DOCUMENT

document title/ titre du document

TECHNOLOGY READINESS LEVELS HANDBOOK FOR SPACE APPLICATIONS

prepared by/*préparé par*	TEC-SHS
reference/*réference*	TEC-SHS/5551/MG/ap
issue/*édition*	1
revision/*révision*	6
date of issue/*date d'édition*	September 2008
status/*état*	
Document type/*type de document*	
Distribution/*distribution*	

A P P R O V A L

Title *Titre*	TRL Handbook	issue 1 *issue*	revision 6 *revision*

author *auteur*	TEC-SHS	date March 2009 *date*

approved by *approuvé par*		date *date*

C H A N G E   L O G

reason for change /*raison du changement*	issue/*issue*	revision/*revision*	date/*date*

C H A N G E   R E C O R D

Issue: 1 Revision: 6

reason for change/*raison du changement*	page(s)/*page(s)*	paragraph(s)/*paragraph(s)*

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1 EXECUTIVE SUMMARY

1.1 Background

The ability to make good decisions concerning the inclusion or exclusion of new technologies and novel concepts, and to do so in the absence of perfect information, is essential to success of many space programs. Accurate and timely 'technology readiness assessments' (TRAs) are very important for the cost-effective management of advanced technology R&D portfolios, whether at the program manager level, the prime contactor level or the supplier level. Numerous approaches have been developed to assist in meeting this management challenge, including the use of a variety of decision support tools. A critical step in all such methodologies, however, is the consistent assessment of maturity of various advanced technologies prior to their incorporation in new system development projects.

1.2 General Principles

Generally speaking, the purpose of timely and accurate technology readiness assessments is to inform management and support decisions as part of the implementation of advanced technology system development projects. The Technology Readiness Levels have been defined to provide a common metric by means of which knowledge of new technology's maturity might be communicated among program executives, system developers and technology researchers, and among individuals from different organizations. The TRL are therefore not linked to a specific technical discipline. In addition, the use of TRLs can provide a needed foundation for developing and communicating insight into the risks involved in advancing a new system and its constituent new technology components.

1.3 Purpose of this Document

This document is a "Technology Readiness Level Handbook", the standard measure of the maturity of new technologies. This TRL Handbook is intended to provide clear definitions of the various TRL levels and of the questions that must be answered in order to go from one level to the other.

The decision on how to link the TRL assessment to the actual use of a given technology in a specific application programme is out of the scope of the present document.

2 INTRODUCTION

2.1 OVERVIEW

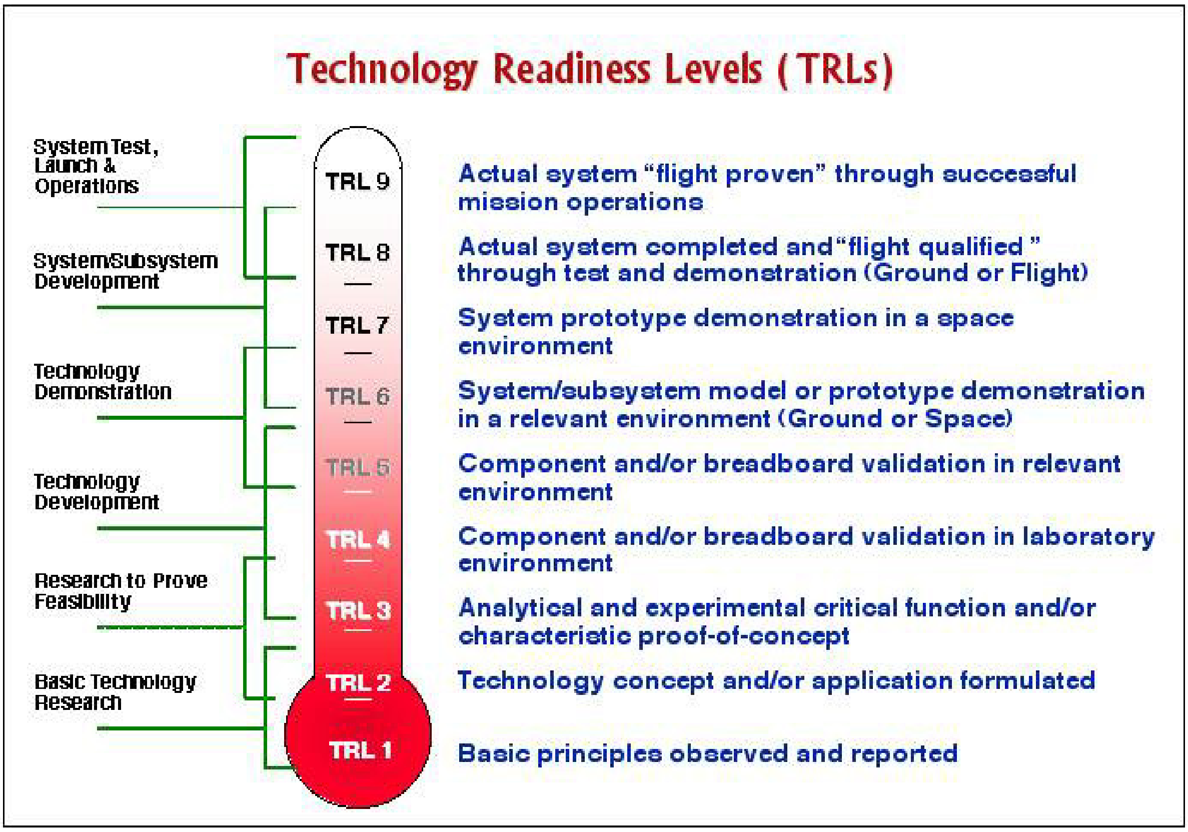
Effectively evaluating and managing science and technology risk and the maturation of critical new technologies are critical to the success of advanced technology systems development projects. Systems that depend upon the application of new technologies inevitably face three major challenges during development: performance, schedule and budget. Technology R&D programs are typically advocated on the argument that early investments in technology will substantially reduce the uncertainty in all three of these dimensions of project management. In this context, therefore, a metric is needed in order to support the evaluation of the maturity of a given technology within the scope of the envisaged application. The Technology Readiness Levels (TRLs) defined in this handbook are intended to provide an answer to this need.

3 TECHNOLOGY READINESS LEVEL DEFINITIONS

3.1 TECHNOLOGY READINESS LEVELS DEFINITION

TRLs are a set of management metrics that enable the assessment of the maturity of a particular technology and the consistent comparison of maturity between different types of technology—all in the context of a specific system, application and operational environment. **Figure 3.1-1** provides a high-level illustration of the TRL scale, using the well known "thermometer diagram" as a metaphor for increasing technology maturity, in the context of the progression from basic research to system operations.

Figure 3.1-1 Technology Readiness Levels – Thermometer Diagram



The following section provides more detailed definitions of the TRLs.

3.2 TECHNOLOGY READINESS LEVEL DETAILED DEFINITIONS

At a fundamental level, TRLs are, as previously noted, a set of metrics that enable the assessment of the maturity of a particular technology and the consistent comparison of maturity between different types of technology, all in the context of a specific system, application and operational environment.

Table 3.2-1 provides the complete set of basic definitions and explanations of the TRLs applicable to hardware (Appendix A for guidelines for the definition of software technology readiness levels).

Table 3.2-1. The Basic Technology Readiness Levels

Readiness Level	Definition	Explanation
TRL 1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. (See Paragraph 4.2)
TRL 2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented and R&D started. Applications are speculative and may be unproven. (See Paragraph 4.3).
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept	Active research and development is initiated, including analytical / laboratory studies to validate predictions regarding the technology. (See Paragraph 4.4)
TRL 4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. (See Paragraph 4.5)
TRL 5	Component and/or breadboard validation in relevant environment	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. (See Paragraph 4.6)
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	A representative model or prototype system is tested in a relevant environment. (See Paragraph 4.7)
TRL 7	System prototype demonstration in a space environment	A prototype system that is near, or at, the planned operational system. (See Paragraph 4.8)
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	In an actual system, the technology has been proven to work in its final form and under expected conditions. (See Paragraph 4.9)
TRL 9	Actual system "flight proven" through successful mission operations	The system incorporating the new technology in its final form has been used under actual mission conditions. (See Paragraph 4.2.10)

4 TECHNOLOGY READINESS ASSESSMENT GUIDELINES

4.1 OVERVIEW

4.1.1 INTRODUCTION

The following section provides a standard, internally consistent set of guidelines for the use of the TRLs in conducting Technology Readiness Assessments (TRAs). The Section begins with a description of a typical process for conducting TRAs. Following this section are a series of detailed guidelines for TRAs, one for each Technology Readiness Level. The Section is concluded with considerations concerning the reuse of already matured technologies in new applications.

4.1.2 TYPICAL TECHNOLOGY READINESS ASSESSMENT PROCESS

The details of an appropriate technology readiness assessment process depend on the specifics of the prospective system applications and program requirements, and is, therefore, beyond the scope of this document. However, general steps in the process for conducting an effective TRA include:

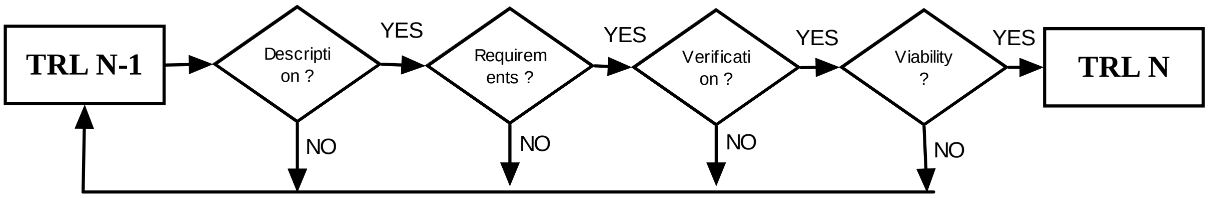
- Formal definition of the terms of reference for the assessment (including timing, how technology data will be provided to the process, the detailed criteria for the TRA, etc.)
- Identification of key supporting data (e.g., operating environment, expected system applications, etc.)
- Identification of TRA Participants (including appropriate involvement of technologists and/or systems program participants).
- Development and delivery of technology data to the TRA (often including preparatory meetings and/or studies by members of the technology community involved).
- Implementation of the TRA itself (often involving meetings of a formal review committee)
- Development of a TRA report.

4.1.3 TRA CRITERIA

Generally speaking, a set of specific criteria should be applied in conducting a formal technology readiness assessment; and more specifically “exit criteria”. In other words, these criteria are used to determine whether a new technology has satisfied the various aspects of maturation that define a TRL: a given TRL is only achieved after all of the criteria are satisfied and not before.

