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Technology Readiness Assessments using NASA's Best Practices Guide

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January 11, 2023

2023 Technology Showcase

Topics

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- A short history of the NASA Best Practices Guide
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- An example of how we use the Guide at JPL

Why do we need Technology Readiness Assessments?

- Communicating technology development maturity across disciplines
- Determining if a new technology is ready for infusion into a Flight Project
  - If assessments of technology are done rigorously and consistently, then more technology is likely to be infused
- Evaluating proposals against technology readiness criteria
  - For example, assess proposed new technology maturity to ensure that TRL 6 can be achieved by PDR
- Evaluating flight projects readiness to proceed at PDR
  - TRL 6 is used as a success criteria for new technology at PDR
- Tracking technology development
  - The TRL scale can be useful in many areas such as:
    - Early monitoring of basic or specific technology developments serving a given future mission or a family of future missions
    - Providing a status on the technical readiness of a future project, as input to the project implementation decision process
    - Monitoring the technology progress throughout development
- Managing a technology portfolio
- Responding to the Government Accountability Office (GAO) criticism that NASA has too much subjectivity in the processes used to identify and assess critical technologies
  - Understate the development risk that its major projects face.

History of Technology Readiness Levels and Assessments

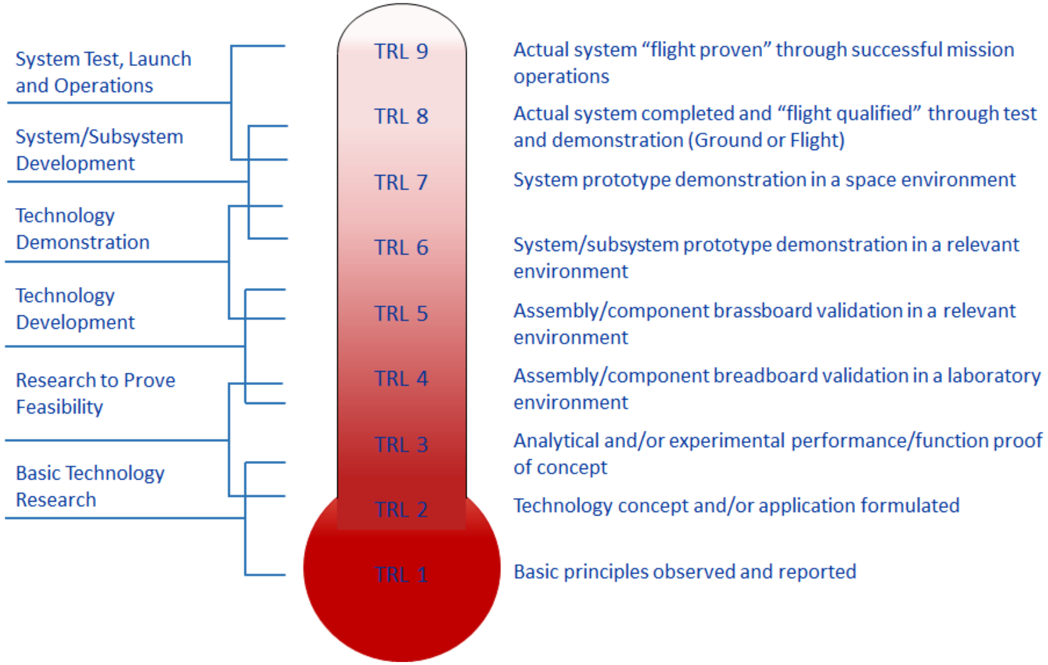
- **NASA 1988** : Sadin, Stanley R.; Povinelli, Frederick P.; Rosen, Robert (October 1, 1988). "The NASA technology push towards future space mission systems, presented at the IAF, International Astronautical Congress, 39th, Bangalore, India, Oct. 8-15, 1988."
- **NASA 1995**: J. C. Mankins "Technology Readiness Levels: A White Paper" (PDF). NASA Office of Space Access and Technology, Advanced Concepts Office.
- **DOD 2003**: "Technology Readiness Assessment (TRA) Guidance" U.S. Dept of Defense.
- **DOE 2004**: "Technology Readiness Assessment Guide (DOE G 413.3-4)."Us Dept of Energy, Office of Management.
- **ESA 2008**: "Technology Readiness Levels Handbook for Space Applications," European Space Agency, TEC-SHS/5551/MG/ap, Sep. 6, 2008.
- **JPL 2016**: "JPL Technology Readiness Assessment Guideline" M. A. Frerking and P. M. Beauchamp, IEEExplore.ieee.org/iel7/7494113/7500496/07500924.pdf
- **GAO 2019**: NASA Assessments of Major Projects (*NASA is planning to clarify its guidance on technology readiness*)
- **NASA 2020** "NASA Technology Readiness Assessment: Best Practices Guide," SP 20205003605, https://ntrs.nasa.gov/citations/20205003605

