion inlet temp (K) | 1200 (threshold), 1400 (target) |
| CTE 2 power output (MW$_e$) | 2-4 |
| CTE 4 total thruster operating time (hours) | 13,000-17,000<br>(EP system choice dependent) |
| CTE 2 outlet/CTE 5 inlet temp (K) | 625-750 |
| CTE 5 outlet/CTE 2 compressor inlet temp (K) | 350-500 |

## III. Maturation Philosophy

In discussing the SNP NEP technology maturation philosophy, it is useful to introduce a few concepts. One is technology readiness level (TRL), which is a static descriptor of a technology's status. This descriptor (ranging from 1-9, with larger values assigned to more mature or 'ready' technologies) gives a quantified readiness based on NASA document NPR 7123.1B, Appendix E.[21] The goal of a technology maturation plan is to raise the TRL of a system through focused development. Descriptions for TRLs 2-6 are given in Table 2. This is the range of highest relevance because all the critical technologies under consideration for the NEP application fall at the lower end of this range, and it is the initial goal of the SNP NEP TMP to raise those levels up to TRL 5.

**Table 2**: Definitions for technology readiness levels (TRLs) from 2 to 6, as given in Ref. [21].

| TRL | Definition | Hardware Definition | Exit Criteria |
|---|---|---|---|
| 2 | Technology concept and/or application formulated. | Invention begins, practical applications is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. | Documented description of the application/concept that addresses feasibility and benefit. |
| 3 | Analytical and experimental proof-of-concept of critical function and/or characteristics. | Research and development are initiated, including analytical and laboratory studies to validate predictions regarding the technology. | Documented analytical/experimental results validating predictions of key parameters. |
| 4 | Component and/or breadboard validation in laboratory environment. | A low fidelity system/component breadboard is built and operated to demonstrate basic functionality in a laboratory environment. | Documented test performance demonstrating agreement with analytical predictions. Documented definition of potentially relevant environment. |
| 5 | Component and/or brassboard validation in relevant environment. | A medium-fidelity component and/or brassboard, with realistic support elements, is built and operated for validation in a relevant environment so as to demonstrate overall performance in critical areas. | Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements. Performance predictions are made for subsequent development phases. |
| 6 | System/sub-system model or prototype demonstration in a relevant environment. | A high-fidelity prototype of the system/subsystems that adequately addresses all critical scaling issues is built and tested in a relevant environment to demonstrate performance under critical environmental conditions. | Documented test performance demonstrating agreement with analytical predictions. |

The advancement degree of difficult ($AD^2$) is another useful term when discussing technology maturation.[22,23] This term is a dynamic descriptor designed to provide insight into the effort required to move a system, subsystem, or component from one TRL to the next. It is a measure to be used in conjunction with TRL to understand the present state of readiness of a technology, quantify the difficulty in further advancing that technology for a given application, and estimating the likelihood that the advancement effort will be successful. The definitions of $AD^2$ are given in Table 3, with lower values being easier to advance and less risky for a project. During a technology maturation effort, a reduction of the $AD^2$ for a technology will accompany successful TRL advancement for that technology.

**Table 3**: Definitions for the levels of advancement degree of difficulty ($AD^2$) from Refs. [22,23].

| $AD^2$ | Definition | Risk | Comment |
|---|---|---|---|
| 1 | Exists with no or only minor modifications being required. A single development approach is adequate. | 0% | |
| 2 | Exists but requires major modifications. A single development approach is adequate. | 10% | |
| 3 | Requires new development well within the experience base. A single development approach is adequate. | 20% | |
| 4 | Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success. | 30% | Well understood (variation) |
| 5 | Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success. | 40% | Known unknowns |
| 6 | Requires new development but similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. Desired performance can be achieved in subsequent block upgrades with high confidence. | 50% | |
| 7 | Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued. | 70% | |
| 8 | Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be prepared. | 80% | Unknown unknowns |
| 9 | Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined. | 100% | Almost nothing known |

The definitions in Tables 2 and 3 are helpful guidelines for quantifying technology status and the degree of difficulty for advancement. By evaluating technologies using NASA best practices,[24] competing technologies can be compared relative to their ability to achieve the applicable KPP's to support technically sound decision-making. While the definitions of TRL are useful in qualitatively understanding technology readiness, it is a project that develops specific milestones and quantifiable criteria that are acceptable to demonstrate advancement in TRL. Those specific criteria as developed for SNP will be discussed in the next section.

