Milestones for Demonstrating Technology Readiness Level Advancement in Nuclear Electric Propulsion Systems

IEPC-2025-004

Presented at the 39th International Electric Propulsion Conference
Imperial College • London, England, UK
14-19 September 2025

Kurt A. Polzin[a]
NASA Marshall Space Flight Center, Huntsville, AL, 35812, USA

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

Natalia A. Tenenbaum
Apex Alignment Consulting, Bothell, WA, 98021, USA

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

Andrew L. Presby[b]
NASA Glenn Research Center, Cleveland, OH, 44135, USA

A unified set of TRL criteria for space nuclear systems, including nuclear electric propulsion (NEP). are presented, reconciling definitions and differences found in NASA, U.S. Department of Defense (DoD*), and U.S. Department of Energy (DOE) guidance documents. The intent is to provide a common framework for consistent TRL assessment across government agencies and industry partners, thereby reducing ambiguity, limiting overstatement of readiness, and supporting programmatic decisions for advancing space nuclear technologies toward flight readiness. Detailed definitions are provided for each level from TRL 1 through TRL 9, with accompanying explanations and examples on the intent and evidence that should be presented to demonstrate advancement. Definitions and explanations emphasize hardware fidelity, software maturity, integration level, environments, lifetime considerations, and validation against analytical predictions and modeling and simulation results.

I. Introduction

Over the course of the past six decades, NASA made multiple large investments in the nuclear electric propulsion (NEP) arena. Major examples include the Systems for Nuclear Auxiliary Power (SNAP) program of the late 1950s-early 1970s,[1,2] the Space Exploration Initiative (SEI) effort that was conducted in parallel with the Space reactor Prototype (SP-100) effort to develop a 100 kW-class NEP system in the early to mid-1990s,[3-6] and the Jupiter Icy Moons Orbiter (JIMO)/Project Prometheus effort in the early 2000s that targeted a 100 kW_e-class system.[7,8] While the SNAP-10A reactor in-space demonstration unit flew in 1965, none of the cited efforts resulted in an operational in-space nuclear power / NEP system. Each of these programs matured the NEP-supporting technologies to varying degrees, but technology readiness diminishes over time when those technologies are not actively employed. Two recent,

---

[a] Chief Engineer, Space Nuclear Propulsion (SNP) Program
[b] Deputy SNP Program Manager
[*] U.S. Department of War (DoW) [as of 5 Sept 2025]

independent reviews[9,10] found that lack of either successful technology transfer or a cessation of sustained development efforts resulted in the regression of technology readiness level (TRL) for all the major NEP power subsystems, most notably but not exclusively those for high-power multi-MW_e systems.

Electric propulsion (EP) systems at power levels of 10 kW_e and below have been broadly accepted for commercial, DOD, and space science applications. They enjoy high levels of sustained investment, especially over the past 40 years, and maintain high TRL due to their continued operational use.[11] However, in-space nuclear power generation systems in the 10-100 kW_e regime have not received the same levels of investment and thus lag the propulsion system in technology readiness. The readiness of all subsystems is even lower for electric thrusters and nuclear power generation systems capable of operating at 100 kW_e to multi-MW_e. Significant technology maturation and development are needed to increase the TRL and eventually result in operational NEP systems that are mass-efficient and long-lived.

The odds of achieving these goals increases through an open, non-advocate assessment of the current TRLs for various NEP components, subsystems, and systems and an understanding of what is required to demonstrate that development efforts are increasing those levels. However, a recent independent review[9] focusing on space nuclear propulsion (SNP) provided the following conclusions to demonstrate that this simple-sounding proposition was not so easy to fulfill in practice. Specifically, the report found that:

- The TRL values found in the literature are often overestimated by advocates of the technologies.
- An assessment of the baseline TRLs and "estimation of requirements and resources required for advancement have been consistent issues for NEP."

This paper represents the first step in addressing these issues by outlining a set of criteria for achieving each TRL that can be used by NASA's Space Nuclear Propulsion (SNP) program. This includes providing more detail as to the intent of the criteria for each TRL beyond the definitions found in reference documents. It is the goal of this activity to write criteria not just for use by NASA, but by any organization developing and attempting to field space nuclear systems. Consequently, this paper attempts to unify the TRL definitions of the three most relevant U.S. Government organizations – NASA, the Department of Defense (DoD), and the Department of Energy (DOE). While the general *intent* of the TRL definitions for all three agencies is similar, unification of these criteria is challenging because each organization uses slightly different terminology. In addition, the DOE criteria concerning nuclear reactor TRLs has an additional challenge due to the availably of special nuclear materials, the specific nuclear waste streams produced by operation of a reactor, and the need to achieve criticality in a reactor limiting the ability to build 'subscale' fissioning reactors below a certain size.

Discussed in Section II are ground rules and assumptions that should be employed when quantifying TRL and determining if advancement has occurred. In general, these hold for any technology, not just space nuclear systems. In Section III are a set of TRL definitions, unified across NASA, DoD, and DOE requirements, for each level (from 1 to 9). Accompanying these definitions are short descriptions for each level to expound upon the requirements and provide insight into their intent. This includes noting where the three agencies employ different terms and providing a path for understanding and reconciling these in the context of space nuclear system development.

II. Quantifying TRL: Ground Rules and Assumptions

Inherent in the demonstration of each TRL are various factors.

- **Hardware fidelity & integration**: TRL depends on how close the test article is to the operational system (scale, form/fit/function, subsystem integration).
- **Environment fidelity**: Higher TRLs require testing in environments closer to operational (ambient: vacuum, albedo, solar, GCR; induced: reactor fluxes, onboard thermal).

- **Lifetime linkage to mission / concept-of-operations (ConOps)**: Required lifetime comes from ConOps. If ConOps changes, TRL should be reassessed against the new requirements. This may result in a regression of TRL.
- **TRL advancement without a specific mission**: Possible up to a point if hardware fidelity, relevant environmental and life testing, and validated modeling/simulation exist.
- **TRL regression if development stops**: Workforce / facilities / knowledge base atrophy over time, so TRL must be reassessed when restarting development.
- **TRL can regress even if development or production is continuous**: As a specific example, any system involving electronics can experience TRL regression owing to "parts obsolescence."
- **Disagreements over a technology's TRL**: A common occurrence between technologists and project offices. Independent determinations / non-advocate review should be employed to resolve these issues, with such assessments occurring prior to the start of any new program and at every major advancement milestone.

III. Unified TRL Definitions

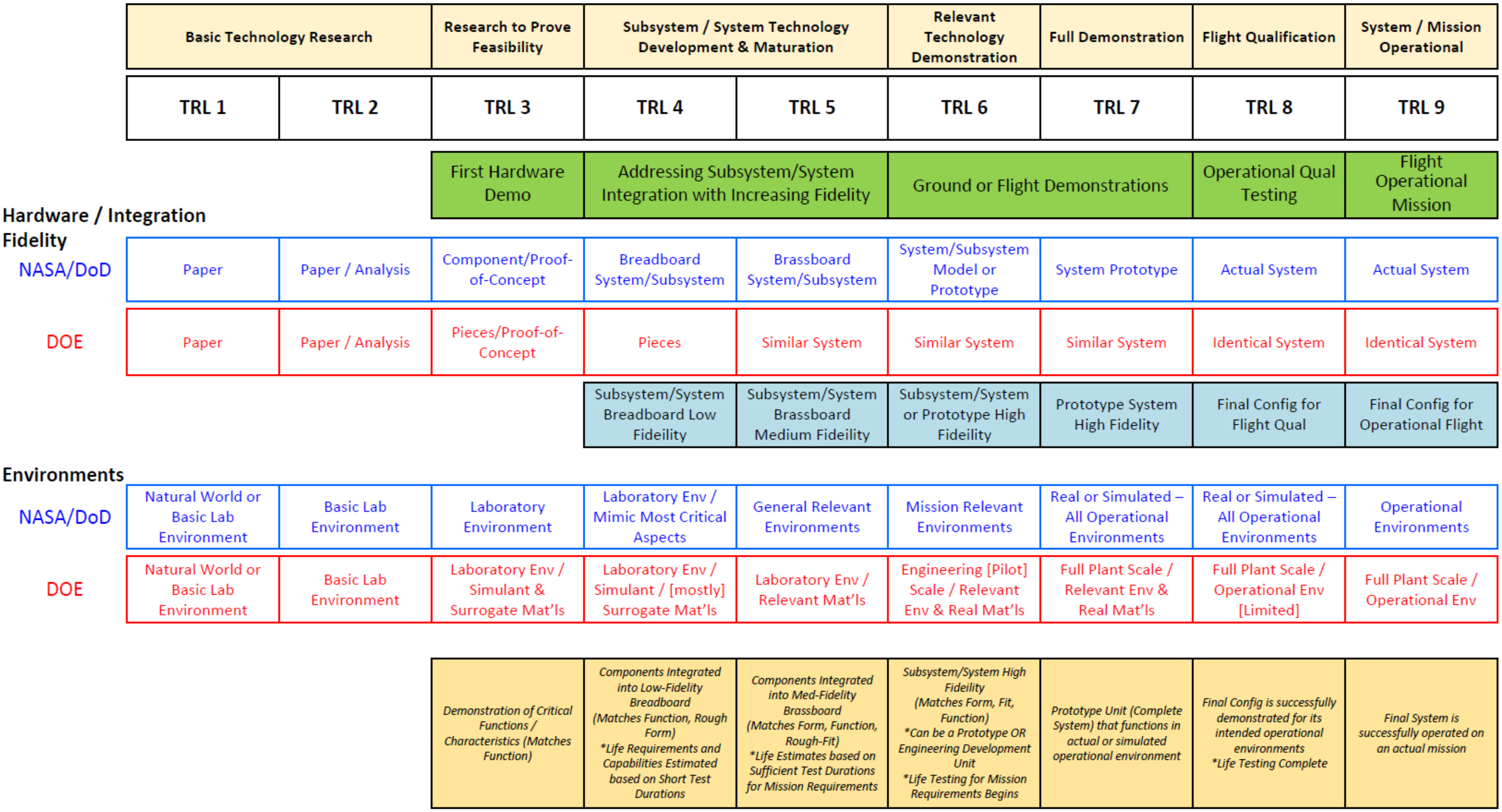
In this section we step through each TRL from 1 to 9, providing a short explanation of what should be accomplished when a level is completed. The definitions, descriptions, success criteria, and environments for each TRL are unified across the definitions from NASA,[12] the DoD,[13] and the DOE.[14] (The U.S. Government Accountability Office also has a document containing TRL definitions,[15] but these match the definitions from the DoD documentation.)