A short history of the NASA TRA Best Practices Guide

- **2010-11** Dr Jim Green convened the **Planetary Science Technology Review Panel** to support PSD in developing a coordinated and integrated technology development plan that will better utilize technology resources
  - Major Process recommendations were:
    - MR-6) Develop a more consistent and accurate TRL assessment process
    - MR-7) Develop clear, transparent, and consistent decision and review processes
    - MR-8) Develop a more structured and rigorous process to create interactions between technologists, scientists, and missions
- **2012-13** Conducted surveys of all NASA Centers and presented findings to PSD, the PE Forum, OCT and OCE
- **2014-15** NASA OCE and OCT convened a working group to identify issues and address NASA TRA practices and update TRL definitions. Government Accountability Office (GAO) was also getting interested at this time.
- **2016-2017** NASA Administrator Bridenstine requested a new NASA-wide TRL/TRA Guideline in response to a GAO action. OCE and OCT reinstated a sub-set of the multi-Center working group to carry develop the Best Practices Guide and OCE updated NASA documents to reflect changes.
- **2020-21** Technology Readiness Assessment Best Practices Guide published after reviews. Updated in 2021.

Technology Readiness Levels: What was the issue?

- TRL definitions were not clear – could be interpreted differently
- TRL definitions and guidelines distributed among several NASA Procedural Requirement (NPR) documents (NPR 7123, NPR 7120.8, NASA Systems Engineering Handbook)
- TRL assessment was inconsistent
  - Technologist over-estimate readiness
  - Flight projects are overly risk averse
  - Proposal review boards assess differently from AO to AO
  - Variation from NASA Center-to-Center
- Unclear requirements against which TRL was assessed (e.g. new technology qualified for Earth-orbit but not Mars surface)
- Software TRLs not standard for software community – Software TRLs are now removed from the NASA Guideline



Thermometer Scale for NASA's Technology Readiness Levels

What is new in the Guideline?

- Modifies TRL definitions for completeness and clarity
  - Includes examples at each TRL plus a complete technology maturation life example for Terrain Relative Navigation.
- Provides clarity of Technology Readiness Level factors
  - Performance/Functionality
  - Form and fit
  - Environments
  - Analysis
- Develops distinction between Standard Engineering and New Technology Development
- Includes development to address lifetime requirements
- Does *not* include software development
- Defines roll-up TRL to integrated elements
  - Level of integration is required to verify by test to achieve a TRL
- Identifies 5-step Technology Readiness Assessment Process
  - Identify the performance/functionality and environmental requirements against which the TRL will be assessed.
  - Identify the new technology elements.
  - Identify the level of integration or configuration in which the technology readiness needs to be tested.
  - Conduct the TRA of each element.
  - Roll-up the TRA to higher levels of integration.

What does the Guide tell us?

