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Thermal Test Tailoring Guidelines for Class C and D Space Programs

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Abstract

A significant portion of a space vehicle's development budget is allocated to integration and testing. Expenses associated with mission assurance prior to launch (e.g., ground testing) is justified given the resources invested in developing the space program, the harsh space environment, and the impossibility of rework following launch. To that end, rigorous government and industry standards for ground testing have been developed to ensure that test effectiveness and mission assurance objectives are met. Historically, these specifications have been written for national security space programs of high-priority and high-cost space vehicles with the expectation that mission assurance requirements will be tailored for lower priority space vehicles. With the proliferation of space programs targeting lower cost and higher risk tolerance, there is a need for more thorough documentation of how ground testing requirements might be tailored to ensure consistency with reduced mission assurance expectations.

Class C and D military space programs are characterized by a willingness to accept higher mission risks because these programs do not have the same resource investment and flight success expectation of Class A and B programs. Test effectiveness goals seem to be reasonably defined for Class A and B programs, but not for Class C and D programs, so requirements tailoring for these class of vehicles is typically accomplished subjectively and without clear objectives. The purpose of this work is to compare the historical tailoring documents used in industry, describe the common perceptions of Class C and D programs, and propose reasonable Class C and D vehicle thermal test requirements for given program constraints.

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1. Introduction

A primary reason National Security Space (NSS) programs achieve mission success is compliance to rigorous requirements of government and industry standards and specifications. This compliance reduces mission risk during space vehicle development. A common difficulty with applying general specifications and standards across all military programs is that space vehicles have different flight environments (e.g., geosynchronous, low-Earth orbit, exo-atmospheric), expected life durations (from less than 30 minutes for booster launch and missile programs to over 15 years for large spacecraft programs), levels of complexity, levels of national security criticality, and development cost and schedule constraints.

The standards and specifications are typically written conservatively and are primarily applicable to large space programs, with the expectation that these requirements will be tailored for less complex and less critical missions. Methods for tailoring are commonly described qualitatively and the actual tailoring process requires subject matter experts in several areas of expertise. Although tailoring decisions can have a significant impact on program cost and schedule, tailoring is typically a very subjective process.

To better characterize various program types, government standards and handbooks have defined four mission risk classes. Definition parameters for these classes provide a structured approach for establishing a hierarchy of risk combinations for NSS space vehicles by considering such criteria as national significance, type of payload (operational or experimental), mission life, magnitude of investment, and other relevant factors [1]. A summary of the most general mission risk categories is shown in Table 1. These definitions were historically developed in MIL-HDBK-343 [1] and were updated in Aerospace Mission Assurance and Tailoring Guidelines [2 - 4] based upon present acquisition experience. Other parameters that could be added to Table 1 to distinguish between the mission classes include use of redundancy, vehicle complexity, schedule constraints, and vehicle redundancy within mission constellation.

Table 1. General Parameter Descriptions for Different Space Mission Risk Classes

	Class A	Class B	Class C	Class D
Mission risk acceptance	Lowest	Low	Moderate	Highest
National significance	Extremely critical	Critical	Not critical	Not critical
Payloads	Operational	Demonstrates operational utility, may become operational	Typically experimental	Typically experimental
Acquisition cost	Highest	High	Medium	Lowest
Development time	May take 4 or more years	May take 3 or more years	May take 2 or more years	May take 1 or more years
Mission life	Long, greater than 5 years (typically 8 to 10+ years)	Medium, up to 5 years	Short, typically less than 2 years	Short, typically less than 1 year
Launch constraints	Critical	Medium	Few	Few to None

The determination of a space vehicle class is critical in establishing the mission risk posture for the program and setting expectations for tailoring requirements. The process typically begins with clarifying the national significance and failure implications. While there can be wide variability in the Table 1 parameters for acquisition cost, development time, and mission life, cost is a common primary discriminator in establishing space vehicle classes [2]. The associated risk that a customer is willing to accept is commonly inversely proportional to vehicle cost, so acquisition cost remains important in determining mission risk postures.

In terms of compliance documents, higher class programs will have more mandatory standards and specifications than lower class vehicles. Each Class A acquisition typically has 35 to 40 compliance documents (specifications or standards with formal requirements) on contract with required deliverables. Each Class B acquisition may have about 30 compliance documents with required deliverables. Each Class C acquisition may have about 20 compliance documents on contract with few deliverables. Class D programs may have no formal contract requirements other than technical or critical safety verifications. When compliance documents are placed on contract, the tailoring process helps align expectations and mission risk postures with the program class.

A common top-level assessment of risk posturing views the four mission classes in two groupings: Classes A-B and Classes C-D. It is common for a space program to consist of both Class A and B payloads and features, and it is also common for Class A and B space vehicles to have very similar risk postures and tailoring approaches. The risk posture gap in Table 1 is between Class B and Class C space programs. Perhaps the most obvious difference is that Class C programs are not mission critical. While there is a significant difference in how Class D missions are acquired and developed as compared to Class C programs, there is still a perception that Class C and D missions are more closely grouped with similar features. This results in tailoring processes nearly identical for Class A and B missions, and room for significant and similar tailoring on Class C and D programs. Perceptions related to the different mission risk classes and how they influence test tailoring decisions are discussed more fully in Chapter 4.

One key area that receives considerable attention during the tailoring process is the environmental test program. Given that the assembly, integration, and test phases can be a significant portion of the space program budget, any activity not directly related to building the flight hardware is a likely target for cost reduction. Environmental testing requirements for launch, upper-stage, and space vehicles, as specified in SMC-S-016 [5, 6], verify operation and performance prior to flight for government military space programs. While thermal tests are highly effective in detecting latent defects in space hardware and demonstrating performance capabilities, they are extremely time-consuming and therefore an area of significant tailoring pressure.

The purpose of this report is to provide the historical perspectives on thermal test tailoring of Class C and D space vehicles and assess how these proposed tailoring options align with thermal test objectives, risk tolerance, and class perceptions. Underlying risk perspectives will be discussed and how these mission classes are handled during a program development will be summarized. Recommendations will be provided along with the resultant risks accrued in typical tailoring of thermal test parameters.

Chapter 2 provides a summary of thermal test requirements as stated in SMC-S-016 and the rationale for the most common tailored test parameters. Chapter 3 summarizes historical tailoring recommendations as stated in MIL-HDBK-343 and the Aerospace Tailoring Guidelines [2 - 4]. Chapter 4 discusses the perceptions of the four mission risk classes. Chapter 5 provides recommendations for thermal test tailoring for the various spacecraft classes.

2. Thermal Test Requirements from SMC-S-016

For U.S. military spacecraft, thermal environmental test requirements are specified in SMC-S-016 for unit, subsystem and vehicle hardware in thermal cycling, thermal vacuum and burn-in testing. The thermal test parameters that have the largest influence on test effectiveness are the number of cycles and the test temperature range. The SMC-S-016 requirements for these parameters are shown in Table 2.

Table 2. SMC-S-016 Thermal Test Requirements

Assembly	Test Level	Test	Test Duration	Temperature Range [4]
Unit [1]	Qualification	Thermal cycle	23 cycles	–34°C to +71°C (or Max. Predicted ± 10°C)[5]
		Thermal vacuum	4 cycles	
	Protoqualification	Thermal cycle	16 cycles	–29°C to +66 °C (or Max. Predicted ± 5°C)[5]
		Thermal vacuum	4 cycles	
		Burn-In	200 hours [2]	
	Acceptance	Thermal cycle	10 cycles	–24°C to +61°C (or Max. Predicted)[5]
		Thermal vacuum	4 cycles [3]	
		Burn-In	200 hours [2]	
Subsystem	Qualification	Thermal vacuum	8 cycles	Max Predicted ± 10°C
	Protoqualification	Thermal vacuum	4 cycles	Max Predicted ± 5°C
	Acceptance	Thermal vacuum	4 cycles	Max Predicted
Vehicle	Qualification	Thermal vacuum	8 cycles	Max Predicted ± 10°C
	Protoqualification	Thermal vacuum	4 cycles	Max Predicted ± 5°C
	Acceptance	Thermal vacuum	4 cycles	Max Predicted

Notes:

1. Requirements stated for electrical and electronic units.
2. Burn-in test duration includes time accrued in unit thermal cycle and unit thermal vacuum testing.
3. If vacuum insensitivity can be demonstrated, unit thermal vacuum test can be waived and four cycles are added to the unit thermal cycle test.
4. Maximum predicted temperature range includes ±11°C thermal uncertainty margin.
5. Test temperature range will envelope these two temperature ranges

The total number of thermal cycles for spacecraft units is the test parameter that receives the most discussion during the thermal tailoring process because it directly impacts the test duration and cost. The rationale for the SMC-S-016 total cycles (27, 20 and 14 cycles for qualification, protoqualification, and acceptance units, respectively) has been documented [7, 8] and is based upon test effectiveness goals of 99, 97.5, and 95 percent for qualification, protoqualification, and acceptance testing, respectively. Figure 1 shows how test effectiveness increases with thermal test cycles. The data are from two sets of spacecraft flight units [8, 9] with a polynomial curve fit through both sets of data. Both sources agree that to achieve a test effectiveness of 95 percent, about 14 acceptance cycles are required.

