Technology Readiness Levels (TRLs)

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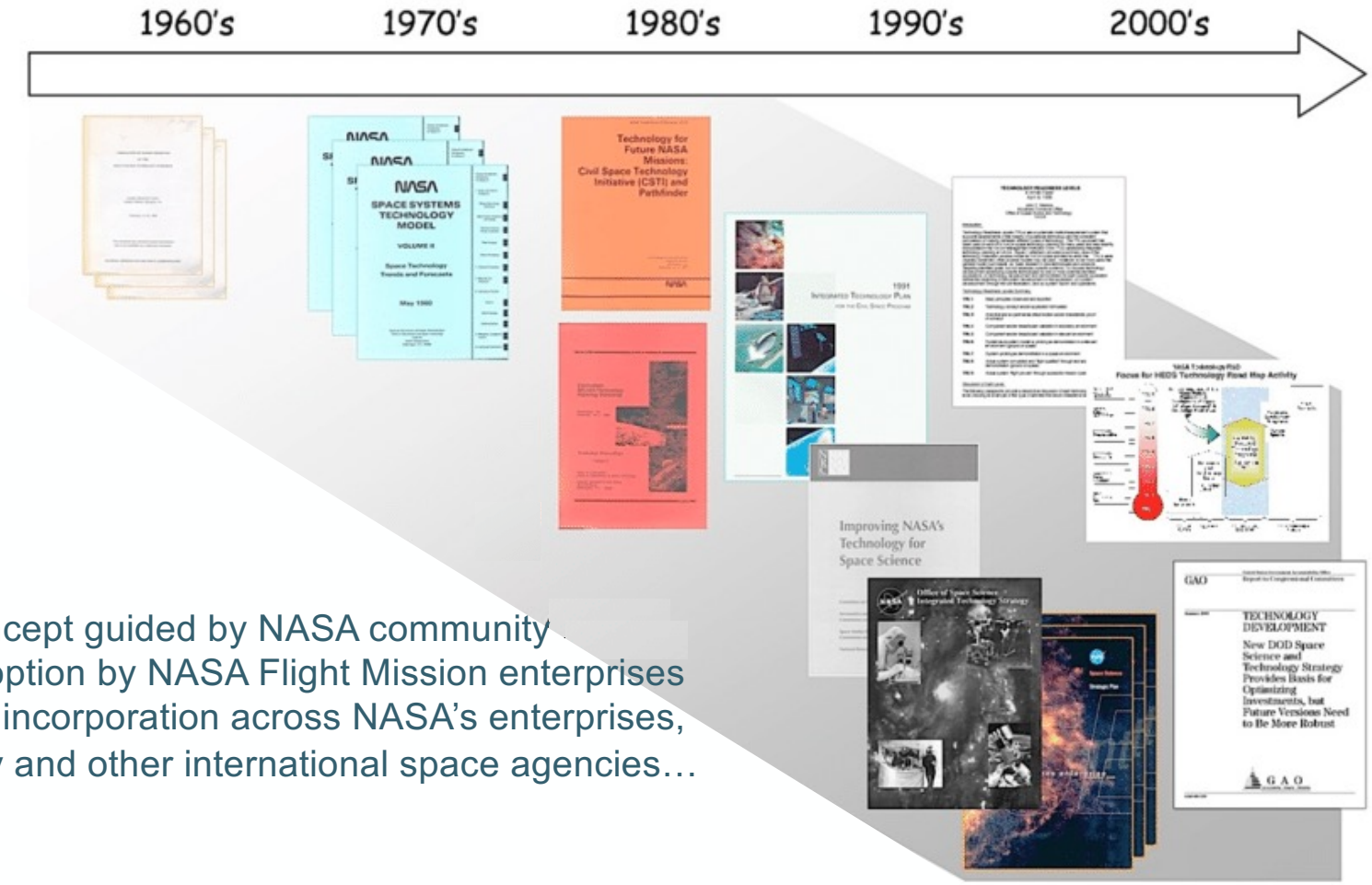
Objective of this presentation

- Be aware of and understand the concept of Technology Readiness Levels and what it entails
- Be acquainted with the new ESA TRL calculator tool

What are TRLs?