Extensive SNP-supported, SME-based technology reviews combined with inputs from external sources and contributors indicate that, at present, no subsystems at the CTE-level have achieved a TRL/$AD^2$ level required to support a detailed NEP system design at a preliminary design review (PDR) level (typically TRL 6 with $AD^2 \leq 2$ for operational missions and TRL 5 with $AD^2 \leq 3$ for technology demonstration missions). In fact, most NEP technologies are significantly below this level – an SNP finding fully-consistent with the previous NESC[19] and National Academies[20] study findings. Furthermore, the project has determined that the $AD^2$-values for all CTEs are at a high-enough level where parallel-track technology development should be pursued for each of the CTEs.

It is the goal of the SNP NEP technology maturation plan to increase the TRL of each CTE and reduce the corresponding $AD^2$ to support down-select decisions, first between parallel technology development paths for each CTE and then for a potential down-selection between NEP and NTP for a human-Mars mission.

As with all complex systems, understanding and managing the interfaces between CTEs is critical to the development of an operational system. Under the SNP TMP, each interface is carefully defined by SMEs to assure that the technology decisions and specified milestones lead to subsystems that will be compatible when integrated at the system level. SNP will manage these internal interfaces to assure that individual CTE developments do not result in subsystems that are incompatible or that are inconsistent with the system-level requirements.

## IV. Maturation Plan Milestones

In this section we discuss the maturation plan milestones SNP is targeting to demonstrate advancement of the technologies in each CTE, first from the present values to TRL 4 and then from TRL 4 to TRL 5. The focus of the TMP is on the critical and long-lead developments that must be executed to show technology advancement and readiness. Straightforward engineering tasks that are extensions of existing state-of-the art are not necessarily part of the NEP TMP since those items, while important, do not limit the technology readiness or significantly add to the $AD^2$ of the system. The advancement milestones for the non-nuclear systems elements are described first, followed by those for the nuclear reactor (CTE 1).

While we will not discuss it in detail in this paper, it should be noted that no technology advancement plan of this magnitude would be complete without an accompanying plan for the test facilities that would be used. In fact, availability of test facilities capable of adequately simulating the on-orbit environment may be a key discriminator for the technology selection process. Many of the tests contemplated in the NEP TMP are challenging and will either require significant upgrades to existing facilities or the commissioning of new facilities to perform testing at the relevant physical sizes and power levels required for technology maturation. Consequently, full advancement plans must account for the long-term planning and cost required to bring those test capabilities into existence and to execute some of the testing described in the NEP TMP.

The maturation plan milestones discuss modeling and simulation activities that must accompany the work performed on each CTE to demonstrate understanding of the important and controlling physical phenomena in the system and to aid in the prediction of lifetime capability for a full-duration mission. Not included in this document but included in the overall NEP TMP are the modeling and simulation activities required to understand the overall integrated system. This includes quantification of the effects that different technology choices have on overall system performance and the development of control strategies and algorithms to handle nominal and off-nominal operational conditions. It also feeds into the identification and development of the required instrumentation and control systems required for the fully integrated NEP system.

