JPL Technology Readiness Level Assessment Guideline

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Abstract— New capabilities in space flight missions are enabled by new technologies. Transitioning new technology to space flight elements is difficult and introduces risk but finding the right balance between benefit and risk leads to advancement for space missions. A clear understanding of the risks of new technology can create an environment where innovation is *nurtured* rather than avoided. The Technology Readiness Level (TRL) was developed as a metric for the maturity of new technology, but, in the past, assessing the TRL was often done informally and consistent reviews were not applied. This frequently led to discrepancies between the TRL as perceived by the technologist and that perceived by a project. JPL has developed a guideline for their projects to provide a basis for a consistent TRL Assessment (TRA). Highlights of this guideline will be presented here. It is anticipated that the result of such a process will enable a better understanding between technologists and project leading to greater acceptance of technologies by flight projects. On completion of a satisfactory TRA, an agreement can be made between the parties on the maturation plan required for successful infusion of the technology into a flight mission.

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1. Introduction

The benefit of using new technology in space flight projects is to enable new scientific results and technical capabilities otherwise unachievable. However, transitioning new technology to flight elements is difficult and may introduce significant risks. Finding the right balance between benefit and risk leads to progress for space missions. A clear-eyed view of the risks balanced against benefits can create an environment where innovation is *nurtured*, rather than avoided. A Technology Readiness Assessment (TRA) is a systematic, metrics-based process that assesses the maturity level of new technologies and facilitates the handoff from technology development to engineering development. The ability to make good decisions about whether to include or exclude new technologies and novel concepts is essential to the success of space flight missions. Project managers and system engineers need to understand and agree with the technologists about the readiness of a particular technology being considering for a mission.

Technology Readiness Levels (TRLs) are a set of metrics that enable the standardized assessment of the maturity of a particular technology and the consistent comparison of the maturity between different types of technology in the context of a specific application, implementation, and operational environment. Figure 1 provides a high-level illustration of the TRL scale, using the well-known "thermometer diagram" as a metaphor for increasing technology maturity, evolving through nine levels starting with basic research and progressing through space flight system operation. The official NASA TRL definitions are found in NPR 7123 Appendix E [1]. NASA has undertaken a revision of these definitions, but the updated versions have not yet been formally adopted.

The TRL scale measures the progression of new technology from concept to use in an operational space flight mission. The new technology conception occurs starting at TRL 1 through TRL3, development and demonstration occurs at TRL 4 through 6. Once TRL 6 is demonstrated, the risk associated with the new technology is roughly equivalent to the risk of a new design that employs standard engineering practice and is bounded by previously implemented ground-