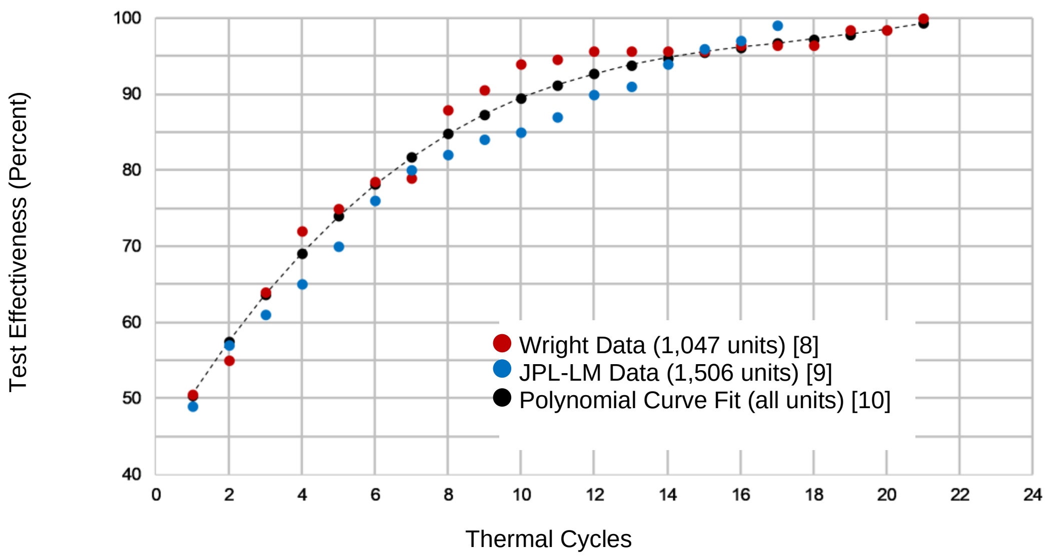

Figure 1. Test effectiveness for thermal test cycles. [8, 9]

The number of unit thermal cycles and the test temperature range work together to establish the necessary environmental stresses for electronic unit parts, connectors and solder joints to force latent defects into observable failures. Exposure to these test conditions, which are more severe than expected in flight, essentially moves the hardware through the infant mortality part of the bathtub reliability curve using low-cycle fatigue stresses. While the SMC-S-016 screening requirements establish effective levels of latent defect detection at an early level of assembly, the curves can be used in tailoring thermal test cycle for programs that have adopted a higher mission risk posture.

3. Historical Thermal Test Tailoring for Different Mission Risk Classes

Primary sources for understanding how testing requirements might be tailored for different mission risk classes are MIL- HDBK-343 [1] and Aerospace Mission Risk and Tailoring Guidelines [2 - 4]. In these latter three reports, typical practices to ensure mission success across the mission risk classes are described [2], guidelines for tailoring across the mission risk classes are discussed [3], and deviations from baseline requirements that could impact typical mission assurance postures across the mission risk classes are identified [4]. This section summarizes the requirements and recommendations applicable to characterizing the mission risk classes.

3.1 Thermal Design and Test Requirements from MIL-HDBK-343

Thermal design requirements from MIL-HDBK-343 are shown in Table 3. For Class A, B, and C programs, a thermal analytic model is required, so resulting temperature predictions will be compared to thermal requirements to demonstrate margins. For these classes, the thermal model will be verified though correlation with test data prior to flight. Verification shall be with a thermal balance test, although for simple Class C vehicles an ambient pressure environment thermal test may be used instead. For Class D programs, no thermal model is required.

Table 3. Thermal Design Requirements for Different Mission Risk Classes

	Class A	Class B	Class C	Class D
Computer thermal model	Required	Required	Required	Not required
Thermal verification of computer model	Thermal balance test	Thermal balance test	Thermal balance or thermal test	Not required
Use of redundancy	Used to ensure all critical functions, if practical	Used to ensure all critical functions, if practical	Usually a single string; redundancy used if safety critical	Usually a single string; redundancy used if safety critical

For Class A and B missions, use of redundancy is required to ensure that a single unit failure does not jeopardize functions that comprise primary objectives and capabilities of the mission. For Class C and D missions, redundancy is more selective and focuses on functions that could jeopardize the safety of personnel or other vehicle payloads (“do no harm”). Although not stated in MIL-HDBK-343, the intent is clear that thermal control subsystems of space vehicles of all four classes would be designed with the ±11°C thermal uncertainty margin and the 25% heater control authority margin.

Thermal test approach requirements from MIL-HDBK-343 are shown in Table 4. For Class A space programs, a full qualification test approach is required with a 10°C design margin. The first article would be acceptance and then qualification tested. Qualified units would not be flown and an assessment would be necessary to determine if qualified subsystems, payloads, and vehicle could be flown. Subsequent hardware would be acceptance tested and flown. For Class B space programs, the first articles are protoqualification tested (5°C design margin) and then flown. Subsequent articles would be acceptance tested. For Class C missions, all hardware is acceptance tested with no additional design margin (beyond the 11°C thermal uncertainty margin). For Class D programs, unit thermal testing is optional, but if performed, testing is done to acceptance levels. The text provides no clarification or criteria as to the conditions under which an optional test should be conducted. Subsystem and vehicle thermal tests are to acceptance levels.

A comparison of the requirements for the different mission risk classes confirms perceptions that Class A and B space programs are thermally tested in a similar manner, while Class C and D space programs accept a significantly higher risk in their test practices. While there are differences between all four classes, the similarities in these two groupings (Classes A–B and Classes C–D) are apparent.

Table 4. Test Approach Requirements for Different Mission Risk Classes

Level or Parameter	Build	Class A	Class B	Class C	Class D
Unit test	First unit	Qualification	Protoqualification	Acceptance	Optional (1)
	Subsequent units	Acceptance	Acceptance	Acceptance	
Subsystem test	First article / payload	Qualification	Protoqualification	Acceptance	Acceptance
	Subsequent articles	Acceptance	Acceptance	Acceptance	Acceptance
Vehicle test	First vehicle	Qualification	Protoqualification	Acceptance	Acceptance
	Subsequent vehicles	Acceptance	Acceptance	Acceptance	Acceptance
Thermal Margins (2)	First build	10°C (Qual.)	5°C (Protoqual.)	Not required	Not required
	Subsequent builds	Not required	Not required	Not required	Not required

(1) Testing is optional, but if performed, tests should be conducted at acceptance levels
(2) Thermal margins beyond the acceptance level. All hardware levels include ±11ºC thermal uncertainty margin

Therefore, to summarize the implications of MIL-HDBK-343 on thermal testing:

- A thermal model is required for Class A, B and C programs. A thermal balance test is required to correlate the model for Class A and B programs, and either a thermal balance test or another thermal test is required for model correlation for Class C programs. A thermal model is not required for Class D programs.
- Class A programs should use a qualification test approach on first hardware articles (unit, subsystem and vehicle with a 10°C margin) and these items are not flown (an assessment may result in flying the qualification vehicle). Subsequent articles are acceptance tested and flown.
- Class B programs should use a protoqualification test approach (5°C margin) on first hardware articles (and flown) and subsequent items are acceptance tested.
- Class C programs should use an acceptance test approach for all hardware items.
- Class D programs have optional unit testing (and if performed, to acceptance levels, but with no clarification as to when optional tests should be conducted) and have acceptance subsystem and vehicle testing.

3.2 Thermal Design and Test Requirements from the Aerospace Reports

From the Aerospace reports, design requirement approaches (verification methodology and use of redundancy) for the different mission risk classes are provided in Table 5 [2]. For Class A programs, formal testing verification is required, operational requirements are verified in test with significant margin, and single point failures are not allowed (full redundancy). Class B program verification approaches are similar with some allowances to non-test verifications and very few single point failures.

Class C program testing will focus on verification of critical requirements that align with primary mission objectives, with more allowance for single point failures. For Class D programs, testing will be for only primary mission and safety requirements, and single point failures are allowed. For Class A, B, and C programs, verification of operational requirements is demonstrated. For Class D programs, operational requirements are demonstrated but without margins and rarely with physical testing.

Table 5. Verification Requirements for Different Mission Risk Classes

	Class A	Class B	Class C	Class D
Testing requirements	• Established for each requirement • Mandatory physical testing to satisfy requirements • Must meet or exceed all established safety margins	• Same as Class A except: • May allow Analysis and Models and Simulation (M&S) for noncritical requirements only	• Established for critical requirements • Mandatory physical testing to satisfy mission-critical requirements • Analysis may be used for most requirements. • Must meet all established safety margins	• Established for major requirements or as designated by primary mission • Analysis or non-stressing tests acceptable for most requirements • Must meet basic safety margins and those mandated by primary payload and mission

Operational requirements	• Fully vetted for planned orbit / position
	• Tested with significant margins over expected lifetime of systems
	• Use of physical testing required where practical
		• Same as Class A	• Same as Class A	• Same as Class A except:
				  • Tested without margins
				  • Minimal use of physical testing

Single point failures (SPF) policy and redundancy	• SPFs not allowed. Redundancy required for all critical space vehicle functions and key instruments. High reliability cross-strapping methods followed.	• SPFs accepted by exception • Redundancy required for all essential space vehicle functions and key instruments	• SPFs allowed • Single string design allowed with selective redundancy for higher risk assemblies	• SPFs allowed • Single string design or selective redundant design approaches used

Differences in the thermal control subsystem design for the mission risk classes are shown in Table 6. Thermal modeling and test verification of the model results are required for Class A, B, and C programs. For Class D programs, thermal analyses are performed at the discretion of the developer, and if a thermal model is built, it may be simple with no thermal test verification.

Table 6. Thermal Control Subsystem Design Attributes for Different Mission Risk Classes

Class A	Class B	Class C	Class D
• Verification analysis / test must demonstrate design meets allocated requirements; overall design meets requirements under all mission conditions • Thermal balance modeling and testing required at all levels of design • Demonstrate and/or assess with thermal modeling: adequacy of thermal margins and acceptance limits for all thermal hardware • Independent thermal assessments conducted	• Similar to Class A • Exceptions include where thermal subsystem has heritage flight history and level of testing may be tailored as appropriate • Spot checks may be substituted for independent thermal analysis	• Designed to meet requirements under worse-case conditions plus protoqualification margins; assumptions and analysis must demonstrate operating and recovery from sate mode operations with margin • Thermal balance test verifies the thermal model • Government typically does no independent thermal analysis of the space vehicle	• Discretion of satellite manufacturer • Usually a simple thermal model is used (less detail than Class C models)

Environmental test approaches are summarized in Table 7. Environmental stress screening is formally required for Class A and B program, selectively required for Class C programs, and not required for Class D programs. Qualification testing is the baseline test approach for Class A programs, although minimal protoqualification testing is allowed. Protoqualification testing is the baseline test approach for Class B programs. Acceptance testing is the baseline test approach for Class C programs and for Class D programs, but testing is at the discretion of the developer.