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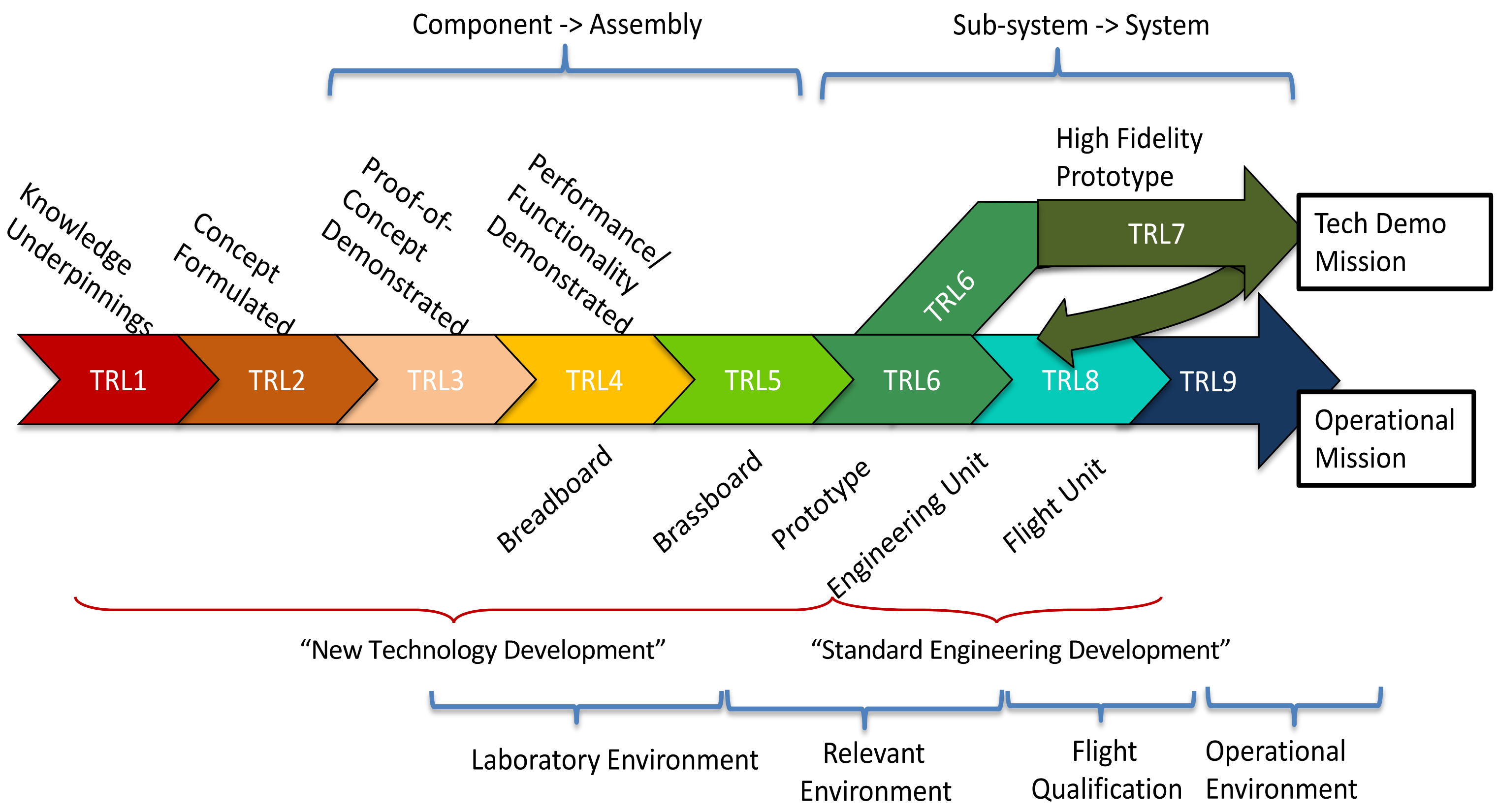
New Technology Development Cycle



- New Technology development cycle includes steps to demonstrate performance and robustness leading to TRL 6
- Once TRL 6 is demonstrated follow “standard engineering” development cycle for new designs; e.g. engineering unit then flight unit

Life-cycle Example of Technology Readiness Levels – Terrain Relative Navigation

TRL	Year Achieved	Technology State
1	1989	Mars pinpoint landing concepts and enabling technologies were explored under the Mars Rover Sample Return mission study (A. Klumpp, “Pinpoint landing concepts for the Mars Rover Sample Return mission”, AAS Paper 89-046, Annual Rocky Mountain Guidance and Control Conference, 1989).
2	2004	Formulated the concept of terrain relative navigation, its benefits, and desired performance characteristics for many solar system bodies. Responded to release of the NASA Research Announcement for the New Millennium Program Space Technology – 9 (ST-9) mission, with Appendix D on Terrain-Guided Automatic Landing System for Spacecraft (TGALS).
3	2005	Studies funded by Mars Technology program provided analytical and experimental proof-of-concept of onboard registration of features seen in descent imagery to Mars orbital imagery (Y. Cheng, “Landmark based position estimation for pinpoint landing on Mars”, IEEE International Conference on Robotics and Automation, 2005)
4	2007	By the end of the Study Phase of the ST-9 mission, terrain relative navigation algorithms were tested by off-line processing of a set of IMU, descent image, and ground truth data collected during a sounding rocket flight conducted to emulate the conditions of Mars landing (A. Johnson, et al, “A general approach to terrain relative navigation for planetary landing,” AIAA Infotech@Aerospace Conference, 2007). Performance agreed with analytical predictions from planetary imagery and a simulation of Mars imagery.
5	2013	Using funding from the NASA SMD Mars technology Program, the real-time Lander Vision System (LVS) was designed and implemented on prototype computing hardware with a path to flight implementation. The compute element was interfaced to a COTS camera and IMU that met the requirements for Mars landing. The performance of the working system was demonstrated to meet processing time requirements in the lab. Short range lab test results scaled well to predicted performance at Mars EDL ranges. (A. Johnson et al., “Design and Ground Test Results for the Lander Vision System”, AAS GN&C Conference 2013).
6	2015	The prototype LVS implementation was completed and tested in real-time on a manned helicopter over a wide variety of scenes. (A. Johnson et al., “Real-Time Terrain Relative Navigation Test Results from a Relevant Environment for Mars Landing” AIAA SciTech Conference 2015). The LVS preliminary design for Mars 2020 was completed and reviewed at the Mars 2020 TRN PDR, which included extensive simulation results for Mars 2020 landing.
7	2015	The LVS prototype was integrated with a vertical take-off and vertical landing rocket and used successfully in two closed loop pin-point landing demonstrations (N. Trawny et al., “Flight testing of terrain-relative navigation and large-divert guidance on a VTVL rocket,” AIAA Space Conference 2015).
8	2020	Mars 2020 LVS implementation was completed, environmentally tested and delivered to spacecraft integration. (2018). Software and firmware completed (2019). Real-time LVS helicopter field test completed successfully and results match simulation (A. Johnson et al., “The Mars 2020 Lander Vision System Field Test, AAS GN&C Conference, 2020). All V&V completed including flight system testing (April 2020).
9	2021	The 2020 Mars rover mission achieved this milestone by using TRN successfully during terminal descent.