In order to conduct a technology readiness assessment at any of the various technology readiness levels, the same types of information should be examined to establish that a given TRL has / has not been achieved. See **Figure 4.1.3-1** for a generic technology readiness assessment flow diagram, including four principal areas for TRL criteria.

Figure 4.1.3-1 Generic Technology Readiness Assessment Steps



These areas include:

- Description. A description of the details of the research and development that has been performed, or the technology that has been advanced. Including considerations concerning the degree to which actual space qualified materials, devices, components or tools are used in making the item of technology that has been tested.
- Requirements. The degree to which a future application of a technology is known; and in particular whether the characteristics of the application are well enough defined to judge whether a new technology will be able to meet those requirements.
- Verification. The environment in which testing of the new technology has occurred, and the degree to which that environment is similar to, or the same as the environment in which technology will be used in operations. The degree of similarity of test articles incorporating the new technology to an actual systems application. The degree to which required levels of performance are achieved, and in the needed environment.
- Viability. The prospective future viability of the technology being advanced, including both technical (risk) and programmatic viability (effort) needs to be clearly established. In particular, it is important to know if a given technology can indeed be further developed and, if so, with what technical risk and effort.

An additional element that must always be considered in connection with technology evaluation is time. In particular, if a technology development was carried out in the past and the technology needs to be reused or reevaluated again today, particular attention must be paid to the possible "obsolescence" of the technology. This is because if a long time has elapsed between the time of the last technology development action and the time of the reevaluation, a number of key technology components or processes may no longer be available or viable (obsolescence).

Furthermore, when the evaluation involves more than one technology that are intended to work together, a useful approach is to evaluate the individual technologies in their own merit and then associate to the complete set of technologies two TRL values, namely, the average and the lowest.

Table 4.1.3-1 (on the next page) presents an integrated summary of these data requirements at each TRL, correlated with the degree of specificity in prospective applications that is expected at each level. The detailed TRA criteria should be keyed to the specific TRL expected for the technology development effort that is being assessed. These detailed criteria are provided in the paragraphs that follow.

Table 4.1.3-1 Data Requirements for Each Technology Readiness Level

APPLICATIONS	TRL / Question	DESCRIPTION	REQUIREMENTS	VERIFICATION	VIABILITY
Broad Range of Applications	1	1.1) Physical Principle	1.2) Needed Capability	1.3) Analytical or Experimental	N.4) Advancement to the Next Level Technical & Programmtics (N = 1-8)
	2	2.1 Basic Concept	2.2) Needed Functionality	2.3) Analytical or Experimental	
	3	3.1) Key Technology Characteristics	3.2) Basic Requirements (Family)	3.3) Simulation or Experimental	
	4	4.1) Full Technology (in the Laboratory)	4.2) Complete Requirements (Narrower Range and Interactions)	4.3) Rigorous Experimental	
Family of Applications	5	5.1) Full Technology & Interactions (in a Relevant Environment)	5.2) Complete Requirements (Specific)	5.3) Rigorous Testing at Component and/or Breadboard in Relevant Environment	
	6	6.1) Full Technology in System or Subsystem	6.2) Full Requirements (System or Subsystem)	6.3) Rigorous Testing at System and/or Subsystem in Relevant Environment	
Preliminary Definition for Specific Application	7	7.1) Full Technology in System or Subsystem	7.2) Full Requirements in Space Environment (System or subsystem)	7.3) In Space Demonstration	
Specific Application	8	8.1) Full Technology in System (Manufactured)	8.2) Full System and Qualification Requirements	8.3)Qualification Campaign	
	9	9.1) Final Manufacturing & Operations Plans	9.2) Performance and Manufacturing Requirements	9.3) System Operations Verification (including life)	9.4) Failure Analysis (if needed) and/or Future Evolution

4.1.4 TRA DATA REQUIREMENTS

The key data that are necessary to conduct an effective and informative TRA include:

- Description. A description of the key technology being discussed including also other technologies that may be needed and, if appropriate, the interactions between the various technologies

- System / Mission Requirements, including

  - Operational Environment/Concept of Operations. A well defined operating environment, along with an appropriately defined concept of operations ("CONOPS") of the future system are essential. In the case of an orbiter mission to the outer planets of our solar system, this might include specification of what is the planet to which the mission will journey, at what distance from the planet will the spacecraft orbit, etc.

  - Performance Objectives. A clear understanding of the performance objectives for the new technology and/or system capability (including as appropriate both engineering measures of performance, such as mass, as well as operational measures of performance, such as cost, availability, mean-time-between-failure, etc.)

- Validated R&D Results. An understanding of the current, well-established readiness level for the technology and/or system capability in question, as well as for any key supporting technologies. In a rigorous TRA, this should include clear evidence that the stated TRL has been achieved—such as a photo of a 'breadboard in the laboratory', quantitative data from validation testing, etc.

- Viability. A thorough discussion of the approach forward from the already achieved R&D results—including establishing the technical and programmatic viability of those additional R&D activities. These considerations of viability include other factors of interest in a formal TRA, such as:

  - Technology R&D Risk. It is also important during a formal TRA to develop a clear understanding of the remaining 'development hurdles' and the projected uncertainty in the likelihood of development success for novel technologies.

  - R&D Effort (Cost / Feasibility). Finally, it is important during a formal TRA to acquire some understanding of the effort in terms of costs and/or programmatic feasibility involved in overcoming the 'development hurdles' mentioned above. This should include some indication of challenges in providing a relevant environment, any special R&D facilities that may be needed, etc.

4.1.5 INDEPENDENT REVIEW AND VALIDATION OF TRA RESULTS

As technology maturation continues, it becomes increasingly important that there should be independent review and validation of the results of a technology readiness assessment. In particular, as the degree of integration of individual technologies increases and the testing environment more closely approaches the planned operating environment, the role of prospective customer organizations should also increase. Details are provided in the paragraphs that follow; Table 4.1.5-1 summarizes this information.

Table 4.1.5-1 Summary of Independent Review and Validation Processes[1]

TRL Levels	TRA Independent Review and Validation Participants
TRL 1-3	The technologists involved in the conduct of the R&D should lead Review and Validation of TRA results. However, even at this level a TRA should involve the participation of the management of the technology development organization.
TRL 4	Independent Review and Validation of TRA results should be led by management of the technology organization, with the participation of both the technologists involved and the leadership of prospective system organizations.
TRL 5	Independent Review and Validation of TRA results should be led cooperatively by the management of the organization responsible for development of the technology and by that of the prospective system application of the new technologies being developed. Technologists and participants in the system development project (e.g., subsystem managers) should play significant roles in the conduct of such reviews.
TRL 6-9	Independent Review and Validation of TRA results should be led by the management of the organization responsible for development of the prospective system application of the new technologies under development (or operation for TRL 9). Technologists and participants in the system development project (e.g., subsystem managers) should play significant roles in the conduct of such reviews.

[1] A special case is that of high-risk, systems-level technologies that require a higher-fidelity demonstration of a prototype system in the operational environment (i.e., TRL 7). In such cases, responsibility for the technology R&D efforts (including reviews) may very well remain with the R&D organization.

4.1.6 STRUCTURE OF THESE GUIDELINES

The paragraphs that follow provide definitions and guidance regarding each of the nine technology readiness levels. Each paragraph provides (1) a general description of the respective TRL; (2) some high-level questions to be posed during a technology readiness assessment that are intended to facilitate determination of whether a given technology is or is not at a given TRL; and (3) some notional and/or specific examples of the type(s) of accomplishments that would characterize each level.

4.2 TRL 1: BASIC PRINCIPLES OBSERVED AND REPORTED

4.2.1 DETAILED DEFINITION OF TRL 1

TRL 1 occurs at the end of scientific research and the beginnings of technology development; it is lowest level of technology maturation, just beyond basic science, at which an assessment of technology readiness might be performed. At this level, basic scientific research has resulted in the observation and reporting of basic principles and these begin to be translated into more applied research and development.

Examples of TRL 1 might include studies of basic properties of materials (e.g., tensile strength as a function of temperature for a new fiber). Such activities would typically be pursued by scientific research organizations, or by individuals such as university researchers.

4.2.2 TECHNOLOGY READINESS ASSESSMENT AT TRL 1

An assessment at TRL 1 should involve at least the researchers involved in advancing the scientific discipline, as well as technologists and/or inventors who may be able to devise new concepts based on new discoveries and/or new insights. Some process for independent reviewers is also important at this stage, and might involve competitive acquisition processes. An example of this sort of independent review would be the evaluation of proposals by a government agency that sponsors scientific research. Key questions and supporting evidence required for a meaningful assessment are sketched in the paragraphs that follow.

4.2.2.1 Key Questions to Address

In conducting a technology readiness assessment (TRA) the following questions should be posed in the context some prospective application or benefit that may be derived from a new scientific discovery, or an existing scientific fact when viewed in a new light.

- TRA QUESTION 1.1: Has a hitherto-unknown scientific fact or principle been discovered that suggests one or more potentially useful new capabilities? What is the new fact or principle? What are the new capabilities?

- TRA QUESTION 1.2: For a desired new capability, is (are) there (a) fundamental, perhaps newly discovered scientific fact and/or principle that suggests a path to technical feasibility to implement the new capability on the basis of the principles described in 1.1? What is the new capability? How can it be technically implemented?

- TRA QUESTION 1.3: Have conceptual studies suggested any possible new concepts and/or technology that might emerge as a result of the new phenomena observed?

- TRA QUESTION 1.4: For the scientific phenomena involved, is further scientific research possible in the foreseeable future? Does it appear likely that technology R&D will be viable?[2] Can the technical risk and required effort be evaluated?

4.2.2.2 Appropriate Evidence Required

The answer to the above questions should be supported by appropriate evidence, including:

1.A Clear identification of relevant and fundamental physical principles.

1.B Description of new capabilities that might result from the principles (in 1.A).

1.C Presentation of the results of new analysis and modeling to demonstrate the relevant fundamental physical principles. Delineation of any and all references documenting the results of analysis and modeling performed by others that demonstrate the relevant physical principles.

1.D Compelling arguments that indicate the technical feasibility of the new capability (1.B) on the basis of the new principle(s) described in 1.A. An evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level.

[2] At this point in the technology maturation process, no detailed concept has been framed; however, it should still be possible to determine whether the observed scientific phenomena are amenable to future technology research and development.