### A. Non-Nuclear System Elements

In general, the non-nuclear system elements of the NEP system (CTEs 2-5) should achieve similar developmental milestones to demonstrate TRL advancement. While there will be some tailoring, both for each CTE and for different possible options within a CTE, the general scope is the same. At each step, hardware of a given fidelity much be tested at relevant conditions (power levels, environments, etc.) for certain durations. These tests, in addition to providing experimental evidence that the system can be operated at the scales required for the $MW_e$-class NEP application, also provide data on system performance, mass, and long-duration operation. These data are subsequently used to anchor or validate models, refine overall expectations for both system performance and mass for ongoing and future design and mission architecture studies, and enable predictions of lifetime and life-limiting failure mechanisms in support of detailed failure modes and effects analyses (FMEA).

Presented in Table 4 is a listing of the general (non-tailored) milestones for advancement of the electric propulsion subsystem (CTE 4) from its present state to TRL 4/AD$^2$ 3 and then to TRL 5/AD$^2$ 2. The required hardware fidelity increases and the milestones become more challenging as the scale advances, including operation for 2,500 hours (or roughly 10% of the overall mission duration). Non-advocate review of progress made during the execution of the plan will assure the required advancements in hardware readiness and modeling and simulation capabilities are being achieved.

**Table 4**: SNP milestones for successful demonstration of technology advancement for the electric propulsion subsystem (CTE 4).

| **For advancement from the present status to TRL 4/AD$^2$ 3** |
|---|
| • Successful operation for 1000 hours of sub-scale breadboard-level fidelity thruster pod (with the number of thrusters and operational power level per thruster selected to support model validation) using power processing unit (PPU) emulators.<br>• Successful operation of an integrated single full-scale engine and PPU (both at breadboard-level fidelity) for a minimum of 1000 hours.<br>• Demonstration of predictive thermal, plume, and thruster/PPU interaction modeling capabilities, validated with data from the TRL 4 advancement effort.<br>• Delivery of a detailed preliminary failure modes and effects analysis (FMEA) showing no insurmountable issues that will prevent achieving program goals. |
| **For advancement from TRL 4/AD$^2$ 3 to TRL 5/AD$^2$ 2** |
| • Successful operation for 2500 hours of an integrated sub-scale thruster pod consisting of brassboard-fidelity thrusters and PPUs operating at the full scale that would be needed for a 1 $MW_e$ capability (with the quantity of thruster/PPU elements in the pod set to ensure the capture of all effects associated with multi-thruster operation).<br>• Successful plume test of a pod of breadboard-fidelity thrusters operating in a facility of a size that is capable of quantifying plume effects.<br>• Demonstration of predictive thermal, plume, and thruster/PPU model capabilities validated with data from the TRL 5 advancement effort and used to extrapolate full-power pod-level performance, lifetime, and plume interaction impacts.<br>• Delivery of a final FMEA showing no insurmountable issues that will prevent achieving program goals. |

CTE 2 (Power Conversion Subsystem), CTE 3 (Power Management and Distribution Subsystem), and CTE 5 (Primary Heat Rejection Subsystem) will likewise have milestones of comparable scope and scale designed to advance them to TRL 5 and AD$^2$ 2.

## B. Nuclear Reactor and Coolant Subsystem (CTE 1)

The nuclear aspects of the reactor necessitate some adjustment of the TRL advancement strategy for CTE 1. The nuclear operating conditions in the NEP system are like the well-understood terrestrial power plant reactor conditions, and the very mature models that have been developed to design the latter can be applied to the former. However, the reactor temperatures for a high-power NEP system are higher than what is found in most terrestrial nuclear power plants (coolant outlet temperatures of 1200-1400 K compared to < 600 K, respectively), but these are not nearly as high as the temperatures required for a nuclear thermal rocket (propellant temperature of > 2700 K). Since operation at higher temperatures is known to impact reactor material properties and component performance, the TMP for CTE 1 includes significantly more materials quantification and component-level work, with tasks focusing on fuel and moderator material property measurements for the temperature ranges of interest as well as heat-transfer mode demonstration and verification. Advancement to TRL 5 involves the fabrication and testing of a reactor with a goal of operation at conditions that achieve the target KPPs given in Table 1. A general (non-tailored) list of milestones for advancement of the nuclear reactor subsystem from its present state to TRL 4/AD$^2$ 3 and then to TRL 5/AD$^2$ 2 is given in Table 5.

