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

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Electric propulsion being developed for CubeSats and other small satellites with the taught expectation that high risk is generally acceptable are resulting in devices that do not meet a minimum expectation of engineering rigor for many missions, including appropriate qualification testing. This paper proffers a preliminary set of recommended guidelines and best practices in dialogue with the smallsat community to strike a better balance between engineering rigor and cost effectiveness for the qualification of EP technologies under consideration for NASA small spacecraft.

Introduction and Scope

Improved capability and miniaturization of spacecraft systems, along with common use of EELV (Evolved Expendable Launch Vehicle) secondary payload adapters (ESPA) to sell off excess launch capacity, provides increased opportunity to accomplish scientific, commercial, and military space missions at a fraction of historic costs. As such, ESPA-class and smaller satellites (< 500 kg) are rapidly growing in both utility and popularity. However, they still lack the high delta-*v* propulsive capabilities currently available in the larger state-of-the-art (SOA) all-electric spacecraft buses. Although recent years have experienced a relative explosion of smallsat electric propulsion (EP) concepts and varying levels of development, the number of mature and qualified devices remains low. [1-8]

At first glance, the lack of suitable EP devices is unexpected given a relatively high frequency of recent EP small spacecraft investments by NASA (National Aeronautics and Space Administration), the DoD (Department of Defense), and industry. However, these investments are largely associated with the surge in development of nano-satellites (i.e., CubeSats), which began in 1999 with the creation of the CubeSat specification through a joint venture between California Polytechnic State University (Cal Poly) and Stanford University. The CubeSat specification provides a structured approach to small satellite development and launch, which promotes a low-cost, hands-on learning experience towards designing, manufacturing, testing, and flying spacecraft. CubeSat programs throughout the world are proving fruitful in cultivating the next generation of aerospace engineers, just as university programs such as Formula SAE have for decades successfully cultivated engineers for the automotive industry.

Unfortunately, the promise and appeal of small satellites — namely lower cost and quicker turnaround — are somewhat tempered by significantly higher risks and failure rates associated with minimal expectations for qualification of devices targeting the CubeSat market. A higher level of risk may be perfectly acceptable for some purposes, including student learning opportunities, high-volume commercial concepts, and new technology demonstrations. However, for a growing subset of small spacecraft missions — where the scientific data or commercial service from the payload is the primary objective and the small spacecraft is not readily replaceable — a rebalancing of acceptable risk versus cost and schedule is in order. This includes small spacecraft in consideration as secondary payloads on NASA deep-space exploration and science missions — which are typically classified as Small Category 3, Risk Classification D (cat3/classD) missions, NASA's lowest cost and highest risk categories [9-11] — but still have a much lower acceptable risk profile than university CubeSats or other spacecraft flown on NASA's CubeSat Launch Initiative. In other words, EP and other systems largely being developed for CubeSats and other small satellites with the taught expectation that high risk is generally acceptable is resulting in many devices which do not meet a minimum expectation of engineering rigor for missions, including appropriate qualification testing.

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A number of reviews of spacecraft failures, including ones focused on CubeSats and small spacecraft, have been conducted in recent years and shed some light on potential causes and areas of failure. Propulsion systems and electrical systems, both inherently tied to EP, are two of the highest failure areas noted. [12-13] In addition, failures of the propulsion system typically lead to a hard failure — that is, a major degradation of spacecraft functionality that often lead to loss of mission — contrasted with soft failures (e.g., failure of a reaction wheel or gyro) that do not directly lead to loss of mission. [14] Thus it is imperative that new small spacecraft EP technologies and hardware undergo sufficient qualification activities to reduce these failures. Additional investigation of secondary payload and small spacecraft failures have noted that these failures have been disproportionately experienced as "infant mortality" failures and encountered by relatively inexperienced developers. [15-16] Speculation for these differences point out lack of best practices in design and qualification, inadequate testing, and inherent small mass / volume constraints among potential driving causes.

The main question addressed in this paper, then, is what minimum set of qualification activities are necessary for a new EP device developed with an eye for NASA cat3/classD missions (hereafter referred to as "Class-D" missions), such that a minimum body of evidence exists to assess a technology's readiness and appropriateness for a given mission. The guidelines outlined later in the paper are recommendations to avoid recurring issues and common pitfalls based on past experience in qualifying electric propulsion subsystems for spaceflight. It should be emphasized that these recommendations are merely a minimum floor — that is, if not met, then there may be red flags that indicate inadequate technology maturity and readiness level. Beyond these recommendations, further requirements and delta qualifications will almost certainly be levied by the mission and will need to be accounted for. In addition, it would be expected that other lower-level engineering development testing and analyses have already been performed prior to implementing the activities recommended here.

