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Mission Assurance Implications of Space Vehicle (SV) Thermal Vacuum Retest

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This document has been produced as a collaborative effort of the Mission Assurance Improvement Workshop. The forum was organized to enhance mission assurance processes and supporting disciplines through collaboration between industry and government across the U.S. space program community utilizing an issue-based approach. The process is to engage the appropriate subject matter experts to share best practices across the community in order to produce valuable mission assurance guidance documentation.

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Executive Summary

The decision to retest a space vehicle in a system level thermal vacuum will, in most cases, incur significant impact to a program's cost and schedule, and may impact the vehicle's mission life reliability. Despite the consequences of such testing, it is sometimes necessary to re-verify the workmanship associated with removing, reworking/repairing, and replacing flight hardware following an initial vehicle thermal vacuum test. The study was conducted to evaluate the technical risks associated with conducting a vehicle thermal vacuum test by:

- Assessing the decision process for a space vehicle (SV) thermal vacuum retest used by industry.
- Determining the technical rationale used for conducting a SV thermal vacuum retest.
- Identifying risks associated with retesting (and not retesting).
- Comparing government and commercial SV thermal vacuum retest decision processes.
- Measuring the test effectiveness of the SV thermal vacuum retest.

The team that compiled this report developed a list of 16 technical considerations that should be assessed during the retest decision process to address and quantify associated risks. Data collected from 350 space vehicles across 6 major aerospace contractors with thermal vacuum tests between 2000 and 2016 was obtained and the results indicated that overall, 41 space vehicles (12 percent) were retested following the initial thermal vacuum test environment. The percentage was higher (18 percent) for government U.S. Department of Defense (DOD) space programs than for commercial programs (11 percent), with the lowest rate observed for government civil programs (5 percent). The primary reasons for retesting were anomalies in the initial thermal vacuum test associated with unit workmanship and subsystem interfaces. Retests detected significantly fewer defects than the initial SV thermal vacuum test with less than one failure per retest. It should be noted that the focus of this study was on SVs that were retested; the on-orbit success of SVs with post-thermal vacuum test rework/repair that were not retested was not explored.

Key recommendations from this report are:

- Center thermal vacuum retest decision process on technical risk using the 16 industry-defined considerations to quantify and potentially mitigate risk, including alternative verification methods in lieu of a full SV thermal vacuum retest

- Establish risk assessments though existing board reviews (e.g., failure review boards, program review boards) to ensure completeness of the decision process

- Ensure rigorous unit-level thermal testing to reduce the number of unit-level defect escapes

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1. Introduction

1.1 Background and Problem Statement

Space vehicle (SV) level environmental thermal vacuum retesting is sometimes necessary following an initial thermal vacuum test for the purpose of verifying workmanship rework/repair and re-integration, and demonstrating mission performance requirements. There may also be contractual retest requirements to retest space flight hardware in the test environment where the failure occurred.

A consequence of thermal vacuum retesting is that it will significantly impact the space program development. It adds cost and critical path schedule in SV assembly, integration and test (AI&T) and it has the potential to reduce the useful life of the flight hardware.

A recent study performed for 29 national security SVs showed that the SV thermal vacuum retest rate is as high as 38 percent, with some SVs seeing multiple retests [3]. Recognizing that the topic is applicable industry wide, a Mission Assurance Improvement Workshop (MAIW) team was assembled to better understand the thermal vacuum retest topic and its underlying causes. With decreasing government budgets and a need to be more efficient in AI&T, the team investigated the process of determining when a SV thermal vacuum retest is warranted, the technical considerations that are part of the decision process and successful alternative approaches employed in lieu of a SV thermal vacuum retest. Acknowledging the substantial commitment of resources required to subject the SV to a thermal vacuum test, there is significant benefit in providing a framework and a set of historical industry-defined technical considerations to assess the risk of subjecting or not subjecting the SV to a thermal vacuum retest. The goal of this report is to assemble the SV thermal vacuum industry retest knowledge, spanning six SV prime contractors, focusing on SV thermal vacuum retest decision making, the associated considerations and criteria used, and provide guidance on how risks may potentially be mitigated.

The team's charter was to provide the community with a consolidated report on how to technically assess the implications of SV thermal vacuum retesting. Specifically, this report:

1. Discusses the technical rationale on why SV thermal vacuum retests occur and are warranted
2. Identifies post-thermal vacuum SV rework/repair risk mitigation methodologies including alternate methods other than SV thermal vacuum retesting
3. Compares government (civil and DOD) and commercial experiences, decision processes and approaches for SV thermal vacuum retesting
4. Quantifies the test effectiveness of the SV thermal vacuum retesting

This report is intended to discuss these four areas and provide guidance for the decision process in addressing risks associated with SV thermal vacuum retesting and not retesting. Alternative approaches to the SV thermal vacuum retest will also be discussed. The effort was divided into two tasks:

1. Understanding current thermal vacuum retest decision processes used in industry and the risk associated with thermal vacuum retesting
2. Gathering data from recent thermal vacuum tests to better understand the reasons for SV thermal vacuum retesting and the test effectiveness of the retesting

The team decided, based upon the relevancy and ability to obtain a statistically significant same size, to define the dataset as SV thermal vacuum tests between 2000 and 2016, and categorized as Class A or Class B missions [4]. Such vehicles are characterized as low mission risk vehicles with critical national significances, relatively high acquisition costs and mission lives greater than five years (typically greater than eight years).

Toward this end, the following four questions were the focus of the team:

1. What quantity and percentage of SVs were thermal vacuum retested across USG-DOD, USG-civil and commercial space programs?

2. What were the primary reasons these SVs were retested?

3. What considerations were used in the SV thermal vacuum retest decision approach?

4. What were the results of the SV thermal vacuum retests?

It is envisioned that this report will be used by customer and contractor program office managers and test teams to help formulate discussions regarding the implications and risks associated with not retesting based upon technical arguments with supporting test and heritage data.

The report summarizes data and experiences from several community-based organizations. To provide these findings for public release, it was necessary to delete specific SV and program names, and delete naming individual organizations, other than the general acknowledgement of contribution to the study.

1.2 Purpose of Thermal Vacuum Testing and Retesting

A SV thermal vacuum test demonstrates the ability of the vehicle to meet mission performance requirements under thermal vacuum conditions and temperature extremes. For a qualification or protoqualification vehicle, the thermal vacuum test demonstrates design requirements and establishes the design margin and vehicle performance. This includes verification of the SV's thermal design in thermal balance testing. (For this study, protoflight and protoqualification are used interchangeably.) For an acceptance vehicle, the thermal vacuum test demonstrates the ability to withstand the kind of thermal stressing environment expected in flight and meet performance requirements with margin. It also detects material, process, and workmanship defects associated with thermal vacuum and thermal stress conditions.

In the SV thermal vacuum test, functional and performance tests are conducted at hot and cold temperatures in the vacuum environment. It is common for large SVs to require more than 50 days in vacuum to complete a four-cycle SV thermal vacuum test. With its long durations in performance testing, there is ample opportunity to detect anomalies in this test. An earlier study of 39 military space vehicles by Wright and Arnheim [5] found that the SV thermal vacuum test detected an average of 4.1 mission degrading failures per satellite. For the "first in the block" satellites, the test detected 6.0 failures per satellite. These findings were recently confirmed by Takahashi and Shi [6] in a study where an average of 4.9 failures were detected in Japanese (JAXA) SV thermal vacuum testing. Given the nature of this test environment to reveal significant mission failures, rework/repair of flight units to some degree will likely occur following every thermal vacuum test, and the question of retesting should be expected.

Retest is the repeat of previously conducted tests due to any rework/repair, subsequent to the initial testing, including redesign, a change in a manufacturing process, test anomalies, an increase in flight environments, piece part or other alert, or a change in requirements resulting in rework/repair of items previously tested. The most common reason for retesting is the result of test discrepancies or anomalies requiring post-test hardware rework/repair. The primary purpose of retest is to verify the rework/repair or the re-integration of the reworked/repaired hardware. Redesign may be the result of a test anomaly or a change in environments, flight application, manufacturing processes, or requirements. In such cases, the redesign is similar to rework/repair following a test discrepancy, but has the additional consideration that the rework/repair may have invalidated previous qualification or protoqualification test results. Full or limited requalification retesting on non-flight hardware may be necessary in such cases. Regarding changes to requirements, if the new requirements exceed the original requirements, then retesting may be conducted to demonstrate adequate margins for the new application. Regardless of the reason, retest has as its primary purpose, the restoration of confidence in the functionality, performance, and flightworthiness of the flight item to meet mission requirements.

1.3 Current Industry Practices and Processes

Failures may occur at any point in space hardware development and when they occur, they can have a significant impact on retesting considerations. When detected early, rework/repair, retest, and reintegration will have the least impact to the program development schedule and cost. When detected at the SV level, the programmatic impact can be significant. When such anomalies occur, a failure analysis is conducted and the anomaly is investigated. Rigorous identification of the root cause is critical in this process. A failure review board (FRB) may be convened to ensure that the anomaly investigation is exhaustive and complete, and that the corrective action is adequately detailed and supports the program's risk posture. Additional tests may be necessary to isolate problems and verify root causes. In many cases, reverifications at lower levels of assembly (e.g., unit level) to verify the rework/repair and performance of the reworked/repaired item will be necessary. This may be in addition to SV-level retest to verify re-integration of the reworked/repaired item and performance of the reworked/repaired item in conjunction with other subsystems.

Retesting of any ground test environment is often the subject of considerable debate primarily due to cost and schedule implications of re-subjecting hardware to a previously tested environment. Besides programmatic considerations, there are technical issues that have considerable impact on the decision process. Despite the significance of the retest decision, the stakeholders rarely agree on the decision approach and process, and the debate can center on subjective risk assessments. When considerations and criteria are applied, the decision process has traditionally followed guidelines discussed in a report written by Hamberg in 1984 [7]. The original set of retest criteria was expanded upon over the years [8], but the central themes discussed by Hamberg remain applicable.

1.3.1 Retest Philosophy Differences between Government and Commercial Programs

With regard to differences between government and commercial customers, the common goal is the same: both groups want the SV to be fully functional and meet its performance requirements. Both entities take a similar risk posture depending on the mission and will approach issues in the same manner. There are, however, inherent differences between government and commercial space programs that will influence the SV thermal vacuum retest decision process.

