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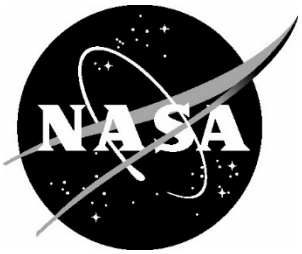

Technology Maturation Plan for Space Nuclear Propulsion Systems

Kurt A. Polzin
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November 2026

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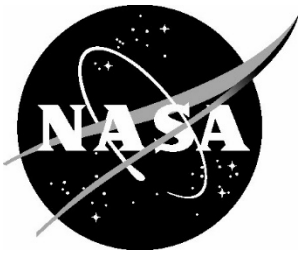

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National Aeronautics and
Space Administration

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Abstract

This Technical Memorandum presents a technology maturation plan for nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) systems. The plan applies unified, evidence-based Technology Readiness Level (TRL) criteria to define the activities and objective evidence needed to advance nuclear, propulsion, power, and integrated-system technologies through TRLs 4, 5, and 6. It assesses the current technology baseline and persistent gaps, including statistical materials data, combined-effects testing, validated multiphysics modeling and simulation, system integration, and long-lead nuclear test and post-test examination capabilities. The resulting milestones progress from component-level separate-effects testing to relevant-environment combined-effects testing and high-fidelity subsystem and integrated-system demonstrations, with requirements tailored to the operating conditions, environments, lifetime, and concept of operations of the intended mission. The analysis concludes that timely maturation and certification of space nuclear propulsion systems depend on early, coordinated investment in specialized test infrastructure, representative interfaces, integrated test articles, post-irradiation examination, and models anchored by test data. Implementing this framework provides a systematic basis for reducing technical and programmatic risk and establishing confidence in the safety, performance, reliability, and extensibility of future NTP and NEP systems.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AD^2	Advancement Degree of Difficulty
CERCER	Ceramic-Ceramic
CERMET	Ceramic-Metallic
CFEET	Compact Fuel Element Environmental Test
CFM	Cryogenic Fluid Management
CTE	Critical Technology Element
ConOps	Concept of Operations
DDT&E	Design, Development, Test, and Evaluation
DoD	Department of Defense
DOE	Department of Energy
DoW	Department of War
DRACO	Demonstration Rocket for Agile Cislunar Operations
EDU	Engineering Development Unit
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EP	Electric Propulsion
EPS	Electric Propulsion Subsystem
FCM	Fuel and Core Materials
FMEA	Failure Modes and Effects Analysis
H^2EAT	Hot Hydrogen Environmental Atmospheric Test
HA	Hazards Analysis
HALEU	High-Assay Low-Enriched Uranium
HIL	Hardware in the Loop
HVDC	High-Voltage DC
I&C	Instrumentation & Control
ISAM	In-Space Servicing, Assembly, and Manufacturing
KPP	Key Performance Parameters
LR-1	Lunar Reactor-1
M&S	Modeling and Simulation

MARVL	Modular Assembled Radiators for NEP VehicLes
MCNP	Monte Carlo N-Particle
MEL	Master Equipment List
MMOD	Micrometeoroids and Orbital Debris
MOOSE	Multiphysics Object-Oriented Simulation Environment
MPD	Magnetoplasmadynamic
MRL	Manufacturing Readiness Level
MTE	Materials Test and Evaluation
NEP	Nuclear Electric Propulsion
NESC	NASA Engineering and Safety Center
NERVA	Nuclear Engine for Rocket Vehicle Application
NF	Nuclear Furnace
NNC	Non-Nuclear Components
NPSS	Numerical Propulsion System Simulation
NRC	Nuclear Regulatory Commission
NSPM	National Security Presidential Memorandum
NSTM	National Space Technology Memorandum
NTP	Nuclear Thermal Propulsion
NTREES	Nuclear Thermal Rocket Element Environment Simulator
PCS	Power Conversion System
PIE	Post-Irradiation Examination
PIRT	Phenomena Identification and Ranking Table
PMAD	Power Management and Distribution
PRA	Probabilistic Risk Assessment
RS	Radiation & Shielding
RCC	Reactor and Core Components
ROCETS	ROCket Engine Transient Simulation
SI	Systems Integration
SNAP	Systems for Nuclear Auxiliary Power
SNP	Space Nuclear Propulsion
SNTP	Space Nuclear Thermal Propulsion
SR-1	Space Reactor-1 *Freedom*

SRTC	Space Reactor Test Capabilities
TM	Thermal Management
TMP	Technology Maturation Plan
TREAT	Transient REActor Test
TRL	Technology Readiness Level
TVAC	Thermal Vacuum
UN	Uranium Nitride
UO_2	Uranium Oxide
UQ	Uncertainty Quantification

TECHNICAL MEMORANDUM

TECHNOLOGY MATURATION PLAN FOR SPACE NUCLEAR PROPULSION SYSTEMS

EXECUTIVE SUMMARY

This technology maturation plan (TMP) for space nuclear propulsion systems provides a structured, milestone-driven roadmap for advancing the technologies required for operational nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) systems. This plan can build directly upon the activities undertaken and data produced by early flight demonstrations such as Space Reactor-1 *Freedom* (SR-1), announced at NASA's Ignition event in March 2026, and Lunar Reactor-1 (LR-1). While SR-1 provides essential early heritage for a low-power, high-assay low-enriched uranium (HALEU)-fueled reactor system using a closed Brayton cycle for power conversion, it includes limited design, development, test, and evaluation (DDT&E) activities and does not undergo full integrated ground testing prior to flight. Therefore, this TMP focuses on closing critical gaps and maturing higher-performance capabilities for NTP and NEP beyond the presently announced demonstration flights to support a range of national missions. While it is beyond the scope of this TMP, additional work beyond that contemplated for NTP and NEP technology maturation would focus on activities aimed at combining the two systems into one bimodal nuclear rocket, where a single reactor was used to produce both high thrust and electrical power.

TECHNOLOGY MATURATION PURPOSE

Technology maturation is performed to minimize technical and programmatic risks for future operational space nuclear systems. This is accomplished for space nuclear systems across three interconnected activity types: (1) maturing the underlying technologies and generating foundational data while uncovering unknowns early; (2) building essential capabilities such as specialized test infrastructure, workforce expertise, and programmatic frameworks; and (3) supporting system integration and certification strategies that align investments with mission needs.

The vision is to establish a robust technology and capability foundation that enables a sustainable space nuclear future. This foundation will support missions of increasing ambition in cislunar space and beyond while ensuring the United States maintains technological leadership.

APPROACH

This TMP draws upon a unified Technology Readiness Level (TRL) advancement criteria developed for space nuclear systems, which harmonize guidance from NASA, the Department of Defense (DoD [Department of War (DoW)]), and the Department of Energy (DOE). Progress will be measured against clear, quantitative and qualitative acceptance criteria at TRL 4, 5, 6, and beyond. Priority is placed on:

- Quantifiable milestones and metrics,
- Commonality of activities,
- The need for long-lead test and evaluation capabilities,
- Reference system designs and interface definitions to uncover integration risks,
- A balanced investment portfolio that leverages heritage from legacy programs while addressing persistent gaps in combined-effects testing and statistical-basis materials data.

By the time key subsystems are expected to reach TRL 5–6, the foundational test and evaluation infrastructure should be established to support higher TRL subsystem testing, integrated system testing, and flight qualification. This approach reduces verification risks for future operational systems and positions the nation for extensible, cost-effective space nuclear propulsion leadership.

1. INTRODUCTION

Technology maturation represents a deliberate investment phase undertaken prior to the development of an operational flight system that is focused on reducing uncertainty in the fundamental building blocks of complex systems. Unlike mission-specific engineering development, which produces hardware and designs tailored to a single application, technology maturation generates reusable knowledge, demonstrated components, validated models, and enabling infrastructure that can support multiple future systems within a given class of missions. For space nuclear propulsion, this distinction is particularly important because nuclear systems must remain safe and reliable while operating under harsh conditions in challenging environments, and there can be significant verification costs for testing involving nuclear systems.

1.1 The Importance of Technology Maturation

The objective of technology maturation is to field operational space nuclear propulsion systems that consistently meet requirements for performance, lifetime, reliability, cost-efficiency, repeatability, and future scalability. Achieving this goal through "normal-risk" system development requires an adequate level of maturity of foundational technologies before system development begins.

Historical experience shows that programs are most successful when they balance early maturation of critical technologies with timely integrated system development. Attempting to mature key technologies too late, concurrent with system design, often leads to schedule delays, cost growth, and difficult verification challenges that can drive descoping or cancellation. Conversely, focusing too heavily on maturing technologies in isolation, without adequate emphasis on integrated system operation, can delay the discovery of interface, operability, and performance issues until late in the program, when they are far more costly to resolve.

A disciplined approach that matures essential technologies to an appropriate readiness level while progressively integrating and testing them within increasingly more realistic and complete system environments provides the most reliable path to achieving intended mission capability and advancing technology.

1.2 National and Program Context

The National Space Technology Memorandum 3 (NSTM-3), issued by the Office of Science and Technology Policy in April 2026,[1] provides the overarching policy direction for this Technology Maturation Plan (TMP). NSTM-3 emphasizes parallel development of nuclear power and propulsion capabilities, commonality between nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) wherever practical, and rapid demonstration missions. Space Reactor-1 *Freedom* (SR-1) serves as an important early milestone but, by design, incorporates limited design, development, test, and evaluation (DDT&E) and no full integrated ground testing.

1.3 Technology Maturation Mission & Vision for Space Nuclear Systems

Mission: Minimize technical and programmatic execution risks across successive space nuclear systems through three complementary lines of effort:

- Advancing enabling technologies and supporting data (Technical)
- Establishing critical capabilities such as test infrastructure and workforce capacity (Capabilities)
- Informing optimal system concepts and architectures alongside robust certification strategies (Integration & Certification).

Vision: Establish an enduring foundation of technologies and capabilities that enable transformative innovation in space nuclear systems. This foundation will position the United States to pursue increasingly ambitious missions in cislunar space, to Mars, and beyond while preserving technological leadership and ensuring continued advancement.

1.4 Strategic Focus Areas

Technology maturation for space nuclear propulsion should address both systems that can support nearer-term mission opportunities and systems that require significant advances in technology, engineering, and system integration to enable future missions. The objective is not to establish an exhaustive taxonomy of nuclear propulsion systems, nor to imply that only four discrete classes warrant consideration. Rather, four representative system classes are identified here as strategic bookends for technology maturation: two NTP classes differentiated primarily by thrust level and two NEP classes differentiated primarily by electrical power level. Intermediate system classes, including mid-thrust NTP and mid-power NEP systems, remain relevant and may be addressed as mission needs and technology opportunities dictate.