NASA evaluators for secondary payloads with EP have two main areas of concern. First and foremost is to minimize the risk of impacting the primary exploration or science mission via a propulsion loss of control, plume impingement or contamination, and end-of-life disposal (with respect to any orbital debris and/or planetary protection requirements). The second goal — which is also shared by the secondary payload mission primary investigator (PI) and spacecraft bus vendor / integrator — is to have a reasonable expectation of accomplishing the mission objectives of the secondary payload. This entails ensuring sufficient device life and performance while minimizing negative interactions with the rest of the small spacecraft. On the other hand, in the case of a technology push, rather than mission pull as described above, these guidelines provide a minimum level of expectation for EP technology developers to appropriately plan for subsystem qualification for a given NASA Class-D mission.

This paper, with a preliminary set of recommended guidelines and best practices, is intended to initiate a dialogue with the smallsat community regarding smallsat EP qualification. Future updates of this paper intends to incorporate feedback from other NASA centers, government agencies, industry, and academia to maximize utility for the community.

General Qualification Process Overview and Recommendations

Qualification Entrance Criteria

An EP subsystem will need to achieve a certain level of development maturity before it should even consider undergoing a qualification process. Perhaps one of the most important yet all too often neglected aspect is the identification of customers and the establishment of well-formed requirements. Qualification of spaceflight hardware is not a one-time event or process, nor does it produce a generic and broadly applicable result. Qualification is a very tailored and specific verification of a particular set of requirements provided by an identified customer and defined mission. The customers may be a combination of the spacecraft bus integrator, the mission principal investigator team, and/or the NASA directorate the mission is provisioned under. The requirements will be driven by specific mission objectives, concept of operations, spacecraft integration needs, and environmental constraints. Without a given mission and customer, the requirements will necessarily be vague or rough estimate placeholders, and portions will likely be insufficient or inapplicable for future missions.

That being said, it is understood for EP subsystem developers and vendors that a certain level of technology push is required before it can be considered for a mission pull that can provide specific requirements. A market

survey is strongly recommended to understand the situations and scenarios for which the particular EP technology is competitive as a propulsive option, as well as to understand the resulting basic needs (e.g., performance, reliability and life, integration, environments, etc.) that need to be addressed. Corresponding design reference missions (DRM) can be formulated to generate a set of target requirements to meet to advance the relative technology readiness level (TRL) of the given device. [17] However, it should be made very clear that even if the hardware is "qualified" to those generic requirements, it is to be expected a fair amount of re-qualification or delta qualification activities may be required to meet later customer- and mission-specific requirements. This holds even for EP subsystems that have successfully flown for one spacecraft or mission; a delta qualification process will still in all likelihood be necessary for a different mission.

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 likely require substantial additional delta qualification activities for an actual manifested mission.*

It is expected prior to commencing subsystem qualification activities that a sufficient level of design refinement and development has been already met. This includes meeting basic spaceflight hardware guidelines regarding approved and prohibited materials selection, process development, fasteners and welding implementation, range safety considerations, and electrical, electronic, and electromechanical (EEE) parts derating to name just a few. [18-20] These documents are based on decades of spaceflight hardware experience, and common mistakes and potential pitfalls can be averted early in the process by incorporating these practices during the transition from a laboratory unit into a more flight-like design and packaging. It should be noted that the various standards are just a starting point, and a thorough and careful evaluation of the EP subsystem — typically with a critical design review (CDR) presented to a panel of experienced personnel including systems and safety engineers, mission or spacecraft customers, and other impartial third parties — should be performed to ensure the system design is sound for spaceflight and likely to pass the subsequent qualification activities. The propulsion technology should also be at TRL 5 (as applied to micro-propulsion systems) to be ready for qualification activities. [17]

One perhaps common pitfall is assuming a successful demonstration flight (i.e., "skipping" the TRL 6 gate to reach TRL 7) assures the hardware is qualified for all future flights. While successful operation in space is certainly attractive from an advertising standpoint and may even partially buy down some risks, there is no guarantee that one successful flight will lead to another. A one-off demonstration, with limited telemetry on thruster condition, performance, and life, offers little assurance that the hardware will also be successful for a different mission. The purpose of a proper qualification program is to rigorously push the hardware beyond the expected imposed limits such that probability of mission success is maximized, 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.*

