Appendix E. Technology Readiness Levels

TRL	Definition	Hardware Description	Software Description	Success criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	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.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	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.
	Examples: a. Carbon nanotube composites were created for lightweight, high-strength structural materials for space structures. b. Mini-CO_2 Scrubber: Applies advanced processes to remove carbon dioxide and potentially other undesirable gases from spacecraft cabin air.			

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<tr><td rowspan="2">3</td><td>Analytical and experimental proof-of-concept of critical function and/or characteristics.</td><td>Research and development are initiated, including analytical and laboratory studies to validate predictions regarding the technology.</td><td>Development of limited functionality to validate critical properties and predictions using non-integrated software components.</td><td>Documented analytical/experimental results validating predictions of key parameters.</td></tr>
<tr><td colspan="4">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 CO_2 acquisition and microwave processor for water extraction from soils.</td></tr>
<tr><td>4</td><td>Component and/or breadboard validation in a laboratory environment.</td><td>A low fidelity system/component breadboard is built and operated to demonstrate basic functionality in a laboratory environment.</td><td>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.</td><td>Documented test performance demonstrating agreement with analytical predictions. Documented definition of potentially relevant environment.</td></tr>
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<td colspan="4">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.
d. Variable Specific Impulse Magnetosphere Rocket (VASIMR): 100 kW magnetoplasma engine operated 10 hours cumulative (up to 3 minutes continuous) in a laboratory vacuum chamber.</td>
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<td>5</td>
<td>Component and/or brassboard validated in a relevant environment.</td>
<td>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.</td>
<td>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.</td>
<td>Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements. Performance predictions are made for subsequent development phases.</td>
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	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 1m 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.

6	System/sub-system model or prototype demonstration in a relevant environment.	A high-fidelity prototype of the system/subsystems that adequately addresses all critical scaling issues is built and tested in a relevant environment to demonstrate performance under critical environmental conditions.	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.	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).	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.

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<tr><td></td><td colspan="4">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.</td></tr>
<tr><td>8</td><td>Actual system completed and “flight qualified” through test and demonstration.</td><td>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.</td><td>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.</td><td>Documented test performance verifying analytical predictions.</td></tr>
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*“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.

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.</td></tr>
<tr><td rowspan="2">9</td><td>Actual system flight proven through successful mission operations.</td><td>The final product is successfully operated in an actual mission.</td><td>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.</td><td>Documented mission operational results.</td></tr>
<tr><td colspan="4">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.</td></tr>
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Note: In cases of conflict between NASA directives concerning TRL definitions, NPR 7123.1 will take precedence.