- A systematic metric to assess the maturity of a particular technology
- Provide a clear framework for assessing the progression of technologies from concept to deployment.

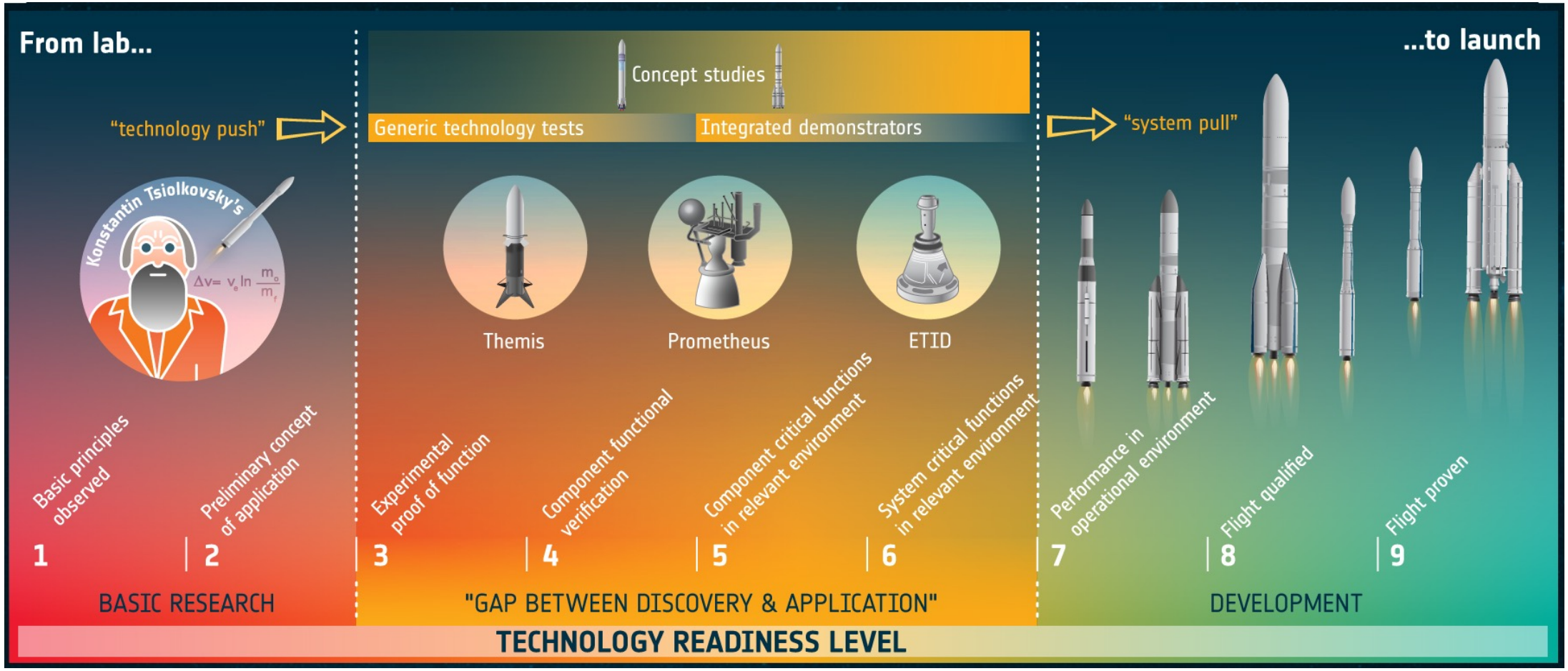
Historical background



- Early concept guided by NASA community
- Later adoption by NASA Flight Mission enterprises
- Eventual incorporation across NASA's enterprises, industry and other international space agencies…

