Electric Propulsion Qualification Guidelines and Best Practices for NASA Small Spacecraft Missions

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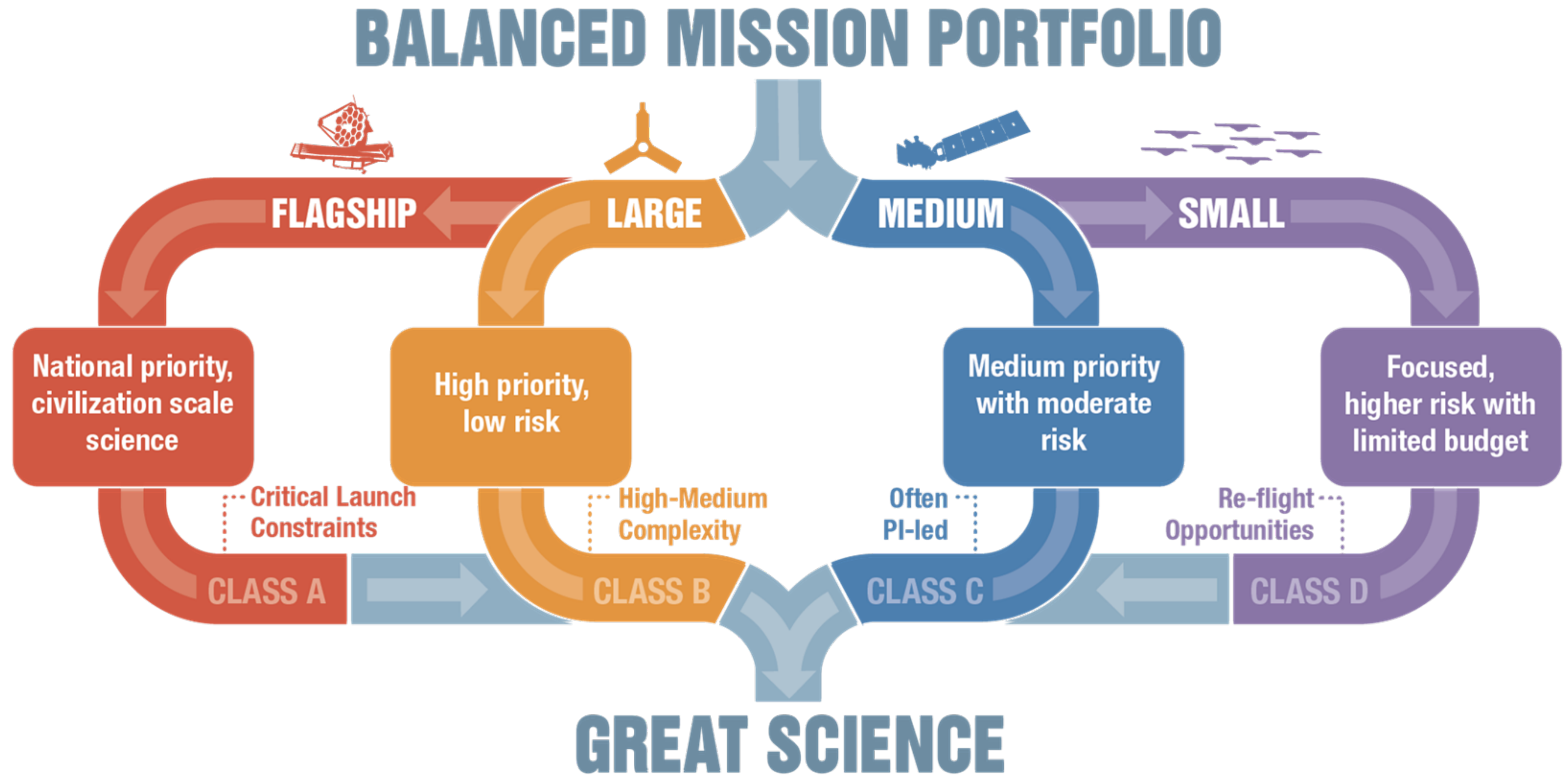
S3VI Community of Practice Seminar
December 14, 2022