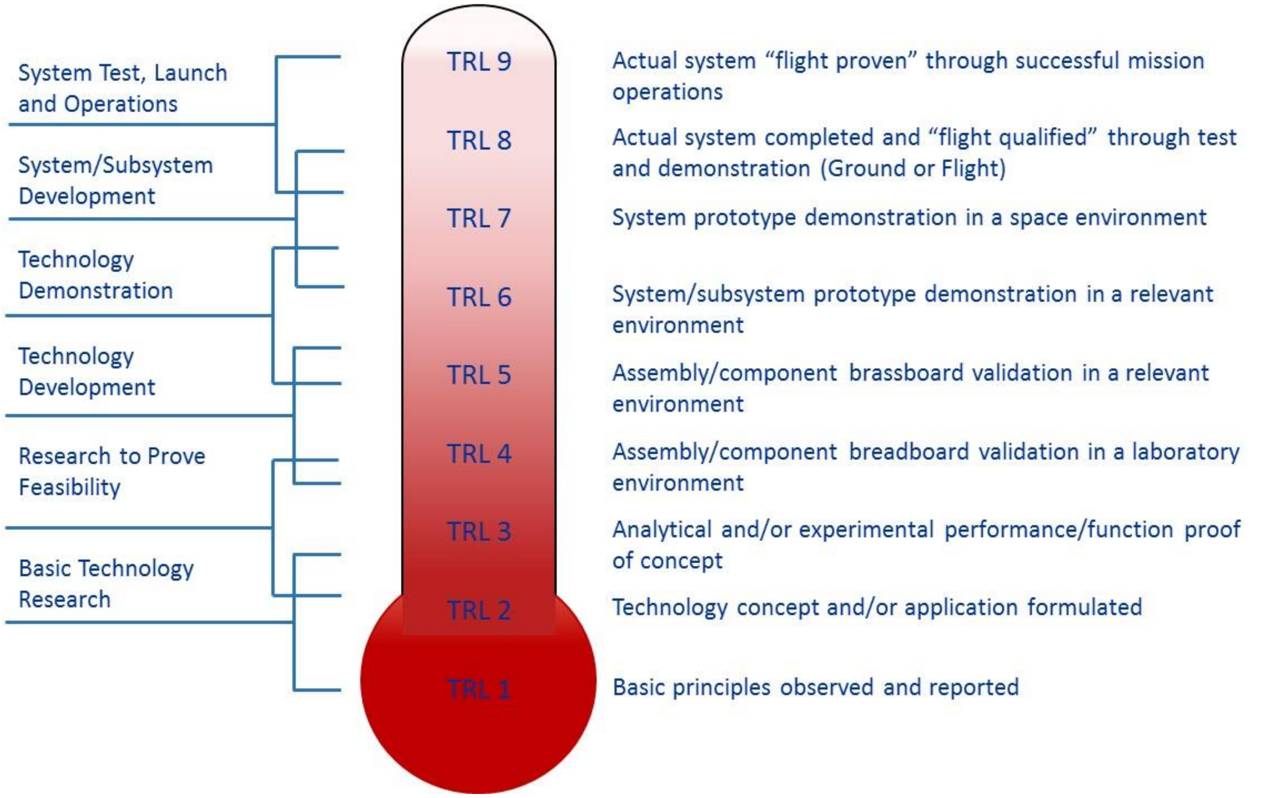

Figure 1. Thermometer Scale for NASA's Technology Readiness Levels

based systems. NASA's best practices require that a technology demonstrate TRL 6 prior to the Preliminary Design Review (PDR) [2]. Following TRL 6 demonstration, the standard engineering development cycle for new designs is followed that includes building and testing an engineering unit, detailed analysis, and detailed drawings prior to the Critical Design Review (CDR). The design is flight qualified at the subsystem and system level by the flight project, leading to flight readiness at TRL 8. Successful operation in space flight constitutes TRL 9 completion. In some cases it is desirable to demonstrate a new technology in space prior to incorporation in the flight program. This space flight pathfinder constitutes TRL 7.

The TRL methodology was originated at NASA in 1988 by S. R. Sadin, et. al. [2]. In 1995, J. C. Mankins wrote a paper [3] that discussed NASA's use of TRLs and proposed expanded descriptions for each TRL. Subsequently, it has been widely adopted in both the United States and Europe. The Department of Defense developed detailed guidance for using TRLs in the 2003 [4], the Department of Energy in 2004 [5], and the European Space Agency in 2008 [6].

The purpose of the guideline described here is to clarify the NASA TRLs and provide an outline of a standard Technology Readiness Assessment (TRA) process as a basis for consistent assessment of TRL.

2. Decomposition of Technology Readiness Level Definitions

The factors that affect the TRL include performance/function, fidelity of the physical realization of the technology often referred to as "form and fit", and survivability in the operational environment. These are measured against a set of requirements derived for the intended use of the technology in an applicable mission. Since part of technology development includes understanding the physical basis for the technology, completion criteria for each of the TRLs also depends on analyses that predict technology performance. Table 1a and Table 1b summarize the TRL definitions broken down by these factors.