Technology readiness level (TRL) guidelines

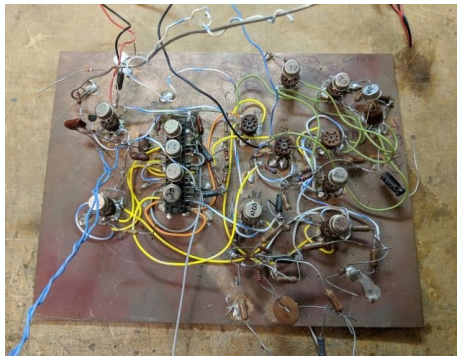
Reference: ECSS-E-HB-11A



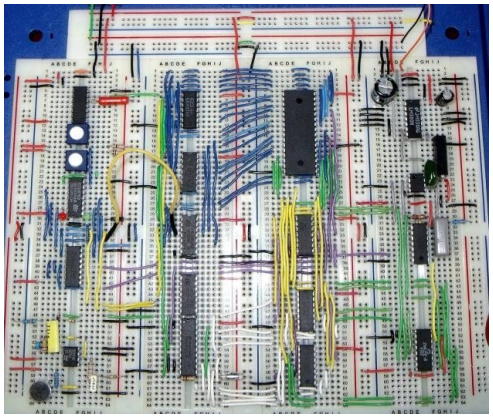
TRLs 1-3

TRL	Achievements	Documented Work
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/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

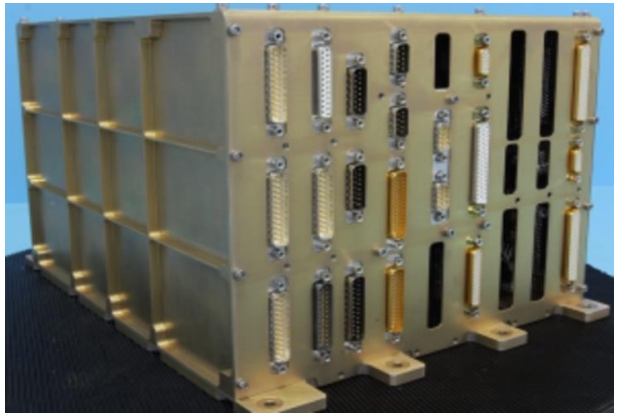
TRL 4

TRL 4	Achievements	Documented Work
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

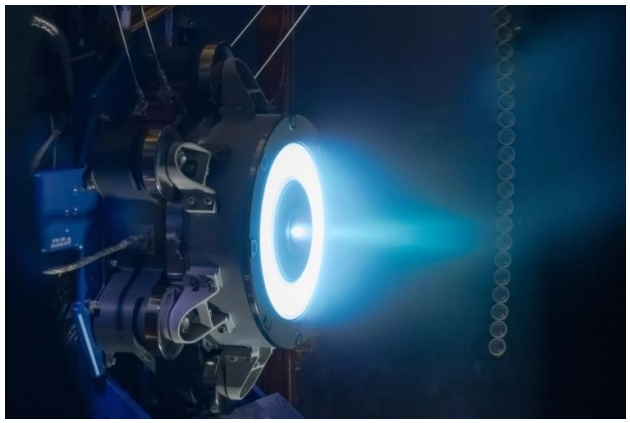
TRL 5

TRL 5	Achievements	Documented Work
Component and/or breadboard critical function verification in relevant environment	Critical functions of the element are identified The associated relevant environment is identified 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

TRL 6

TRL 6	Achievements	Documented Work
Model demonstrating the critical functions of the element in the relevant environment	Critical functions of the element are verified Performance is demonstrated in the relevant environment with representative models in form, fit and function 	• Definition of performance requirements • Definition of the relevant environment • Identification & analysis of the critical functions • Definition of the model • Design of the element, supported by appropriate models for the verification of the critical functions • Critical function test plan • Test reports

TRL 7

TRL 7	Achievements	Documented Work
Model demonstrating the element performances 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 flight model design, is built 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

TRL 8

TRL 8	Achievements	Documented Work
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

