Aerospace Science and Technology 46 (2015) 312–320

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

In search of technology readiness level (TRL) 10

Jeremy Straub *

Department of Computer Science, University of North Dakota, 3950 Campus Road, Stop 9015, Grand Forks, ND 58202-9015, United States

ARTICLE INFO

Article history:
Received 13 February 2014
Accepted 11 July 2015
Available online 29 July 2015

Keywords:
Technology readiness levels
Technology maturity
TRL
Technology assessment
TRL 10

ABSTRACT

The NASA nine-level technology readiness level (TRL) system's top level is reached by a system being proven through use in a space mission. NASA, though, is not just an organization that seeks to develop unproven technologies. Future space activities require technologies more akin to an airliner than an Apollo Capsule. This paper considers the need for a higher TRL category indicating a proven technology demonstrated through extended operations, and it discusses its definition and sufficiency.

1. Introduction

In 1974, the precursor of the current NASA technology readiness level (TRL) system was developed by Stan Sadin [1]. This system, which contained seven levels, was codified in a 1989 paper [2]. The system was adapted to include nine levels in 1990 [1]. In 1995, John Mankins codified the nine-level TRL system in a white paper [3] which provided a limited description of each level and its attainment criteria. Level 9 of this system was defined as an "actual system 'flight proven' through successful mission operations", which Mankins defined as having as including "small fixes/changes to address problems found following launch" [3]. This is suggested, nominally, as occurring within 30 days of operations (though it is noted that another timeframe could also be utilized). Derivatives of the NASA TRL system are found defining technical readiness for the European Space Agency (ESA) [4], the U.S. Department of Energy (DoE) [5], the Department of Homeland Security (DHS) [6], the Department of Defense [7] and others. These systems all follow, generally, the level definitions of the NASA nine-level system (with adaptations to the specific agency needs). Within NASA, the TRL system has been used for both space [8] and aeronautics (e.g., [9,10]) applications.

In 2000, Brown and McCleskey [11] proposed a new TRL containing a level 10 which indicated "flight-certified maturity" akin to "FAA commercial air transport certification for airports and airliners"; however, they provided no definition. A similar description was included in a 2009 paper by Robinson et al. [12] which described this proposed technical readiness model for "space transportation generation 2 and beyond". This paper presents a background of the NASA TRL system, how it is used and the use of NASA-like TRLs by other agencies. Next, it considers why TRL 10 is required. Then it defines, formally, what TRL 10 entails. Then, whether augmenting the TRL scale with level 10 is enough is considered.

2. Background

This section provides background information on technology readiness levels. This begins with a discussion of the NASA TRL System. The use of TRLs at NASA is then discussed. Finally, the TRL systems used by other agencies are discussed.

2.1. The NASA TRL system

Mankins [13] proffers that the notion of TRLs started in the 1960s, with its codification in a 1969 report describing a needed "technology readiness review". In the 1970s, the need for a "technology-independent scale" was identified and this was referred to as "technology readiness levels" in the late 1970s [13]. The initial TRL scales, developed by Stan Sadin, consisted of either six or seven levels (Banke [1] indicates that it was seven; Mankins [13] states that versions had either six or seven) with "brief one-line characterizations of the definition" [13] for each of the levels. A version of the seven-level system was published in 1989 [2]; however in this same year, Mankins (in the context of the Space Exploration Initiative) added levels 8 and 9 to the TRL scale.

The TRL scale gained widespread use in the 1990s [13] as part of the development of the "Integrated Technology Plan for the Civil Space Program" [14]. The TRL scale was also used for numerous

* Tel.: +1 (701) 777 4107; fax: +1 (701) 777 3330.
E-mail address: jeremy.straub@my.und.edu.

http://dx.doi.org/10.1016/j.ast.2015.07.007
1270-9638/

NASA documents throughout the early 1990s: both for management of internal technical development and external communications [13]. In 1995, Mankins created the "Technology readiness levels" white paper [3] that provided a "compressive set of definitions of the technology readiness levels" which serve as the basis for the TRL system to this day. Mankins [13] indicates that this report also served as the basis for the General Accountability Office recommendation that the Department of Defense should use a similar (or the same) system, leading to the DoD adopting the NASA TRL system in 2000. Between the release of the 1995 report and 2006, the system gained popularity internationally as well; Mankins [13] indicates that it has "been formally adopted world-wide". The TRL system is part of the technology readiness assessment process, along with performance objective and research/development "degree of difficulty" data [13].

Clearly, however, this basic system of TRLs was not meeting the needs of all prospective users at NASA (or working on NASA projects). In 2000, Brown and McCleskey [11] proposed a TRL level 10 to augment the TRL scale to denote the difference between a single use in operation and prolonged operational use. Sauser et al. [15] proposed, in 2006, the use of a systems-level readiness metric (the "systems readiness level"). This solved the problem of a lack of understanding how readily various technologies were to be integrated and the categorization of readiness of systems comprised of multiple technologies. It utilized a seven-level integration readiness level scale and a five-level system readiness level scale.

Robinson et al. [12] use Brown and McCleskey's [11] proposed TRL level 10 in their work on discussing life cycle costs. They also note an only tangentially related problem: the differences in perception/assignment to TRLs, noting that between technology developers and application developers (those who use a technology to meet a mission need) the perception of the TRL may differ by as many as three levels. The "Research and Development Degree of Difficulty", proposed by Mankins [16] and the "Advancement Degree of Difficulty" proposed by Bilbro [17,18] are seen as prospective solutions. The incorporation of risk management into the technology assessment process is another area where the TRL system is lacking. Shenhar et al. [19] propose a matrix of TRLs and technology uncertainty as part of a risk classification system. Shishko, Ebbeler and Fox [20], alternately, propose that NASA technology assessment efforts must also incorporate expected value (and the time to provide this value) and riskiness. The TRL level serves as part of the riskiness assessment process.