Table 1a: TRL 1-6 Definition and Decomposition by Factor

TRL	Definition from NPR 7123.1e [1]	Completion Criteria from NPR 7123.1e [1]	Mission Req.	Performance/ Function	Fidelity of Analysis	Fidelity of Build	Level of Integration	Environment Verification
1	Basic Principles observed and reported	Peer reviewed documented principles	Generic class of missions	Knowledge underpinning technology concept/ applications	Physical principles identified	NA	NA	NA
2	Technology concept and/or application formulated	Documented description that addresses feasibility and benefit	Generic class of missions	Concept formulated	Feasibility presented	NA	NA	NA
3	Analytical and/or experimental proof-of-concept of critical function.	Documented analytical/ experimental results validating predictions of key parameters	Generic class of missions	Proof-of-Concept demonstrated analytically and/or by experiment	Low fidelity: to predict key performance parameters	NA, but could be low fidelity bread-board	NA	NA
4	Component and/or bread-board validated in laboratory environment	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.	Generic class of missions	Basic functionality/ performance demonstrated	Medium fidelity: to predict key performance parameters and life limiting factors as a function of relevant environments	Low fidelity: bread-board	Component /Assembly	Tested in laboratory for critical environments Relevant environments identified. Life-limiting mechanisms identified.
5	Component and/or brass-board validated in relevant environment	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.	Generic or specific class of missions	Basic functionality/ performance maintained	Medium fidelity: to predict key performance parameters and life limiting factors as a function of relevant environments	Medium fidelity: brass-board with realistic support elements	Component / Assembly	Tested in relevant environments. Characterize physics of life-limiting mechanisms and failure modes.
6	System/ subsystem model or prototype demonstrated in a relevant environment	Documented test performance demonstrating agreement with analytical predictions	Specific mission	Required functionality/ performance demonstrated	Medium fidelity: to predict key performance parameters and life limiting factors as a function of operational environments	High fidelity: prototype that addresses all critical scaling issues	Subsystem/ System	Tested in relevant environments. Verify by test that the technology is resilient to the effects of life-limiting mechanisms

Table 1 b: TRL 7-9 Definition and Decomposition by Factor								
TRL	**Definition from NPR 7123.1e [1]**	**Completion Criteria from NPR 7123.1e [1]**	**Mission Req.**	**Performance/ Function**	**Fidelity of Analysis**	**Fidelity of Build**	**Level of Integration**	**Environment Verification**
7	System prototype demonstration in an operational environment	Documented test performance demonstrating agreement with analytical predictions	Tech-nology demon-stration mission	Required functionality/ performance demonstrated	High fidelity: to predict key performance parameters and life limiting factors as a function of operational environments	High Fidelity: prototype or engineering unit that addresses all critical scaling issues	Subsystem/ System	Tested in actual operational environment
8	Actual system completed and "flight qualified" through test and demonstration	Documented test performance verifying requirements and analytical predictions	Specific mission	Required functionality/ performance demonstrated	High fidelity: to predict key performance parameters and life limiting factors as a function of operational environments	Final product: Flight unit; Life test unit for life limited items	System	Tested in project environmental verification program. Completed life tests
9	Actual system flight proven through successful mission operations	Documented mission operational results verifying requirements	Specific mission	Required functionality/ performance demonstrated	High fidelity: to predict key performance parameters and life limiting factors as a function of operational environments	Final product: Flight unit	System	Operated in actual operational environment

Fidelity of Analysis

Analysis and the development of analytical models for new technology is important for predicting performance during tests, understanding margins, conducting trades, assessing risks for "Test as You Fly" exceptions, as part of test beds, and many other reasons. Analysis is a key part of the completion criteria for each TRL. The fidelity of the analysis is assessed against three aspects – its content, its basis, and its validity.

Low fidelity analysis content covers key performance parameters for critical parts. Qualitative relationships between the key performance parameters are used to predict values at one design point. The analysis can be based on "rules of thumb" and empirical knowledge. No validation of the analysis is needed.

Medium fidelity analysis content covers life-limiting factors as well as key performance parameters for interfaces as well as critical parts. Qualitative relationships between the key performance parameters and life limiting factors are used to predict performance over relevant environmental ranges. It is based on analytical physical principles and "first order" equations. The analysis is validated against test to provide a moderate level of uncertainty. The range of applicability and limitations are identified and understood.

High fidelity analysis content covers a near complete set of parameters for a near complete set of parts and interfaces. Quantitative relationships between these parameters are used to predict performance over the range of operational environments. It is based on analytical physical principles, equations, and statistical methods.

High fidelity modeling tools such as finite element structural and thermal analysis and detailed optical codes are used. The analysis is validated against test to a low level of uncertainty. The range of applicability and limitations are identified and understood.

Fidelity of Build

For new technology development, the fidelity of the physical realization progresses from low fidelity breadboards to medium fidelity brass-boards to high fidelity prototypes. Once the new technology has been demonstrated as a prototype at the subsystem or system level it can be treated using the "standard engineering" approach for a new design with an engineering unit followed by qualification unit and a flight unit or, if the protoflight approach to qualification is used, by just the protoflight unit. Table 2 summarizes fidelity characteristics for various build units.

