TECHNOLOGY READINESS LEVEL DESCRIPTION FOR THE NEW MILLENNIUM PROGRAM

Introduction

Technology readiness levels are intended to describe increasing levels of technological maturity as an advanced technology progresses from an initial idea to a flight-quality device. They are not applicable to assessing the engineering or development maturity. Consider an S-Band transmitter, an item that has been built and used in space for close to forty years. The design and fabrication of a new S-Band transmitter is at a high level of technological maturity, even though a particular design has just begun. In assessing the maturity of an advanced technology, it is important to identify the technology advance before attempting to assess its Technology Readiness Level (TRL). If there is no advancement then the technology is mature and has a high TRL rating.

The technology readiness levels described below are the same ones that have long been in general use in NASA. Added to their description are criteria used by NASA's New Millennium Program (NMP) to determine when a particular TRL has been reached. The descriptions that accompany each TRL determine when that milestone has been reached; they are intended to serve as "exit" or "graduation" criteria.

Technology Readiness Level Definitions

TRL 1: *Basic principles observed and reported.*

This is the lowest "level" of technology maturation at which conceptualization and scientific research transitions to applied research and development and a new technology advance begins the journey to technological maturity. At this level, typically no hardware may exist, or if it does it is for a different purpose that by serendipity suggests a radical new technology that may have use or importance (e.g., the discovery of "safety glass").

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 may be identified. TRL 2 is characterized by identified applications in which the technology advancement can be shown analytically to offer significant, quantifiable benefit as compared to the existing state of the art. It is this elucidation of potential benefit that spurs the investment necessary to carry the technology advancement to higher TRL's.

TRL 3: *Analytical and experimental critical function and/or characteristic proof-of-concept achieved in a laboratory environment.*

At this step in the maturation process, active research and development (R&D) is initiated. This includes both analytical studies to set the technology into an appropriate context and laboratory-based studies to validate empirically that the analytical predictions are correct. These studies and experiments validate the benefits offered by the technology advancement to the applications/concepts formulated at TRL 2.

To be at TRL 3, the following conditions should exist:

1. Laboratory tests have demonstrated that the technology advance is as predicted by the analytical model and has the potential to evolve to a practical device; and
2. A determination of the "relevant environment" (see notes below) for the technology advance has been made.

TRL 4: *Component and/or breadboard validated in a 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 be 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; and may be composed of *ad hoc* discrete components in a laboratory.

To be at TRL 4, the technology advance will satisfy several conditions:

1. A "component" or "breadboard" version of the technology advance will have been implemented and tested in a laboratory environment (see notes below);
2. Analytical models of the technology advance fully replicate the TRL 4 test data; and
3. Analytical models of the performance of the component or breadboard configuration of the technology advance predict its performance when operated in its "relevant environment" and the environments to which the technology advance would be exposed during qualification testing for an operational mission.

TRL 5: *Component and/or breadboard validated in a relevant environment.*

At this TRL, the fidelity of the environment in which the component and/or breadboard has been tested has increased 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 "relevant environment."

The difference between TRL 4 and TRL 5 is found in the level of stress applied to the advanced technology during test. To be tested successfully in a "relevant environment" (see notes below), the quality of the component or breadboard may have to be improved from that tested at the TRL 4.

To be at TRL 5, the technology advance will satisfy several conditions:

1. The "relevant environment" is fully defined;
2. The technology advance has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to

those to which the technology advance would be exposed during qualification testing for an operational mission;
3. Analytical models of the technology advance replicate the performance of the technology advance operating in the "relevant environment;" and
4. Analytical predictions of the performance of the technology advance in a prototype or flight-like configuration have been made.

For some technology advances, testing in space is the only means by which the technology advance can experience its "relevant environment." For example, consider deployment or control of a solar sail. In these cases, TRL 5 can only be accomplished analytically. A model that describes the technology advance's relevant physics, chemistry, and engineering and that replicates all the experience gained from testing on Earth can be used to predict the performance of the technology advance in the appropriate "relevant environment." This model and its predictions then become the demonstration of operation in a "relevant environment."