In 2009, Mankins [16] proposed the "Research and Development Degree of Difficulty" system which combines the TRL concept with the "risk matrix" used previously for risk assessment and the "technology need value". This combined system considers how desirable it is to advance the TRL of a technology to a mission-usable level, the amount of advancement required and the difficulty for each TRL phase of advancement required. The Technology Readiness and Risk Assessment (TRRA) approach combines these values into a "technology risk matrix", which Mankins frames as a reformulation of the traditional risk matrix. The TRL system used in this work is the nine-level version which still fails to differentiate between technologies that have been used in a single mission and those which have been demonstrated in recurring operations.

2.2. NASA use of TRLs

The use of TRLs is pervasive at NASA. Technology readiness levels are used in the qualification and assessment of proposals; they are discussed in the NASA Strategic Space Technology Investment Plan [21], the NASA Systems Engineering Processes and Requirements document [22], the NASA System Safety Handbook [23], the NASA Systems Engineering Handbook [24] and the NASA Risk-Informed Decision Making Handbook [25], among others.

Some NASA solicitations (particularly those related to technology development) restrict applicability for proposing to technologies meeting specific starting and projected ending TRLs. The NASA Earth Science Technology Office's Instrument Incubator Program (IIP) requires technologies to enter at TRL 3 and be projected to exit at TRL 5 [26], for example; the NASA Unique and Innovative Game Changing Technology Solicitation focuses on "mid-TRL" technologies [27]. The In-Space Validation of Earth Science Technologies solicitation (which houses IIP) also includes programs to support TRL 2 to 6, 2 to 7 and 5 to 7 progression, as well [28].

In the NASA Strategic Space Technology Investment Plan [21], it states that NASA will "balance investments across all levels of technology readiness" and devote at least 10% of its technology portfolio to TRL 1 and TRL 2 technologies. The TRL level is utilized to manage the pipeline of technologies. In 2012, 8% of investment was made in TRL-1 technologies, 10% in TRL-2, 36% in TRL 3, 24% in TRL-4, 19% in TRL 5, 3% in TRL 6 and 0.1% in TRL 7 technologies. The TRL level is also used in the classification of "advanced" propulsion technologies (which must be below TRL 3).

The NASA Systems Engineering Processes and Requirements document [22] lists the TRL as a success criteria evaluation mechanism for program implementation reviews and program status reviews. Reviewers should check to ensure that "adequate progress has been made relative to plans, including the technology readiness levels". Programs and projects, it states, must use "technology readiness levels (TRLs) and/or other measures of technology maturity are used to assess maturity throughout the life cycle of the project". It explicitly utilizes the nine-level TRL scale, including a version that defines hardware and software descriptions and exit criteria as an appendix.

Readers of the NASA System Safety Handbook [23] are instructed to consider the appropriateness of the TRL of technologies to determine whether "the design minimizes the potential for vulnerability to unknown hazards" as part of determining whether "the system design meets or exceeds the minimum tolerable level of safety". The TRL is also considered as part of assessing whether "appropriate historically-informed defenses against unknown and un-quantified safety hazards are incorporated into the design" as part of determining whether "the system design is as safe as reasonably practicable (ASARP)" and the overall adequacy of the system's safety.

In the NASA Systems Engineering Handbook [24], the process of technology assessment is described in the context of managing technology insertion (use on a project). The technology assessment method described therein utilizes a technology maturity assessment process to ascertain the appropriate TRL and the Advancement Degree of Difficulty assessment process to determine the costs and risks of advancing the technology to the requisite level for use. A set of questions to ascertain TRL levels is provided in an appendix.

The NASA Risk-Informed Decision Making Handbook [25] utilizes the TRL metric for the science package as part of the risk assessment framework for mission analysis. It is also discussed in assessing risks in other areas of the mission as a useful quantitative metric.

2.3. Use of TRLs and TRL-like systems by others

Numerous entities beyond NASA have adopted a NASA-derived or NASA-like TRL system. Mankins [13] proffers that the NASA TRL system has been adopted worldwide. Some of these users have utilized the system as-is, while others have modified it to better suit their own needs. Still others have created guides to assist in the classification of technologies under the NASA or other systems.

The European Space Agency has utilized substantively the same TRLs as NASA; however, unlike NASA's limited descriptions in

Mankins white paper [3] and other sources, the ESA has issued a more detailed description. The ESA' handbook [4] defines each level and numerous standards that a technology must meet to be categorized at this level. While NASA's Systems Engineering Handbook [24] asks only a single question for classification for each level, the ESA handbook asks several and also defines evidence required to support classification. The ESA handbook also discusses software classification in a separate section. Some NASA TRL definition documents include a separate (or combined) discussion of software (such as the NASA Systems Engineering Processes and Requirements document [22]). The ESA TRLs, like NASAs, do not differentiate between the level of maturity of a technology used for a single successful mission and a technology which is frequently used.