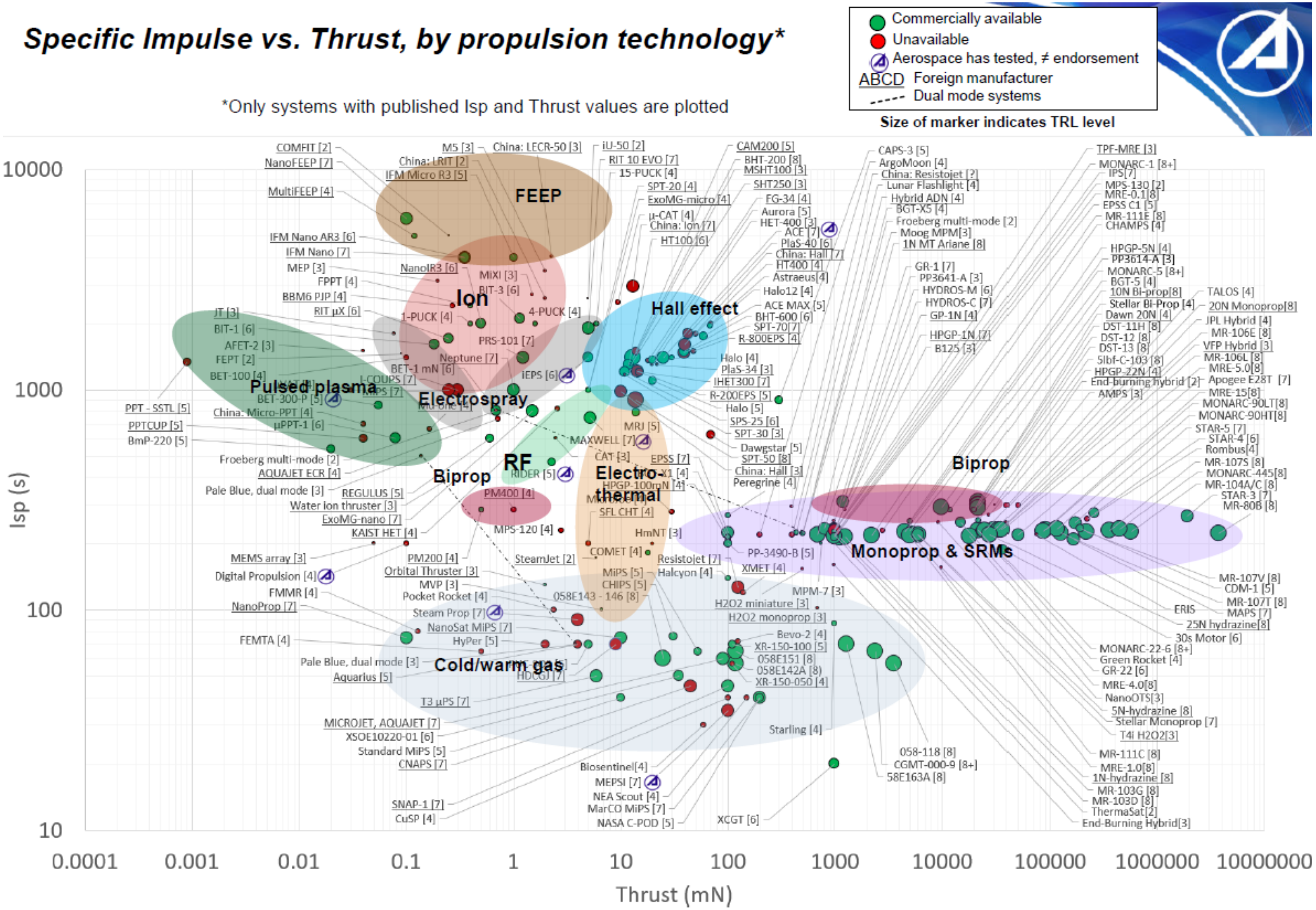
Outline

- NASA Class-D missions
- Electric propulsion for smallsats
- Micro-Propulsion Technology Readiness Levels
  - Hardware fidelity
  - Environments
- Qualification entrance criteria
  - Requirements
  - Maturity
- Qualification Philosophy
  - Documentation
  - Hardware type
  - Testing
- EP-specific recommendations

NASA Science Missions



Electric Propulsion for SmallSats (1/2)



Source:
A.G. Hsu *et al.*, *"2021 Small Satellite Propulsion Technologies Compendium", ATR-2022-00364, DISTRO A, Version 1.38, The Aerospace Corporation, December 2021.*

Electric Propulsion for SmallSats (2/2)

