TECHNOLOGY READINESS LEVELS

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Introduction

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL approach has been used on-and-off in NASA space technology planning for many years and was recently incorporated in the NASA Management Instruction (NMI 7100) addressing integrated technology planning at NASA. Figure 1 (attached) provides a summary view of the technology maturation process model for NASA space activities for which the TRL's were originally conceived; other process models may be used. However, to be most useful the general model must include: (a) 'basic' research in new technologies and concepts (targeting identified goals, but not necessary specific systems), (b) focused technology development addressing specific technologies for one or more potential identified applications, (c) technology development and demonstration for each specific application before the beginning of full system development of that application, (d) system development (through first unit fabrication), and (e) system 'launch' and operations.

Technology Readiness Levels Summary

TRL 1 Basic principles observed and reported

TRL 2 Technology concept and/or application formulated

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 4 Component and/or breadboard validation in laboratory environment

TRL 5 Component and/or breadboard validation in relevant environment

TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 7 System prototype demonstration in a space environment

TRL 8 Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 9 Actual system "flight proven" through successful mission operations

Discussion of Each Level

The following paragraphs provide a descriptive discussion of each technology readiness level, including an example of the type of activities that would characterize each TRL.

TRL 1

Basic principles observed and reported

This is the lowest "level" of technology maturation. At this level, scientific research begins to be translated into applied research and development. Examples might include studies of basic properties of materials (e.g., tensile strength as a function of temperature for a new fiber).

Cost to Achieve: Very Low 'Unique' Cost
(investment cost is borne by scientific research programs)

TRL 2

Technology concept and/or application formulated

Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be 'invented' or identified. For example, following the observation of high critical temperature (Htc) superconductivity, potential applications of the new material for thin film devices (e.g., SIS mixers) and in instrument systems (e.g., telescope sensors) can be defined. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.

Cost to Achieve: Very Low 'Unique' Cost
(investment cost is borne by scientific research programs)

TRL 3

Analytical and experimental critical function and/or characteristic proof-of-concept

At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2. For example, a concept for High Energy Density Matter (HEDM) propulsion might depend on slush or super-cooled hydrogen as a propellant: TRL 3 might be attained when the concept-enabling phase/temperature/pressure for the fluid was achieved in a laboratory.

Cost to Achieve: Low 'Unique' Cost
(technology specific)

TRL 4

Component and/or breadboard validation in laboratory environment

Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively "low-fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory. For example, a TRL 4 demonstration of a new 'fuzzy logic' approach to avionics might consist of testing the algorithms in a partially computer-based, partially bench-top component (e.g., fiber optic gyros) demonstration in a controls lab using simulated vehicle inputs.

Cost to Achieve: Low-to-moderate 'Unique' Cost
(investment will be technology specific, but probably
several factors greater than investment required for TRL 3)

TRL 5

Component and/or breadboard validation in relevant environment

At this, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment. From one-to-several new technologies might be involved in the demonstration. For example, a new type of solar photovoltaic material promising higher efficiencies would at this level be used in an actual fabricated solar array 'blanket' that would be integrated with power supplies, supporting structure, etc., and tested in a thermal vacuum chamber with solar simulation capability.

Cost to Achieve: Moderate 'Unique' Cost
(investment cost will be technology dependent, but likely to be several factors
greater that cost to achieve TRL 4)

TRL 6

System/subsystem model or prototype demonstration in a relevant environment (ground or space)

A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system — which would go well beyond ad hoc, 'patch-cord' or discrete component level breadboarding — would be tested in a relevant environment. At this level, if the only 'relevant environment' is the environment of space, then the model/prototype must be demonstrated in space. Of course, the demonstration should be successful to represent a true TRL 6. Not all technologies will undergo a TRL 6 demonstration: at this point the maturation step is driven more by assuring management confidence than by R&D requirements. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies. At this level, several-to-many new technologies might be integrated into the demonstration. For example, a innovative approach to high temperature/low mass radiators, involving liquid droplets and composite materials, would be demonstrated to TRL 6 by actually flying a working, sub-scale (but scaleable) model of the system on a Space Shuttle or International Space Station 'pallet'. In this example, the reason space is the 'relevant' environment is that microgravity plus vacuum plus thermal environment effects will dictate the success/failure of the system — and the only way to validate the technology is in space.

Cost to Achieve: Technology and demonstration specific; a fraction of TRL 7 if on ground; nearly the same if space is required

TRL 7

System prototype demonstration in a space environment

TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. It has not always been implemented in the past. In this case, the prototype should be near or at the scale of the planned operational system and the demonstration must take place in space. The driving purposes for achieving this level of maturity are to assure system engineering and development management confidence (more than for purposes of technology R&D). Therefore, the demonstration must be of a prototype of that application. Not all technologies in all systems will go to this level. TRL 7 would normally only be performed in cases where the technology and/or subsystem application is mission critical and relatively high risk. Example: the Mars Pathfinder Rover is a TRL 7 technology demonstration for future Mars micro-rovers based on that system design. Example: X-vehicles are TRL 7, as are the demonstration projects planned in the New Millennium spacecraft program.

Cost to Achieve: Technology and demonstration specific, but a significant fraction of the cost of TRL 8 (investment = "Phase C/D to TFU" for demonstration system)

TRL 8

Actual system completed and "flight qualified" through test and demonstration (ground or space)

By definition, all technologies being applied in actual systems go through TRL 8. In almost all cases, this level is the end of true 'system development' for most technology elements. Example: this would include DDT&E through Theoretical First Unit (TFU) for a new reusable launch vehicle. This might include integration of new technology into an existing system. Example: loading and testing successfully a new control algorithm into the onboard computer on Hubble Space Telescope while in orbit.

Cost to Achieve: Mission specific; typically highest unique cost for a new technology (investment = "Phase C/D to TFU" for actual system)

TRL 9

Actual system "flight proven" through successful mission operations

By definition, all technologies being applied in actual systems go through TRL 9. In almost all cases, the end of last 'bug fixing' aspects of true 'system development'. For example, small fixes/changes to address problems found following launch (through '30 days' or some related date). This might include integration of new technology into an existing system (such operating a new artificial intelligence tool into operational mission control at JSC). This TRL does not include planned product improvement of ongoing or reusable systems. For example, a new engine for an existing RLV would not start at TRL 9: such 'technology' upgrades would start over at the appropriate level in the TRL system.

Cost to Achieve: Mission Specific; less than cost of TRL 8
(e.g., cost of launch plus 30 days of mission operations)