Table 7. Test Approach Objectives for Different Mission Risk Classes [2]

	Class A	Class B	Class C	Class D
Environmental stress screening (ESS)	• Required	• Same as Class A	• Recommended for high volume production units, per customer and developed accepted processes. Reduced screening may be used	• Not required
Qualification	• Qualification method is documented with customer approval • Qualification article and levels • Minimal use of protoqualification testing of flight units • Systems and units functionally tested to environments plus margin at qualification / protoqualification levels	• Qualification method is documented with customer review • General use of proto-qualification testing of flight units • Systems and units are similar to Class A, except number of cycles, margins, and duration of test may be tailored based on program risk assessment and acceptance	• System test plan required with customer review • System functional and protoqualification tests to acceptance levels • Subsystem functionally stress tested to margins exceeding what will be experienced during system testing. Unit testing conducted to meet mission requirements, usually at acceptance levels	• No formal qualification testing. Safety and compatibility testing required by the launch vehicle provider and/or launch base • Other testing at discretion of developer with an informal test program usually followed. Unit tests at discretion of developer • Customer or other independent reviews are limited or not conducted at all

Test requirements for unit, subsystem, and vehicle-level testing at the different mission risk classes are summarized in Table 8. For all three hardware levels, testing is generally described as qualification and protoqualification for Class A and B programs, and protoqualification and acceptance for Class C programs. The possibility of protoqualification testing Class A program hardware (Table 8) is interesting, because elsewhere in Ref. 2, Class A programs are required to follow a qualification test approach with only minimal use of protoqualification testing. This may be the result of a general trend toward allowing more protoqualification testing of Class A hardware as a means of reducing program costs.

Testing requirements and oversight appear more flexible for Class C programs as compared to Class A and B programs. This is evidenced by two uses of the word “usually” in describing the type of oversight required for Class C programs. For Class D programs, there is no formal test requirements for unit and subsystem hardware, and vehicle-level testing will focus on requirements associated with safety, the launch vehicle, and the launch base.

Table 8. Test Level Approaches for Different Mission Risk Classes [2]

Test Levels	Class A	Class B	Class C	Class D
Unit test approach	• Unit functionality tested to environments plus margin at qualification and protoqualification levels	• Similar to Class A, except number of cycles, margins, and duration of test may be tailored based on program risk assessment and acceptance	• Unit testing conducted to meet mission requirements, usually at protoqualification levels	• Discretion of developer
Subsystem integration and test	• Subsystem functionally tested to environments plus margin at qualification / proto-qualification levels	• Same as Class A	• Subsystems functionally stress tested to margins exceeding what will be experienced during system testing	• Discretion of developer
Vehicle integration and test	• Complete system to subsystem to unit requirement verification plan is developed and delivered; qualification method selected is documented with government approval • Qualification / protoqualification levels required	• Qualification / protoqualification levels required; simulators may be used	• System test plan required with government review / oversight • System functional test to protoqualification levels required • Government usually present at system tests	• Safety and compatibility testing required by the launch vehicle provider and/or launch base • Other testing at discretion of developer with an informal test program usually followed

Recommended thermal test tailoring [3] for the different mission classes is shown in Tables 9a (for procurements of one or two vehicles) and 9b (for procurements of three or more vehicles). In these tables, MPT refers to the maximum predicted temperature range, the range that includes the thermal uncertainty margin.

Table 9a. Thermal Testing for Procurements of 1 to 2 Space Vehicles [3]

Hardware Level	Flight item	Class A	Class B	Class C	Class D
Unit level	First unit – non-flight	Qualification: MPT ± 10°C (1) 27 cycles	Not applicable	Not applicable	Not applicable
	First unit – flight	Protoqualification: MPT ± 5°C (1) 20 cycles	Flightproof MPT ± 5°C 14 cycles	Flightproof MPT ± 5°C 14 cycles	(2)
	Subsequent flight units	Acceptance: MPT (1) 14 cycles	Flightproof MPT ± 5°C 14 cycles	Flightproof MPT ± 5°C 14 cycles	(2)
Payload level		Same as Vehicle			
Vehicle level	First vehicle – non-flight	Not applicable	Not applicable	Not applicable	Not applicable
	First vehicle – flight	Protoqualification: MPT ± 5°C 4 cycles	Flightproof MPT ± 5°C 4 cycles	Flightproof MPT ± 5°C 4 cycles	(2)
	Subsequent flight vehicles	Acceptance: MPT 4 cycles	Flightproof MPT ± 5°C 4 cycles	Acceptance: MPT 4 cycles	(2)

Notes:
(1) Unit level testing is to MPT plus appropriate margins or standard screening temperature ranges (–34°C to +71°C for qualification, –29°C to +66°C for protoqualification, and –24°C to +61°C for acceptance)
(2) Verification tailoring will establish flightproof, acceptance, none, or a combination thereof

Table 9b. Thermal Testing for Procurements of 3 or More Space Vehicles [3]

Hardware Level	Flight item	Class A	Class B	Class C	Class D
Unit level	First unit – non-flight	Qualification: MPT ± 10°C (1) 27 cycles	Not applicable	Not applicable	Not applicable
	First unit – flight	Protoqualification: MPT ± 5°C (1) 20 cycles	Protoqualification: MPT ± 5°C (1) 20 cycles	Flightproof MPT ± 5°C 14 cycles	(2)
	Subsequent units	Acceptance: MPT (1) 14 cycles	Acceptance: MPT (1) 14 cycles	Flightproof MPT ± 5°C 14 cycles	(2)
Payload level		Same as Vehicle			
Vehicle level	First vehicle – non-flight	Qualification: MPT ± 10°C 8 cycles	Not applicable	Not applicable	Not applicable
	First vehicle – flight	Protoqualification: MPT ± 5°C 4 cycles	Protoqualification: MPT ± 5°C 4 cycles	Flightproof MPT ± 5°C 4 cycles	(2)
	Subsequent vehicles	Acceptance: MPT 4 cycles	Acceptance: MPT 4 cycles	Acceptance: MPT 4 cycles	(2)

Notes:
(1) Unit level testing is to MPT plus appropriate margins or standard screening temperature ranges (–34°C to +71°C for qualification, –29°C to +66°C for protoqualification, and –24°C to +61°C for acceptance)
(2) Verification tailoring will establish flightproof, acceptance, none, or a combination thereof

The values shown in Tables 9a and 9b do not reflect the most recent requirements in SMC-S-016. Changes were made to the number of thermal cycles for protoqualification units (Table 2) and the use of flightproof. The distinction between protoqualification and flightproof is:

- Protoqualification
  - First flight unit: Tested to stresses (temperatures) and durations (cycles) about halfway between acceptance and qualification
  - Subsequent flight units: Tested to acceptance levels
- Flightproof
  - All flight units: Tested to protoqualification stresses (temperature levels) and acceptance durations (cycles)

Flightproof is listed as the baseline test approach for Class B and C hardware (1 or 2 vehicles) in Table 9a and Class C hardware (3 or more vehicles) in Table 9b. A consequence of such testing is that for Class B and C subsequent flight units, subsystems and vehicles may be tested to higher stresses than Class A hardware. As a result, SMC-S-016 disallows flightproof thermal testing. Therefore, Tables 9a and 9b can be combined into Table 9c. The recommendations given in Table 9c are consistent with previous class descriptions with qualification and protoqualification testing for Class A programs, protoqualification testing for Class B programs, and acceptance testing for Class C programs.

Table 9c. Summary of Thermal Test Tailoring Recommendations [3]

Hardware Level	Hardware Item	Class A	Class B	Class C	Class D
Unit level	First unit – non-flight	Qualification: MPT ± 10°C (1) 27 cycles	Not applicable	Not applicable	Not applicable
	First unit – flight	Protoqualification: MPT ± 5°C (1) 20 cycles	Protoqualification: MPT ± 5°C (1) 20 cycles	Acceptance MPT (1) 14 cycles	(2)
	Subsequent units	Acceptance: MPT (1) 14 cycles	Acceptance: MPT (1) 14 cycles	Acceptance MPT (1) 14 cycles	(2)
Payload level		Same as Vehicle			
Vehicle level	First vehicle – non-flight	Not applicable (3)	Not applicable	Not applicable	Not applicable
	First vehicle – flight	Protoqualification: MPT ± 5°C 4 cycles	Protoqualification: MPT ± 5°C 4 cycles	Acceptance: MPT 4 cycles	(2)
	Subsequent vehicles	Acceptance: MPT 4 cycles	Acceptance: MPT 4 cycles	Acceptance: MPT 4 cycles	(2)

Notes:
(1) Unit level testing is to MPT plus appropriate margins or standard screening temperature ranges (–34°C to +71°C for qualification, –29°C to +66°C for protoqualification, and –24°C to +61°C for acceptance), whichever is more severe.
(2) Verification tailoring will establish acceptance, none, or a combination thereof.
(3) If there is a qualification space vehicle that will not be flown, it should be tested to MPT ± 10°C for 8 cycles.