The four strategic classes are:

- **NTP Low-Thrust Class**: Less than 50,000 pounds-force of thrust, targeting a specific impulse of approximately 900 s or greater. This class represents a relatively near-term NTP capability with potential applicability to science missions, planetary defense, and cislunar cargo and logistics missions operating from nuclear-safe Earth orbits. Development of systems in this class can therefore be informed increasingly by specific mission requirements and concepts of operations, providing a mission-pull pathway for technology maturation.

- **NTP High-Thrust Class**: Greater than approximately 50,000 pounds-force of thrust, with a specific impulse threshold goal of approximately 900 s and a stretch goal of approximately 1,035 s or greater. This class represents a more challenging technology target intended to enable high-energy missions, including human Mars exploration, for which higher thrust and overall propulsion system performance may be required. Development of this class provides a deliberate technology-push pathway to address demanding reactor, fuel, materials, turbomachinery, thermal, and integrated system requirements.

- **NEP Low-Power Class**: Approximately 20–100 kWe. This class represents an evolutionary pathway from demonstrated or developing NEP capabilities, including the SR-1/ Lunar Reactor-1 (LR-1) technology baseline, toward more capable, reliable, mass-efficient systems for deep-space science and other nearer-term applications. As

with the NTP Low-Thrust Class, technology maturation in this regime can increasingly be guided by specific mission needs and therefore provides a mission-pull pathway.

- **NEP High-Power Class**: Approximately 1 MWe, with scalability to higher power levels through increases in individual unit capability, parallel power-conversion units, or combinations thereof. This class represents a deliberate technology-push objective intended to drive advances in reactor power density, power conversion, power management and distribution, thermal management, radiation tolerance, system integration, and lifetime. The technologies and engineering approaches developed at these power levels are also expected to provide benefits to lower-power NEP systems through improvements in mass efficiency, reliability, lifetime, and system integration.

These four classes should be viewed as development anchors rather than discrete boundaries. The intent is to establish representative near-term and long-term targets that frame technology maturation activities while retaining flexibility to develop intermediate capabilities where warranted by mission requirements. A mid-thrust NTP system, for example, may ultimately prove to be the most appropriate solution for a particular mission even though it is not represented as a separate strategic class here. Similarly, NEP systems between the low- and high-power classes may provide valuable mission capabilities or serve as important development steps toward higher-power systems.

The ultimate objective should be to develop a portfolio of propulsion capabilities that addresses an increasing fraction of the potential mission space rather than to optimize individual propulsion systems in isolation. The potential mission classes and associated key performance parameters (KPPs) considered in this technology maturation strategy are provided in the Appendix. These KPPs provide a basis for identifying common requirements and opportunities for technology reuse across missions. In particular, technology development should seek the intersection of mission requirements: propulsion system classes capable of satisfying multiple mission sets can provide greater architectural utility than systems optimized for a single application. Evaluating the overlap among mission KPPs therefore provides a means of identifying the number, type, and performance levels of nuclear propulsion systems that warrant focused maturation.

1.5 Technology Maturation Across System Classes

Although the required performance levels and operating environments differ among the propulsion classes described above, the fundamental process for maturing the underlying technologies does not. The tasks required to establish and advance technology readiness, and the objective evidence needed to demonstrate that advancement, are broadly common across NTP and NEP systems. NTP- and NEP-specific technologies introduce differences in the particular technical challenges that must be addressed, but these differences do not fundamentally change the technology maturation process.

The extent and rigor of the maturation activities are instead driven by the operating characteristics and environments of the propulsion system and its intended mission. These include characteristics such as reactor power, thrust, operating temperature, power-conversion requirements, thermal loads, radiation exposure, duty cycle, and operating duration. Mission requirements establish the duration and frequency of operation, required thrust or electrical power,

number and duration of propulsive cycles, and other operational characteristics. The mission destination establishes the natural environments to which the system will be exposed, including the relevant radiation, thermal, vacuum, micrometeoroid, and orbital environments. In addition, the propulsion system itself creates environments, such as reactor radiation fields, high temperatures, thermal gradients, vibration, and electromagnetic or other system-level effects, that must be considered in maturation and qualification activities.

Consequently, technology readiness levels (TRLs) are inherently dependent on the expected operating conditions and mission. A technology or system may have achieved a high TRL for one set of operating conditions and environments while remaining at a lower TRL for a more demanding application. For example, demonstrated operation at a particular power level, temperature, lifetime, radiation exposure, or duty cycle does not by itself establish readiness for operation at a more demanding condition. The technology maturation process remains the same, but the starting point and the amount of additional evidence required to establish readiness will depend on the extent to which the intended application differs from previously demonstrated conditions.

This distinction is particularly important for space nuclear propulsion, where previous work may provide substantial heritage at the component, subsystem, or system level without necessarily demonstrating the complete set of conditions required for a new system or mission. Existing technology development and flight experience should therefore be leveraged wherever applicable, but the maturity assessment must remain tied to the specific operating conditions and environments of the intended application. Prior work performed by other programs or projects may establish a higher starting TRL for an underlying technology, reducing the amount of new maturation required, but it does not eliminate the need to demonstrate that the technology is suitable for the intended application.

1.6 TRL Assessment and Technology Program Management

Establishing technology readiness represents both a technical assessment and a project management responsibility. The engineering organization provides the technical basis for determining the current state of a technology, including the demonstrated capabilities, limitations, test results, analytical evidence, and remaining gaps. However, the resulting TRL assessment must be established as part of the project's technical baseline and used by project management to plan and control the technology maturation effort.

This distinction is important because a TRL is not simply a statement of technical opinion. A credible TRL assessment must be supported by objective evidence demonstrating that the technology satisfies the conditions associated with the applicable readiness level. The NASA Engineering and Safety Center (NESC) has identified several recurring concerns in the assessment and advancement of nuclear propulsion technologies, including a tendency for TRLs reported in the literature to be overestimated, persistent challenges in establishing appropriate baseline TRLs and Advancement Degree of Difficulty (AD^2) values, and difficulty in accurately estimating the requirements and resources needed to advance technologies. NESC has also emphasized the value of non-advocate reviews at the initiation of technology programs and at key program milestones.[2]

Accordingly, the technical team or chief engineer should establish the technical basis and recommend the appropriate TRL, while project management is responsible for incorporating that assessment into the project baseline and using it to establish the maturation strategy, schedule, resource requirements, and associated risks. This approach provides an important separation between assessing what has been demonstrated and deciding what the project must do next to achieve the required level of maturity.

The purpose of this TMP is not to prescribe how a project must execute its technology development activities. Decisions regarding test sequencing, development approaches, staffing, funding, contracting, risk acceptance, and other implementation details appropriately remain with project management within the resources and constraints of the project. Instead, this TMP identifies the types of maturation activities that should be performed and, critically, the objective evidence that should be generated to demonstrate achievement of the corresponding TRLs. Projects can then apply these criteria to establish their baseline maturity, identify technology gaps, determine the work required for advancement, and objectively assess whether the targeted TRL has been achieved.

This approach is particularly important when assessing technologies proposed by external organizations or when relying on heritage claims from previous programs. A claimed TRL should not be accepted solely based on a technology developer's assessment. The evidence associated with the claimed readiness level should be examined against the applicable operating characteristics and environments, and the project should independently determine whether the available evidence satisfies its technical baseline. Non-advocate assessments at program initiation and key maturation milestones provide an additional mechanism for maintaining objectivity and avoiding systematic overestimation of technology readiness.

Taken together, these principles provide a consistent framework for maturation across the four strategic propulsion classes. The mission-pull classes provide opportunities to mature technologies against specific, nearer-term applications, while the technology-push classes establish demanding performance targets that can drive advances in technologies with broader future applicability. Intermediate capabilities can be introduced where mission analysis identifies a compelling need. In all cases, the appropriate maturation path is determined not simply by whether a system is classified as low- or high-thrust or low- or high-power, but by the combination of its required operating characteristics, mission demands, and natural and self-induced environments.

2. TECHNOLOGY READINESS FRAMEWORK

Consistent and defensible assessment of technology maturity is foundational to effective program management in space nuclear propulsion. Without a shared understanding of what constitutes meaningful progress, programs risk overstated readiness levels, misallocated resources, and late-stage surprises during system verification and qualification. This TMP therefore adopts the unified TRL advancement criteria specifically developed for space nuclear systems.[3] These criteria reconcile differences across NASA, the Department of Defense (DoD), and the Department of Energy (DOE) guidance documents while explicitly addressing nuclear-unique challenges. Such challenges include the handling of special nuclear materials, the requirement for reactor criticality, radiation effects on materials and instrumentation, management of nuclear waste streams, and the practical need to use surrogates and simulants early in development before transitioning to real fissile materials.

2.1 Core Principles

TRL advancement is not determined by any single factor but by the convergence of several interrelated dimensions. Hardware and integration fidelity must increase progressively, moving from paper studies and basic components toward subsystems and systems that closely approximate the form, fit, and function of the eventual operational article. Environmental fidelity must advance from simplified laboratory conditions to relevant environments that capture the most stressing aspects of the anticipated mission (including combined thermal, hydraulic, radiation, and, for NTP, hot hydrogen propellant effects). Lifetime requirements are always tied to a specific concept of operations (ConOps); any significant change in the ConOps necessitates reassessment and can result in TRL regression. The use of phenomena identification and ranking table (PIRT) activities, which are systematic, expert-driven methodologies commonly employed in nuclear reactor safety, thermal-hydraulics, and complex engineering systems, should be incorporated to identify and prioritize key physical processes, challenges, and knowledge gaps throughout the TRL advancement process. Modeling and simulation (M&S) must be rigorously anchored by test data at every stage, and comprehensive failure modes and effects analysis (FMEA) along with hazards analysis (HA) are mandatory at each gate to demonstrate that no insurmountable issues remain. Independent or non-advocate technical reviews are strongly encouraged to maintain objectivity, particularly given the limited flight heritage in space nuclear systems. Finally, manufacturing readiness levels (MRL) should be considered in parallel, as changes in production processes, supply chains, or materials can themselves cause apparent TRL regression even if development is ongoing.

2.2 TRL Advancement Descriptions

TRL advancement, and the levels of fidelity required to demonstrate it, are summarized in Figure 1 across the scale from TRLs 1 through 9. For TRLs 1 and 2, a physical phenomenon is observed in either the natural environment or a laboratory, and its potential applications are formulated. At TRL 3, the first hardware demonstrations of the application are conducted, serving as analytical and experimental proof-of-concept demonstrations of critical functions and characteristics.