The "standard engineering" development cycle uses engineering design tools to produce the preliminary design for PDR. The detailed design, completed by CDR, includes detailed analysis, drawings or analytical models, and, for new designs, an engineering unit that is tested over the range of relevant environments. For designs that incorporate new technology an additional step, prior to PDR, is added to the design process culminating with a prototype tested in relevant

Table 2: Fidelity of Build

	Unit	Purpose	Performance/ Function	Form and Fit/ Scaling	Environmental Requirements	Parts Pedigree
New Technology	Breadboard	Proof-of-concept for a potential design	Demonstrate performance/ function	Not required, e.g. laid out flat on lab table	Tested in a laboratory environment	NA
New Technology	Brassboard	Demonstrate feasibility of form and fit, environments	Demonstrate performance/ function	Approximate (not flat) with scaling factors understood	Designed to meet relevant environmental requirements	NA
New Technology	Prototype	Representative design; pathfinder; demonstrator	Tested to meet performance/ function requirements	Representative with scaling factors understood	Tested to meet relevant environmental requirements	NA, but may be partial or full
Engineering Development	Engineering Unit	Finalize detailed design	Tested to meet performance/ function requirements	Exact as known at time of build	Tested to meet relevant environmental requirements	NA, but may be partial or full
Engineering Development	Qualification Unit	Qualify design	Tested to meet performance/ function requirements	Exact as known at time of build	Tested to meet flight qualification environmental requirements	Full
Engineering Development	Flight Unit	Final Product	Tested to meet performance/ function requirements	Exact	Tested to meet flight qualification environmental requirements	Full
Engineering Development	Flight Spare	Final Product	Tested to meet performance/ function requirements	Exact	Tested to meet flight qualification environmental requirements	Full

environments that demonstrates TRL 6. The objective of this additional design step is to bring the new technology to a similar level of maturity as the "standard engineering" elements. Once TRL 6 is achieved the "standard engineering" design approach is followed.

Fidelity of Environments

Laboratory Environment: Tests in a laboratory or field environment are for the purpose of demonstrating the underlying principles of technical performance/functionality without respect to the impact of environment. A laboratory or field environment is not required to address the environment to be encountered by the system, subsystem, or component during its intended operation.

Relevant Environment: A relevant environment approximates a specific *subset* of the operational environment that focuses specifically on "stressing" the technology advance in question. 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 simulated in ground test facilities required to demonstrate critical "at risk" aspects of the final product performance in an operational environment.

Flight Qualification Environment: A qualification environment is simulated in ground test facilities that the flight project defines will verify the system with margin (see JPL Design Principles for required margins).

Operational Environment: The operational environment is where the final product will be operated. In the case of space flight equipment, it is the space or planetary body environment.

Lifetime Requirements

For technologies where lifetime is a major consideration and a key technology issue, it needs to be addressed as part of the technology readiness assessment.

Technology maturation programs can address life requirements as follows:
For TRL 4, identify life-limiting mechanisms and failure modes.
For TRL 5, characterize, by means of test, the physics of the life-limiting mechanisms and failure modes and develop and validate an analytical model/simulation that predicts life limiting mechanisms and failure modes from which predictions of life duration can be made with some confidence.
For TRL 6, verify by test that the technology is resilient to the effects of life-limiting mechanisms. One method for this is to predict through analytical models the end-of-life conditions and then test that performance is met under those conditions.
For TRL 8 complete the life tests.

3. Technology Readiness Assessment

There are five steps in the Technology Readiness Assessment process.

1. Identify the performance/functionality and environmental requirements against which the TRL will be assessed.
2. Identify the new technology elements.
3. Identify the level of integration or configuration in which the technology readiness needs to be tested.
4. Conduct the TRA of each element.
5. Roll-up the TRL to higher levels of integration.

Each of these steps is discussed in more detail below.