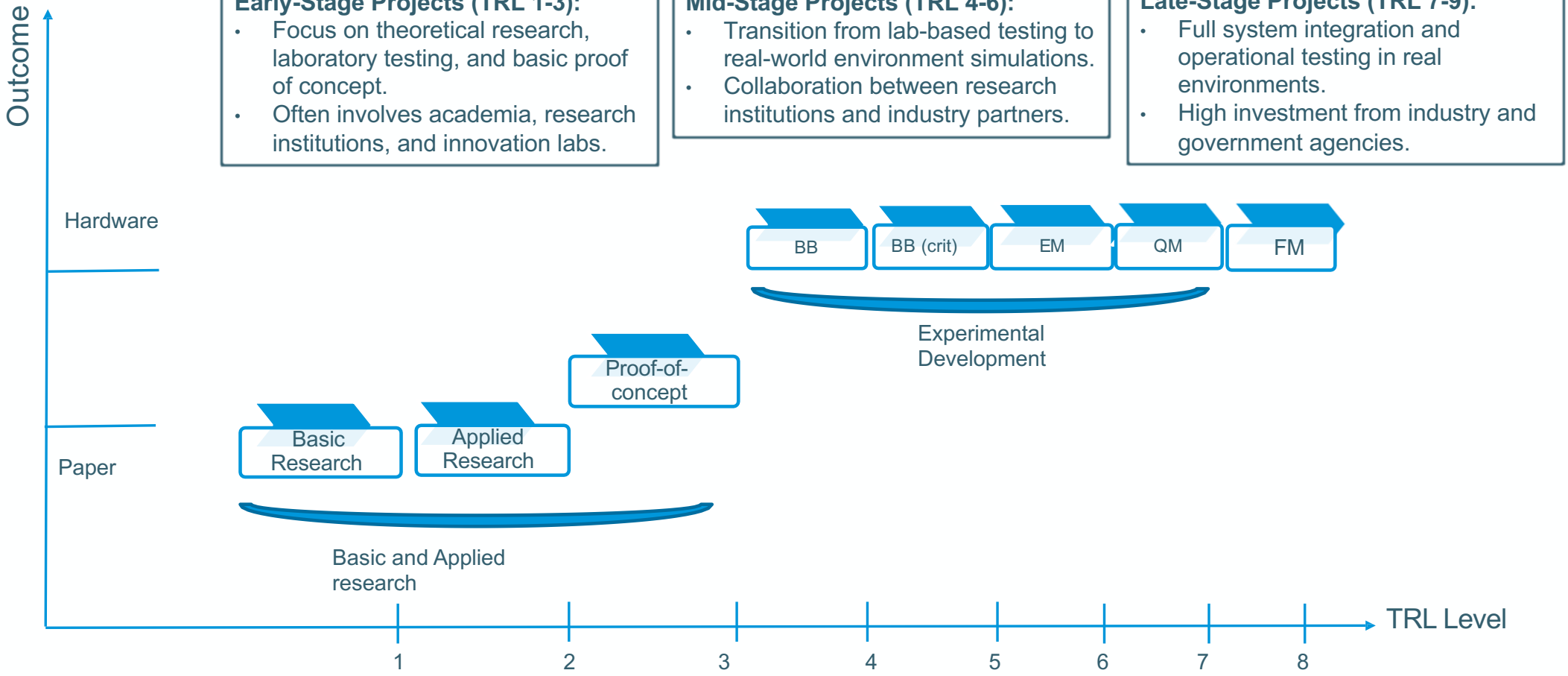
TRL 9	Achievements	Documented Work
Actual system flight proven through successful mission operations	Technology is mature. The element is successfully in service for the assigned mission in the actual operational environment 	• Commissioning in early operation phase • In-orbit operation report

TRL Scale - Landscape

Early-Stage Projects (TRL 1-3):
- Focus on theoretical research, laboratory testing, and basic proof of concept.
- Often involves academia, research institutions, and innovation labs.

Mid-Stage Projects (TRL 4-6):
- Transition from lab-based testing to real-world environment simulations.
- Collaboration between research institutions and industry partners.