Government programs tend to be driven by imminent need. There could be a gap in U.S. weather satellites that could degrade forecasts and jeopardize the country's ability to make decisions for military or domestic purposes. Such space programs are commonly unique or of smaller builds. Contractors have made great strides in the use of heritage hardware and common buses and subsystems, but new technologies and complex payloads result in long procurement and AI&T durations. Contracts for such programs are commonly cost-plus and will be firm fixed price only after there is considerable confidence in the development process. Furthermore, government programs are developed to rigidly-held specifications and standards with significant oversight and verification.

In contrast, commercial programs have a different drive for success. A SV in orbit, and at full operational capability, is a revenue stream and return on investment. Commercial programs tend to make higher use of proven technologies and firm fixed price contracts. Commercial SVs are produced on a more production line process, using high heritage of proven designs. Commercial customers will provide oversight, but there is generally less rigidity in the use of contractor's internal specifications and best practices in the development process. Commercial standards tend to be more flexible and fluid in their application of these specifications and requirements.

Approach and rationale may be different, but the overall objective of both government and commercial programs is to have successful programs. This results in similar risk postures when it comes to the SV thermal vacuum retest decision process. A higher use of heritage hardware may be the most significant reason why commercial programs are viewed as less likely to perform a SV thermal vacuum retest, which will be discussed in this report following the assessment of SV thermal vacuum test data.

1.4 Thermal Vacuum Retest Implications

There are several programmatic impacts associated with a space vehicle thermal vacuum retest. Perhaps the most obvious is the cost associated with a retest. The cost is not solely for the retest itself, but also with a schedule slip to the ship date of the vehicle from the factory. For a large national security program, a SV thermal vacuum retest can require six months or more of schedule after all rework/repairs have been completed. Program and contractor recurring costs will vary, but the bottom line is that the cost of a SV thermal vacuum test will be significant, and any penalty fees, commonly associated with commercial contracts, will incur an additional burden to the program.

Another significant impact is the lost-opportunity cost. If a SV thermal vacuum retest is conducted:

- For a commercial vehicle, there may be lost revenue from various customers due to late delivery, or reduced capability.
- For a national security vehicle, the warfighter may not have the necessary improved capabilities.
- For scientific missions, collecting data associated with uniquely-timed events may not be possible.

Although difficult to quantify, these costs may represent a far more important factor than the program costs associated with a schedule slip.

Finally, there are technical impacts with retesting. Ground testing is not a benign environment for flight hardware. While the vehicle will operate at vacuum conditions in flight, the thermal conditions are typically more severe in the vehicle test than seen in flight. The diurnal temperature swings for electronic units mounted internally on low-earth orbit and geosynchronous orbit vehicles are typically about 15°C and 5°C, respectively, while in a thermal vacuum test, the temperature swing from hot to cold conditions may be 50°C or larger.

When an anomaly occurs in the SV thermal vacuum test and rework/repair of a flight item is necessary, the customer's perspective is that the rework/repair process poses many opportunities for things to go wrong. Removal of the reworked/repaired unit may involve handling flight hardware in a confined environment, may require removal of other units to gain access to the unit requiring rework/repair, and may have limited access for quality assurance verifications. The rework/repair of the unit may be the most straight-forward action in the process as the flight item is away from the SV, but there will still be uncertainty about whether the true root cause was identified, whether corrective actions were accomplished correctly, and whether fixing one problem introduced new problems. Re-integration poses the same concerns identified with unit removal, along with the possibility of damaging adjacent flight hardware. These concerns cannot be fully mitigated by analysis, so from the customer's perspective, the only way to fully restore confidence in the flightworthiness of the hardware may be by retesting.

The contractor's perspective may be quite different from that of the customer regarding the need for retesting. While there are risks with unit removal, rework/repair and re-integration, the contractor may feel that these processes are clearly specified and demonstrated with previous or similar removals. The contractor may feel that work-arounds to the root cause adequately meet mission requirements. The contractor may believe that the additional handling of the rework/repair poses the most significant risk to the flight hardware and that additional ground testing incurs undue stresses to the flight hardware beyond flight expectations, consuming valuable life remaining in the hardware. For these reasons, "use-as-is" may seem to be the most reasonable position for preserving the integrity of the flight hardware. The contractor may hold to these assertions even when the customer directs the contractor to perform the test, absorbing the schedule and cost impact of the decision.

It is common for both sides to agree that unit rework/repair needs to be verified before flight and the most efficient means of mitigating rework/repair concerns is by demonstrating functional and performance requirements in unit-level environmental testing prior to re-integration into the SV. The environmental tests conducted will depend upon the rework/repair performed, but typically includes a thermal test. If the original unit-level thermal test included a thermal vacuum test, then the unit-level penalty test is typically a thermal vacuum test. If unit-level thermal testing was thermal cycling only, then it is likely that the penalty test will also be thermal cycling only, unless vacuum was a contributing factor to the anomaly. Random vibration testing is typically included if there is any concern that the rework/repair may have invalidated the confidence gained from the original vibration test. SMC-S-016 (2014) contains minimum unit environmental retest requirements consisting of both random vibration and thermal testing.

Despite the rigor of the unit-level penalty testing, there may still be concerns with the re-integration of the reworked/repaired hardware and whether the reworked/repaired units will meet performance requirements interacting with other subsystem units. The contractor and the customer will discuss remaining concerns and will attempt to quantify the mission risk associated with these concerns. While these concerns are primarily technical in nature, program cost and schedule can be contributing factors and may have significant influence on the final decision. Other programmatic considerations, such as the relative importance of the mission, may also be significant factors in the discussion.

1.5 Defining Space Vehicle Thermal Vacuum Retest

In an effort to clearly specify what constitutes a SV thermal vacuum retest, the following definition is adopted by the team and used throughout this effort:

Space Vehicle Thermal Vacuum Retest	Any unplanned subsequent thermal vacuum exposure of the SV after the initial TV 1 test, specifically driven by SV hardware discrepancies or changes requiring rework/repair, and detected in 1) the previous thermal vacuum exposure, or 2) immediate post-thermal vacuum events (e.g., functional testing or GIDEP alerts).

Therefore, thermal vacuum exposure is a retest if it follows:

- A SV hardware discrepancy, observation, or anomaly in functionality or performance that resulted in rework/repair, where the verification of the rework/repair or reintegration of the hardware is a primary purpose of the subsequent thermal vacuum exposure.

- A SV hardware design or workmanship modification, where the verification of the modification or reintegration of the hardware is a primary purpose of the subsequent thermal vacuum exposure.

A subsequent thermal vacuum exposure is not a retest if it was:

- Planned prior to TV 1 (such as might occur when flight hardware is not present for TV 1).

- The result of rework/repair associated with test equipment or chamber capabilities or performance.

- A continuation of the initial TV 1. For example, if TV 1 is halted after the first cycle to correct a flight hardware or test equipment problem, the continuation of the test for the remaining number of cycles does not constitute a retest. While the test stoppage was the result of an unanticipated discrepancy, the continuation of the test represents meeting original contractual obligations. During the stoppage, there is no question that the test must be restarted, so the test continuation is not a retest.

- Additional penalty cycles as part of the continuation test. For example, if TV 1 was halted in the final cycle of a four-cycle test for hardware rework/repair and restarted to complete the final cycle with additional penalty cycles, the final cycle and penalty cycles do not constitute a retest.

For the purpose of assessing historical data, it was decided that a SV thermal cycle test that is conducted after the initial SV thermal vacuum test is considered a retest in the same manner as a SV thermal vacuum retest is if the SV thermal cycle test is: 1) unplanned (not part of the original contractual program development), and 2) performed with the same objectives as a SV thermal vacuum test, namely the verification of rework/repair and re-installation of flight hardware.

1.6 Environmental Testing Definitions

The following definitions were adopted and used by the team in preparation of this report:

Mission Degrading Failure (MDR)	A failure that results in the permanent loss of redundancy or a permanent reliability decrease and/or that results in the temporary inability of the space vehicle or an operational payload to meets it baseline mission requirements.
Remove and Replace (R&R)	Disassembly of a damaged part or unit from a subsystem or space vehicle for the purpose of rework/repair. Removal becomes necessary because of the potential for hardware damage would be difficult or risky to make the necessary rework/repair in situ.
Space Vehicle (SV)	A space vehicle is an integrated set of subsystems and units, including their software, capable of supporting a specified mission [1].

	Therefore, a SV is not a separate bus, payload, or any subset of either of these two (e.g., equipment panel). For this work, a SV includes any vehicle in which part of its mission is exo-atmospheric.
Test Discrepancy	A test discrepancy is any anomalous or unexpected condition encountered during a test process. Test discrepancies include those associated with performance, functionality, premature operation, or failure to operate [1]. For the purpose of this study, discrepancies, anomalies and failures are used interchangeably.
Unit and Unit Types	A unit is a functional item that is viewed as a complete and separate entity for purposes of manufacturing, maintenance, record keeping, and environmental testing [1]. Unit types are defined Table 6.3-1 of SMC-S-016 (2014) [1] and Aerospace TR-RS-2014-00016 [2]. Hardware rework/repair (R&R) can either be at the unit level or rework/repairs on the SV (examples: rewiring flight heaters, insulation changes, and EMC/EMI taping changes).

2. Retest Assessment Process

In this section, a typical assessment process is described for the SV thermal vacuum retest decision. A primary purpose of this effort is in the development of technical considerations that should be part of the retest decision. A list of considerations is presented and discussed. The section concludes with mitigations and alternative approaches for the SV thermal vacuum retest.

2.1 Background

The building and testing of space flight hardware is a complex process involving many detailed steps in order to provide a high-probability of success for meeting performance requirements over mission life. Testing flight hardware ensures that requirements have been met, demonstrates flightworthiness by detecting and correcting design and workmanship defects, and decreases the overall risk by demonstrating that the hardware functions as-designed. Environmental testing is conducted to verify that the hardware can endure ground, launch, and on-orbit environments with margin, above maximum predicted environment (MPE), and meet all engineering requirements [1].