Along with prior development and design reviews, successful qualification practices have typically implemented some form of qualification planning, reporting, and review processes. Formal deliverable documentation of a plan, data package, and reports along with establishment of a standing and independent review board to oversee these activities are not strictly necessary within the confines of Class-D missions. [11] However, even if informal, these are basic concepts (i.e., have a plan, document methods and results, and invite others to review) that go a long way towards ensuring no major gaps or misses are inherent in the qualification process. A high-level qualification plan can perhaps be merged into the overall project plan documentation or set aside as an informal document. The actual qualification test setup, data collection methods, and processed data should be documented in some form as general good test procedures. Reviews of the qualification plan and of the qualification status at key milestones can help ensure the qualification process is fundamentally sound and provide confidence that the EP subsystem will be able to meet the mission requirements. Some level of independent review of the subsystem qualification should be performed to ensure the qualification approach, procedures, and results are satisfactory. It is strongly recommended that the mission customers be included as reviewers to ensure their needs are being addressed adequately, but valuable insight can be

obtained from additional reviews from the spacecraft bus integrator, EP subject matter experts, and other independent peers.

Recommendation 3: *Though perhaps not required as formal deliverables, a qualification plan, a 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.*

In addition to documentation specific to the qualification process itself, additional documentation is typically required of spaceflight hardware — for example, contamination control plan, parts / materials / processes, safety, reliability analysis, etc. It is recommended that the mission customer determine which content and documents need to be explicitly generated, but general guidance regarding NASA Class-D missions is that documentation can be merged and tailored to reduce documentation and configuration management burden. [11] While it is acknowledged that documentation can become an onerous process, the practice ensures at least some coverage of the multitude of aspects that can potentially endanger a spaceflight mission if not considered.

Qualification Philosophy

Before the details of the specifics of qualification activities can be delved into, a few items regarding an overall qualification approach philosophy for the mission and technology should be discussed. For example, what qualification strategy will be acceptable for the mission? Typically, two primary approaches have been pursued at NASA: prototype vs protoflight qualification hardware and test levels. In NASA parlance, prototype is flight-like hardware (but will not be flown) that is tested to full qualification levels and durations while protoflight is hardware intended for actual flight and tested to typically qualification levels, but for reduced durations. [20-24] As will be a recurring theme throughout this paper, there can be much tailoring involved depending on specific mission needs, technology concerns, and cost / schedule constraints. Examples include performing qualification tests on engineering models instead of flight production prototypes, or qualifying protoflight hardware with reduced levels instead of, or in addition to, reduced durations. While the full prototype approach provides the least amount of risk, protoflight approaches may not incur a significant jump in the risk posture. [25] It should be noted that this is not a blanket acceptance of protoflight over prototype, but provided proper risk management is in place, protoflight qualification may be an acceptable approach for many smallsat EP subsystems. For prototype qualification, design differences or late changes between the qualification hardware and flight hardware should be avoided. Numerous failures, close call mishaps, and lessons learned have resulted from inadequate qualification and verification of late design changes. As much as possible, a test like you fly (TLYF) philosophy should be followed, and qualification should be performed on as close to flight-like hardware as possible.

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 TLYF and minimize the risk of late design changes.*

Qualification can also occur at various levels of assembly ranging from components to subassemblies to subsystems up to the spacecraft level. In general, qualification at higher levels of assembly reduce risks of flight as all interfaces and integration concerns are included in the qualification activity. However, qualification at lower levels of assembly reduce development risk that could be caught much earlier in the process with less cost and schedule impact. Qualification can and often does occur across multiple levels of assembly to reduce both sets of risk. This paper will not go into a recommendation of qualification activities at lower levels of assembly but will instead focus on the minimum floor of qualification for the EP subsystem, which is defined here to be generally comprised of the thruster head, power processing unit (PPU) and other electronics, and the propellant feed system.

Qualification activities at the integrated assembly level (i.e., how it will be delivered to the customer) is recommended. For tightly integrated EP subsystems, the whole subsystem should be qualified as a unit as the impacts of mechanical, thermal, electrical, and other interfaces should not be ignored. For more loosely coupled EP subsystems (e.g., if power electronics and feed system are well separated from the thruster and each other), then some qualification activities could occur at a sub-assembly level without much additional incurred risk.