Identification of Requirements

TRL assessments are done against a specific set of requirements. A new technology can be at a different TRL depending on the requirements. For instance a technology that has been demonstrated in low earth orbit, and is hence TRL 9 for an Earth remote-sensing mission, may be TRL 4 for an orbiting mission at Venus. Hence the mission requirements need to be identified and agreed upon by the technology provider and the customer. Each technology even if it has been

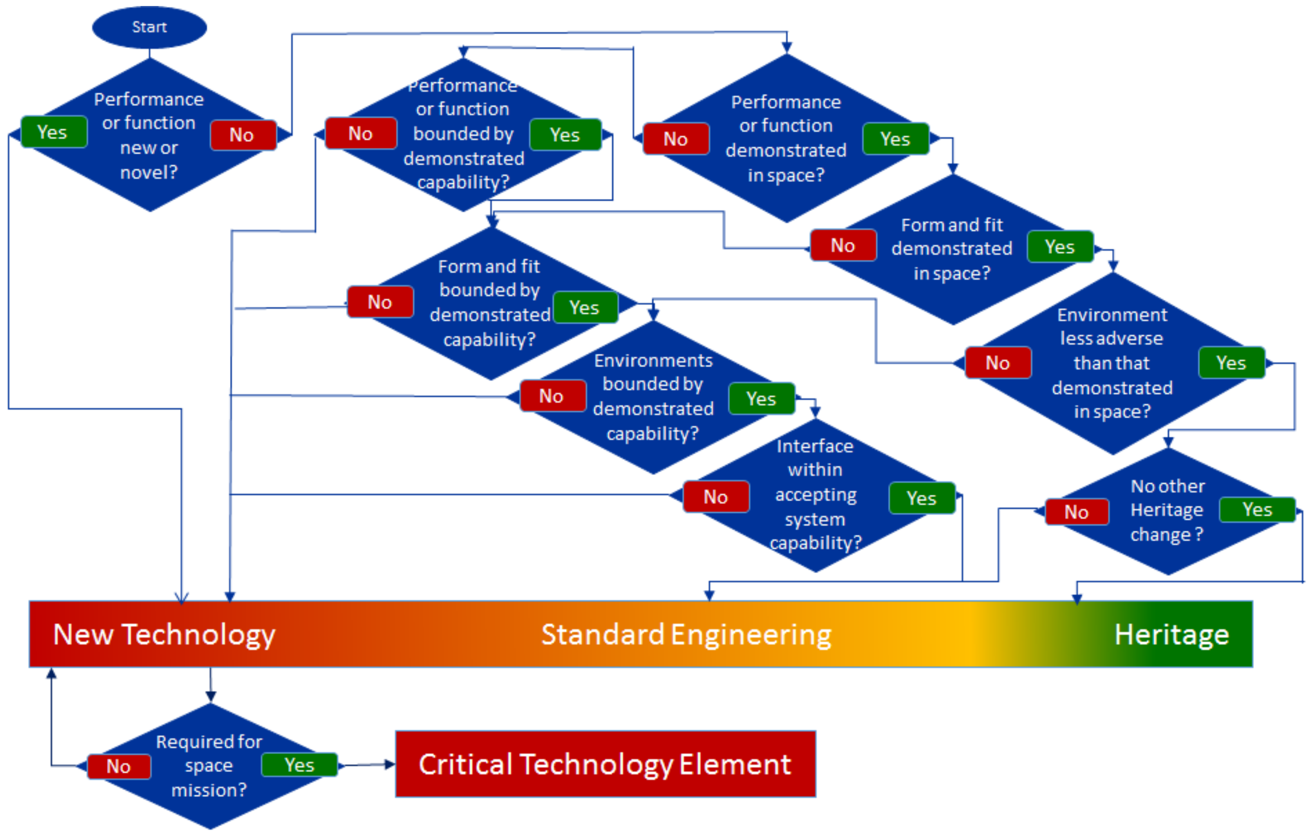

Figure 2. Flow Chart to identify whether an element is a new technology, standard engineering, or heritage. A new technology is critical if it is *required* for the space mission.

flown needs to be assessed with respect to its TRL when being used in a different environment.

Identification of New Technologies and Critical Elements

Only new technology elements are assessed for technology readiness. For instance, not all new designs are necessarily new technology. Some may be considered standard engineering. The flow chart in Figure 2 is provided to bin the elements of a flight system into one of three categories: new technology, standard engineering, or heritage. The flow chart is based on whether or not the characteristic of the system element is new or novel, bounded by demonstrated capability on the ground, or demonstrated in space flight operations. Often the boundary between new technology and standard engineering is somewhat fuzzy. Hence, the technology developer and the customer of the technology need to agree upon the identification of new technology elements. For low TRL, the technologist might have to estimate this with the help of a program office or a project system engineer. A Critical Technology Element (CTE) is defined as a new technology that is *required* for an operational mission.