4.3 TRL 2: TECHNOLOGY CONCEPT AND /OR APPLICATION FORMULATED

4.3.1 DETAILED DEFINITION OF TRL 2

Once basic physical principles are observed, practical applications of those characteristics can be identified or 'invented'. This step in the maturation of a new technology is TRL 2: the creation of a new concept based on a new or existing physical or mathematical principle. At TRL 2, prospective system applications are still rather speculative; at this point, there is no specific experimental proof or detailed analysis to support the conjecture. However, it is still necessary that the new technology or concept should be described in sufficient, internally consistent detail such that anyone skilled in the field can understand it, and evaluate its potential usefulness.

4.3.2 TECHNOLOGY READINESS ASSESSMENT AT TRL 2

At this stage, an assessment of technology readiness should involve at least the researchers and/or technologists involved in advancing the new concept and independent reviewers representing the management of their organization. Key questions and supporting evidence required for a meaningful assessment are sketched in the paragraphs that follow.

4.3.2.1 Key Questions to Address

A TRA involving technologies purported to be at TRL 2 should attempt to answer affirmatively all of the following questions with regard to a novel concept and/or invention based a new scientific discovery, or an existing scientific fact when viewed in a new light.

- TRA QUESTION 2.1: Has a potential new technology been identified that employs the new scientific fact or principle identified at TRL 1 to be applied in a component or system in such a way so as to establish a potentially useful new capability? What is this new conceptual approach? On what scientific fact or principle is it based?

- TRA QUESTION 2.2: Has the potential new concept and/or technology been framed with sufficient detail that possible future functional and/or environmental application requirements have been defined?

- TRA QUESTION 2.3: Has an analytical study been performed that confirms the potential usefulness of the new concept and/or technology identified above in Question 2.1 for the application described in Question 2.2?

- TRA QUESTION 2.4: Is there a viable path forward that would lead from the invention to the system application? What are the requirements of this path to realize the new capabilities? Can the technical risk and required effort be evaluated?

4.3.2.2 Appropriate Evidence Required

The answer to these questions should be supported by appropriate evidence, including the documentary evidence indicating that TRL 1 was achieved, plus the following additional information:

2.A A clear description of the proposed new concept or invention, including the quantitative analyses involving the relevant and fundamental physical principles upon which the invention depends. Identification of existing technologies and/or systems that would need to be applied eventually in combination with the new concept/invention to produce the viable application; Delineation of references documenting the results of any definition of the concept (e.g., patents) or studies performed up to this point.

2.B A description of possible application(s), including any prospective operational environment, performance requirements and constituent technologies.

2.C A description of the results of the verifications performed including the environment(s) in which scientific studies to verify the relevant phenomena have been conducted. Delineation of any and all references documenting the results of analysis and modeling performed by others that demonstrate the relevant phenomena.

2.D Compelling arguments that demonstrate the future viability of the technology and/or concept and the useful new system capability (identified in 2.B above). An evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level.

4.4 TRL 3: ANALYTICAL AND/OR EXPERIMENTAL CRITICAL FUNCTION AND/OR CHARACTERISTIC PROOF-OF-CONCEPT

4.4.1 DETAILED DEFINITION OF TRL 3

At this step in the technology maturation process, active R&D is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory based research or tests 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. TRL 3 includes both analytical and experimental approaches to proving a particular concept.

Which approach is appropriate depends in part on the physical phenomena involved in the invention. For example, relatively straightforward physical or chemical systems concepts might be able to be proven even using simple analytical derivations. Similarly, new algorithms or computational techniques may be proven analytically. However, other inventions will require physical experimental validation, such as those involving highly complicated concepts or those involving environmentally dependent phenomena or novel materials effects.

4.4.2 TECHNOLOGY READINESS ASSESSMENT AT TRL 3

At this stage, an assessment of technology readiness should involve at least the researchers and/or technologists involved in advancing the new concept and independent reviewers representing the management of their organization, as well technically competent representatives of prospective customers for the new technology. Key questions and supporting evidence required for a rigorous assessment are sketched in the paragraphs that follow.

4.4.2.1 Key Questions to Address

A technology readiness assessment involving technologies that have reached TRL 3 should address all of the questions up to TRL 2 (identified previously), and, in addition, answer affirmatively to <u>all</u> of the following questions with regard to analytical and/or experimental research studies.

- <u>TRA QUESTION 3.1</u>: Have the key technologies and their functions been clearly identified and defined that would enable the utilization in the context of one or more system applications?

- TRA QUESTION 3.2: Has a prospective family of applications been identified, even if superficially, in terms of a possible family of operational environments, performance requirements, and relevant technologies?

- TRA QUESTION 3.3: Have the critical functions of the new technology described in Question 3.1 been validated analytically and/or experimentally so as to establish the technology to be used to implement the application(s) described in Question 3.2?

  - If analytical studies have been used to demonstrate a new capability, has this new conceptual approach been clearly modeled? Do the results of completed analytical studies verify that the prospective applications of the technology are valid and would, if developed successfully, result in the effective implementation of the new capability?

  - If laboratory experimentation has been involved or used to demonstrate a new concept, has this experimentation been conducted under rigorous, verifiable conditions? Do the results of completed experiments verify that the prospective applications of the technology are valid and would, if developed successfully, result in the effective implementation of the new capability?

- TRA QUESTION 3.4: Is there a viable path forward that would lead the experiment and/or analytical result forward to a future application? What are the likely capabilities that will be needed to follow that path (including operational environments, testing environments, etc.)? Can the technical risk and effort be evaluated?

4.4.2.2 Appropriate Evidence Required

The answer to the questions above should be supported by appropriate evidence, including the documentary evidence indicating that TRL 2 was previously achieved, plus the following additional information:

3.A A clear and comprehensive description of the new concept and/or technology, including the key functionality needed in the context of the application(s) identified.

3.B A preliminary description of the prospective application(s) in terms of quantified range of performance requirements and possible family of operational environments.

3.C Documentation describing in full detail the results of all experimental and/or analytical studies that have been performed to demonstrate that the technology can achieve the critical functions upon which future system applications depend. Delineation of any and all references documenting the results of experiments, analysis and modeling performed by others that demonstrate the critical functions.

3.D Compelling arguments that indicate likely connection between the new concept and/or technology and the future capability in question. An evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level.

4.5 TRL 4: COMPONENT AND/OR BREADBAORD VALIDATION IN A LABORATORY ENVIRONMENT

4.5.1 DETAILED DEFINITION OF TRL 4

Following successful proof-of-concept testing for critical functions or characteristics, the basic technological elements involved in an invention must be integrated to establish that the pieces will work together to achieve concept-enabling levels of performance at the level of a component and/or breadboard. This validation at TRL 4 must be devised to best support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. However, validation at this level is relatively low-fidelity compared to the eventual system applications. In addition, at TRL 4, a more quantitative characterization of prospective applications of the new technology must be accomplished. This characterization should comprise (a) high-level performance and/or operations-oriented metrics (e.g., mass, reliability, etc.), (b) expected operational environments, and (c) financial metrics (e.g., cost-related characteristics). The results of these studies should be used to inform the identification of key elements of the new technology, definition of performance objectives for laboratory demonstrations, and formulation of potential pathways forward for the technology.

4.5.2 TECHNOLOGY READINESS ASSESSMENT AT TRL 4

At this stage, an assessment of technology readiness must involve at least the researchers and/or technologists involved in advancing the new concept and independent reviewers representing the management of their organization. Depending on sources of funding, it may be appropriate to also include technically competent representatives of prospective customers for the new technology. Key questions and supporting evidence required for a rigorous assessment are sketched in the paragraphs that follow.

4.5.2.1 Key Questions to Address

A TRA involving technologies at TRL 4 should attempt to respond affirmatively to <u>all</u> of the following questions with regard to R&D results and laboratory demonstrations that have been accomplished.

- TRA QUESTION 4.1: Has the new technology and/or concept been clearly described? What are the critical functions that would be performed by any intended applications of the conceptual approach, device, and/or software? What are the new capabilities that would result from this new concept?

- TRA QUESTION 4.2: Has a prospective application been identified and defined in sufficient detail in terms of expected operational environment, performance requirements, and constituent technologies?[3] Are the interactions among those elements well understood?[4]

- TRA QUESTION 4.3: Has the new concept, technology and/or approach been clearly and rigorously modeled and tested? Is it technically feasible? Do the results of analytical and/or laboratory studies verify that the new technology can satisfy the requirements of the prospective applications (per Question 4.2 above)? [5] What metrics were used to conclude that the laboratory experiments(s) worked as desired?

- TRA QUESTION 4.4: Based on the results, is there a viable path forward that would lead the experiment and/or demonstrations forward to the envisioned future application? What are the likely capabilities that will be needed to follow that path (including operational environments, testing environments, etc.)? Can the technical risk and effort be evaluated?

4.5.2.2 Appropriate Evidence Required

The answer to these questions should be supported by appropriate evidence, including the evidence indicating that TRL 3 was achieved previously, plus the following additional information:

4.A A clear description of the new technology and/or concept been including characterization of the critical functions that would be performed.

4.B A clear and relatively detailed description of the intended application(s) in terms of operating environment, performance requirements, additional constituent technologies and interactions among these factors.

4.C Identification of any or all rigorous experiments and/or analytical studies that have been performed, and the results of demonstrations performed, upon which the feasibility of the technology depends. Delineation of any and all references documenting the results of

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3 In particular, this question refers to the importance of achieving an adequate degree of R&D success to many applications. For example, it may be critical to a system application that an electronic device achieve a certain level of efficiency, speed, etc. Such details of technology performance should be incorporated both into demonstration design and applications modeling as part of achieving TRL 4.

4 It is of greatest importance that integrated experimentation and/or demonstration should involve those elements that are expected to have numerous and/or subtle interactions in an operational system.

5 Types of characteristics might typically include engineering performance, levels of reliability, mean-time-between failure, etc.

analysis and modeling, performed laboratory demonstrations, and/or experimentation performed by others that establish the technical and/or economic feasibility of new technology.

4.D Compelling arguments that indicate likely connection between the demonstrations performed in a laboratory environment and yet-to-be-performed experiments and demonstrations in simulated and/or operational environments. An evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level.

4.6 TRL 5: COMPONENT AND/OR BREADBOARD VALIDATION IN A RELEVANT ENVIRONMENT

4.6.1 DETAILED DEFINITION OF TRL 5

TRL 5 requires the validation of a component and/or breadboard in a relevant environment (i.e., one that represents the expected operational environment in critical aspects). This means that the basic technological elements must be integrated with reasonably realistic supporting elements so that the total application (e.g., at the component-level, sub-system level, and/or system-level) can be tested in a ‘simulated’ or somewhat realistic environment. Anywhere from one to several new technologies might be involved in the demonstration. In other words, at this stage, the fidelity of the component and/or breadboard being tested has to increase significantly beyond those that were demonstrated at TRL 4 or lower.

