System Thermal Testing (D-22011), Rev. 0

OFFICIAL
Standard

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1. Applicability

This standard is applicable to all JPL projects developing flight hardware systems, both integrated and tested in-house, or integrated and tested by a JPL contractor in their facilities. In the context of this standard, flight hardware systems have completed a Protoflight/Qualification thermal test program at lower levels of assembly and their thermal and functional interactions can only be assessed as a whole system. The tests specified herein are applicable to each flight hardware system on a given project. Deviation from these requirements shall be documented and approved in the Project Implementation Plan (PIP) or by using the waiver processes defined in D-15032 and D-53052.

2. Scope

2.1 Purpose of Standard

This standard establishes minimum requirements for flight hardware System Thermal Testing (STT). This testing is required by JPL to validate the thermal design and verify functional integrity when the flight hardware system is exposed to simulated mission thermal environments.

2.2 Structure of Standard

Relevant definitions and abbreviations are contained in Section 3 and 4.

Test purpose and test objectives are described in Section 5.

Minimum test program requirements are defined in Section 6.

The minimum implementation requirements that are essential to successfully meet the test program requirements are provided in Section 7. Section 7.1.2 contains requirements on the test environment that are conditional and depend on the individual mission environments that need to be simulated to meet the requirements in Section 6.

Sections 6 and 7 are the only place in this standard where requirements are established. Several notes and appendices are included in this standard to provide supportive information. These notes and appendices do not constitute requirements.

3. Definitions

3.1 Thermal Control Design

The thermal control design consists of design features (coatings, materials, etc.), thermal hardware (MLI, PRTs, Louvers, Heaters, Thermostats, Heat Pipes, etc.), and operational constraints (power modes, pointing restrictions, etc.) that enable the flight hardware system temperatures to remain within the specified Allowable Flight Temperature Range

3.2 Temperature Requirements

A graph depicting the relationship between the temperature requirements definitions below is presented in Appendix A, Temperature Range Definition.

3.2.1 Allowable Flight Temperature Range

The Allowable Flight Temperature (AFT) range is the operating/non-operating temperature range within which the thermal design must maintain the flight hardware system temperatures during all phases of the mission for non-fault conditions.

3.2.2 Flight Acceptance Temperature Range

The Flight Acceptance (FA) temperature range is defined as the upper AFT +5°C and the lower AFT -5°C. Applicable to credible abnormal conditions, resulting from anomaly-induced power dissipation and or off nominal sun attitude conditions.

3.2.3 Protoflight/Qualification Temperature Range

The Protoflight/Qualification (PF/Qual) temperature range is defined as the upper AFT +20°C and the lower AFT -15°C. Applicable to failure conditions.

3.2.4 Thermal Reliability Margin

Thermal Reliability Margin is defined as the difference between the AFT and the Qualification/Protoflight temperature limits of the unit.

3.2.5 Thermal Design Margin

Thermal design margin is the temperature difference between the AFT range and the worst-case hot and cold predicted temperatures. Temperature predictions outside the AFT range result in negative thermal design margin. The difference between the AFT and FA ranges is not included as part of the thermal design margin at JPL.

3.2.6 Worst-case Hot/Cold Temperature Predictions

Worst-case is defined as that combination of realistically stacked thermal design parameter extremes that produce the maximum and minimum predicted temperatures for all phases of the mission. In the STT and in flight, the hardware would not be expected to exceed these temperature predictions.

3.3 Flight Hardware System

A flight hardware system is defined by a completed Protoflight/Qualification thermal test program at lower levels of assembly and a level of thermal and functional interactions that can only be assessed as a whole system. Examples of flight hardware systems are Galileo, Cassini, Mars Pathfinder, Mars Odyssey, Genesis, MER, WFPC, SeaWinds, MLS, and TES.

3.4 Protoflight Thermal Test

Protoflight testing is performed on flight hardware that is intended to be flown and having no previous qualification test article. Protoflight testing accomplishes in one test the combined purposes of design qualification and flight acceptance.

3.5 Verification

Verification provides objective evidence through test or analysis that specified requirements have been fulfilled by the thermal design implementation. ***Did we build the thing right?***

3.6 Validation

Validation of the thermal design implementation results in official approval by assessing or corroborating its soundness for the intended use through testing or comparisons. ***Did we build the right thing?***

3.7 Category A Waiver

A document that is required when an institutional (JPL/NASA/Program) requirement cannot be met and justification for its approval exists.

3.8 Category B Waiver

A document that is required when a Project requirement cannot be met and justification for its approval exists.

4. Abbreviations

AFT	Allowable Flight Temperature
ATLO	Assemble/Test/Launch/Operate
EM	Engineering Model
ETRR	Environmental Test Readiness Review
FA	Flight Acceptance
PF	Proto Flight
PIP	Project Implementation Plan
Qual	Qualification
RFA	Request For Action
STT	System Thermal Testing
T/B	Thermal Balance
TCM	Temperature Control Model
TDM	Thermal Development Model

5. Test Purpose

The purpose of the STT is to significantly contribute to mission success by validating the thermal design in simulated environments representative of the expected mission environments and by verifying functional performance against specifications over temperature extremes.