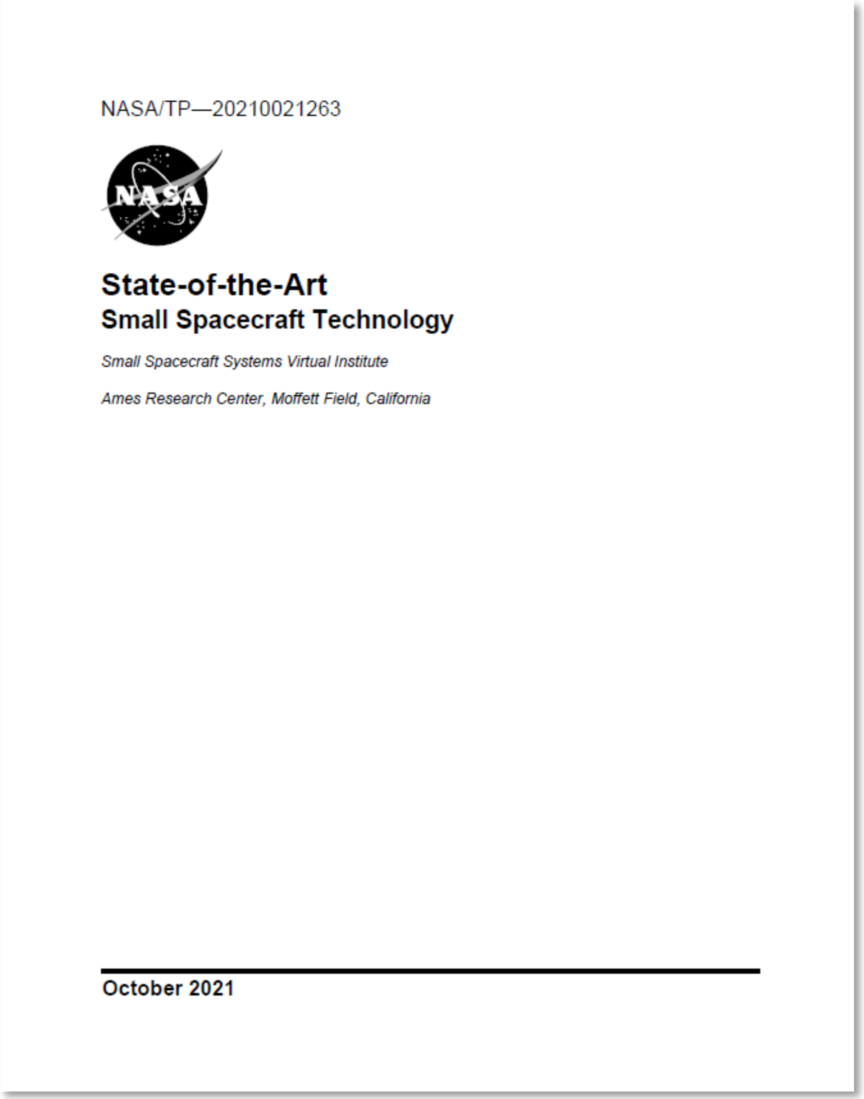
SOA Chapter 4: *In-Space Propulsion*

- Technology description
- Key integration and operational considerations
- Current and planned missions
- Summary table of devices
- Notable advancements

Manufacturer	Product	Propellant	Thrust*	Specific Impulse*	Total Impulse*	Mass	Envelope	Power	Neutralizer	Status	Missions	References
---	---	---	[µN]	[s]	[N-s]	[kg]	[cm^3 or U]	[W]	---	C,D,E,F	---	---

https://www.nasa.gov/smallsat-institute/sst-soa

Editor: Sasha Weston (NASA ARC)


NASA/TP—20210021263

State-of-the-Art
Small Spacecraft Technology

Small Spacecraft Systems Virtual Institute

Ames Research Center, Moffett Field, California

October 2021

What Is TRL?

Grant Tremblay
@astrogrant

.@NASA okay fine

NASA Technology Readiness Levels

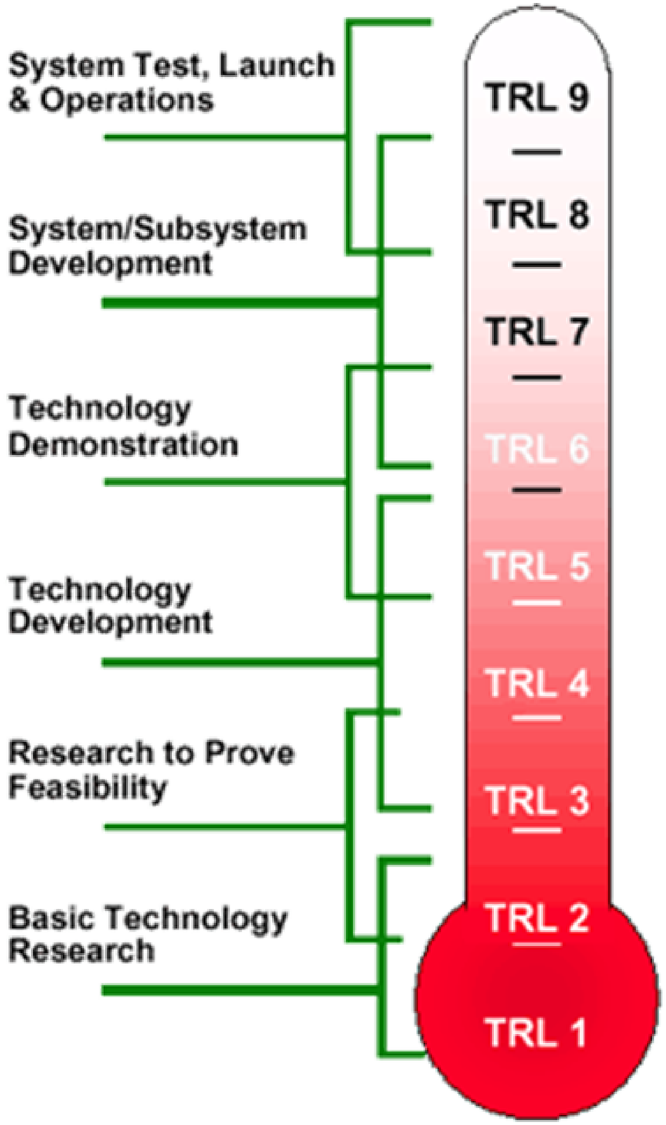
TRL 1: What if there were Unicorns
TRL 2: We have drawn a Unicorn
TRL 3: `unicorn_v8_final_final.cad`
TRL 4: We have placed a horn on a horse in our lab
TRL 5: We took the horse outside
TRL 6: We're now calling the horse a Unicorn
TRL 7: We're pretty sure the Unicorn might survive if we launch it into space
TRL 8: omg it survived
TRL 9: Our reference design incorporates high-heritage Space Unicorns