Example of TRL Definitions -TRL 5

TRL	Definition	Description	Success criteria
5	Component and/or brassboard validated in relevant environment.	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 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. International Space Station (ISS) Additive Manufacturing Facility: Characterization tests compare parts and material properties of polymer specimens printed on ISS to copies printed on the ground.

Decomposition Factors used to Assess TRL- example TRL 6

- Definition and Completion Criteria
- Nature of requirements
- Performance/function
- Fidelity of analysis
- Fidelity of build (form, fit and function for TRL 6)
- Level of Integration
- Fidelity of environmental test

TRL	Definition	Completion Criteria	Mission Req.	Performance/ Function	Fidelity of Analysis	Fidelity of Build	Level of Integration	Environment Verification
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

Fidelity of Analysis

Fidelity	Content	Basis	Validation
Low	Key performance parameters (KPPs). Includes critical parts.	Quantitative relationship between KPPs to predict values at one design point. May be based of on “rules of thumb” and empirical knowledge.	NA
Medium	Key performance parameters and life limiting factors. Includes critical parts and interfaces.	Quantitative relationship between KPPs and life limiting factors to predict values as a function of relevant environments. Based on analytical physical principles and “first order” equations.	Validation against test of technology with moderate level of Model Uncertainty Factor (MUF) assessed. Range of applicability and limitations identified and understood.
High	Near complete set of parameters including key performance parameters, life limiting factors, and other relevant parameters. Includes near complete set of parts and interfaces.	Quantitative relationship between KPPs and life limiting factors with additional level of detail to predict values as a function of operational environments. Based on analytical physical principles, equations, and statistical methods. Use of high fidelity modeling tools such as finite element analysis structural, and thermal codes and detailed optical codes.	Validation against test and other analytical models with low level of Model Uncertainty Factor (MUF) assessed. Range of applicability and limitations identified and understood.

Fidelity of Build

Unit		Purpose	Performance/ Function	Form and Fit/ Scaling	Environmental Requirements	Pedigree
New Technology Development	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
	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
	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
	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
	Flight Unit	Final Product	Tested to meet performance/ function requirements	Exact	Tested to meet flight qualification environmental requirements	Full
	Flight Spare	Final Product	Tested to meet performance/ function requirements	Exact	Tested to meet flight qualification environmental requirements	Full

Fidelity of Environments

- **Laboratory Environment**
  - Tests in a laboratory 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 and 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 flight qualification environment is simulated in ground test facilities that the flight project defines will verify the system with margin.
- **Operational (Space) Environment**
  - The operational environment is where the final product will be operated. In the case of space flight equipment, it is the space or planet environment.

TRL and Lifetime Requirements

- Address lifetime when it is a critical consideration
- Lifetime verification stages
  - TRL 4: Identify life-limiting elements
  - TRL 5: Characterize, by test, the basis of life-limiting mechanisms and failure modes
  - TRL 6: Verify by test that new technology is resilient to life-limiting mechanisms
  - TRL 8: Complete life tests

TRL and Scaling

- TRLs 5, 6, and 7 mention scaling
  - Form and Fit: scaling factors and issues understood
- Concept of “scaling” came from aeronautics where scale models were tested in wind tunnels
- Sometimes difficult to determine how to handle in SMD.