Identification of Level of Integration for Test

The configuration for TRL verification occurs at the lowest level of integration that exhibits the new performance/functionality and for which the interfaces remain in the realm of standard engineering. Figure 3 illustrates a hierarchical breakdown of a system into its levels of integration including subsystems, consisting of assemblies that in turn consist of lower level elements. The elements determined to be new technology are colored red, while those defined as standard engineering are colored grey. In this example, Element A and B are new technologies that when combined into Assembly A provide the new capability.

Another factor is the maturity of the interfaces

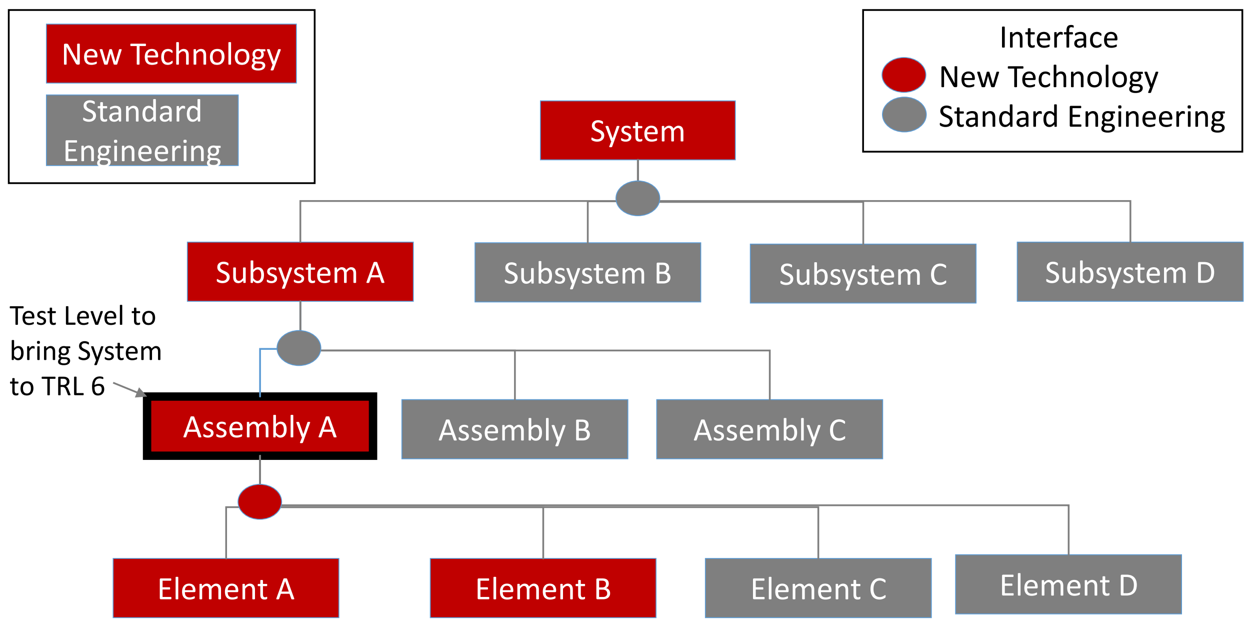

Figure 3. Level of integration needed to demonstrate system level TRL is determined by the lowest level at which the new technology can be demonstrated with interfaces that are standard engineering.

(mechanical, thermal, electrical, data, etc.). Interfaces can be characterized in a manner similar to elements. If the new technology is a "drop in" replacement for the element it is replacing, then the interface is heritage. That is, no change is required to the interface. If the interface requirements are within the bounds of previously demonstrated interfaces, then it is standard engineering. An example might be that the data throughput is 10 kbps, easily achievable with standard protocols. However, if the data throughput were 10 Tbps, it is outside the bounds of demonstrated performance, and then the interface, itself, requires new technology development.

TRL 4 and 5 can be demonstrated at the assembly level and do not necessarily address the interaction with other elements of the system.

TRL 6 is demonstrated at the lowest level of integration for which new behavior can be tested and the interface is standard. In Figure 3 this corresponds to Assembly A. Once TRL 6 is demonstrated for Assembly A, then the whole system is also at TRL 6 since there are no challenging interfaces for the higher level of integration.