For this, we attempt to unify the definitions to the greatest extent possible while not losing specific requirements that are important but may not be found in the documents of all three agencies. Where the various government agencies use different terms, those differences are explained. If the differing terms convey the same intent, we select one term for use. If they convey different intents, we have generally opted to retain the more stringent requirements. Finally, if the terms in the documents of different agencies convey different meanings or requirements, we attempt to retain each meaning to not lose critical TRL advancement requirements. Note that after publication of this paper, the authors fully expect to receive additional suggestions and critiques on the definitions contained herein – getting all of the nuances of predicting technology readiness is a constantly evolving process and helpful inputs will be incorporated into a future publication updating the requirements.

A graphical representation of advancement requirements, needed hardware and integrated system fidelity, test environments, and a description of the types of activities undertaken at each TRL is presented in Figure 1. This figure is a useful visualization of the progression in TRL, and how the definitions of different agencies (especially the DOE compared to NASA and the DoD). In the discussion that follows, this figure is useful for providing clarity and guidance on the progression and intent of each TRL.

It is important to recognize that the TRL metric does not address manufacturing changes, where supply chain, production equipment or tooling changes can result in failures and an apparent regression of TRL. The DoD guide[16] on manufacturing readiness levels (MRL) shows how those the advancement of manufacturing readiness aligns with TRL. While the present paper is generally focused on TRL and not MRL, it is important to note that to produce[‡] many copies of a qualified, high TRL system, the unit-to-unit manufacturing variability must be within allowable tolerances to ensure that each copy produced will meet the performance and lifetime requirements. To that end, there are a few locations in this paper where we do highlight the need to address various manufacturing issues.

[‡] "Production" refers to manufacturing, assembly and test. Manufacturing is producing the parts or components, assembly is putting them together, and test is verifying manufacturing and assembly were performed correctly. Unit-to-unit variation can be introduced in any of these phases thru variation of equipment, tooling, and personnel, but also in lot-to-lot material property variations. A good production process qualification program will demonstrate that performance and lifetime have margin under the expected unit-to-unit variations owing to these various factors.



	Basic Technology Research		Research to Prove Feasibility	Subsystem / System Technology Development & Maturation		Relevant Technology Demonstration	Full Demonstration	Flight Qualification	System / Mission Operational
	TRL 1	**TRL 2**	**TRL 3**	**TRL 4**	**TRL 5**	**TRL 6**	**TRL 7**	**TRL 8**	**TRL 9**
			First Hardware Demo	Addressing Subsystem/System Integration with Increasing Fidelity		Ground or Flight Demonstrations		Operational Qual Testing	Flight Operational Mission
Hardware / Integration Fidelity									
NASA/DoD	Paper	Paper / Analysis	Component/Proof-of-Concept	Breadboard System/Subsystem	Brassboard System/Subsystem	System/Subsystem Model or Prototype	System Prototype	Actual System	Actual System
DOE	Paper	Paper / Analysis	Pieces/Proof-of-Concept	Pieces	Similar System	Similar System	Similar System	Identical System	Identical System
				Subsystem/System Breadboard Low Fideility	Subsystem/System Brassboard Medium Fideility	Subsystem/System or Prototype High Fideility	Prototype System High Fidelity	Final Config for Flight Qual	Final Config for Operational Flight
Environments									
NASA/DoD	Natural World or Basic Lab Environment	Basic Lab Environment	Laboratory Environment	Laboratory Env / Mimic Most Critical Aspects	General Relevant Environments	Mission Relevant Environments	Real or Simulated – All Operational Environments	Real or Simulated – All Operational Environments	Operational Environments
DOE	Natural World or Basic Lab Environment	Basic Lab Environment	Laboratory Env / Simulant & Surrogate Mat'ls	Laboratory Env / Simulant / [mostly] Surrogate Mat'ls	Laboratory Env / Relevant Mat'ls	Engineering [Pilot] Scale / Relevant Env & Real Mat'ls	Full Plant Scale / Relevant Env & Real Mat'ls	Full Plant Scale / Operational Env [Limited]	Full Plant Scale / Operational Env
			Demonstration of Critical Functions / Characteristics (Matches Function)	*Components Integrated into Low-Fidelity Breadboard (Matches Function, Rough Form)* **Life Requirements and Capabilities Estimated based on Short Test Durations*	*Components Integrated into Med-Fidelity Brassboard (Matches Form, Function, Rough-Fit)* **Life Estimates based on Sufficient Test Durations for Mission Requirements*	*Subsystem/System High Fideility (Matches Form, Fit, Function)* **Can be a Prototype OR Engineering Development Unit* **Life Testing for Mission Requirements Begins*	*Prototype Unit (Complete System) that functions in actual or simulated operational environment*	*Final Config is successfully demonstrated for its intended operational environments* **Life Testing Complete*	*Final System is successfully operated on an actual mission*

Figure 1: Graphical representation of the NASA/DoD/DOE TRL progression.

As a last note, TRL requirements are often not simple and straightforward. In some instances, mission requirements cannot be fully demonstrated (e.g., endurance for long missions) . In those instances, it is critical to meet, the *intent* of the requirements. For example, hardware testing accompanied by inspection and approved analysis may be sufficient. It is not sufficient for technologists/advocates to claim the intent has been met without proof that satisfies an independent technical authority and/or non-advocate review panel.

III.A TRL 1

The path for technology development starts at TRL 1, where a physical phenomenon is observed in the natural environment or in a laboratory. These observations fall into the realm of pure scientific research – Chadwick's discovery of the neutron in 1932 is one such example of TRL 1. The technology concept and/or application of the physical phenomenon has not yet been invented or 'reduced to practice' at this stage, but early observations have resulted in a basic understanding of the governing physical principles. Peer-reviewed scientific publications in the literature are the accepted primary means of demonstrating TRL 1. The entry for TRL 1, unified across NASA, DoD, and DOE definitions, is provided in Table 1.

Table 1: Unified entry for TRL 1.

TRL 1 – Basic Principles Observed	
Element	**Unified Entry**
Unified Definition	Basic principles observed and reported.
Unified Description	**Hardware**: Scientific observation of natural or laboratory phenomena results in a basic understanding of governing principles that could be translated into applied research and development. Basic properties of materials, processes, or physical principles defined. **Software**: Scientific research and applied R&D starts to be translated into proof of concept for algorithms or computational approaches. Basic properties of software concepts identified.
Unified Success Criteria / Supporting Information	**Success Criteria**: Publication of research results showing basic properties and principles. Identification of technology applications. **Added Software-Specific Criteria**: Documentation of mathematical formulations, initial algorithms, and feasibility studies of computational approaches.
Typical Environment	**Hardware**: Descriptive studies, basic lab research, scientific journals. **Software**: Conceptual exploration; applied mathematical analysis and simulation.