In general, this implies that the cited validation of new technologies should be done in the context of a specific future system or sub-system level application. Although there may be exceptions, at the level of TRL 5, the specific test articles involved are based on some specific expected application.

4.6.2 TECHNOLOGY READINESS ASSESSMENT AT TRL 5

At this stage, an assessment of technology readiness should involve at least the researchers and/or technologists involved in advancing the new concept and independent reviewers representing the management of their organization, as well technically-competent representatives of prospective customers for the new technology. Depending on the details of R&D financing, this technology assessment could be organized and implemented by either the customer organization, or the technology development organization. Key questions and supporting evidence required for a rigorous assessment are sketched in the paragraphs that follow.

4.6.2.1 Key Questions to Address

A technology readiness assessment at TRL 5 should attempt to answer affirmatively all of the following questions with regard to technology research and development accomplishments.

- TRA QUESTION 5.1: Has the new concept, technology and/or approach been clearly described and modeled? What are the critical functions that would be performed by the conceptual approach, device, and/or software? What are the new capabilities that would result from this new concept?

- TRA QUESTION 5.2: Has a prospective application been defined with sufficient fidelity that the necessary technological elements involved in the new capability have been fully identified? Are the interactions among those elements well understood? Have the functional, operational environment and performance metrics for this application been defined, and do prospective customers agree?

- TRA QUESTION 5.3: Have laboratory demonstrations been performed rigorously and successfully that included key elements[6] being tested individually and/or in an integrated fashion? In such tests, were the results consistent with the characteristics[7] (identified in Question 5.2) that the new technology must possess in order for a prospective future application to be technically and/or economically viable? Are the tests performed representative of the whole environment, in term of type (temperature, mechanical stress, radiation, duration…), sequence (vibration first then thermal…), simultaneity (radiation with temperature…). What metrics were used to conclude that the laboratory demonstration(s) worked as desired?

- TRA QUESTION 5.4: Is there a clearly identified path forward that would lead the experiment and/or demonstrations forward to the specific application described in Question 5.2? What are the likely capabilities that will be needed to follow that path (including operational environments, testing environments, etc.)? Can the technical risk and effort be evaluated?

Generally, beginning at TRL 5, an overarching question is: “has the new technology been subjected to a formal/independent review for the planned system application?”.

4.6.2.2 Appropriate Evidence Required

[6] It is of greatest importance that integrated experimentation and/or demonstration should involve those elements that are expected to have numerous and/or subtle interactions in an operational system.

[7] Types of characteristics might typically include engineering performance, levels of reliability, mean-time-between failure, etc.

The answer to these questions should be supported by appropriate evidence, the documents demonstrating that TRL 4 was achieved previously, plus the following additional information specific to TRL 5:

5.A A clear description of the new technology, including the design of demonstrations performed and explanation of how the testing environment is relevant to the expected operational environment.

5.B Documentation presenting customer-focused applications functionality and resulting performance metrics that were used to drive the selection of technology demonstrations, including definition of appropriate concepts of operations and operational environments for the prospective applications.

5.C Identification and detailed descriptions of any or all demonstrations and/or analytical studies that have been performed, upon which the feasibility of the technology depends. Delineation of any and all references documenting the results of analysis and modeling, performed demonstrations, as well as any experimentation or demonstrations performed by others that establish the technical and/or economic feasibility of new technology.

5.D Compelling arguments that indicate likely connections between the component and/or breadboard demonstrations performed in a relevant environment and yet-to-be-performed demonstrations at higher levels of integration (e.g., systems-level), in relevant and/or operational environments. An evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level.

4.7 TRL 6: SYSTEM/SUBSYSTEM MODEL OR PROTOTYPE DEMONSTRATION IN A RELEVANT ENVIRONMENT (GROUND OR SPACE)

4.7.1 DETAILED DEFINITION OF TRL 6

A major step in the level of integration and/or fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system, which would go well beyond an *ad hoc* discrete component level breadboard, must be tested in a relevant environment. It is important to note that although reaching TRL 6 does not generally require flight of a complete system in space, if the only relevant environment is the environment of space, then the system model/prototype must be demonstrated in space. As is true for each of the TRLs, this demonstration must be successful in order to represent the accomplishment of TRL 6.

At TRL 6, several (or many) new technologies will typically be integrated into the demonstration. For example, a innovative approach to high temperature/low mass radiators, involving liquid droplets and composite materials, would be demonstrated to TRL 6 by actually flying a working, sub-scale (but scaleable) model of the system on a Space Shuttle or International Space Station 'pallet'. In this example, the reason space is the 'relevant' environment is that microgravity plus vacuum plus thermal environment effects will dictate the success/failure of the system, and the only way to validate the technology is in space.

4.7.2 TECHNOLOGY READINESS ASSESSMENT AT TRL 6

At this stage, an assessment of technology readiness must involve not only the technologists and engineers involved in demonstrating the new technology and independent reviewers representing the management of their organization, it must also involve technically competent representatives of prospective customers for the new technology. This technology assessment should be organized and implemented by the customer organization, rather than the technology organization. Key questions and supporting evidence required for a rigorous assessment are sketched in the paragraphs that follow.

4.7.2.1 Key Questions to Address

A technology readiness assessment at TRL 6 should attempt to answer affirmatively all of the following questions with regard to technology development and system-level demonstration accomplishments.

- TRA QUESTION 6.1: Has the new system (or subsystem) that incorporates the new technology been clearly described and modeled? What are the critical functions that would be performed by the new technology in the system? What are the new capabilities that would result?

- TRA QUESTION 6.2: Have one or more specific applications been defined with sufficient fidelity that the detailed technologies involved in that sub-system or system can be identified, including preliminary designs and cost estimates? Have the relevant technology requirements been identified and are the interactions among the various technologies within the system well understood?

- TRA QUESTION 6.3: Have rigorous system-level demonstrations been performed successfully in a relevant environment? Have those demonstrations included key elements being tested individually and/or in an integrated fashion? In such tests, were the results consistent with the levels of performance, cost, etc. that the new technology must possess for the intended system applications to be technically and/or economically viable? What functionality was demonstrated? Was the demonstration been clearly documented and articulated? Are the tests performed representative of the whole environment, in term of type (temperature, mechanical stress, radiation, duration…), sequence (vibration first then thermal…), simultaneity (radiation with temperature…). What metrics were used to conclude that the system-level demonstration(s) worked as desired?

- TRA QUESTION 6.4: Is there a viable path forward that would lead the demonstration accomplished forward the intended application? Is a demonstration at TRL 7 needed, and if so, why? What are the likely capabilities that will be needed to follow that path (including operational environments, testing environments, etc.)? Can the technical risk and effort be evaluated?

4.7.2.2 Appropriate Evidence Required

The answer to these questions should be supported by appropriate evidence, including the documents validating that TRL 5 was achieved previously, plus the following additional information:

6.A A clear description of the new technology, including the design of demonstrations performed and explanation of how the testing environment is relevant to the expected operational environment.

6.B A document describing in full detail the expected functional and environmental requirements that the new technology must satisfy within the context of the envisaged application.

6.C Identification of any or all demonstrations and/or analytical studies that have been performed, and the results of demonstrations performed, upon which the feasibility of the technology depends. Delineation of any and all references documenting the results of analysis and modeling, performed demonstrations, as well as any experimentation or demonstrations performed by others that establish the technical and/or economic feasibility of new technology.

6.D Compelling arguments that indicate likely connections between the subsystem- or system-level demonstrations performed in a relevant environment and yet-to-be-performed demonstrations at higher levels of integration (e.g., systems-level) in an operational environment. An evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level.

4.8 TRL 7: SYSTEM PROTOTYPE DEMONSTRATION IN A SPACE ENVIRONMENT

4.8.1 DETAILED DEFINITION OF TRL 7

TRL 7 is a significant but optional maturation step beyond TRL 6, requiring an actual system prototype demonstration in the expected operational environment (e.g., in space in the case of space applications). Implementing TRL 7 has seldom been done in past technology development programs because it is seldom necessary. Typically, a TRL 7 demonstration is only implemented in cases of high technical risk and/or when systems-level innovation is necessary to achieve mission goals and objectives.

In the event that a TRL 7 demonstration is called for, the prototype should be near or at the scale of the planned operational system and the demonstration must take place in the actual expected operational environment. The driving purpose for achieving this level of maturity must be tied to assuring system engineering and development management confidence (more than for purposes of technology R&D). Therefore, the demonstration must be of a prototype of an actual planned application. Of course, not all technologies in all systems must be demonstrated at this level.

This programmatic maturation step would normally only be performed in cases where the technology and/or subsystem application is both mission critical and relatively high risk. Examples might include situations where the programmatic consequences of poor technology validation would be too great for a subsequent system development program. Another case might involve situations where a new technology and/or conceptual approach are too unusual to be accepted by the system development community without a system-level demonstration.

4.8.2 TECHNOLOGY READINESS ASSESSMENT AT TRL 7

At this stage, an assessment of technology readiness must involve not only the technologists and engineers involved in demonstrating the new technology and independent reviewers representing the management of their organization, it must also involve technically competent representatives of prospective customers for the new technology. This technology assessment is typically organized and implemented by the customer organization, rather than the technology organization. Key questions and supporting evidence required for a rigorous assessment are sketched in the paragraphs that follow.

4.8.2.1 Key Questions to Address

A TRA at TRL 7 should answer affirmatively all of the following questions with regard to technology development and system-level demonstration accomplishments.

- TRA QUESTION 7.1: Has the new system that incorporates the new technology been clearly described and modeled? What are the critical functions that would be performed by the new system / technology? What are the new capabilities that would result?

- TRA QUESTION 7.2: Has the specific intended application been fully defined including all functional and environment requirements.

- TRA QUESTION 7.3: Have rigorous and verifiable system-level demonstrations been performed successfully in the actual expected operational environment (e.g., in space for spacecraft)? Have those demonstrations included key elements being tested in an integrated fashion? In such tests, were the results consistent with the levels of performance, cost, etc. that the new system must possess to fully satisfy the requirements identified in Question 7.2? What functionality was demonstrated? Are the tests performed representative of the whole environment, in term of type (temperature, mechanical stress, radiation, duration…), sequence (vibration first then thermal…), simultaneity (radiation with temperature…). What metrics were used to conclude that the system-level demonstration(s) worked as desired?

