ECSS-E-HB-11A
1 March 2017

Space engineering

Technology readiness level (TRL) guidelines

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands

Foreword

This Handbook is one document of the series of ECSS Documents intended to be used as supporting material for ECSS Standards in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards.

The material in this Handbook is defined in terms of description and recommendation how to organize and perform the work of Technology Readiness Level (TRL) assignment through the Technology Readiness Assessment (TRA) and reporting through the Technology Readiness Status List (TRSL)

This handbook has been prepared by the ECSS TRL Task Force, reviewed by the ECSS Executive Secretariat and approved by the ECSS Technical Authority.

Disclaimer

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Introduction

This Handbook supports the application of the TRL, and provides guidelines to its use in projects and its independent verification within each specific project context.

This Handbook provides guidelines for best practice for interpretation of the requirements contained in ECSS-E-AS-11 and for the implementation of the process of technology readiness assessment for technologies applied to a critical function of an element.

The ECSS-E-AS-11 - "Adoption Notice of ISO 16290 Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment" adopts ISO 16290 with a minimum set of modifications, to allow for reference and for a consistent integration in ECSS system of standards.

TRL is a scale for technology maturity assessment and not a method of technology engineering nor development. TRL is used in R&T&D activities and also in project activities.

For project activities, a technology readiness assessment informs the project manager (until the end of B phase) of the risk when adopting a new technology for a critical function of an element of the system. In the C and D phases TRL is no longer used by the project and the maturity of technology is managed in the critical item list.

For other projects the information of the declared technology maturity can be reused and an assessment of the new project use conditions are considered in the assessment.

In this handbook the three main actors and the respective role of each actor are clearly identified. The three discrete actors are: technology developers, projects teams (using the technology) and the TRA participants (i.e. those who perform the technology readiness assessment).

1
Scope

The present handbook is provided to support the implementation of the requirements of ECSS-E-AS-11 to space projects.

With this purpose, this handbook provides guidelines on the way to assess the maturity of a technology of a product in a given environment, to use the TRL assessment outcome in the product development framework, and to introduce some further refinements for specific disciplines or products to which the TRL assessment methodology can be extended.

The concept of Manufacturing Readiness Level (MRL) is not addressed in this document, whilst the concept of TRL can be applied to the technology-related aspects of manufacturing.

2
References

The following documents are referenced in this text or provide additional information useful for the reader.

ECSS-S-ST-00-01	ECSS system – Glossary of terms
ECSS-E-ST-10	Space engineering – System engineering general requirements
ECSS-E-ST-10-02	Space engineering – Verification
ECSS-E-ST-10-03	Space engineering – Testing
ECSS-E-ST-10-06	Space engineering – Technical requirements specification
ECSS-E-ST-10-24	Space engineering – Interface management
ECSS-E-AS-11	Adoption notice of ISO 16290, Space systems – Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment (1 October 2014)
ECSS-E-HB-10-02	Space engineering – Verification guidelines
ECSS-E-ST-40	Space engineering – Software
ECSS-E-ST-70	Space engineering – Ground systems and operations
ECSS-M-ST-10-01	Space project management – Organization and conduct of reviews
ECSS-M-ST-60	Space project management – Cost and schedule management
ECSS-M-ST-80	Space project management – Risk management
ECSS-Q-ST-10	Space product assurance – Product assurance management
ECSS-Q-ST-10-04	Space product assurance – Critical-item control
ECSS-Q-ST-20	Space product assurance – Quality assurance
ECSS-Q-ST-20-10	Space product assurance – Off-the-shelf items utilization in space systems
ECSS-Q-ST-30	Space product assurance – Dependability
ECSS-Q-ST-40	Space product assurance - Safety
ECSS-Q-ST-60	Space product assurance – Electrical, electronic and electromechanical (EEE) components
ECSS-Q-ST-60-13	Space product assurance – Commercial electrical, electronic and electromechanical (EEE) components
ECSS-Q-ST-70	Space product assurance – Materials, mechanical parts and processes
ECSS-Q-ST-70-71	Spaced product assurance – Materials, processes and their data selection
ECSS-Q-ST-80	Space product assurance – Software product assurance

ISO 16290:2013	Space systems - Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment
Mankins 95 reference (M95r)	TECHNOLOGY READINESS LEVELS, A White Paper, April 6, 1995, John C. Mankins Advanced Concepts Office, Office of Space Access and Technology NASA 1 https://www.hq.nasa.gov/office/codeq/trl/trl.pdf

3
Terms, definitions and abbreviated terms

3.1 Terms defined in other documents

a. For the purpose of this document, the terms and definitions from ECSS-E-AS-11 apply, in particular for the following terms:

1. critical function of an element

   NOTE The synonym of "critical function" is "critical function of an element".

2. element

   NOTE It is important to realize that the term element has a different meaning in ECSS-E-AS-11 (that refer to ISO 16290) than in the ECSS Glossary of terms (ECSS-S-ST-00-02). This guidelines use the term element as defined in ISO 16290.

3. breadboard
4. laboratory environment
5. mature technology
6. operational environment
7. relevant environment
8. reproducible process
9. validation

b. For the purpose of this document the terms from ECSS-S-ST-00-01, except the terms listed in 3.1a apply, in particular for the following terms:

1. commissioning result review
2. component (context EEE)

   NOTE For TRL 4 and TRL 5 the term "component" is understood as "part of a larger whole".

3. environment
4. ground segment
5. technology readiness level

c. For the purpose of this document the terms from ECSS-E-ST-70, except the terms listed in 3.1a. and 3.1b apply, in particular for the following term:

1. Ground Segment QR (GSQR)
2. Operations QR (OQR)
3. Software Requirement Specification (SRS)

3.2 Terms specific to the present document

3.2.1 Research and Technology and Development (R&T&D)

activities to mature from research to technology to development as they are progressing from lower to high TRL levels

3.3 Abbreviated terms and symbols

For the purpose of this document, the abbreviated terms from ECSS-S-ST-00-01 and the following apply:

Abbreviation	Meaning
AR	acceptance review
CDR	critical design review
CRR	commissioning readiness review
CIL	critical item list
DM	development model
DD	displacement damage
EEE	electrical, electronic and electromechanical
EM	engineering model
EMC	electromagnetic compatibility
EQM	engineering qualification model
EQSR	equipment qualification status review
ESCC	European Space Components Coordination
FM	flight model
IOOR	In-orbit operations review
ISO	International Standardization Organization
ITT	invitation to tender
LEOP	Launch and early orbit phase
M95r	Mankins 95 reference
MDR	mission definition review
NASA	National Aeronautics and Space Administration
NWIP	new work item proposal
PA	Product Assurance
PCB	printed circuit board
PDR	preliminary design review
PFM	protoflight model
POC	proof of concept
PRR	preliminary requirements review
QM	qualification model

Abbreviation	Meaning
QMS	quality management system
QR	qualification review
RAMS	reliability, availability, maintainability and safety
RF	radiofrequency
R&T&D	Research and Technology and Development
SEE	single event effect
SEL	single event latch-up
SM	structural model
SPR	software problem report
SRF	software reuse file
STM	structural thermal model
TID	total ionising dose
TM	thermal model
ToR	terms of reference
TP	technology plan
TRA	technology readiness assessment
TRL	technology readiness level
TRSL	technology readiness status list
V&V	verification and validation
WG	working group
w.r.t.	with respect to

4
TRL history and evolution

4.1 History and evolution

The TRL methodology was originated at NASA in the 1970s in order to establish a method by which NASA selected new technology amongst numerous candidates for their complex spaceflight programmes. The scale progressed until 1995 with the definition of nine levels that became the Mankins 95 reference (M95r) [see clause2]. From that moment, the principle of a maturity scale was adopted by many companies and government agencies around the world. However, although they were somewhat similar, different definitions or interpretation of the M95r were used. ECSS decided, in 2008, to first make a harmonization at European level and then to propose to ISO a global harmonization in 2009. This then resulted in an ISO New Work Item Proposal (NWIP) "Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment".

The ISO standard 16290 was published in 2013 and as a result, TRL are now globally harmonized. ECSS actively contributed to this ISO standard by providing members to the ISO WG. The ISO standard concerns the definition and the criteria of assessment, however the procedure for the TRL assessment or the way to use them within a project's framework was not the purpose of the standard. The standard is applicable primarily to space system hardware, although the definitions are used in a wider domain in many cases.

It is important to recognise that the ISO standard introduces some modifications with regards to the M95r previous interpretation in ECSS documents.

4.2 Differences between M95r and ISO 16290 standard as seen by ECSS (European interpretation)

Below is given a summary of the differences between M95r and ISO 16290 standard, supported by Figure 4-1:

- ISO levels 1, 2, 3 and 4 definitions are equivalent to M95r (see clause 2) .
- ISO level 5 is a new intermediate level defined for when breadboards at sub-scales are used (the breadboards used to demonstrate the critical function in a relevant environment are not full scale or full function representations of the flight equipment).
- ISO level 6 is equivalent to M95r level 5.
- ISO level 7 is equivalent to M95r level 6.
- ISO does not recognize M95r level 7 which was "System prototype demonstration in space environment".
- ISO levels 8 and 9 are equivalent to M95r definitions respectively defining "flight qualified" (qualified for flight) and "flight proven" for the actual systems.

Differences between M95r and ISO are summed up in Figure 4-1.

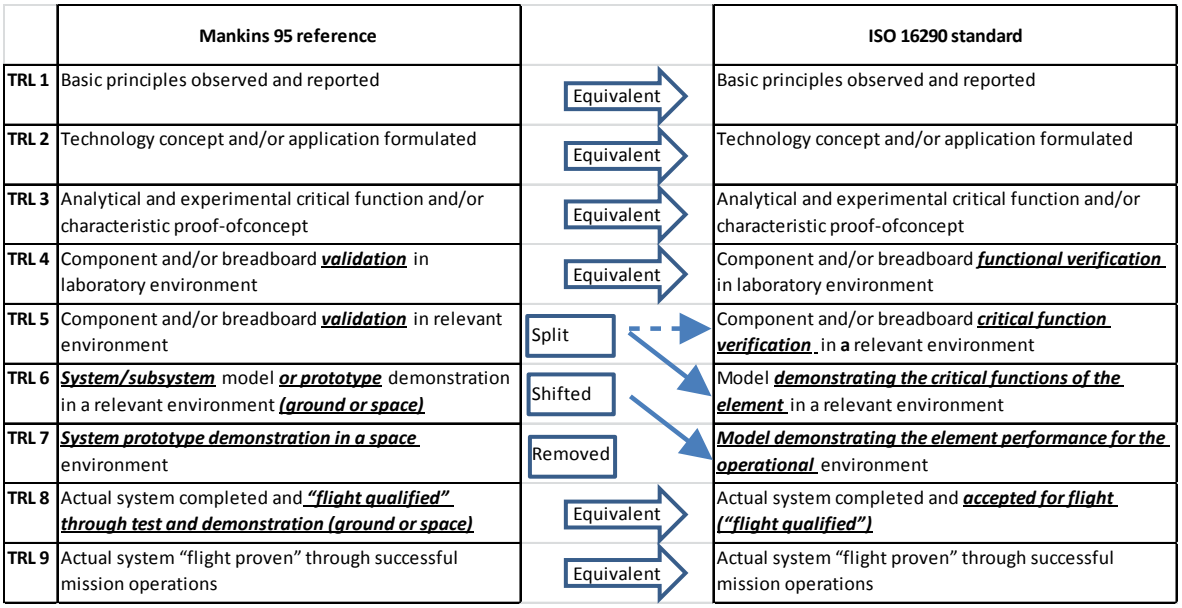

Figure 4-1: Illustration of differences between M95r (European interpretation) and ECSS-E-AS-11

The M95r scale is now obsolete and for the remainder of this handbook, the term TRL is referring to ECSS-E-AS-11 definition.