Therefore, to summarize the implications of the Aerospace reports on thermal testing:

- For Class A programs:
  - Formal testing is required for units, subsystems and vehicles with operational and performance verification and environmental stress screening
  - A thermal model is required with thermal balance test correlation
  - Units are tested with a qualification or protoqualification test approach (first units) with acceptance testing on subsequent units
  - Subsystems and vehicles will typically use a protoqualification test approach (first item) and acceptance testing on subsequent items. Qualification may be performed, but not typical
- For Class B programs:
  - Formal testing is required for units, subsystems and vehicles with operational and performance verification and environmental stress screening (same as Class A)
  - A thermal model is required with thermal balance test correlation (same as Class A)
  - Units are tested with a protoqualification test approach (first units) with acceptance testing on subsequent units
  - Subsystems and vehicles will typically use a protoqualification test approach (first items) and acceptance testing on subsequent items (same as Class A)
- For Class C programs:
  - Formal testing is required for mission-critical requirements with operational and performance verification, and it is recommended that testing include environmental stress screening
  - A thermal model is required with correlation using a thermal balance test or another type of thermal test
  - Units are to be tested with a protoqualification or acceptance test approach (first units) with acceptance testing on subsequent units
  - Subsystems and vehicles will be acceptance tested

- For Class D programs:
  - Physical testing is not required for units, subsystems and vehicles, but may be performed to acceptance levels. If conducted, testing will verify critical operational and performance requirements, and environmental stress screening is optional. Testing will also focus on verification of safety requirements and those mandated from the launch vehicle and launch pad facilities
  - A very simple thermal model may be constructed, but thermal model verification is not required
  - Units, subsystems, and vehicles may be tested to acceptance levels. Requirements associated with safety, the launch vehicle and the launch facilities will need to be verified during program development

3.3 Comparison of Recommendations between MIL-HDBK-343 and the Aerospace Reports

There is very good consistency between the thermal test requirements and recommendations found in MIL-HDBK-343 and the Aerospace reports. A minor difference is that while both sources require thermal model correlation, the Aerospace reports allow for Class C program thermal model correlation data to be from ambient pressure testing. Given that radiation heat transport is a prominent mode of heat transfer in most space vehicles and that vehicle thermal vacuum testing will be conducted, a thermal balance test as part of the vehicle thermal vacuum test makes the most sense.

The other key difference is that MIL-HDBK-343 takes a stronger qualification position on Class A hardware. In MIL-HDBK-343, qualification and protoqualification are baseline test approaches for units, subsystems, and vehicles, while in the Aerospace reports, qualification and protoqualification are a baseline test approach for units, but subsystems and vehicles will tend more toward protoqualification testing. It is believed that this difference can be attributed to the fact that current programs are significantly more cost-conscious than in previous decades, and that building and not flying subsystems and vehicles is rare for nearly all space programs.

4. Common Perceptions of Program Risk Classes

Perceptions play an important role in setting expectations for the characteristics of the different risk classes. While perceptions can vary significantly from one customer to another and within contractor organizations, it is nevertheless important to understand common perceptions and how they influence the risk posture and tailoring opportunities. While the focus of this report is on Class C and D space programs, this section will begin with typical perceptions for Class A and B space programs.

4.1 Perceptions of Class A and B Space Programs

The general perception of the different mission risk classes is that Class A and B space programs are nearly interchangeable for mission risk and baseline verification methodologies. They are extremely low risk ventures with a high emphasis on ensuring mission success. Both risk classes will use protoqualification development strategies with significant customer oversight. There is high confidence that these missions will be successful, meeting operational and performance objectives, and exceeding operational life spans.

With respect to establishing an environmental test program for Class A and B programs, there is an expectation that these space vehicles will be tested to the test effectiveness levels discussed in Section 2. Qualification tests should achieve an effectiveness of 99 percent, protoqualification tests, 97.5 percent; and acceptance tests, 95 percent. Historical test effectiveness data, such as provided in Figures 1, can be used to determine the rigor of the test programs.

4.2 Perceptions of Class C Space Programs

Class C space programs are characterized as carrying greater risk, but with a high expectation of mission success. Often, the balance between these two conflicting perspectives results in program management and decision-making conflict. Common reasons for a Class C designation and typical conflicting opinions that arise during the development process are shown in Table 10. The text that immediately follows Table 10 provides more discussion of the reasons and perspectives.

Table 10. Primary Reasons and Conflicting Perceptions for Class C Space Programs

Primary Reason for Class C Designation	Counter Perspective for Class C Designation
The mission is deemed not critical to national security	• Customer: “But this thing needs to work after launch” • Negative public perception from mission failures is hard to recover from • Contractor’s personal pride in excellence does not tolerate failures • Criticality (to mission success) is sometimes subjective and may differ between factions
There is a desire for program cost control	• There is a common perception that adding money will improve the likelihood of mission success • Budgets are difficult for some customers to reasonably control • There are baseline costs in space programs that cannot be scaled
Schedule constraints are paramount toward meeting mission goals and objectives	• Schedule delays are common in the space industry and sometime necessary to correct problems. Such delays to fix problems will increase the likelihood of mission success • Schedule windows are typically less critical for military programs than they may be for NASA, scientific, and commercial programs
The space vehicle design is simple compared to Class A and B vehicles	• The simplicity of a space vehicle may be subjective • There are baseline complexity issues for all space vehicles that cannot be adjusted or scaled with cost

A key designation for Class C programs is that they are not critical to national security. While this may be well understood, many times the customer expects performance to the same levels as Class A and B programs. Personal and corporate reputations are attached to the success of individual Class C programs to the point where there is low tolerance for mission failure. Furthermore, the importance of each space mission is somewhat subjective. The customer and the contractor working the program take personal pride in the mission and may tend to increase its importance above that held by other organizations.

Limitations on program costs and control of development schedules may be another reason for designating a space program as Class C. Schedule control is tied directly to cost control so these two reasons can be viewed as having the same source. Once in development, however, problems arise and it takes time and money to fix these problems. Space programs are notorious for overrunning their budgets and the tendency to blame the contractor for these overruns is not always fair. Even Class C space programs are complex systems that will have workmanship and design issues like Class A and B programs. Not fixing a problem almost certainly guarantees mission impact and given the high costs invested in the program and fixed launch costs, even for a Class C program, it remains in the best interest of the program to spend additional resources to increase the likelihood of mission success. There are common expectations that launch delays and cost overruns are characteristic of space programs and these are necessary to gain confidence in mission success before launch, even for a Class C program.

Finally, the perception that a space program is relatively simple may be a reason for a Class C designation. As previously stated, even Class C programs have design and workmanship challenges that need formal verifications to establish mission assurance baselines. Relative simplicity does not neatly scale with cost as there are fixed requirements and launch activities that need to be satisfied regardless of the program’s class designation.

These conflicting arguments sometimes result in Class C programs being designed, built and tested similarly to Class A and B programs, with cost reductions due to the reduced size and relative simplicity of the program. Often, the customer’s high mission success expectation makes tailoring of test verifications difficult. Another event that complicates the development of these types of programs is when a program starts out at Class C, but then gets changed to Class B during its development. In such cases, the nature of the development cycles and verification methodologies are difficult to modify because program costs are rarely increased to a level necessary to bring the program up to a Class B level. In such cases, compromises are made and best efforts are proposed to increase mission assurance.

For Class A and B programs, test effectiveness levels are understood for qualification, protoqualification, and acceptance hardware, such that environmental test parameters can be established. Setting a 95 percent test effectiveness expectation for acceptance hardware means that a 14-cycle thermal test will be required (Figure 1). The difficulty with tailoring test requirements for Class C programs is that there is no established test effectiveness expectation for these programs. If there were, mission assurance data could be used to appropriately tailor test standards from Class A and B program levels. As long as customers want the cost savings expected of Class C programs but expect mission success typical of Class A and B programs, these conflicting goals will make tailoring program requirements a difficult, inconsistent, and subjective process.

4.3 Perceptions of Class D Space Programs

A review of the recommendations in Section 3 would appear to suggest that there are few consistent expectations for the Class D verification methodologies. Vehicles are designed and tested to acceptance requirements with no environmental stress screening of hardware and with no design margins. Testing will focus on the verification of major mission requirements only. Safety and compatibility testing will be required by the launch vehicle provider, but all other testing is at the discretion of the developer.

Class D programs can be divided into two groups based upon expected mission success. There are some Class D efforts that are developed with extremely low expectation for mission success. These might be experimental ventures with no national security objective. Many originate as university and high school projects and a significant number of satellites in this category are cubesats. The second category of Class D programs are ones with a higher mission success expectation, not as high as a Class C, but higher than a typical college project. Cubesats are found in the second category along with larger vehicles.

Besides mission purpose, a primary discriminator between these two groups is program cost. The typical cost for a university 1U (1 unit) cubesat (10 cm x 10 cm x 10 cm) would about $10,000 to $100,000 to build the hardware and about another $50,000 to launch into space. Cubesats in this range have little mission assurance. In contrast, cubesats in the second category with higher launch success expectations will cost in the millions of dollars for construction and launch costs at about $100,000 per U.

Environmental testing recommendations will need to distinguish between these two groups because the cost of the test program needs to be consistent with mission assurance plans and flight success expectations. This is especially true given that many Class D programs are being built with extremely tight budgets and limited resources by universities and high schools.

5. Thermal Test Tailoring Recommendations for Class C and D Space Programs

This chapter provides thermal test tailoring recommendations for Class C and D space programs. It is recommended that Class A and B space programs follow baseline test requirements per SMC-S-016, with tailoring specific to mission criticality, heritage, and design characteristics of the vehicle. As explained in Chapters 3 and 4, there will be greater effort and resources put into the test program for Class C vehicles as compared to Class D vehicles. Flight success expectations, mission life, and mission assurance goals will be greater for Class C programs, so the ground test verifications must reflect this.