- TRA QUESTION 7.4: Is there a viable path forward that would lead from the system demonstration accomplished forward to the intended application? What are the likely capabilities that will be needed to follow that path forward? Can the technical risk and effort be evaluated?

4.8.2.2 Appropriate Evidence Required

The answer to these questions should be supported by appropriate evidence, including the evidence that TRL 6 was achieved previously, plus the following additional information specific to TRL 7:

7.A A clear and comprehensive description of the new technology, including the design of demonstrations performed and explanation of how the testing environment is relevant to the expected operational environment.

7.B A document describing in full detail the expected functional and environmental requirements that the new technology must satisfy within the context of the envisaged application.

7.C Identification of any or all demonstrations and/or analytical studies that have been performed, and the results of demonstrations performed, showing compliance with documented user requirements. Delineation of any and all references documenting the results of analysis and modeling, performed demonstrations, as well as any experimentation or demonstrations performed by others that establish the technical and/or economic feasibility of new technology.

7.D Compelling arguments that indicate likely connections between the subsystem- or system-level demonstrations performed in a relevant environment and yet-to-be-performed demonstrations at higher levels of integration (e.g., systems-level) in an operational environment. An evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level.

4.9 TRL 8: ACTUAL SYSTEM COMPLETED AND "FLIGHT QUALIFIED" THROUGH TEST AND DEMONSTRATION (GROUND OR SPACE)

4.9.1 DETAILED DEFINITION OF TRL 8

By definition, all technologies being applied in actual systems go through TRL 8. In almost all cases, this level is the end of true system development for most technology elements. In the case of a space transportation system being developed, for example, TRL 8 could comprise the completion of Design, Development, Test and Evaluation (DDT&E) through Theoretical First Unit (TFU) for a new type of vehicle. TRL 8 could also often also involve cases in which a new technology is being manufactured and integrated into an existing system (rather than the development of an entirely new system). Alternatively, TRL 8 might also involve developing, loading, testing and deploying for operations successfully some new software involving a revised approach to control algorithms in a spacecraft while it is in orbit.

Systems development efforts will, of course involve any one of a range of program and/or project management methodologies and tools. For example, many projects use the classical systems engineering process that emerged during the 1950s-1960s as a result of various complex systems projects (e.g., the development of the nuclear submarine, Project Apollo, the A300, etc.). There are also a number of distinct methods and tools used in managing information technology (IT) projects. For example, many IT projects use methods codified by the Software Engineering Institute (SEI) at Carnegie Mellon University (CMU). In most cases, the technologies incorporated into a system development project should already be at TRL 6-7 when the project is formally started. (See Section 4.2 for a link between TRL and the typical project phases.) In most cases, the critical goal of technology readiness assessment activities during a systems project (including the use of TRLs) is to manage those technologies that are not yet at TRL 6-7 when the project starts.

4.9.2 TECHNOLOGY READINESS ASSESSMENT AT TRL 8

At this stage, an assessment of technology readiness must be implemented as part of the system development project or program, with the oversight of the project organizational management and/or sponsors. These reviews should be synchronized with other project events. For example, a technology readiness assessment should be conducted as part of a critical design review (CDR), or a preliminary design review (PDR) for the system project. Such an assessment effort should also involve where possible those technologists and engineers who were involved in demonstrating the new technology earlier, as well as and independent reviewers representing the management of system project organization.

These reviews must also involve technically competent representatives of prospective customers for the new system. (Depending on the details of system project/program financing, such technology assessments should be organized and implemented by the customer organization, rather than the technology organization.) Key questions and supporting evidence required for a rigorous assessment are sketched in the paragraphs that follow.

4.9.2.1 Key Questions to Address

Several individual technology readiness assessments are likely to be required during the course of achieving TRL 8; however, these will be incorporated into system development project management events, such as the "critical design review" (CDR) or the Preliminary Design Review (PDR). Also, only at the successful conclusion of the system development project will "TRL 8" be achieved. These assessments should attempt to answer affirmatively all of the following questions with regard to technology development and system-level demonstration accomplishments.

- TRA QUESTION 8.1: Has a production unit (i.e., the actual subsystem or system deliverable from the project) been fully described and successfully manufactured?

- TRA QUESTION 8.2: Has the specific system in which the technology is to be used been defined with sufficient fidelity to allow accurate cost estimates? Have detailed designs for the system been identified both in terms of performance and operational environment? Are the interactions among the various technologies within the system well understood?

- TRA QUESTION 8.3: Has system-level testing verified that the new technology(ies) performed successfully in the appropriate test environments? Are the tests performed representative of the whole environment, in term of type (temperature, mechanical stress, radiation, duration…), sequence (vibration first then thermal…), simultaneity (radiation with temperature…). Has the testing included key elements being tested individually and/or in an integrated fashion? To what extent did the selected new technologies involved play a significant role in the failure or the success of the project? Has a production unit been qualified to the satisfaction of one or more customers?

- TRA QUESTION 8.4: Is there a viable path forward? Are there any remaining barriers to system/mission operations as originally planned? If there are such barriers, are they amenable to solution through changes in mission operations plans? Can the technical risk and effort be evaluated?

4.9.2.2 Appropriate Evidence Required

The answer to the questions above should be supported by appropriate evidence, including documentation that demonstrates that TRL 7 was achieved, plus the following additional information required to establish TRL 8:

8.A A clear description of the production unit, and how that unit will be manufactured and operated, and how it will be integrated into the customers systems and/or system-of-systems. 8.B A document describing in full detail the detailed design of the customer system and/or system-of-systems and resulting system and environmental requirements that the new technology must satisfy within the content of the envisaged application. This should include clear documentation that any prospective customers agree with the results.

8.C A clear description of the results of tests performed using the production unit indicating how the qualification testing results and environment are compliant with the expected operational requirements and environments. Delineation of any and all references documenting the results of analysis and modeling, system designs, performed tests and demonstrations, as well as any experimentation or demonstrations performed by others that establish the technical and/or economic feasibility of any new technology for the system being developed.

8.D Documentation describing the viability of planned mission operations using the developed system to achieve mission goals and objectives. An evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to advance to the next TRL level.

4.10 TRL 9: ACTUAL SYSTEM "FLIGHT PROVEN" THROUGH SUCCESSFUL MISSION OPERATIONS

4.10.1 DETAILED DEFINITION OF TRL 9

TRL 9 is the level of maturity reached by a new system when it is launched and operated successfully (together with all of its constituent technologies). Typically, this level of maturation requires that the system be operated in the originally planned environment, and with performance characteristics that satisfy the requirements of the system and the mission. The key distinction between TRL 8 and TRL 9 is the final step of launch and operations.

4.10.2 TECHNOLOGY ASSESSMENT AT TRL 9

Properly speaking, TRL 9 is demonstrated explicitly by the successful launch and operation of the new system. No technology assessment is necessary to establish whether the system is operating successfully. However, it may be appropriate under special circumstances to conduct a technology assessment for other purposes.

At this stage, assessments of technology, if required, would be implemented either (a) as part of the mission/system operations, with the oversight of system developers, as well as the mission operations organizational management and/or sponsors, or (b) as input to future system planning efforts. The first type of review typically would be synchronized with appropriate operational events, and might occur only as a result of a mission failure. For example, this type of a technology readiness assessment might be conducted as part of a mission problem/failure review board convened following some issue or unexpected event. Alternatively, a technology readiness review might be also conducted in support to future system planning efforts, or for the purpose of obsolescence evaluation in the case of reuse of a technology that has been operating in space for a long time.

Either type of TRL 9 technology readiness assessment effort should involve (where possible) those technologists and engineers who were involved in demonstrating the new technology earlier, the system developers, as well as independent reviewers representing the management of system project organization. These reviews must also involve technically competent representatives of prospective customers for the new system. Such assessments should be organized and implemented by the operational organization, rather than the system development or technology organization. Key questions and supporting evidence required for a rigorous assessment are sketched in the paragraphs that follow.

4.10.2.1 Key Questions to Address

Generally speaking, system assessments will be integrated into mission operations management processes, rather than as stand-alone events. Only a technology assessment that is forward looking is relevant here, one that is intended to inform future system developments. Such assessments should attempt to answer affirmatively the following questions with regard to technology development and system-level demonstration accomplishments.

- <u>TRA QUESTION 9.1</u>: Is the new technology fully described in terms of its final manufacturing and operational plans.

- TRA QUESTION 9.2: Is the new unit (subsystem or system) being produced at the levels of performance, cost, quality, reliability, etc. that were originally anticipated? Are any previously unforeseen barriers to cost effective manufacturing of high-quality units that operate as intended been eliminated?

- TRA QUESTION 9.3: Has the new technology performed as expected? Are the subsystem and the various technologies within the system operating as expected?

- TRA QUESTION 9.4: Are significant barriers remaining to successful system operations (if any) been removed, possibly through applications of new technology? Is the customer happy? Can performance improvements be achieved (if required) with further technology developments? Can the technology be reproduced given the current know-how? Can the technical risk and effort be evaluated?

4.10.2.2 Appropriate Evidence Required

The answer to the questions above should be supported by appropriate evidence, including:

9.A A clear description of the production unit, how that unit was manufactured and operated, and how it was integrated into the customers systems and/or systems-of-systems. This should include clear documentation as to whether the customer agrees with the results.

9.B Documentation describing in full detail the launched system and its planned functionality, along with environmental requirements, and the concept of operations, including the technologies involved, and actual operating requirements and environments.

9.C A description of the approach used for operations verification, including identification of tests done and compelling arguments indicating likely connections between the component- and subsystem-level tests performed previously including system operations. Delineation of any and all references documenting the results of operations assessments, analysis and modeling, performed tests and demonstrations, as well as any experimentation or demonstrations performed that establish the capabilities of the system being operated, and of any new technology used.

9.D Documentation describing any failure analysis that may have been necessary, including details of any the technologies involved and actual environments. Description of any analysis or trade offs performed to identify further development steps to improve the overall system performance (if required). An evaluation of the technical risk (Low, Medium, High), and required effort (Low, Medium, High) to reproduce the same (or improved) technology given the current industrial know-how (if required).

4.11 REUSE OF TECHNOLOGIES IN DIFFERENT SYSTEMS/APPLICATIONS

The higher levels of technology maturity are increasingly dependent on the particular application being considered. Even though a specific technology may have been matured to a high TRL for one application, it will typically not be judged to be at the same readiness level for a different application. For example, an advanced thermal protection system (TPS) may have been used at TRL 9 for atmospheric reentry from low Earth orbit (LEO). However, the same TPS must be judged at no greater than TRL 4 for a substantially new application involving new operating environments, such as reentry at high velocities from an interplanetary trajectory.