4.3 TRL implementation in ECSS system

TRL are implemented in ECSS system following four ways:

1. adoption of the ISO 16290 with an Adoption Notice (AN ref ECSS-E-AS-11),
2. introduction in the ECSS standards of the reference to the AN when TRL are used,
3. introduction in the ECSS standards of the requirements to manage the use of TRL,
4. provision of guidelines in this handbook.

The adoption notice ECSS-E-AS-11 was necessary to provide a concise method of introducing the ISO standard in ECSS system. The AN was needed to make normative the TRL following ECSS editorial rules, to align the terms definition and to make reference when necessary to ECSS type of reviews.

This handbook provides guidelines on the way to assess a product, to use the TRL assessment outcome in the product and project development framework, and to introduce some refinements for specific disciplines or products.

4.4 TRL and assessment basic principles

Technology readiness assessment (TRA, see clause 5) allows for the assignment of a measure of the maturity of a technology. It is important to make clear that undertaking a TRA is not a method to develop technologies. The way to develop, to test, to qualify or to verify the development cycle of products, or the model philosophy defined by projects, are not the object of TRL but the purpose of others discipline-specific ECSS standards and handbooks.

The measure provided by TRL assessment is valid for a given element, at a given point in time, and a given defined environment. It changes if the conditions (such as operational environment) that

prevailed at the time of the assessment are no longer valid. Such a situation leads to TRL reassessment and re-grading, which can occur in particular when the re-build or re-use of an element is envisioned with variation in the design, development process, targeted environment or operations.

During Research and Development, or Research and Technology (R&T&D) activities, TRL can be used by the specialists developing the technologies to present their development plans (e.g. technology roadmaps) and to communicate with non-specialists or project managers, the costs or risks involved in taking particular technology choices with different TRLs.

In the framework of projects, TRL is used during preliminary phases (0, A, B) as a tool supporting the decision whether or not to use or integrate specific technology in a space mission, and allowing such decision to be taken with sufficient knowledge of any risk relating to the degree of maturity.

Generally R&T&D programs push ("research push") the technologies maturity as far as the intermediate TRLs. Projects then pull some technologies and develop these to the higher levels of maturity.

The intermediate levels of maturity (typically TRLs 4, 5 and 6) are sometimes called "valley of death" since some technologies are developed until TRL 4 or below, however they are not developed beyond this achieved level (i.e. in the absence of a project "pull"), noting that projects are normally interested in TRL 6 or above (see Figure 4-2).

The costs associated with a specific technology achieving a higher level of TRL are generally increasing with each level attained.

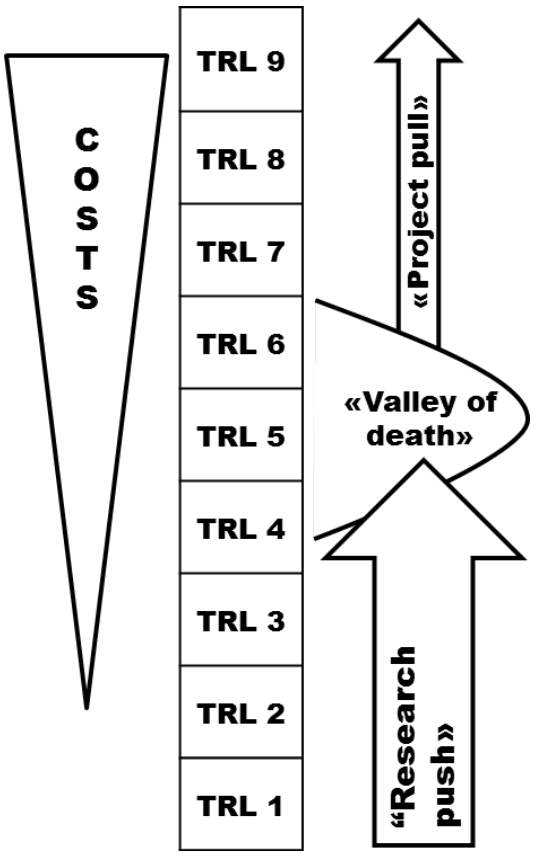

Figure 4-2: Evolution technology maturity

It is important to highlight the following aspects in the application of TRL:

- TRL assessment is not intrinsic to a technology: if a new target environment has different constraints or performance requirements, a TRL needs to be reduced (e.g. a TRL 9 in one application falls even as far as TRL 4 in another).
- TRL 5 and higher are assessed to a specific mission environment. When an element at a TRL higher than 5 is intended to be used in a different environment, in this case there is a potential that the TRL is downgraded.
- TRL does not take into account industrial capacities of production or technology access constraints (e.g. export control regulations).
- TRL does not take into account technology obsolescence, however conversely obsolescence can drive the need for a TRL re-assessment.
- If the production of anything inside an element is discontinued, the TRL of the element can be affected (see example "Heritage category C" in Table 7-3).
- TRL does not replace development cycle or quality rules.
- TRL is not mandatorily incremental: it is not mandatory to achieve level 5 (sub-scale) before proceeding to level 6. More generally, it is not mandatory to go systematically through all levels.
- A TRL can only be reached by an element if all of the sub-elements are at least at the same level.
- An R&T&D action does not necessarily lead to an increment in TRL.
- The time or effort to move from one TRL to another is technology dependent and cannot be linearly projected along the TRL scale.
- The proof necessary for the assessment of TRL is as follows:
  - For TRL 7 and 8, when the derivation of the evidence for the assessment of TRL is based on testing, the test is performed using the requirements of ECSS-E-ST-10-03. It is important to note that testing alone is not sufficient when assessing a product for TRL 7 and TRL 8.
  - However, for TRL 1 to 6 where the derivation of the evidence for the assessment of TRL is selected to be based on testing, the test is performed using the state-of-the-art rules relevant to the TRL being assessed. For further details of the expected documentation see clause 5.

5
Technology readiness assessment (TRA) guidelines

5.1 Introduction

The value of a technology readiness assessment (TRA) exercise is to inform new programmes about the work already achieved on new technologies and optimise synergies between programmes. Technologies are often developed in the frame of institutional programmes, or through R&T&D activities to prepare commercial programmes. For teams working in technology development, TRL is a way to promote (i.e. push) technologies into programmes. Determining the evolution of TRL helps to build roadmaps and to optimise funding opportunities by providing a framework for the assessment of risk associated with the related technology.

This clause 5 provides a set of guidelines to perform a TRA, starting with some general description of a typical process for conducting a TRA, followed by a series of detailed guidelines for a TRA, one for each Technology Readiness Level is proposed.

As stated in the Introduction, it is important to recall that there are potentially three entities concerned with the TRA: the entity requesting the TRA, the supplier of the technology, and the TRA participants (selected to achieve an independent assessment).

NOTE The entity requesting the TRA, e.g. a project or an R&T&D programme, can be internal or external to the technology developer organisation.

5.2 General principles for technology readiness assessment

5.2.1 TRL standard

A TRA implements the requirements of TRL Adoption Notice ECSS-E-AS-11 (which adopts the definitions and criteria of assessment of ISO 16290) which are provided in Table 5-1.

Table 5-1: TRL summary - Milestones and work achievement (*adapted from ISO 16290*)

Technology Readiness Level	Milestone achieved for the element	Work achievement (documented)
TRL 1: Basic principles observed and reported	Potential applications are identified following basic observations but element concept not yet formulated.	• Expression of the basic principles intended for use. • Identification of potential applications.
TRL 2: Technology concept and/or application formulated	Formulation of potential applications and preliminary element concept. No proof of concept yet.	• Formulation of potential applications. • Preliminary conceptual design of the element, providing understanding of how the basic principles would be used.
TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept	Element concept is elaborated and expected performance is demonstrated through analytical models supported by experimental data and characteristics.	• Preliminary performance requirements (can target several missions) including definition of functional performance requirements. • Conceptual design of the element. • Experimental data inputs, laboratory-based experiment definition and results. • Element analytical models for the proof-of-concept.
TRL 4: Component and/or breadboard functional verification in laboratory environment	Element functional performance is demonstrated by breadboard testing in laboratory environment.	• Preliminary performance requirements (can target several missions) with definition of functional performance requirements. • Conceptual design of the element. • Functional performance test plan. • Breadboard definition for the functional performance verification. • Breadboard test reports.

Technology Readiness Level	Milestone achieved for the element	Work achievement (documented)
TRL 5: Component and/or breadboard critical function verification in a relevant environment	Critical functions of the element are identified and the associated relevant environment is defined. Breadboards not full-scale are built for verifying the performance through testing in the relevant environment, subject to scaling effects.	• Preliminary definition of performance requirements and of the relevant environment. • Identification and analysis of the element critical functions. • Preliminary design of the element, supported by appropriate models for the critical functions verification. • Critical function test plan. Analysis of scaling effects. • Breadboard definition for the critical function verification. • Breadboard test reports.
TRL 6: Model demonstrating the critical functions of the element in a relevant environment	Critical functions of the element are verified, performance is demonstrated in the relevant environment and representative model(s) in form, fit and function.	• Definition of performance requirements and of the relevant environment. • Identification and analysis of the element critical functions. • Design of the element, supported by appropriate models for the critical functions verification. • Critical function test plan. • Model definition for the critical function verifications. • Model test reports.
TRL 7: Model demonstrating the element performance for the operational environment	Performance is demonstrated for the operational environment, on the ground or if necessary in space. A representative model, fully reflecting all aspects of the flight model design, is build and tested with adequate margins for demonstrating the performance in the operational environment.	• Definition of performance requirements, including definition of the operational environment. • Model definition and realisation. • Model test plan. • Model test results.

Technology Readiness Level	Milestone achieved for the element	Work achievement (documented)
TRL 8: Actual system completed and accepted for flight ("flight qualified")	Flight model is qualified and integrated in the final system ready for flight.	• Flight model is built and integrated into the final system. • Flight acceptance of the final system.
TRL 9: Actual system "flight proven" through successful mission operations	Technology is mature. The element is successfully in service for the assigned mission in the actual operational environment.	• Commissioning in early operation phase. • In-orbit operation report.
NOTE: The present Table, taken from ISO 16290, is reproduced with the permission of the International Organization for Standardization, ISO. This standard can be obtained from any ISO member and from the Web site of the ISO Central Secretariat at the following address: www.iso.org. Copyright remains with ISO. The standard can be obtained from ISO or its members, see www.iso.org		

5.2.2 TRA pre-requisites

A pre-requisite of any TRA is the clear identification of the element that is subject to assessment.

In general, the reason for this clear identification is that:

- the degree of integration of the element under assessment increases when moving up in the TRL scale (particularly for TRL 5 and over),
- when moving up the TRL scale, critical function of an element and performance need to be demonstrated in varying ways:
  - in the laboratory environment (TRL 4),
  - in the relevant environment (TRL 5 and 6),
  - for the operational environment (TRL 7), or
  - in the flight configuration of the complete system (TRL 8 and 9),
- other products interfacing with or integrated in the product can have an impact on the critical function of an element, and therefore influence the TRL.

Many of these interactions are easily predictable, but some others can be not so evident until verified by test. For example, electromagnetic compatibility (EMC) is an issue to be considered when increasing the level of integration.

The level of integration and correspondent environment typically increases when TRL is incrementing. For example a transistor, using new technology, can be assessed as a single component in low TRL (e.g. until level 4). It is then integrated into an equipment (e.g. amplifier) which is finally itself integrated in the flight system (e.g. level 5 to 7 and finally 8 to 9). See Figure 5-1 as an example of this integration.