1:41 PM · May 22, 2019 · Twitter Web Client

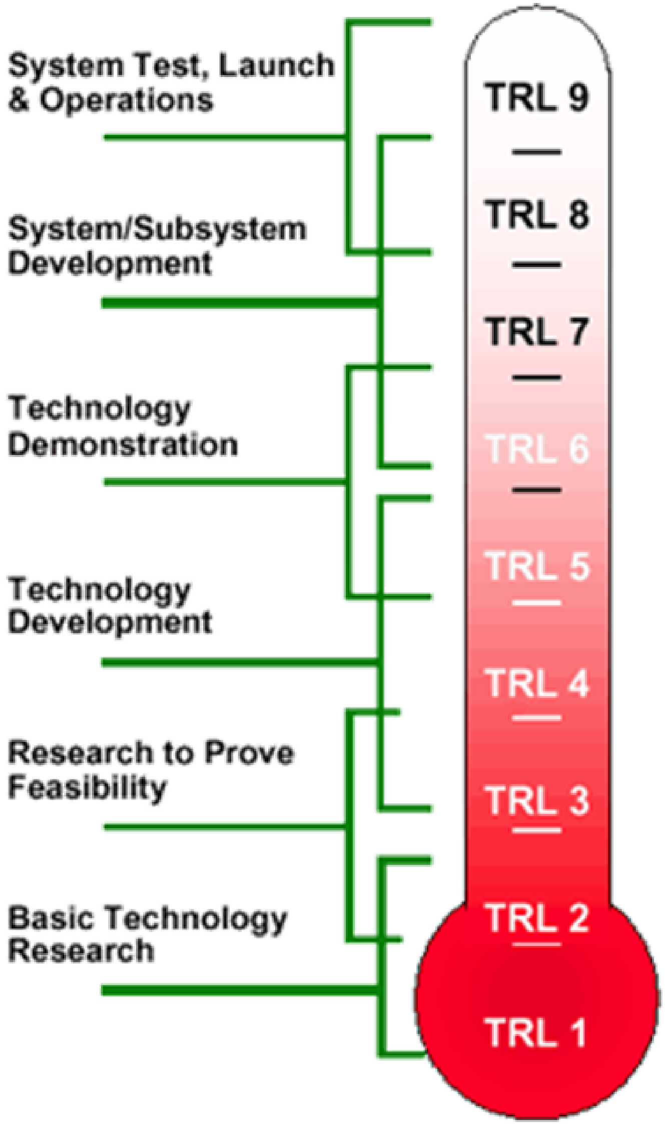
Micro-Propulsion TRL (1/2)

Problem: **Application of TRL can be inconsistent, and self-evaluations are frequently overstated**

- JANNAF paper (Distribution A): *JANNAF Guidelines for the Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems*
  - Collaboration between AFRL and NASA (GRC / GSFC / JPL)
  - Updates with community feedback
- Key features of framework
  - Tailors to micro-propulsion systems for small spacecraft
  - Seeks common ground between DoD / NASA interpretations and terminology
  - Focuses on system rather than component TRL
  - Specifies entrance / exit criteria for TRL
  - Emphasizes TRL process as being dynamic with both progression and regression paths



Micro-Propulsion TRL (2/2)



Routine Operations

Flight Proven

Flight Demonstration

Flight Qualification

Brassboard System

Breadboard System

Breadboard Thruster

Thrust Generation

Eureka!

TRL 1: Eureka!

Scientific knowledge generated underpinning hardware technology concepts / applications.

Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.

- ✓ Propellant acceleration mechanism is identified.
- ✓ Propulsion concept's similarity to relevant literature is demonstrated.
- ✓ Research is limited to paper studies or observations of prior work.
- ✓ Extrapolation of a concept for thrust generation capability is made.

TRL 2: Thrust Generation

Invention begins. Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture.

Practical application is identified but is speculative; no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations, and concepts defined. Basic principles coded. Experiments performed with synthetic data.

- ✓ Propellant acceleration mechanism is observed directly or from literature.
- ✓ Subsystems and their general functions are identified based on application.
- ✓ Thruster performance is estimated parametrically or from first principles.

TRL 3: Breadboard Thruster

Research and development are initiated, including analytical and laboratory studies to validate predictions regarding the technology.

Development of limited functionality to validate critical properties and predictions using non-integrated software components.

- ✓ Performance is directly measured with quantified uncertainty estimates at an operational mode closely approximating intended flight operations.
- ✓ Ranges of thruster head performance are measured to determine optimization.
- ✓ Thruster life-limiting mechanisms are identified, and thruster lifetime is estimated from limited measurements and models.
- ✓ Thruster lifetime is expressed in unambiguous engineering units (total impulse suggested).
- ✓ Test environment suitability is verified via analysis and models.
- ✓ Subsystems are identified via laboratory surrogates.