Similarly, a mechanism that has been validated at TRL 6 in a thermal-vacuum simulation chamber for operations in lunar orbit might well be judged in a technology readiness assessment as no better than TRL 4 for application in a permanently shadowed region on the Moon that involved a substantially different thermal and dust environment.

Finally, a technology that has been operating correctly in space for many years may not be judged to be still at TRL9 because of problems in manufacturing the same technology with the current industrial know-how (technology obsolescence).

4.12 CORRESPONDENCE BETWEEN TRLS AND COMMONLY-USED ENGINEERING TERMS

Some commonly used engineering terms may be correlated to the various technology readiness levels; Table 4.12-1 summarizes some of the typically cross-correlations with these terms.

Table 4.12-1 Technology Readiness Levels and Common Engineering Terms

Readiness Level	TRL Definition	Commonly Used Engineering / R&D Terms
TRL 1	Basic principles observed and reported	Scientific Research.
TRL 2	Technology concept and/or application formulated	Systems Analyses. Pre-Phase A Studies.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept	Laboratory Experiments.
TRL 4	Component and/or breadboard validation in laboratory environment	Component. Breadboard.
TRL 5	Component and/or breadboard validation in relevant environment	High-Fidelity Breadboard. Brassboard. Engineering Breadboard. Function-Oriented Model.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	High-Fidelity Laboratory Prototype. Engineering Qualification Model. Subsystem model. Development Model. System Model.
TRL 7	System prototype demonstration in a space environment	System Demonstration.
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	Theoretical First Unit. Flight Unit. Flight Spare.
TRL 9	Actual system "flight proven" through successful mission operations	Mission Operations. Flight Qualified Hardware.

Appendix B ("Glossary of Terms") provides additional information.

5 APPENDIX A: GUIDELINES FOR THE DEFINITION OF THE SOFTWARE TECHNOLOGY READINESS LEVELS

5.1 Objectives

The objective of this Appendix is to describe the basic guidelines for the definition of the Technology Readiness Levels relevant to software.

5.2 Basic principles

Software TRL (SW TRL) shall be applied to assess the maturity of technologies implemented in software which may be part of the flight segment (flight software), ground segment (ground software) or engineering tools (software tools).

Due to their very different development and application characteristics, three types of software need to be identified for the purpose of TRL definition:

1. Software building block to be reused in a range of missions, either flight or ground software. This software is executed in a wider software application context. It interacts with other software and also with HW
2. Software tools. They run in a stand-alone mode
3. Software that cannot be considered separated from the HW it runs on, e.g. equipment embedded software.

We propose to use the SW TRL to evaluate the first two types of software, while for the third, we propose to use the TRL classification of the system of which the specific software is part of.

As for HW TRL, the SW TRL are not meant to be applied to the management of a software development project, for which typically the software engineering standard (std) (e.g. ECSS E 40) is applied. The SW TRL is then simply a tool for the evaluation of the maturity of a given software technology (building blocks, tools) within the context of its intended application.

The underlying principles are summarized below:

- TRL 1-4 implies that a large range of application is targeted
- TRL 5-6 has a more focused range of application
- TRL 7 is In Orbit Demonstration (IOD)
- TRL 8-9 is operational in space projects

5.2.1 RELEVANT DEFINITIONS AND PHILOSOPHY

Building blocks (BB)[8]

A software building block is a software element that has an identifiable function within a more complex (software) system, and that can potentially be reused for a range of applications.

TRL philosophy

The range of targeted application is translated into the domain of reuse of the building block.

- For low TRL levels, there is a fuzzy idea of which application could reuse the building block (1-4). The differences between the 4 levels play:
  - on the range of problems and the variability of the solutions,
  - on the amount of functionality implemented,
  - on the level of V&V
- Then the building block becomes mature enough, his domain of reuse has been thoroughly established (e.g. through domain engineering or equivalent), it is a product (5-6). The difference between the two level can be the fact that the test suite is also (or not) reusable and configurable in the domain.
- Then it is used in IOD (7), this is also true for ground segment software
- Then it is used in an operational mission (8-9). The difference between the two levels is that, in the upper level, the building block has actually been used during the mission execution and has been validated by means of in-flight data.

Tools[9]

A software tool is a software element that performs a function in a stand alone mode.

TRL philosophy

- The first 4 levels are used to increase the level of functionality of the tool, from the mathematical formulation and through prototyping and incremental enhancement up to the level of an “alpha” version.

[8] The definition of Building block shall be included in the appendix of the TRLH where relevant engineering terms are defined.
[9] The definition of Tools shall be included in the appendix of the TRLH where relevant engineering terms are defined.

- The next two are used to improve the tool up to the level of a (commercial or otherwise) released product
- The last three levels cover the deployment of the tool in a project, starting with a pilot application (an IOD) and up to a fully operational project.

5.3 Summary Table

The principles described in the previous sections are summarized in the following table:

TRL	DEFINITION	Engineering terms relevant to SW	ADDITIONAL EXPLANATION TO COVER SOFTWARE	DESCRIPTION	REQUIREMENTS	VERIFICATION	VIABILITY
1	Same as HW	MATHEMATICAL FORMULATION	Scientific Knowledge	Detailed mathematical formulation description. Publication of research results.	Expression of a problem and of a concept of solution	Proven mathematical formulation.	Feasibility to be implemented in software with available computing facilities demonstrated
2	Same as HW	ALGORITHM	Individual algorithms or functions are prototyped	Algorithm implementation documented. Results documented.	Practical application identified A concrete specification of a part of the problem	Single algorithms are tested resulting in their characterisation and feasibility demonstration.	feasibility to build critical functions in a system architecture demonstrated

TRL	DEFINITION	Engineering terms relevant to SW	ADDITIONAL EXPLANATION TO COVER SOFTWARE	DESCRIPTION	REQUIREMENTS	VERIFICATION	VIABILITY
3	Same as HW	PROTOTYPE	Prototype of the integrated critical system	Architectural design of critical functions. Depending on size and complexity of the implementation.	Some solutions to a range of problem Main use cases implemented	A subset of the overall functionality is implemented and tested to allow the demonstration of performance. V&V in a simulated laboratory environment	Feasibility to build an operational system taking into account performance and usability aspects demonstrated
4	Same as HW	ALPHA version	Most functionality implemented	Documentation as for TRL 3 plus: • User Manual • Design File	Clear identification of the domain of applicability. Requirements for solutions to a range of problems specified. All use cases implemented	Verification & Validation process is partially completed, or completed for only a subset of the functionality or problem domain V&V in a representative simulated laboratory environment	Feasibility to complete missing functionality and reach a product level quality demonstrated

TRL	DEFINITION	Engineering terms relevant to SW	ADDITIONAL EXPLANATION TO COVER SOFTWARE	DESCRIPTION	REQUIREMENTS	VERIFICATION	VIABILITY
5	Same as HW	BETA version	Implementation of the complete software functionality	Full documentation according to the applicable software standards, including test reports and application examples.	Formal definition of the domain of (re)use and associated variability features of the implementation All use cases and error handling specified.	Validated against the requirements of the complete domain of applicability including robustness Quality assurance aspects taken into account. V&V in an End-to-end representative laboratory environment including real target.	Feasibility to fix all the reported problems (e.g. all open SPRs) within available resources demonstrated. User support organization in place.

TRL	DEFINITION	Engineering terms relevant to SW	ADDITIONAL EXPLANATION TO COVER SOFTWARE	DESCRIPTION	REQUIREMENTS	VERIFICATION	VIABILITY
6	Same as HW	Product RELEASE	Ready for use in an operational/production context, including user support.	Documentation according to the applicable SW eng and Quality standards for a software product.	BB: Process for reuse, for instantiation in the domain of the implementation and its test environment Tools: All use cases and error handling implemented. User friendliness validated.	BB: Validated against the requirements of the complete domain, validation environment also reusable, reuse file available Tools: Verification and Validation process is complete for the intended scope, (including robustness. Configuration control and Quality assurance processes fully deployed V&V in an End-to-end fully representative laboratory environment including real target,	Feasibility to be applied in an operational project demonstrated. This might require a previous pilot application or IOD.

TRL	DEFINITION	Engineering terms relevant to SW	ADDITIONAL EXPLANATION TO COVER SOFTWARE	DESCRIPTION	REQUIREMENTS	VERIFICATION	VIABILITY
7	Same as HW	Early adopter version	BB: Used in IOD Tool: applied to pilot project	In addition to TRL 6 documentation, updates to documentation and qualification file SPR database Lessons learnt report	Requirements traced to IOD mission requirements Validity of solution confirmed within intended application Requirements specification validated by the users	BB: Integrated in the spacecraft following the applicable software standards Tools: The tool has been successfully validated in a pilot case, representative of the intended project application	Engineering support and maintenance organization in place, including helpdesk

TRL	DEFINITION	Engineering terms relevant to SW	ADDITIONAL EXPLANATION TO COVER SOFTWARE	DESCRIPTION	REQUIREMENTS	VERIFICATION	VIABILITY
8	Same as HW	General product	Ready to be applied in the execution of a real space mission	Full documentation including specifications, design definition, design justification, verification & validation (qualification file), users and installation manuals and software problem reports and non-compliances. Including also qualification files, SPR database. Lessons learnt report.	Requirements traced to mission requirements Validity of solution confirmed within intended application Requirements specification validated by the users	BB: Integrated in the spacecraft/ground segment and completed successfully system qualification campaign. Tool: the tool has been successfully applied in an operational project but has not yet been validated against the in-flight experience	Engineering support and maintenance organization in place, including helpdesk. Capability for in-orbit data exploitation and post flight analysis. Capabilities.