TRL/TRA Guideline Highlights: 5-Step TRA 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 new technology element.

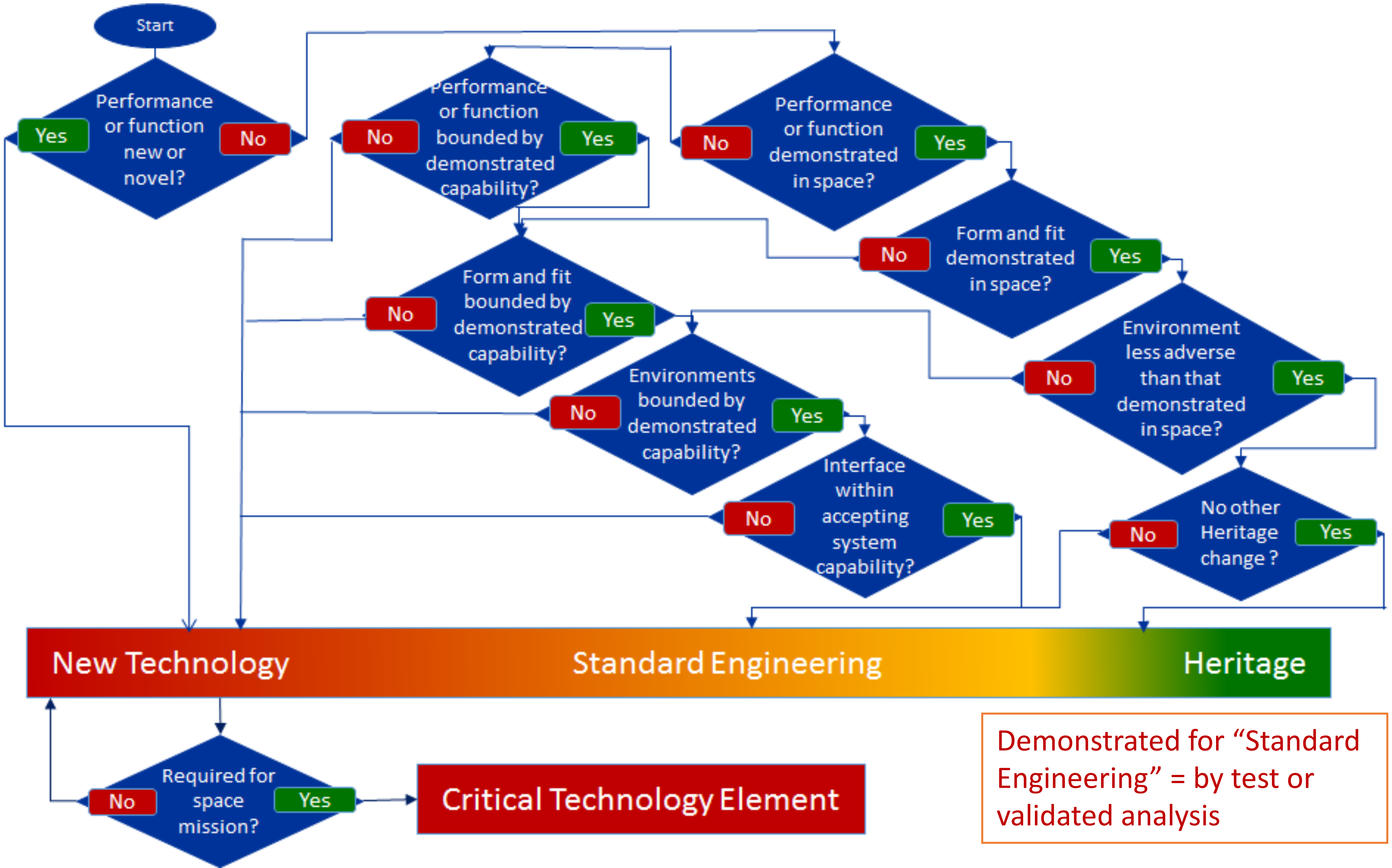
5. Roll-up the TRA to higher levels of integration.