The primary focus of this TMP is on TRLs 4 through 6. These levels in the technology development life cycle present the greatest advancement challenges, as significant unknowns must be discovered and addressed before achieving an operational system at higher TRLs. The framework of this TMP provides projects with clear, evidence-based activities and criteria for prioritizing investments and measuring progress. What follows is a brief description of the work performed to advance to TRLs 4, 5, and 6; more detailed advancement criteria are presented in Section 4.

At TRL 4, individual components are integrated into low-fidelity breadboard subsystems or systems that successfully demonstrate the basic function of the eventual operational system. These breadboard assemblies roughly match the form (overall topography and layout) of the operational system, but the specific components, interconnections, and interfaces remain lowfidelity. Although not absolute criteria for TRL 4, reliability and lifetime of the components are also important metrics to begin quantifying at this point in development.

At TRL 5, subsystems advance to medium-fidelity brassboard units that demonstrate functionality in a relevant environment using representative interfaces. These brassboard assemblies achieve both the function and general form of the eventual operational system. Components, interconnections, and interfaces are of the types expected in flight hardware, though they remain approximate because the final mission and detailed system design are not yet fixed. The physical packaging (fit) is sufficiently representative to show that a viable packaged configuration can be achieved, with any remaining thermal or integration challenges well understood and resolvable through straightforward engineering. The subsystem's reliability and lifetime are also further developed, although these remain as mission-aspirational metrics rather than requirements.

At TRL 6, a high-fidelity engineering development unit (EDU) or prototype is produced that matches the form, fit, and function of the eventual operational system. The choice between an EDU (which may include test-specific accommodations) and a prototype (closer to flight hardware) is determined by project management. The EDU or prototype is tested to address all critical issues associated with the application, including exposure to relevant operational environments (thermal, dynamic, radiation) and operating conditions, as well as demonstrating reliability and lifetime.

Higher TRLs (7–9) shift focus to full system prototypes demonstrated in operational environments, formal qualification testing, and ultimately flight-proven mission operations, with increasing alignment to MRLs. These later stages are beyond the primary scope of this TMP but are supported by the long-lead infrastructure investments outlined in later sections.

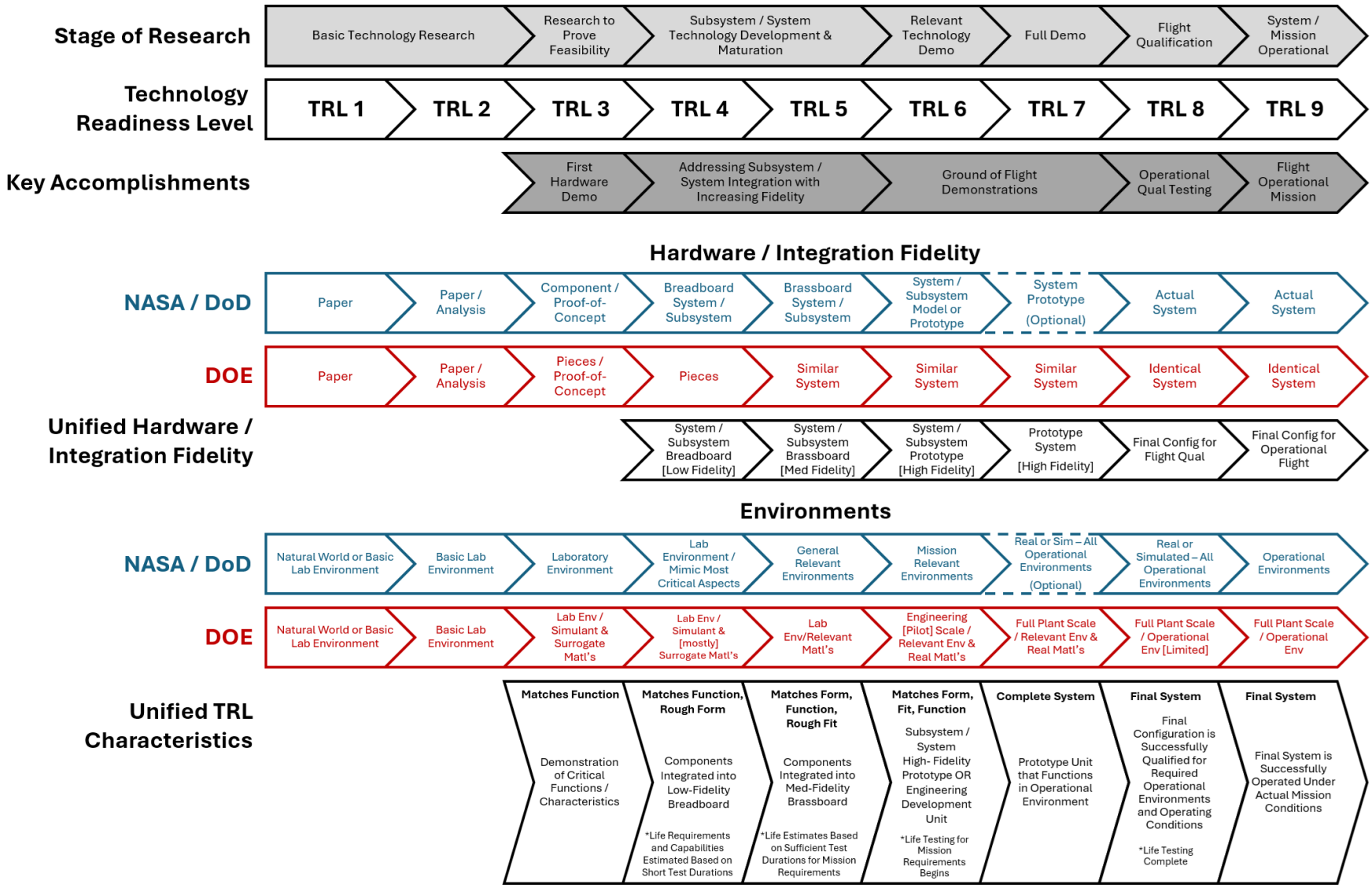

Figure 1. Summary of TRL advancement and the levels of fidelity required to demonstrate such advancement.

3. CURRENT BASELINE AND GAP ANALYSIS

A clear-eyed assessment of the current state of space nuclear propulsion technology is essential for developing a credible maturation plan. This section summarizes the rich but discontinuous heritage of U.S. efforts, provides an element-by-element view of the status and current development activities for space nuclear systems, and discusses the implications for the target system classes described earlier in this plan. The analysis draws upon historical program outcomes, recent independent reviews, and the author's internal element assessments. It highlights both substantial progress and persistent gaps—particularly in integrated testing, statistical materials data, combined-effects quantification, validation of nuclear and multi-physics modeling and simulation tools, and the realization of long-lead test infrastructure—that this TMP is designed to close.[4]

3.1 Summary of Past and Current Activities and Heritage

U.S. investment in space nuclear propulsion spans more than six decades, with periods of intense activity followed by significant gaps that have led to technology regression. For NTP, the foundational Rover and Nuclear Engine for Rocket Vehicle Application (NERVA) programs (1955–1973) conducted extensive ground testing of graphite-based reactors and achieved impressive performance in hot hydrogen flow environments. These efforts demonstrated the basic feasibility of nuclear thermal rockets but were canceled before flight demonstration due to shifting national priorities. Subsequent efforts included the classified Project Timberwind and the follow-on Space Nuclear Thermal Propulsion (SNTP) program in the late 1980s and early 1990s, which explored particle-bed reactor concepts for high-acceleration applications. More recently, the Defense Advanced Research Projects Agency (DARPA)-NASA Demonstration Rocket for Agile Cislunar Operations (DRACO) program advanced modern NTP concepts, focusing on higher-performance fuels and rapid development, though it faced termination prior to flight.

For NEP and related nuclear power systems, the Systems for Nuclear Auxiliary Power (SNAP) program produced the only U.S. in-space fission demonstration with SNAP-10A in 1965. Later efforts such as SP-100 and Project Prometheus (Jupiter Icy Moons Orbiter) advanced higher-power reactor and power conversion technologies but did not reach flight. These programs matured many supporting subsystems but suffered from the same pattern of interrupted development that caused knowledge and capability atrophy.

The current baseline is anchored by SR-1 *Freedom*, the accelerated NEP demonstration mission targeting launch by the end of 2028. SR-1 pairs a HALEU fueled reactor with closed Brayton cycle power conversion and advanced Hall-effect electric thrusters, leveraging existing hardware such as the repurposed Power and Propulsion Element. While this mission will deliver critical early flight heritage and regulatory pathfinding, its minimal pre-flight DDT&E and lack of full integrated ground testing intentionally prioritize speed over comprehensive risk reduction. This creates both an opportunity and a necessity for the TMP to mature technologies beyond the SR-1 configuration.

3.2 Element-by-Element Status

Recent work has been organized across three broad technology maturation categories: cross-cutting disciplines that benefit both NTP and NEP, NTP-specific non-nuclear components (NNC) and integrated systems, and NEP-specific critical technology elements (CTEs) and integrated systems. Overall progress varies significantly. There have been notable successes in conceptual design, component-level testing, reactor EDU testing, increasing fuel manufacturing readiness, and leveraging historical data and experience. However, persistent gaps remain in integrated, relevant-environment demonstration; production-relevant statistical data; combined-effects testing; integrated multi-physics modeling and simulation, and long-lead test infrastructure. These gaps directly influence the ability to achieve the TRL 4–6 advancement criteria outlined in Section 2, particularly the requirements for hardware fidelity, relevant environments, anchored modeling, and comprehensive FMEA/hazards analysis. The following assessment provides a candid, element-by-element view based on current NASA activities, independent reviews, and historical context. It serves as the foundation for the targeted maturation activities described later in this plan.

- **Fuel and Core Materials (FCM)**: Recent NASA space nuclear activities have built upon the substantial Rover/NERVA heritage, initially investigating ceramic-metallic (CERMET) composite fuels before pivoting to ceramic-ceramic (CERCER) composites and then to carbide fuels (both composite and solid-solution variants). For NEP applications, uranium oxide (UO_2)-based fuels suitable for the SR-1 baseline have been advanced; such fuels at lower enrichment levels have been used in terrestrial power plants for decades, but they have yet to be fully tested and qualified at HALEU enrichment levels for operational mission durations and temperatures required in space. Earlier testing and evaluation of uranium nitride (UN)-based fuels for NEP was performed under the SP-100 and Prometheus programs. Moderator materials, particularly beryllium and hydride-based options for NTP, have seen manufacturing and materials quantification progress, as have various coatings for fuel element flow channels and insulators designed to contain high-temperature reactor regions while isolating lower-temperature portions.