Late-Stage Projects (TRL 7-9):
- Full system integration and operational testing in real environments.
- High investment from industry and government agencies.



TRL Scale and Model Philosophy

TRL	Model	Performances	Environment	Comments
TRL 1	Scientific papers	n/a	n/a	Preliminary scientific studies. No specific application envisaged.
TRL 2	Scientific papers	n/a	n/a	Basic research. Some applications are defined and discussed.
TRL 3	Proof of concept	Functions defined	Laboratory	Applied research. Applications identified.
TRL 4	Breadboard (BB)	Functions defined and prel. performance defined	Laboratory	HW available. Applied research continues to investigate for feasibility.
TRL 5	Breadboard (BB)	Critical functions identified	Relevant Environment	BB closer to EM but subject to scaling effects. Full experimental development.
TRL 6	Engineering Model (EM)	Critical functions verified and performances identified	Relevant Environment	Form/Fit/Function (FFF) representative. Reliability not an issue.
TRL 7	Qualification Model (QM)	Full performance verification (QR)	Operation. Environment	Design verified against margins.
TRL 8	Flight Model (FM)	Design change is over Element accepted (AR)	Actual Operational Environment	No latent defects and element integrated into sytem. Product Lifecycle starts.
TRL 9	Flight proven	Actual operational environment	Actual Operational Environment	Heritage data available (EQSR for OTS equipment)

Source: ECSS-E-HB-11A

Benefits of using TRLs

Risk Management:

- Ensures that technologies are mature enough for critical mission phases.
- Reduces the risk of mission failure due to immature technologies.

Budget and Resource Allocation:

- Guides investment decisions, focusing funds on technologies likely to succeed.
- Streamlines the development process, avoiding costly delays.

Communication:

- Provides a common language for stakeholders, including engineers, managers, and funding bodies.
- Enhances transparency in technology development progress.

Challenges in Implementing TRLs

Subjectivity:

- Determining the exact TRL can sometimes be subjective and dependent on interpretation.

Integration Complexity:

- Moving from TRL 6 to TRL 7 involves significant integration challenges.

Costs:

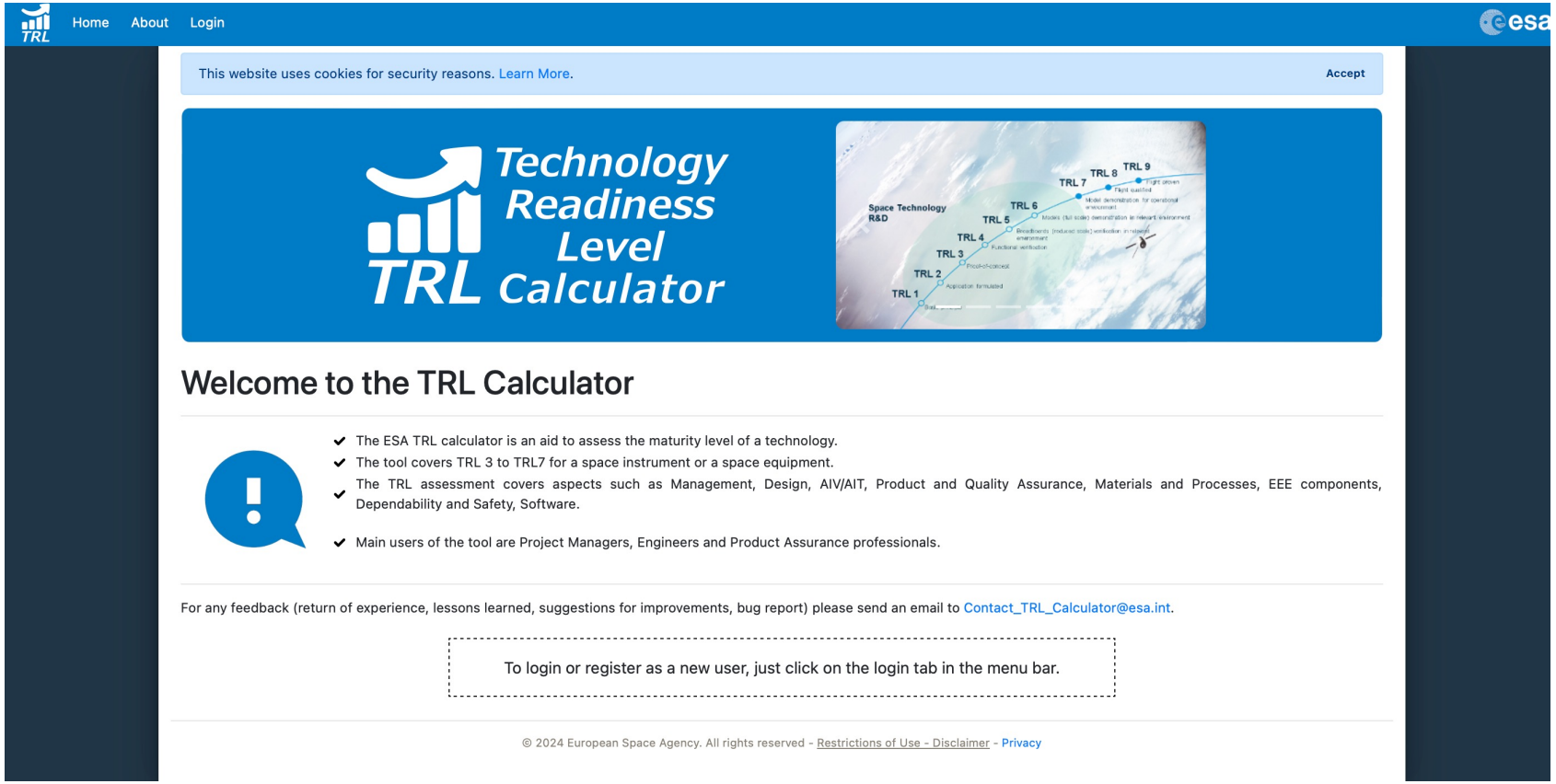
- Advancing from low to high TRLs can be expensive, especially for space projects where testing in operational environments is critical.

Time:

- Developing technologies from TRL 1 to TRL 9 can take years or even decades.

ESA's TRL calculator

- The tool covers TRL 3 to TRL 7, i.e. the complete development lifecycle for a space product.



ESA's TRL calculator

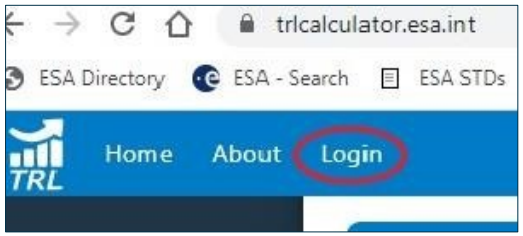
- Each question is answered with a **yes** or **no**
- If the technology implies that some specific technologies are not implemented, then the pertaining question can be skipped.
- Questions are mandatory or non-mandatory
  - Mandatory: essential to achieve the target TRL
  - Non-mandatory: needed to assess the risk related to missing information when moving to a higher TRL (*e.g.* missing derating analysis or flight grade counterpart for a EEE component in TRL 6)
- Path-to-flight approach embedded inside the checklist