Different qualification activities can and should be performed at different levels of assembly as appropriate. For example, system performance should always be measured with an end-to-end EP subsystem setup. Environmental testing could be performed at the sub-assembly level if the various sub-assemblies are not tightly integrated to each other mechanically or thermally. Further specific details will be provided in the following sections. In general, the overarching philosophy behind test setups should be a TLYF approach, where the setup of the hardware is as close to expected flight integrated and environment configuration as possible.

Recommendation 5: *Qualification tests should 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.*

Another aspect of TLYF is the qualification test flow. Typically, a flight unit will first undergo acceptance testing, then encounter the most stressing mechanical environments during launch, then experience stressing thermal environments after deployment, then need to provide mission performance and life. Other qualification tests are usually most applicable after environmental testing while some destructive tests (for a prototype approach) are of course applied at the very end. Various inspections, functional checks, and/or performance mapping may be performed in between various qualification test entries to ensure the EP subsystem passed those steps and to troubleshoot any potential issues that may have arisen.

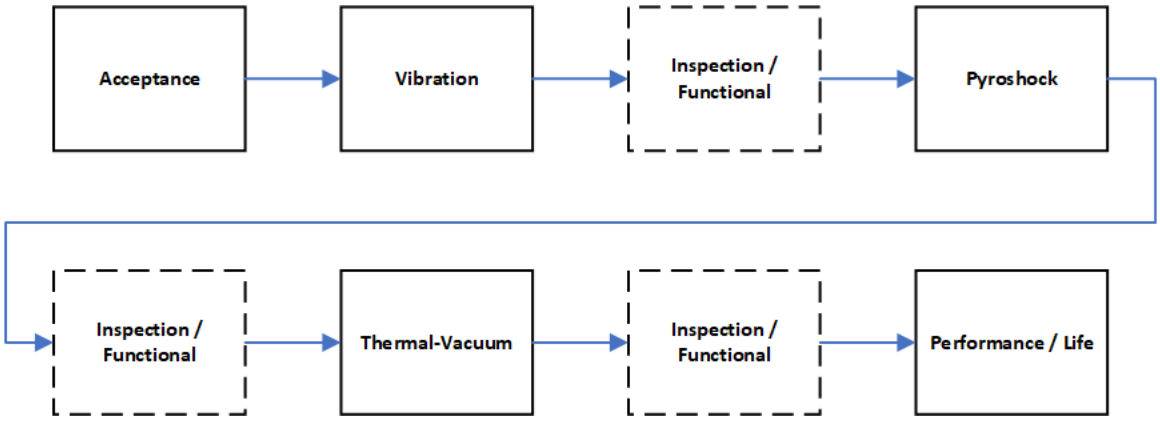

Figure 1: Typical qualification test flow.

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

Finally, the qualification method for each requirement needs to be determined. Qualification of non-trivial requirements are typically addressed via test or analysis approaches. Direct testing to verify a given requirement is typically preferred, but in certain cases tests may be impractical (due to limitations of ground vacuum facilities) or otherwise resource-constrained, making analysis a more attractive solution. The caveat with analyses (and even some tests) is that they can be subject to a number of assumptions and uncertainties that are not appropriately addressed. Analyses will also typically require some anchoring or validation to some level of experimental data to ensure confidence in the results. Specifics of where test versus analysis may be appropriate for smallsat EP qualification are provided in the later sections.

Qualification by similarity or heritage is in essence making the argument that hardware qualified for another flight mission can effectively transfer its qualifications to a different flight mission. Or qualification by similarity may be argued for applying the generic qualification from a technology-push versus the likely requalification needed to meet the well-defined requirements obtained from a mission-pull. However, it cannot be stated strongly enough that there are many nuances involved with the underlying reasoning for qualification by similarity [23,24] and these points need to be clearly and adequately met or addressed; otherwise, qualification by similarity is not recommended, even for Class-D missions. Any claims of heritage need to be assessed against several categories, and even minor deviations from prior design, build, and application only result in partial heritage while any major changes essentially lead to no claimable heritage. [26]

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.*

Table 1: Heritage elements [26]

	Full heritage	**Partial heritage**	**No heritage**
Design	Identical	Minimal modifications	Major modifications
Manufacture	Identical	Limited update of parts and processes necessary	Many updates of parts or processes necessary
Software	Identical	Identical functionality with limited update of software modules (<50%)	Major modifications (≥50%)
Provider	Identical provider and development team	Different however with substantial involvement of original team	Different and minimal or no involvement of original team
Use	Identical	Same interfaces and similar use within a novel overall context	Significantly different from original
Operating Environment	Identical	Within margins of original	Significantly different from original
Prior Use	In operation	Built and successfully ground tested	Not yet successfully ground tested