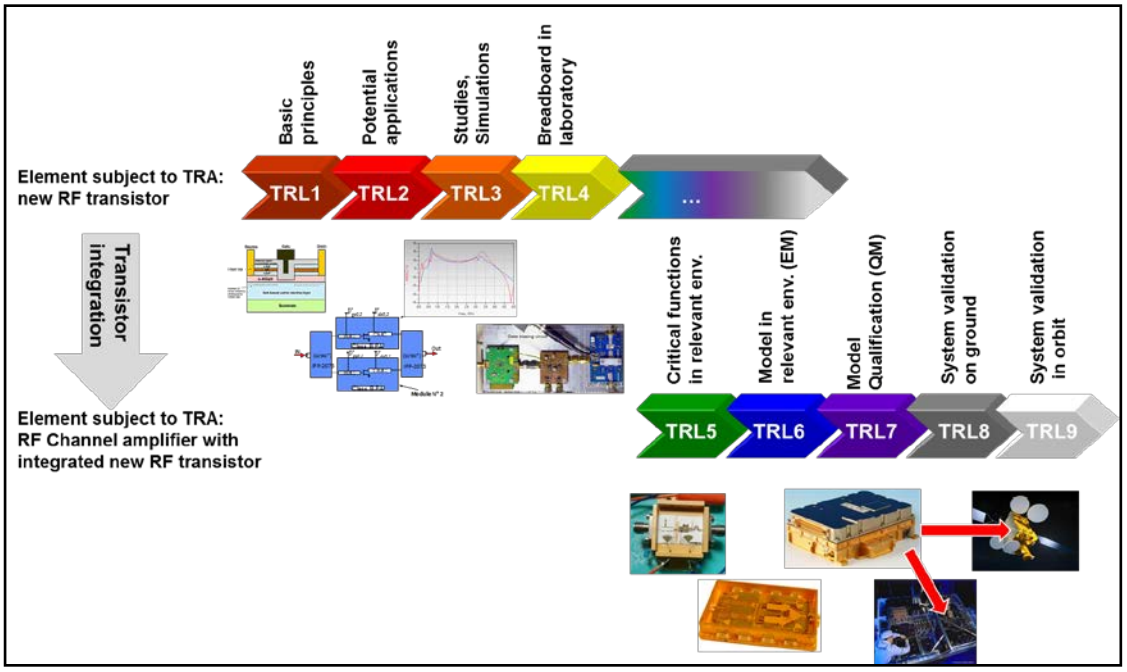

Figure 5-1: Illustration of a new RF transistor then RF amplifier progressing through TRL

5.2.3 Independent verification of the TRL

The following are guidelines to ensure independent verification of the TRL:

- In order to ensure that a TRA of an element is objective, it is completed by independent expertise in the discipline, i.e. not part of the technology developer engineering team.

  NOTE In project framework the PA manager could be part of the independent verification function.

- Principle of independence in TRA process is similar to any review process (see example of independence principle in ECSS-M-ST-10-01 where review board is independent from project team).
- Access, for TRA team, to the necessary information and data concerning the technology and the level to be assessed (see more details in 5.3) is ensured by the entity requesting the TRA.

5.2.4 Discipline specific TRA process

Software, EEE components and Materials, and Manufacturing Processes have their own dedicated development and qualification processes consistent with the generic TRA approach given. For these disciplines more specific TRA guidelines are undertaken as covered respectively in Annex A, Annex B and Annex C.

5.2.5 Typical technology readiness assessment (TRA) process

For the main milestones in the technology development, a TRA could be requested. It is necessary to follow some basic principles, which are captured in a specific Terms of Reference (ToR) for the assessment team:

- TRA inputs:
  - Formal ToR for the assessment generally including:
    - clear identification of the element to be assessed,
    - target TRL and recall of its targeted achievements (see in 5.3, for each level, the detailed evaluation aspects),
    - identification of key technology data to be provided concerning:
      - element definition status (see in 5.3, for each level, the detailed associated documentation),
      - performance requirements status (see in 5.3, for each level, the detailed associated documentation),
      - V&V status (see in 5.3, for each level, the detailed associated documentation),
      - others existing element TRA (e.g. previous TRA reports of lower levels)
    - expected TRA output,
    - planning for the assessment,
    - identification of TRA participants and expertise (see 5.2.3 for principle of independence).
  - Key technology data as identified in the ToR or asked by the TRA participants.

    NOTE For low TRL, the TRA process could be streamlined and adapted to the context.

- TRA organisation:
  - Identification of TRA participants including:
    - TRA leader, independent from the technology development,
    - technical experts, one or more of whom are independent,
    - in a project framework, project participants (e.g. PA manager).
  - Implementation of the TRA itself (often involving formal meetings of TRA participants).
- TRA outputs:
  - Development and endorsement of a TRA report by the TRA participants (in line with the ToR).
    - TRA report details whether the targeted TRL is reached or identifies the lacking aspects and associated evidence necessary to reach the targeted TRL.

5.2.6 TRA criteria

Generally speaking, a set of specific criteria is applied in conducting a TRA. The principal areas for TRA criteria are:

- Element definition status:

  A description of the element, the associated critical function of an element and technology being assessed including also other technologies that are involved and, if appropriate, the interactions between the various technologies

  NOTE In case of multiple technologies being assessed within a single element, the TRA assess each technology.

- Performance requirements status:
  - Identified applications
  - Functional performance, operational performance
- V&V status:
  - Test environment (i.e. “laboratory”, “relevant”, or “operational” environments)
  - Test support used (e.g. “breadboard”, “representative models”, “qualification models”)

5.2.7 Viability of TRL progression

It is good practice to include as part of the TRA an optional evaluation of viability for further progression of the element through the TRLs. This option, although primarily in the R&T&D programmes, is considered on the basis that the additional effort to perform this analysis is limited, and provides considerable risk-related data to the potential future users of the element being evaluated. This evaluation is made on the basis of:

- predicted time for maturity progression,
- cost,
- complexity, and
- consideration of programmatic constraints.

5.3 TRL evaluation by level

5.3.1 TRL 1: Basic principles observed and reported

- Element definition status:

  Expression of basic principles for intended use.

  NOTE Space Agencies and Industries are generally not involved in this scientific research activity.

- Performance requirements status:
  - Potential applications identified
  - Performance requirements are not yet specified
- V&V status:

  Not Applicable for Space Agencies and Industries.

  NOTE TRA is not performed on this level.

5.3.2 TRL 2: Technology concept and/or application formulated

- Element definition status:

  Preliminary conceptual design of the element, providing understanding of how the basic principles are used.

- Performance requirements status:
  - Formulation of potential application
  - Performance requirements are general and broadly defined
- V&V status:

  No proof of concept yet.

  NOTE TRA is not performed on this level.

5.3.3 TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept

5.3.3.1 General evaluation aspects

- Element definition status:

  Proof of the critical function of the element or characteristic by analysis possibly supported by laboratory experiments (such as technological samples supporting “proof-of-concept”) based on a conceptual design.

- Performance requirements status:

  Preliminary functional performance requirements are established (targeting several missions or applications)

- V&V status:

  Analytical model, study, simulation, laboratory experiment

5.3.3.2 Documentation for TRA

Study report with verification results (laboratory experiments, analysis, simulation) and including:

- "Preliminary performance requirements (can target several missions) including definition of functional performance requirements" (as specified in ECSS-E-AS-11).
- Conceptual design of the element.
- Experimental data inputs, laboratory-based experiment definition and results.
- Element analytical models for the proof-of-concept.

5.3.4 TRL 4 : Component and/or breadboard functional verification in laboratory environment

5.3.4.1 General evaluation aspects

- Element definition status:

  The same as TRL 3 updated with breadboard test results
- Performance requirements status:

  The same as TRL 3 updated with breadboard test results.
- V&V status:

  A laboratory breadboard model of the element is integrated to establish that the "pieces" work together to demonstrate the basic functional performance of the element. The verification is "low fidelity" compared to the eventual system and is limited to laboratory environment.

5.3.4.2 Documentation for TRA

Report with breadboard definition, test plan and test results demonstrating functional performance verification and including:

- "Preliminary performance requirements (can target several missions) including definition of functional performance requirements" (as specified in ECSS-E-AS-11). Requirements are updated from TRL3, as available.
- Conceptual design of the element. (updated from TRL3, as available).
- Functional performance test plan (which were used to achieve the TRL).
- Breadboard definition for the functional performance verification.
- Breadboard test reports.

5.3.5 TRL 5 : Component and/or breadboard critical function verification in a relevant environment

5.3.5.1 General evaluation aspects

- Element definition status:

  Critical functions of the element are identified and verified in a relevant environment on non-full-scale breadboard(s). Preliminary functional and technical design of the element is achieved.

- Performance requirements status:

  In particular for critical functions:

  – Preliminary definition of performance requirements

  – Definition of the relevant environment.

- V&V status:

  – "Breadboards not full-scale are built for verifying the performance through testing in the relevant environment, subject to scaling effects" (as specified in ECSS-E-AS-11).

  – At this stage "the element feasibility can be considered as demonstrated, subject to scaling effects" (as specified in ECSS-E-AS-11).

5.3.5.2 Documentation for TRA

- Preliminary definition of performance requirements and of the relevant environment:
  – Preliminary technical requirements specification (see ECSS-E-ST-10-06 Annex A)
- Identification and analysis of critical function of an element :
  – Analysis report (see ECSS-E-ST-10 Annex Q) for technology associated with critical function of an element
- Preliminary design of the element, supported by appropriate models for the verification of the critical function of an element :
  – Preliminary design definition file (see ECSS-E-ST-10 Annex G)
  – Preliminary design justification file (see ECSS-E-ST-10 Annex K), including:
    - identification of computational design methods and tools;
    - analysis of scaling effects;
    - breadboard definition for the verification of the critical function of an element;
    - Test plan of the critical function of an element (which were used to achieve the TRL);

      NOTE For a test plan template see DRD in ECSS-E-ST-10-03 Annex A.

    - Breadboard test reports

      NOTE For a test report template see DRD in ECSS-E-ST-10-02 Annex C.

5.3.6 TRL 6: Model demonstrating the critical functions of the element in a relevant environment

5.3.6.1 General evaluation aspects

- Element definition status:

  Critical functions of the element are verified and design of the element is achieved, supported by appropriate models for the verification of a critical function of an element.

- Performance requirements status:

  Mission objectives, operational environment and the operational performance requirements are established and agreed upon by the stakeholders, taking into account the element integration in the final system.

- V&V status:

  The critical functions of the element are verified in the relevant environment (relevant for critical functions). For that purpose, a representative model(s) in terms of form, fit and function is used for demonstrating the critical functions and unambiguously demonstrating the element performance. It is confirmed that the test performance is in agreement with analytical predictions. The model types used (see ECSS-E-HB-10-02 clause 5.2.5.2) for this verification include one or more of the following for critical functions:

  – engineering model (EM),
  – structural model (SM),
  – structural thermal model (STM),
  – thermal model (ThM),
  – development model (DM).

  This list is not exhaustive, and depends on model philosophy and critical functions, the objective being to achieve the design of the element.