Step 1: Identify Requirements

- Performance/functional
- Environmental
- Lifetime

Note – These needs to be agreed upon between technology developer and customer or program office

Step 2: Identify New Technology Elements

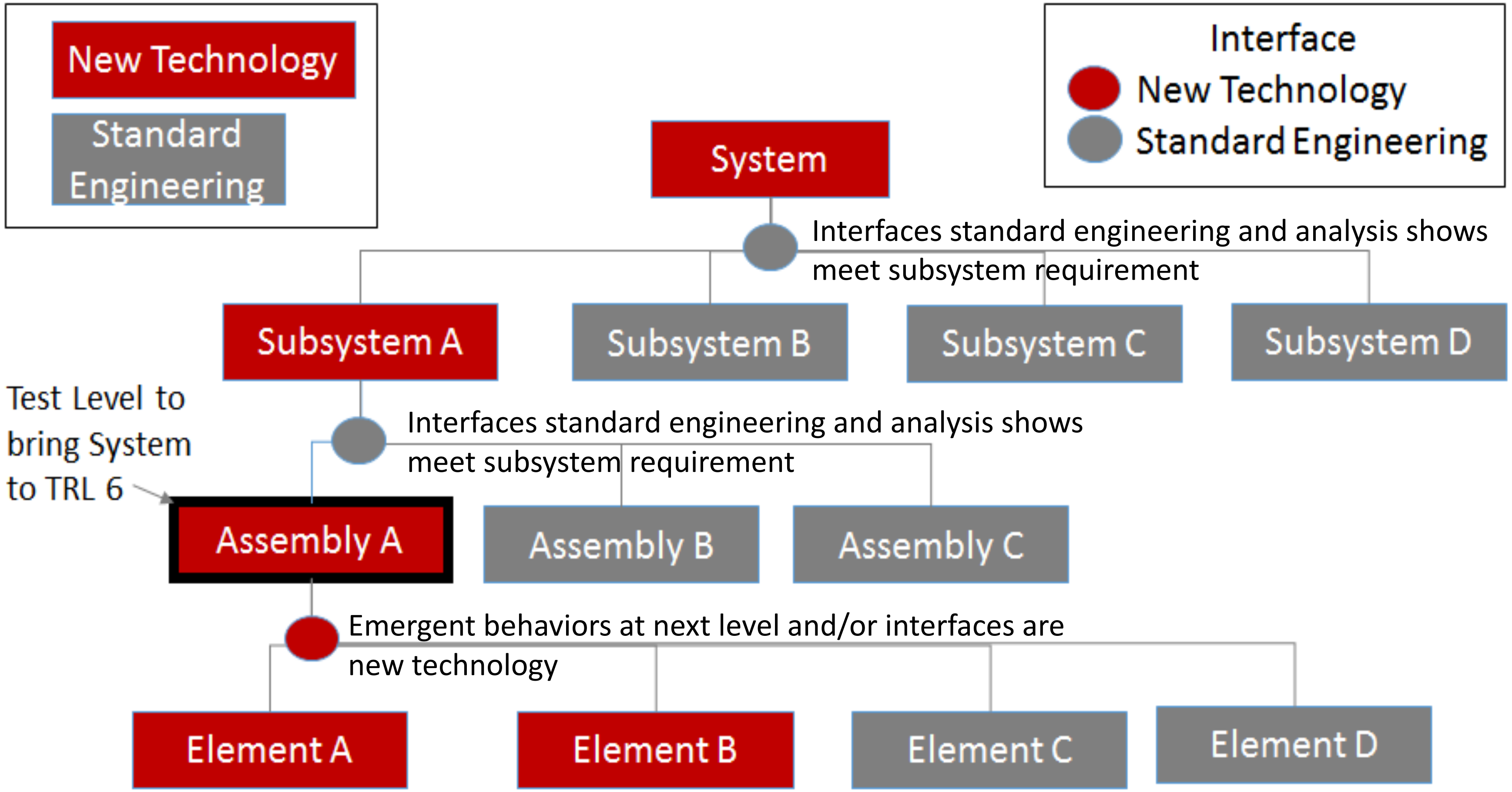


Demonstrated for "Standard Engineering" = by test or validated analysis

Discussion

- New design doesn't have to be New Technology
- Crux of the Standard Engineering versus New Technology debate
  - Go back to basics – this is about risk of unforeseen problems
    - New design that is "Standard Engineering" is lower risk than a new design that is "New Technology" because it is bounded by similar designs that have been proven to work in space-like environments
    - Life cycle of new design that is "New Technology" has an additional "spin" – the TRL 6 demonstration prior to PDR; it then follows the "Standard Engineering" process for new designs – engineering unit prior to CDR followed by the flight unit that goes through flight qualification
- If an element is not within bounds through test, but its design employs **well-validated analysis using verified inputs**; then it may be classified as "Standard Engineering"
  - Structural design
  - Thermal design
  - Circuit layout