III.B TRL 2

At TRL 2, additional studies have been conducted to further understand the observed physical phenomenon and its potential application. Based on those studies, a useful technology concept and/or application has been formulated with accompanying analytical studies showing feasibility. This moves the technology from the realm of pure scientific research into the realm of applied research where the concept is 'reduced to practice' and its basic elements, functions, and benefits are more than simple conjecture. Experimental proof is not required but very basic tests may have been performed. The primary means of demonstrating a technology is at TRL 2 is through peer-reviewed scientific publications in the literature reporting additional physical observations and providing the results of analytical, physics-based speculative studies on the proposed concept and/or application. The entry for TRL 2, unified across NASA, DoD, and DOE definitions, is provided in Table 2.

Table 2: Unified entry for TRL 2.

TRL 2 – Technology Concept Formulated	
Element	**Unified Entry**
Unified Definition	Technology concept and/or application formulated.
Unified Description	**Hardware**: Applied research initiated, practical applications identified but speculative. No experimental proof or validation. **Software**: Applied research begins with practical applications identified. Basic software concept formulated, speculative without full validation.
Unified Success Criteria / Supporting Information	**Success Criteria**: Publications or analytical studies describe application area. Technology concept defined and possible approaches identified. **Added Software-Specific Criteria**: Basic principles coded; experiments performed with synthetic data. Analytic studies, small code units, and papers comparing competing options.
Typical Environment	**Hardware**: Analytical studies, paper studies. **Software**: Early algorithmic development, analytic studies, experiments with synthetic data.
Notes on Term Alignment	NASA and DoD emphasize early application identification, DOE highlights analytical study. Harmonized as "concept/application formulated." Speculative, not validated.

III.C TRL 3

Translation of the technology into dedicated hardware is required is for the first time at TRL 3, where proof-of-concept experiments and accompanying analytical studies are performed in the laboratory environment to demonstrate the critical functions and the key characteristics identified in TRL 2. This work validates analytical predictions and understanding of the basic science and underlying physics, verifying feasibility of the application by showing that the intended performance can be achieved and that no obvious limitations on performance or lifetime preclude further development (i.e., no insurmountable issues present or major scientific breakthroughs required beyond this point that would prevent realization of an operational system). In terms of demonstrating *form*, *fit*, and *function*, efforts at TRL 3 are primarily concerned with demonstrating critical/major functions. For hardware, structural and thermal behavior are bounded by analysis and simple tests while electrical functions are confirmed at the circuit or bench level. For software, proof-of-concept components are developed and validated, with critical properties demonstrated through analytical studies, simulations, and limited laboratory testing of algorithms on partially simulated data sets.

Nuclear processes require a certain level of enriched nuclear fuel to achieve criticality. To avoid requiring this level of maturity, nuclear development at TRL 3 emphasizes manufacturing and testing of 'pieces' of hardware (defined as pieces of the final application (reactor)) instead of manufacturing components (items that will function independently). This is typically accomplished by utilizing surrogate materials and simulants in proof-of-concept studies in lieu of actual nuclear materials or actual nuclear wastes. However, since such evaluations are inherently non-nuclear in nature, they must be accompanied by significant modeling and simulation of the nuclear processes to demonstrate that the pieces will function as required when surrogate materials are replaced by actual nuclear materials and integrated in a reactor.

Additional information that should be generated while achieving TRL 3 include but may not be limited to studies that indicate components will function properly when integrated into a system (especially as noted for nuclear systems), preliminary estimates of system performance characteristics supported by available experimental data and analytical studies, the establishment of preliminary system performance metrics (key performance parameters) to guide development towards ends that fulfill specific needs, and the identification of general risk areas and mitigation strategies. The entry for TRL 3, unified across NASA, DoD, and DOE definitions, is provided in Table 3.

Table 3: Unified entry for TRL 3.

TRL 3 – Proof of Concept	
Element	**Unified Entry**
Unified Definition	Analytical and experimental proof-of-concept demonstrated for critical functions or characteristics.
Unified Description	**Hardware**: Active R&D begins. Critical function proof-of-concept demonstrated by analytical and laboratory experiments. Key components tested to verify concept works (nuclear components tested on simulants). **Software**: Development and validation on non-integrated software components. Proof-of-concept of critical properties demonstrated through analytical studies, simulations, or lab tests.
Unified Success Criteria / Supporting Information	**Success Criteria**: Results from lab experiments and analytical models document feasibility of critical functions. Predictions validated against limited test data. Modeling/simulation may complement experiments. Preliminary estimates of system performance, including lifetime, and the establishment of preliminary system performance metrics. **Added Software-Specific Criteria**: Testing of code modules using non-integrated components and partially representative data. Supporting information includes results that validate critical properties (including cybersecurity) with documentation of comparisons between benchmark tests and predictions.
Typical Environment	**Hardware**: Lab bench experiments, analytical modeling, experiments with simulants (nuclear). **Software**: Non-integrated modules, modeling tools, surrogate processors, with potential limited integration into research environments.
Notes on Term Alignment	NASA, DoD, and DOE highlight "analytical and experimental proof-of-concept"; DOE adds "modeling/simulation may complement experiments" to the Success Criteria / Supporting Information.

III.D TRL 4

At TRL 4, components are integrated into breadboard subsystems/systems. These are subsystems/systems that meet the *function* of the eventual operational system, but the types of components and interconnections are low-fidelity. Such systems only roughly match the *form* of the operational system, aligning with the topography but lacking fidelity in the components, interconnects, and interfaces. However, even at this fidelity the breadboard subsystems/systems tested in the laboratory environment must address and demonstrate the most critical aspects of the technology. Examples of breadboard-fidelity subsystems and interfaces would be a simplified laboratory arrangement where a test unit was powered by oversized, non-flight-like lab supplies of where the apparatus was water cooled using an external, industrial-scale chiller. Care must be taken, not to underestimate environmental issues at TRL 4 or TRL 5 – there should be no insurmountable issues discovered that will prevent realization of an operational system, and estimates should be made to demonstrate that the testing results are consistent with an operational implementation. Finally, an initial hazards analysis and an evaluation of failure modes and their effects should be completed to ensure that there are no major surprises later in development and to guide future development, testing, and analysis to reduce overall risk in successfully fielding and operating a system.

At this level, operational system design closure is demonstrated primarily through analysis that is anchored by limited, low-fidelity test data. Testing is typically focused on the highest-risk components and is performed to demonstrate compliance with performance requirements. Lifetime requirements are estimated and life capabilities are bounded or extrapolated using simplified models.

Specific examples of the types of testing and analyses to support advancement to TRL 4 may include structural modeling demonstrating closure with positive margin, anchored by static or proof load testing; analyses of the structure under dynamic loading to ensure adequacy of the design; thermal modeling demonstrating closure with margin under worst-case hot and cold conditions, anchored by laboratory test data; and extrapolation of thermal soak-back and hot-spot behavior (to the extent these can be performed without a finalized flight configuration), providing confidence that performance and lifetime margins are achievable. For nuclear systems, non-nuclear testing (separate effects testing) is performed to assess chemical compatibility and thermodynamic stability of various materials under relevant thermal and hydraulic conditions, while irradiation testing and post irradiation examination are completed on critical reactor components showing operational margin (supported by modeling predictions) for the expected duration of an operational mission. Electrical closure is demonstrated through stable operation of subsystems/systems using laboratory supplies and representative routing/harnessing, with input and output filters to demonstrate stability with more realistic interfaces. For plasma thrusters in particular, demonstrating the ability to handle dynamic current–voltage transients during ignition / gas breakdown is as critical as demonstrated operation at steady-state. Consequently, electronics emulators (e.g., power supplies that mimic the performance of a power processing unit (PPU)) must be capable of not just steady-state operation but also realistic emulation of the most critical transients. Software closure is achieved through early integration of control or diagnostic code with prototype modules integrated into lab-based, stand-alone breadboard-fidelity subsystems with partial emulation of interfaces and the use of representative data sets.

Definitions in the NASA, DoD, and DOE requirements all include ‘component and/or breadboard/system validation’, but it is clear from reading the accompanying descriptions in the documentation that the intent of TRL 4 is to demonstrate the operation of components joined together in subsystems/systems. Consequently, we have omitted the ‘components’ portion of the definition in the unified entry for TRL 4, provided in Table 4.

Table 4: Unified entry for TRL 4.