TRL	DEFINITION	Engineering terms relevant to SW	ADDITIONAL EXPLANATION TO COVER SOFTWARE	DESCRIPTION	REQUIREMENTS	VERIFICATION	VIABILITY
9	Same as HW	Live product	Has been applied in the execution of a real space mission	In addition to TRL 8 Updates to documentation and qualification file SPR database Lessons learnt report Track record of application in space projects	BB: Maintained Tools: Full process implemented, Maintenance, updates, etc	BB: fully validated for the mission and qualified for intended range of applicability. Tool: the tool has been successfully validated in one or several space missions, including exploitation of in-orbit data. All anomalies encountered have been analyzed and resolved.	sustaining engineering, including maintenance and upgrades in place

6 APPENDIX B

6.1 GLOSSARY OF ACRONYMS

ASTRO	Autonomous Space Transport Robotic Operations
BB	Breadboard
CDR	Critical Design Review
CEV	Crew Exploration Vehicle
CNES	Centre National d'Études Spatiales (The French Space Agency)
CONOPS	Concept of Operations
DARPA	(DOD) Defense Advanced Research Projects Agency
DDR&E	(DOD) Director of Defense Research and Engineering
DDT&E	Design, Development, Test and Engineering
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (The German Aerospace Center)
DOD	(U.S.) Department of Defense
DOE	(U.S.) Department of Energy
EBB	Engineering Breadboard
EMC	Electromagnetic Compatibility
EQM	Engineering/Qualification Model (or “Engineering Qualifying Model”)
ESA	European Space Agency
ESTEC	ESA Space Technology Research and Engineering Centre

ETS	(JAXA) Engineering Test Satellite
FRR	Flight Readiness Review
FY	Fiscal Year
GAO	(U.S.) General Accountability Office
GEO	Geostationary Earth Orbit
GFE	Government Furnished Equipment
GSE	Ground Support Equipment
GSP	(ESA) General Studies Program
GW	Gigawatt(s)
H/W	Hardware
HTSC	High-Temperature Superconductors
IAA	International Academy of Astronautics
IAC	International Astronautical Congress
IAF	International Astronautical Federation
IRL	Integration Readiness level
ISAS	(Japan) Institute of Space and Astronautical Science
Isp	Specific Impulse
ISS	International Space Station
IT	Information Technology
ITP	(NASA) Integrated Technology Plan
JAXA	Japan Aerospace Exploration Agency
JPL	(NASA) Jet Propulsion Laboratory
JSC	(NASA) Johnson Space Center
JSF	(USAF) Joint Strike Fighter

kg	Kilogram(s)
km	Kilometer(s)
kW	Kilowatt
LEO	Low Earth Orbit
LRL	Logistics Readiness Level
LRR	Launch Readiness Review
m	Meter
MDR	Mission Definition Review
MoD	(U.K.) Ministry of Defense
MRL	Manufacturing Readiness Level
MS	Milestone (e.g., MS A, MS B, etc.; used by the U.S. DOD)
MW	Megawatt(s)
NACA	(U.S.) National Advisory Committee on Aeronautics
NAR	Non-Advocate Review
NAS	(U.S.) National Academy of Sciences
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NRC	(U.S.) National Research Council
NSF	(U.S.) National Science Foundation
NSS	National Space Society
OAST	(NASA) Office of Aeronautics and Space Technology
OS	Operating System
POC	Point of Contact
R&D	Research and Development

R&D3	R&D Degree of Difficulty
R&T	Research and Technology (Development)
SBIR	(U.S.) Small Business Innovation Research
SCR	System Concept Review
SEI	Space Exploration Initiative
SEI	Software Engineering Institute
SRL (1)	System Readiness Level
SRL (2)	Software Readiness Level
S/W	Software
TBD	To Be Determined
TFU	Theoretical First Unit
TPS	Thermal Protection System
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
TRRA	Technology Readiness and Risk Assessment
U.K.	United Kingdom
USAF	United States Air Force
USEF	(Japan) Unmanned Space Experiments Free-flyer Institute
VSE	(U.S.) Vision for Space Exploration

7 APPENDIX C

7.1 GLOSSARY OF TERMS

The following table provides a glossary of the terms that are typically used in advanced technology systems and technology readiness assessments. The table is organized into the following major categories of definitions: (1) General Definitions; (2) Generic Hardware Definitions; (3) Environment Related Definitions; (4) Testing Related Definitions; and (5) Flight and/or Operational System Development Related Definitions.

Term	Definition of the Term
GENERAL DEFINITIONS	
High Fidelity	In the case of a piece of hardware that is high fidelity, it would address form, fit and function with respect to a specific application. A high-fidelity laboratory environment would be one that involves testing with equipment that can simulate and validate all system specifications within a laboratory setting.
Logistics	Logistics is the management of the flow of hardware items, information and/or other resources, including energy and people, between the point of origin and the point of consumption in order to meet the requirements of consumers (frequently, and originally, military organizations). Logistics involves the integration of information, transportation, inventory, warehousing, material handling, and packaging.
Low Fidelity	In the case of a piece of hardware that is high-fidelity, it would be a representative of the component or system that has limited ability to provide anything other than first order information about the end-product. A low-fidelity assessment would be one that provided an overall trend analysis and little detailed insight.
GENERIC HARDWARE DEFINITIONS	

Term	**Definition of the Term**
Assembly (or Unit)	A complete and separate lowest level functional item – e.g., a valve.
Component (or Subassembly)	Two or more parts capable of disassembly or replacement – e.g., a device-populated printed circuit board.
Part and/or Device	Single piece or joined pieces the functionality of which would be impaired or destroyed if disassembled – e.g., a resistor.
Subsystem	An integrated collection of components, devices and other elements (including both hardware and software) that perform some specific function or functions, typically as part of a larger system.
System	An integrated collection of subsystems and other elements (including both hardware and software) that performs some specific function or functions, typically as part of a larger mission and/or application, and operating often in combination with other systems.
Segment	A Segment is the constellation of systems, segments, (also software), ground support, and other attributes required for an integrated constellation of systems.
ENVIRONMENT RELATED DEFINITIONS	
Laboratory Environment	A Laboratory Environment is an environment that does not address in any manner the environment to be encountered by the system, subsystem or component (hardware or software) during its intended operation. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions) without respect to the impact of environment.
Operational Environment	The operational environment is the actual environment in which the final system and/or product will be operated. In the case of spaceflight hardware/software it is space. In the case of ground based or airborne systems that are not directed toward space flight it will be the environments defined by the scope of operations.

Term	Definition of the Term
Relevant Environment	A relevant environment is a testing environment that simulates the key aspects of the operational environment. Not all systems, subsystems and/or components need to be operated in an operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical "at risk" aspects of the final product performance in an operational environment.
TESTING RELATED DEFINITIONS	
Proof-of-Concept	The term "Proof-of-Concept" refers to the analytical and physical experiments that demonstrate hardware/software concepts that may or may not be incorporated into subsequent development and/or operational units.
Validation	Demonstration by test that a device meets its functional and environmental requirements. (i.e., did I build the thing right?)
Verification	Determination that a device was built in accordance with the totality of its prescribed requirements by any appropriate method. Commonly uses a verification matrix of requirement and method of verification. (ie., did I build the right thing?)
Testbed	A Testbed is a collection of equipment, software and supporting facilities enabling a technology to be tested in a moderate- to high-fidelity environment that typically includes other new technologies also likely integrated into an operational system. Often, a Testbed is used to validate new/advanced technology subsystems at a TRL 4/5 level of maturity.

<table>
<tr><th>Term</th><th>Definition of the Term</th></tr>
<tr><td>Simulator</td><td>Simulators are used at all levels to simulate items, functions, conditions or interfaces in absence of the real hardware and software during integration and test activities. Simulators of physical characteristics (e.g. 3-D digital mock-up's) are used to support integration activities in terms of accessibility demonstration, handling, interfaces with launcher, GSE and facilities etc. Simulators of functional characteristics (e.g. virtual functional models) are used to support verification activities in terms of simulating missing equipment, test procedure validation, support equipment interfaces, etc

Simulators are also used for the validation of operational scenarios whenever the actual system constituents are not available. Usual simulators and their uses can be:

▪ I/F simulators: structural interface device, integration testing;

▪ Environmental simulators: environmental testing, operational scenario validation (e.g. solar chambers, water submersion model); and,

▪ System (full or partial) simulators: operational scenario validation, integrated flight and ground operations training, mission simulations, joint integrated simulations.

Depending on the individual mission and purpose common model fidelity can range from mock-up to simple front-end fidelity or to flight representative.</td></tr>
<tr><td colspan="2">FLIGHT / OPERATIONAL SYSTEM DEVELOPMENT RELATED DEFINITIONS</td></tr>
<tr><td>Breadboard</td><td>A Breadboard is a low fidelity unit that integrates some components to demonstrate function and concept feasibility only, and may develop technical data—without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance. A breadboard would typically be configured for laboratory use to demonstrate the technical principles of immediate interest. (The term originates with early electronics development efforts in which various components (e.g., tubes, resisters, etc.) were initially connected to one another on a plank of wood that resembled a cutting board for bread.)</td></tr>
</table>

Term	Definition of the Term
Brassboard	A mid-fidelity functional unit that typically tries to make use of as much operational hardware/software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects, but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.
Prototype	A prototype is a physical or virtual model that is used to evaluate the technical or manufacturing feasibility or operational utility of a particular technology or process, concept, end item or system. A prototype demonstrates form (shape and interfaces), fit (must be at a scale to adequately address critical full size issues), and function (full performance capability) of the final hardware. It can be considered as the first Engineering Model. It does not have the engineering pedigree or data to support its use in environments outside of a controlled laboratory environment – except for instances where a specific environment is required to enable the functional operation including in-space. It is to the maximum extent possible identical to operational/flight hardware and/or software and is built to test the manufacturing and testing processes at a scale that is appropriate to address critical full-scale issues.
“Model”	Various types of models can be employed according to verification requirements. These models can either be hardware models, virtual models (simulators and analytical models) or a combination of both (hybrid models)
Developmental Model/ Developmental Test Model	Any of a series of units built to evaluate various aspects of form, fit, function or any combination thereof. In general these units may have some high fidelity aspects but overall will be in the breadboard category.
Virtual or Hybrid Model	In the functional and electrical domain simulation models are used for development and verification. These models exist either in pure software configuration (simulators) or in a combination of software and hardware components. Their composition may change in course of the project life cycle.

<table>
<tr><th>Term</th><th>Definition of the Term</th></tr>
<tr><td>Mock-Up(s)</td><td>Mock-ups are used in support to design definition for overall architecture analyses, configuration design and assessment, interface control and definition, human factors and human computer interface (HCI) assessment, operational procedures evaluation and layout optimization. According to their the degree to which it may represent the anticipated system application, mock-ups are classified as:
Low fidelity: to be used in the initial verification phases (generally, mock-ups for human factors engineering requirement development activities or for validation of software HCI requirements are low fidelity type).
High fidelity: under configuration control in all areas where interface control and flight hardware manufacturing support is provided (e.g. area of utility routing, connector brackets and attach points).
Mock-ups can be incremental tools; iin other words, a given mock-up may be progressively upgraded to better (and better) reflect a final configuration.