Anomalies may occur at any point in the qualification or acceptance test sequence of unit or vehicle development. When an anomaly occurs in verification testing, the test may be interrupted and a determination is made as to whether the anomaly is due to a failure of the item under test or a failure of the system performing the test (test setup, software, procedures, human error, or equipment), and the anomaly is documented for evaluation. The operating agency is responsible for assessing the effect of the anomaly and determines whether the anomaly has jeopardized the probable success of the remainder of the test and subsequent flight. Typically, this anomaly investigation is handled by the FRB that is part of every Class A/B program [4].

A representative flow for the decision process is shown in Figure 1. The flowchart represents a retest decision process for the case of anomalies detected in an initial SV thermal vacuum test. Following the SV thermal vacuum test, the anomalies, deficiencies, and observations noted in the test will be reviewed. If there were no anomalies in the SV thermal vacuum test, the program would progress to the next environmental test. If there were anomalies, they would be discussed individually in the review board (e.g., FRB and PRB) with an emphasis on understanding the test data around the anomaly, most likely root cause(s) for the anomaly, planned corrective action, and how the rework/repair will be verified (e.g., analysis, testing). Following the board's decisions, activities will progress along parallel paths. Rework/repair activities will address removing and reworking/repairing units and conducting subsequent acceptance penalty testing on the units to verify the rework/repair. Other tests and analyses may be part of this verification process. In parallel to the rework/repair activity, the need for a SV thermal vacuum retest will be held. Perspectives will be provided by the customer and the contractor (Section 1.4). To assess the inherent risk with the rework/repair activities, technical considerations (Section 2.2) will be discussed. The conclusions from this assessment, along with programmatic considerations (cost, schedule, resource availability, hardware risk, etc.) will lead to the SV thermal vacuum retest decision. The decision may be made by the contractor, may be directed by the customer, or may be a joint decision by the contractor and customer. If the decision is made to not retest, the program will move forward to the next test or to alternative tests that will accomplish the intent of a retest without the thermal vacuum environment. If the decision is made to retest, test planning will commence with the test scoped and procedures written for the test. Following the SV thermal vacuum retest, data will be reviewed to verify that the rework/repair and re-installation was conducted correctly. If anomalies are found in the retest, these will need to be brought back to the board. Otherwise, the program progresses to the next ground test.

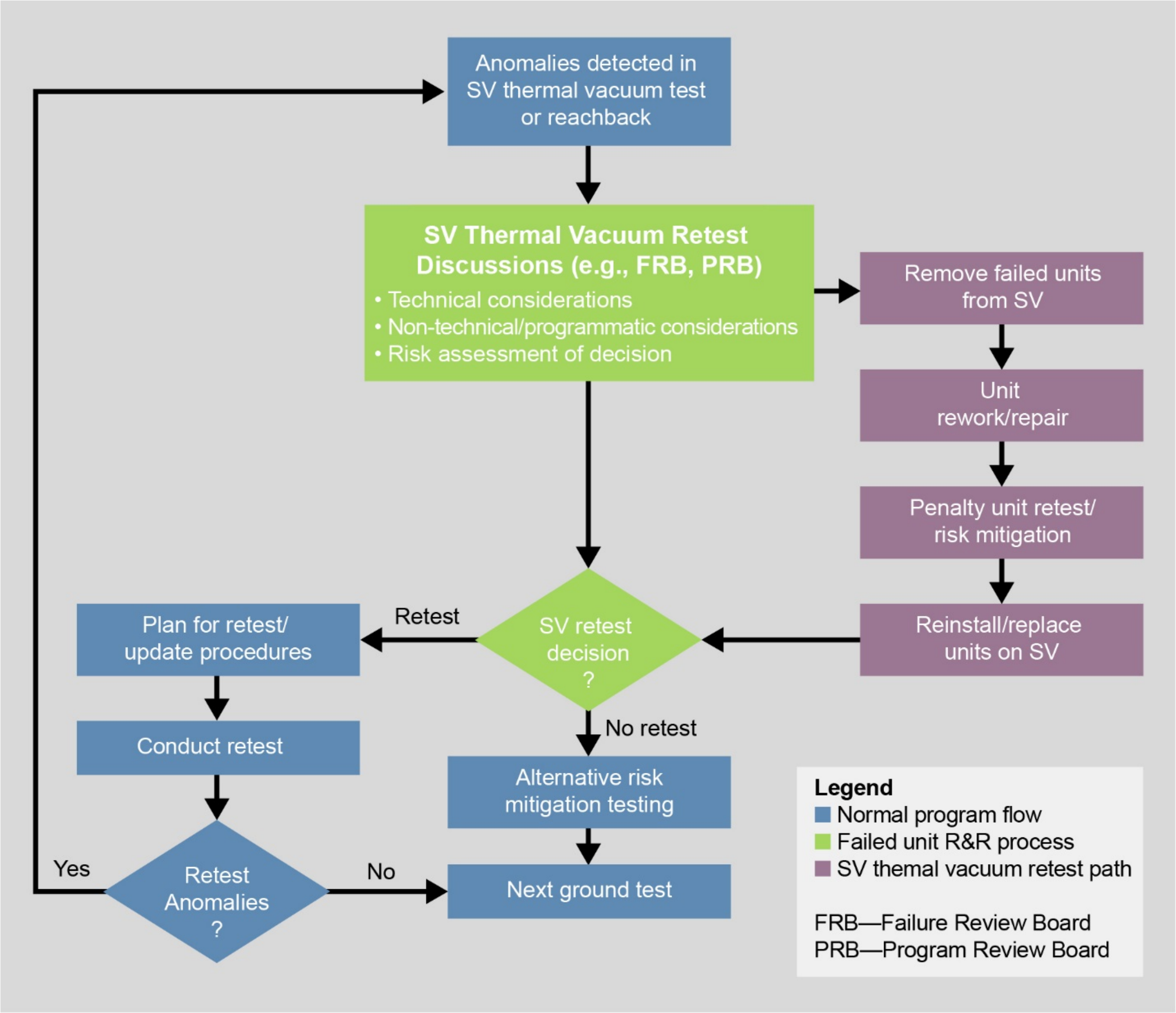

Figure 1. Flowchart of typical space vehicle thermal vacuum retest decision.

2.2 Thermal Vacuum Retest Considerations

Subsequent to the initial SV thermal vacuum test, there are typically items to rework/repair due to either failures that occurred as a result of the test, failures in subsequent tests, post-test design modifications, or reach-back item rework/repair such as parts alerts. The level and degree of intrusiveness and test perceptivity following rework/repair are key factors when evaluating the need or risk of whether or not to subject the SV to another thermal vacuum environmental retest. Below are sixteen collectively defined historical industry issues to consider when performing the thermal vacuum retest risk decision assessment. These items have been mapped to the thermal vacuum retest database to understand the most common considerations for repeating SV thermal vacuum testing and their potential mitigations including alternative approaches to retesting. The sixteen considerations are grouped in five categories.

1. Units Removed and Replaced

    a. <u>Number of Units Removed and Replaced (R&Rs)</u> – This is the number of units that need to be removed and replaced following the SV thermal vacuum test. This is typically one of the most important considerations, because, as the number of removed units increases, so does the chance of a SV thermal vacuum retest. Although there are no specific criteria for the types and quantity of R&R units that requires retesting, this consideration should be identified and evaluated for susceptibility to the thermal vacuum environment. For example, radio frequency (RF) or high power dissipation units should be assessed to evaluate how sufficiently they can be re-verified at ambient conditions. Regression testing of thermal interfaces and other vacuum sensitive installations should be assessed as well as the nature of the original failed item(s). A percentage of R&R units is a useful way to provide an overall assessment of the amount of the vehicle impacted by the rework/repair.

b. Number of Reworks/Repairs – This consideration assesses the level and complexity of the rework/repair necessary of removed hardware. Although there are no specific criteria defining the overall quantity of the total number of reworks/repairs that would lead to retesting, this consideration captures the overall compilation of reworks/repairs performed on the space vehicle. When a unit has a relatively large number of reworks/repairs or the rework/repair is relatively complicated, this may indicate a more thorough verification penalty test program at the unit level and perhaps a contributing factor towards vehicle-level retest.

c. Percentage of the SV touched during the R&R – This consideration assesses the aggregated percentage of the space vehicle disturbed by the rework/repair. The larger the percentage, the greater the likelihood for collateral damage and the greater the need for reverification of mission requirements and interactions between units and subsystems. Implications of “break in configuration” are included here and should track all flight hardware touched and moved during the R&R process.

d. Type of R&R Unit Thermal Interface – The need for a thermal vacuum environment to confirm thermal interface integrity post-rework/repair including ambient characterization perceptivity is evaluated in this consideration. The integrity of the thermal interface during the unit re-integration process for wet-mounted interfaces (e.g., RTV) may depend upon the SV orientation. Vertical mounting of units has a higher likelihood for interface voiding from filler material dripping than horizontal mounting.

e. Power Dissipation/Density – This item considers the power being dissipated and the power density of the unit potentially requiring a thermal vacuum environment to re-verify the integrity of the thermal interface. Units with high power dissipation or power density need conductive thermal interfaces to remove internally generated heat, so these units will require greater confidence that the unit remounting did not compromise the thermal interface integrity.

2. Flight Harnesses and Connectors

   a. Flight Harness Modification/Manipulation/Routing – This assesses the degree that the flight harness has been disturbed due to either modification, or manipulation for access, including connector de-mating and service loop allowances are important considerations. Bend radius exceedances, ESD susceptibility/controls, edges capable of inducing damage and overall flexibility to allow manipulation without incurring damage should be addressed. The ability and degree to which the harness/cabling can be inspected for any induced damage should be included in the evaluation. As a minimum, full copper path functional testing should be performed, including high and low RF power, to provide cable integrity confidence. Thermal levels should also be considered if stressing temperature levels are predicted.

  b. Number of Connectors and Conductors Demated/Remated – The more connectors that need to be demated and remated for rework/repair, the higher the likelihood that a connector will not be connected properly during re-integration. Although there are no specific quantified criteria for the number of connector and conductor remates that would lead to retesting, the total quantity of connectors/conductors disconnected/reconnected should be evaluated including any potential thermal vacuum environmental susceptibility.

  c. Type of Connectors Demated/Remated for Each Unit – Type of connectors demated/remated should be evaluated for the potential to introduce a latent defect. Thermal vacuum sensitivity such as multipaction effects on RF connectors should be assessed. Connector robustness aspects such as low density, scoop proofing and mate/demate variabilities should be included in this consideration.

  d. Type of Signals Running through Each Demate/Remate Connector (DC, analog, digital, RF) – Type of power and signals in each connector disturbed (demated/mated, modified, or manipulated) should be tracked with emphasis on RF multipaction susceptibility, high speed and temperature sensitive end-to-end paths.

  e. Number of Blind Mates – Blind mates introduce a risk area and should be thoroughly evaluated for the level of post-mate verification confidence and susceptibility to thermal vacuum.