Electric Propulsion System-Specific Qualification Recommendations

Performance

Performance of the EP subsystem is one of the more salient and evaluated features of technology development and qualification, yet there are aspects of system performance and its verification that are often glossed over. One of the first items to highlight is that it is system-level performance that missions and spacecraft bus vendors are interested in. While it can be very useful to understand the thruster-only or power electronics-only performance, it is often insufficient to extrapolate these lower-level values in assuming end system performance. This is particularly true regarding efficiency metrics, where the impacts of the power electronics and feed system losses on the system-level efficiency are significant. The interfaces and interactions between the various subassemblies can lead to additional performance losses and potentially unexpected effects. In particular, for many smallsat applications where tight volumetric packaging and mass limitations are an issue, these interactions (whether electrical, thermal, fluid, or other) can be exacerbated. At the other extreme for relatively separated systems, long harnessing or propellant piping can also introduce unexpected interactions via changes in electrical inductance or impedance and fluid flow time constants that impact system responsiveness and performance. For all of these reasons, as well as others stated above, it is strongly recommended that performance be qualified at the EP subsystem level. A proper fully integrated subsystem test will also fulfill a functional end-to-end checkout of the system.

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.*

A rich heritage of EP performance measurement techniques, primarily of the thrust and mass flow rate which are then used to calculate the specific impulse (I_{sp}) and efficiency, have been accrued over the years by the community. The best practices for these performance measurements have been recently distilled into a series of recommendation publications. [27,28] It is acknowledged that these recommendations are focused

more on the pendulum-style thrust stands and for gaseous propellant flow meters, so some tailoring will be required for EP technologies where these methods are not appropriate. However, the focus on proper calibration along with consideration and mitigation of sources of error is generally applicable to any approach and should be assessed if the direct details of the referenced standards do not apply.

In addition, it is strongly recommended that thrust and propellant use be measured via direct means instead of indirect methods or analysis. Estimations of thrust via measurements made in the plume downstream of the thruster are typically inadequate for qualification purposes. If a strong and robust correlation between direct thrust measurements and beam parameters is demonstrated and verified, perhaps that may be deemed suitable for acceptance testing or later delta-qualification via similarity, but again the recommendation here is that performance parameters should be measured by direct means for qualification.

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.*

Depending on the nature of the technology and its intended application, the specific measures of performance may vary. For example, for pulsed thruster technologies, measurement of the impulse bit will be of high priority. Variations of steady-state thrust and I_{sp} or the impulse bit over different time scales may also be of particular interest. These may include pulse repeatability or discharge instabilities at short time scales, changes with thermal conditions over intermediate time scales, and degradation with thruster wear over longer time scales. For many technologies and missions, determination of the thrust vector, swirl or roll torque, and their transient and steady-state behaviors may also be key parameters to quantify. The measurement methods for some of these parameters are still not well established and are an active area of research and development. The qualification effort will still need to determine how to best demonstrate performance over these parameters as dictated by the mission requirement needs.

In addition, there are a number of known ground facility effects on EP device performance. Vacuum chambers provide limitations on true space-like conditions through a finite background pressure and conducting surface interactions. These factors, and perhaps even thermal or gravitational considerations, may affect prediction of in-space operation and performance. It is recommended that these factors be considered prior to qualification and are well characterized and accounted for, designed out, or otherwise mitigated during qualification.

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.*

Reliability and Life

System reliability and life capability are difficult parameters to fully characterize and qualify. Since there are always known and unknown uncertainties inherent in systems affecting failure outcomes, the ideal proper approach would be to embark on a large sample size statistical assessment of life and reliability. However, that is almost always infeasible in the small-scale, low-volume, high-expense realm of spaceflight hardware. Electric propulsion compounds this further by typically requiring duration or throughput requirements that are impractical to fully test even once, let alone multiple times. Thus, life and reliability qualification will always require a compromise of some nature.

A failure modes, effects, and analysis (FMEA) or its variations is a common approach in starting to address system failures. At its core, the FMEA attempts to explore potential failure mechanisms and life-limiting parameters, understand their likelihood and consequences, and generate mitigation options for addressing them. Even an informal FMEA (again, third party reviews and feedback are always strongly encouraged to prevent blind spots) can help anticipate a number of failure modes and address them via design, operation, or alternative mitigation means. It is expected that most of the anticipated failure modes would have been characterized and designed out or minimized during the development phase. Life qualification efforts will then

ensure the flight design can meet its requirements. Again as a reminder, the life requirements can vary significantly from mission to mission, and delta qualification will likely be necessary for different mission requirements.