The Department of Energy (DoE) utilizes a nine-level system [5] that is very similar to the NASA TRLs. The DoE definition for TRLs 1 to 4 actually match the wording (with minor deviations) used by Mankins 1995 white paper [3] (which has been altered by NASA in some subsequent publications such as [22]). The TRL 5 wording changes are minimal, clarifying that it is a system validation on a "laboratory scale" required for this TRL. For TRL 6 minor wording changes have been made (including the removal of a reference to "ground or space"). TRL 7 also keeps a similar meaning while removing a reference to the "space environment" and noting that this demonstration must be "full-scale" (which is implied in the NASA language). TRL 8 removes the word "flight" from "flight qualified" and removes a reference to "ground or space". It is TRL 9 where the greatest difference occurs. NASA requires the system to be "'flight proven' through successful mission operations", a criteria that can be met by a single mission using the technology (which is made clear in the question in the NASA Systems Engineering Handbook [24], "has an identical unit been successfully operated/launched in identical configuration/environment?"). The DoE, on the other hand, requires the "actual system" to have been "operated over the full range of expected conditions" [5], a standard exceeding NASA's significantly.

The Department of Homeland Security (DHS) also has adopted the NASA standards. Their adoption is nearly verbatim [6], with the removal of references to air and space. Their TRL 9, unlike the DoE's requires only that the "actual system" be "proven through successful mission operations". However, to augment the TRLs, the DHS has also adopted a set of Manufacturing Readiness Levels and Programmatic Readiness Levels. McGarvey, Olson and Savitz [6] also discuss the utility of integration and system readiness levels to DHS work, but note that they are not presently (2009) part of DHS acquisition procedures. The Department of Defense has adopted NASA's TRLs directly [13,29,30].

Others have created derivative systems. Lee, Chang and Chien [31], for example, have created a set of six innovation readiness levels, based off of the DoD/NASA TRLS. Vyakarnam [32] fits the NASA nine-level TRL system within the first three levels of a technology commercialization framework, using Rogers [33] "Technology Adoption Life Cycle model" for the remaining four levels. Hicks et al. [34] define TRL levels 10 and 11 (including at least eight sub-steps of TRL 10) for a product development process. While not necessarily aligned with a TRL 10 implementation for aerospace applications, it does demonstrate the deficiency of the nine-level TRL model for capturing later phases after initial successful use.

3. The need for TRL 10

This section reviews the need for a new level on the TRL scale, TRL 10. Five need-sources are now discussed. First, the use of TRL 10 in supporting commercial space operations is discussed. Then, the utility of TRL 10 for aligning air and space TRLs is considered. Third, the benefits related to supporting the use of commodity parts in spacecraft are presented. Next, there is a discussion of the use of TRL 10 in aligning the TRL systems across agencies (and relevant industries). Fifth, the role of TRL 10 in promoting space activity best practices is considered. Sixth, the drawbacks of making this change are discussed. Finally, whether the TRL 10 approach is the most appropriate for providing these benefits is assessed.

3.1. Supporting commercial space operations

Companies such as SpaceX and Virgin Galactic are planning recurring operations, not one-time missions as has been typical for most space operations. In assessing the suitability of technologies, such as new technologies that may be developed and spun-off by NASA, other agencies and private developers, companies planning recurring space operations will need to differentiate between technologies that have been used once and technologies for which longer-term performance characteristics are known. Grouping all technologies that have been successfully used for mission operations (whether one or one-million times) under a single TRL obfuscates the required evaluation process.

3.2. Aligning TRL systems for air and space

Aeronautics has already arrived (for many applications) at the destination that new space operators are aiming for. Airlines, air freight companies, militaries and other government agencies, private operators, flight schools and others operate numerous flights each day. Duty cycles for equipment are well understood and the technologies that are incorporated in these flight systems are proven. Newer technologies (such as some autonomous command systems and teleportation systems for drones) may have been used successfully for missions (e.g., drones have been used extensively for military purposes [35]) but are differentiated from more developed technologies (e.g., drones are currently now allowed to be generally used in U.S. airspace [36]). This distinction is clearly recognized in aeronautics and the addition of TRL 10 would allow unification of the TRL assessment process between NASA's air and space technology development efforts.

3.3. Supporting the use of commodity parts/products for spacecraft

The use of commercial off-the-shelf (COTS) parts for the construction of spacecraft has been promoted. Systems, such as Goldin's Faster, Better, Cheaper (FBC) approach use COTS components (or pre-developed technologies) to increase speed or decrease cost [37]. While FBC had been considered as discredited for some time, some recent studies [38] have been challenging this notion. Small spacecraft have been a key user of COTS parts, with several vendors [39] proving components or complete kits that can be used, integrated or adapted by spacecraft developers/integrators.

3.4. Aligning TRL systems across agencies and industries

Other agencies, such as the DoE, have modified the nine-level TRL system to support their own needs [5]. The DoE, in particular, has adapted TRL 9 to require more than demonstrated performance in a mission. Instead, the DoE looks at whether the technology has been tested across all expected usage conditions. Adding TRL 10 allows a single system to be utilized across multiple agencies. Additional sub-categories can be added to distinguish between different states that may need to be categorized (for various applications) within a single TRL.

3.5. Promoting best practices for future space activities

Future space activities may be able to take advantage of frequently used technologies that are not only demonstrated, but which have a history of successful performance (and for which the failure rates and conditions have been characterized over the operating history). In order to effect effective comparison of these technologies with other, less developed (but demonstrated through successful operations) ones, a separate classification is required.

3.6. Drawbacks of making a change

There are several prospective drawbacks to making this type of change. First, as has been demonstrated by the fact that several other agencies have not yet adopted changes made to the NASA TRLs after their initial adoption, making this type of change would create a period of discrepancy (where some have a ten-level TRL system and others still use a nine-level system). This may be particularly confusing if some who have created TRL 10-like conditions for TRL 9 fail to adopt the system (making the TRL 9 status user-dependent). Some agencies may not adopt the ten-level system, creating a permanent discrepancy. Ten-level systems (e.g., [11]) have been proposed before, but have not gained the traction of the nine-level system.