3. Handling and Access

  a. Installation Difficulty/Access Difficulty including Special GSE – This consideration takes into account the difficulty of access to perform the rework/repair whether it is a straightforward task using previously proven access methods or requires significant gymnastics and specialized GSE to accomplish introducing higher potential to induce a latent defect. Difficult access increases the likelihood for collateral damage and improper unit re-integration, thermally (voiding in the interface) and electrically (misconnections).

  b. Potential for Collateral Damage – Collateral damage potential due to intrusions in areas adjacent to the rework/repair. Such damage can occur during unit removal or re-integration. When the risk for hardware collateral damage is high, due to limited accessibility or excessive unit weight, there is an increased likelihood that a SV thermal vacuum retest will be necessary to verify the proper reinstallation of unit hardware. Unlike many other considerations, this one cannot be mitigated by unit testing.

4. Design and Test History

  a. Mission Criticality and Redundancy Architecture for all R&R Units – This consideration assesses the mission criticality of the R&R units taking into account redundancy architecture, including internal versus external designs, and the potential impacts to the mission. A mission critical unit with limited- or no redundancy may have a greater need for workmanship or performance verification in a SV thermal vacuum retest. Non-redundant units with high mission criticality would pose the highest mission risk while externally redundant units with low mission impact would pose the lowest mission risk.

b. Previous R&R Unit Failure History – This consideration tracks the unit failure history and pedigree in terms of the unit history and the number of retests and penalty tests accrued. This consideration addresses items which have typically failed in unit thermal vacuum testing, but if there is a problematic test history in other environmental tests, additional confidence testing may be necessary.

5. Performance Verification

   a. Degree of Post Rework/Repair Vehicle Performance Testing – This item addresses the amount and degree of vehicle level functional/performance regression testing needed post-rework/repair to include the benefit for demonstration in a thermal vacuum environment. If a unit's operation is significantly complex such that extensive performance testing is necessary, this may become an important factor in the SV thermal vacuum retest decision. This consideration also considers the thermal design and performance of the unit. If thermal features of the unit cannot be verified as lower levels of assembly after the rework/repair, consideration needs to be given to how the thermal requirements will be verified, including the need for SV thermal vacuum retest.

   b. Confidence Testing Required – This consideration addresses the need for a SV thermal vacuum test to demonstrate confidence in the on-orbit mission environment of the vehicle post-rework/repair.

2.3 Mitigating and Alternative Approaches

Nearly every SV will incur flight hardware failures during the SV thermal vacuum test. Three independent studies that investigated SV thermal vacuum test data from a number of space programs discovered that SV thermal vacuum tests results in between 4.6 and 6.9 failures [5]. The results are shown in Figure 2. Despite extensive unit-level testing, most of the failures found in the SV thermal vacuum test were escapes from previous testing. As discussed in the previous section, the number of unit failures is one of several considerations that must be assessed in the retest decision.

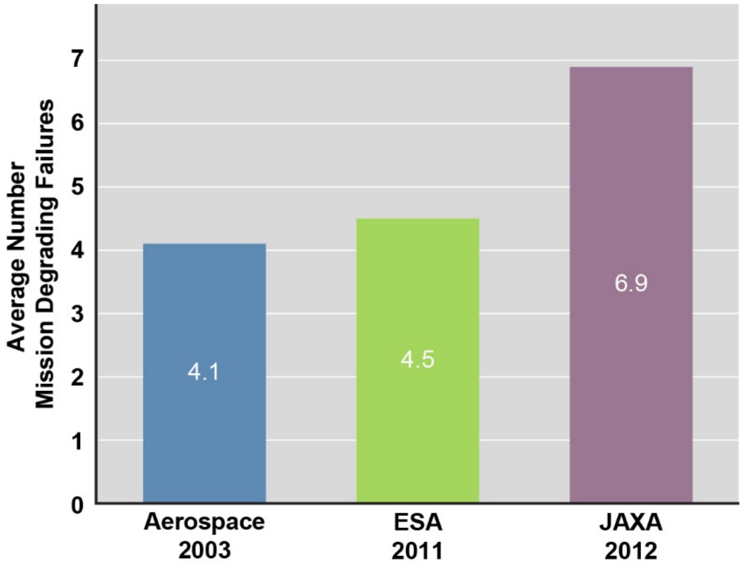

Figure 2. Number of mission-degrading failures per space vehicle thermal vacuum test.

Throughout the anomaly resolution process and any SV thermal vacuum retest discussion, it is important to keep an open mind and not focus on a single option of retesting at the SV level. The goal should be establishing the workmanship verification effort that provides a reasonable demonstration of the rework/ repair and re-integration with the least impact to the flight hardware and test program schedule. In some cases, this will require a SV thermal vacuum retest, but in other cases, other methods may be employed to mitigate the associated risks without the need for a SV thermal vacuum retest. The purpose of this section is to discuss mitigating and alternative approaches in lieu of the SV thermal vacuum retest.

Paragraph 1.2 discusses the purposes of a SV thermal vacuum test. The initial thermal vacuum test detects defects in the flight hardware, verifies mission performance, and demonstrates the flightworthiness of the SV. An event or anomaly during the initial thermal vacuum test may result in corrective actions that cast doubt on the hardware or software flightworthiness. Any time a box is opened, and more so if components are replaced, some retesting should be considered. Verifications in penalty testing will be necessary to validate the integrity of rework/repair workmanship and re-integration and re-establish the flightworthiness of the SV. A SV thermal vacuum retest may be one option for mitigating these associated concerns, but alternative efforts should also be considered. For example, testing at a lower level of assembly is a better method to exonerate the initial anomaly in a more stressing and perceptive environment. As a general rule, retesting should be conducted at the lowest level of complete assembly at which re-establishing flightworthiness can be demonstrated. Analyses may be performed at the SV level to show any changes to the unit does not produce degradation at the SV level of assembly.

2.3.1 Analysis Proving Minimal Risk to Design Integrity

With any retest approach, some analysis should be performed to verify that retesting does not exceed any hardware design threshold or performance limit. The rationale and basis of retest is in the analysis that backs the retest performed. The level of climatic rigor after rework/repair should demonstrate minimal probability of additional induced anomalies and demonstrate an environment in which the original problem was found. Reliability will also need to access the probability that the failure is relevant to the single build or heritage hardware. Assessment of the retest should show minimal life and performance degradation of the mission. Analysis should also support the path to complete closure of the anomaly resolution process. This may implicate other SVs if it is proven to be more than a single fault or a common design issue.

Once root cause is identified, it will need to be categorized as single fault failure, workmanship, design, part, or some other type of failure. Each failure will have fallout and require a different revalidation approach. Many SVs rely on heritage design and hardware, which could create multi-vehicle consequences if the anomaly is design or part related. For heritage or assembly-line SVs, reliability analyses should be performed to demonstrate that the issue discovered is isolated to the single unit/fault. Otherwise, a plan needs to be developed to implement any rework/repair on remaining heritage units. If a redesign is required to fix the original anomaly, analysis shall show a more robust system and eliminate any deficiencies stemming from the original design.

In limited situations, analyses may be used in lieu of retesting to re-establish the baseline integrity of the flight hardware. These situations should be limited to cases where the anomaly root cause is clearly identified, the rework/repair is minimal, removal and replacement of the unit is very simple, and operational and performance margins are greater than program requirements. In most cases, it is expected that this approach would be used sparingly with some retesting required.

2.3.2 Unit Thermal Testing

Following the rework/repair associated with rework/repair of a unit that failed in the initial SV thermal vacuum test, the unit will need to be retested at the unit level. Testing at the unit level is the most efficient verification of the flightworthiness of the reworked/repaired unit. Two considerations are made when establishing the nature of the unit-level retesting:

1. Was the initial unit thermal test a thermal vacuum test? If it was, then the retesting should be conducted in a thermal vacuum test as well. If it can be demonstrated that the unit's design and performance are not vacuum-sensitive, then unit thermal cycle testing may be conducted in lieu of the thermal vacuum test. This approach can improve test rigor by increasing ramp rates with an increase in overall cycles. If the unit is not vacuum susceptible, the unit thermal cycle test is the most efficient directive to vindicate the unit in a more stressful environment than a full up thermal vacuum test.

2. Were there any aspects of the SV thermal vacuum test failure related to vacuum conditions? If so, then the unit-level retest needs to be conducted in vacuum. Even if the initial thermal testing did not include a unit thermal vacuum test, if the test failure is vacuum sensitive, then the unit retest should be done in vacuum.

In most cases, the unit-level thermal retest will be conducted to the same unit-level temperature ranges (to adequately screen the new and reworked/repaired hardware), but the number of cycles is greatly reduced (to avoid overstressing the existing hardware). The verifications accomplished at the unit level may be adequate to completely demonstrate the validity of the rework/repair. In some situations, the results (full performance, excess design margin, etc.) from the unit thermal test may then be used to show that a SV thermal vacuum test is not necessary. Unit-level testing, however, cannot verify the re-integration of the unit back into the SV.

Test standards typically define minimum retest conditions for reworked/repaired items. For example, in SMC-S-016 (2014), the minimum acceptance retesting includes three axes of random vibration testing (one minute each) and three cycles of thermal testing (thermal vacuum or thermal cycle). An option to this minimum retest requirement is to perform a full acceptance test of any reworked/repaired unit. This approach is conservative and has been successfully adopted on some space programs. If significant rework/repair is conducted on a unit, this option may be necessary to regain confidence in the unit workmanship and functional and performance mission capabilities.

2.3.3 Subsystem Thermal Vacuum Testing

If the unit failure is dependent on other units to vindicate root cause and demonstrate rework/repair workmanship, testing solely at the unit level will not adequately demonstrate the rework/repair. In addition to unit testing, a subsystem or panel thermal test may also be necessary. It is not advisable for subsystem testing to replace unit-level testing because the rework/repair workmanship needs to be verified at the lowest possible level. In most cases, rework/repair is conducted at the unit level of assembly and not at the subsystem level. Therefore, subsystem testing should be in addition to unit testing.