For the thruster, a life or an extended wear test is the most direct approach to addressing these requirements. However, as stated above, a single test will not fully demonstrate life, but only provide a single data point in the life and reliability distribution. The true strength in a life or wear test is to discover unanticipated failure mechanisms or wear rates and to characterize how the failures occur. Assessment of life by analysis or modeling alone will not capture these previously unknown effects. Since uncovering new failures is undesirable at a qualification stage, preliminary life or wear tests should be done prior to qualification during development to understand the primary failure modes and to establish analysis models to project life under different conditions. Depending on the configuration and outcome of the development wear testing, qualification efforts may require additional life or wear testing or may proceed primarily on analysis results (anchored by the prior testing) at this point. Life qualification by test alone is limited by number of data points as stated above, but also due to facility interactions such as backsputter that can compound the results of the life test. As with other testing, adhering to a TLYF approach as close as possible will produce the most relevant results. Further discussion and recommendations on EP thruster life qualification are available in published literature. [29] Though the referenced publication is targeted more towards NASA Class A or B missions, most of the general guidelines and philosophy behind life qualification are applicable to any level, and ultimately the customer and mission will drive the specifics of what is necessary and sufficient.

Unless the mission required life is substantially below the expected thruster life, a protoflight approach will generally be infeasible. A dedicated flight-like qualification prototype unit is the most straightforward, but life testing on an engineering unit (not quite flight-like) may still be applicable provided any design differences between the engineering unit and flight design have negligible impact on the failure modes. Any design changes that have a potential impact on the life or failure mechanisms should have a follow-on life or wear testing to ensure the flight design can meet the mission needs. Similarly, qualification for a different mission with new life requirements — perhaps with total throughput or cycles, but also considering different throttling profiles and mission imposed stresses — will likely necessitate a revision of the life analysis and potentially require a delta life or wear test as well. As discussed above, should qualification by similarity from one mission to another be pursued, the assessment should ensure all the various nuances involved with similarity arguments are sufficiently addressed to the customer.

Recommendation 11: *A life or extended wear test should be performed 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.*

For PPUs and other electronics, generation of a FMEA and implementation of proper design and selection of components is generally suitable for ensuring life and reliability. During the design and development phase, selection of radiation-hardened components properly derated for both steady-state and transient conditions will contribute the most to electronics life and reliability. Tests while integrated with the rest of the EP subsystem, such as during performance qualification, can cover the stressing corners of the operational envelope to confirm successful operation across all expected conditions. Specific voltage / temperature margin testing can also be performed to specifically assess operation of the electronics at worst-case voltages (with a nominal margin) at high and low test temperatures. A burn-in test, also sometimes combined with or partially covered by a thermal-vacuum test, is recommended to capture infant mortality issues arising from material or workmanship defects. Further qualification by analysis can be performed via a reliability assessment of the electronic components and thermal cycle fatigue analysis of critical solder joints as determined necessary by the customer. [30]

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

Life qualification needs for propellant feed systems can vary dramatically depending on the nature of the propellant and feed system. Component-level cyclic life testing of valve actuations may be the most common item of concern for gaseous and liquid propellant feed systems. EP technologies utilizing a phase change (sublimation or vaporization) of a propellant may need to consider specific thermal and pressure cycling tests. Use of solid or liquid propellants may also need to consider tank expulsion testing (e.g., for liquid acquisition

or propellant management devices, diaphragm or piston tanks, etc.) to ensure total throughput can be reliably met. Typical qualification for propellant feed systems and the integrated EP subsystem will also require leak testing for all wetted surfaces and proof pressure testing for storage and other sealable sections of the feed system.

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

Interfaces and Interactions

For flight integration, a number of interfaces between the EP subsystem and the spacecraft need to be properly assessed and verified. The thermal interface is an often neglected aspect of spacecraft integration, yet can have significant impacts on accommodation and operation. Typically a spacecraft will impose a temperature and/or waste heat interface requirement that will need to be verified. The waste heat from PPU operation, thermal soak back from thruster operation, or heating for propellant management will need to be assessed. If heat rejection to the spacecraft exceeds limits, there will be subsequent impacts to the EP subsystem to otherwise handle excess heat or accommodate additional implementation of thermal control schemes. Qualification of thermal interface requirements can be verified by analysis and models, where the models are anchored to thermal vacuum testing. Implementing flight-like thermal interfaces during thermal vacuum testing is recommended to better capture these potential issues.