Hardware Fidelity

Term	Definition (NPR 7120.8A)
Breadboard Unit	A low-fidelity unit that demonstrates function only, without respect to form or fit in the case of hardware, or platform in the case of software. It often uses commercial and/or ad hoc components and is not intended to provide definitive information regarding operational performance.
Brassboard Unit	A medium-fidelity functional unit that typically tries to make use of as much operational hardware / software as possible and begins to address scaling issues associated with the operational system. It does not have the engineering pedigree in all aspects but is structured to be able to operate in simulated operational environments in order to assess performance of critical functions.
Prototype Unit	The prototype unit demonstrates form, fit, and function at a scale deemed to be representative of the final product operating in its operational environment. A subscale test article provides fidelity sufficient to permit validation of analytical models capable of predicting the behavior of full-scale systems in an operational environment.
Engineering Unit	A high-fidelity unit that demonstrates critical aspects of the engineering processes involved in the development of the operational unit. Engineering test units are intended to closely resemble the final product (hardware / software) to the maximum extent possible and are built and tested so as to establish confidence that the design will function in the expected environments. In some cases, the engineering unit will become the final product, assuming proper traceability has been exercised over the components and hardware handling.

TRL 4: Breadboard System (1/2)

A low-fidelity system / component breadboard is built and operated to demonstrate basic functionality in a laboratory environment.

Key, functionality-critical software components are integrated and functionally validated to establish interoperability and begin architecture development. Relevant environments defined and performance in the environment predicted.

- ✓ Focus shifts from thruster head to overall system performance.
- ✓ Micro-propulsion system requirements are defined with end-user engagement or derived from a design reference mission (DRM).
- ✓ System architecture is completely identified.
- ✓ All subsystems are demonstrated for functionality at breadboard-level fidelity.
- ✓ Micro-propulsion system is integrated and demonstrated at breadboard-level fidelity in an appropriate environment.

TRL 4: Breadboard System (2/2)

A low-fidelity system / component breadboard is built and operated to demonstrate basic functionality in a laboratory environment.

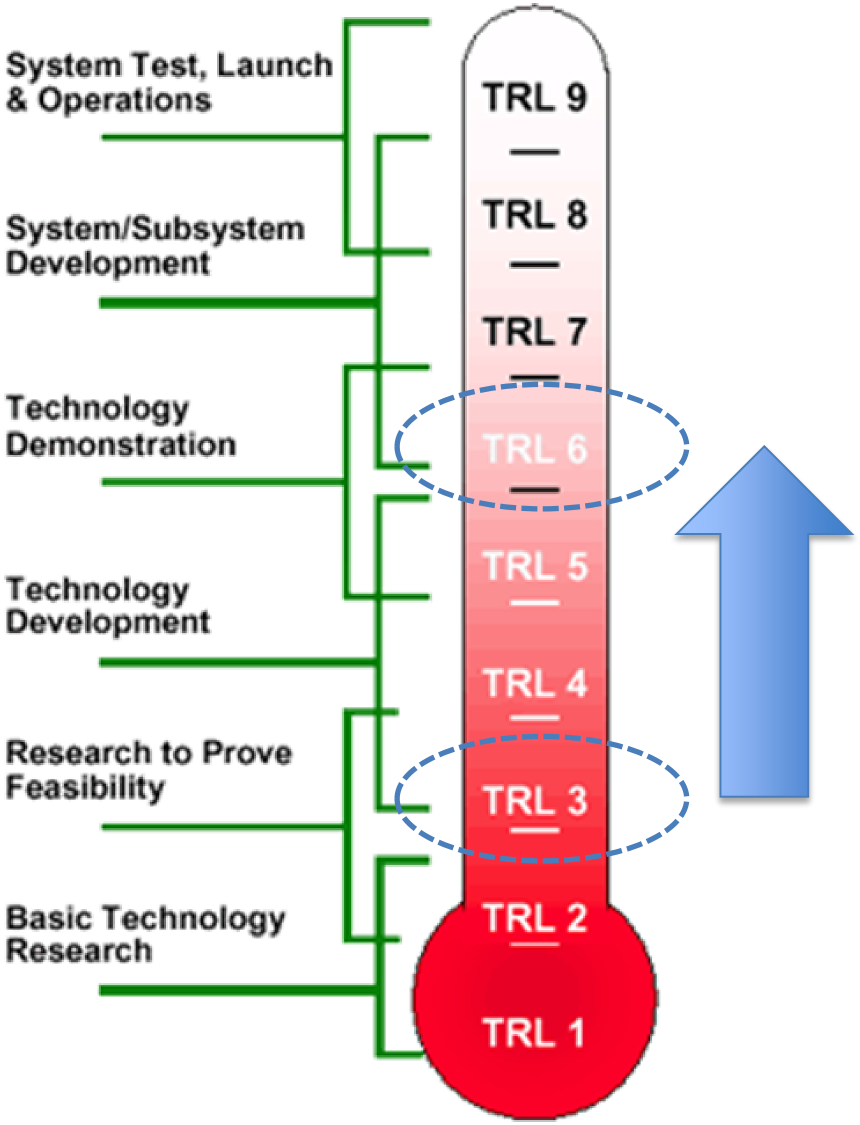
Key, functionality-critical software components are integrated and functionally validated to establish interoperability and begin architecture development. Relevant environments defined and performance in the environment predicted.