5.3.6.2 Documentation for TRA

- Definition of performance requirements and of the relevant environment:
  – Technical requirements specification (see ECSS-E-ST-10-06 Annex A),
  – Interface requirement document (see ECSS-E-ST-10-24 Annex A).
- Identification and analysis of the element critical functions:
  – Analysis report (see ECSS-E-ST-10 Annex Q) for critical functions.
- Design of the element, supported by appropriate models for the critical functions verification:
  – Design definition file (see ECSS-E-ST-10 Annex G),
  – Design justification file (see ECSS-E-ST-10 Annex K) including:
    - model definition for the critical function verification;
    - identification of computational design methods and tools;
    - test plan of the critical function of an element (which were used to achieve the TRL);
    - Test specification (see E-ST-10-03C Annex B) for critical functions
    - Model test reports

    NOTE 1 For a test plan template see DRD in ECSS-E-ST-10-03 Annex A.

    NOTE 2 For a test report template see DRD in ECSS-E-ST-10-02 Annex C.

5.3.7 TRL 7 : Model demonstrating the element performance for the operational environment

5.3.7.1 General evaluation aspects

- Element definition status:

  Final definition of the element established in its operational environment.

- Performance requirements status:

  The mission objectives, operational environment and the operational performance requirements are established and agreed upon by the stakeholders, taking into account the element integration in the relevant system.

- V&V status:

  The validation of the element performance is established through testing to demonstrate performance in the operational environment and validation of qualification margins. The element is successfully tested following qualification test requirements as described in ECSS-E-ST-10-03. Those tests are conducted on a QM (or, depending on the models philosophy, on EQM or PFM, see ECSS-E-HB-10-02 clause 5.2.5.2).

5.3.7.2 Documentation for TRA

- Definition of performance requirements, including definition of the operational environment:
  - Technical requirement specification (see ECSS-E-ST-10-06 Annex A),
  - Interface requirement document (see ECSS-E-ST-10-24 Annex A)
- Model definition and realisation:
  - Design definition file (see ECSS-E-ST-10 Annex G),
  - Design justification file (see ECSS-E-ST-10 Annex K) including:
    - assembly, integration and test plan (see ECSS-E-ST-10-03 Annex A) for the element,
    - test specification (see ECSS-E-ST-10-03 Annex B),
    - test procedure (see ECSS-E-ST-10-03 Annex C) for the element,
    - test report (see ECSS-E-ST-10-02 Annex C),
- Qualification review (QR) report of the review team (see ECSS-M-ST-10-01 Annex C) or the review authority (see ECSS-M-ST-10-01 Annex D) assessing successful qualification.

5.3.8 TRL 8 : Actual system completed and accepted for flight (“flight qualified”)

5.3.8.1 General evaluation aspects

By definition, all technologies being applied in actual systems go through TRL 8.

- Element definition status:

  The same as TRL 7.

- Performance requirements status:

  The same as TRL 7.

- V&V status:

  The qualified element (FM or PFM) is integrated into the final system which were accepted for flight (successful acceptance review).

5.3.8.2 Documentation for TRA

"Flight acceptance of the final system":

- Acceptance review (AR) report of the review team (see ECSS-M-ST-10-01 Annex C) or the review authority (see ECSS-M-ST-10-01 Annex D), assessing successful flight acceptance with documentation for the element as established by the project (see ECSS-E-ST-10 Annex A, and ECSS-Q-ST-20 Annex I).

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

5.3.9.1 General evaluation aspects

- Element definition status:

  The same as TRL 8.

- Performance requirements status:

  The same as TRL 8 with the inclusion of mission operations duration.

- V&V status:

  The element is successfully in service for the assigned mission in the intended operational environment. A system, integrating the element, has passed through a successful CRR.

  NOTE In the case of anomaly post CRR, and a redesign is necessary, a TRL is only assigned after a TRA is performed (see also clause 7.2 "Re-assessment of TRL for re-use of element with existing TRA").

5.3.9.2 Documentation for TRA

"Commissioning in early operation phase. In-orbit operation report":

- Commissioning readiness review (CRR) report of the review team (see ECSS-M-ST-10-01 Annex C) and the review authority (see ECSS-M-ST-10-01 Annex D), assessing successful commissioning results, with documentation for the element as established by the project (see ECSS-E-ST-10 Annex A, and ECSS-Q-ST-20 Annex I).

  NOTE The TRA can consider, as additional information, the duration of operations achieved at the time of assessment.

5.4 Guidelines for other uses of TRLs in R&T&D activities

TRLs are also used in planning and managing the implementation of R&T&D programs. TRLs can be used in:

- establishing and applying the criteria for acceptance of a technology into an R&T&D program: for example some programs can be dedicated to activities from TRL 2 to TRL 3, some others from TRL 4 to TRL 6;

- establishing objectives for individual technology proposals to a R&T&D program: for example the proposal forms include fields such as "Estimated current TRL" and "Target TRL" (see example Figure 5-2);
- completing an R&T&D individual technology activity with a TRA (see 5.2 and 5.3).

The use of TRL in R&T&D programs is highly beneficial to clarify technical policy and objectives, to assess the results and to ease the transition from research activities to projects.

In addition TRLs are also used in framing and articulating technology roadmaps. The application of the scale in technology roadmaps allows projecting the evolution of a technology maturity against programmatic goals and future missions needs and synergies (see example Figure 5-3.)

Technology Activity TEMPLATE

Programme: *TRP, GSTP, ARTES, CTP, EOEP, …*
Ref. Number:
Activity Title:

Budget:

Ref. to Dossier 0: *Requirement ref.*

Description: *Objective*

Background/Heritage (Continuation of TRP, GSTP, ARTES, CTP, … activity)

Activity Description

Tasks / Phases

Deliverables: *List of Deliverables. If Contract Clause 42 on SW is applicable then justification is also provided.*

Estimated Current TRL:

Target TRL: *TRL by end of Activity …*

Estimated Duration:

Application / Timeframe: *Applications (Missions/services)of Activity proposed and when these should be available*

Proc. Policy: *If Direct Negotiation or special measure (C1, C2, …) then justification provided.*

Consistency with harmonisation Roadmap and conclusions(*):
Technology harmonized (Y/N)
Consistency Y/N, substantiated if necessary

Note to AC:

- *Initiator (TO) and other relevant information (candidate programme for continuation, cost to completion, interest / support already expressed by a Delegation, etc.) provided to AC but not to IPC.*
- Part of 3 year/Annual Plan – *Y/N*

(*) IPC (ESA/IPC(2004)71, rev 3, corr.1 parag 3.2.1

Figure 5-2: Example of ESA technology activity template

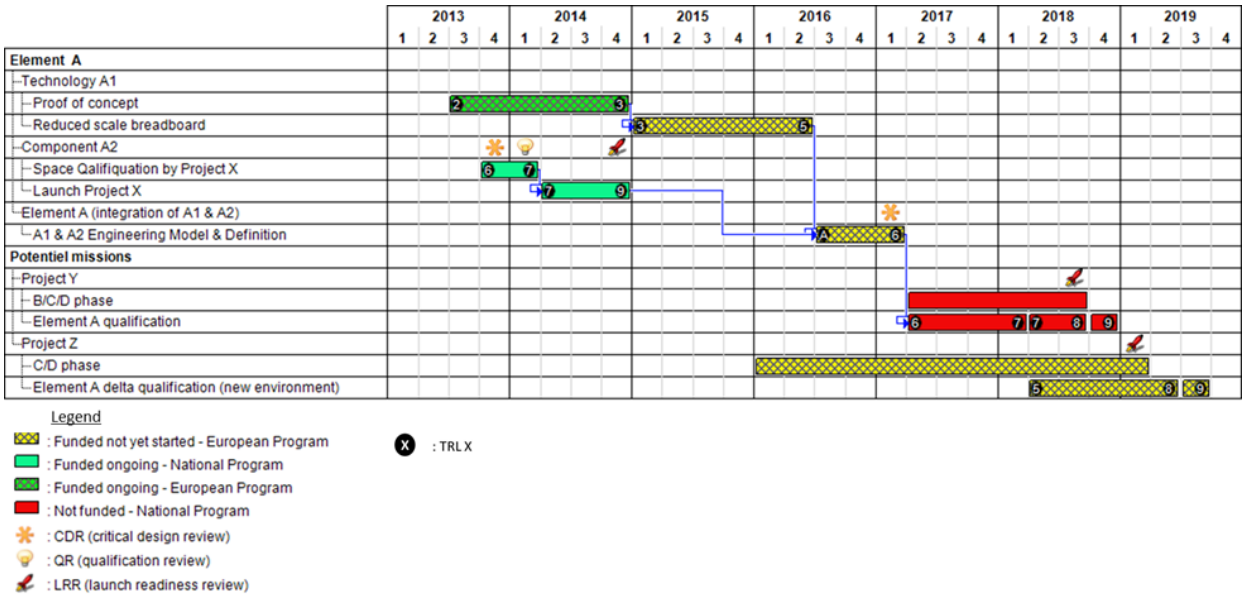

Figure 5-3: Illustration of a Technology Roadmap

6
Implementation in projects

6.1 General

In any project where new technologies are intended to be used, or existing technologies are used in new ways, it is important to understand the risks associated with technology maturity. Technology readiness levels (TRLs) provide a structure for the evaluation of such risks by setting out criteria to be met to reach each level.

In order for an organization to apply TRL to the benefit of projects, it is important that TRAs become embedded as a standard project management practice. TRLs add value when projects use them routinely.

In this way, TRA outcomes are able to:

- support go – no-go decisions, during Phase 0, A and B, about the inclusion of new technologies in a system;
- mitigate risk to projects by identifying exactly what development was performed to date;
- provide a consistent ranking system to reliably compare the maturity of different technologies.

Projects exist within an organisation and the following clauses only consider the project aspects. The use of TRL and associated TRA, along with the technology readiness status list (TRSL), as defined in ECSS-E-ST-10 Annex E, can also provide organisational insight in to the technology-related risk profile of projects and therefore contribute to the decision-making process at the key projects go – no-go decision points.

It is important to note that for the project use of TRL for technologies providing critical functions the following topics are not addressed, but are known to be necessary project considerations such as:

- architectural sensitivity,
- AIT sensitivity,
- complexity, and
- immature technologies not providing critical functions.

TRL is one factor for the evaluation of risks due to technologies. Amongst the other factors, complexity is also an important one and Figure 6-1 gives a qualitative evaluation of risks versus TRL and complexity.

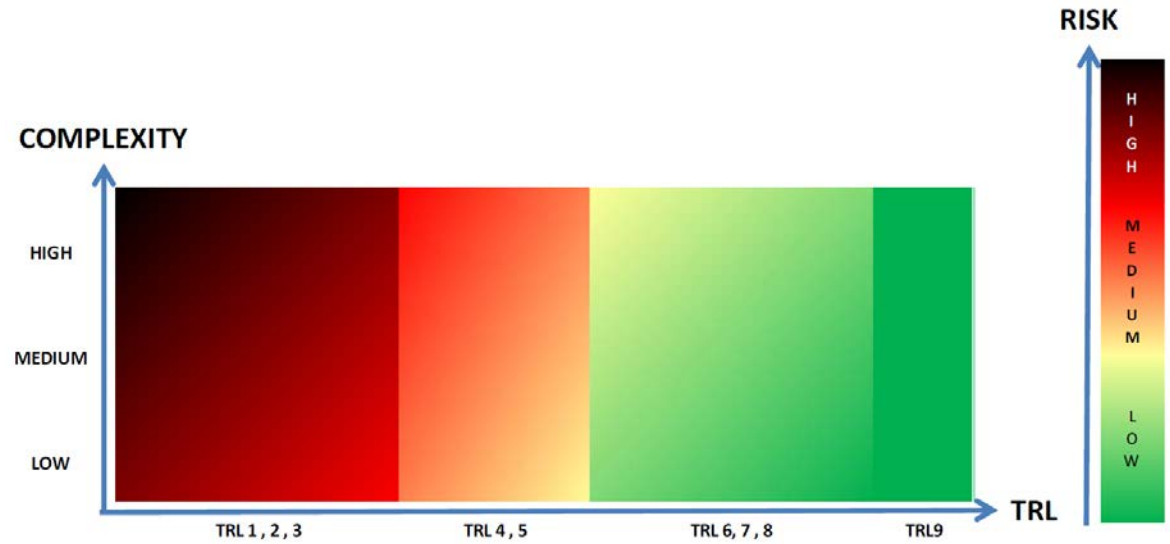

Figure 6-1: Risk versus TRL and complexity

6.2 Critical functions and technologies in projects

6.2.1 Overview

Through the adoption of ISO 16290, ECSS-E-AS-ST-11 introduces into the ECSS system definitions such as *Critical function of an element*, *Critical part of an element*, and *Element function*. In particular, the *Critical function of an element*, is defined as a "*mandatory function which requires specific technology verification*", providing for a differentiation between a technology and a function. On this basis, the project conducts an analysis to determine the critical functions performing the mission requirements, and in turn the related technologies are selected for a TRA.