  Key successes include high-temperature testing demonstrating initial robustness of fuel concepts, along with some irradiation testing and post-irradiation examination (PIE) of NTP fuel candidates. These results, in part, drove the evolution from CERMET to CERCER to the current carbide-based options. Other successes include full-scale testing of relevant fuel assembly surrogates to launch and space environments and flight production level fuel production development, including the first Nuclear Regulatory Commission (NRC)-licensed fuel facility established in 65 years. Remaining gaps include the development, and eventual qualification of space nuclear fuel manufacturing processes, the need for statistical (A/B-basis) data at full operating conditions, combined-effects testing at mission-relevant conditions, long-duration testing, and development of even higher-temperature materials to support stretch performance goals in both NTP and high-power NEP systems.

- **Materials Test and Evaluation (MTE)**: Standardized protocols have been established for many separate-effects tests; however, comprehensive acquisition of data across the

full operational range of NEP and NTP systems remains incomplete. Key properties—including mechanical (e.g., Young's modulus, yield strength), thermal (e.g., heat transfer coefficients, coefficients of thermal expansion), and nuclear cross-section data—are often temperature-dependent and require quantification at relevant operating conditions. Coordinated national efforts are needed to characterize space nuclear materials, collect, validate, and publish these datasets through established processes. This challenge is particularly pronounced at peak NTP temperatures. Current limitations include scarce combined thermal-hydraulic-radiation-hydrogen exposure materials datasets and a lack of test apparatus capable of simultaneously replicating some or all mission-relevant conditions.

Successes include improved fundamental understanding of degradation mechanisms and the development of specific test capabilities for limited separate-effects work (detailed further under Space Reactor Test Capabilities (SRTC)). Gaps center on the volume and fidelity of data required for credible lifetime and transient predictions, uncertainty quantification in modeling, and assessments of manufacturing variability. These shortfalls directly impact the ability to demonstrate design closure with margin at TRL 5 and beyond and make it challenging to adequately support design, analysis, and modeling activities for NTP and NEP systems.

- **Reactor and Core Components (RCC)**: Multiple reactor architectures—including moderator-block, heat-pipe, and gas-cooled variants—have been explored, with various reference designs developed. Progress includes component and system fabrication and non-nuclear testing. For both NEP and NTP, immediate needs include continued development, road mapping for certification and qualification of reactor classes, and fabrication of individual components and assemblies (e.g., fuel elements, moderator assemblies, fuel bundles, coolant/heat transfer pathways, reflectors, anti-criticality measures, bonding technologies, insulation, and control drum assemblies). These must undergo rigorous separate- and combined-effects testing in relevant non-nuclear and nuclear environments culminating in integrated reactor and propulsion system testing at scale that demonstrates performance, lifetime, and reliability over mission durations.

- **Modeling & Simulation**: Extensive development has been undertaken to advance multi-scale modeling tools that address nuclear, thermal, fluid, and structural physics within the nuclear core, interfacing these high-fidelity models with broader engine system and controls models. M&S platforms leverage established national laboratory-developed workflows, such as the Multiphysics Object-Oriented Simulation Environment (MOOSE) and combined Abaqus-MCNP (Monte Carlo N-particle) framework, as well as NASA-developed propulsion simulation tools like ROCket Engine Transient Simulation (ROCETS) and Numerical Propulsion System Simulation (NPSS). Current efforts focus on expanding these workflows to improve fidelity (e.g., MCNP with unstructured mesh capability) and add new features. These modeling and simulation capabilities are crucial for preliminary design closure and sensitivity analysis. Despite this progress, notable gaps remain: translating data across modeling scales (from micro- to meso- to macro-/system-level), integrating toolsets originally developed for different purposes (such as combining NTP reactor models with power-

balance models from pump-fed liquid rocket engines), achieving full-system uncertainty quantification, validating models against relevant experimental data, and developing tightly coupled mission and vehicle models. The sources of modeling uncertainty also underscore the need for higher-fidelity data and quantification efforts in MTE, RCC, FCM, and Instrumentation & Control (I&C).

- **Radiation & Shielding (RS)**: High-fidelity modeling capabilities exist for some scenarios, but further development is needed for accurate prediction of reactor-induced radiation fields and the resulting requirements for shielding materials. Some shielding materials have been identified and tested, but mass efficiency remains a challenge, and there are significant gaps in relevant irradiation testing and evaluation of shield material combinations. Key needs include optimization of lightweight shielding concepts and integrated radiation environment validation for sensitive hardware, payloads, and (where applicable) crewed missions.

- **Instrumentation & Control**: Terrestrial reactor and space-rated aerospace instrumentation components both separately exist, but they are typically not rated for the high radiation fluxes of NEP or NTP systems while functioning in a flight environment. They are also typically not designed for long-term operation in thermal-vacuum environments without recalibration or replacement. Instrumentation for power systems (NEP) and fluid flow systems (NTP) — such as pressure, temperature, flow meters, and accelerometers — has seen some space-relevant development but requires further hardening against reactor-induced radiation. Substantial work remains to develop a comprehensive suite of instruments for real-time operational monitoring, health assessment, and control. Control systems must also mature, including reactor power output regulation, integrated coolant, power conversion, distribution, and electric thruster operation for NEP and combined reactor/turbopump control (startup, nominal operation, shutdown) for NTP. Control actuators and effectors, such as reactor control drums and motors, must survive launch loads and operate reliably in space.

  Some testing has subjected NTP control drum/motor assemblies to vibrational launch loads with successful post-test actuation. Limited-fidelity hardware-in-the-loop testbeds have been established. Gaps remain in long-duration reliability, autonomous fault response under combined environments, and comprehensive testing of nominal and fault-mode operations.

- **Systems Integration (SI)**: Carefully integrated propulsion system designs and interface definitions are critical for complex nuclear system development. If one subsystem changes without that change properly propagating to a nearby subsystem's design assumptions, the whole system is set back. To mature nuclear technology, interfaces must be identified and values must be set for those interfaces so hardware can mature independently to the point where it is integrated into one overall system. Because system interfaces and configurations were set and controlled, the individual pieces will eventually work together to realize the overall system when assembled.

  Integrated propulsion system designs and interface definitions are more mature for NTP systems, while NEP systems require additional work to fully define power loop,

thruster, and spacecraft interfaces. Historically, there were several integrated systems at various levels of fidelity fabricated and tested during the Rover/NERVA NTP programs and SNAP nuclear electric power and propulsion program of the 1950s-early 1970s. One integrated system was the SNAP 10A that launched and operated in space, which had a reasonably good level of understanding of some of the interfaces. The rocket engine or power conversion cycles of systems presently under consideration may not exactly match those historical examples, but there is significant data to leverage. Interface definitions were also mapped for the DRACO NTP project, and there is ongoing configuration definition work under the SR-1 *Freedom* NEP demonstration effort. The challenges for any system, however, and the reason why one must exercise care in claiming greater maturity than is warranted, is that each system (even a reference design) may be different in terms of the types of hardware being integrated. Small variances in the quantities of power, heat, mass, controls, measurement or the physical footprint of each component or subsystem can have a large net effect on what can be claimed as mature and what cannot. This is also true of the interconnections between components, the environments to which each item is exposed, and even how the integration of components may itself affect the environment. While control and configuration management processes are emerging, they need additional maturation for complex nuclear subsystem integration.

Limited experience exists with full power loops operating in space-like conditions under autonomous control. This represents a critical gap, particularly for complex NEP architectures and tightly coupled NTP reactor/turbopump systems. Additional gaps include the full definition and simulation of launch and operational environments to guide integrated thermal-vacuum, shock, and vibration testing. The development of closed-loop, autonomously operated, fully integrated NTP and NEP propulsion systems remains an open challenge.

A significant gap is the mapping of the varying mission pull criteria to the NTP/NEP technology and capability push. Mission needs must be identified and categorized, which would drive sets of KPPs and performance requirements to which common NTP/NEP technology maturation efforts should be pursued to maximize the applicability of development. Historically, such a wide-survey mapping has not been performed, resulting in past efforts focusing on and limited to point mission designs past space nuclear propulsion development efforts have always been in the pursuit. Establishing this mapping permits progress to continue even as changes in priorities and target missions arise.

- **Space Reactor Test Capabilities**: Existing facilities such as the Nuclear Thermal Rocket Element Environment Simulator (NTREES), Compact Fuel Element Environmental Test (CFEET), and Hot Hydrogen Environmental Atmospheric Test (H^2EAT) support separate-effects and limited non-nuclear combined-effects testing. Research reactors, including the Idaho National Laboratory Transient REActor Test (TREAT) facility and university reactors (MIT, Ohio State), enable limited combined-effects irradiation of materials and components.

Major gaps in SRTC include a dedicated driver-core test reactor capable of long-duration irradiation or combined-effects irradiation at very high temperatures and power densities under representative mission conditions, integrated engine test stands, facilities for long-duration testing of power reactors in simulated space environments, and hot cells for post-irradiation disassembly and inspection. Nuclear fuels and non-fuel materials PIE represents another significant gap, including the hot-cell capacity needed to disassemble and inspect items ranging from in-core test articles to full-scale reactor units and to package irradiated materials for shipment to PIE laboratories. Although many of these capabilities existed during the Rover/NERVA/SNAP era, they have since atrophied. The ad hoc use of limited existing facilities has supported early-stage development but will not be sufficient to advance technologies to TRL 6 and beyond. Establishing full-scale space nuclear propulsion test facilities will require sustained, multiyear development; however, an incremental approach can progressively expand functionality while delivering useful capabilities at intermediate stages.

- **Non-Nuclear Components (NTP-specific)**: Turbopumps, valves, and nozzles benefit from broader rocket propulsion heritage and ongoing development. However, many standard materials in these components are susceptible to rapid degradation under irradiation and must be replaced or qualified. Successes include cold-flow testing that has helped validate modeling techniques. Gaps remain in manufacturing processes, material irradiation effects, hydrogen exposure, full non-nuclear system testing, and scaling to high-thrust performance levels.

- **Power Conversion System (PCS — NEP-specific)**: Brayton cycle systems have been fabricated and tested at low power levels, but no new flight-relevant units have been built and tested in decades. Terrestrial Brayton systems exist but operate far outside space nuclear power conditions. Gaps include scale-up for high-power applications, mass efficiency improvements, high-temperature materials qualification (including fatigue and creep), and exploration of alternatives such as very high-temperature solid-state conversion (supported by related Space Force research).

- **Power Management and Distribution (PMAD — NEP-specific)**: In-space fission power generation, management, and distribution have been demonstrated by the United States only at very low power (SNAP-10A). Components capable of handling the required power levels for both low- and high-power NEP classes do not currently exist in forms qualified for the reactor-induced radiation environment. Architectures must be finalized, as AC versus high-voltage DC (HVDC) distribution approaches drive fundamentally different component needs. Significant testing and qualification in relevant environments are required.