5.1 Thermal Test Recommendations for Class C Space Programs

Class C space vehicles should have test programs tailored from SMC-S-016 baseline requirements. The extent to which the requirements are modified depend upon the mission success expectations, program cost, program schedule, heritage experience, vehicle size, and other factors. Class C programs are developed with a moderate risk postures, but there is still a desire that these risks be adequately understood and controlled, such that the mission will be successful. If it were just a matter of redefining test effectiveness levels for Class C efforts, test parameters could be adjusted within known historical databases. There has been no effort to clearly specify a reduced mission success standard for higher risk programs. As a result, customers expect and contractors propose test tailoring with little conformity to consistent mission assurance levels.

Nevertheless, historical understanding of the various test objectives can help determine risks associated with test deletions under consideration so appropriate tailoring can be made. The following text describes each thermal test, its test objectives and tailoring risks.

5.1.1 Unit Thermal Cycle Test Recommendations for Class C Space Programs

For Class C programs, the unit thermal cycle test should never be deleted from the test program. This is the most effective test for finding defects and workmanship errors in flight hardware. Elimination of this test will result in an increased number of defect escapes into higher levels of assembly and into flight. The stresses associated with the unit thermal cycle test are different than seen in the unit thermal vacuum test, so the thermal vacuum test will not reliably find the escapes that would be discovered from the thermal cycle test.

Regarding test parameters, the test program should adhere to the prescribed test temperature ranges. Most electronics are designed to operate and perform well within the -24°C to +61°C range, so testing should be conducted at least with this minimum range. The test temperature range is not a significant contributor to the test duration so testing to the widest temperature range practical should be a standard practice.

The test parameter with the most impact on the test duration is the number of cycles, and it is not surprising that this parameter is the most discussed feature of a test program for tailoring possibilities. The rationale for the number of test cycles is based on the results presented in Figures 1. From these results, 14 acceptance cycles (14 thermal cycles or 10 thermal cycles with 4 thermal vacuum cycles) are necessary to achieve the 95 percent test effectiveness goal. Reducing testing to 8 thermal cycles decreases the test effectiveness to about 85 percent, thus increasing the failure escape rate from 5 percent to 15 percent, a three-fold increase in the number of escapes. Furthermore, the knee in the curve, at about 10 cycles, transitions from a steep slope where test effectiveness will vary greatly with cycle number to a more nearly constant value where test effectiveness does not change significantly with cycles. For this reason, testing with fewer than 10 cycles has a higher test effectiveness uncertainty as compared to testing with 10 cycles or more. Therefore, 10 cycles (with a test effectiveness of about 90 percent) should be the minimum number of cycles a unit thermal test adopts.

The risk with any reduction in the number of thermal cycles is that design and workmanship problems will go undetected in the test and will escape to higher levels of assembly where rework is more expensive and time-consuming. As test stresses are less severe at higher levels of assembly, there is also increased risk that these escapes will not be caught in vehicle testing, but rather pass into flight.

5.1.2 Unit Burn-In Test Recommendations for Class C Space Programs

Unit burn-in testing ensures a consistent thermal exposure for all spacecraft electronic units and their associated parts and connectors. The requirements accomplish time-at-temperature objectives, although the burn-in test duration is a total thermal test exposure and includes time at cold temperature plateaus and temperature transitions. The burn-in duration requirement includes the time accrued in unit thermal cycle and unit thermal vacuum testing, so for some units that spend considerable time in these two tests, burn-in test requirements can be accomplished without a burn-in test.

Burn-in testing is an environmental stress screening test that adds time at stressing temperatures. This is a critical objective for many electronic parts. Compared to the unit thermal cycle test, the unit burn-in test detects fewer defects because the burn-in test is a continuation of the thermal cycle test and an effective thermal cycle test will find many of the same types of failures as would be found in the burn-in test. Nevertheless, sufficient burn-in duration should not be deleted from a Class C thermal test program because it serves an important role in verifying part and unit integrity.

Important burn-in test parameters are the test temperature range and test duration. The 200-hour duration requirement from SMC-S-016 has as its basis results from a study conducted by Smith [11]. Although these results, shown in Figure 2, are dated, they provide the most complete assessment of failures detected as a function of total thermal test exposure.

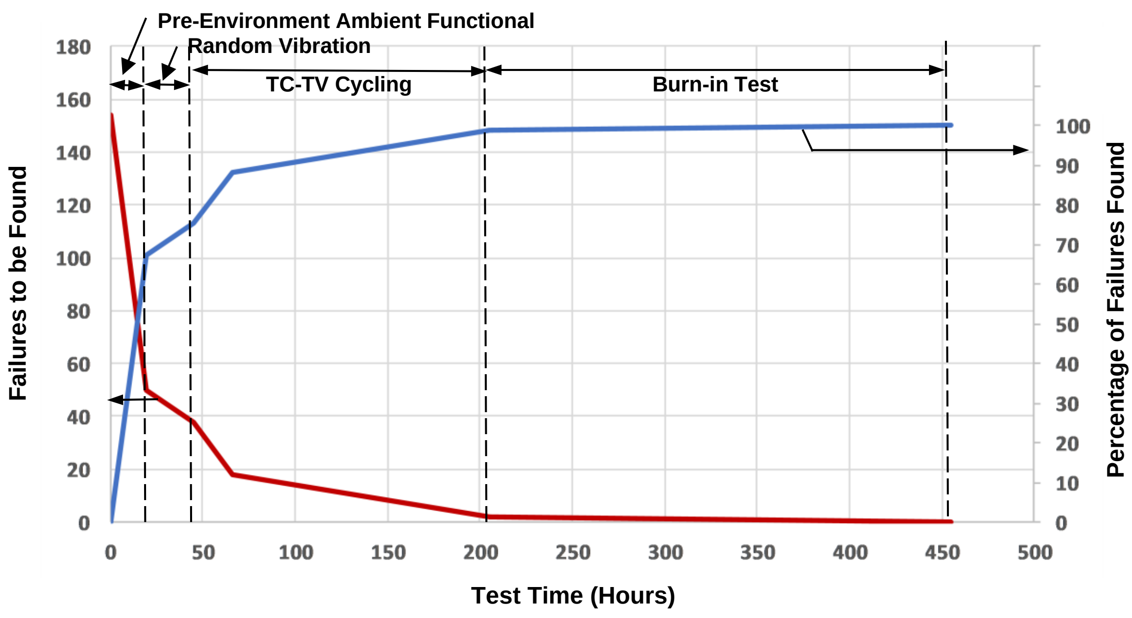

Figure 2. Failures detected across different test environments.

Insight can be gained with a more in-depth scrutiny of Smith's data. Beginning at about 48 hours, thermal cycle and thermal vacuum testing exposed units to the thermal test environment. The change in slope at hour 66 is due to a higher number of failures found during the first thermal cycle compared to later cycles.

At about 205 hours, burn-in began and continued for about another 250 hours. For the 65 units in this dataset, at 48 hours, there were 38 failures still to be detected. Twenty failures were found in the first thermal cycle leaving 18 failures to be found in the remaining thermal exposure (through 450 hours). In the remaining thermal cycle/vacuum testing (cycles 2 through 8), 16 failures were found leaving only two failures to be found in the burn-in test that began at hour 205. Ninety-five percent of 38 failures is about 36, so thermal cycle and thermal vacuum testing on these units found 95 percent of the remaining failures. This was accomplished between hours 48 and 205, or over 157 hours of testing. Subtracting the time for the first cycle and assuming a linear detection of failures over cycles 2 through 8, this results in a failure detected every 8.5 hours for cycles 2 through 8 (16 failures over 137 hours).

Figure 2 also shows the percentage of failures detected in these environmental tests based upon the total number of failures (154). A similar plot for the 157-hour TC-TV test is shown in Figure 3. This is essentially the same Figure 2 data for only the TC-TV test using 38 available failures to be found. The TV-TC test effectiveness is computed by dividing the number of failures detected by the total number of failures to be detected (38). Although Smith's data extends to 450 hours, Figure 3 ends at 157 hours because it was not clear when the remaining two failures were detected. Characteristic of Figure 1, the first thermal cycle detects a significant share of the latent defects, in this case 53 percent of them.

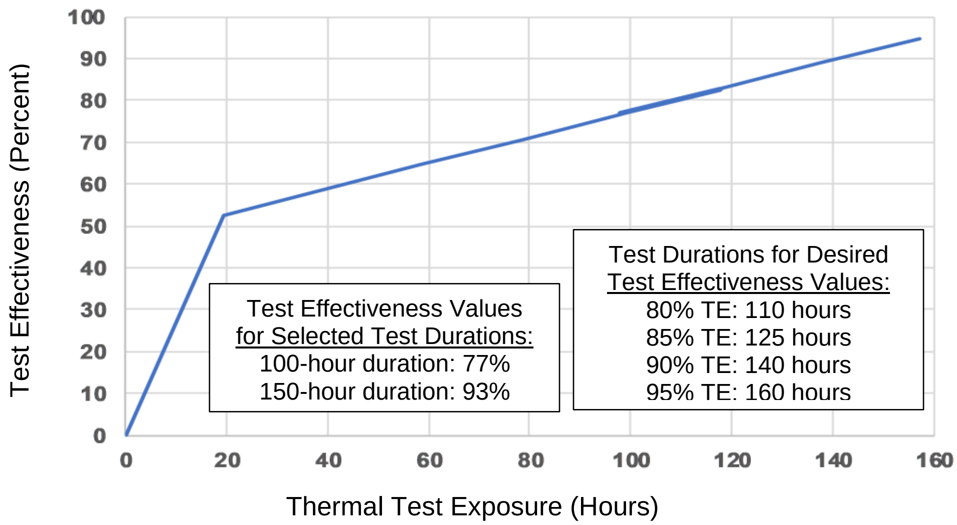

Figure 3. Burn-in test (including thermal cycles) effectiveness as a function of thermal test duration.