In order to identify which elements of a system are "critical" for the mission the project uses the following criteria:

- their function is "*mandatory*" for the mission accomplishment, i.e. for cost, schedule or performance, and,
- their technology needs "*specific technology verification*" (see ISO 16290 clause 2.2) when either the element or sub-element are new and cannot be assessed by relying on previous realizations, or when the element is used in a new domain, such as new environmental conditions or a new specific use not previously demonstrated.

It is through this approach that the TRA provides a project tool for the tracking of potential impacts of immature technology on cost estimation (Ref ECSS-M-ST-60), project schedule (Ref ECSS-M-ST-60) and risk identification and management (Ref ECSS-M-ST-80) at the early phases of a project, i.e. Phase 0 to Phase B. At Phase B the TRA provides the necessary rationale for transferring specific identified technologies or elements on to the Critical Item List, for which ECSS-Q-ST-10-04 applies.

In summary, the key questions for identifying the technologies candidates for assessment for a project or programme, are:

a. is the function (associated with the technology) mandatory to meet the mission requirements?

b. is further "*specific technology verification*" (performing the critical function) necessary?

If the answer to *both* questions is yes, the technology maturity is assessed through a TRA.

6.2.2 Technology readiness status list (TRSL) and transference to critical item list

The critical functions are established within the TRSL in the preliminary phases (Phase 0, A and B), then the identified elements are transferred to the Critical Item List (as defined in ECSS-Q-ST-10-04).

In accordance with ECSS-E-ST-10, the system engineering function identifies and collects the critical functions in the TRSL (as per ECSS-E-ST-10 Annex E). Such a list provides, for each critical function:

a. the element (the technology providing the critical function),

b. the element TRL,

c. the reference to the TRA report and its date,

d. a concise rationale of the TRA,

e. the planned way forward in terms of TRL evolution (specifying ongoing and future activities and the planned date at which the target TRL is expected), and

f. the indication whether or not the element is a candidate for inclusion in the critical item list.

At the end of the phase B (Preliminary Design Review) the elements whose functions are critical from the technology point of view, are candidates for being transferred in to the Critical Item List (see ECSS-Q-ST-10-04). The risk due to technology maturity is managed as a critical item of the project and generally a TRA is no longer performed by the project.

6.3 Technology readiness assessment (TRA) in projects

TRAs are performed at many stages of a technology or product development, for instance at the time of R&T&D reviews. TRAs are certainly also performed in early feasibility studies.

It is expected that formal TRAs are performed in both institutional and commercial projects.

TRAs are applied at the following project stages:

- In institutional projects during Phase 0, A and B,
- In commercial projects prior to commencement (see 6.4).

The TRAs status are collected in the TRSL which is reviewed at the end of Phase 0 (Mission Definition Review, MDR), Phase A (Preliminary Requirements Review, PDR) and Phase B (System Requirements Review, SRR, and Preliminary Design Review, PDR). It is a project choice to take the classic milestones or to select an equivalent approach as the appropriate milestone prior to PDR. The TRA is carried out by the TRA participants, one or more of whom are independent technical experts (see clause 5.2.3), depending on the complexity of the item. ECSS-E-ST-10 clause 5.6.7 refers to the TRA delivered as part of the technology plan, as given in ECSS-E-ST-10 Annex E 2.1<5>.

On the basis of the outcome of the TRA, technologies of interest to a project (in the preliminary phases) are refined to better support the technology selection process, as presented in Figure 6-2.

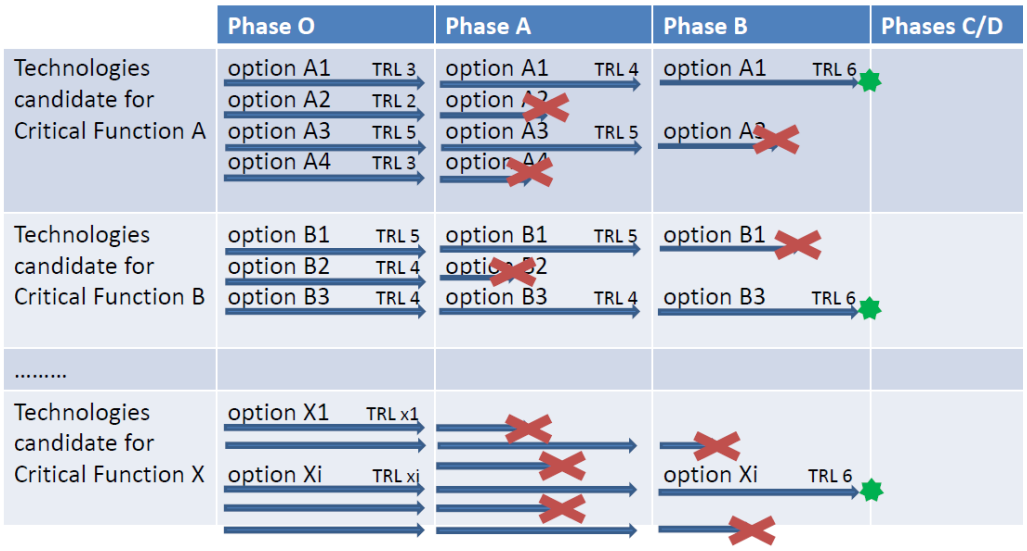

Figure 6-2: Evolution of technology options during preliminary project phases

TRAs are typically run under the accountability of the project, and the execution of TRAs is typically performed under the responsibility of the (project) system engineering supported by the PA organization. ECSS-Q-ST-10 clause 5.2.1 defines the PA manager role in the technology readiness status list (TRSL) and the technology plan (TP).

The leader of the TRA is responsible for assigning tasks and roles to personnel and to secure their availability and participation. The different assessment steps are planned by the TRA leader in cooperation with the project management. To reduce any necessary extra effort for the project, the assessment is performed in line with the project schedule, i.e. utilise nominal project milestones and is provided through the delivery of TRSL (as part of the technology plan) to customer, as defined in ECSS-E-ST-10 Annex A, Table A-1.

The leader of the TRA is responsible for reporting the TRA outcomes, and also for alerting the project management of TRL related risks in need of mitigation. Any corrective measures established are then injected into the project under the responsibility of the project management.

The PA manager checks, for each critical item and for each project, that the TRA was correctly carried out in accordance with the organization procedures. The PA manager also checks that the TRSL was correctly produced in accordance with ECSS-Q-ST-10 clause 5.2.1.

Some organizations have an overall TRL process owner, in charge of generating and updating TRL procedure documentation and tools and liaise with the TRL managers.

6.4 Typical levels linked to project phases and milestones

When considering the relationship between projects phases and the technology maturity of the critical functions, it is considered normal practice to achieve TRL 6 prior to entering the detailed definition phase (Phase C). It is highlighted that there is a specific project decision to proceed from Phase B to C (i.e. at system-level PDR) to accept greater risk through the adoption of technologies below TRL 6 at this milestone.

NOTE 1 In cooperative space programmes within U.S. national institutions, for the US projects to enter the detailed definition phase (phase C), flight hardware providing a critical function meets or exceeds TRL 6.

NOTE 2 For ground segment project developments, the specificities of managing readiness levels differ from that approach.

In the early project phases (0, A, B), the development of the technology plan and of the TRSL, is essential to properly support the assessment of the mission achievable performance, the overall project schedule and the related costs and risk. An outline of benefits of engaging the TRA at these early stages in provided in Table 6-1.

Table 6-1: Benefits of use of TRA

Project Phase	Benefits of use of TRA
Phase 0 (MDR)	• Establish the TRSL – listing candidate technologies for the same critical functions • Re-orient the system concept for optimizing technology readiness and technology selection decision schedule • TRSL also provides a connection from the project to the technology developers (R&T&D programmes)
Phase A (PRR)	• Contribution to the technology plan (TP) • Consolidate TRSL within the TP • Refine list of candidate technologies for the same critical function
Phase B (up to SRR)	• Consolidate TRSL within the TP. • Preliminary identification of items for transfer to critical item list (CIL)
Phase B (from SRR to PDR)	• Inputs from TRSL to the CIL • TRSL provides risk data supporting the decision to move to detailed design phase (C) • Final selection of (suppliers for) candidate technologies for the critical functions

Passing through preliminary phases, the number of technology options for a critical function of the project is decreasing until the end of phase B where generally only one option is kept with a TRL at least 6.

It is worth noting that in the technology plan the project defines a model philosophy for the technology development (and TRL progression) followed over the project phases. The model philosophy selected for the technology critical elements drives their TRL upgrades during the early project phases.

Once the project is within the detailed design phase (i.e. Phase C), the evolution of the critical items related to technology maturity (now included in the CIL) follows the project development process as specified in ECSS standards.

Figure 6-3 gives a generalized example of when formal TRAs are typically performed during institutional projects. Institutional projects generally develop critical functions (provided by technologies) and models from lower TRL through to TRL 6 during the early phases of the project (prior to Phase C).

NOTE For Commercial or recurring product development (product development without Phase A or B) refer to ECSS-Q-ST-60-13 and ECSS-Q-ST-20-10.