Depending upon the bus configuration and redundancy, thermal vacuum testing at a lower unit level could be executed while other bus level tasks can be performed in parallel. In such cases, and when this testing can be conducted in lieu of the SV thermal vacuum test, subsystem testing can have minimal impact of the overall SV program.

When re-integration of units and subsystem-level performance can be verified at a subsystem level of assembly, and if re-integration of the subsystem into the SV is not a concern, thermal vacuum testing at the subsystem should be considered in lieu of the SV thermal vacuum testing, In most cases, a subsystem level thermal vacuum test will have a lower impact on the program.

2.3.4 Alternative Vehicle-Level Testing

Thermal Cycle Testing: Even after unit or subsystem thermal testing is completed, there may still be concerns about the workmanship of the rework/repair or the re-integration of the reworked/repaired flight hardware into the SV. When these concerns persist and it is clear that they are not vacuum-related, a SV thermal cycle test may be considered in lieu of the SV thermal vacuum test. In most cases, a SV thermal cycle test will have less impact on the program. However, this option typically only makes sense when the contractor has a thermal cycle chamber large enough for the SV. Other considerations that are necessary when considering a SV thermal cycle testing include:

1. The SV thermal cycle test may be a test environment that is too severe for flight hardware (more severe than the SV thermal vacuum test due to temperature ramp rates). The risk of overshooting test temperature limits may be greater in the SV thermal cycle test.

2. There may be more confidence in executing a SV thermal vacuum test than a SV thermal cycle test because in most cases, a SV thermal cycle test was not part of the initial SV test program.

3. A SV thermal cycle test will require the development of new test procedures, whereas a SV thermal vacuum test requires only the modification of the initial SV thermal vacuum test procedures.

4. A SV thermal cycle test carries an added risk of moisture condensing on flight hardware. This risk needs to be minimized by proper test planning and test execution. Experience has shown that in some instances, this risk is more severe than typically thought.

Non-Environmental Vehicle-Level Testing: When SV-level concerns persist and it is clear that they are not vacuum-related or temperature-related, consideration should also be given as to whether the concerns can be adequately cleared during the final integrated systems test (FIST) and a dedicated non-environmental test. The advantage with this option is that it requires no additional vehicle-level environmental retesting. The FIST procedures may require modifications and additional functional testing to clear lingering concerns.

2.3.5 Non-Environmental Test Assessments

There are other mitigating actions that can provide significant confidence in rework/repair and re-integration without the need for environmental testing. These may be conducted at the unit level of assembly with the intent of demonstrating flightworthiness of the rework/repair or reconfigured flight hardware. They include:

- X-ray inspection of connectors
- Ultrasound inspection of thermal bond-lines
- Additional quality control checks (including photographic evidence)
- Prior evidence and experience with similar R&R activities
- Additional scrutiny of ambient test data following rework/repair activities

While there may be subjectivity to these assessments, they can provide valuable information to help mitigate concerns that might otherwise require a significantly more impactful environmental test.

3. Space Vehicle Thermal Vacuum Data Collection and Analysis

3.1 Discussion of Data Collection

Data from 350 SV thermal vacuum tests, conducted between January 2000 and December 2016, was obtained and reviewed. As shown in Figure 3, the data was categorized according to the mission type (commercial, government-civil, and government-DOD) and whether the vehicles were protoqualification or acceptance vehicles. Most of the SVs tested were from commercial programs (226, 64 percent). Government-civil vehicles and government-DOD vehicles comprised 13 percent and 23 percent of the vehicles in the study, respectively. Of the 350 SV thermal vacuum tests, 56 percent were protoqualification vehicles.

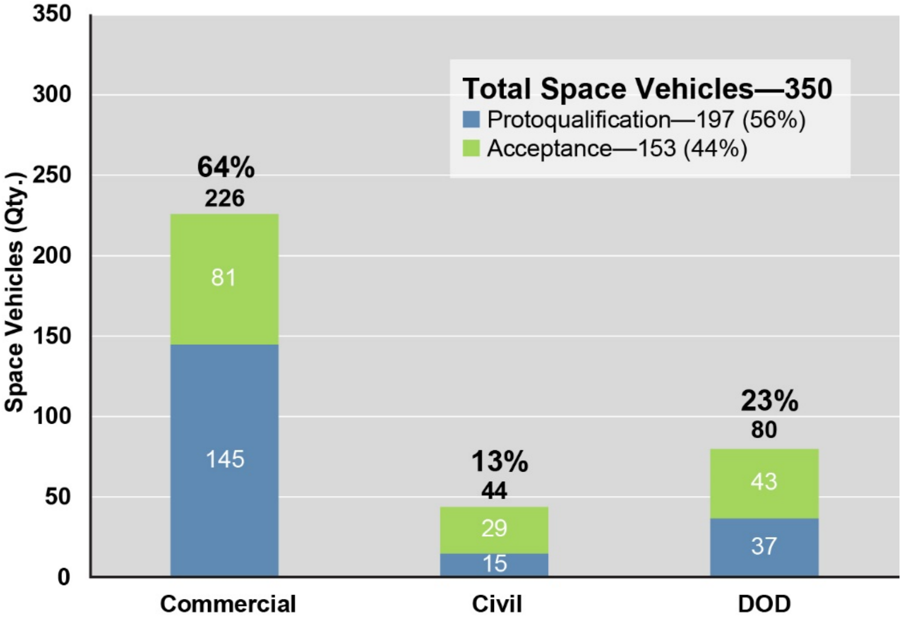

Figure 3. Number of space vehicles tested in thermal vacuum (2000–2016).

There was an expectation that there would be more acceptance vehicles than protoqualification vehicles in the data set, but that was not the case. More than half (56 percent) of the vehicles were protoqualification vehicles. The government SVs were predominantly acceptance vehicles (58 percent), but for commercial SVs, most (64 percent) were protoqualification vehicles.

Figure 4 compares the SV types as to how they were procured (fixed price or cost plus). Of the 350 SVs that were tested in the thermal vacuum test, most (87 percent) were purchased under fixed price contracts. All but one commercial SV was procured under fixed price contracts. The government-civil SVs were split about in half (52 percent fixed price) and the government-DOD SV had more (69 percent) fixed price vehicles. Whether the contract type influenced the decision to conduct a SV thermal vacuum retest will be discussed in the next section.

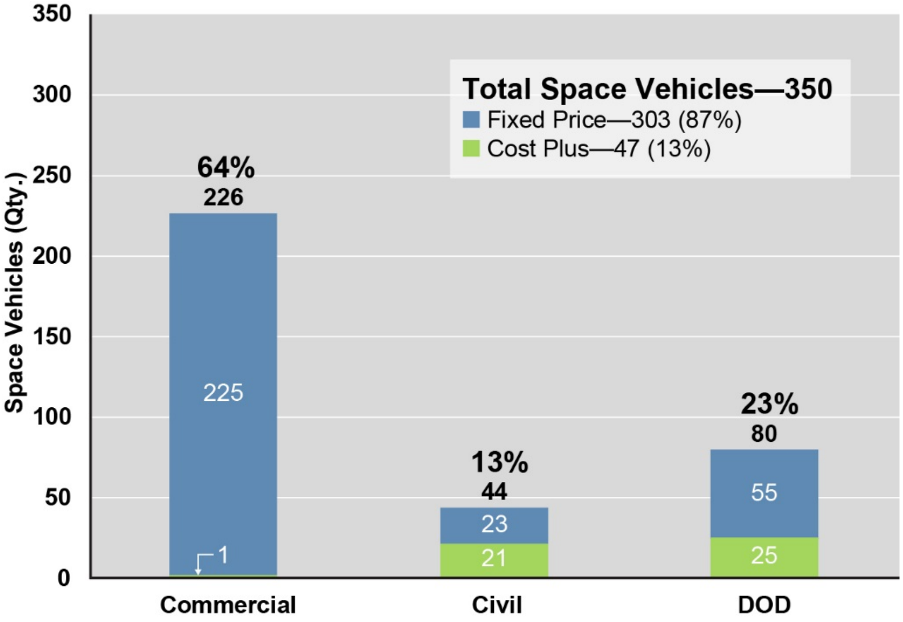

Figure 4. Distribution of space vehicles by contract type.

3.3 Results of Data Collection

The number of SV thermal vacuum retests for the different program types are shown in Figure 5. Across the 350 SVs that had a thermal vacuum test conducted, 41 retests were performed (12 percent). Commercial vehicles saw 11 percent retesting, government-civil programs saw 5 percent retesting, and government-DOD programs saw 18 percent retests.

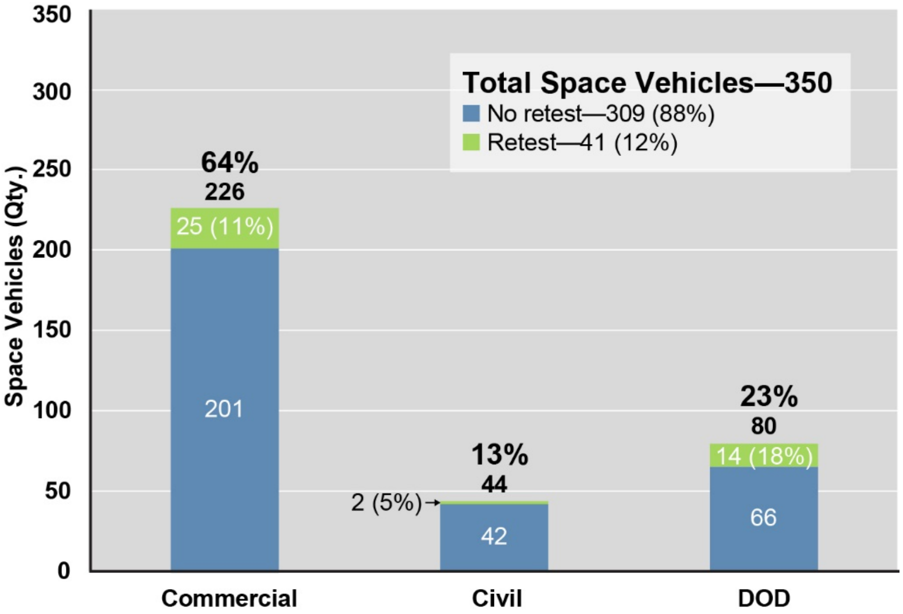

Figure 5. Number of space vehicles retested.