Step 3: Identify test level for each new technology element to demonstrate TRL 6



- Only assess TRL for "New Technology Elements"
- Interface and emergent behavior determines level of integration to achieve next TRL level – in general test at lowest level of integration possible to reduce cost

Step 4: TRL Assessment

- A number of questions in four categories
  1. Agreement between technology deliverer and customer on requirements, environments, etc.
  2. Analysis results
  3. Test results
  4. Data Products
- **Pass Criteria**: Positive response to all questions ***<u>with objective evidence</u>***

TRL/TRA Guideline Highlights: Assessment Questions: TRL 3

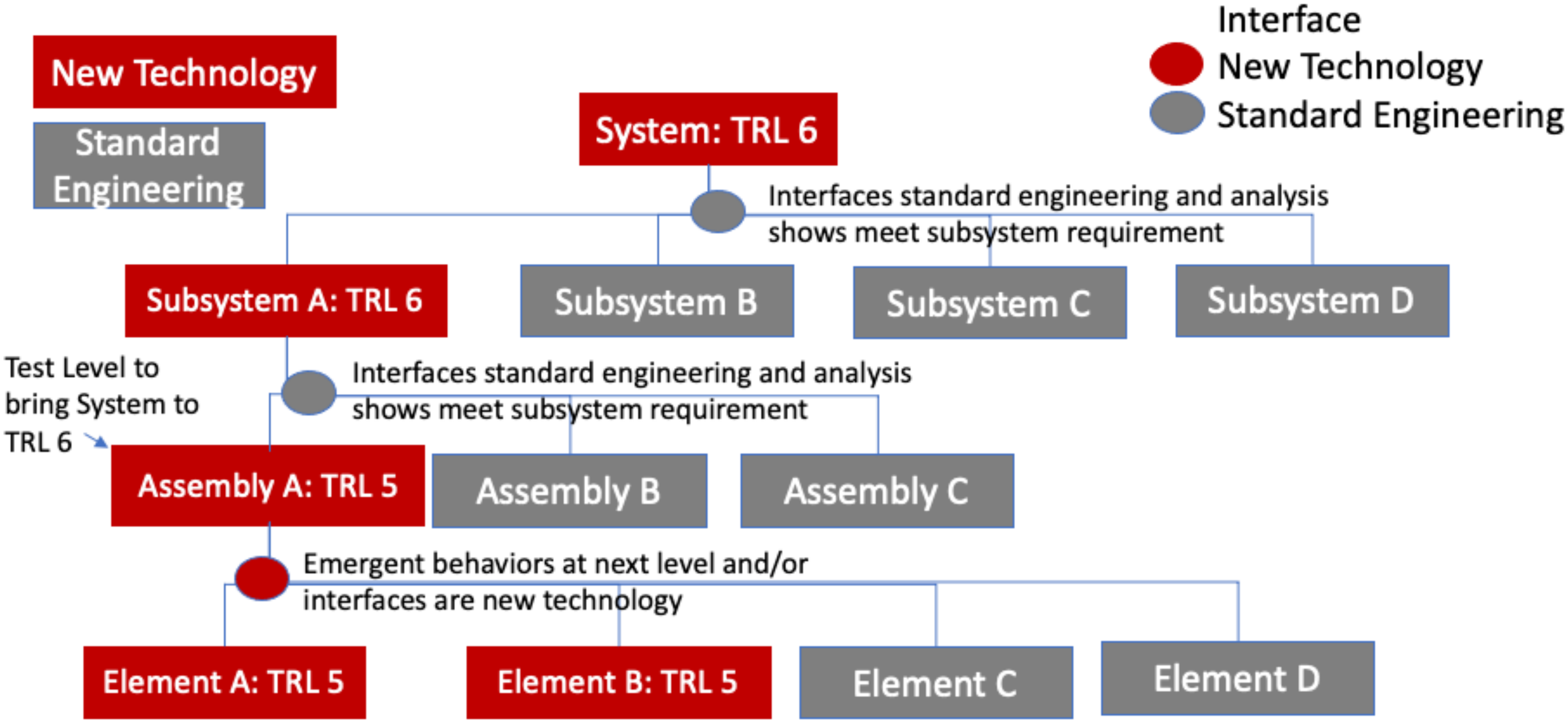
- **Questions: TRL 3**
- *Agreement between technology deliverer and customer: customer (here the customer is, for instance, the sponsor supporting the research).*
  1. What are the Critical Technology Elements?
  2. What are the benefits of the new technology?
  3. What are the applications and the performance/function needed for those applications?
  4. What are the likely operating environments?
  5. What are the analysis requirements? This includes, at a minimum, the following:
     - Key performance parameters (KPPs)
     - Relationship between KPPs based on empirical knowledge and "rules of thumb"
  6. What are the analyses and/or experiments needed to provide a "proof-of-concept"?
  7. What data are used to capture the agreements and results?
- *Analysis results*
  8. Does the predicted performance for the key parameters provide the "proof-of-concept"?
- *Test results (when applicable)*
  9. Is the "proof-of-concept" successfully demonstrated?
- *Data Products:*
  10. Are the data products, agreed to in Question 5, above, complete? (Here this could be a report to the sponsor.)