Electrical interfaces for EP subsystems are another area of integration concern. The grounding architecture of the EP subsystem electrical circuit relative to the spacecraft should be implemented during ground testing as much as possible. Any non-flight-like electrical interactions between the thruster, plume, and ground facility — which may not be completely avoidable in most configurations — may introduce errors in the characterization of system operation, performance, and interactions.

For the PPU, the input electrical interfaces should be verified to accommodate the spacecraft power buses required for operation and their respective voltage ranges, which are often unregulated. Various operational response parameters such as maximum and no-load power draws, in-rush currents, and fault handling (e.g., under-voltage droop) also need to be verified. For EP subsystems with integrated control software, the corresponding interfaces should be fully developed and verified. Algorithms for basic operation (e.g., ignition, pulsing, throttling, etc.) need to be tested to ensure repeatable and reliable operation. Any fault detection, mitigation steps, system safing, and recovery sequences should be thoroughly vetted.

Recommendation 14: *Flight-like thermal, electrical, and control / software interfaces should be implemented and monitored during qualification of the EP subsystem to prevent unanticipated integration issues.*

Electromagnetic interference (EMI) and compatibility (EMC) tests are standard for most electrical and electronic devices. With smallsats, the power level of EP devices will generally be low and perhaps the EMI noise will also correspondingly be low, but it is likely the communication systems will also be low power with lower link margins available as well. It will need to be determined at a system or spacecraft-level what tests will be necessary for which devices. It would be expected that the PPU and other power electronics for the EP system will be tested as standard for spaceflight electrical and electronic hardware; however, EMI/EMC testing at the EP subsystem-level may need to be specially addressed as that will require unique facilities that can provide sufficient pumping speed for thruster operation while not interfering with EMI/EMC measurements. [31] The requirements may also need to be specifically evaluated as the EMI noise from EP device operation in these special ground facilities can often exceed the standard MIL-STD-461 baselines. This has been observed with steady-state operation EP technologies, but special consideration should also be given to pulsed and microwave or radio-frequency EP technologies as their electromagnetic noise characteristics can be significantly different than steady-state direct current devices.

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.*

Though not typically considered a direct part of EP subsystem qualification, characterization of plume interactions is a critical aspect of spacecraft integration and mission evaluation. One primary concern is plume

impingement on spacecraft surfaces leading to either erosive wear or deposition contamination. The deposition can be of the propellant itself (particularly condensable or conductive propellants), eroded thruster materials, or eroded spacecraft materials. Another item of concern is spacecraft charging and how the plume environment affects and is affected by thruster and spacecraft surfaces at various potentials. Finally, measurements and characterization of the plume can also provide indirect estimates of thruster performance parameters, thrust vector, and any impingement-imparted momentum fluxes.

Use of witness plates and other contamination or erosion sensors (e.g., quartz crystal microbalances) can provide data on plume impacts with specific materials, surfaces, and geometries. Plume modeling analyses will likely require measures of the plasma parameters themselves. With respect to sputtering and deposition, characterization of the fluxes, energies, and incidence angles for each ion species will be important to project plume interactions to future spacecraft and mission designs. For spacecraft charging, the various plasma currents, potentials, and temperatures will need to be known to estimate how the plume interacts electrically with the spacecraft and/or ground facility. Various standards for EP plume plasma parameter measurements are available to guide best practices in making these measurements. [32]

As noted above for other parameters, facility effects will also impact the plume behavior and characteristics, and care should be taken to translate ground measurements to in-space predictions. Facility backsputter contamination can affect erosion and deposition measurements. Charge exchange collisions can be significantly enhanced in ground vacuum chambers, and facility electrical interactions can also strongly affect the nature of the plume and the resultant current paths for ions and electrons. Depending on the technology, studies to vary the facility pressure or to vary the electrical environment may be needed to generate confidence for in-space operation.