There was an expectation that commercial SVs would see the fewest number of retests. The data supported this expectation when compared to the government-DOD SVs with commercial SVs retesting at a rate of about half that of government-DOD SVs. The data, however, did not support this expectation when compared to government-civil SVs whose retest rates were less than half of the commercial SV rate. There may be several possible reasons for this expectation, including:

- There is a perception that commercial programs have more mature heritage units and there may be less failure risk associated with heritage hardware.
- Commercial program customers may be more willing to take higher risks than government-DOD customers.
- There may be a perception that government-civil customers regard not performing a SV thermal vacuum retest as a lower risk as compared to government-DOD and commercial customers.
- Commercial programs are predominantly procured with firm fixed-price contracts (Figure 4) and this may influence the retest decision.

It is not clear from the data collected that any one of these reasons governed the retest decision-making process. About one in nine commercial SVs were retested, so commercial contractors are not entirely averse to conducting a retest when it is deemed necessary.

Government-DOD SVs had the highest percent of retesting and the reasons for this may include the perception that:

- Government-DOD programs typically have complex payloads with little or no heritage, increasing the likelihood in failures at the system level and less comprehensive understanding in payload performance.
- Government-DOD customers are extremely risk averse.

Government-civil SVs had the lowest percent of retesting and although the data collected could not confirm the reason for this, it may be due to the perception that:

- Government-civil programs may have schedule and cost constraints that influence the retest decision.
- Government-civil programs are willing to take higher risks as compared to government-DOD and commercial programs.

For the 41 SV thermal vacuum retests recorded over this time period, the number of protoqualification and acceptances vehicles are shown in Figure 6. Retests were approximately evenly split between protoqualification and acceptance vehicles for the total and for each SV type. However, based upon the data shown in Figure 3,

- For commercial programs, 17 percent of the acceptance SVs were retested while 8 percent of the protoqualification vehicles were retested.
- For government-civil programs, 3 percent of the acceptance SVs were retested and 7 percent of the protoqualification SVs were retested.
- For government-DOD programs, 16 percent of the acceptance SVs were retested and 19 percent of the protoqualification SVs were retested.

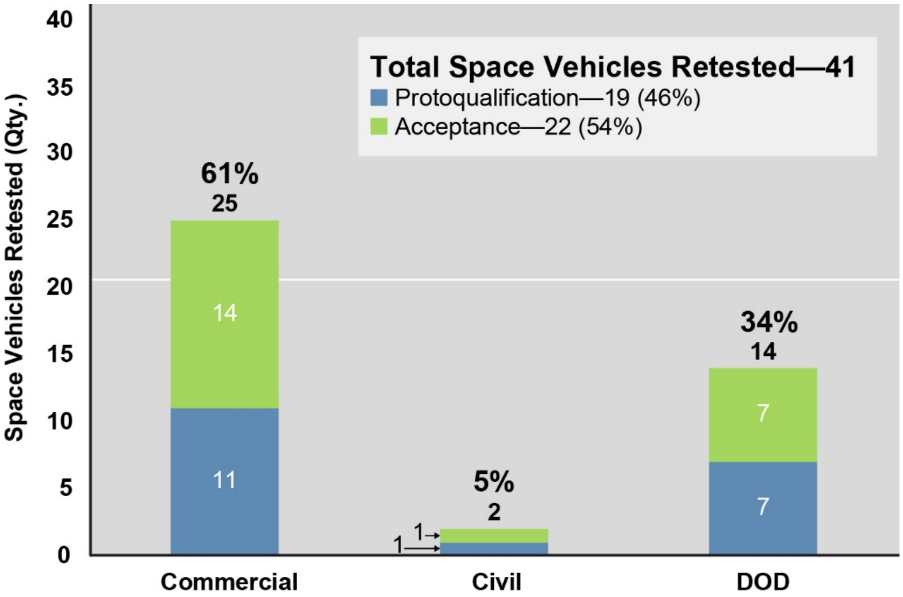

Figure 6. Retested space vehicles by program type.

The primary decision-maker to conduct a SV thermal vacuum retest can be the contractor, the customer, or by joint decision (contractor and customer). Figure 7 shows who made the final decision to conduct the SV thermal vacuum retest. The decisionmaker data was collected on 37 vehicles (four SVs did not provide data on this information). Most (57 percent) retest decisions were made jointly by the contractor and the customer and over a third (35 percent) of the retest decisions were made primarily by the contractor. Very few retest decisions (8 percent) were made solely by customer direction.

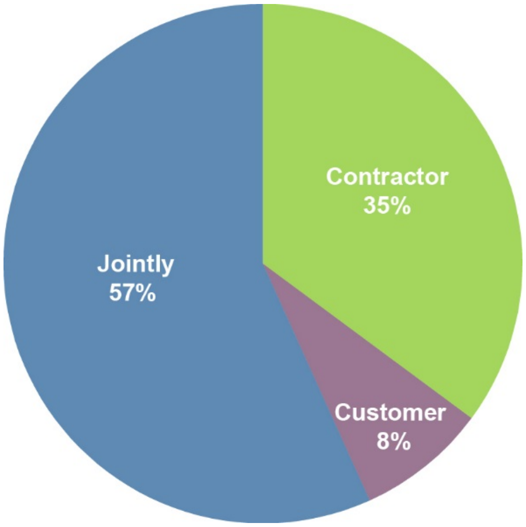

Figure 7. Primary decision-maker for retesting.

3.5 Reasons for Retesting from Data Collection

This section discusses the primary reasons that led to the SV thermal vacuum retests for the 41 vehicles. As shown in Figure 8, the primary reason for retesting was workmanship escapes. For example, a unit anomaly in the initial SV thermal vacuum test has, as its root cause, a workmanship defect that leads to retesting. In this example, the primary reason for the root cause was workmanship. For the 41 vehicles that conducted a retest, data on primary reasons was reported from 34 of these tests. Of the 34 reasons reported, 26 (63 percent) were due to workmanship verification and 6 (15 percent) were due to design verification. Two primary reasons (5 percent) were a combination of workmanship and design issues. The distribution of reasons was approximately evenly split between acceptance and protoqualification vehicles.

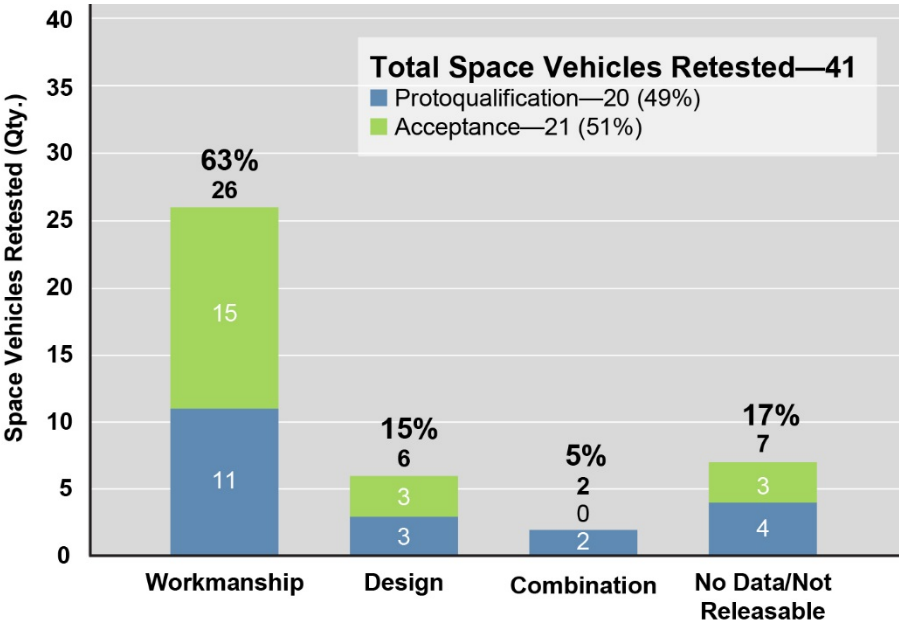

Figure 8. Primary reasons for space vehicle thermal vacuum retest.

The nature of the failure that led to the retest is shown Figure 9. Of the 41 retests, the nature of the failures was reported for 34 tests. System interface issues (32 percent), unit performance (22 percent) and the combination of the two failure types (24 percent) were the primary reasons for conducting the SV thermal vacuum retest. Reach-back from subsequent testing was a very small contributor (5 percent) for the reason for conducting the retest.

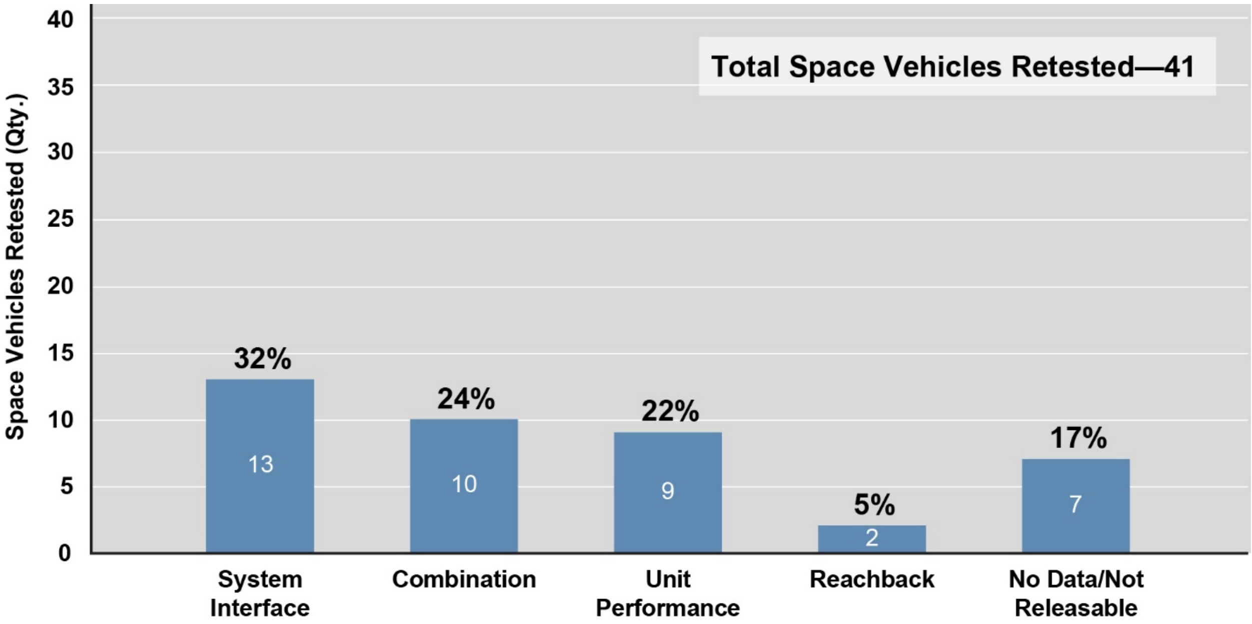

Figure 9. Nature of failure that led to space vehicle thermal vacuum retest.