Second, the exact benefits proposed (the ability to discriminate between tested-and-true and used-once technologies) may impair technology adoption, as programs and craft developers favor the TRL 10 technologies over the up-and-coming TRL 9 ones. This may result in a delay in implementing promising mission-enabling technologies, as not only will a first-user need to embrace and demonstrate them, but others may need to use them several times, before they will be embraced for use in high-profile missions or for mission-critical applications.

Third, the implementation of the ten-level TRL system may impair the implementation of another TRL refinement or the replacement of the TRL system with another methodology. This issue is discussed in the following section.

3.7. Is TRL 10 the best way to fill these needs?

The continued use of the TRL system and the augmentation of it with the TRL 10 level is not the only way to serve the communities discussed in the foregoing sections. Within NASA and the federal technology development community, numerous other methodologies have been utilized to enhance, partially replace, augment or complement the TRL system. These include the "Research and Development Degree of Difficulty" [16] system, the "Advancement Degree of Difficulty" system [17,18] and augmentative integration and system readiness levels [6], among numerous others.

While a complete assessment of whether TRL 10 is the absolute best solution is not possible within the limited scope of this paper (and will certainly be a part of the community consideration process required to advance the technology assessment framework), it would seem that it offers two key benefits. First, the TRL system is easy to understand (and many already work with it). Given this, making this simple augmentation does involves less comparative disruption than a switch to another assessment system. Second, the proposed change would likely be less controversial (though there is no way of predicting this with any certainty) than a system-wide replacement. It would also allow the TRL system to continue to be utilized in conjunction with other augmentative and complementary systems with limited changes required to support the new level.

If additional granularity is required, multiple sub-classifications can be defined to further refine classifications to sub-TRL granularity levels. The use of sub-classifications within the proposed TRL 10 is discussed in Section 5.2.

4. Defining TRL 10

This section provides a definition for TRL 10. First, a definition statement is proposed, in line with the format used by Mankins [3] and NASA TRL overview documents. Next, a definition for TRL 10 for both hardware and software (in line with the descriptions used in [22]) is provided. Third, a question to add to the TMA thought process is presented. Finally, a definition of TRL 10 in a format similar to that used by the ESA (in [4]) is presented. Each section (except 4.4) presents the complete ten-level TRL system including the new level 10 (Section 4.4 is unable to present this, due to the length of the ESA document).

4.1. Definition relative to NASA TRLs

A definition for TRL 10 is proposed as follows:
Proven Operations

- The technology has been used without incident (or with incident levels within an acceptable range) for a protracted period of time.
- The technology has been certified (if applicable) via appropriate technology-type certification mechanisms through evaluation of repeated operations and other means.
- Failure rates for the technology are known and failure conditions and their causes are understood.
- The technology/system operates without unacceptable levels of unplanned troubleshooting or repair being required.

The definition draws on the notion of certification advanced by Brown and McCleskey [11] and extrapolated on by Robinson et al. [12]. It also draws upon the notion advanced by Robinson et al. [12] of not requiring significant unexpected repairs and troubleshooting. Robinson et al. had used this as one part of their definition of the phrase "without loss of system integrity" used in both their and Brown and McCleskey's definition for TRL 10, in addition to suggesting that operations should not require the system to be routinely disassembled or to require ongoing verification activities (e.g., electrical, fluid and structural integrity). However, given that the routine operations of aircraft require these elements on a regular basis, this has been removed from the TRL 10 definition. Table 1 presents the TRL definitions with level 10 added, Fig. 1 depicts this visually.

4.2. Hardware and software definitions

Proposed hardware and software definitions for TRL 10 are now presented. A complete set of hardware and software definitions for TRL levels 1–10 is presented in Table 2.

The proposed hardware description for TRL 10 is:

Use of the technology in a recurrent manner as part of a tested, validated and use-certified system with characterized and acceptable levels of unplanned troubleshooting and repair required. This TRL includes upgrades and refinements to improve the functionality of the operating system, repair latent defects and reduce troubleshooting and repair requirements.

The proposed software description for TRL 10 is:

Use of software in a recurrent manner on its own or as part of a tested, validated and use-certified hardware–software system with characterized and acceptable levels of unplanned troubleshooting and repair required. Ongoing support operations are established and upgrades and refinements may be made to improve the functionality of the software, repair latent defects and reduce troubleshooting and repair requirements.

Table 1
TRL definitions (levels 1–9 from [22]).