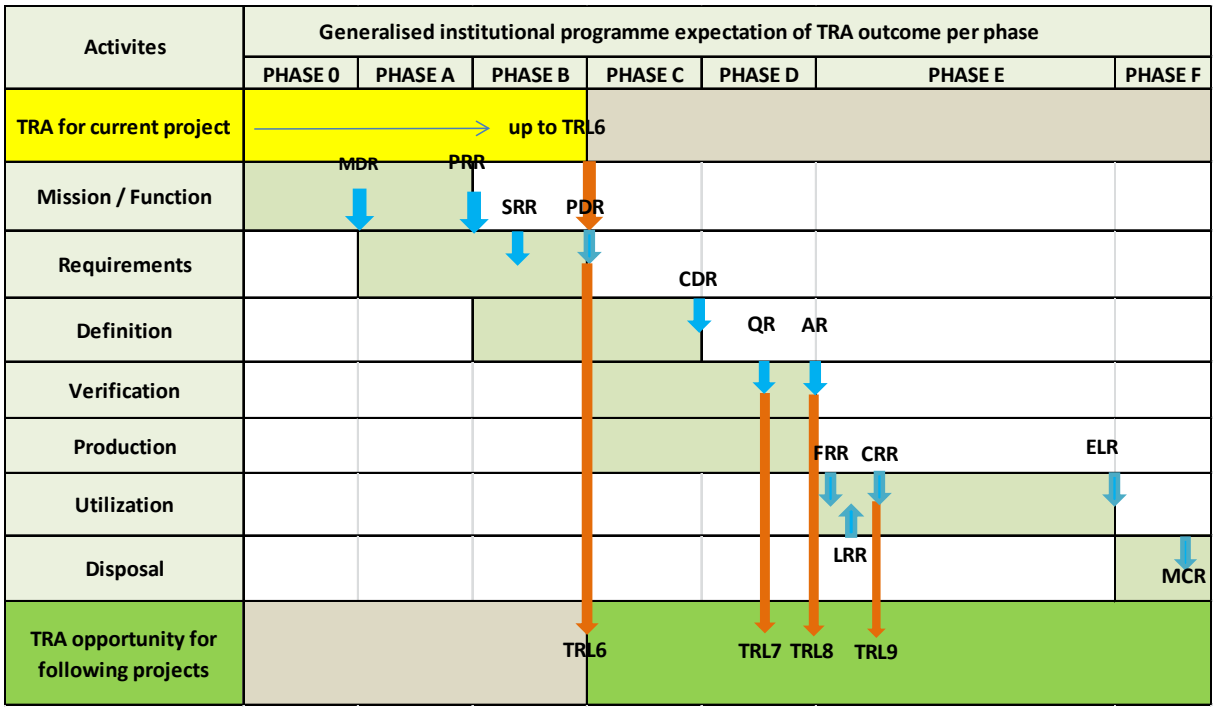

Figure 6-3: Project phases and generalised institutional expectation of TRA outcome

Figure 6-4 illustrates the link between project phases and expectation of TRA outcomes for commercial projects where the TRL of a technology is below TRL 7. In this case the phases are shown, to illustrate that for commercial projects, TRL is more linked to key project milestones. This is because the TRL of technologies selected for use on commercial projects are targeted at high maturity (i.e. TRL 7, 8 or 9) whenever possible. Commercial projects therefore tend not to include phases 0, A and B prior to project start. Hence commercial customers expect all or most of the products used to be already TRL 7, 8 and 9 prior to their release of the invitation to tender (ITT). This is not always possible. Commercial customers often expect more functionality and capacity from one project to the next, whilst not directly funding any pre-development activities. It is rare for a technology below TRL 5 to be allowed into a commercial project, as the schedule for the overall mission is put at too much risk. Accordingly prime contractors request TRL information from their suppliers in order to support their bid – no bid assessment. If the prime enters into final negotiation with the customer, a TRA is normally performed prior to project start. This is to verify TRL claims made by selected suppliers are valid. It also enables the credibility of development plans to be examined in the case where it is essential to develop technology during the project from TRL 5 or 6 to 7 prior to spacecraft flight. Commercial primes typically conduct EQSRs (equipment qualification status reviews) or equivalent shortly after contract signature. Normally the project performs a system QR (S-QR) after the system CDR. The outcome of which is to ensure all technologies employed are at TRL 7 or higher.

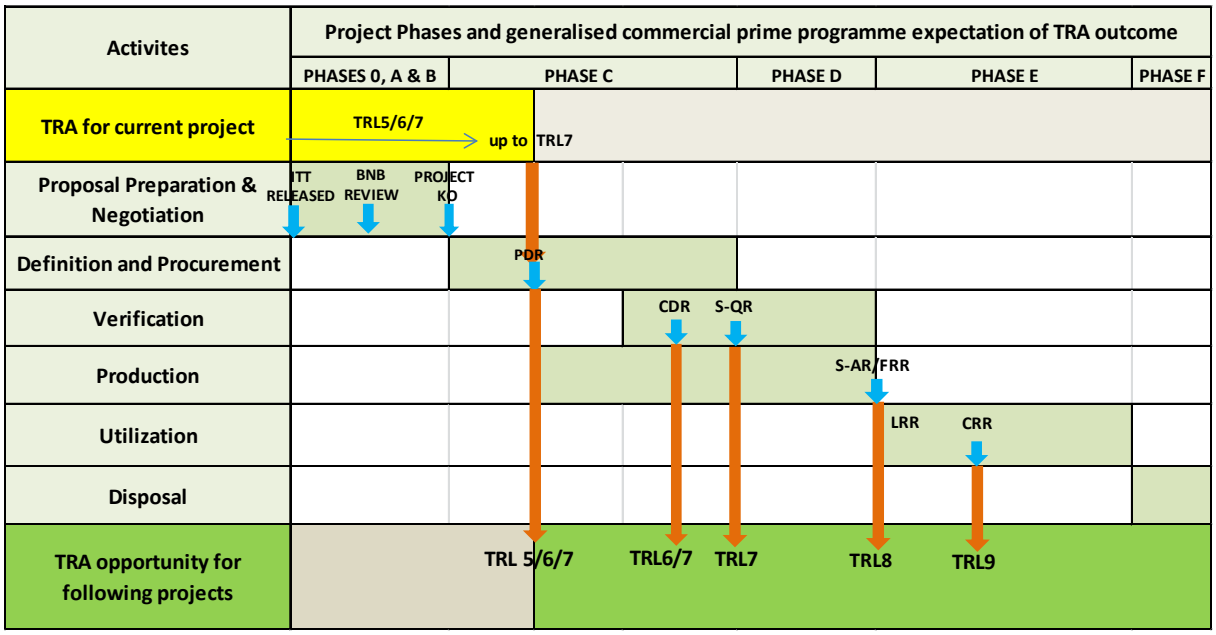

Figure 6-4: Project phases and generalised commercial expectation of TRA outcome

The main difference between the two types of projects being that commercial projects generally use already flight qualified, or high TRL, models from the outset whenever possible (i.e. models that have achieved TRL 6 or above). In both cases conducting TRAs for the project at the time of proposal vetting (i.e. for phase C of an institutional programme) is key to risk mitigation.

7
Links with model philosophy and technology demonstration and reassessment

7.1 Links with model types and technology demonstration

7.1.1 Link between TRL and model types

For TRL 6 to TRL 9 the V&V is supported by models (e.g. EM, QM, PFM, FM).

Table 7-1 provides model types typically associated to TRLs.

Table 7-2 provides the range of applicability for the work achievement (in support of the TRA) that is obtained from the various models developed during a project (as defined in ECSS-E-HB-10-02).

Some other model types described in ECSS-E-HB-10-02 are also used for TRL progression for dedicated purposes, examples of which being; function-oriented models, electrical or functional models.

Table 7-1: Models types associated to TRLs

TRL #	TRL definition	Associated model	Performance requirements	Test environment	Comments and practical use
1	Basic principles observed and reported	Not applicable	Normally not defined at this TRL	Not applicable	Survey of emerging technology to establish candidate technologies.
2	Technology concept and/or application formulated	Synoptic, block diagram	Generally and broadly defined	Not applicable	Potential maturity level for starting technology R&T&D activity
3	Analytical and experimental critical function and/or characteristic proof-of-concept	Proof of concept model, such as mathematical models, simulations, supported by experimental data or characteristics	Generally and broadly defined (e.g. formalised in a preliminary definition file) NOTE: At this level of maturity, some Phase[a] 0 requirements can be taken into consideration	Laboratory	Typical starting maturity level for technology R&T&D activity. Also minimum maturity level for a project Phase[a] 0 TRSL. Characterising technology potential before breadboard integration.
4	Component and/or breadboard functional verification in laboratory environment	Breadboard of the element (integration of functionally representative breadboard).	Generally and broadly defined	Laboratory	Evaluate pure performances of the technology applied to the element.
5	Component and/or breadboard critical function verification in a relevant environment	Breadboard, also referred to as sub-scaled EM for the critical functions	Preliminarily defined, possibly incomplete due to model scaling effects	Relevant environment. Test results can be subject to model scaling effects	In a few cases, where scaling effects were assessed as negligible, the level of risk presented by technology being at TRL 5 can be considered equivalent to that of TRL 6 for a project to enter the detailed definition (Phase[a] C).

TRL #	TRL definition	Associated model	Performance requirements	Test environment	Comments and practical use
6	Model demonstrating the critical functions of the element in a relevant environment	One or more of the following: Full scale EM(s), SM, STM, TM, DM(s), representative **for critical functions** in form fit and function.	Established and agreed upon between the customer and supplier	Relevant environment	Normal threshold for enabling the start of detailed definition and production phases[a] (Phases C and D)
7	Model demonstrating the element performance for the operational environment	QM	Established and agreed upon between the customer and supplier	Operational (capable of being tested on-ground with qualification margins)	QM validated NOTE: Project can consider to allow use of EQM or PFM instead of QM
8	Actual system completed and accepted for flight ("flight qualified")	FM acceptance tested, integrated in the final system	Established and agreed upon between the customer and supplier	Operational (as conducted for an AR)	A system integrating the element has passed through a successful AR. FM integrated in a system whose acceptance was achieved through test and demonstration. Threshold for operations phase[a] (Phase E).
9	Actual system "flight proven" through successful mission operations	FM, flight proven	Established and agreed upon between the customer and supplier	Actual operational	Corresponds to technology reaching a "mature" status.

[a] Phases referred to herein are stated from a project perspective (and not the phases relative to the technology development).

Table 7-2: Use of commonly-used models for TRL progression

Model	Potential use with respect to TRL scale
Structural model	Used, when necessary, to progress to TRL 6
Thermal model	Used, when necessary, to progress to TRL 6
Structural-thermal model	Used, when necessary, to progress to TRL 6
Engineering model (scaled)	Used, when necessary, to progress from TRL 4 to TRL 5
Development model	Used, when necessary, to progress from TRL 4 to TRL 6
Engineering model (full scale)	Used, when necessary, to progress to TRL 6
Engineering qualification model	Used to progress to TRL 7
Qualification model	Used to progress to TRL 7
Human related models	Used, when necessary, to progress to TRL 7
Life test model	Used, when necessary, to progress to TRL 7 in conjunction with model(s) used for qualification
Protoflight model	Used, when decided, to achieve TRL 7, TRL 8 and TRL 9.
Flight model	Used to progress to TRL 8 and 9.
Software and ground segment specific models	Refer to Annex A for specific details of software and ground segment models used in TRL progression

7.1.2 Link between TRL and technology demonstrators

7.1.2.1 Introduction

To realize a desired maturity of the TRL there are various classes of demonstrators used to provide the necessary data or evidence in support of the TRA. The following demonstrator types are developed:

- Ground demonstrators,
- Space demonstrators for technology,
- Mission precursor demonstrators.

NOTE Space environment demonstrators are not addressed in this handbook as its objective is not the maturity demonstration of a technology but to measure the space environment linked to the mission environment constraints.

7.1.2.2 Ground demonstrators for technologies

The objective of this type of demonstrator is to ease the transition from the research and technology part of R&T&D activities to the development part of R&T&D for the project (i.e. to take the technology through the “valley of death”), by undertaking ground-based data collection supporting the TRA.

This activity is undertaken to reassure the final customer in terms of reduced risk, and to reduce future potential costs for the project. As such this activity is undertaken during the R&T&D activities up to space qualification (generic, i.e. not dedicated to a specific mission, or project). Sometimes specific missions or projects take this activity within the scope of their project development plan (but not necessarily directly funded by the project). As this activity is associated with product development, the beneficiary is the product developers. As such in industrial competition, this activity helps companies to develop a product to be well placed on a dedicated market.

For those demonstrators, the TRL transition achieved is generally from TRL 4 or 5 to TRL 6 or 7. Examples include data handling receivers for micro or nanosats, and batteries lifetime testing.

7.1.2.3 Space demonstrators for technologies

7.1.2.3.1 General

The objective of this type of demonstrator is to demonstrate the adequacy of the technology performance in the relevant space environment (for example: radiation, microgravity, or life duration).

In any case the space demonstrators for technologies are managed as regular programmes with mission definition and development of a ground segment. The technologies being demonstrated on-orbit are qualified as far as possible on ground.