Smith's results show that thermal test exposures of 100 and 150 hours result in detecting about 77 percent and 93 percent, respectively, of the total failures. Testing to 157 hours would have detected 95 percent of the total failures to be found. In addition to determining test effectiveness values, Figure 3 results can also be used to select a burn-in test duration to achieve a desired test effectiveness. Representative values for both cases are shown in the inserts in Figure 3. The results shown in Figure 3 represent results from one set of 65 units and may not be representative of other sets of units.

The other burn-in test parameter of importance is the test temperature range. Burn-in testing should be conducted as a continuation of the unit thermal cycle test with the unit either cycling over the acceptance test temperature range or held at the hot acceptance temperature. In recent years there has been an increasing number of proposals for ambient temperature burn-in testing. This should be avoided as burn-in testing is an environmental screen and testing at hot and cold temperatures is significantly more effective than at room temperature. Results from the Smith, Wright and JPL-LM studies are based upon unit thermal testing cycling over the acceptance temperature range.

The impact of reducing the number of cycles in or deleting the burn-in test from for a Class C test program is that some units will not be environmentally screened to recommended thermal thresholds for duration. Defects that would have been detected in the unit test program will become escapes and either be detected in higher levels of tests where repair is more expensive or slip into flight where failure can jeopardize mission objectives. The burn-in test is a continuation of the thermal cycle test and therefore does not involve any additional test set-up or tear-down time. While it is an environmental test that is not as effective as the unit thermal cycle test, it should be included in test programs for Class C programs where mission success is important.

5.1.3 Unit Thermal Vacuum Test Recommendations for Class C Space Programs

The unit thermal vacuum test provides environmental stress screening of electronic units with vacuum-sensitive features and verifies unit performance in a flight-like environment. Unit thermal testing tends to emphasize failure detection, and as a result the unit thermal vacuum test is sometimes tailored out of Class C space vehicle test programs. This is commonly done to save schedule time, but technical considerations should be used to justify the deletion of this test. The unit thermal vacuum test detects different types of failures than the unit thermal cycle test [12], so deletion of the test should only be proposed after a technical assessment of vacuum sensitivity of the unit.

For some Class C programs, a technical assessment may appropriately justify the deletion of some unit-level thermal vacuum testing. When vacuum insensitivity can be demonstrated, the unit thermal vacuum test may be waived as it would for units on a Class A or B program. For some Class C vehicle designs, the vehicle thermal vacuum testing may be nearly as perceptive as the unit thermal vacuum test for small vehicles with the following design features:

- Limited number of electronic units
- Electronic units that are not vacuum sensitive
- Simple, low power electronic units
- Space vehicle designs that are not highly dependent on radiation heat transfer for thermal control
- Relatively easy access to internal units

If all units are insensitive to vacuum conditions, deletion of the unit thermal vacuum test poses a very small risk to the unit verification process. If all units have very low power dissipation and the rest of the vehicle does not rely on radiation heat transfer to maintain temperature limits, deletion of the unit thermal vacuum test poses a small risk because the unit and vehicle thermal design relies on conduction instead of radiation and thermal gradients should be small. In such cases, the unit thermal cycle test likely is as perceptive at finding workmanship defects. Finally, a vehicle with easy internal access will simplify the rework obstacles if anomalies are later found in the vehicle thermal vacuum test.

If unit thermal vacuum testing is eliminated from the test program, then unit operation and performance verifications that would have been accomplished at the unit level may need to be conducted in the vehicle thermal vacuum test. Vehicle tests are never as perceptive as unit tests, so additional testing may be necessary to fully understand unit performance and integrity.

If the above considerations are not satisfied and the unit thermal vacuum test is deleted, defects that would have been found in the unit test will escape to a higher level of assembly or into flight. Test anomalies found in vehicle-level test will be more expensive to correct even if unit access is simple. Therefore, careful consideration should be taken when considering deleting this test. If properly managed, however, the elimination of this test may be a positive opportunity for maintaining the program's cost and schedule requirements.

5.1.4 Vehicle Thermal Cycle Test Recommendations for Class C Space Programs

The vehicle thermal cycle test is not in the baseline SMC-S-016 test program. It was included as an option for contractors that desire more screening of their flight hardware. It is therefore recommended that this test not be included in the test sequence of Class C programs. It might be added later if unit level thermal test results suggest that additional screening is still needed, but the preference is to accomplish unit-level test objectives at the unit level and not at a higher level of assembly. Deleting this test from the test program should have a negligible risk to the test program because the emphasis of vehicle thermal testing will be the thermal vacuum test.

5.1.5 Vehicle Thermal Vacuum Test Recommendations for Class C Space Programs

The vehicle thermal vacuum test is a critical test in the verification process of the space vehicle. Of all ground testing, this one best simulates a flight environment for the verification of mission objectives and demonstration of flight-worthiness. The concern with including this test will be its duration, but the vehicle thermal vacuum test provides the mission assurance under flightlike conditions necessary to have confidence in meeting mission performance. For these reasons, the vehicle thermal vacuum test needs to be included in the Class C program test sequence. The number of test cycles and the methodology of establishing the test temperature ranges should be the same as used for Class A and B space programs. There may be some interest in reducing the number of cycles, and in some cases schedule needs may require such a reduction. Given the value of this test and the small schedule impact for each additional cycle, there is good technical rationale for maintaining at least the four-cycle baseline.

Thermal balance testing should be included as part of the vehicle thermal vacuum test for the first of any identically built vehicles. Class C vehicles do not include protoqualification hardware, but tests are needed to verify the thermal control subsystem design. Depending upon the complexity of the thermal control subsystem and the thermal modeling, thermal balance testing should be like that conducted for Class A and B vehicles (e.g., hot operational, cold operational, and cold non-operational test phases with thermal model correlation after the test).

5.1.6 Summary of Thermal Test Recommendations for Class C Space Programs

Table 11 summarizes considerations when unit and vehicle ground tests might be deleted from a test program for Class C vehicles and the associated risks for deleting these tests. While Class C programs should not be tested to the same fidelity as Class A and B programs, a sufficient test program is still needed to meet mission assurance expectations for these programs. At the very least, this will include unit thermal cycle testing, perhaps with embedded burn-in requirements, and a vehicle thermal vacuum test. For Class C programs of greater complexity or longer life missions, additional testing should be included.

Table 11. Considerations and Risks Associated with Class C Program Thermal Test Deletion

Test	Conditions where Test Deletion Might be Considered	Risk with Test Deletion
Unit thermal cycle test	• **None: this test should not be deleted** • Number of thermal cycles may be reduced to align with test effectiveness goals	• Unit thermal cycle test most effective ground test for detecting defects • Deletion or reduction in cycles will increase likelihood of not detecting defects at unit level (Testing to less than 10 cycles is discouraged)
Unit burn-in test	• Test duration may be reduced to align with test effectiveness goals	• Reduction in test duration will increase likelihood of not detecting defects at unit level
Unit thermal vacuum test	• Units are vacuum insensitive • Units are simple and low power • Vehicle design is simple with few units and easy access to units	• If there are vacuum-sensitive units and this test is eliminated, vacuum-related failures will need to be detected at vehicle level where rework is costlier • If unit thermal designs depend on radiation heat transfer for thermal control, eliminating this test will defer flight-like verification to vehicle level • If vehicle access is difficult, eliminating this test will increase rework costs when failures are found at the vehicle level
Vehicle thermal cycle test	• Generally acceptable to delete, but may used for added vehicle and unit stress screening	• With a properly planned vehicle thermal vacuum test, there should be no impact to program risk if this test is deleted
Vehicle thermal vacuum test	• **None, this test should not be deleted** • Number of thermal vacuum cycles may be reduced to meet schedule goals	• Vehicle thermal vacuum test is the best simulation of ground test environments for mission performance verification • This test demonstrates workmanship integrity and overall flight-worthiness for meeting mission objectives • Deletion of this test will increase uncertainty regarding mission objectives being met

A case study of an actual Class C space vehicle thermal test program [13] is provided in the appendix. It is included not as a baseline set of recommendations, but rather as an example of typical tailoring events that occur on cost and schedule constrained Class C programs and some the implications of the tailoring. Lessons learned are also described.

5.2 Thermal Test Recommendations for Class D Space Programs

As previously discussed, Class D space program can be divided into two groups based upon their mission success expectation, program cost, and program schedule. Table 12 provides a summary of the differentiation between the two types of Class D programs. Thermal test recommendations for Class D programs with a relatively high expectation of mission success will be discussed in Section 5.2.1. Recommendations for Class D programs that are more experimental will be discussed in Section 5.2.2.

Table 12. Differentiation between Two Types of Class D Space Programs

Program Feature	Class D Space Program	
	High Success Expectations	Lower Success Expectations
Program development cost	More than 1 million dollars	Less than 100,000 dollars
Ground testing	Yes	Safety (1)
Test levels	Acceptance	Not applicable
Thermal model development	Simple model	None
Thermal subsystem verification	Thermal balance test or analysis	None
Use of redundancy	Very limited	Very limited to none

(1) Only for the verification of safety margins as mandated by launch vehicle and payload requirements.

5.2.1 Thermal Test Recommendations for Class D Programs with High Success Expectations

With a relatively high expectation that the mission will succeed, these Class D vehicles will require ground testing to verify the design and workmanship of the flight hardware. In deciding what ground tests should be included for a space vehicle in this category, it is helpful to begin with the testing recommendations outlined for Class C vehicles and tailor from this perspective using technical rationale based upon the size and complexity of the vehicle as well as practical cost and schedule constraints. The reason for beginning from this starting part is that in many cases, customers of these types of Class D vehicles have very similar experience and flight success expectations as Class C missions.

Class D space vehicles will typically be much smaller in size than Class C programs, so it may be possible to combine unit and vehicle environmental testing without a significant risk to the test program schedule. If unit-level testing is deferred to the vehicle level, one should expect to find unit-related failures in the vehicle test. If these units would be difficult to access, remove, and replace, the option of deferring the unit test may need to be reconsidered. Furthermore, unit-level testing should be considered for any unit that has vacuum-sensitive features, is relatively complex, or is critical to the mission. If unit-level testing is deferred to the vehicle-level of assembly, the test parameters should be consistent with the test objectives of unit testing (e.g., more cycles, wider temperature ranges, and higher stresses) to satisfy test objectives associated with unit testing.