- **Electric Propulsion (EP — NEP-specific)**: Xenon-fed Hall-effect thrusters are at relatively high readiness up to approximately 12.5 kW for low-power applications. Clustering offers a path to higher power, but limited data exist on multi-thruster interactions and performance. Higher-power concepts, such as lithium-fed magnetoplasmadynamic (MPD) thrusters, have demonstrated operation above 100 kW, with potential scalability to 1 MW per unit. Key gaps include power processing units

(which must handle thruster transients and isolate the spacecraft), ground testing challenges for high-power noble-gas thrusters, lifetime and reliability, and overall system integration at scale.

- **Thermal Management (TM — NEP-specific):** For high-power NEP systems, the TM subsystem (primarily radiators and heat rejection loops) can dominate system mass and size. Improvements are needed in radiator panel mass, robustness, heat transfer efficiency, and in-space deployment mechanisms for large structures. Work under the Modular Assembled Radiators for NEP VehicLes (MARVL) effort has advanced in-space servicing, assembly, and manufacturing (ISAM) techniques, identifying both promising approaches and remaining gaps. Integrated nuclear power system and power-thruster testing capabilities also remain limited.

Overall Assessment: Cross-cutting elements and the low-power NEP and NTP classes are generally closer to supporting engineering development, benefiting specifically from SR-1 and DRACO (respectively) and more mature subsystems in general at those scales. In contrast, high-thrust NTP and high-power NEP classes require more substantial maturation to meet performance stretch goals while maintaining reliability and mass efficiency. Closing the identified gaps — particularly in SRTC, combined-effects data, and integration — will be essential to achieving the TRL advancement criteria in Section 2 and enabling the extensible, operationally viable systems envisioned in NSTM-3.

Current and active space nuclear technology maturation activities position the low-power NEP class well for incremental improvement beyond SR-1, with many subsystems already demonstrating relevant performance. Extensive historical ground testing, and recent progress on solid-solution carbide fuels and associated modeling provide a strong starting point for both NTP classes, though high-thrust variants will demand higher power density and I_{sp} performance. The high-power NEP class represents the greatest stretch, offering substantial spillover benefits but requiring focused investment in scale-up and integration. Across all classes, closing SRTC and combined-effects gaps is critical to reducing verification risks and enabling the extensibility emphasized in NSTM-3. This TMP directly targets these through milestone-driven activities.

By building systematically on existing strengths while addressing documented gaps, adherence to this plan minimizes risk and maximizes return on national investment in space nuclear capabilities.

4. TRL ADVANCEMENT MILESTONES FOR NTP AND NEP SYSTEMS

Achieving consistent and defensible technology maturation requires clear criteria for advancement at each TRL. Building on the unified TRL framework in Section 2 and the baseline and gap assessment in Section 3, this section outlines specific, evidence-based milestones for TRL 4, 5, and 6 across cross-cutting, NTP-specific, and NEP-specific elements. NEP-specific elements are informed by the high-power NEP technology maturation plan referenced in Polzin *et al*., "Technology Maturation Plan for High Power Nuclear Electric Propulsion."[5]

The milestones described in this section are purposefully specific and require evidence for compliance. These gates provide clear, actionable targets for investment prioritization and milestone tracking and directly support closure of the gaps identified in Section 3. Projects can tailor the requirements and justify variances (with independent review) while still maintaining rigor. Not all activities have to be undertaken by the specific project of record — data and results obtained from any recent project or activity (such as SR-1 or LR-1 demonstrations) can be used to fulfill TRL advancement criteria, and it is the project's decision as to what level of credit can be granted for these activities.

Note: While the milestones below are specific and actionable, they are generalized for power/thrust levels and architectures. In other words, the "checklist" of required data for the following milestones does not depend on the power/thrust level of the nuclear system. Power and thrust specifics are set by the design/architecture, and it is up to the team performing the development to define what those levels are and to evaluate against the "checklist" to determine where on the TRL scale they fall. It could be that previous work at given power/thrust levels has already advanced the technology to a higher TRL for the specific application, while at a higher power/thrust, the TRL may be lower/undemonstrated.

We begin with an overview of key terminology and advancement principles and requirements that apply across all NTP and NEP systems and subsystems. This discussion is drawn from the unified criteria[3] and source guidance[6,7,8,9,10,11], and it will direct and guide the discussion throughout the balance of this section.

- **Hardware Fidelity**: Advancement to TRL 4 requires breadboard-level articles that demonstrate *function* (basic operation) and a rough match of *form* (topography and layout). Nuclear development at this stage relies on simulants and surrogate materials. TRL 5 is achieved with brassboard-level articles that match both *function* and *form*, and approximate *fit* (packaging and interfaces), using reactor-relevant materials and demonstrating scalable production with real materials. For TRL 6, high-fidelity EDUs or prototypes must demonstrate *form*, *function*, and *fit* of the operational system. For nuclear systems, an engineering or pilot-scale plant is produced and used for reactor testing.

- **Interfaces**: At TRL 4, interfaces are defined but not fully confirmed for mission applications. Testing uses functional equivalents, with evaluation through emulated interfaces via on-hand equipment, simulators, and special-purpose test components to realistically mimic critical operational aspects and transients. TRL 5 requires reasonably realistic supporting elements, including representative harnesses,

connectors, and hardware (such as power supplies and pumps) for testing. At TRL 6, interfaces are integrated at high fidelity, precisely mimicking those of the intended application.

- **Operating Conditions and Environments**: These combined concepts define how hardware is operated (temperatures, flow rates, duration, power levels) and the external conditions it encounters. Testing for TRL advancement must reflect these, differentiating the unique ways in which any-sized NEP or and NTP system should be tested. Understanding operating conditions and environments is essential for effective test and analysis.

  TRL 4 focuses on laboratory environments that mimic the most critical aspects, emphasizing high-risk components and functions. Relevant mission environments should be defined and used to guide laboratory testing, which is mostly separate-effects tests. TRL 5 employs representative materials and conditions in relevant environments, incorporating anticipated mission conditions (such as combined thermal-hydraulic effects, radiation fields, vacuum), although some mission-specific details may remain undefined and full combined-effects testing may not be performed. TRL 6 requires testing in mission-relevant environments, addressing all critical issues for the intended application. Hardware must be exposed to combined operational environments (thermal, dynamic, radiation) and conditions to demonstrate performance, endurance, and safety across all mission phases.

- **Levels of Hardware Integration**: The required hardware fidelity at each TRL also dictates the integration level.
  - Constituent Materials: While materials themselves do not reach TRLs 4, 5, or 6, increasing data on their properties must be collected at each level to support advancement.
  - Components: Components can perform functions and roughly match the intended application's form, but as isolated units, they typically cannot be advanced beyond TRL 4. Examples include nuclear fuel wafers, valves, and discharge cathodes.
  - Subassemblies: Subassemblies integrate components into higher-level units capable of matching function and form, and potentially fit, if interfaces are sufficiently high-fidelity. For example, a turbopump for NTP could advance to TRL 5, but further advancement requires integration with additional components and subassemblies (like a reactor). An electric propulsion thruster subassembly for NEP could reach TRL 5 using lab power supplies and propellant feed hardware. A nuclear fuel element or fuel bundle could advance to TRL 5 through testing in a driver-core reactor that mimics most critical conditions in the final application.
  - Assemblies/Systems: Hardware at this integration level, tested in environments matching the TRL, can reach TRL 6 if constituent hardware and interface fidelity are sufficient. For either an NTP or NEP application, a pilot-scale reactor can be an assembly advanced to TRL 6. The integrated NTP engine would be another assembly/system that could be advanced to TRL 6. For NEP, assembly examples include the electric propulsion element (integrating

thrusters, Power Processing Units, flow controllers) or a full power conversion system, tested in operational environments (matching thermal, vacuum, radiation conditions). Higher integration level assemblies may be achieved by combining multiple NEP elements, with an NEP system being realized once complete end-to-end integration is performed.

- **Lifetime and Mission Capabilities**: Lifetime requirements are always tied to a specific ConOps, which may not be finalized until later in development. This is the main area of divergence between NTP and NEP, as their operational profiles differ. NTP operates for tens of minutes per thruster with several operations per mission, while NEP may run for thousands of hours continuously. Advancement requirements are defined for each.

    - **NEP**: At TRL 4, lifetime and mission capabilities are estimated from short test durations — as a rough rule of thumb, either 5% of expected mission duration or sufficiently long to permit a lifetime estimate (whichever is greater). These tests identify failure modes, but short duration and lower fidelity limit the ability to capture all failure modes. TRL 5 involves longer tests — again, as a rough rule of thumb, about one-eighth of mission duration or sufficiently long to support life estimates using test data and validated analyses (whichever is greater). Higher fidelity enables discovery and assessment of most wear and failure modes. At TRL 6, mission requirements are defined and a long-duration reactor assembly or NEP system life test with high-fidelity hardware begins. It may be possible to separately test some NEP assemblies without a full end-to-end test if the interfaces can be emulated with high fidelity and the operational environments can be properly matched. Completion of such testing for operational readiness is not required until TRL 8. Post-test inspections at each TRL are expected to confirm test data interpretation and gauge the state of the hardware after operation.

    - **NTP**: At TRL 4, testing includes expected ramp rates for startup and shutdown, with a dwell time at nominal operating conditions sufficient for steady state across key parameters (temperatures, pressures, mass loss, pump speeds, etc.). Test articles must endure multiple cycles matching a representative mission. TRL 5 uses higher-fidelity hardware and materials, with combined-effects testing for components, and separate-effects for subassemblies and systems. Hardware is operated to mimic mission application, including realistic ramp rates, full durations at nominal conditions, and operating cycles equal to or greater than mission requirements. At TRL 6, the reactor assembly or NTP system is tested through multiple cycles simulating the full mission duty cycle, including critical off-nominal cases for robustness and control. Post-test inspections at each TRL are expected to confirm test data interpretation and gauge the state of the hardware after operation.

- **Design Closure and Analysis vs. Test**: At TRL 4, design closure is achieved primarily through analytical methods supported by limited, low-fidelity test data and conservative, well-documented assumptions. Testing efforts are concentrated on high-

risk components to demonstrate compliance with performance requirements. Lifetime requirements are formally established and tied to specific applications, with capabilities bounded or extrapolated using simplified models. At TRL 5, design closure is driven mainly by test demonstrations conducted in relevant environments, with analysis serving to interpret and supplement the test results. Testing for a significant fraction of the required lifetime and validated analyses are used to demonstrate both performance and lifetime requirements, ensuring adequate margin. At TRL 6, design closure is based on test results obtained in mission-relevant environments, with analysis confirming margins and broadening coverage across the operational envelope. Where feasible, lifetime should be verified through testing with added margin. Lifetime testing is initiated at TRL 6, but completion may extend to TRL 8, especially for NEP systems that require thousands of hours of operation. In contrast, NTP systems with much shorter operational durations (tens of minutes per thrust maneuver and several hours of aggregate operation per mission) are more likely able to complete an initial full mission duration test at TRL 6, followed by additional full mission duration testing at subsequent TRLs for qualification and certification. If qualification and flight schedules do not allow for comprehensive lifetime testing, testing should be as extensive as possible. Projected full-duration capability can then be based on endurance test data, post-test inspections, and physics-based modeling.