The technology demonstration is performed as part of a project main mission, or is hosted or piggy-backed technologies not part of the project main mission.

Space demonstration is undertaken in a way to provide heritage to ensure the achievement of TRL 8 and TRL 9:

- to reassure the final customer in terms of reduced risk,
- to reduce future potential costs for the project (e.g. PROBA and STENTOR),
- in cases where the validation of the critical function in the space environment is the only viable solution (e.g. operation of heatpipe fluidic loop in microgravity).

The activity purpose ranges from mission-dedicated to technologies demonstration.

The TRL transition achieved by space demonstrator development projects is generally from TRL 4 (or TRL 5) to TRL 8. In some cases where the technology forms part of the main mission, it follows that TRL 9 is achieved.

7.1.2.3.2 Demonstrators for educational purposes

In the case of technology demonstration satellites for educational purposes (e.g. cubesats) the reached TRL depends on the project framework. Typically this provides valuable information to assist in the transition between TRL 4 and 5 or 6 (the “valley of death”). In all likelihood any data collected to support the maturity of critical functions, technology, or models developed specifically for use on such missions are not sufficient to demonstrate having reached TRL 6 or 7 in accordance with the ECSS requirements prior embarking on a flight. Similarly the educational project is unlikely to have the relevant TRA evidence needed for subsequent use on either institutional or commercial main missions. The implication of this is that the technology is not used as flight qualified (for either an institutional or commercial main mission) until sufficient additional verification has taken place. The model needs to achieve TRL 6 commensurate with the mission environment prior to consideration; or a careful risk mitigation plan is embarked upon by a project intending to use the technology.

7.1.2.4 Mission precursor demonstrator

The objective of this type of demonstrator is to prepare the technologies for a future operational mission.

The elements under consideration for this type of activity are instruments or system concepts. These generally have a dedicated project (commonly for science), or be hosted or piggy-backed by another project (e.g. Q and V frequency band hosted experimental payload on Alphasat).

This activity is to refine technology or mission and system definition needs for future applications or use.

The TRL transition achieved by this demonstration is generally from TRL 4 or 5 to TRL 6 through to 9. Examples include EDRS optical link, LISA Pathfinder, and Galileo in-orbit validation satellites.

7.2 Re-assessment of TRL for re-use of element with existing TRA

7.2.1 Technical guidelines

When re-using an item the qualification or the design of the item is assessed for the impact to TRL. ECSS-E-ST-10-02 (clause 5.2.4.2) provides the conditions under which the qualification of a heritage item is still valid in a new project.

Table 7-3 provides the assessment guidelines for the re-use cases for each of the heritage categories, A, B, C and D.

Table 7-3: Links between TRL and Heritage Category

Heritage category	A	B	C	D
Description	Off the shelf product without modifications and • subjected to a qualification test programme at least as severe as that imposed by the actual project specifications including environment, and • produced by the same manufacturer or supplier and using the same tools and manufacturing processes and procedures	Off the shelf product without modifications. However: It has been subjected to a qualification test programme less severe or different to that imposed by the actual project specifications (including environment).	Off the shelf product with design modifications. Modification includes changes to design, parts, materials, tools, processes, procedures, supplier, or manufacturer	Newly designed and developed product.
Qualification programme	None	Delta qualification programme, decided on a case by case basis.	Delta or full qualification programme (including testing), decided on a case by case basis depending on the impact of the modification.	Full qualification programme.
TRL considerations for re-use cases	The existing TRA is still valid	The product is re-assigned as TRL 6 for the re-use project.	The original TRA is no longer valid, and therefore a TRL cannot be assigned until a new TRA is performed. The outcome of the TRA can range between TRL 4 and 6 on a case by case basis. If the design changes impact the technology providing the critical function, then TRA gives TRL<6.	A TRA is needed
NOTE: The data of grey rows are taken from ECSS-E-ST-10-02, Table 5-1.				

7.2.2 Technology re-use in a new environment

When re-using a mature technology within a new operational environment, there is an assessment of the impact to TRL. The potential outcomes of the TRA is given in Table 7-4.

Table 7-4: Technology maturity transfer for re-use

Initial TRL	Characteristics of the item w.r.t. the new environment	TRA guideline outcome
7 - 9	Same or less severe operational environment	TRA is still valid - TRL declared is same as initial TRL
	Same or less severe relevant environment, and operational environment is changed outside of that given in the TRA	TRL 5 or TRL 6
	Relevant environment and operational environment is changed outside of that given in the TRA	TRL 4 (as a maximum)

For clarification the following definitions are applied from ECSS-E-AS-11 to this table:

operational environment

"set of natural and induced conditions that constrain the element from its design definition to its operation"

relevant environment

"minimum subset of the operational environment that is required to demonstrate critical functions of the element performance in its operational environment"

Annex A
TRL considerations for software

A.1 Terms specific to the present annex

A.1.1 alpha version

preliminary release of not-mature software version, distributed to a community at an early stage of the software development life-cycle, that implements the main functionality of the software and by which preliminary V&V activities are achieved

NOTE The term alpha version is used by analogy with name used outside of the space domain, but do not intend to carry any of this non-space meaning.

A.1.2 beta version

preliminary release of not-mature software version, distributed to a community at an early stage of the software development life-cycle, that implements the complete functionality of the software and by which preliminary V&V activities are achieved

NOTE The term beta version is used by analogy with name used outside of the space domain, but do not intend to carry any of this non-space meaning.

A.1.3 building blocks

software element that has an identifiable function within a software product, and that can potentially be reused for a range of applications

A.1.4 customized generic software product

generic software product adapted to a dedicated environment including code modification

A.1.5 generic software product

software tool or building block

A.1.6 software element

technology provided by software under consideration of TRL assessment

NOTE Examples are building blocks, COTS, and open source software.

A.1.7 software product

software that is developed for an application, and which is composed of several software elements, with its associated procedures, documentation and data

A.1.8 software tool

software element that is used for supporting specific activities of the software life-cycle

A.1.9 tailoring

adaptation to a dedicated environment, without code modification

NOTE An example is the modification of the Generic software product configuration.

A.1.10 tailored generic software product

generic software product adapted to a dedicated environment, without code modification

NOTE An example is the modification of the generic software product configuration.

A.2 ISO TRL scale and software developments

ISO TRL definition does not address the use of TRLs for software and there is no international or even European uniform approach for using TRLs for software developments. For convenience and for avoiding the introduction of a specific scale for software, it is proposed to use the same ISO scale for software developments by providing a clear definition of the expected development state at each TRL.

A.3 Basic principles

The purpose of this Annex is to propose some guidelines to assess a technology maturity (here software) and how to use TRLs. The purpose *is not* to replace software development cycle, to describe the way to develop or to reuse software (TRL is a measure not really a target). Software engineering and PA are the object of other ECSS standards and handbooks in E40 and Q80 disciplines respectively, that they remain fully applicable.

Software TRA is used to assess the maturity of technologies implemented in software which can be part of the flight segment (flight software), ground segment (ground software) or engineering tools (software tools).

When the software under assessment includes external open source or procured software from a third party (libraries or application modules in source or binary format) the overall TRL assessment takes into account the assessed maturity of the third party software.

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

a. Software tool.

b. Software element: software that necessarily interacts with other software and possibly also with hardware. Two categories exist as follows:

   1. Building block: software conceived to be reused in a range of missions, either flight or ground software. This software is executed as part of a larger software application.

   2. Specific software: software that is targeting a specific application and that is not conceived to be reused in another domain of application, for example equipment embedded software.

c. Generic software product (software tool or building block)

   1. Tailored generic software product

   2. Customized generic software product

This clause clarifies the notion of software TRL for the software types 1, 2.a and 3.a. For the software types 2.b, the TRL ISO classification is applicable as is since the software is part of the hardware TRL assessment. For software type 3.b, the TRL level gained before the modification of the source code is lost by the modification, and the TRL need to be reassessed (probably down to 4 or 5).

As for hardware TRLs, the software TRLs are not meant to be applied to the management of a software development project, for which typically the software standards (e.g. ECSS-E-ST-40 and ECSS-Q-ST-80) are applied. The software TRL is then simply a tool for the evaluation of the maturity of a given software technology (e.g. building blocks, tools) within the context of its intended application.

The underlying principles are summarized for the following TRL:

- **TRLs 1 to 4** covers the beginning of the development as the level of implemented functionality increases.
- **TRLs 5 and 6** cover the transformation of the prototype into a product with frozen requirements. A pre-qualification data package is produced by making use of the ECSS-E-ST-40 and ECSS-Q-ST-80 standards, giving confidence that the product performs as expected in the final environment.

  At least TRL 6 is established for a generic software product and for a building block during Phase C of the instantiating project.
- **TRL 7** corresponds to the software qualification for the foreseen application verifying the software performance in its intended environment.
  - For a software tool, this corresponds to full validation on a representative pilot case.
  - For a building block, it is fully integrated in the qualified software as part of the foreseen application.

  TRL 7 is established for a tailored generic software product or a building block integrated in a complete software which was successfully qualified (i.e. it has passed a successful software QR).
- **TRL 8** corresponds to the final product acceptance for operation.
  - For a software tool, it corresponds to the readiness for the full deployment in operation.
  - For a building block, this corresponds to the end of the system qualification.

  TRL 8 is established for a tailored generic software product or a building block which was integrated and completed, qualified in the ground segment or system (i.e. it has passed a successful ground segment QR (GSQR), operations QR (OQR), or system QR). It is ready to support LEOP and commissioning phases.
- **TRL 9** corresponds to successful operations and performance achievement in the application. Ground Segment is periodically evaluated (e.g. on a yearly basis) during IOOR. TRL 9 for a tailored generic software product or a building block is established during one of these reviews (potentially several years after FQR).

A.4 Use of TRL with Software

Table A-1 provides an overview of the generalized alignment of the software development cycle and that of the associated TRLs. Similar to the development of hardware, TRL is not proposed as a development tool, but as a method for risk assessment associated with critical functionality provided by an identified software element through its various stages of development.

For TRL 5 to 9, requirements of ECSS-E-ST-40 and ECSS-Q-ST-80 are fully applied.

Table A-1: Link between Software development status and TRL

TRL	Engineering terms relevant to software	Additional explanation to cover software	Description	Requirements	Verification	Viability
1	First formulation	Scientific knowledge	Preliminary algorithmic stage. Publication of research results.	Expression of a problem and of a concept of solution.	Clear algorithmic formulation.	Feasibility to be implemented in software with available computing facilities demonstrated.
2	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 prototyped and tested with synthetic data resulting in their characterization and feasibility demonstration. Execution target is not necessarily representative of the final target.	Feasibility to build important functions in a system architecture demonstrated.
3	Prototype	Prototype of the main functionalities of the integrated system	Specification and architectural design of important functions is documented.	Preliminary solution to specific needs. Main use cases implemented.	Some functionalities are implemented and tested to allow the demonstration of global operation and performance. Execution target is representative of the final target. Preliminary V&V activities executed in a simulated laboratory environment.	Feasibility to build an operational system taking into account preliminary performance and usability aspects demonstrated.

TRL	Engineering terms relevant to software	Additional explanation to cover software	Description	Requirements	Verification	Viability
4	Alpha version	See definition in A.1.1	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.	V&V process is partially completed, or completed for only a subset of the functionality or problem domain. Execution target is representative of the final target, including hardware aspects. V&V activities executed in a representative simulated laboratory environment.	Feasibility to complete missing functionality and reach a product level quality demonstrated.
5	Beta version	See definition in A.1.2	Full documentation according to the applicable software engineering and quality 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 activities executed in an end-to-end representative laboratory environment including real target (hardware execution target).	Feasibility to fix reported problems within available resources evaluated. User support organization in place.