TRL 4 – Breadboard Validation in Laboratory Environment	
Element	**Unified Entry**
Unified Definition	Breadboard validation in laboratory environment.
Unified Description	**Hardware**: Low-fidelity breadboard of components integrated to demonstrate basic subsystem/system functionality and critical functionality in lab environment. Could include mix of on-hand equipment, simulator hardware, and special purpose test components. Analyses anchored to or extrapolated from test data and a comprehensive hazards analysis and failure modes & effects analysis show compliance to performance and lifetime requirements. Components not yet advanced enough for relevant environment. **Software**: Basic components integrated to demonstrate functionality. Architecture development initiated, relevant environments defined, and performance predicted. Stand-alone modules/subsystems brought together in lab environment. Early emulation of interfaces and limited functional validation performed.
Unified Success Criteria / Supporting Information	**Success Criteria**: Experimental evidence of subsystem performance at lab scale. Documentation of approach to validate interfaces and subsystem functions. **Added Software-Specific Criteria**: Prototype modules integrated and tested with simulated inputs/outputs. Evidence of functioning logical/data interfaces. Documentation of integration approach and initial interface-level verification for interoperability, reliability, maintainability, scalability, and cybersecurity.
Typical Environment	**Hardware**: Laboratory breadboard or bench-top setup with non-prototypical components. **Software**: Lab-based stand-alone integration platform with partial emulation of interfaces, limited simulations of full-scale problems, representative data sets.
Notes on Term Alignment	NASA and DoD both use "low-fidelity breadboard," which has been shortened to "breadboard" in the unified definition. DOE emphasizes "mix of simulator hardware and special-purpose components." Unified under lab-scale.

III.E TRL 5

At TRL 5, subsystems/systems advance to medium-fidelity brassboard units that demonstrate functionality in a relevant environment with representative interfaces. These integrated components meet the *function* and the *form* of the eventual operational system. The components, interconnects, and interfaces for the system generally match the types that will be found in the operational system, but they will only be an approximate match because the operational mission and system design are not yet fixed at this point. The *fit* of this unit (that is, the packaging of all the components into a subsystem/system) only needs to match the eventual operational system well enough to show that final packaging is achievable.

The relevant environment is a step up from the laboratory environment in TRL 4, in that it includes more aspects of an expected operational environment. Since the operational mission may not be fully-defined until TRL 6, there are some details of the environment that will not be captured in TRL 5 testing. For example, it is known that a flight design will be subjected to dynamic loads on launch, but a launch vehicle may not yet be selected so the specific dynamic loading profile is not yet known. Nuclear testing starts using real fissile materials, with irradiation testing undertaken for TRL 5 advancement yielding actual waste products.

At this stage, design closure is established primarily through test demonstrations in relevant environments, with analysis used to supplement and interpret the results. Using a combination of testing (lasting a "significant" fraction of the required lifetime) and *validated* analyses, the design must close with margin on both performance and lifetime requirements, demonstrating that it is fundamentally viable and leaving only the completion of straightforward engineering to meet the *fit* of the eventual operational system (e.g., final sizing, added redundancy) and planned testing activities. An updated hazard analysis and failure modes & effects analysis should reflect testing results, updated environmental impacts and material or manufacturing information.

There are several specific examples of the types of tests and analyses that would support advancement to TRL 5. These include structural closure demonstrated by models with positive margins correlated to preliminary dynamic test campaigns (modal, sine sweep, partial shock/vibration tests) and thermal closure of models anchored by more extensive thermal-vac or equivalent testing than at TRL 4 that show thermal margin at worst-case hot and cold extremes. Ancillary, non-flight-like cooling systems are minimized since the brassboard is closer to the form and fit of an operational system, and thermal soak-back and hot-spot behaviors are exercised to quantify their effects on performance and lifetime margins. Electrical closure is demonstrated by stable operation through representative harnessing, connectors, and bus-like emulation or inclusion of realistic power supplies and PPUs in testing, with data confirming acceptable steady-state and

Table 5: Unified entry for TRL 5.

TRL 5 – Brassboard Validation in Relevant Environment	
Element	**Unified Entry**
Unified Definition	Brassboard validation in relevant environment.
Unified Description	**Hardware**: Brassboard validation in relevant environment, integrated with reasonably realistic supporting and interfacing elements. Test demonstrations in relevant environments, supported by analysis, show compliance to performance and lifetime requirements with margin. Hazard Analysis and failure modes & effects analysis completed and used to guide future testing. DOE defines "near-prototypical system" (laboratory scale, similar to the final application in almost all respects). **Software**: Integrated software components tested in relevant environment. Interfaces with hardware/software subsystems validated. Early versions of full system functionality represented.
Unified Success Criteria / Supporting Information	**Success Criteria**: Documented test results demonstrate brassboard performance in relevant environment. Evidence system functions under realistic conditions. Performance predictions made for subsequent phases. **Added Software-Specific Criteria**: Prototype integrated software executed on realistic problems with relevant data sets. Integration with hardware/software demonstrated. Verification of data, logical, and security interfaces. Documentation of architecture, requirements (throughput, scalability, reliability), and environments. Software under configuration management. Components identified for future development.
Typical Environment	**Hardware**: Relevant environment test facilities, representative test rigs. **Software**: Simulated operational environment with realistic inputs; partial integration into operational systems for interface/end-to-end testing.
Notes on Term Alignment	DOE emphasizes "near-prototypical / similar system." DoD term "high-fidelity breadboard" taken as equivalent to NASA term "brassboard"

transient behavior across the operational envelope. Initial circuit and electrical component stress analysis is performed on high risk components and evaluated for failure modes and effects. Software closure is demonstrated using brassboard hardware that is partially integrated into operational systems for interface and end-to-end testing, running software in relevant physical and computational environments with realistic inputs to demonstrate full system functionality including closed-loop control, data handling, and fault management. Lifetime estimates are established through models with stronger anchoring to relevant-environment data and longer-duration testing, and while some extrapolation remains, it is supported by a more complete physics-based understanding of the wear and life-limiting failure mechanisms which have been validated during shorter duration testing.

For nuclear systems, plant-scale components are fabricated, demonstrating the capability to produce hardware at scale. Critical reactor subassemblies at laboratory scale are produced to match the final application in almost all respects, moving closer to the use of real materials and away from the use of surrogates in as many components as possible (e.g., depleted or natural uranium in non-nuclear test articles, enriched uranium in components undergoing irradiation testing). These are tested under a range of operating conditions, with the testing environments shifting more towards those favoring combined thermal, hydraulic, and irradiation conditions at the approximate levels expected in an operational system. While test durations may still be somewhat limited at this stage, to the extent possible those tests should be used to validate lifetime predictions and safety functions.

At TRL 5, the brassboard provides evidence that the subsystem/system can operate with representative interfaces in a relevant environment, confirming that the design closes with margin and is ready to advance into final design engineering. where the 'fit' of the unit will match that of the eventual operational system. The entry for TRL 5, unified across NASA, DoD, and DOE definitions, is provided in Table 5.

Corresponding to TRL 5 is MRL 5, defined as "capability to produce prototype components in a production relevant environment." At this point the processes are in place to make small numbers of components using "prototype materials, tooling and test equipment," which supports TRL 6 development efforts, using the types of equipment that would be used in full-scale production. However, the processes and procedures for full scale production have not yet been completely developed.

III.F TRL 6

At TRL 6, a high-fidelity engineering development unit (EDU) or prototype is produced match the *form*, *fit*, and *function* of the eventual operational system. (Requiring either an EDU or prototype allows program management some flexibility in the type of system tested.) A mission application has been selected for the operational system, permitting the definition of a real mission ConOps and the derivation of the associated full set of performance and lifetime requirements as well as the expected environments for the operational mission. An EDU may also be used at the subsystem level, with certain design decisions incorporated to simplify ground test and evaluation without losing the critical aspects of the test unit. A prototype is much closer to an initial flight demonstration unit in that it could support either ground test and evaluation or, with minor modifications, an actual flight demonstration. An EDU or a prototype are tested to address all critical issues associated with the intended application. These include tests that expose the hardware to the relevant environments for the specific operational mission (thermal, dynamic, radiation) and testing that demonstrates and validates the understanding of system scaling, endurance, failure mode responses, and reliability.

Design closure is demonstrated primarily through test results in relevant environments, with analysis used to confirm margins and extend coverage across the full operational envelope. In many programs, the prototype unit fabricated at TRL 6 is proto-flight hardware fabricated to match the overall operational flight system and capable of a flight demonstration without additional design cycles. An operational mission is defined at TRL 6 and is used to set requirements such as lifetime. Hardware and test environments at TRL 6 are of sufficient fidelity to permit the start of full lifetime verification through testing, which should start at TRL 6 but may not be complete until TRL 8. Where practical, this should involve verification by test of lifetime plus margin. In cases where there will not be sufficient time between this stage of development and the qualification and flight of the operational system, lifetime should be tested to the greatest extent possible with the full duration capability projected using available endurance test data, post-test inspection, and physics-based modeling. Rigorous use of the failure modes and effects analysis should be made to ensure that these efforts address all known reasonable causes for system failure.

For nuclear systems, an engineering scale/'pilot scale' plant is produced and used for testing of the nuclear reactor. At this scale, the system can demonstrate all critical aspects of operation, including performance, endurance, and safety in the expected operational environments. Examples of this include the X-10 graphite reactor at Oak Ridge that demonstrated plutonium production on a small scale during the Manhattan project or the reactors produced for the Rover and NERVA programs, which were up to full-scale but incorporated non-flight-like design features, especially with respect to radiation shielding.