4.1 Nuclear System TRL Milestones

As noted above, nuclear development teams must first determine the power and thrust of a given system then, based on historic advancements, assign a TRL to the specific milestones for that power/thrust system. The following "checklist" of TRL criteria must be adjusted by the development team based on previous work at given power/thrust levels.

4.1.1 Nuclear System TRL 4 Criteria

- Relevant environments are predicted and defined for each component.

- Demonstrate full-scale (correct scale and geometry) breadboard-fidelity reactor component fabrication and integration/assembly using representative materials (e.g., depleted uranium, other surrogates) and fabrication processes.

- Assess the ability of components to properly mate together through demonstration or analysis.

- Collect material properties, relevant failure limits, and uncertainty criteria for newly developed key materials to assess neutronic behavior, chemical compatibility and thermodynamic stability under relevant thermal and hydraulic conditions. Assess degradation mechanisms, including swelling, embrittlement, gas generation and release, and loss of ductility or strength. Begin statistical basis data collection for key material properties.

- Demonstrate manufacturing and assembly of reactor components, including fuel, moderator, insulator, core structural components, reflector assembly, control drums, and internal and spot shields.

- Validate form and basic function in the laboratory and conduct post-test inspection of critical reactor core components (fuel, moderator, insulator, control drums, core structural components, shield materials) under relevant separate effects conditions.
    - Maintain steady-state peak operating conditions for relevant time scales.
    - Withstand start-up and shut-down transients relevant to reference designs.
    - Exposure to relevant irradiation for relevant time scales, with PIE demonstrating basic stability, compatibility, and ability to meet lifetime requirements.
    - [For NTP reactors] Demonstrate hydrogen (non-nuclear) operation at prototypic temperature and pressure for relevant time scales.

- Conduct successful functional testing and post-test inspection of critical components.
    - Test functional control electronics, relays, actuators, and control drum motor and mechanism, including actuation, resolution, and speed.
    - Perform reactor component flow testing, if applicable.

- Demonstrate functionality of I&C sensor components under relevant separate effects conditions.
    - Components include but are not limited to state-of-the-art sensors for detecting temperatures, pressures, and other relevant parameters.

- Complete testing to demonstrate ability to meet lifetime requirements for this TRL, supported by post-test inspection.

- Develop and validate modeling and simulation tools in support of fabrication and testing using available test data.
    - Perform activities to inform TRL 5 and above fabrication, testing plans including relevant environments (e.g., thermal-vacuum (TVAC) conditions, neutron and gamma heating, thermal loads, etc.), and lifetime capability.

- Complete preliminary Reactor FMEA and HA. Use FMEA and HA, along with testing and modeling activities, to quantify reliability for reactor architecture and demonstrate no insurmountable issues.

- Demonstrate component-level functionality for the proposed National Security Presidential Memorandum (NSPM)-20 safety plan (e.g., safety, anti-criticality, etc.).

- Perform modeling and simulation to inform TRL 5 fabrication and testing requirements, including relevant environments (e.g., TVAC conditions, neutron and gamma heating, thermal loads, etc.) and to perform uncertainty quantification (UQ) on models and sources of uncertainty.

4.1.2 Nuclear System TRL 5 Criteria

- Demonstrate full-scale unit cell fabrication and assembly using commercial scale manufacturing processes and prototypic feedstocks.

- Manufacture and assemble a non-enriched unit cell assembly.

- Manufacture and assemble a fueled unit cell assembly (prototypic enrichment).

- Assess manufacturing variability.

- Collect statistical materials data for the full range of operating conditions under separate-effects testing, with additional data gathered under combined-effects testing. Determine which materials require A- or B-basis statistical data and specify data collection methods based on verification needs and feasibility.

- Demonstrate fabrication and assembly of a mockup reactor (non-enriched) using representative components and assembly processes.

- Update expected operational environments and, where necessary, radiation shielding requirements based on TRL 4 activities.

- Demonstration of fueled test articles under relevant combined effects to quantify performance, reliability, and lifetime and conduct post-test inspection.
    - Combined effects testing campaign includes prototypic temperature, pressure, flow rates, power density, thermal vacuum, relevant fluids exposure, cycles, and radiation environmental conditions at a relevant time scale.

- Conduct successful functional testing and post-test inspection of a mockup reactor (non-enriched).
    - Perform cold flow testing to demonstrate structural integrity under vibrational and other loads caused by fluid flow.
    - Conduct environmental (shock, vibration) tests to verify robustness for transportation and launch loads.
    - Incorporate brassboard-fidelity instrumentation and controls system to characterize system response.

- Successfully complete and inspect zero-power/low-power criticality benchmark testing and dynamic performance under transients using a zero-power critical assembly representative of the reactor design, including working fluids, nuclear fuel, and moderator materials.

- Conduct hardware-in-the-loop (HIL) testing of functionality and control algorithms and demonstrate capability to meet lifetime requirements. Perform post-test inspection of I&C components (actuators and sensors) under relevant combined effects conditions.

    - When possible, performed combined effects testing campaigns including prototypic temperature, pressure, and irradiation environments.
    - Test key off-nominal scenarios with the I&C system in the loop.

- Complete testing to demonstrate compliance with performance, lifetime (up to the level for this TRL), and packaging requirements, including margin.

- Demonstrate the ability to meet the proposed NSPM-20 safety plan (e.g., safety, anti-criticality, etc.).

- Using available test data, update and validate models and refine UQ analyses to support fabrication, testing, and lifetime prediction.

- Update FMEA and HA using updated models validated with component- and subsystem-level test data to ensure sufficient reliability.

- Characterize off-nominal operations consistent with major failure modes identified in FMEA.

- Obtain sufficient data to support regulatory approval for the system and any subsystem-level TRL 6 ground testing.

4.1.3 Nuclear System TRL 6 Criteria

- Demonstrate prototypic-scale (pilot plant) reactor fabrication and assembly using commercial-scale manufacturing processes. Prototypes may be subscale compared to the operational use case if data show extensibility to the operational system with validated models and analyses. All critical relevant physics phenomena and operating conditions must be demonstrated within the same combined-effects regime expected of the operational system, through:
    - Zero- and low-power critical testing
    - Cold- and hot-flow high power nuclear operation
    - Expected environmental testing (TVAC, etc.)

- Update the proposed NSPM-20 safety plan (e.g., safety, anti-criticality, etc.) based on test results.

- Complete materials data quantification campaign, acquiring (as determined during TRL 5 activities) A- or B-basis data sets under separate-effects or combined-effects testing.

- Update and validate models developed in support of fabrication, testing, and lifetime prediction using available test data.

- Update FMEA and HA using updated models validated with reactor-level test data to ensure sufficient reliability.

- Demonstrate response to and recovery from off-nominal operations consistent with major failure or safety-critical modes identified in FMEA.

4.2 NTP-Specific Elements

In an NTP system, components outside the reactor are collectively referred to as non-nuclear components (NNC). For the purposes of this TMP, NNC includes the conventional rocket components that, when assembled, constitute the balance of the NTP engine.

4.2.1 NTP-Specific NNC TRL 4 Criteria

- Define the relevant environment for each component (turbopumps, boost pumps, valves, nozzles, instrumentation, controllers, etc.).

- Fabricate full-scale components and assemblies using representative materials and fabrication processes.

- Assess the ability of components to properly mate together in assemblies through demonstration or analysis.

- Collect material properties, relevant failure limits, and uncertainty criteria for newly developed materials or processes.

- Assess critical functional interfaces (e.g., chamber and nozzle, fluid interfaces).

- Conduct irradiation testing and collect material properties for radiation-sensitive materials (e.g., seal and bearing materials, electronics).

- Develop options or alternatives for components that exhibit radiation sensitivity.

- Demonstrate and perform post-test inspection of component performance and functionality in laboratory environments with flight propellant through flow testing (at minimum, cold flow with relevant flow rates and pressures, and separately, exposure to the relevant thermal environments). Combined testing matching both the thermal and hydraulic environments is beneficial but not required for TRL 4.

- Demonstrate component actuation within the nominal performance envelope.

- Operate at anticipated steady-state temperature, pressure, and flow consistent with the reference mission ConOps.

- Withstand anticipated start-up and shut-down transients relevant to reference designs.

- Map turbopump performance with parameter sweeps to demonstrate stability, ramp rate, and minimum throttle level consistent with the ConOps.

- Demonstrate acceptable sealing performance of components, including radiation-sensitive seal materials, and quantify leakage rates.

- Quantify the electromagnetic interference (EMI) and electromagnetic capability (EMC) environments for high-power electrical components.

- Complete testing and modeling to demonstrate the ability to meet lifetime requirements for this TRL.

- Complete preliminary FMEA and HA. FMEA and HA, together with testing and modeling activities, quantify reliability and demonstrate no insurmountable issues.

- Validate models for analytical predictions of pump and turbine maps, valve actuation resolution and speed, and nozzle heat transfer.

- Use modeling and simulation to inform TRL 5 and above fabrication and testing requirements, including relevant environments (e.g., TVAC, neutron and gamma heating, thermal, etc.).

4.2.2 NTP-Specific NNC TRL 5 Criteria

- Fabricate full-scale assemblies (correct scale and geometry) using flight-like materials and fabrication processes.

- Integrate components into assemblies, demonstrating and assessing critical interfaces.

- Assess manufacturing variability.

- Demonstrate nominal and transient assembly performance and functionality in relevant combined environments (including irradiation, if applicable) with flight propellant, followed by post-test inspection.
    - Confirm anticipated functionality with components receiving commands from the control system.
    - Perform thermal conditioning and validate pressure losses, leakage, and temperatures of lines and ducts.
    - Conduct flow testing on lines, ducts, and valves with sensitivity testing.
    - Operate at anticipated steady-state temperature, pressure, and flow consistent with the ConOps (including duration and restarts).
    - Map turbopump performance with parameter sweeps to demonstrate stability and throttling consistent with the ConOps.
    - Conduct performance testing (e.g., flow rate, actuation resolution, speed, and leakage) of assembled valves.

- Perform environmental testing (cold flow, vibration, acoustic, shock, thermal cycling) and post-test inspection of NNC subsystem integrated with mock-up reactor.