TRL	Engineering terms relevant to software	Additional explanation to cover software	Description	Requirements	Verification	Viability
6	Product release	Ready for use in an operational or production context, including user support, as a building block or a tool.	Documentation according to the applicable software engineering and quality standards for a software product.	Building block and generic software product: Process for reuse, for instantiation in the domain of the implementation and its test environment. Documentation is compliant with critically level of the target application. Tools: All use cases and error handling implemented. User friendliness validated.	Building block and generic software product: Validated against the requirements of the complete domain, validation environment also reusable, reuse file (SRF) available. Tools: V&V process is complete for the intended scope, including robustness. Configuration control and Quality Assurance processes fully deployed. V&V activities executed in an end-to-end fully representative laboratory environment including real target.	Feasibility to be applied in an operational project demonstrated. Availability of a data package suitable to support future qualification.

TRL	Engineering terms relevant to software	Additional explanation to cover software	Description	Requirements	Verification	Viability
7	Early adopter version	Building block and tailored generic software product: qualified for a particular purpose Tool: ready for market deployment	Documentation as for TRL 6 plus: • Documentation, updates to documentation and qualification files • SPR database Lessons learnt report. • Documentation and tooling, if any, related to the tailoring of the generic software product.	Requirements traced to mission requirements. Validity of solution confirmed within intended application. Requirements specification validated by the users.	Building block and tailored generic software product: Integrated in the spacecraft or ground segment following the applicable software standards. Tools: The tool was successfully validated in a pilot case, representative of the intended project application.	Engineering support and maintenance organization in place, including helpdesk.

TRL	Engineering terms relevant to software	Additional explanation to cover software	Description	Requirements	Verification	Viability
8	General product	System qualified and ready to be applied in the execution of a real space mission	Full documentation including specifications, design definition, design justification, V&V (qualification file), users and installation manuals and software problem reports and non- compliances. Includes also qualification files, SPR database and lessons learnt report.	Requirements traced to mission requirements. Validity of solution confirmed within intended application. Requirements specification validated by the users.	Building block and tailored generic software product: Integrated in the spacecraft or ground segment and completed successfully system qualification campaign. Tool: The tool was 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.

TRL	Engineering terms relevant to software	Additional explanation to cover software	Description	Requirements	Verification	Viability
9	Live product	Has been applied in the execution of a real space mission	Documentation as for TRL 8, plus: • Updates to documentation and qualification file. • SPR database updated. • Lessons learnt report. • Track record of application in space projects.	Building block and generic software product maintained. Tools: Full process implemented, maintenance, and updates.	Building block and tailored generic software product is operational for the mission and performance is in line with operation procedures. This state is reached after IOOR. Tool: The tool was successfully validated in one or several space missions, including exploitation of in-orbit data. All anomalies encountered were analysed and resolved.	Sustaining engineering, including maintenance and upgrades in place.

A.5 Relationship between TRL and criticality categories

Critical software is defined to be at Category A, B or C. The software criticality category, as defined for dependability and safety (ref. ECSS-Q-ST-30 and ECSS-Q-ST-40) is according to the consequences of failures and is not linked with the maturity of the software described by the TRL. As such, the software criticality level of a function or product is independent from the TRL and is based on system and software RAMS analysis. However, from the perspective of reusing a building block in a software product, it is clear that there is a direct relationship with the needed maturity of the building block and its level of criticality.

The two main use cases to consider for TRL and critical software apply to "Developing a building block" and "Using a building block".

a. Developing a building block:

   The TRL does not apply to a specific software product (see A.3, software types 2.b and 3.b), but only to a building block such as a real-time operating system, that is later used in a software product. As such, software criticality and TRL are linked at the level of pre-qualification, e.g. the building block is pre-qualified for category A, B or C at TRL 6. At TRL 6 and higher, ECSS is by construction fully applied.

   In addition, it is important to note that the criticality is given by a system dependability analysis that does not apply specifically to the building block. However, the building block is expected to be used into a system where it receives criticality A, B or C. Therefore, the building block is pre-qualified to the identified level of criticality. Since the criticality determines the level of engineering and PA, this is adjusted in TRL 5 or 6, by applying appropriately the ECSS standards.

b. Using a building block:

   Given that a building block of TRL 6 pre-qualified for category X is available to be used in a software product of category Y, then:

   – if X is the same or of a higher critical category than Y, the building block can be used as is;
   – on the contrary, if X has a lower criticality category than Y, the building block needs to be re-engineered to raise its criticality category (see ECSS-Q-ST-80, clause 6.2.7.8). The gap in the functionality and the delta qualification needed is documented in the software reuse file (SRF).

   In the case of the integration of a building block of TRL 6 or above (and a declared level of criticality) in a Software product of a higher level of criticality, the TRL of the building block is downgraded to at least TRL 6 depending on the level of building block re-engineering.

   For a building block developed iteratively, with the aim of progressively increasing its functionality and maturity, the tailoring of the software engineering and PA standards (ECSS-E-ST-40 and ECSS-Q-ST-80) in each iteration depends on both the criticality of the function in its final environment and on its TRL. As such, an early beta version with TRL 5, for example, is developed with Category D tailoring. This tailoring is then progressively aligned with the criticality level of the software in its final environments, as the TRL is increased.

   It is expected that for TRL 1, 2, 3 and 4 the ECSS tailoring, if any, is below Category D.

   NOTE ECSS-Q-ST-80 clause 7.1.8 covers the analysis of software maturity and its reporting for critical software.

Annex B
TRL considerations for EEE components

This Annex covers EEE components in the meaning of ECSS-Q-ST-60. For practical purposes it is sufficient to distinguish between active (semiconductor technologies), passive and hybrid microcircuits where necessary.

This does not apply to commercial EEE components in the meaning of ECSS-Q-ST-60-13 due to the lack of assured lot homogeneity and typically insufficient product traceability as well as the inherent limitations of the up-screening concept.

With few exceptions EEE components are recurrent products intended for use in a wide variety of system applications, specified and designed with sufficient margins to suit a wide variety of mission profiles. Demonstrated robustness against stresses induced by the application and operating environment are key criteria for TRL determination. Full maturity (space qualification) is typically achieved with TRL 7 or 8 due to the nearly complete test coverage for operational conditions in the relevant environment achievable on ground and with coverage of synergy effects by use of margin policies.

NOTE Although hybrid microcircuits are electric circuits assembled from individual components in a common dedicated protective package, the requirements for components apply.

Table B-1 gives the milestones and work achievement for EEE components TRL.

Table B-1: Milestones and work achievement for EEE components TRL

TRL 1	Milestones: possible constituent materials, processes, manufacturing tools, design rules and tools exist and are identified and documented. A principal adequacy for the intended application has a high probability. Work achievement: basic function(s) defined and constituent prerequisites initially documented.
TRL 2	Milestones: Basic test structures (initial prototypes for passives) exist and were used to demonstrate basic technology or component capabilities and parametric limits and major potential failure modes are known. This includes an initial characterization of robustness toward ionising radiation (TID), if applicable. Work achievement: initial hardware based test data obtained, initial quantification of possible performance parameters.

TRL 3	Milestones and work achievements: Design library and special functions for the intended application and environment and eventually hardened against TID, if applicable, exist. Relevant failure modes (wear out and overstress driven) are known, characterized and compatible with the intended application. First simulation models and tools are available to allow functional verification of a component design, if applicable. Representative test structures are produced and suitable to demonstrate functionality, operating temperature range and a level of radiation tolerance as intended for the final product.
TRL 4	Milestones: A comprehensive component detail specification exists, test programmes were developed, evaluation boards designed and fabricated, if needed, and prototypes were produced and successfully tested to demonstrate compliance with functional and performance requirements at least including temperature range, TID, DD and SEL (if applicable) testing to validate the component design. The manufacturer evaluation was successfully completed. Work achievements: design maturity and manufacturability confirmed.
TRL 5	Milestones: The component is available in its intended space qualified package (if applicable), has passed thermal and mechanical tests (e.g. shock, vibration, thermal cycling) and the substrate and PCB mounting process was qualified. The necessary SEE testing was successfully completed.
TRL 6	Milestones: The component has successfully completed the applicable evaluation test programme (ESCC or other) and reliability test data exists to confirm the specified mission life time. Derating requirements were defined. The supply chain was consolidated and operates under an independently certified QMS. The component design is fully approved, its functional and performance characteristics are fully specified and it is recurrently producible in a stabilized manufacturing process with a known yield. Work achievements: the functional and performance validation in the intended application environment was completed, or a manufacturer's in house qualification is achieved, if applicable.
TRL 7	Milestones: The component has successfully completed the applicable evaluation test programme (ESCC, ECSS-Q-ST-60 class 1 or equivalent requirements from other standardization systems) and reliability test data exists to confirm the specified mission life time. Derating requirements were defined. The supply chain was consolidated and operates under an independently certified QMS. All radiation hardness assurance tests have been successfully completed and complementary mitigation options identified. Component was qualified against ESCC or equivalent EEE space component qualification systems or for custom mission specific components achieved the full demonstration of meeting the mission requirements.
TRL 8	Milestones and work achievements: Component was qualified against ESCC or equivalent EEE space component qualification systems or for custom mission specific components achieved the full demonstration of meeting the mission requirements. A space qualified component was demonstrated to meet mission requirements which exceed the envelope of space qualification requirements, if necessary, including the effectiveness demonstration of system level mitigation measures (e.g. with external error detection and correction).
TRL 9	Milestones and work achievements: The component has achieved flight heritage as per qualification envelope or under specific mission approval constraints after a typical duration of two years of nominal performance under nominal mission conditions.

Annex C
TRL considerations for materials and manufacturing processes

A challenge for materials technology readiness level is the inherent link to the maturity status of the manufacturing process as well as associated supply chain risks in maintaining the manufacturing capability. Table C-1 provides an overview that relates the TRL to the manufacturing capability and provisions for product assurance.

Table C-1: Use of TRL for with materials and manufacturing process development

TRL	Testing requirements	Materials and manufacturing process requirements	Legal and regulatory requirements
1 2	For TRL 1 and 2, the benefit of using the TRL scale in assessing technology risk is not considered relevant for imposing requirements.		
3	Feasibility test Analytical test	Materials and processes assessed for manufacturability and availability. Definition of supply chain requirements.	General assessment of obsolescence risks (supply chain, regulatory) for materials and processes. Full assessment of exposure to environmental regulations (e.g. REACH, RoHS) other obsolescence risks for materials and processes in line with product life-cycle. Lessons learned.
4	Test configuration, relevant environment, and results recorded in traceable manner. Implementation of Test Readiness Review (TRR).	Function of critical materials and processes recorded and followed up. Materials performance and process parameters characterised at elementary level.	
5	Implementation of Test Review Board (TRB).	Representative materials performance and process parameters characterised in relation to their end-use.	ECSS-Q-ST-70 and ECSS-Q-ST-70-71 and relevant level 3 standards are applicable.
6	Test plan with relevant technical and PA expertise. Test reports Analytical report	Processes are in place to ensure manufacturability and quality for production of demonstrator. Materials performance and process parameters characterised in relation to their end-use.	
7	QM Test plan with relevant technical and PA expertise. QM Test reports	Full capability is in place for manufacturing QM model in relevant (controlled) environment.	

TRL	Testing requirements	Materials and manufacturing process requirements	Legal and regulatory requirements
8	FM Test plan with relevant technical and PA expertise. FM Test reports	Flight model is built	Flight acceptance
9	In orbit operation report	In orbit operation	Flight proven