In an NEP system, the various critical technology elements/subsystems (reactor, power conversion , power management & distribution, EP, and primary heat rejection) can still be tested independently at TRL 6, so long as the interfaces are well-understood and implemented at high fidelity to precisely mimic the expected interfaces of the integrated system. In a nuclear thermal propulsion (NTP), the reactor can be tested as a subsystem (engineering or 'pilot scale' plant) at TRL 6 as long as the interfaces between the reactor and the rest of the nuclear thermal rocket engine (NTRE) components are properly emulated. However, unless the nuclear heat source can be properly emulated the overall NTRE can only be tested at TRL 6 fidelity when a real reactor is integrated with the turbopumps, valves, an expansion nozzle, and the associated lines and ducting that assemble to produce a full engine.

Table 6: Unified entry for TRL 6.

TRL 6 – System/Subsystem Model or Prototype Demonstration in Relevant Environment	
Element	**Unified Entry**
Unified Definition	System/subsystem model or prototype demonstrated in relevant environment.
Unified Description	**Hardware**: Representative engineering development unit or prototype demonstrated in relevant environment. Prototype design form and fit sufficient to translate to flight with only simple/known adjustments. Testing includes demonstration of all critical aspects – performance, endurance, safety, environments, system failure mode response, maintainability, etc. Very limited acceptance by analysis **Software**: Engineering-scale software prototype (near desired configuration in performance, logical/data/security interfaces) demonstrated in relevant environment. Partial functionality integrated and tested with realistic data.
Unified Success Criteria / Supporting Information	**Success Criteria**: Demonstration shows subsystem/system performance consistent with analytical predictions. Data used to refine predictive models. Documentation of performance limits and corrective actions. **Added Software-Specific Criteria**: Test reports show integrated functionality under realistic loads. Evidence of reliability, maintainability, and cybersecurity validation. Initial documentation of sustainment needs.
Typical Environment	**Hardware**: Relevant engineering test facility, pilot-scale rigs, or nuclear test loop. **Software**: Lab or pilot-scale testbed integrated with hardware/software, realistic data sets, near-realistic scenarios.
Notes on Term Alignment	NASA "high-fidelity prototype of the system/subsystem"; DoD "representative model/prototype"; DOE "engineering/pilot-scale demonstration." Harmonized as prototype demonstration at system/subsystem level.

For hardware development, TRL 6 is the level where verification and validation (V&V) on almost all aspects of the design and operation can be accomplished through test, with very little acceptance by analysis. Operational mission requirements and environments are defined, making it possible to perform testing in all the relevant environments that are expected to be the most stringent and stressing. The TRL 6 prototype system could perform a flight demonstration mission, but a flight is not required at TRL 6. If such a flight is undertaken, it differs from a flight demonstration at TRL 7 in that the TRL 6 demonstration does not require a full range of operational demonstrations (full environments and/or endurance) – analyses can be employed to show that these unmet requirements would be met by the prototype system. For software, components are integrated into engineering/prototype hardware that is near the desired configuration in performance and integration. Software functionality is demonstrated through testing performed in relevant computational environments with realistic data sets, showing operability on near-realistic mission scenarios. The entry for TRL 6, unified across NASA, DoD, and DOE definitions, is provided in Table 6.

Corresponding to TRL 6 is MRL 6, defined as "Capability to produce a prototype system or subsystem in a production relevant environment." This is a step up from MRL 5, moving from prototype component manufacturing to production of an integrated prototype system. The manufactured products and test performance of a prototype system or systems have been compared to target objectives. An initial assessment of build processes has been performed to identify all critical and/or high risk processes (prior to fabricating qualification hardware for TRL 8 efforts). This is to ensure that the qualification hardware will be fabricated with equipment and tooling that is consistent with the expected production requirements.

III.G TRL 7

At TRL 7, a full high-fidelity system prototype is produced and used to demonstrate that the unit functions in all operational mission environments. Such testing can be conducted in the actual operating environment (such as when a launch vehicle flies for the first time, experiencing all the combined operational environments in ways that cannot be simulated) or it may be tested under simulated conditions precisely matching those expected for the operational mission. If a system prototype of sufficient fidelity and durability for flight was produced for TRL 6, that design could also be used for a TRL 7 ground or flight demonstration. The difference between a TRL 6 and TRL 7 demonstration is the latter's requirement to perform in all the expected operational mission environments (though even for TRL 7 the prototype system may be restricted or limited in operational time, which could limit the ability to demonstrate by test the overall lifetime required for the operational mission). Software at TRL 7 is operating on fully-integrated hardware components and is capable of full system control. The software can operate the prototype hardware during all phases of a ground or flight demonstration with limited user inputs and intervention. The entry for TRL 7, unified across NASA, DoD, and DOE definitions, is provided in Table 7.

Corresponding to TRL 7 is MRLs 7 and 8. MRL 7 is defined as "Capability to produce systems, subsystems, or components in a production representative environment." This is where the production hardware that fulfills the needs and goals found in TRL 6/MRL 6 is procured to support production of the qualification unit and eventual flight units. MRL 8 is "Pilot line capability demonstrated; Ready to begin Low Rate Initial Production." At this point, the proper application-specific production hardware has been received and an initial Pilot production line is completed to support low rate production of qualification-model hardware.

Table 7: Unified entry for TRL 7.

TRL 7 – System Prototype Demonstration in Operational Environment	
Element	**Unified Entry**
Unified Definition	System prototype fully demonstrated in operational environment.
Unified Description	**Hardware**: Full-scale system prototype (essentially flight hardware) demonstrated in the real or complete simulated operational environment (e.g., thermal, vacuum/pressure, dynamics, radiation). Includes integration of performance, safety, and maintainability features. DOE emphasizes "nuclear cold commissioning" — testing nuclear systems with non-radioactive materials to verify integration and readiness before hot commissioning – which might be appropriate for commissioning of a terrestrial nuclear plant (and may be acceptable for a certain level of ground demonstration), but it is expected that TRL 7 for a space nuclear prototype system will involve hot nuclear reactor operation. **Software**: Integrated software system prototype demonstrated in operational environment. Documentation, training, and sustainment planning near completion.
Unified Success Criteria / Supporting Information	**Success Criteria**: Test performance documented in operational environment. Reliability and maintainability assessed. Corrective actions tracked/resolved. Cold commissioning complete for nuclear applications. **Added Software-Specific Criteria**: Test results confirm integrated functionality and performance. Defect tracking active. Verification of scalability, cybersecurity, and interoperability. Documentation nearly complete.
Typical Environment	**Hardware**: Operational test facilities, flight platforms, nuclear cold commissioning testbeds. **Software**: Integrated with hardware/software in operational environment, real mission data, operational user workflows.
Notes on Term Alignment	NASA/DoD emphasize "system prototype in operational environment"; DOE emphasizes "nuclear cold commissioning." Harmonized as prototype demonstration in operational environment with DOE nuance.

III.H TRL 8

At TRL 8, either the actual operational mission system (hardware and software) or an identical copy of the operational system is fabricated for full flight qualification. The term qualification is often used colloquially or inaccurately at other points in the TRL advancement process, but technology readiness assessment documentation makes it clear that true flight qualification is to be performed on an operational system evaluated through the entire envelope of operational environments. These environments can still be simulated so long as they provide for this type of full system and operational mission evaluation. If it has not been completed prior to this point, it is expected that any ongoing life qualification testing will be completed at TRL 8. Test performance data have been documented and validated against high-fidelity analytical predictions and modeling and simulation results. Operational mission procedures are completed, and the system is ready for operational use. The entry for TRL 8, unified across NASA, DoD, and DOE definitions, is provided in Table 8.

Table 8: Unified entry for TRL 8.

TRL 8 – System Qualification	
Element	**Unified Entry**
Unified Definition	Actual system completed and qualified through test and demonstration.
Unified Description	**Hardware**: Final product in final configuration successfully demonstrated in intended operational environment. Life testing completed if required. Operational procedures complete. **Software**: All software debugged, fully integrated with operational systems. Documentation (user, training, maintenance) complete. Functionality successfully demonstrated in simulated operational scenarios with V&V completed.
Unified Success Criteria / Supporting Information	**Success Criteria**: Final product/system performance verified against predictions. Qualification tests confirm full operational performance. Operational Readiness Review (ORR) successfully completed. Issues resolved/tracked. **Added Software-Specific Criteria**: Documentation complete. Technology refresh/build schedule published. Resource reserves measured. Cybersecurity protections verified. All severity 1/2 defects resolved; only minor defects remain.
Typical Environment	**Hardware**: Final system test beds, prototypical facilities, or intended platforms. **Software**: Fully integrated with operational systems, exercised against full-scale test problems and scenarios.
Notes on Term Alignment	“Flight qualified” (NASA/DoD) and “Qualified” (DOE) harmonized. DOE emphasizes ORR and hot commissioning for nuclear contexts.