Mock-ups intended for human factors evaluation are also used for parabolic flight, buoyancy and swimming pool tests. Their the degree to which a given mock-up represents the ultimate sytem depends on the type of testing to be performed.</td></tr>
<tr><td>Development Model</td><td>In general, Development Models are used in the development areas of new design or where substantial redesign is performed. They are applicable to every type of product (e.g. electronic box, mechanisms, structural parts and thermal equipment) and can be subjected to functional and environmental testing. Development models of subsystems are also envisaged such as: thermal control active control loop breadboards, attitude and orbit control system and guidance, and navigation control benches.</td></tr>
<tr><td>Integration Model</td><td>Integration Models (sometimes called also electrical models) are functionally representative of end items in electrical and software terms. They are used for functional and interface tests and for failure mode investigations. Commercial parts are utilized, but they are typically procured from the same manufacturer of the high reliability parts to be used in the flight end item.</td></tr>
</table>

Term	Definition of the Term
Suitcase (Model)	A Suitcase (model) is designed to simulate telemetry and telecommand performance both in terms of data handling (e.g. transmission formats, bit rates and packet type) and of radio frequency (including ranging). The suitcase includes all the functional simulations (e.g. decoder and transponder). The suitcase is used to test the links with the ground segment or other external infrastructures.
Structural Model	A Structural Model is fully representative of the end item with respect to its structural aspects. It is used for qualification of the structural design and for revision/correction of mathematical models of the structure. Generally, a system structural model consists of a representative structure, with structural dummies of the equipment. It includes also representative mechanical parts of other subsystems (e.g. mechanisms and solar panels). The structural model is also used for a final validation of test facilities and ground support equipment (GSE), and related procedures.
Thermal Model	A Thermal Model is fully representative of the thermal properties of the end item. It is used for the qualification of the thermal design and for the correlation of mathematical models. Generally, the system thermal model consists of a representative structure with thermal dummies of the equipment. It includes also representative thermal parts of other subsystems.
Structural-Thermal Model	A StructuralThermal Model combines the objectives of the structural model and thermal model (defined above). At a system level, this type of model of a representative structure equipped with thermo-structural dummies of equipment. On the other hand, the structural-thermal model can be also a structural model refurbished for thermal verification purposes after structural qualification (in this event no potentially destructive tests are performed on the structural model).

Term	Definition of the Term
Function-Oriented Models	A Function-Oriented Model is dedicated to the qualification of particular functional requirements. They are end item representative for the limited qualification objectives. The definition of these models depends on project characteristics and verification requirements. Examples of function oriented models are ▪ Aerodynamic models, ▪ Robotics and automation models, or ▪ Ground segment functional models.
Engineering Model	An Engineering Model (EM) is a full scale high-fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. It demonstrates function, form, fit or any combination thereof at a scale that is deemed to be representative of the final product operating in its operational environment. Engineering test units are intended to closely resemble the final product (hardware/software) to the maximum extent possible. EM's are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit will become the proto-flight or final product, assuming proper traceability has been exercised over the components and hardware handling. The engineering model is representative of the future operational system in form, fit and function, without full redundancy and high reliability parts. The engineering models are used for functional qualification, except redundancy verification, failure survival demonstration and parameter drift checking. The engineering model is also used for final validation of test facilities and GSE and the related procedures.
Engineering Qualification Model (aka, "Qualification Model")	The Engineering Qualification Model (a.k.a., "Qualifcation Model") fully reflects the design of the end item, except for the parts standard (commercial parts can be used, but these are normally procured from the same manufacturer of the high reliability parts). The engineering qualification models are used for functional performance qualification (including verification of procedures for failure detection, confirmation, isolation and recovery and for redundancy management) and electromagnetic compatibility (EMC) testing. They may also be used for environmental testing if the system customer accepts the risk. Engineering Qualification Models are not used for flight.

Term	Definition of the Term
Training Model	Training Models are dedicated to development and training of flight procedures. Therefore, they are usually a functional representative of the flight model, but modified to function in normal gravity. Training models may be used to ▪ Train flight crew and ground personnel, ▪ Develop and verify procedures, ▪ Establish training records, and/or ▪ Perform baseline data collection.
Flight Proven (System)	A "Flight-Proven" system is one involving hardware and/or software that is identical to hardware and/or software that has been successfully operated in an actual space mission.
Flight Qualification Unit	Flight hardware that is tested to the levels that demonstrate the desired margins, particularly for exposing fatigue stress, typically 20-30%. Sometimes this means testing to failure. This unit is never flown. Key over-test levels are usually +6db above maximum expected for 3 minutes in all axes for shock, acoustic, and vibration; thermal vacuum 10C beyond acceptance for 6 cycles, and 1.25 times static load for unmanned flight.
Protoflight Model	The Protoflight Model is the developmental end item (intended for flight) on which a partial or complete protoflight qualification test campaign is performed before flight. The applicability of a protoflight model, is carefully evaluated (limited life problems) especially when mechanisms are present,
Flight Model (aka, Theoretical First Unit)	The Flight Model is the actual developmental end item that is intended for deployment and operations. It is subjected to formal functional and environmental acceptance testing. The first Flight Model produced may also be known as the "Theoretical First Unit" (TFU).
Flight Spare	The Flight Spare is the spare end item for flight. It is subjected to formal acceptance testing. Refurbished qualification items can be used as flight spares.

Term	Definition of the Term
Flight Qualified	Actual flight hardware/software that has been through acceptance testing is described as “Flight Qualified”. Acceptance test levels are designed to demonstrate flight-worthiness and to screen for potential failures without degrading performance. The levels (e.g., levels of vibration on a “shake table”) used in such testing are typically less than levels that are anticipated in the actual mission.
Mass Model	A Mass Model is a piece of nonfunctional hardware that demonstrates form and/or fit. This model is used in interface testing, handling, and modal anchoring.
Mission Configuration	A Mission Configuration is the final architecture/system design of the product that will be used in the operational environment. If the product is a subsystem/component then it is embedded in the actual system in the actual configuration used in operation.
Proof Model	Hardware built for functional validation up to the breaking point, usually associated with fluid system over pressure, vibration, force loads, environmental extremes, and other mechanical stresses.
Proto-flight Unit	Hardware built for the flight mission that includes the lessons learned from the Engineering Model but where no Qualification model was built to reduce cost. It is however tested to enhanced environmental acceptance levels. It becomes the mission flight article. A higher risk tolerance is accepted as a tradeoff. Key proto-flight over-test levels are usually +3db for shock, vibration, and acoustic; 5C beyond acceptance levels for thermal-vacuum tests.
Subscale Model	Hardware demonstrated in subscale to reduce cost and address critical aspects of the final system. If done at a scale that is adequate to address final system performance issue it may become the prototype.
DDT&E (Design, Development, Test and Engineering)	“DDT&E” is a term-of-art that is synonymous for “Phase C/D” in the lexicon of system development. It comprises that portion of the system development life cycle that begins the detailed designs and systems requirements, and results typically in operational hardware, ready for deployment. The term is used, for example, by NASA and the USAF in discussing flight project planning and cost estimation. Historically, this terminology was already in established use in the mid-1960s within Project Apollo.

7.2 SUMMARY OF SYSTEM DEVELOPMENT TERMS

The following table summarizes the high-level characteristics of the several system development terms defined in the table above.

Model	Objectives	Correspondence to Future System	Applicability	Remarks
Mock-up (MU)	– I/F layout optimization/ assessment – Integration procedure validation – Accommodation checks	– Geometrical configuration – Layouts – Interfaces	– System / element levels	According to their correspondence, MU's are classified as: –Low fidelity, or –High fidelity (to be maintained under configuration control
Mock-up (MU)	– I/F layout optimization/ assessment – Integration procedure validation – Accommodation checks	– Geometrical configuration – Layouts – Interfaces	– System/ element levels	According to their correspondence, MU's are classified as: – Low fidelity – High fidelity (to be maintained under configuration control
Development model (DM)	– Confirmation of design feasibility	– Total conformity with functional electrical & S/W requirements in agreement with verification objectives (size, shape & I/Fs could not be representative)	– All levels	–Development testing –Sometime it is also called breadboard (BB)
Integration model (IM)	– Functional development – S/W development – Procedure validation	– Functional correspondence – Commercial parts – Simulators of missing parts	– All levels	–Development testing –It could be considered something in between a mock-up and an EM –Sometime is called also Electrical Model

Model	Objectives	Correspondence to Future System	Applicability	Remarks
Suitcase	– ·Simulation of functional & RF performances	– Flight design – Commercial parts – Functional representativity	– Equipment level – System level	–Qualification testing

Model	Objectives	Correspondence to Future System	Applicability	Remarks
Structural model (SM)	– Qualification structural design – Validation of structural mathematical model	– Flight standard with respect to structural parameters – Equipment structural dummies	– SS level (structure) – Sometime it could be considered system level if involves other SS or is merged with the system test flow	–Qualification testing
Thermal model (ThM)	– Qualification of thermal design – Validation of thermal mathematical model	– Flight standard with respect to thermal parameters – Equipment thermal dummies	– SS level (thermal control) – Sometime it could be considered system level if involves other SS or is merged with the system test flow	–Qualification testing
Structural thermal model (STM)	– SM & ThM objectives	– SM & ThM representativity – Equipment thermo structural dummies	– System level	–Qualification testing
Engineering model (EM)	– Functional qualification failure survival demonstration & parameter drift checking	– Flight representative in formfitfunction – Flight design without redundancies and high reliability parts	– All levels	–Partial functional qualification testing
Engineering qualification model (EQM)	– Functional qualification of design & I/Fs – EMC	– Full flight design – MILGrade parts procured from the same manufacturer of high reliability parts	– All levels	–Functional qualification testing

Model	Objectives	Correspondence to Future System	Applicability	Remarks
Qualification model (QM)	– Design qualification	– Full flight design & flight standard	– Equipment level – SS level	–Qualification testing
Flight model (FM)	– Flight use	– Full flight design & flight standard	– All levels	–Acceptance testing
Protoflight model (PFM)	– Flight use design qualification	– Full flight design & flight standard	– All levels	–Protoflight qualification testing
Flight spare (FS)	– Spare for flight use	– Full flight design & flight standard	– Equipment level	–Acceptance testing
Function oriented models	– Qualification against the applicable functional requirements	– Flight representative as necessary for the limited qualification objectives	– All levels	–Qualification testing oriented to a specific function or requirement
Training model	– Flight training baseline data	– Flight representative with modifications to allow for normal gravity operation	– All levels	– Q ualification testing oriented to specific HFE requirements
Simulators	– Validation of operations concepts	– Flight representative as necessary for the applicable qualification objectives	– All levels	– Qualification testing oriented to specific HFE requirements
Other crew oriented models	– Qualification against the applicable HFE requirements	– Flight representative as necessary for the limited qualification objectives	– All levels	– Qualification testing oriented to specific HFE requirements