Assessment of TRL

The TRL assessment for each element is conducted based on a set of questions for each level in a manner similar to that pioneered by James Bilbro [7]. The response to these questions is provided through *objective evidence* that can be a test report, a signed document, an analytical result, etc. All questions must be answered successfully to demonstrate the given TRL level. The questions are broken into four groups. The first identifies agreements between the technology provider and the customer. ~~The customer may be the technology development sponsor~~ For low TRLs in lieu of a customer this information can be obtained from program offices, knowledgeable system engineers or found in engineering specifications (e.g. for launch vehicles) or planetary body environmental specifications. For TRL 6 the customer is the project office.. These agreements identify the scope of the technology development. In some cases, both design requirements and test requirements are identified. The design requirements are associated with a specific mission or a range of missions, but not all those requirements need be demonstrated by test to achieve a given TRL. However it should be feasible for the new technology to meet the design requirements. The second addresses the analysis results while the third addresses the test results. These show the outcome of the technology development effort. Lastly, the fourth addresses the data package needed to document the agreements and results. This data package can range from a report or publication at lower TRLs to detailed design and performance data for higher TRLs. As an example, the questions for TRL 6 assessment are given below.

Questions to Assess TRL 6 Demonstration

Agreement between technology deliverer and customer:

1. What are the Critical Technology Elements?
2. What are the benefits of the new technology?
3. What are the *design* requirements? These typically include the following.
    a. Performance/Function (sensitivity, concept of operation, calibration, modes, autonomy, etc.)
    b. Form/Fit (mass, volume, layout)
    c. Interfaces (thermal, mechanical, power, electrical, data, signal/sample input, etc.)
    d. Operating environments (mechanical, dynamics, thermal, vacuum, radiation, EMI/EMC, etc.)
    e. Lifetime
4. What are the relevant environments?
5. What are the analysis requirements? This includes the following.
    a. Key performance parameters, life limiting factors, lower level of parameters
    b. Analysis based on “first order” equations
    c. Validation that provides a moderate analysis uncertainty factor and limitations
6. What are the test requirements? Note: Not all design requirements are tested. These include at minimum the following.
    a. Performance/Function
    b. Relevant environments
7. What is the level of integration and test configuration? For TRL 6, at minimum, the subsystem level is demonstrated by means of a prototype in the relevant environment.
8. What data are used to capture the agreements and results?

Analysis results:

9. What performance is predicted for the key parameters and life limiting factors for the test conditions? Note: these are in place prior to the test.
10. What are the analysis uncertainty factors and limitations?
11. Are the analyses updated based on the test results?

Test results:

12. Are the test requirements successfully demonstrated?
13. Are the variances between the test results within the analysis uncertainty? If not, are the variances understood?
14. Were there any unpredicted behaviors and if so was root cause determined and impact assessed and found to be acceptable?

End Item Data Package:

15. Is the end item data package complete?

Roll up of TRL

The “weakest link” approach is used to determine the TRL of a system. That is, the TRL of a level of integration can be no higher than the lowest TRL of its elements. It should be noted that there might be scenarios where a system’s TRL is lower than that of all its elements. An example might be a new architecture is used to provide new performance, but it uses all heritage parts. Then, to achieve TRL 6, the system would need to be integrated and tested to demonstrate the new performance. However, since the parts are all heritage, no environmental verification would be needed.

4. Risk Assessment associated with Progression to Higher TRLs

TRLs establish the maturity of a new technology at a given time. The degree of difficulty and the risk associated with progressing to a higher-level of maturity may vary significantly from one new technology to another. Several measures for this assessment have been suggested such as the Advancement Degree of Difficulty (AD2) [1]. However, these have yet to be implemented and validated as useful tools. Hence for the JPL TRA process the standard 5x5 risk matrix developed for flight project risk assessment will be used. Typically the risk assessment will be for one of the following as requested by the TRA convening authority:

1. Progression from TRL n to TRL n+1
2. Progression from current TRL to TRL 6
3. Progression from current TRL to TRL 9

5. Technology Readiness Assessment during Project Life Cycle

The TRA can be conducted either as a self-assessment within the project or program or for TRL 6 a preferred approach is that the flight program/project office elect to convene an independent TRA review board to provide an outside assessment. It is advantageous if the chair of this review board be a member of the project Standing Review Board (SRB) to ensure continuity and oversight.