III.I TRL 9

Systems at TRL 9 have achieved operational status and have been mission proven through at least one successful operational mission. Multiple copies of this system may be required for various missions or platforms. While production may have started at an earlier TRL, by TRL 9 the system will transition from low-rate production to the production rate required to support the mission with spares. Changes to the operational system (e.g., block upgrades) often necessitate a regression of the new system to TRL 8 for delta-qualification testing to ensure the system will still perform as expected in all operational environments. Similarly, changes to the operational mission requirements (longer lifetime or different environments) will regress the system TRL to a lower level dependent on the magnitude of the changes. It is important to recognize that the TRL metric does not address manufacturing changes, where supply chain, production equipment, or alternations in tooling can result in unanticipated failures and an apparent regression of TRL. The entry for TRL 9, unified across NASA, DoD, and DOE definitions, is provided in Table 9.

Table 9: Unified entry for TRL 9.

TRL 9 – System Operations	
Element	**Unified Entry**
Unified Definition	Actual system flight proven/mission proven through successful mission operations.
Unified Description	**Hardware**: Final product operated successfully in actual missions and full expected operating conditions. **Software**: Fully integrated, debugged, and sustained in operational environment. Documentation verified. Operational use confirmed. Sustaining engineering support in place.
Unified Success Criteria / Supporting Information	**Success Criteria**: Documented mission operational results. Operational, test, and evaluation (OT&E) reports available. **Added Software-Specific Criteria**: Production configuration management in place. Defect resolution process operational. Reusability/ repeatability confirmed. Technology in reuse repositories/tools. Sustaining software support active.
Typical Environment	**Hardware**: Actual mission platforms/environments (flight missions, nuclear hot commissioning and operations, deployed systems). **Software**: Deployed operational systems, actual mission loads and conditions.
Notes on Term Alignment	NASA/DoD emphasize "flight proven"; DOE emphasizes "operated under full range of mission conditions." Harmonized as "mission proven." DOE adds nuclear hot operations.

IV.Conclusions

Establishing clear criteria for technology readiness is essential for the development and maturation of any technology. For nuclear electric propulsion systems, differing interpretations of the technology readiness requirements and terminology have historically complicated assessments of maturity. This is confounded by the fact that there are subtle differences in the terminology and guidance found in the requirements of the three U.S. Government organizations that are most relevant to the development of space nuclear systems. The issue is further complicated by advocates often overstating TRLs for their specific technology. Projects can address this by using independent technical authorities or non-advocate review panels to determine initial technology readiness and to verify at each major milestone whether technology advancement has occurred. It is important to emphasize that TRL is not static: levels may regress when mission requirements or ConOps change, or when development efforts lapse and expertise, facilities, or technical or production capabilities are lost.

This paper provides unified TRL definitions and supporting criteria that integrate the intent of NASA, DoD, and DOE requirements and standards while highlighting and clarifying where differences exist. By tying TRL advancement explicitly to hardware fidelity, software maturity, integration level, environments, lifetime considerations, an understanding of failure modes and validation against analytical predictions and modeling and simulation results, this framework provides a consistent and defensible basis for assessing progress. Applying these unified definitions will permit space nuclear programs to more effectively identify gaps, allocate resources, and prioritize demonstrations that genuinely increase readiness. Doing so will produce a more reliable path for advancing space nuclear technologies from research concepts to operational systems.

References

[1] Wood, P.I., Forrest, D.L., and Wilner, B.M, "SNAP-8, The First Electric Propulsion, Power System," American Rocket Society, TID-13905, October 1961.

[2] Wallner, L. E. and Czika, Jr., J., "Arc-Jet Thrustor for Space Propulsion," Lewis Research Center, NASA Report TN D-2868, 1965.

[3] Bennett, G.L. and Miller, T.J., "Planning for the Space Exploration Initiative, The Nuclear Propulsion Option," *AIP Conference Proceedings*, Volume 217, Number 1, 1991.

[4] Brophy, J.R. and Barnett, J.W., "Benefits of Electric Propulsion for the Space Exploration Initiative," *26th AIAA Joint Propulsion Conference*, AIAA 90-2756, 1990. https://doi.org/10.2514/6.1990-2756

[5] Hogan, T., "Mars Wars: The Rise and Fall of the Space Exploration Initiative," NASA Special Publication/SP-2807-4410, August 2007.

[6] Buden, D., "Summary of Space Nuclear Reactor Power Systems (1983-1992)," 10th Anniversary Book for Symposium on Space Nuclear Power and Propulsion, INEL/MISC-93085, Conference-930103, revised version, August 1993.

[7] Oleson, S., "Electric Propulsion Technology Development for the Jupiter Icy Moon Orbiter Program," *40th AIAA Joint Propulsion Conference*, AIAA 2004-3449, July 2004. https://doi.org/10.2514/6.2004-3449

[8] Project Prometheus Final Report, Jet Propulsion Laboratory, 982-R120461, October 2006.

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

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

[11] Lev, D., Myers, R.M., Lemmer, K.M., Kolbeck, J., Koizumi, H., Polzin, K., "The Technological and Commercial Expansion of Electric Propulsion," *Acta Astronautica*, Vol 159, Pp 213-227 (2019). DOI: 10.1016/j.actaastro.2019.03.058

[12] NASA Systems Engineering Processes and Requirements, NASA Procedural Requirement NPR 7123.1D, National Aeronautics and Space Administration, 5 July 2023.

[13] Technology Readiness Assessment Guidebook, Office of the Under Secretary of Defense for Research and Engineering, U.S. Department of Defense, June 2023.

[14] Technology Readiness Assessment Guide, DOE G 413.3-4A, U.S. Department of Energy, 22 Oct 2015.

[15] Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects, Report GAO-20-48G, U.S. Government Accountability Office, 2020.

[16] Manufacturing Readiness Level (MRL) Deskbook, Ver 2.0, Manufacturing Technology Program Best Practice, U.S. Department of Defense, May 2011.

Appendix A: NASA TRL Definitions

Table A-1: NASA TRL definitions[12] as found in NASA Procedural Requirement NPR 7123.1D.

TRL	Definition	Description	Success Criteria
1	Basic principles observed and reported.	***Hardware***: Scientific knowledge generated. Underpinning hardware technology concepts/applications. ***Software***: Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed documentation of research underlying the proposed concept/application. Examples: a) Initial Paper published providing representative examples of phenomenon as well as supporting equations for a concept. b) Conference presentations on concepts and basic observations presented within the scientific community.
2	Technology concept and/or application formulated.	***Hardware***: Invention begins. Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. ***Software***: Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations, and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit. Example: Carbon nanotube composites were created for lightweight, high-strength structural materials for space structures.
3	Analytical and experimental proof-of-concept of critical function and/or characteristics.	***Hardware***: Research and development are initiated, including analytical and laboratory studies to validate predictions regarding the technology. ***Software***: Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters. Examples: a) High efficiency Gallium Arsenide solar panels for space application is conceived for use over a wide temperature range. The concept critically relies on improved welding technology for the cell assembly. Samples of solar cell assemblies are manufactured and submitted to a preliminary thermal environment test at ambient pressure for demonstrating the concept viability. b) A fiber optic laser gyroscope is envisioned using optical fibers for the light propagation and Sagnac Effect. The overall concept is modeled including the laser source, the optical fiber loop, and the phase shift measurement. The laser injection in the optical fiber and the detection principles are supported by dedicated experiments. c) *In Situ* Resource Utilization: Demonstrated the application of a cryofreezer for CO2 acquisition and microwave processor for water extraction from soils.