- ✓ Significant portion of thruster head lifetime is demonstrated (50% or greater recommended, or sufficient to explore major failure modes).
- ✓ Thruster lifetime is estimated based on long-duration tests; any required extrapolation is reviewed and documented.
- ✓ Thruster performance is measured at beginning of life (BoL) and estimated for end of life (EoL).
- ✓ Thruster plume behavior is estimated from limited measurements and models.

Design Reference Missions (DRM)

Problem: Technology development frequently lacks relevant mission application requirements for flight qualification and demonstrations

- Reduce risk of micro-propulsion technologies being delivered for flight demonstrations with limited success or failures
- Develop representative DRMs ("eigen-missions") that capture key mission requirements for guiding technology maturation and validation
- Led by C. Marrese-Reading (NASA JPL) and JANNAF Spacecraft Propulsion Subcommittee



Environments

Term	Definition (NPR 7120.8A)
Laboratory Environment	An environment that does not address in any manner the environment to be encountered by the system, subsystem, or component (hardware or software) during its intended operation. Tests in a laboratory environment are solely for the purpose of demonstrating the underlying principles of technical performance (functions) without respect to the impact of environment.
Relevant Environment	Not all systems, subsystems, and/or components need to be operated in the operational environment in order to satisfactorily address performance margin requirements. Consequently, the relevant environment is the specific subset of the operational environment that is required to demonstrate critical ”at risk” aspects of the final product performance in an operational environment. It is an environment that focuses specifically on ”stressing” the technology advance in question.
Operational Environment	The environment in which the final product will be operated. In the case of spaceflight hardware / software, it is space. In the case of ground-based or airborne systems that are not directed toward spaceflight, it will be the environments defined by the scope of operations. For software, the environment will be defined by the operational platform.

TRL 5: Brassboard System (1/2)

A medium-fidelity component and/or brassboard, with realistic support elements, is built and operated for validation in a relevant environment so as to demonstrate overall performance in critical areas.

End-to-end software elements implemented and interfaced with existing systems / simulations conforming to target environment. End-to-end software system tested in relevant environment and meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.

- ✓ Thruster head design is finalized as appropriate for flight.
- ✓ All subsystem designs are upgraded to brassboard-level fidelity with control interfaces implemented through a model spacecraft simulator.
- ✓ Integrated (as flight-like as possible) brassboard system performance is verified in a simulated flight environment.

TRL 5: Brassboard System (2/2)

A medium-fidelity component and/or brassboard, with realistic support elements, is built and operated for validation in a relevant environment so as to demonstrate overall performance in critical areas.

End-to-end software elements implemented and interfaced with existing systems / simulations conforming to target environment. End-to-end software system tested in relevant environment and meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.

- ✓ Significant portion of propulsion system lifetime is demonstrated (50% or greater recommended, or sufficient to explore major failure modes).
- ✓ Propulsion system lifetime is estimated based on long-duration tests; any required extrapolation is reviewed and documented.
- ✓ Propulsion system performance is measured at beginning of life (BoL) and estimated for end of life (EoL).
- ✓ System impact (e.g., thermal soakback, electromagnetic interference, plume contamination, etc.) on host spacecraft is quantified.

TRL 6: Flight Qualification (1/2)

A high-fidelity prototype of the system / subsystems that adequately addresses all critical scaling issues is built and tested in a relevant environment to demonstrate performance under critical environmental conditions.

Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware / software systems. Limited documentation available. Engineering feasibility fully demonstrated.

- ✓ Integrated (as flight-like as possible) prototype system is demonstrated and verified in a relevant environment consistent with the anticipated operational environment (e.g., vacuum, microgravity, radiation, thermal cycling, electromagnetic compatibility, etc.).
- ✓ Launch environment survival (vibrational, shock, and thermal) is demonstrated and verified for the integrated prototype system.
- ✓ Micro-propulsion system lifetime is directly measured with lifetime margin explicitly defined; the lifetime margin may be reduced if multiple life tests provide improved statistical certainty.
- ✓ Micro-propulsion system performance is measured and verified at BoL and EoL.

TRL 6: Flight Qualification (2/2)

A high-fidelity prototype of the system / subsystems that adequately addresses all critical scaling issues is built and tested in a relevant environment to demonstrate performance under critical environmental conditions.

Prototype implementations of the software demonstrated on full-scale, realistic problems. Partially integrated with existing hardware / software systems. Limited documentation available. Engineering feasibility fully demonstrated.

- ✓ Thermal soakback, EMI, and plume contamination / charging impacts on the host spacecraft are mitigated.
- ✓ Software interfaces are fully identified, developed, and verified with prototype-level hardware.
- ✓ Peer review verifies achieving TRL 6.

TRL 7: Flight Demonstration

A high-fidelity prototype or engineering unit that adequately addresses all critical scaling issues is built and functions in the actual operational environment and platform (ground, airborne, or space).

Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware / software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.

- ✓ Protoflight or acceptance-tested micro-propulsion system is developed and demonstrated onboard spacecraft.
- ✓ Protoflight or acceptance-tested system's flight performance is verified via orbital or attitude flight data.
- ✓ Protoflight or acceptance-tested system's anomalous events are traced to root causes and verified with a ground testbed.
- ✓ Protoflight or acceptance-tested system's flight demonstration measurements and results are archived in relevant literature.