In terms of the considerations discussed in Section 2, the SV thermal vacuum retests were based upon the considerations shown in Figure 10. The most prevalent reasons given for the retest was related to the number of R&R units and unit confidence (32 percent each). Unit confidence refers to the assurance provided by the test in the flight hardware (its workmanship, design, and performance capabilities). This is the regaining of confidence in the flight hardware and not confidence in the test. Modifications to harnesses and cabling (10 percent), and the number of connectors (5 percent) were the next most prevalent considerations for retesting.

Secondary and tertiary considerations were also reported, but there were no prevalent trends in these considerations. Secondary and tertiary reasons were spread across the 16 considerations with no single consideration garnering more than two votes.

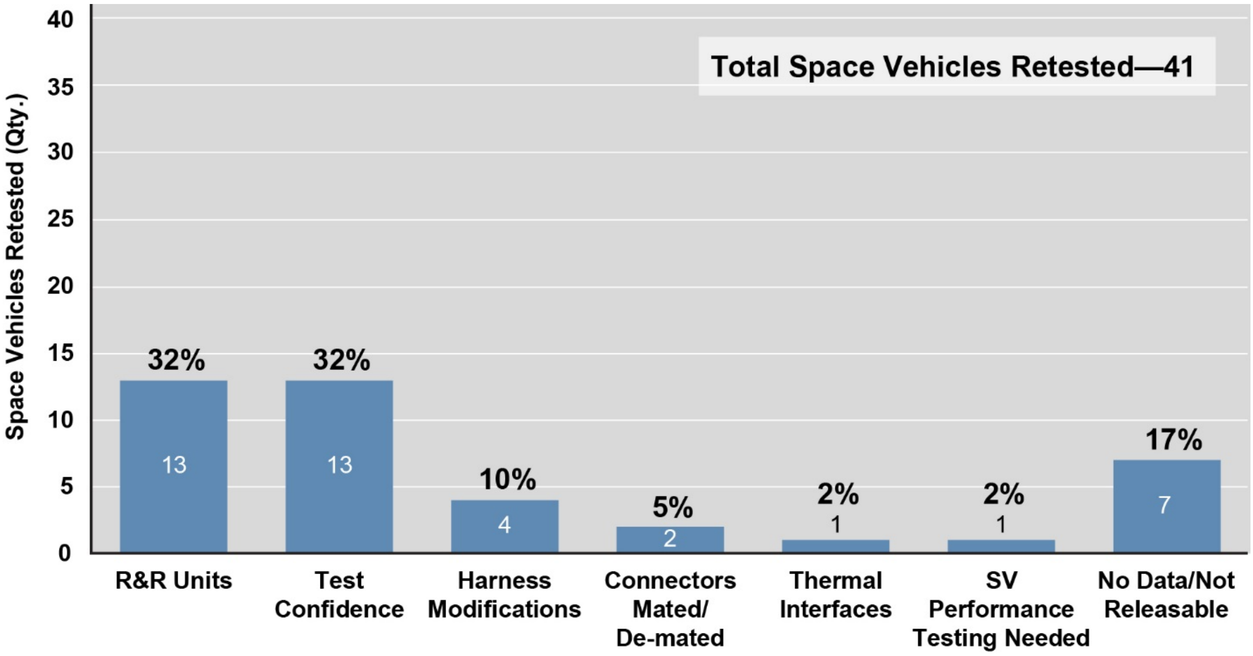

Figure 10. Contributing considerations for the space vehicle thermal vacuum retest.

As shown in Figure 11, over half of the failures that led to retesting the SV were associated with the payload. The implications are that payload failures will have a higher likelihood of resulting in a SV thermal vacuum retest than bus failures. This may be due to a perception that the bus units have more heritage units and have better understood performance. It may also be due to a perception that payload units have higher mission criticality than bus units.

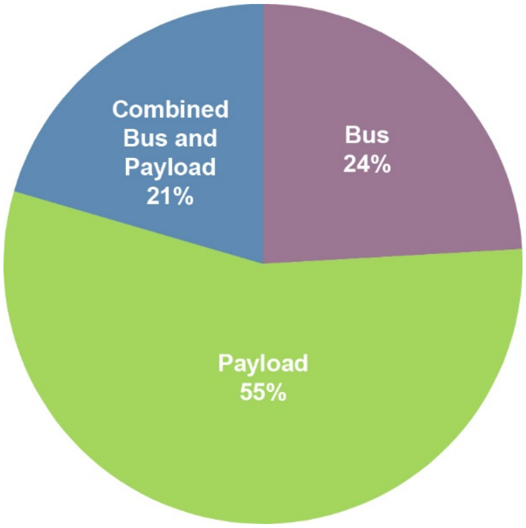

Figure 11. Failures that led to retesting by hardware type.

The distribution of test year is shown in Figure 12. There does not seem to be any trend on increasing or decreasing rates of retest over the years for the retests assessed. It is noted that during the first three years of the study (2000-2002), the percentage of SVs retested (17 percent) is higher than during the last three years (4 percent). More data beyond 2016 will be needed to determine if this is forming a statistically valid trend.

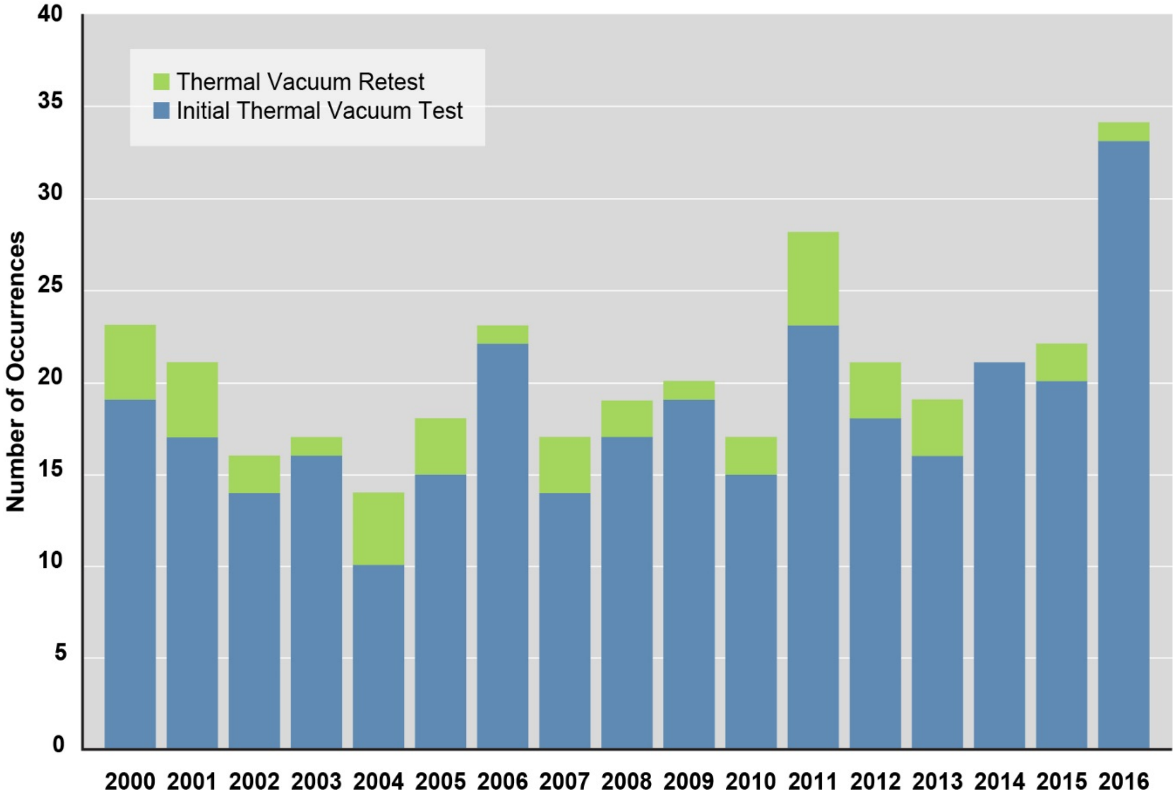

Figure 12. Year of space vehicle thermal vacuum test and retest.

3.6 Space Vehicle Retest Effectiveness

The classical definition of test effectiveness as provided by Hamberg and Tosney [9]:

$$TE = {}^{F_T}/_{F_A}\ X\ 100$$

TE = Test Effectiveness for the test of interest
F_T = Total failures found in the test of interest
F_A = Total failures available to be found including early flight

The traditional test effectiveness calculation requires knowledge of the number of failures that occur following the test of interest and during early flight. For the MAIW study, only the failures found in the initial SV thermal vacuum test for retested vehicles and the failures found in the retest were obtained as assessed. Therefore, this equation cannot be used to quantify the effectiveness of the SV thermal vacuum retest.

Use of the above equation typically concludes that the more effective a test is in detecting failures, the more valuable the test to establishing flightworthiness. The interpretation is somewhat different for a thermal vacuum retest. As previously discussed, the goal for the retest is to demonstrate the vehicle's flightworthiness by detecting no additional discrepancies. The ultimate goal of the retest is to show that unit rework/repair, removal, and re-integration was successful as evidenced by no additional failures in the retest. A retest that finds no new defects or fully verifies the workmanship rework/repair and re-integration is not an ineffective test. On the contrary, running a defect-free thermal vacuum retest demonstrates the vehicle's flightworthiness in the simulated environments.