TRL	Definition
1	Technology Research – Basic principles observed and reported
2	Technology concept – Concept and/or application formulated
3	Proof-of-Concept – Analytical and experimental critical function and/or characteristic proof-of-concept
4	Technology Demonstration – Generic design demonstrating concept-enabling performance consistent with potential applications – Low-fidelity validation of critical functions using breadboards/brass-boards with non-flight-like parts and packaging in a laboratory environment at room temperature or environment required for functional validation
5	Conceptual Design and Prototype Demonstration – Flight performance requirements, definition of critical environments, preliminary interfaces, and conceptual design complete – Components characterized – Performance, lifetime, and "robustness" in critical environments validated by analysis – Components and subassemblies with new technology or moderate to significant engineering development validated in newly developed areas using stand-alone subassembly-level prototypes of approximate size, mass, and power and built with anticipated "flight-like" parts and materials tested in a laboratory environment at extremes of temperature and radiation (if relevant)
6	Preliminary Design and Prototype Validation – Preliminary assembly, subsystem, and system hardware and software design complete – Multiple assemblies or subassemblies incorporating new technology or moderate to significant engineering development validated in newly developed areas using engineering models (integrated form, fit, function prototypes) of the correct size, mass, and power, built with flight-like parts, materials, and processing and packaging, tested in a flight-like environment over the range of critical flight-like conditions
7	Detailed Design and Assembly Level Build – Final assembly, subsystem, and system hardware and software design, interfaces, performance, and constraints documented – Production capability and/or parts availability, discrepancy paper, drawings, CAD/CAM files, and vendor's current capability validated – Near flight-like assemblies pass stress and life tests that demonstrate significant margins operating at extremes of input and output over a range of driving environments – Flight-like assemblies or subsystems successfully pass function/performance validation tests
8	Subsystem Build and Test – Flight assemblies fabricated, integrated, and functionally tested – Build and test procedures qualified in subsystem assembly facility – Flight subsystems built and functionally tested – Identical/actual flight subsystem environmentally tested
9	System Operational – Flight system build and test procedures qualified in flight system integration facility – Flight system integrated and functionally tested against requirements and operating scenarios – Flight system environmentally tested
10	Proven Operations – The technology has been used without incident (or with incident levels within an acceptable range) for a protracted period of time – The technology has been certified (if applicable) via appropriate technology-type certification mechanisms through evaluation of repeated operations and other means – Failure rates for the technology are known and failure conditions and their causes are understood – The technology/system operates without unacceptable levels of unplanned troubleshooting or repair being required

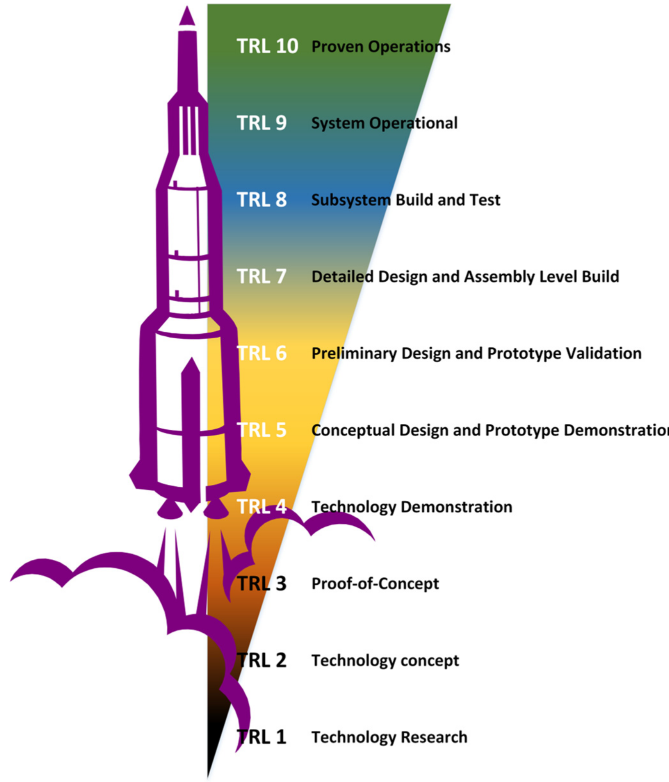

Fig. 1. Diagram of technology readiness levels including TRL 10.

4.3. Exit criteria

The proposed exit criterion for TRL 10 is now presented. A complete set of exit criteria for TRL levels 1–10 is presented in Table 3.

The proposed exit criteria for TRL 10 is:

Documented use of technology without incident for a protracted time period, documentation of certification, documentation of failure rates, known failure conditions and assessment of acceptability of troubleshooting/repair requirements.

4.4. Additional question for the TMA thought process question progression

An additional question for the technology maturity assessment (TMA) thought process, presented in [24], is now presented. Fig. 2 presents a revised TMA thought process.

TRL 10 classification question:

Has the system been operated with incident levels within an acceptable range for a protracted period of time, been certified, have known failure rates and understood failure conditions and not require unacceptable levels of unplanned troubleshooting?

4.5. Definition relative to the ESA framework

This section supplies the requisite information to merge TRL 10 into the ESA's Technology Readiness Levels Handbook for Space Applications [4]. This includes a detailed description, technology assessment at TRL 10 description and lists of key questions and requisite evidence, in the handbook's format.

4.5.1. Detailed definition of TRL 10

TRL 10 is the readiness/maturity level applicable to a system/technology which has been proven through extended operations. A TRL 10 system typically will have been demonstrated in all typical operating environments and its performance levels and

Table 2
TRL hardware and software descriptions (levels 1–9 from [22]).