- Validate models for analytical predictions of temperature, pressure, and flow rate at assembly interfaces.

- Complete testing and modeling to demonstrate the ability to meet lifetime requirements for this TRL.

- Update FMEA and HA using updated models validated with component- and subsystem-level test data to ensure sufficient reliability.

- Characterize off-nominal operations consistent with major failure modes identified in FMEA.

4.2.3 NTP-Specific NNC TRL 6 Criteria

There are no NNC-specific TRL 6 criteria. At TRL 6, an NTP system EDU or prototype is assembled, and all testing, modeling, and analysis of NNC components and subsystems are performed at the integrated system level.

4.3 NEP-Specific Elements

The NEP-specific elements (PCS subsystem, PMAD subsystem, electric propulsion subsystem [EPS], and TM subsystem) must undergo similar activities as given in this section to advance their TRL.

4.3.1 NEP-Specific TRL 4 Criteria

- Demonstrate relevant-scale (correct order of magnitude scale and geometry) breadboard-fidelity component fabrication and integration/assembly using representative materials and fabrication processes.

- Establish operational system design closure primarily through analysis anchored by limited breadboard-fidelity testing focused on the highest-risk components, performed to demonstrate compliance with performance requirements. Conduct testing at nominal and expected transient conditions.

- Conduct irradiation testing and collect material properties for radiation-sensitive materials (e.g., seal and bearing materials, wires, cables, electronics).

- Develop options and alternatives for components exhibiting radiation sensitivity.

- Formalize lifetime requirements and link them to the intended application. Bound or extrapolate life capabilities using simplified models. Complete testing and modeling to demonstrate the ability to meet lifetime requirements for this TRL and analyze potential event-based and wear-based failure mechanisms. Perform additional modeling to

validate thermal, structural, and electrical margins, and quantify plasma plume extent and interactions.

- Validate models for analytical predictions of operation and performance.

- Use modeling and simulation to inform fabrication and testing requirements for TRL 5 and above, including relevant environments.

- Complete preliminary FMEA and HA. Quantify reliability through FMEA, HA, testing, and modeling activities, demonstrating no insurmountable issues.

- Simulate electrical interfaces using laboratory supplies and representative routing/harnessing, with input and output filters to demonstrate stability and mimic realistic interfaces.
    - For thrusters, demonstrate the ability to handle dynamic current–voltage transients during ignition/gas breakdown in addition to steady-state operation. Ensure electronics emulators are capable of realistic emulation of the most critical transients, not just steady-state operation.

4.3.2 NEP-Specific TRL 5 Criteria

- Fabricate full-scale assemblies (correct scale and geometry) using flight-like materials and fabrication processes.

- Integrate components into assemblies, demonstrating and assessing critical interfaces.

- Assess manufacturing variability.

- Demonstrate and inspect assembly performance and functionality under nominal and transient conditions in relevant combined environments (including irradiation, if applicable).

- Integrate each subsystem or critical technology element at brassboard-fidelity.

- Test in relevant environments, including representative aspects, operating conditions, and important or design-controlling environmental conditions based on the anticipated mission ConOps.
    - Establish design closure primarily through test demonstrations and post-test inspections and evaluations, supplementing and interpreting results with analyses.
    - If the anticipated operational system involves multiple parallel assemblies, include testing to quantify any assembly-to-assembly effects (steady-state and transient electrical, thermal, magnetic, plasma effects, and interactions).

- Demonstrate design closure with margin on both performance and lifetime through a combination of testing (lasting a significant fraction of the required lifetime, as specified for this TRL) and validated modeling and analysis.

- Update models, correlate and validate with test campaigns, demonstrating closure with positive margin (structural, vibrational, thermal, etc.) and quantifying plasma plume extent. If the anticipated operational system involves multiple parallel assemblies, ensure models account for this aspect.

- Verify compliance with interface requirements, including any updated requirements.

- Update FMEA and HA using updated models, validated with component- and subsystem-level test data to ensure sufficient reliability.

- Characterize off-nominal operations consistent with major failure modes identified in FMEA.

4.3.3 NEP-Specific TRL 6 Criteria

- Accomplish verification and validation (V&V) on almost all aspects of the design and operation through testing, using analysis primarily to extend and interpret test results where direct verification is impractical.

- Operate a fully-integrated NEP subsystem or subsystems as a prototype/ EDU ground test article (which could later be integrated into a flight system), demonstrating:
    - Manufacture, assemble, and integrate the subject subsystems.
    - Demonstrate system operation, including autonomous control, for nominal conditions during all mission phases and under expected transients and off-nominal operations consistent with major failure modes identified in FMEA.
    - Demonstrate design closure with margin on both performance and lifetime through a combination of testing with required margin based on the uncertainty associated with dominant and controlling failure mechanisms (up to the amount of testing required for lifetime demonstration at this TRL). Ensure performance and lifetime measurements and predictions align with validated modeling and analysis, supported by post-test inspection.
    - If the anticipated operational system involves multiple parallel assemblies, demonstrate simultaneous operation of those subsystems.

- Verify compliance with interface requirements.

4.4 Integrated System

4.4.1 Integrated System TRL 4 Criteria

- Develop and enhance a medium-fidelity integrated nuclear propulsion system model that connects primary components, uses representative fluid and material properties, and incorporates relevant interconnection physics. Demonstrate operational system design closure primarily through analysis. Select and approve a multiphysics software environment for TRL 5+ usage. Ensure the model tracks nominal performance and temporal changes in the system (includes, at a minimum, a pseudo-transient model with time derivatives of key parameters). Validate the model using all existing data and TRL 4 experimental results.
    - Inform required component and subsystem-level KPPs and ongoing FMEA and HA.
    - Define relevant environments using the system model and inform test needs for TRL 5 testing.
    - [NTP] Calculate power balance for nominal (with uncertainty limits) and highest-risk off-nominal scenarios.
    - [NEP] Calculate power distribution and conversion for nominal (with uncertainty limits) and highest-risk off-nominal scenarios.
    - Use separate effects hardware testing results to improve model input accuracy and quantify system performance metrics with material- and system-level response.
    - Incorporate results from controller testing, dynamic/turbomachinery start-up and shutdown, and control drum mechanism testing as inputs to transient feedback and system-level convergence models.
    - Account for element-level uncertainties and component tolerance stack-up in the system model to quantify uncertainty in KPP predictions. Include identified operational margin allocations for each system subcomponent in uncertainty analysis.
    - Include a model plan with a development path to deeper integration with component-level models.

- Define interfaces between each subsystem.

- System and Vehicle Risk and Failure Assessment
    - Conduct preliminary FMEA and HA for each critical technology, classify the highest risk areas, and identify failure mechanisms and effects to inform the technology development plan.
    - Identify design-basis accident scenarios using TRL 4 test data to mature TRL 5 combined effects testing efforts.
    - Predict consequences of catastrophic failure during transport, launch, and nominal operation through worst-case analysis. Develop an NSPM-20 compliance plan to identify appropriate launch risk mitigation strategies.

- Mission Model
    - Demonstrate closure of the selected mission ConOps with system performance, spacecraft sizing, and relevant margins.
    - Include analyses of mission abort scenarios and uncertainty propagation in the model, quantifying the impact on meeting mission requirements based on system KPPs.
    - Spacecraft Model
    - Ensure the spacecraft model is consistent with the selected ConOps and includes a propellant budget.
    - Calculate and document component-level contributions to the total system mass based on system KPPs and selected mission criteria using a master equipment list (MEL).
    - Assess error quantification with mass growth allowance estimates and mass uncertainty analysis.
    - Mature propellant management models (Cryogenic Fluid Management [CFM], high-pressure and/or supercritical gas, liquid metal propellant, as appropriate).
        - Develop tank sizing algorithms that include mission-specific propellant supply, propellant feeding, and testing of the selected thermal management/heat rejection cycle.
        - Determine thermal management/heat rejection requirements based on system size and induced environments.
        - Quantify applicable margins to failure and propellant longevity for the mission/ConOps.

- Environment Model
    - Establish general ConOps.
    - Predict radiation shielding and mitigation requirements to inform critical equipment dose estimates for both flight operations and ground testing. Use inputs from the natural space radiation environment and reactor-induced radiation through mission ConOps.
    - Define environments for ground and in-space operation (e.g., launch loads, charging and oxidizing environment, micrometeoroids and orbital debris (MMOD), thermal albedo, solar insulation, etc.).

4.4.2 Integrated System TRL 5 Criteria

- Develop and enhance a high-fidelity integrated nuclear propulsion system model using the software framework selected during TRL 4. Connect primary components, represent fluid properties, and interconnect multiphysics. Track nominal performance and temporal changes in the system (integrated time-variant transient model). Validate the model using all existing data and TRL 5 experimental results.
    - Predict KPPs with quantified uncertainties informed by testing.
    - Enhance FMEA development using results from the integrated multiphysics model.
    - Use combined effects hardware testing results to improve model input accuracy and quantify demonstration system performance metrics with material- and integrated system-level response.

    - Predict TRL 6 system performance at fast time scales using integrated multiphysics system simulations.
    - Quantify uncertainty across the entire operational condition range, providing sufficient confidence regarding margins to failure for all system subcomponents and ensuring successful technology maturation.

- Risk and Failure Assessment Model
    - Improve FMEA to reflect the integrated testing approach.
    - Identify design-basis accident scenarios for TRL 6 testing, informed by TRL 5 testing.
    - Expand worst-case analysis to include all off-nominal transients prior to full-system testing. Improve the NSPM-20 compliance plan for launch risk mitigation strategies.
    - Assess adequacy of instrumentation and control system to detect, isolate, and control anticipated off-nominal and failure modes predicted by FMEA.
    - Perform preliminary probabilistic risk assessment (PRA) using inputs from failure and hazards analyses and the fully integrated system model.

- Mission, Spacecraft, and System Model Integration
    - Update subsystem interfaces as required based on TRL 5 activities.
    - Complete the development of a preliminary modeling approach that integrates all major spacecraft and nuclear subsystems into the specified ConOps architecture.
    - Demonstrate through system-level analysis that the demonstration meets or exceeds KPPs and mission reliability requirements.

- Spacecraft Model
    - Refine component-level mass allocations to represent any needed modifications to the MEL.
    - Provide traceability to the mission architecture model, including mass uncertainty to assess margin of error.
    - Mature propellant management models.
        - Improve tank development with combined effects testing of the candidate tank using flight propellant in a prototypic heat flux and radiation environment.
        - Verify the thermal management modeling approach separately with heat transfer testing under expected operating conditions and environments.
        - Quantify and analyze applicable margins to failure to inform system-level impact.

- Environment Model
    - Refine mission ConOps as required for the expected target mission.
    - Improve environment models to account for the key spacecraft components, expected system configuration, and operating conditions.