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.*

Environments

Structural and thermal environments are some of the primary concerns for spaceflight hardware qualification. The specific environments, along with their levels and extremes, can vary significantly between different missions, operations, interfaces, spacecraft, and launch vehicles. Attempting to apply a worst-case envelope for all potential scenarios is typically too difficult to meet or even derive. The best approach, as stated before, is to obtain specific requirements from a specific mission customer with a known launch vehicle and spacecraft bus. Attempting to "qualify" to a generic set of requirements will likely result in unusable results for a future mission, necessitating delta-qualification. One pitfall is targeting or modifying a design to meet the generic load levels, which is then found insufficient for later realized load levels, necessitating a costly and consequential redesign. However, environmental testing to a set of generic levels will be useful at a development-level to identify weak points in the hardware design and at least establish an initial level of confidence in the hardware's ability to potentially meet future environments and loads. Testing early and often will also help provide inputs and correlation for the structural and thermal models of the hardware. It is worth repeating that structural and thermal testing without defined mission-specific environments and loads requirements will be insufficient from a qualification perspective. It should also be noted that a prime objective of most environmental testing is to anchor the corresponding analysis models, which then need to ensure positive margins. Testing alone may be insufficient qualification for some environmental concerns.

There are a number of potential structural environments that need to be assessed depending on the launch vehicle, spacecraft interfaces, and the load path to the EP subsystem. Typical dynamic environments to consider are sinusoidal, acoustic, and random vibrations generated from the launch event and shock spectra generated from separation events. Sine vibration testing covers low-frequency vibrations generated by launch. Not all launch vehicles will have severe sine vibration environments, and this test may be omitted for such missions. Acoustic and random vibrations are generated by the interactions of the launch vehicle as it transits through the atmosphere. Typically, only one or the other is tested for a given unit or subsystem — whichever one is expected to provoke a stronger response for the hardware. Hardware with a large area-to-mass ratio are more susceptible to acoustic environments while hardware with a low area-to-mass ratio are impacted more from random vibration loads. Most smallsat EP subsystems would be expected to fall under the latter, but this should be determined on a case-by-case basis. Shock loads encompass the high-frequency vibrations typically generated by the various pyrotechnic devices used to separate stages, fairings, spacecraft, or other deployment

mechanisms. In addition to the above dynamic loads, there will also be quasi-static loads and an imposed pressure profile from the launch environment that may need to be included in the verification. The qualification of hardware for launch environments requires a combination of test and analysis, the latter typically with finite-element analysis software. Outside of launch environments, proper verification of deployment mechanisms operation and process is another concern if present.

Testing for random vibration environments is typically one of the more acknowledged concerns for spacecraft qualification, and there is always present the question of what level of load spectra to apply for qualification. Despite all of the warnings and caveats discussed earlier in this section, in many instances mission-specific load levels are not available for qualification of a technology. There are a few general guidelines perhaps available in this case, none of them completely satisfactory, but testing early and often will help identify potential weak points in the design to reduce the amount of any anticipated rework during true qualification (or delta qualification) activities. Before even loads are applied, a modal survey or sinusoidal sweep can help partially validate the dynamic model of the system through identification of resonant frequencies and modes. Workmanship levels of vibration provide a minimum screening test to identify any flaws in the design or assembly. The Goddard Space Flight Center's General Environmental Verification Standard (GEVS) also provides a set of load spectra at higher levels that can be used without any other information available, though they may still be insufficient for specific missions. [33] Mass acceleration curves (MAC) for various launch vehicles may provide a better sense of overall load levels, especially for lightweight components and assemblies.

Apart from the primary structural and thermal environments, there may be additional environmental concerns. These may include, for example, humidity and contamination environments. Many EP technologies and devices have materials, components, or propellants that are susceptible to degradation due to water vapor absorption or condensation, or from other chemically-reactive contaminants. Corrosion, also including aspects of galvanic and stress corrosion cracking, is another potential issue particularly for seaside launch environments. Smallsat devices, due to their smaller nature, may also be especially susceptible to physical (e.g., dust particles, debris, etc.) contamination clogging small orifices and passageways. Conductive contamination, perhaps from facility backsputter deposition during protoflight or acceptance testing, can degrade electrical isolation. Proper contamination control or cleaning processes (both internal and external) may need to be considered for these EP subsystems.

Smallsat missions may encounter longer than anticipated delays to launch as their participation as a rideshare is subject to delays from higher-priority launch payloads and issues. As a result, sufficient storage life capability may be important to demonstrate. In addition to contamination concerns, propellant leakage or stability may also be a point of concern. As a result of these considerable impacts, proper storage, handling, and conditioning environments will need to be considered and either tested against or planned for. Qualification tests or analyses may be required to ensure these other environmental concerns are not a significant issue.

Conclusions

This paper proffers a preliminary set of recommended guidelines and best practices in dialogue with the smallsat community to strike a better balance between engineering rigor and cost effectiveness for the qualification of EP technologies under consideration for NASA small spacecraft. Feedback from the smallsat community is highly encouraged to support future updates of this paper.

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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