TRL 8: Flight Proven (1/2)

The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space). If necessary, life testing has been completed.

All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and validation (V&V) completed.

- ✓ All flight system demonstration anomalies are mitigated with demonstrated resolution.
- ✓ Final system design is implemented and flight verified.
- ✓ Repeatable system production, manufacturability, and performance are demonstrated and documented.
- ✓ System is ready for operational deployment and no longer deemed an experiment with specialized support.
- ✓ Final system represents the end of actual technology development.

TRL 8: Flight Proven (2/2)

The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space). If necessary, life testing has been completed.

All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and validation (V&V) completed.

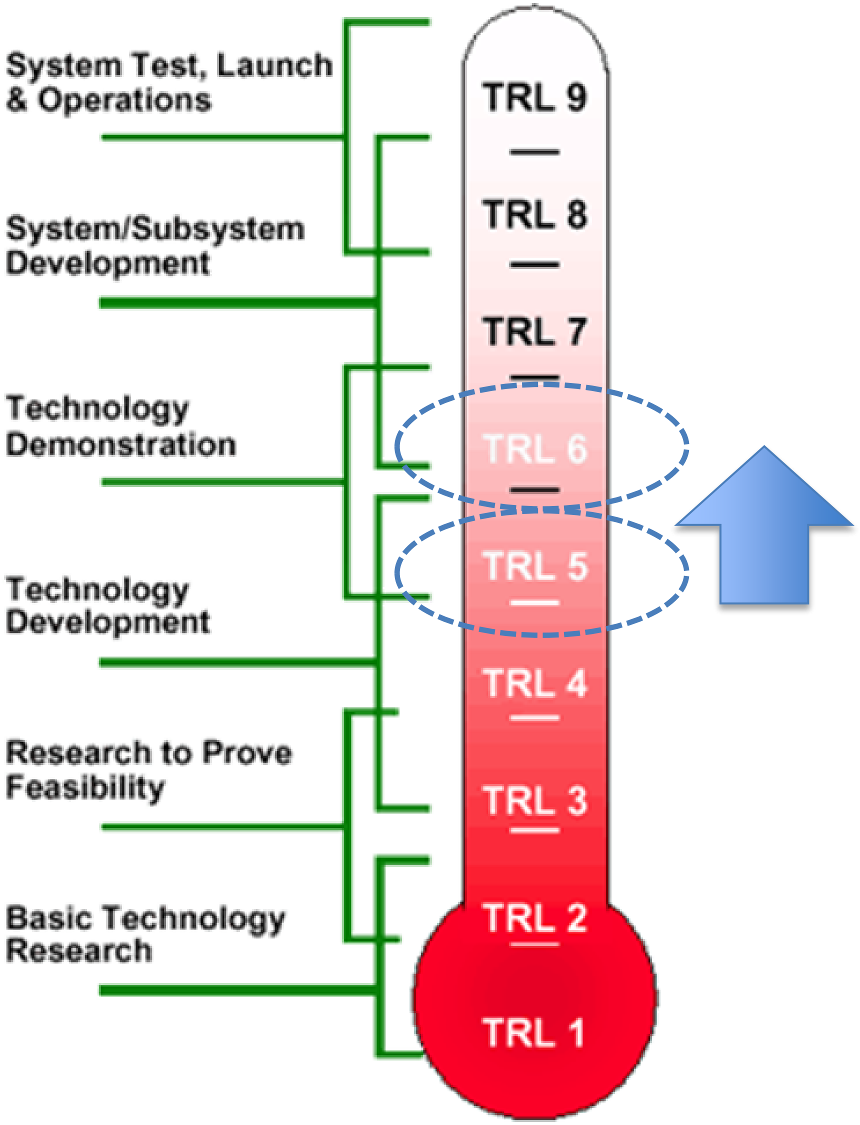
What about TRL 9?

TRL 9 represents an asymptotic final state of maturation in which the micro-propulsion system has a history of successful routine operations.

EP Qualification for NASA Smallsat Missions (1/2)

Problem: **Need exists to strike better balance between cost effectiveness and engineering rigor**

- Recommended guidelines for a minimum floor of EP flight qualification activities
- Best practices to avoid recurring issues and common pitfalls with EP flight qualification
  - Mission-specific requirements verification
  - Integrated assembly level
  - Test-like-you-fly (TLYF) qualification sequence



EP Qualification for NASA Smallsat Missions (2/2)

- Address shortcomings associated with a purely "CubeSat mentality"
  - Great low-cost, hands-on learning experience for design-build-test-fly of space hardware
  - Higher risk and failure rates associated with minimal expectations for technology qualification

- Present proposed framework and preliminary content on avoiding recurring issues and common pitfalls for Class-D missions
  - Recruiting SMEs from other NASA centers to flesh out content and develop NASA consensus

- Initiate dialogue with the smallsat community regarding desired content
  - Mission pull: How to minimize risk of impacting primary mission and accomplish mission objectives of secondary payload?
  - Technology push: How to plan for propulsion subsystem qualification for a given NASA Class-D mission?