TRL	Hardware description	Software description
1	Lowest level of technology readiness. Scientific research begins to be envisioned as applied research and development. Examples might include paper studies of a technology's basic properties.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.
2	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative, and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.	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.
3	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.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.
4	Following successful "proof-of-concept" work, a single technological element is integrated to establish that the pieces will work together to achieve concept-enabling levels of performance for a component and/or breadboard/brass-board. 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.	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.
5	The fidelity of the component and/or subassembly 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, subsystem-level, or system-level) can be tested in a "simulated" or somewhat realistic environment.	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. Prototype implementations developed.
6	A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative engineering model or prototype system or system, which would go well beyond ad hoc, "patch-cord," or discrete component level bread-boarding, would be tested in a relevant environment. At this level, if the only relevant environment is the environment of space, then the model or prototype must be demonstrated in space-like environments.	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.
7	Assemblies near or at planned operational system. TRL 7 is a significant step beyond TRL 6, requiring an actual prototype demonstration in a space environment. The prototype should be near or at the scale of the planned operational system, and the demonstration must take place in space environments. Examples include testing the near flight-like assemblies in an environmentally realistic test bed.	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.
8	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this level is the end of true system development for most technology elements. This might include integration of new technology into an existing system.	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.
9	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. This TRL does not include planned product improvement of ongoing or reusable systems.	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.
10	Use of the technology in a recurrent manner as part of a tested, validated and use-certified system with characterized and acceptable levels of unplanned troubleshooting and repair required. This TRL includes upgrades and refinements to improve the functionality of the operating system, repair latent defects and reduce troubleshooting and repair requirements.	Use of software in a recurrent manner on its own or as part of a tested, validated and use-certified hardware–software system with characterized and acceptable levels of unplanned troubleshooting and repair required. Ongoing support operations are established and upgrades and refinements may be made to improve the functionality of the software, repair latent defects and reduce troubleshooting and repair requirements.

failure rates will be characterized. Failure conditions will be well understood; however, new incidents can be investigated to improve this knowledge base, as applicable. TRL 9 and TRL 10 are distinguished by the duration of operations: where TRL 9 requires only a single successful implementation/use, TRL 10 requires user confidence levels to be built through repeated use and (if applicable) a certification process.

4.5.2. Technology assessment at TRL 10

As with TRL 9, the attainment of TRL 10 can be explicitly determined from the technology's demonstrated functionality. Similar to TRL 9, assessment can be utilized to assess mission and system operations (i.e., to determine the cause of an unexpected failure or greater-than-anticipated level of success) or to collect data which will serve to inform future technology development efforts. In line with the system lifecycle model (which will be discussed in Section 5.2), assessment can also focus on identifying methods to improve the technology. While a major enhancement or refinement would proceed through the TRL classification system in its own right, minor enhancements or changes designed to lower failure rates or reduce unplanned troubleshooting and maintenance can be identified and assessed within the context of TRL 10.

Table 3
TRL exit criteria (levels 1–9 from [22]).

TRL	Exit criteria
1	Peer reviewed publication of research underlying the proposed concept/application.
2	Documented description of the application/concept that addresses feasibility and benefit.
3	Documented analytical/experimental results validating predictions of key parameters.
4	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	Documented test performance demonstrating agreement with analytical predictions.
7	Documented test performance demonstrating agreement with analytical predictions.
8	Documented test performance verifying analytical predictions.
9	Documented mission operational results.
10	Documented use of technology without incident for a protracted time period, documentation of certification, documentation of failure rates, known failure conditions and assessment of acceptability of troubleshooting/repair requirements.

This assessment process will require the input of system users (to ascertain how the system/technology's operations differed from expectations or specifications) as well as designing and implementing engineers and technicians.

4.5.3. Key questions to address

TRA Question 10.1: Has the technology has been used without incident (or with incident levels within an acceptable range) for a protracted period of time?

TRA Question 10.2: Has the technology has been certified (if applicable) via appropriate technology-type certification mechanisms through evaluation of repeated operations and other means?

TRA Question 10.3: Are failure rates for the technology known and failure conditions and their causes are understood?

TRA Question 10.4: Can the technology/system operate without unacceptable levels of unplanned troubleshooting or repair being required?

4.5.4. Appropriate evidence required

10.A Documentation regarding the level of use of the technology/system including the frequency and duration of use, number of users and the frequency and magnitude/nature of failure.

10.B Documentation indicating the certification of the technology, including results of testing and use-based validation studies.

10.C Documentation of failure rates, including all data used to calculate the failure rate. Documentation regarding known failures, their analysis, believed cause-of-failure and any corrective action or guidelines taken/issued.

10.D Documentation regarding the rate of unplanned troubleshooting and repair required, including all documentation required to make the rate determination. Details of any corrective measures implemented to reduce troubleshooting/repair rates and their impact.

5. Beyond TRL 10

This section considers what is required beyond TRL 10 for technology maturity assessment to serve the needs of a diverse technology development community. First, whether the proposed TRL 10 system is enough is considered and other areas of need are discussed. Then, the use of sub-levels of TRL 10 (matching up to system development lifecycle phases) is discussed as a way of extending TRL 10s coverage.

5.1. Is TRL 10 enough?

While useful for some forms of decision making, even the TRL system with the TRL 10 augmentation does not fully classify mature technologies. A comparison to the system development life cycle (SDLC) model [40,41] demonstrates why. The SDLC includes initiation, development, implementation/assessment, operations/maintenance and sunset phases. The first nine levels of the TRL scale correspond (roughly) with the initiation through implementation/assessment phases. The remaining two phases correspond to the newly proposed TRL 10. While, if calculated mathematically, it may seem like six TRLs would be required (given the