4	Component and/or breadboard validation in a laboratory environment.	***Hardware***: A low fidelity system/component breadboard is built and operated to demonstrate basic functionality in a laboratory environment.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of potentially relevant environment. Examples: a) Fiber optic laser gyroscope: A breadboard model is built including the proposed laser diode, optical fiber and detection system. The angular velocity measurement performance is demonstrated in the laboratory for one axis rotation. b) Bi-liquid chemical propulsion engine: A breadboard of the engine is built and thrust performance is demonstrated at ambient pressure. Calculations are done to estimate the theoretical performance in the expected environment (e.g., pressure, temperature). c) A new fuzzy logic approach to avionics is validated in a lab environment by testing the algorithms in a partially computer-based, partially bench-top component (with fiber optic gyros) demonstration in a controls lab using simulated vehicle inputs.
		Software: Key, functionality critical software components are integrated and functionally validated to establish interoperability and begin architecture development. Relevant environments defined and performance in the environment predicted.	
5	Component and/or brassboard validated in a relevant environment.	***Hardware***: A medium-fidelity component and/or brassboard, with realistic support elements, is built and operated for validation in a relevant environment so as to demonstrate overall performance in critical areas.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements. Performance predictions are made for subsequent development phases. Examples: a) A 6.0-meter deployable space telescope comprised of multiple petals is proposed for near infrared astronomy operating at 30K. Optical performance of individual petals in a cold environment is a critical function and is driven by material selection. A series of 1-m mirrors (corresponding to a single petal) were fabricated from different materials and tested at 30K to evaluate performance and to select the final material for the telescope. Performance was extrapolated to the full-sized mirror. b) For a launch vehicle, TRL 5 is the level demonstrating the availability of the technology at subscale level (e.g., the fuel management is a critical function for a re-ignitable upper stage). The demonstration of the management of the propellant is achieved on the ground at a subscale level. c) ISS Additive Manufacturing Facility: Characterization tests compare parts and material properties of polymer specimens printed on ISS to copies printed on the ground.
		Software: End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Implementations.	

6	System/sub-system model or prototype demonstration in a relevant environment.	***Hardware***: A high-fidelity prototype of the system/subsystems that adequately addresses all critical scaling issues is built and tested in a relevant environment to demonstrate performance under critical environmental conditions. ***Software***: Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions. Examples: a) A remote sensing camera includes a large 3-meter telescope, a detection assembly, a cooling cabin for the detector cooling, and an electronics control unit. All elements have been demonstrated at TRL 6 except for the mirror assembly and its optical performance in orbit, which is driven by the distance between the primary and secondary mirrors needing to be stable within a fraction of a micrometer. The corresponding critical part includes the two mirrors and their supporting structure. A full-scale prototype consisting of the two mirrors and the supporting structure is built and tested in the relevant environment (e.g., including thermo-elastic distortions and launch vibrations) for demonstrating the required stability can effectively be met with the proposed design. b) Vacuum Pressure Integrated Suit Test (VPIST): Demonstrated the integrated performance of the Orion suit loop when integrated with human-suited test subjects in a vacuum chamber.
7	System prototype demonstration in an operational environment.	***Hardware***: A high-fidelity prototype or engineering unit that adequately addresses all critical scaling issues is built and functions in the actual operational environment and platform (ground, airborne, or space). ***Software***: Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions. Examples: a) Mars Pathfinder Rover flight and operation on Mars as a technology demonstration for future micro-rovers based on that system design. b) First flight test of a new launch vehicle, which is a performance demonstration in the operational environment. Design changes could follow as a result of the flight test. c) In-space demonstration missions for technology (e.g., autonomous robotics and deep space atomic clock). Successful flight demonstration could result in use of the technology in a future operational mission. d) Robotic External Leak Locator (RELL): Originally flown as a technology demonstrator, the test article was subsequently put to use to help operators locate the likely spot where ammonia was leaking from the International Space Station (ISS) External Active Thermal Control System Loop B.

8	Actual system completed and "flight qualified“ through test and demonstration.	***Hardware***: The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space). If necessary*, life testing has been completed.	Documented test performance verifying analytical predictions. Examples: a) The level is reached when the final product is qualified for the operational environment through test and analysis. Examples are when Cassini and Galileo were qualified, but not yet flown. b) Interim Cryo Propulsion Stage (ICPS): A Delta Cryogenic Second Stage modified to meet Space Launch System requirements for Exploration Mission-1 (EM-1). Qualified and accepted by NASA for flight on EM-1.
		Software: All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation completed.	
9	Actual system flight proven through successful mission operations.	***Hardware***: The final product is successfully operated in an actual mission.	Documented mission operational results. Examples: a) Flown spacecraft (e.g., Cassini, Hubble Space telescope). b) Technologies flown in an operational environment. c) Nanoracks CubeSat Deployer: Commercially developed and operated small satellite deployer on-board the ISS.
		Software: All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All documentation has been completed. Sustaining software support is in place. System has been successfully operated in the operational environment.	

* "If necessary" refers to the need to life test either for worn out mechanisms, for temperature stability over time, and for performance over time in extreme environments. An evaluation on a case-by-case basis should be made to determine the system/systems that warrant life testing and the tests begun early in the technology development process to enable completion by TRL 8. It is preferable to have the technology life test initiated and completed at the earliest possible stage in development. Some components may require life testing on or after TRL 5.

Appendix B: Department of Defense (DoD) TRL Definitions

Table B-1: TRL definitions as found in the DoD *Technology Readiness Assessment Guidebook*.[13]

TRL	Definition	Description	Supporting Information
1	Basic principles observed and reported.	***Hardware***: Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D).	Published research that identifies the principles that underlie this technology. References to who, where, when. Examples might include paper studies of a technology's basic properties.
		Software: Lowest level of software technology readiness. A new software domain is being investigated by the basic research community. This level extends to the development of basic use, basic properties of software architecture, mathematical formulations, and general algorithms.	Basic research activities, research articles, peer-reviewed white papers, point papers, early lab model of basic concept may be useful for substantiating the TRL.
2	Technology concept and/or application formulated.	***Hardware***: Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions.	Publications or other references that outline the application being considered and that provide analysis to support the concept. Examples are limited to analytic studies.
		Software: Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions.	Applied research activities, analytic studies, small code units, and papers comparing competing technologies. Examples are limited to analytic studies using synthetic data.
3	Analytical and experimental critical function and/or characteristic proof of concept.	***Hardware***: Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed. Examples include components that are not yet integrated or representative.
		Software: Active R&D is initiated. The level at which scientific feasibility is demonstrated through analytical and laboratory studies. This level extends to the development of limited functionality environments to validate critical properties including cybersecurity and analytical predictions using non-integrated software components and partially representative data.	Algorithms run on a surrogate processor in a laboratory environment, instrumented components operating in a laboratory environment, laboratory results showing validation of critical properties.

4	Component and/or breadboard validation in a laboratory environment.	***Hardware***: Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system.	System concepts that have been considered and the results of testing laboratory-scale breadboard(s). References to who performed this work and when. Provides an estimate of how breadboard hardware and test results differ from the expected system goals. Examples include integration of "ad hoc" hardware in the laboratory.
		Software: Basic software components are integrated to establish that they will work together. They are relatively primitive with regard to efficiency and robustness compared with the eventual system. Architecture development initiated to include interoperability, reliability, maintainability, extensibility, scalability, and security issues. Emulation with current/legacy elements as appropriate. Prototypes developed to demonstrate different aspects of eventual system.	Advanced technology development, stand-alone prototype solving a synthetic full-scale problem, or stand-alone prototype processing fully representative data sets.
5	Component and/or breadboard validation in a relevant environment.	***Hardware***: Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment.	Results from testing a laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals? Examples include "high-fidelity" laboratory integration of components.
		Software: Level at which software technology is ready to start integration with existing systems. The prototype implementations conform to target environment/interfaces. Experiments with realistic problems. Simulated interfaces to existing systems. System software architecture established. Algorithms run on a processor(s) with characteristics expected in the operational environment.	System architecture diagram around technology element with critical performance requirements defined. Processor selection analysis, Simulation/Stimulation (Sim/Stim) Laboratory buildup plan. Software placed under configuration management. Commercial-of-the-shelf/ government-off-the-shelf (COTS/GOTS) components in the system software architecture are identified.

6	System/subsystem model or prototype demonstration in a relevant environment.	***Hardware***: Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level? Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
		Software: Level at which the engineering feasibility of a software technology is demonstrated. This level extends to laboratory prototype implementations on full-scale realistic problems in which the software technology is partially integrated with existing hardware/software systems. Cybersecurity verification should be included in the testing.	Results from laboratory testing of a prototype package that is near the desired configuration in terms of performance, including physical, logical, data, and security interfaces. Comparisons between tested environment and operational environment analytically understood. Analysis and test measurements quantifying contribution to system-wide requirements such as throughput, scalability, and reliability. Analysis of human-computer (user environment) begun.
7	System prototype demonstration in an operational environment.	***Hardware***: Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
		Software: Level at which the program feasibility of a software technology is demonstrated. This level extends to operational environment prototype implementations, where critical technical risk functionality is available for demonstration and a test in which the software technology is well integrated with operational hardware/software systems.	Critical technological properties, including cybersecurity, are measured against requirements in an operational environment. Examples include TacSat, FalconSat flight demonstration missions.