TRL 6: *System/subsystem model or prototype demonstration in a relevant environment on the ground or in 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 of the subsystem or system, well beyond *ad hoc*, "patch-cord" or discrete-component-level breadboarding, would be tested in a "relevant environment". However, commercial parts are still appropriate where not contra-indicated by the environment in which they will be tested. At this level, if the only "relevant environment" is space, then to achieve TRL 6 the model/prototype must be successfully validated in space. However, in many (if not most) cases, TRL 6 can be demonstrated using tests on Earth tests that potentially offer a broader range of operating conditions than those conducted in space.

To be at TRL 6, the technology advance will satisfy several conditions:

1. The technology advance is incorporated in an operational model or prototype similar to the packaging and design needed for use on an operational spacecraft;
2. The system/subsystem model or prototype has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission;
3. Analytical models of the function and performance of the system/subsystem model or prototype, throughout its operating region, in its most stressful environment, have been validated empirically; and
4. The focus of testing and modeling has shifted from understanding the function and performance of the technology advance to examining the effect of packaging and design for flight and the effect of interfaces on that function and performance in its most stressful environment.

TRL 7: *System prototype demonstrated in a space environment.*

TRL 7 can be a significant step beyond TRL 6, requiring both an actual system prototype and its demonstration in a space environment. Because of cost, it is a step that is not always implemented. In the case of TRL 7, the prototype should be at the same scale as the planned operational system and its operation must take place in space. The driving purposes for achieving this level of maturity are to assure that system engineering is adequate, that trans-interface interactions are adequately modeled and understood, and that in-space operation at the appropriate scale is both as expected and as predicted. Therefore, the demonstration must be of a prototype of that application. While not all technologies in all systems will require an in-space test, the actual demonstration of a system prototype in a space environment would normally be performed in cases where the technology and/or subsystem application is both mission critical and high risk.

TRL 8: *Actual system completed and "flight qualified" through test and demonstrated on the ground or in space.*

By definition, all technologies being used on operational spacecraft achieve TRL 8. For most technology advances, TRL 8 represents the end of true "system development."

TRL 9: *Actual system "flight proven" through successful mission operations.*

By definition, all technologies being applied on operational spacecraft achieve TRL 9, including integrating the new technology advance into an existing system and achieving successful operation during a science mission. This TRL does not include product improvement of ongoing or reusable systems or the evolutionary improvement of technology advances already at TRL 9.

Notes:

1) When progressing through the Technology Readiness Levels, some key words and phrases require clarification, and are provided below from the perspective of the NMP.

   a) "Breadboard" and "Prototype" are words that describe different levels of test-article fidelity as compared to the final, flight version of the technology advance. "Breadboard" is meant to convey a bench-top implementation in which all key mechanical and electrical interfaces are simulated but where form, fit, and scale are not considered. "Prototype" is meant to be an initial implementation having the correct form, fit, function, and scale, but not necessarily having flight quality.
   b) "Environment" is a word used often in the above descriptions of TRL's. As used in these definitions, it refers to the spectrum of operating conditions, interfaces (mechanical, electrical, and data), and design conditions (e.g., packaging, miniaturization) to which the technology advance will be exposed both during testing and during flight operations.
   c) "Relevant environment" is a subset of all the "environments" to which the technology advance will be exposed. "Relevant environment" is defined to be that environment, operating condition, or combination of environments and operating conditions that most

stresses the technology advance and is consistent with that expected in the spectrum of likely initial applications.

2) To be confirmed and given approval to begin the Implementation Phase, a selected NMP experiment must first demonstrate that TRL 5 has been achieved. As part of the Formulation Refinement Phase, the PI is responsible for clearly and unambiguously delineating the applicable relevant environment for each of the technology advances associated with the investigation, and defining the experiments and analyses necessary to demonstrate that TRL 5 has been achieved. To ensure that the resulting plan to demonstrate TRL 5 is consistent with the standards of the NMP, the concurrence of the NMP Program Manager and Program Executive is required.