**Table 5**: SNP milestones for successful demonstration of technology advancement for the nuclear reactor subsystem (CTE 1).

| **For advancement from the present status to TRL 4/AD$^2$ 3** |
|---|
| • Successful completion of irradiation of clad $UO_2$ and UN fuel elements fabricated using laboratory feedstock to demonstrate representative fabrication processes. Post irradiation examination (PIE) completed to confirm dimensional stability and cladding hermeticity.<br>• Demonstration of a moderator element protected by thermal barrier coatings/cladding at 1500 K for 2500 hours in a neutron environment.<br>• Demonstration of at least one reliable high temperature heat transfer technology – gas-cooled or heat pipe – operated for at least 2500 hours at 1200 K/1400 K working fluid temperatures.<br>• Successful operation of vessel components – such as, reactor vessel and heat exchanger – in a system at relevant conditions (temperature and heat transfer medium) to demonstrate creep resistance, joining/welding strength, and chemical compatibility.<br>• Delivery of a detailed preliminary FMEA to quantify reliability and assess reactor architecture for redundancy based on data from TRL 4 testing. Use FMEA in combination with latest hardware testing results to ensure there are no insurmountable issues identified that will prevent achieving program goals. |
| **For advancement from TRL 4/AD$^2$ 3 to TRL 5/AD$^2$ 2** |
| • Successful operation for at least 2500 hours at 1200 K/1400 K working fluid temperatures of an appropriately scaled brassboard-level fidelity core assembly equipped with heat-transfer interfaces such as a brassboard-level fidelity heat-exchanger and pressure vessel containment. Target is delivery to CTE 2 (PCS) of a He/Xe fluid mixture[25] at 1400 K and 2 MPa.<br>• Successful engineering-scale demonstration of dynamic performance of the brassboard-level fidelity core assembly using brassboard-level fidelity instrumentation and control systems to demonstrate performance during off-nominal scenarios.<br>• Successful completion of fuel-assembly level nuclear irradiation (in a combined effects environment with representative working fluids and/or heat transfer interfaces).<br>• Demonstration of end-to-end nuclear reactor and coolant subsystem model validated with test data to quantify subsystem specific mass (alpha), performance, lifetime, and robustness.<br>• Using updated models validated using component- and subsystem-level test data, complete a final FMEA to ensure there are no insurmountable issues identified that will prevent achieving program goals. |

## V. Conclusions

NASA's Space Nuclear Propulsion project formulated a methodical technology maturation strategy to advance the technology readiness of the critical technology elements comprising a high-power NEP system while reducing the overall risk associated with further maturation and the eventual use of NEP on a mission. The plan incorporates the results of multiple broad-based technology interchange meetings, extensive subject matter expert inputs and reflects the results of recent non-advocate reviews stating that the TRL of critical technology elements was low and that targeted investment in technology development. The TMP is also responsive to these same reviews by focusing on demonstration efforts at the appropriate sizes and scales accompanied by significant modeling efforts to support the future development of a $MW_e$-class flight NEP system. The focus of the SNP effort is demonstration of 1 $MW_e$-class building blocks for each of the major non-nuclear elements and demonstration of the critical reactor technologies. The TMP targets operation of the various subsystems at the 1 $MW_e$ scale in relevant environments (power levels, temperatures, pressures, etc.) anticipated for a flight system with demonstrated durations necessary to provide confidence in the understanding of wear mechanisms and failure modes in the system. When completed, the expectation is that each subsystem will be at TRL 5 and an $AD^2 \leq 2$, with the overarching goal that further development to TRL 6 and beyond should require straightforward engineering tasks without the need for further research and development.

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