8	Actual system completed and "flight qualified" through test and demonstration.	***Hardware***: Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design? Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
		Software: Level at which a software technology is fully integrated with operational hardware and software systems. Software development documentation is complete. All functionality and cybersecurity measures tested in simulated and operational scenarios.	Published documentation and product technology refresh build schedule. Software resource reserve measured and tracked. All severity 1 and severity 2 defects are resolved/confirmed, and a reasonably low level of severity 3 defects remain open.
9	Actual system "flight proven" through successful mission operations.	***Hardware***: Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E).	Operational, test, and evaluation (OT&E) reports. Examples include using the system under operational mission conditions.
		Software: Level at which a software technology is readily repeatable and reusable. The software based on the technology is fully integrated with operational hardware/software systems. All software documentation verified. Successful operational experience. Sustaining software engineering support in place. Actual system.	Production configuration management reports. Defect resolution system and process is in place for deployed software to address defects discovered in production. Technology is integrated into a reuse "wizard"

Appendix C: Department of Energy (DOE) TRL Definitions

Table C-1: TRL definitions[14] as found in the DOE *Technology Readiness Assessment Guide*, DOE G 413.3-4A.

TRL	Definition	Description	Supporting Information
1	Basic principles observed and reported [Basic Technology Research]	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D).	Supporting Information includes published research or other references that identify the principles that underlie the technology. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world.
2	Technology concept and/or application formulated [Basic Technology Research]	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.	Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. Examples are still limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept [Research to Prove Feasibility]	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.	Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. Examples include components that are not yet integrated or representative tested with simulants. (Simulants should match relevant chemical and physical properties.)

4	Component and/or system validation in laboratory environment [Technology Development]	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.	Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small-scale tests on actual waste. (Testing with as wide a range of actual waste as practicable and consistent with waste availability, safety, ALARA, cost and project risk is highly desirable.)
5	Laboratory scale, similar system validation in relevant environment [Technology Development]	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.	Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants (Simulants should match relevant chemical and physical properties) and with a range of real waste (Testing with as wide a range of actual waste as practicable and consistent with waste availability, safety, ALARA, cost and project risk is highly desirable.)

6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment [Technology Demonstration]	Representative engineering-scale models or prototypes which are well beyond the lab scale tested for TRL 5, are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.	Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. <u>Examples</u> include testing an engineering scale prototypical system with real waste and a range of simulants. (Simulants should match relevant chemical and physical properties).
7	Full-scale, similar (prototypical) system demonstrated in relevant environment [System Commissioning]	Prototype full-scale system. This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Final design is virtually complete.	Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. <u>Examples</u> include testing full-scale prototype in the field with a range of simulants in cold commissioning (Simulants should match relevant chemical and physical properties) and/or real waste and cold commissioning.
8	Actual system completed and qualified through test and demonstration. [System Commissioning]	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development.	Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing. <u>Examples</u> include developmental testing and evaluation of the system with actual waste in hot commissioning.
9	Actual system operated over the full range of expected mission conditions. [System Operations]	The technology is in its final form and operated under the full range of operating mission conditions.	<u>Examples</u> include using the actual system with the full range of wastes in hot operations.

Appendix D: Definitions

Table D-1: The NASA terminology definitions[12] as found in NASA Procedural Requirement NPR 7123.1D, showing which terms apply to which TRL and cross-walking the terms with the DoD equivalent terms found in Table D-2.

Term	Definition
Breadboard Unit [TRL 4]	A low fidelity unit that demonstrates function only, without respect to form or fit. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance. [Corresponds to DoD **Breadboard**. Integrates DoD ***Low Fidelity*** into definition.]
Brassboard Unit [TRL 5]	A medium fidelity functional unit that typically tries to make use of as much of the final product as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions. [DoD terminology uses ***High Fidelity Breadboard***.]
Prototype Unit [TRL 6-7]	The prototype unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment. [Corresponds to DoD ***Prototype***.]
Engineering Unit / Engineering Development Unit (EDU) [TRL 6]	A high-fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. Engineering test units are intended to closely resemble the final product (hardware/software) to the maximum extent possible and are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit can become the final product, assuming proper traceability has been exercised over the components and hardware handling. [No corresponding DoD term in Table D-2, but fidelity approaches but it not quite equivalent to a NASA ***Prototype Unit*** or a DoD ***Prototype***.]
Laboratory Environment [TRL 3-4]	An environment that does not address in any manner the environment to be encountered by the system, subsystem, or component (hardware or software) during its intended operation. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions) without respect to the impact of environment. [No corresponding DoD term in Table D-2, but the term ***Laboratory Environment*** is used in DoD TRL definitions.]
Relevant Environment [TRL 5-6]	Not all systems, subsystems, and/or components need to be operated in the operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical "risk" aspects of the final product performance in an operational environment. It is an environment that focuses specifically on stressing the technology advance in question. [Corresponds to DoD ***Relevant Environment***.]
Operational Environment [TRL 7-9]	The environment in which the final product will be operated. In the case of space flight hardware/software, it is space. In the case of ground-based or airborne systems that are not directed toward space flight, it will be the environments defined by the scope of operations. For software, the environment will be defined by the operational platform. [Corresponds to DoD ***Operational Environment***.]

Table D-2: The DoD terminology definitions as found in the DoD *Technology Readiness Assessment Guidebook*,[13] showing which terms apply to which TRL and cross-walking the terms with the NASA equivalent terms found in Table D-1.

Term	Definition
Breadboard [TRL 4,5]	Integrated components that provide a representation of a system/subsystem and that can be used to determine concept feasibility and to develop technical data. Typically configured for laboratory use to demonstrate the technical principles of immediate interest. May resemble final system/subsystem in function only. [DoD ***Low Fidelity Breadboard*** Corresponds to NASA ***Breadboard Unit***. DoD ***High Fidelity Breadboard*** corresponds to NASA ***Brassboard Unit***.]
Low Fidelity [TRL 4]	A representative of the component or system that has limited ability to provide anything but first-order information about the end product. Low-fidelity assessments are used to provide trend analysis. [Fidelity of components found in a DoD ***Breadboard*** or a NASA ***Breadboard Unit***]
High Fidelity [TRL 6-7]	Addresses form, fit, and function. A high-fidelity laboratory environment would involve testing with equipment that can simulate and validate all system specifications within a laboratory setting. High fidelity models are accredited to represent the system for their defined purpose. [Fidelity of components found in a DoD ***High Fidelity Breadboard*** or ***Prototype*** or a NASA ***Brassboard Unit***, ***Engineering Unit***, or ***Prototype Unit***.]
Prototype [TRL 6-7]	A physical or virtual model used to evaluate the technical or manufacturing feasibility or military utility of a particular technology or process, concept, end item, or system. [Corresponds to NASA ***Prototype Unit***. Fidelity can also correspond to a NASA ***Engineering Unit***.]
Model	A functional form of a system, generally reduced in scale, near or at operational specification. Models will be sufficiently hardened to allow demonstration of the technical and operational capabilities required of the final system. [No corresponding NASA term in Table D-1, but the term ***Model*** is used in NASA TRL definitions.]
Relevant Environment [TRL 5-6]	Testing environment that simulates both the most important and most stressing aspects of the operational environment. [Corresponds to NASA ***Relevant Environment***.]
Operational Environment [TRL 7-9]	Environment that addresses user operational requirements and specifications required of the final system to include platform/packaging. [Corresponds to NASA ***Operational Environment***.]
Simulated Operational Environment [TRL 7-8]	Either (1) a real environment that can simulate all the operational requirements and specifications required of the final system or (2) a simulated environment that allows for testing of a virtual prototype. Used in either case to determine whether a developmental system meets the operational requirements and specifications of the final system. [No corresponding NASA term in Table D-1, but ***Simulated Operational Environment*** has a plain meaning once ***Operational Environment*** is defined.]

Table D-3: The DOE terminology definitions for Scale, Fidelity, and Environments[14] as found in the DOE *Technology Readiness Assessment Guide*, DOE G 413.3-4A.

Term	Definition
Scale	
Full Plant Scale	Matches final application [TRL 7-9]
Engineering Scale[a]	Typical (1/10 < system < Full Scale) [Pilot Scale] [TRL 6]
Laboratory / Bench[a]	Less than 1/10 Full Scale [TRL 3-5]
System Fidelity	
Identical System Configuration	Matches final application in all respects [TRL 8-9]
Similar System Configuration	Matches final application in almost all respects [TRL 5-7]
Pieces	System matches a pieces or pieces of the final application [TRL 3-4]
Paper	System exists on paper (i.e., no hardware system) [TRL 1-2]
Environments (Waste)[b,c]	
Operational (Full Range)	Full range of actual waste [TRL 9]
Operational (Limited Range)	Limited range of actual waste [TRL 8]
Relevant	Simulants plus a limited range of actual wastes [TRL 5-7]
Simulated	Range of simulants [TRL 3-4]

[a] The Engineering scale and Laboratory/Bench scale may vary based on engineering judgment.

[b] Simulants should match relevant physical and chemical properties.

[c] Testing with as wide a range of actual waste as practicable; and consistent with waste availability, safety, cost, and project risk is highly desirable.