Technology development associated with a flight project is identified early in the project life cycle and its maturity level needs to evolve to a confidence level that allows the project to proceed with manageable risk. For NASA operational missions, achieving TRL 6 by PDR has been established as the minimal appropriate maturation level [8]. Other types of projects have established other metrics. For instance NASA Technology Demonstration Missions, have an entry requirement of TRL 5 and a completion requirement of TRL 7.

The recommended guidance is to conduct TRAs during the formulation phase of operational projects, aligned with life cycle reviews (and key decision points) and the development of the Technology Maturation Plan (a gate product). Tables 3 shows the relationship between TRAs and project life cycle reviews. For technology demonstration tasks, the recommended guidance is to conduct TRAs during the concept formulation phase (i.e., proposal submission) and renewal/final review. Table 4 shows the relationship between TRAs and Technology Development Reviews. TRAs are done as part of the proposal/renewal and final reviews.

	Life Cycle Phases	Pre-Phase A Concept Studies	Phase A Concept & Technology Development	Phase B Preliminary Design & Technology Completion	Phase C Final Design & Fabrication
Assigned Missions	NASA Decision Points	KDP A	KDP B	KDP C	KDP D
	Life Cycle Project Reviews	MCR	SRR/ MDR	PDR	CDR
	JPL Technology Readiness Assessments	TRA-A	TRA-B	TRA-C	TRA-D
Competed Missions	NASA Decision Points	Down select	Proposal Selection	KDP C	KDP D
	Life Cycle Events/Reviews	Step 1 sub-mission	Step 2 sub-mission	PMSR PDR	CDR
	JPL Technology Readiness Assessments	TRA-A	TRA-B	TRA-B TRA-C	TRA-D

Table 3. Suggested timing for Technology Readiness Assessments in Flight Project Life Cycle

Life Cycle Phases	Concept Formulation	Technology Development	Concept Completion
Technology Program Decision Points	Proposal Selection	Renewal Approval	Technology Transition to Higher TRL Dev (or Flight)
Life Cycle Events/Reviews	Proposal Submission	Renewal Submission	Final Report
JPL Technology Readiness Assessments	TRA-A	TRA-B	TRA-C

Table 4. Suggested timing for Technology Readiness Assessments in Technology Project Life Cycle

Four TRAs are identified, with the objective of each evolving throughout the technology maturation program. The scopes of the four TRAs are given in Table 5.

Table 5: Scopes of TRAs

	TRA-A	TRA-B	TRA-C	TRA-D (if needed)
Definition of CTEs	Initial	Final	Update.	Update
Requirements	Initial	Final	Update	Update
Maturation Test Plan	Initial	Final	Assess implementation	Update
TRL Assessment	Assess TRL at project start	Assess interim TRL	Assess for TRL 6 at PDR	Update

6. SUMMARY

JPL has adopted TRA guidelines for the assessment of Technology Readiness Levels to provide consistent application for new technologies and increase the rate of infusion into flight projects. The next step is to ensure widespread communication, education and training of the guidelines to promote a common understanding of this methodology.

Acknowledgements

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Biographies

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Patricia M. Beauchamp *received a B.S. in Chemistry and B.A. in Mathematics from CSUF in 1976 and a PhD in Chemistry from Caltech in 1981 followed by a post-doctoral fellowship in Chemical Engineering. Before joining JPL in 1991 she managed a detector and materials research department at Aerojet ElectroSystems. Currently, Dr. Beauchamp is the Chief Technologist for the Engineering and Science Directorate at the Jet Propulsion and also assists the NASA Planetary Science Division in developing their Technology Plan. She is on the executive committees of the Outer Planet and Venus Science Assessment Groups and has been responsible and/or involved in developing technology plans for the Outer Planets, Venus and Small Bodies Assessment Groups. Her previous JPL assignments include serving as Manager of the Planetary Instrument Development Office, Leader of the Center for In-Situ Exploration and Sample Return (CISSR), and Project Manager for the MICAS Instrument on DS1. She is the recipient of the JPL Explorer, NASA Group Achievement, SGV Woman of Achievement in Science and AESC Recognition of Excellence Awards.*