The vehicle thermal vacuum test should remain in the baseline test program for the same reasons given for Class C programs. There may be a desire to reduce the number of cycles, but if there was no unit-level thermal vacuum test, a minimum of four cycles should be maintained because additional workmanship and hardware screening is necessary. If there was unit thermal vacuum testing for most electronic units, the emphasis of the vehicle thermal vacuum test will become demonstration of performance requirements, and requirement compliance during last cycle performance tests will be the primary goal. First and intermediate cycles may consist of shorter functional tests.

Adding a thermal balance test to the thermal vacuum test will depend upon several consideration, including:

- The complexity of the thermal control subsystem and the need to verify the thermal model
- The criticality of the thermal design toward meeting mission success
- An overall risk assessment considering such factors as units with high power dissipation, uncertainties in orbit, attitude, material properties, etc.

If conducted, the thermal balance test should include the same phases as would be planned for a Class C program (e.g., hot operational, cold operational, and cold non-operational test phases with thermal model correlation after the test).

5.2.2 Thermal Test Recommendations for Class D Programs with Lower Success Expectations

Per the Cubesat Design Specification (CDS) [14], ground testing of cubesats is necessary to satisfy all launch provider requirements and to ensure the safety of the cubesat, its deployment device, and the primary mission. The launch provider test requirements will supersede testing environments from other sources and the deployment device will need to be tested in a manner like the cubesat. The CDS states that, at the very least, cubesats will undergo the following tests:

- Random vibration testing to the environment specified by the launch provider
- Thermal vacuum bakeout to ensure adequate outgassing of components to the environment specified by the launch provider
- Shock testing to the environment specified by the launch provider
- Visual inspection and measurement of critical areas and dimensions

The CDS also provides a testing philosophy that should be adopted by low-cost cubesat developers. The baseline approach is like testing for Class A and B vehicles with either qualification or protoqualification (protoflight) testing on the first cubesat and acceptance testing for subsequent identical vehicles. Qualifications tests are performed on non-flight hardware (i.e., engineering units) with test levels defined by the launch provider. If the protoflight test approach is taken, protoflight tests are conducted on the flight cubesat with levels defined by the launch provider. After delivery and integration of the cubesat into the delivery device, additional testing will be conducted with the integrated system to ensure proper integration into the delivery device. These additional tests will be to acceptance levels and defined by the launch vehicle provider. The flow of a typical test sequence is shown in Figure 4.

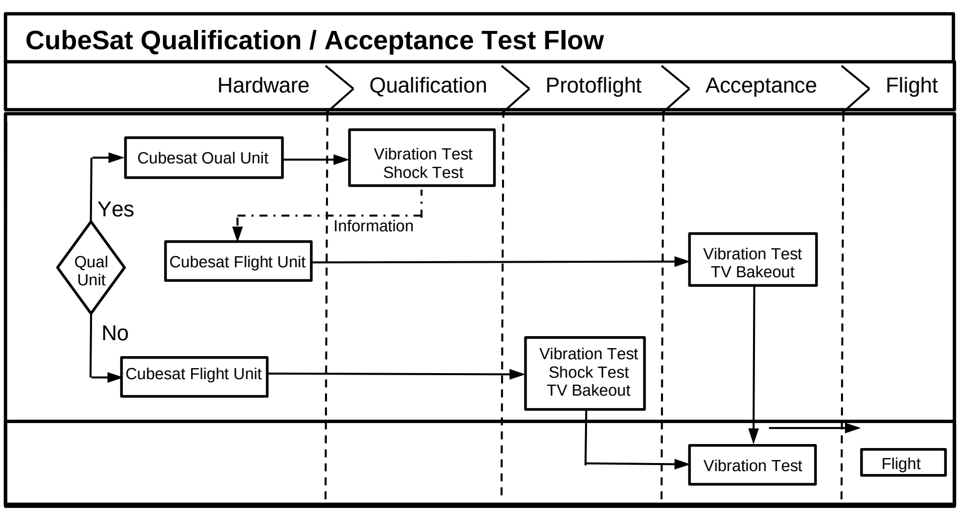

Figure 4. General cubesat test flow diagram. [14]

The only thermal test in the prescribed test flow is a thermal vacuum bakeout. Without any functional or performance tests, this is an environment exposure primarily to ensure outgassing of the cubesat flight hardware. The tests prescribed by the Design Specification are not intended to screen flight units for workmanship defects or to better understand how the flight hardware will operate in a flightlike environment. Rather, these tests have been specified to comply with "Do No Harm" guidelines for other cubesats and payloads being carried by the launch vehicle. The fact that the launch vehicle provider is specifying the test environments is further evidence that the launch vehicle contractor has the primary responsibility of ensuring that cubesats and payloads not interfere with each other while in proximity before orbital deployment. The test environments stipulated by the launch vehicle provider are meant to ensure life through the encapsulated duration of ascent and there is no recognition for the need to test to the harsh space environment seen after deployment.

For cubesats with a very limited budget and schedule, bakeout may be the only realistic thermal test option as specified in [15]. The CDS states that this is minimum testing but does not give any recommendations as to what additional testing might be conducted and for what reasons. The discussions for Class C space programs may be helpful in determining whether additional thermal tests can be accommodated to increase the likelihood in mission success.

Other organizations have provided guidance to what additional testing increases the likelihood in mission success. The European Space Agency (ESA) has an educational program called "Fly Your Satellite!" that started in 2013 to support university students through the assembly, integration, testing, and verification process toward building and flying university-built satellites [16]. As part of the test program and for students to earn their "Ticket to Ride!" the cubesat must pass a four-cycle thermal vacuum test and a vibration test. The thermal vacuum test includes performance testing at temperature plateaus. These tests are conducted at the European Space Research and Technology Centre (ESTEC) with ESA engineering support. Thermal vacuum testing the cubesat provides an opportunity for the students to better understand how their vehicle will operate and perform in flight in the harsh vacuum and thermal conditions expected after deployment. Compared to the minimum requirements specified by the Cubesat Design Specification, ESA's approach better addresses mission assurance capabilities, although this comes at a higher program cost.

Inclusion of vehicle thermal vacuum testing for student projects is not just limited to ESA. Several other aerospace organizations include vehicle thermal vacuum testing to verify mission requirements for student-led cubesat programs [17, 18]. Although many student-developed cubesats still follow the Cal Poly University design guide of testing their vehicles with thermal bake-out only, some organizations require thermal vacuum testing cycling over expected mission temperature ranges with performance testing at hot and cold temperature plateaus. It remains to be seen whether these other low-cost cubesat developers will recognize the value of thermal vacuum testing enough to justify its cost.

6. Conclusions

In this report, historical perspectives on thermal test tailoring of Class C and D space vehicles were presented. Testing recommendations from MIL- HDBK -343 and several recent Aerospace reports were compared to assess the overall goal of meeting thermal test objectives. Risk perspectives of Class C and Class D programs were discussed and aligned with mission success expectations. Finally, thermal test recommendations to achieve desired test effectiveness goals were provided along with the associated risks resulting from tailored thermal test parameters.

Class C thermal testing will not be as thorough as that accomplished on Class A and Class B programs, but there will be a need for environmental stress screening at the unit level of assembly and performance verification to gain mission assurance prior to launch. Class D programs will have test programs that greatly depend upon the expectation of mission success. For a Class D program with a realistic goal of meeting mission requirements, ground thermal testing may be very similar to Class C thermal testing. For a Class D program with a significantly lower expectation of mission success, thermal testing may be limited to an environmental bakeout exposure to levels established by the launch vehicle provider as part of a “Do No Harm” philosophy for other payloads. However, there are organizations that require vehicle thermal vacuum testing for their Class D programs.

7. References

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8. Acronyms

CDS	Cubesat Design Specification
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
JPL	Jet Propulsion Laboratory
LM	Lockheed Martin
M&S	modeling and simulation
MPT	maximum predicted temperature (range)
NSS	National Security Space
SPF	single point failure
TC	thermal cycle
TE	test effectiveness
TV	thermal vacuum
U	unit

Appendix A. Class C Thermal Testing Case Study

As an example of test tailoring that was performed on a Class C space program [13], the following text describes the thermal testing that was planned and executed on four small satellites. This is not intended to be recommendations for Class C space thermal testing, but rather as a specific example of common tailoring and the reasons for it. The text highlights the rationale for the tailoring, how the tailoring was originally developed and how it was modified as the program progressed, and lessons learned from this case study.

The case study comprised one program consisting of three nearly identical satellites and a follow-on satellite very similar to the other three. The individual satellites were approximately 70 kg, cylindrical in shape, 0.7 meters in diameter and 0.3 meters in height. They had a 3-year mission life and flew in low earth orbits. The first three vehicles used passive thermal control and the fourth vehicle had a small battery heater.

Figure A1 summarizes the MIL-STD-1540B thermal test requirements. At the time of the program development, MIL-STD-1540B was the reference document for establishing the environmental test sequence. It required unit thermal cycle, burn-in, and thermal vacuum testing, followed by vehicle thermal cycle and thermal vacuum testing.