Table 1 compares the number of failures found in the initial SV thermal vacuum test with the SV thermal vacuum retest for protoqualification and acceptance vehicle. There were 41 SVs retested, but for this data assessment, failures were reported for 34 vehicles. In the initial SV thermal vacuum test, protoqualification vehicles had an average of 4.6 failures, while acceptance vehicles had an average of 2.0 failures. The results of Arnheim and Wright [5], where for vehicles with a SV thermal vacuum test over the timeframe of 1986 to the mid-1990s, were on average 4.1 acceptance failures per thermal vacuum test and 6.0 protoqualification failures per thermal vacuum test. The comparison of these two sets of results indicates that the latter dataset (2000-2016) had fewer failures per test than the earlier dataset.

Table 1. Comparison of SV Protoqualification and Acceptance Test Failures

Vehicles	Initial SV TV Test Results		SV TV Retest Results
	Retested Vehicles	Failures/Test	Failures/Test
Protoqualification	16	4.6	0.7
Acceptance	18	2.0	0.3
	Total = 34	Average = 3.3	Average = 0.6

In this table, a failure is an R&R units as defined above and in Section 1.5. These can include units removed, reworked/repaired, retested, and reinstalled, as well as rework/repairs made on the SV itself. Table 1 also tabulates the number failures found in the SV thermal vacuum retest. The number of retest failures per test is significantly fewer than experienced in the initial SV thermal vacuum test. It is not zero, but it is close. Furthermore, the number of acceptance retest failures was significantly fewer than the protoqualification retest failures. These results should be expected as the initial thermal vacuum test should be more efficient at finding detects than a subsequent retest.

To assess whether inclusion of commercial vehicles in the 2000-2016 dataset explains why the number of failures is fewer than noted in the Wright and Arnheim study, Table 2 compares test failures for commercial and government SVs in a similar format. In the initial SV thermal vacuum test, the number of failures was relatively equal at slightly more than three. This suggests that the program type is not the reason for the reduction in failures in the more recent dataset.

Table 2. Comparison of SV Commercial and Government Test Failures

Vehicles	Initial SV TV Test Results		SV TV Retest Results
	Retested Vehicles	Failures/Test	Failures/Test
Commercial	24	3.4	0.2
Government	10	3.1	1.7
	Total = 34	Average = 3.3	Average = 0.6

Table 2 indicates that program type has an impact on the number of failures found in the SV thermal vacuum retest. Government programs had significantly more failures in the retest as compared to commercial programs. There was no clear explanation for this result.

3.6.1 Multiple Retests

Of the 41 vehicles that experienced a SV thermal vacuum retest, 7 SVs had multiple retests. For a number of these vehicles, multiple retests were conducted based upon programmatic, and not technical, considerations. Schedule and facility flexibility were the primary reasons. There were no technical reasons that would indicate a SV would require multiple retests.

4. Conclusions and Recommendations

4.1 Data Analysis Conclusions

Open discussions between the customer and the contractor focusing on and quantifying technical risks is the best approach to making a well-informed decision on conducting a SV thermal vacuum retest. Non-technical factors (e.g., cost, schedule, politics, and risk posture) may be important in the decision process. However, these non-technical factors should not be the primary emphasis of the decision process. For example, if a customer does not have the program budget for a retest, the customer and the contractor still have an obligation to identify and thoroughly discuss the mission risk as a consequence of not conducting the retest. The comprehensive list of technical considerations developed in this paper should be utilized in the assessment of risk. It is recommended that these considerations be addressed individually and in their entirety during the assessment of risk.

Results of the SV thermal vacuum retest data assessment indicates that about one in eight SVs will experience a retest after the initial thermal vacuum test. For government-DOD programs, about one in five SVs will be retested. The primary reason for retesting is workmanship failures in flight units. Unit performance and system interface issues were the focus of the failures that led to retesting. In terms of the considerations developed in this report, the number of units requiring rework/repair and the confidence in successfully passing confidence testing were the two reasons given for influencing the retest decision.

While this report focused on the technical decision-making process for SV thermal vacuum retesting, it is recognized that there are non-technical factors that can be significant contributors to the decision. These include:

- Available funding
- Schedule margins and launch date constraints
- Thermal chamber availability
- Test support personnel availability
- Conflicting needs associated with other programs
- The nature of the work, such as accomplishing the rework/repair without removing the SV from the thermal vacuum chamber

4.2 Thermal Vacuum Retest Recommendations

Key recommendations from this report are:

1. Center retest decision process on technical risk using existing board reviews (e.g., failure review boards and program review boards). There may be significant nontechnical issues that have prominent importance in the retest decision process (e.g., cost, schedule, facilities, staffing), but the program personnel and customer should also be well aware of the technical risks associated with the retest decision, and how these risks impact the program mission assurance.

2. Use the 16 industry topic team considerations to form the basis of the space vehicle thermal vacuum retest process. These considerations will provide a comprehensive review of the significant issues that could impact re-establishing confidence in the flight-worthiness of the SV.

It is recommended that each consideration be addressed and be summarized and documented with a risk assessment (Low-Medium-High).

3. Consider alternative verification methods in lieu of the SV thermal vacuum retest to mitigate assessed risks. Given the program impact associated with a thermal vacuum retest, program teams should remain open-minded toward using an alternative approach when it can demonstrated that no additional mission risk is incurred by using alternative testing. This will require a good knowledge of the benefits and limitations associated with all options discussed in this report.

4. Ensure rigorous unit-level testing. The results of this work verified published data that show that unit defect escapes are a significant contributor to necessary rework/repair. Unit thermal cycle, thermal vacuum and burn-in testing need to include the necessary test temperature ranges, number of cycles, temperature transition rates, functional and performance test, as well as overall perceptiveness to detect as many unit-level problems as is reasonably possible.

5. Revise SMC-S-016 (2014) to reflect the current industry practices and recommendations as documented in this report regarding the SV thermal vacuum decision process.

4.3 Future Work

Several future topics were identified during the preparation of this work:

1. A recognized shortcoming of this effort was the team's inability to compare retest results to the rigor of the unit environmental test program and to failures that occurred after launch. Time limitations and access restrictions to unit test and flight data prevented such comparisons. While this would require significant time and effort, it was felt that more insight could be gained from understanding differences in how vehicle units were tested prior to the initial thermal vacuum test. Furthermore, the ultimate proof of test-worth is in the elimination of hardware defects before launch and without early flight failure data; test effectiveness calculations could not be computed.

2. Of the 350 SV thermal vacuum tests conducted, the study focused on the 41 retests and the results from these retests. There would be value in understanding the decision process for the other 309 thermal vacuum tests with rework/repair that did not result in a retest. Were these decisions driven by low technical risks or were non-technical considerations of more importance? Based upon the 16 considerations, should any of these SVs been retested? Would early flight data suggest that a retest should have been conducted?

3. The acquiring of necessary study data was more difficult and labor intensive than expected. The difficulty arose because there is a lack of uniformity among the contractor's failure reporting and corrective action system (FRACAS). First, this lack of uniformity is apparent from contractor to contractor, but also within a contractor's set of internal data management requirements, depending on contract type. Second, heritage FRACAS systems retained for older programs may no longer be supported by cognizant IT and technical staff. Access to these heritage systems may be difficult and time consuming. Third, different FRACAS systems tend to capture different data, certainly in different formats. This difficulty should be the expected condition until deployed FRACAS systems can be normalized. Standardizing the reporting process to include thermal vacuum test reports, and improving the documentation of test results as a future extension of this work could provide significant benefits to the space community.

5. Acronyms

AI&T	Assembly, integration and test
DC	Direct current
DOD	Department of Defense
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
ESD	Electrostatic discharge
FIST	Final integrated system test
FRACAS	Failure reporting and corrective action system
FRB	Failure Review Board
GIDEP	Government-Industry Data Exchange Program
GSE	Ground support equipment
IT	Information technology
JAXA	Japanese Aerospace Exploration Agency
MAIW	Mission Assurance Improvement Workshop
MDF	Mission degrading failures
MPE	Maximum predicted environment
PRB	Program Review Board
R&R	Remove and replace
RF	Radio frequency
RTV	Room temperature vulcanization
SV	Space vehicle
TC	Thermal cycle
TE	Test effectiveness
TV	Thermal vacuum
TV 1	Initial SV thermal vacuum test
USG	United States government

6. References

1. Department of Defense, *Test Requirement for Launch, Upper-Stage and Space Vehicles*, Air Force Space Command, Space and Missile Center Standard, SMC Standard SMC-S-016 (2014), September 5, 2014.

2. Perl, E., A. J. Peterson, J. M. Snyder, C. P. Wright, and J. W. Welch, *Test Requirements for Launch, Upper-Stage, and Space Vehicles*, Aerospace Report No. TR-RS-2014-00016, The Aerospace Corporation, El Segundo, CA, June 25, 2014.

3. *Getting It Right*, The Quarterly Newletter of Mission Assurance, vol. 7, issue 3, The Aerospace Corporation, El Segundo, CA, February 27, 2017.

4. Johnson-Roth, G. and W. F. Tosney, *Mission Risk Planning and Acquisition Tailoring Guidelines for National Security Space Vehicles*, Aerospace Report No. TOR-2011(8591)-5, The Aerospace Corporation, El Segundo, CA, September 13, 2010. Restricted distribution.

5. Wright, C. P. and B. L. Arheim, *Insight into the Value of System Level Thermal Vacuum Testing*, 20th Aerospace Testing Seminar, March 2002.

6. Takahashi, D. and Q. Shi, *Technical Rationale of JAXA Thermal Vacuum Test Requirement based on Test Effectiveness Assessment*, Proceedings of the 30th Aerospace Testing Seminar, March 2017.

7. Hamberg, O., *Retest Considerations for Space Vehicles*, Proceedings of the Institute of Environmental Sciences, March 1984.

8. Tosney, W. F., E. Perl, and W. D. Bjorndahl, *Retest Considerations for Space Vehicles*, Space Vehicle Test and Evaluation Handbook (Chapter 17), 2nd Edition, Aerospace Report No. TOR-2011(8591)-2, The Aerospace Corporation, El Segundo, CA 2011. Restricted distribution.

9. Hamberg, O. and W. F. Tosney, *The Effectiveness of Satellite Environmental Acceptance Tests*, The Journal of the Institute of Environmental Sciences, 1989.

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