4.4.3 Integrated System TRL 6 Criteria

- Accomplish V&V on nearly all aspects of the design and operation through testing, using analysis primarily to extend and interpret test results where direct verification remains impractical.

- Operate a fully integrated NTP engine or NEP system as a prototype/EDU ground or flight test article:
    - Demonstrate manufacture, assembly, and integration of a reactor and other subsystems.
    - Conduct system zero- and low-power critical testing.
    - Conduct system electromagnetic (EM) field testing.
    - Demonstrate system operation, including autonomous control, under nominal conditions during all mission phases and under expected transients and off-nominal operations consistent with major failure/fault modes identified in FMEA.
    - Demonstrate lifetime (up to the required level for this TRL), with required margin based on uncertainty associated with dominant and controlling failure mechanisms, supported by full post-test inspection and PIE to validate lifetime predictions.

- Test system operation (mechanism actuation, etc.) during and/or after exposure to induced and natural environmental loads (TVAC, irradiation, etc.).

- Use high-fidelity integrated models and integrated test data to demonstrate system and mission closure for the full operational envelope and required lifetime, with margin, including operation in environments not accessible through prototype/EDU ground or flight testing.

4.5 Test Capabilities

The development and availability of test capabilities are essential for supporting test and evaluation activities under the environments and conditions required for TRL progression. M&S plays a critical role in defining the types of test facilities, measurements, and data needed, directly informing the test strategy. Accurate test data reduces modeling uncertainties and errors, enabling validated modeling tools to decrease reliance on extensive high-temperature, full-power, combined-effects, and integrated system tests for qualification and certification. Polzin et al. "Integrated Development Strategy for Space Nuclear Propulsion" provides additional discussion on test and evaluation needs and gaps. The following section outlines the testing capabilities needed for TRLs 4 to 6.[12]

4.5.1 Test Capabilities TRL 4

At TRL 4, separate-effects testing is conducted in a combination of non-nuclear and nuclear test facilities that can match prototypic conditions. These conditions vary depending on whether an NTP or NEP system is being considered. The most important conditions to match are determined through modeling & simulation activities and using prior testing results. Non-nuclear

testing should match temperatures (peak values and ramp rates) and potentially flow parameters (type of gas, flow rates, pressures). Upgrades may be necessary to achieve these test conditions. Additionally, irradiation testing is performed in reactor facilities, which can match some conditions (again dependent on NTP or NEP), such as temperature, flux, fluence, dpa (displacements per atom), and flow conditions. Irradiation testing should be conducted not only on candidate nuclear fuel materials and components, but also on other critical materials and components that will be part of the core design.

4.5.2 Test Capabilities TRL 5

At TRL 5, activities advance to combined-effects testing, particularly for critical materials and components that will be part of the core design. This testing involves simultaneously matching most or all conditions a nuclear reactor fuel element or fuel bundle will experience during operation (conditions dependent upon whether the application is NTP or NEP). Testing should be performed in a driver-core reactor (such as the Nuclear Furnace (NF-1) from the early 1970s) capable of matching these conditions. If such a system does not exist, construction and commissioning of suitable test hardware must begin early enough to support this testing. If not all conditions can be matched in one test, the developer must justify why TRL advancement is still achieved and the project can disposition such justifications. Activities at this stage include generating statistical data for materials subjected to combined-effects for the intended application, as well as data supporting safety analyses and regulatory compliance documentation for a full nuclear system ground or flight test (including eventual qualification and certification activities).

4.5.3 Test Capabilities TRL 6

At TRL 6, additional combined-effects testing is performed with test articles representing higher levels of integration. These test and evaluation capabilities support not only TRL 6 advancement, but also qualification and certification activities for the nuclear system beyond TRL 6. For all items in this section, planning must begin early to ensure these capabilities are available when a project is ready for TRL 6 demonstration, testing, and evaluation.

For either an NTP or NEP system, a pilot-scale/prototype nuclear reactor can be tested as a stand-alone subsystem. A test facility must be available to operate the reactor under appropriate environmental conditions (such as TVAC).

If integrated NTP engine ground testing is necessary (likely when advancing these systems to TRLs 7-9), an engine test facility is required. Integrated testing can include the reactor and NNC elements, as well as additional components such as the propellant tank, engine and reactor controllers, and propellant management hardware beyond what is needed to feed propellant to the engine. The facility must allow operation of the integrated engine through a full mission duty cycle, similar to ground testing of chemical propulsion systems for launch vehicles, to fully demonstrate overall performance and mission capability. Such test facilities should employ exhaust capture and scrubbing (either real-time or post-test).

For NEP systems, various integration levels can be tested as part of TRL 6 advancement activities, ranging from stand-alone subsystems to fully integrated NEP systems. Ground testing facilities must match the thermal-vacuum environment for all integrated subsystems. For thrusters,

maintaining a vacuum environment while expending propellant is critical for collecting accurate, flight-applicable data, and this becomes more challenging as propellant flow rates increase in higher power systems. If a subsystem is affected by the induced irradiation environment, it is highly desirable to test it integrated with the reactor in one facility. If it can be shown that a subsystem is far enough from the reactor to not be significantly affected by the induced irradiation fields, those elements may be operated in separate thermal-vacuum facilities, provided the cabling and connections between subsystems (or emulated interfaces) are representative of the actual system's form and fit.

Finally, to fully quantify performance, reliability, and lifetime, subsystems must undergo disassembly and post-test inspection and evaluation, including PIE on irradiated components and materials. Disassembly is complex for irradiated components and must be carried out in a specialized hot cell. Few, if any, hot cells are large enough to support disassembly and inspection of an irradiated reactor, so it may be advantageous to perform disassembly at the test site to reduce transportation risks.

5. CONCLUSION

The maturation of nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) technologies requires a disciplined, evidence-based approach that progressively increases hardware, integration, environmental, and operational fidelity. The framework presented in this Technical Memorandum establishes objective criteria for advancing nuclear, propulsion, power, and integrated-system technologies for in-space applications through Technology Readiness Levels (TRLs) 4, 5, and 6. Although the maturation process is broadly common across NTP and NEP systems, the evidence required for advancement must be tailored to the operating conditions, environments, lifetime, interfaces, and concept of operations of the intended application. Consequently, a technology demonstrated at a given TRL for one application should not be assumed to possess the same maturity for a more demanding mission without additional supporting evidence.

Advancement through these readiness levels requires deliberate progression from component-level separate-effects testing to relevant-environment combined-effects testing and, ultimately, high-fidelity subsystem and integrated-system demonstrations. Test results must be used to identify failure mechanisms, establish performance and lifetime margins, quantify uncertainties, and anchor predictive modeling and simulation. Representative interfaces, configuration control, post-test inspection, post-irradiation examination, and increasingly mature failure modes and effects analyses and hazards analyses are also necessary to demonstrate that technical risks are understood and that no unresolved issue prevents continued development. Where all relevant conditions cannot be reproduced in a single test, projects should establish a documented technical basis showing how complementary testing and validated analysis collectively provide the evidence required for TRL advancement.

The infrastructure needed to generate this evidence is itself a critical element of technology maturation. Specialized nuclear and non-nuclear test facilities, combined-effects capabilities, driver-core reactors, integrated test environments, hot cells, and post-test examination capabilities can require years to design, authorize, construct, and commission. Planning and investment must therefore begin well before the associated project reaches TRL 5 or 6. Early development of these capabilities is essential to prevent infrastructure availability from becoming the controlling constraint on technology advancement, qualification, or certification.

Applied consistently, this framework provides a systematic basis for establishing credible technology readiness, prioritizing investments, and reducing technical and programmatic risk. It also preserves flexibility for projects to tailor their maturation strategies and to credit applicable evidence from prior or parallel efforts, provided that the evidence is relevant to the intended system and mission. The resulting body of test data, validated models, demonstrated hardware, and enabling infrastructure can provide confidence in safety, performance, reliability, lifetime, and extensibility needed to support future operational NTP and NEP systems.

6. APPENDIX

Table 1. Indicative NTP key performance parameters for various missions.

Mission	Hydrogen NTP (cislunar)	NTP GEO Tug	3-LNV* (for Earth Departure)	NTP Human Mars	NTP High Energy Missions
Additional Ground Rules	Reusable	Reusable	Multi-launch	Opposition-class, 720 - 850 day	Solid Core, 360 - 400 day round trip, or >200 mt cargo
Propellant	LH_2	LH_2	LH_2	LH_2	LH_2
Vehicle Thrust [klb$_f$]	25 – 75	5 – 12	50 – 75	45 – 75 (125 stretch goal)	400 – 750
Per Engine Thrust [klb$_f$]	25 – 75	5 – 12	50 – 75	15 – 75	100 – 250+
Steady-state I_{sp} [s]	900+	900+	850+	875 – 900+	900+ – 1100
Mass [kg] (Engine + Shield)	2500	< 3500	2500 – 3500	< 6000	15000
Total Operation Time [min]	40 – 90 per mission	20 – 100 per mission	30 – 120	30 – 240	100 – 300
Single Operation Max Duration [min]	30	35	30 – 40	30 – 60	30 – 60
Number of Starts	5 – 20 (100 stretch goal)	5 per mission, reusable	1 – 2	5 – 8	5 – 20
In-Space Life [yr]	2 – 7	2 – 5	0 – 3 (latter if used at destination)	3 – 5	1 – 10 reusable

* 3-LNV : 3-Launch Vehicle

Table 2. Indicative NEP key performance parameters for various missions.

Mission	Surface Power (as NEP Demonstration)	Flagship Science Propulsion	Mars Cargo	Human Mars Transit	Fast Mars
Power Supply Specific Mass [kg/kW$_e$]	~120 @ 40 kW – 75 @ 100 kW	120 – 180 @ 10 kW$_e$ ~85 – 120 @ 20 kW$_e$, ~120 @ 40 kW$_e$ for Starship launch	TBD	14 – 24	TBD
Power [kW$_e$]	10 – 40 (initial) 100+ (long term)	10 – 45 (initial) 100 (long term)	750 – 2000	1500 – 4000	≥ 6000
I_{sp} [s]	N/A	4000 – 6000	2500 – 6000	2500 – 6000	5000 – 6000+
Thrust Time (hr)	N/A	Up to 85,000	25,000	27,000	≥ 17,500
Total Operation Time [hr]	2500 – 25,000	87,000 – 160,000	30,000	32,000	≥ 17,500
In-Space Life [yr]	0 – 3	10 – 18	2 – 3, longer for reuse	3 – 4, longer for reuse	2 – 4, longer for reuse
Propellant Throughput [kg]	N/A	2,000 – 10,000	TBD	100,000 – 300,000	TBD

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