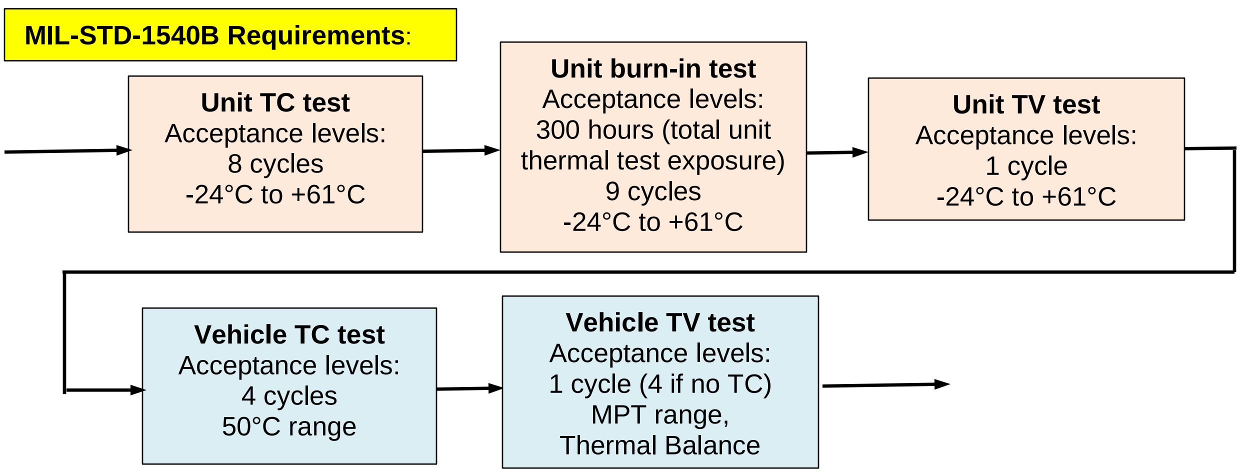

Figure A1. MIL-STD-1540B thermal test requirements

For the initial three vehicles, Thermal Test Plan A was developed by tailoring MIL-STD-1540B requirements. The primary motivations for the tailoring were program schedule and cost. There was good agreement between the contractor and the customer that environmental stress screening at the unit level was critical to ensuring workmanship verification, so the unit thermal cycle and burn-in tests were baselined in the test program. To meet schedule requirements, the unit thermal cycle test duration was reduced from eight cycles (MIL-STD-1540B) to four cycles, and the total unit thermal test exposure (burn-in testing) was reduced from 300 hours to 100 hours. Acceptance testing over a temperature range of at least -24°C to +61°C was kept. The relatively small size of these vehicles was a primary reason for deleting the unit thermal vacuum test. It was felt that the vehicle thermal vacuum test would accomplish the same test objectives with adequate perceptiveness. At the vehicle level, the thermal cycle was removed from the test plan, so the total number of vehicle thermal vacuum cycles was increased from one to four, consistent with the requirements found in MIL-STD-1540B. Thermal balance test phases were included for thermal model correlation and verification of the thermal control subsystem. All three initial vehicles were to be tested to Test Plan A. The sequencing of the testing in Plan A is shown in Figure A2.

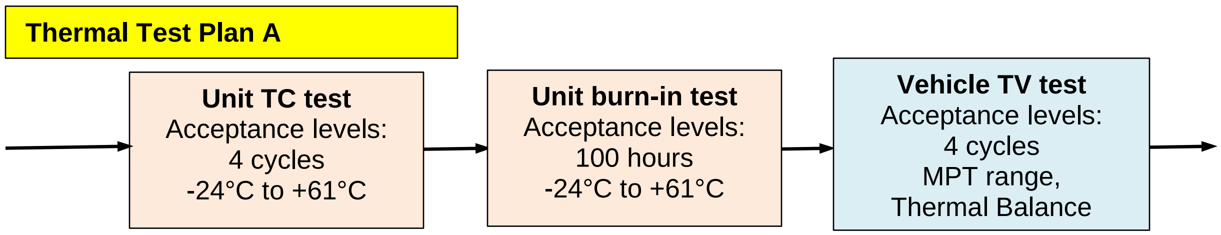

Figure A2. Thermal Test Plan A proposed for initial three vehicles.

Typical of many Class C and D programs, the environmental testing proposed and actually conducted was quite different. The reason for changes was primarily due to problems found during the tests resulting in rework and retesting, thus impacting the program schedule, so additional compromises were necessary. The unit thermal cycle test was performed as planned, but rework and retesting resulted in more thermal cycles on individual units. Burn-in testing needed to be shortened for some units to keep within unit delivery schedule constraints, so in some cases the 100 hours of total thermal test exposure was not satisfied. However, given the number of failures found in unit thermal cycle testing, a vehicle thermal cycle test was added to accrue more screening of the units. The test consisted of four cycles over a 70°C temperature range. The 70°C range is the MIL-STD-1540B requirement for qualification testing in the vehicle thermal cycle test. Following this, the vehicle thermal vacuum test was performed without any changes. Actual testing performed is shown in Figure A3. Changes from Test Plan A are shown with red text.

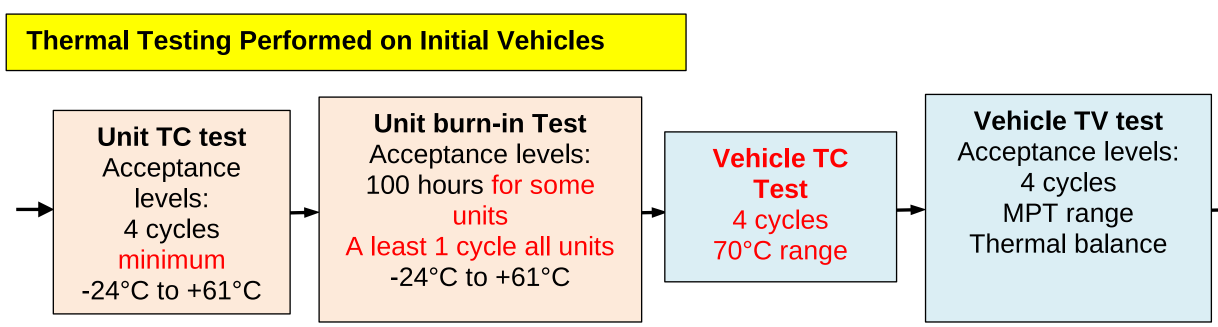

Figure A3. Actual thermal testing conducted on initial three vehicles.

For the follow-on vehicle, lessons learned from the first set of vehicle tests were used to modify Test Plan A in the hopes of strengthening the unit test screening. For Test Plan B, the unit thermal cycle test duration was increased from four cycles to eight cycles in compliance with MIL-STD-1540B. With this larger number of cycles, the burn-in test duration of 100 hours would probably be met, so the unit burn-in test was removed from the test program. Additional screening was still desired, so a vehicle thermal cycle test was added with 8 cycles. The test temperature range was reduced from 70°C to 50°C in agreement with acceptance testing from MIL-STD-1540B. An unmodified thermal vacuum test completed the thermal test program. This plan is shown in Figure A4.

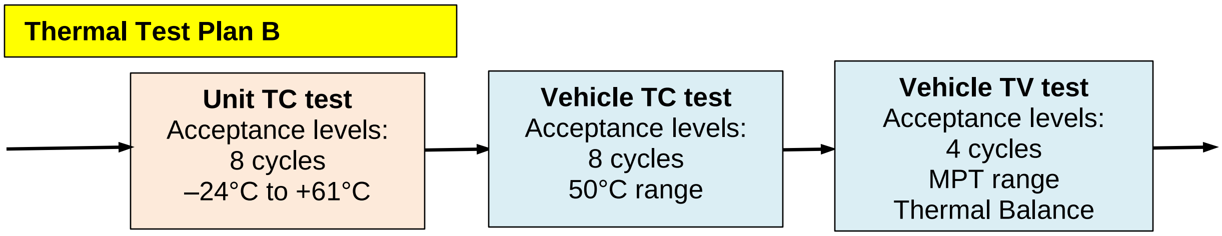

Figure A4. Thermal Test Plan B proposed for follow-on vehicle.

Actual testing of the follow-on vehicle is as shown in Figure A5 with red text highlighting differences from planned testing. The unit thermal test duration was reduced back to 4 cycles, but the temperature range was increased by lowering the cold test temperature to -55°C. This was done because cold temperature predictions from thermal analyses showed a colder vehicle signature than seen on the first three vehicles. Failures were still found in the unit thermal cycle test, so retest cycles were accrued on some units. Vehicle-level thermal tests were accomplished per Plan B.

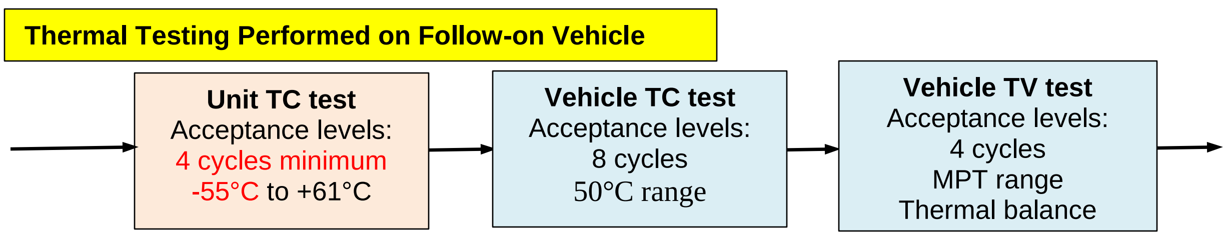

Figure A5. Actual thermal testing conducted on follow-on vehicle.

Lessons learned from the testing conducted on this example program included:

- Scheduling test programs need to anticipate that failures will be found, particularly in unit level thermal cycle testing. It is necessary to build margin into test schedules for rework and retesting
- Weakening the environmental stress screening test parameters in unit level testing resulted in defect escapes into higher levels of assembly. Maintaining a strong unit-level test program to find problems early is prudent
- Understanding that schedule-driven programs may need to modify test plans during program development is important. Being flexible to additional tailoring is important to meet delivery dates
- Tailoring decisions need buy-in from all stakeholders. Keeping the customer well informed of test results and planning activities is necessary so that approvals can be obtained efficiently

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