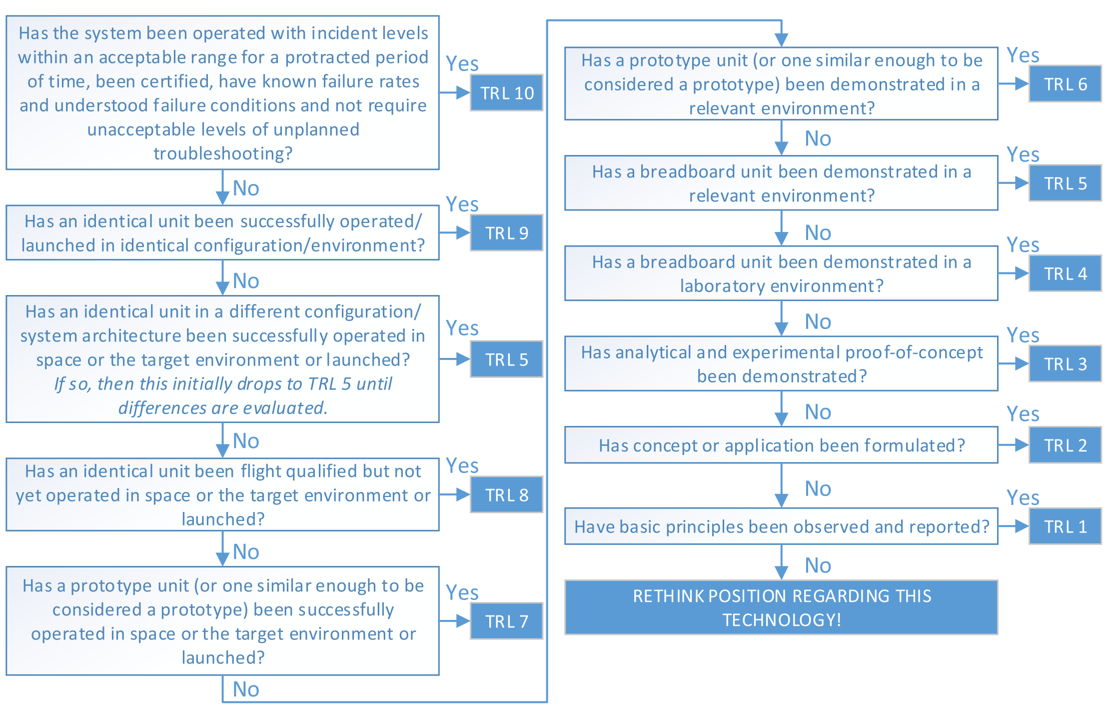

Fig. 2. Updated TMA thought process (based on [24] with TRL 10 question added).

correlation between 9 TRL levels and 3 SDLC phases), this is not the case. From a technology development and maturity perspective, there is much less activity during the operations/maintenance and sunset phases. Distinguishing between technology and systems in these two phases, however, is important as it will drive decisions regarding the level of investment to make. A system in operations/maintenance, for example, may justify expenditures on additional refinement and maintenance to improve its failure rate or reduce maintenance needs. A system in the sunset phase is destined for end-of-life and, thus, should only (generally) be supported to the extent necessary to achieve mission completion.

5.2. Expansion of TRL 10 via the incorporation of phases of the system development life cycle

The incorporation of two sub-levels is, thus, also proposed to allow a more robust system for characterizing a technology or system's place within the TRL 10 category. Levels TRL 10A and 10B are proposed.

TRL 10A denotes technologies and systems that fall within the operations and maintenance phase of the SLDC. These are mature technologies or systems that are ready for use across a wide variety of missions and have been proven to work as specified. They have known failure rates and understood failure conditions. Work is ongoing to (if/as opportunities are identified) reduce failure rates or eliminate or mitigate failure condition causes. These enhancements, however, will be minor and will not change the nature or performance of the technology or system significantly. These technologies can be utilized, relaying on technology/system documentation and demonstrated unit-level functionality and focusing primarily on modification to suite mission-specific needs (if applicable) and testing of these modifications, integration testing and system validation.

TRL 10B denotes technologies which are or look to soon become obsolete and are in their SLDC sunset phase. This includes technologies which have been replaced by an incremental advancement or disruptive technology as well as technologies for which the reason for the technology's use no longer exists or is significantly diminished (e.g., a supporting technology for a steam powered locomotive would be in its sunset phase, or obsolete, due to the obsolescence of the steam locomotive). These technologies should be supported to the extent required to complete missions, but are (generally) not deserving of additional investment.

As a caveat, it is important to note that there are certainly exceptions to these general time/resource investment area recommendations; the actual commitment of resources is a business/public administration decision that is made based on ROI models specific to the situation. As such, there may be times where situational needs dictate the commitment of resources in ways not generally recommended.

6. Conclusions and future work

This paper has considered the need for the augmentation of the NASA technology readiness level scale with a new TRL 10 level. It has discussed the benefits and drawbacks of this TRL 10 level. A proposed implementation of TRL 10 has also been discussed. Its integration into five key systems has been considered. Focus finally has turned to whether the TRL 10 augmentation, by itself, is sufficient to solve the problems described. Two sub-levels have been proposed to aid the further classification of technologies and systems in the TRL 10 category.

This work aims to further a discussion about how to classify the more mature technologies that will be required as part of higher-frequency space access (manned, small spacecraft and otherwise). The path to the adoption of changes to the NASA technology maturity assessment classification scheme will require considerable consideration and discussion within both the space development community as well as other industries, agencies and development communities that have based their technology assessment frameworks on the NASA TRL system.

Conflict of interest statement

None declared.

Acknowledgements

The rocket image in Fig. 1 was sourced from the Microsoft Office Clip Gallery.