Qualification Entrance Criteria: Requirements

- Qualification is a tailored and specific verification of a particular set of requirements provided by an identified customer and defined mission.
- Without a given mission and customer, the requirements will necessarily be vague or rough-estimate placeholders likely to be insufficient or inapplicable for future missions.

Recommendation 1: Establishment of customer- and mission-specific requirements is key to advance and qualify smallsat EP subsystems. Qualification of hardware to a generic set of requirements will still require likely substantial additional delta qualification activities for an actual manifested mission.

Qualification Entrance Criteria: Maturity

- A successful flight demonstration does not assure that the technology is qualified for all future flights.
- A proper qualification program rigorously pushes TRL 5 hardware beyond the expected imposed limits to maximize the probability of mission success even under adverse conditions.

Recommendation 2: Ensure the EP subsystem is at a sufficient level of maturity and that all common and basic aspects of spaceflight hardware design (e.g. materials and processes, EEE parts, etc.) have been considered and accounted for before commencing qualification activities.

Qualification Philosophy: Documentation

- JANNAF micro-propulsion guidelines for TRL 6 stipulates peer review verification.
- NASA Class-D missions permit merging and tailoring of documentation to reduce documentation and configuration management burden.

Recommendation 3: Though perhaps not required as formal deliverables, a qualification plan, qualification data package and reports, and independent reviewers are fundamental good practices to include to ensure no gaps or misses are present in the overall qualification approach and interpretation of results.

Qualification Philosophy: Hardware Type

- Prototype qualification: flight-like hardware (but will not be flown) that is tested to full qualification levels and durations
- Protoflight qualification: hardware intended for actual flight and tested to typically qualification levels but for reduced durations

Recommendation 4: In general, a protoflight qualification approach may be acceptable for Class-D smallsat EP hardware, given proper attention is provided to risk management. For a prototype approach with dedicated qualification hardware, it should mimic the flight hardware as much as possible to adhere to Test Like You Fly (TLYF) and minimize the risk of late design changes.

Qualification Philosophy: Testing

Recommendation 5: Qualification tests should in general be conducted at minimum at the integrated assembly level it will be delivered to the customer. Tests at earlier levels of assembly will help to reduce the risk of issues and failures during qualification of integrated assemblies.

Recommendation 6: Qualification test flow should follow a flight-like sequence where possible. Inspection and functional checks performed between qualification test entries provide feedback and confirmation for each step.

Recommendation 7: In general, verification of requirements should be verified via qualification test or analysis approaches. Qualification by similarity needs to rigorously and comprehensively ensure all the subtleties of heritage transfer are addressed.

EP-Specific Recommendations (1/4)

Recommendation 8: Performance of the EP subsystem should be qualified at a subsystem level — with flight-like integration of the thruster, power electronics, and propellant feed system — to account for potential interactions affecting system-level performance.

Recommendation 9: Direct measurements of thrust and propellant use should be made for qualification of performance parameters. The published EP community recommended practices for thrust and propellant flow rate should be adhered to where applicable. Aspects of calibration and proper consideration of sources and corrections of error need to be handled rigorously for credible measurements.

EP-Specific Recommendations (2/4)

Recommendation 10: All other performance parameters and known or suspected factors that may influence them should be characterized during the qualification process as deemed pertinent for the technology and/or mission for predictions of in-space operation and over time. These may include, but are not limited to: thrust stability, impulse bit repeatability, thrust vector, thermal conditions, facility backpressure, and facility electrical interactions.

Recommendation 11: A life or extended wear test is recommended to identify previously unanticipated failure modes and to characterize the behavior of the failures for the thruster. Life qualification by combined test and analysis is recommended, following the published general guidelines where applicable.

EP-Specific Recommendations (3/4)

Recommendation 12: Power electronics reliability is largely driven by proper component selection, but a burn-in test is recommended to catch infant mortality issues.

Recommendation 13: Life and reliability qualification of propellant feed systems typically should include cyclic, leak, and proof pressure testing.

Recommendation 14: Flight-like thermal interfaces should be strongly considered for implementation and monitoring during qualification of the EP subsystem to prevent unanticipated integration issues.

EP-Specific Recommendations (4/4)

Recommendation 15: EMI/EMC qualification testing is recommended at a minimum for the PPU and other power electronics as is typical for any spaceflight electrical and electronic hardware. Testing at the EP subsystem-level may be necessary depending on the mission, spacecraft, and nature of the technology.

Recommendation 16: The plumes of new EP devices should be sufficiently characterized to understand and predict spacecraft interactions for system-level integration. Specifics of plume mapping details and materials for interaction will need to be derived from the mission and spacecraft customers.

Forward Work?

- Performance, lifetime, and plume model validation
- Electrical interfaces
- Software / algorithm testing
- Structural dynamics
- Thermal environments
- Other environments of concern (e.g., humidity, chemical, etc.)
- Acceptance testing following qualification
- Example case study with DRM and environments
- List of recommended reference documents

Questions?

Acknowledgements

The authors would like to thank the members of the NASA GRC Electric Propulsion Systems branch for their contributions to this proposed framework and preliminary content.

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