Step 5: Roll up of TRL to the System Level

- Weakest Link approach: TRL of a higher level of integration can be no higher than the lowest TRL of its elements
- The maximum TRL of a component or assembly – in isolation – is TRL 5
- System is TRL 6 if
  - Demonstrated by test at the system level,

    or
  - All its new technology component/subsystems are demonstrated to be TRL 5, in isolation, to requirements of the system ***and*** analysis shows that
    - All interfaces are standard engineering ***and***
    - No emergent performance at the system level

Step 5: Roll up TRL to System level



- Only assess TRL for "New Technology Elements"
- Weakest Link – TRL at integrated level is lowest TRL in lower levels
- Interface and emergent behavior determines level of integration to achieve next TRL level – in general test at lowest level of integration possible to reduce cost

How to use the Guide

- Develop consistent approach to Technology Readiness Assessment
- Make sure the Requirements are well defined. TRL is always associated with Requirements
  - Requirements may change as TRL advances
  - Low TRL: Generic class of mission
  - Medium TRL: Design Reference Mission
  - TRL 6-9: Specific mission requirements
- Provide training in Technology Readiness Assessment
- Ensure that the answers to questions are documented
- Encourage independent review (external to project and technology development task)
- The TRA can be convened by many means and tailored depending on the needs of the task or project.
  - Low TRL Project/Task may convene a self-assessment within the project/task
  - Project/Task may convene an independent assessment
  - External source e.g. customer can convene an independent assessment of a task/project

Example of Using the Guide - JPL

- JPL has adopted the NASA TRA BP Guide and conducted training of personnel:
  - Conducted multiple training courses, which are now recorded and exist on a lab-wide website
  - Adopted an independent review process and encouraged low TRL-stage to self-assess.
  - Trained multiple independent reviewers in all divisions of the Engineering and Science Directorates (ESD) as well as the program Directorates, including
    - Division level Engineers, Technologists and SMEs
    - Directorate level Technologists and Engineers
    - Put processes in place to document TRAs (via Memos) and maintain a library of TRA Memos and back-up documents.
  - JPL also has an institutional certification process if requested, which is signed by the JPL ESD and OCE.
- Use for an assessment of an external technology that is needed on a task/project as well as internal technology developments.

Tips on what works well for any TRA Assessment

- Select a TRA Review board chair that is familiar with the technology
- Ensure there are active, knowledgeable participants on the board
- Ensure the technologists associated with the assessed technology provide data to back up the claims associated with answering the TRA questions.
- Once a TRL has been established, the board should ask for ‘best effort’ completion of the questions in the next highest TRL e.g. if a technology is assessed at TRL 5 then answer as many TRL 6 questions, to figure out what remains to be done.
- The difference between what has been accomplished for the next highest TRL and the remaining tasks for that level e.g. TRL 6 constitutes the Technology Development Plan moving forward. This makes an excellent story in a proposal. Effectively, the Technology Plan falls out of the Assessment.

What does the Guide NOT tell us?

- The requirements definitions for the technology
  - Performance/functional
  - Environmental
  - Lifetime
- Risk of advancement to higher TRLs is, e.g. TRL 6 to TRL 9
- Manufacturing readiness

Summary

- NASA Technology Readiness Assessment Best Practices Guide SP 20205003605 is available at https://ntrs.nasa.gov/citations/20205003605
- This guide establishes standard definitions and best practices for conducting technology readiness assessments (TRAs) for in flight projects and NASA's research and technology missions.
- Provides an equitable, consistent methodology to conduct TRAs of internal or external NASA technologies.
- Conflicting NPR documents have been and are being updated to reflect content.
- Thanks to Steve Hirshorn (NASA OCE), Sharon Jeffries (LaRC) and Bill Kimmel (LaRC retired) for leading the NASA working groups.

QUESTIONS?