References

[1] J. Banke, Technology readiness levels demystified, accessed November 5, 2013.
[2] S.R. Sadin, F.P. Povinelli, R. Rosen, The NASA technology push towards future space mission systems, Acta Astronaut. 20 (1989) 73–77.
[3] J.C. Mankins, Technology readiness levels, White Paper, April, 6, 1995.
[4] European Space Agency, Technology readiness levels handbook for space applications, 2008, TEC-SHS/5551/MG/ap.
[5] U.S. Department of Energy, Department of Energy technology readiness assessment guide, 2009, DOE G 413.3-4.
[6] D. McGarvey, J. Olson, S. Savitz, Department of Homeland Security and Technology Readiness Level calculator, 2009, 09-01.03.02.13-02.
[7] B. Sauser, J.E. Ramirez-Marquez, R. Magnaye, W. Tan, A systems approach to expanding the technology readiness level within defense acquisition, 2009, SIT-AM-09-002.
[8] C. Moore, TRL usage at NASA, in: DoDCost Analysis Symposium, vol. 20, February, 2008.
[9] W.N. Felder, Next generation air transportation system demonstration program, J. Air Traffic Control 48 (2006) 27–31.
[10] J.J. Wang, K. Datta, A life-cycle cost estimating methodology for NASA-developed air traffic control decision support tools, National Aeronautics and Space Administration, Ames Research Center, 2002.
[11] K. Brown, C. McCleskey, National spaceport testbed, in: 1999 Space Congress, 2000.
[12] J. Robinson, D. Levack, R. Rhodes, T. Chen, Need for technology maturity of any advanced capability to achieve better life cycle cost, in: 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2009.
[13] J.C. Mankins, Technology readiness assessments: a retrospective, Acta Astronaut. 65 (2009) 1216–1223.
[14] National Aeronautics and Space Administration, Integrated technology plan for the civil space program, 1991.
[15] B. Sauser, D. Verma, J. Ramirez-Marquez, R. Gove, From TRL to SRL: the concept of systems readiness levels, in: Conference on Systems Engineering Research, Los Angeles, CA, 2006.
[16] J.C. Mankins, Technology readiness and risk assessments: a new approach, Acta Astronaut. 65 (2009) 1208–1215.
[17] J.W. Bilbro, R.L. Sackheim, Managing a technology development program, NASA Marshal Space Flight Center, September, 2002.
[18] J.W. Bilbro, Using the advancement degree of difficulty (AD2) as an input to risk management, 2008.
[19] A. Shenhar, D. Dvir, D. Milosevic, J. Mulenburg, P. Patanakul, R. Reilly, M. Ryan, A. Sage, B. Sauser, S. Srivannaboon, Toward a NASA-specific project management framework, Eng. Manag. J. 17 (2005) 9.
[20] R. Shishko, D.H. Ebbeler, G. Fox, NASA technology assessment using real options valuation, Syst. Eng. 7 (2004) 1–13.
[21] National Aeronautics and Space Administration, NASA strategic space technology investment plan, 2012.
[22] National Aeronautics and Space Administration, NASA systems engineering processes and requirements, 2013, NPR 7123.1B.
[23] National Aeronautics and Space Administration, NASA system safety handbook, 2011, NASA/SP–2010-580.
[24] National Aeronautics and Space Administration, NASA systems engineering handbook, 2007, NASA/SP-2007-6105.
[25] National Aeronautics and Space Administration, NASA risk-informed decision making handbook, 2010, NASA/SP-2010-576.
[26] National Aeronautics and Space Administration, The instrument incubator program (IIP), http://esto.nasa.gov/obs_technologies_iip.html.
[27] National Aeronautics and Space Administration NASA, Unique and innovative game changing technology solicitation now open!, accessed November 3, 2013.

[28] National Aeronautics and Space Administration, In-space validation of Earth science technologies, 2012, http://esto.nasa.gov/files/solicitations/INVEST_12/ROSES2012_InVEST_A41.pdf?method=init&solId=%7B2AA1C9F4-C00D-F003-BF4C-28A7344A133B%7D&path=open.
[29] C.R. Kenley, B. El-Khoury, An analysis of TRL-based cost and schedule models, in: Proceedings of the Ninth Annual Acquisition Research Symposium, 2012, DTIC document.
[30] Department of Defense, Defense acquisition guidebook, 2011.
[31] M. Lee, T. Chang, W.C. Chien, An approach for developing concept of innovation readiness levels, Int. J. Manag. Inf. Technol. 3 (2011).
[32] S. Vyakarnam, Emerging Issues in Technology Management: Global Perspectives: The Need for and Understanding of a Technology Commercialization Framework, Emerging Dimensions of Technology Management, Springer, 2013, pp. 1–16.
[33] E.M. Rogers, Diffusion of Innovations, Simon and Schuster, 1962.
[34] B. Hicks, A. Larsson, S. Culley, T. Larsson, A methodology for evaluating technology readiness during product development, Economics 6 (2009) 7.
[35] L. Grossman, Drone home, Time Magazine (2013).
[36] National Association of Criminal Defense Lawyers DDIC Bill Map, accessed October, 2013.
[37] M.E. Paté-Cornell, R.L. Dillon, Success factors and future challenges in the management of faster–better–cheaper projects: lessons learned from NASA, IEEE Trans. Eng. Manag. 48 (2001) 25–35.
[38] O. El-Rawas, T. Menzies, A second look at faster, better, cheaper, Innov. Syst. Softw. Eng. 6 (2010) 319–335.
[39] J. Straub, Cubesats: a low-cost, very high-return space technology, in: Proceedings of the 2012 Reinventing Space Conference, 2012.
[40] S. Radack, The System Development Life Cycle (SDLC), 2009.
[41] J.E. Ramirez-Marquez, B.J. Sauser, System development planning via system maturity optimization, IEEE Trans. Eng. Manag. 56 (2009) 533–548.