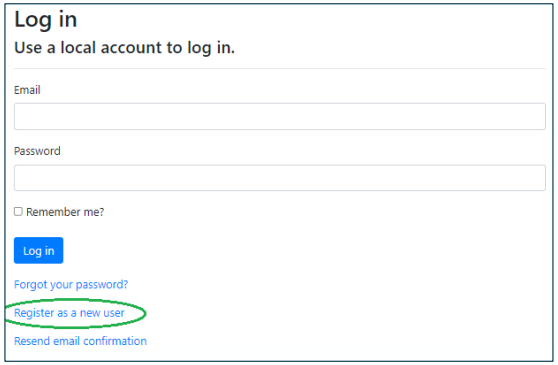
ID ↑	Question	Mandatory
1	Is the operational environment identified?	True
2	Are the functions and performances identified?	True
3	Is there a Qualification Model available?	True
4	Are there analytical models to predict the performances?	True
5	Is a verification plan available?	True
6	Were Qualification Margins in the test plan used in the functional and environmental test campaigns?	True
7	Are as-run integration and test procedures available?	True
8	Are the pass/fail criteria for performance clear and specific to accuracy, repeatability, and accounting for measurement errors in the test procedures?	True
9	Is a Manufacturing, assembly and Integration workflow defined and followed?	True
10	Is there a design defintion/description file available, which also includes lessons learned from previous development activities and interoperability of the relevant sub-elements which were subject to previous TRL assessments?	True
11	In case Space Debris Mitigation requirements are applicable, were the relevant design features implemented and checked?	False

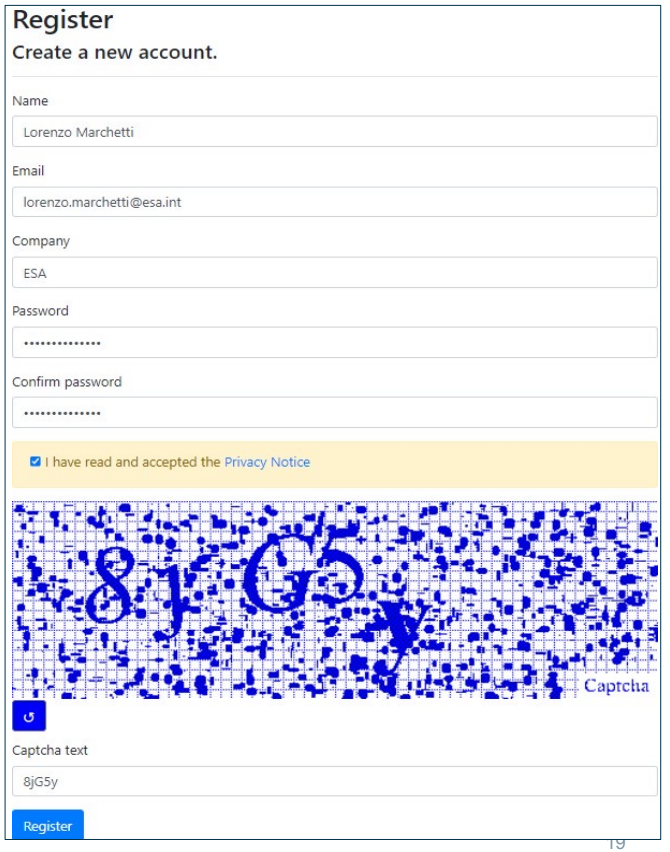
Checklist available for each TRL

ESA's TRL calculator

1. Go to https://trlcalculator.esa.int using your web browser (Internet Explorer not supported!)
2. Click on the "login" tab in the menu bar
3. Click on "Register as a new user"
4. Fill the online form
5. Click on "Register"
6. Wait for email with the confirmation of your registration







Conclusion

Key Takeaways:

- TRLs are crucial for ensuring the success of space missions by managing technology risks and guiding development.
- Effective use of TRLs helps in making informed decisions about technology investments and mission planning.
- As space exploration advances, TRLs will continue to evolve, supporting increasingly complex and ambitious projects.

TRLs provide a roadmap for turning innovative ideas into operational realities, ensuring the continuous advancement of space technology.

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Summary

- TRL 1 Identifies the potential application
- TRL 2 Identifies the potential application, supported by scientific formulas
- TRL 3 Light Testing Activities on Elements in Lab. Applied research
- TRL 4 functional verification, after Breadboard (BB) integration in Lab
- TRL 5 functional verification of the BB in relevant environment
- TRL 6 Testing of EM
- TRL 7 Testing of QM (FFF + redundancy)
- TRL 8 PFM. Acceptance of the workmanship is verified
- TRL 9 FM. Technology is mature, reliable and ready for flight