5.1 Test Objectives

The test objectives are to validate the thermal design and to verify functional performance by:

1. Verifying that the flight hardware system thermal control design satisfies the AFT, thermal gradient, and thermal stability requirements under a combination of extreme simulated mission thermal environmental and operational conditions

2. Collecting sufficient data to enable thermal math model correlation so that un-testable conditions can be validated by analysis

3. Collecting sufficient data to detect a deficient thermal design and to enable corrections through hardware/software changes

4. Verifying that specified functional performance requirements are met under a combination of extreme simulated mission thermal environmental and operational conditions

5. Verifying operation and compatibility of those subsystem and instrument functions that cannot be fully exercised except in simulated, mission-like thermal environments

6. Test Program Requirements

6.1 Minimum Test Program

The minimum STT program shall consist of all of the following:

- Thermal Balance Testing
- Functional Testing

6.1.1 Thermal Balance Test

A Thermal Balance (T/B) test shall be conducted on each flight hardware system in the mechanical configuration(s) and electrical power mode(s) appropriate (operating or non-operating) for the mission thermal event being simulated.

System thermal design robustness shall be demonstrated for off-nominal conditions through testing at temperature extremes beyond worst-case hot and worst-case cold, but not to exceed FA levels anywhere on the test article

Note: *The T/B Test is a dedicated steady state or periodically repeating transient thermal test conducted at the worst-case maximum and minimum test parameters. This test will cover more than one mission phase (e.g., hot/cold environment and/or operating/non-operating) and may require more than one flight hardware system configuration (lander on and lander off, science stowed and science deployed). The goal of this test is to validate the thermal design.*

Note: *Thermal design robustness is demonstrated by the system response to a temperature regime induced by off-nominal flight environments. This regime goes beyond the worst-case hot and cold temperatures established during the thermal balance test but is bounded by the FA limits. It cannot be expected that temperatures of the test article will respond uniformly. The subsystem that approaches the FA limit first will be the test limiting item and temperatures will be stabilized at this point. Once this condition is established, the test article is expected to function predictably and within specifications.*

6.1.2 Functional Testing

A functional test shall be performed to demonstrate functional margin at the worst-case hot and cold environmental conditions.

Functional testing shall be used to verify there have been no unexpected changes or degradation in performance during the course of the STT.

Note: *The functional tests are interwoven in the STT and verify that the subsystems perform together as a system in a flight like environment. The sequences for the functional tests have been run previously in a room environment (ATLO). These may be checkout sequences or actual flight sequences. Functional tests may also be performed during the initial transient cooling/warming periods prior to the T/B steady state test point.*

6.2 Test Hardware and Configuration

6.2.1 Test Article Hardware

The flight hardware system test article shall consist entirely of flight hardware.

Note: *A Category B waiver is required to justify the use of a Temperature Control Model (TCM), an Engineering Model (EM), or a Thermal Development Model (TDM) instead of flight hardware. Guidelines for EM/TCM/TDM design requirements are given in Appendix B, EM/TCM/TDM Design Guidelines.*

6.2.2 Flight Hardware System Test Configuration

The flight hardware system shall be tested in the mission configuration.

A separate thermal design validation test of flight hardware not tested as part of the flight hardware system test and its interaction with the flight hardware system shall be performed

Note: *Exceptions may be solar panels, antennas, science boom, etc. that cannot be deployed because of the chamber size.*

6.3 Planning and Review

Review Board requests for action (RFA) shall be documented.

Action items agreed to by the project shall be completed prior to start of testing.

6.3.1 Environmental Test Readiness Review

An Environmental Test Readiness Review (ETRR) shall be conducted with the JPL Project Manager as the convening authority.

Note: *ETRR guidelines are presented in Appendix C, ETRR Guidelines.*

6.3.2 System Thermal Test Plan Review

A System Thermal Test Plan Review shall be conducted.

Note: *This is a detailed review of System Thermal Test objectives, approach, configuration (s), determination of worst-case hot and worst-case cold conditions to be verified, test phases, timeline, instrumentation, transient tests, special tests, and waivers to the STT requirements, including areas of the design that cannot or will not be tested. A sample Test plan is presented in Appendix D, Sample Table of Contents for STT Plan.*

6.3.3 Test Results Review

A review of summary test results shall be made to the project one week after completion of the STT.

The Test Results Review shall cover requirements compliance, requirements violations, and design findings/surprises.

This review shall identify areas of the thermal design, which require adjustment or further investigation.

Note: *It is critical that this review take place soon after test completion in order to alert the Project team to potential liens to the design and/or ATLO activities.*

6.3.4 Post-Test Review

A review of the validation/verification results of all test phases shall be conducted.

All aspects of the thermal design and flight system operations, which could not be explicitly validated/verified during system thermal testing, shall be reviewed.

The review shall include a definitive set of flight predicts, based on a post-test correlated thermal model, for all aspects of the flight system thermal design and operations.

Note: *Aspects typically not covered during test include launch phase, aero heating, subsystem insolation, off-nominal attitudes, and worst-case subsystem modes.*

6.4 Waivers

Waivers to any requirement specified herein shall be approved prior to the ETRR.

Waivers shall be based on technical or on cost/schedule vs. risk considerations.

Waivers based primarily on technical considerations shall demonstrate that the project has satisfied by alternate means the test purposes cited in Section 5.

Waiver disposition shall include the Thermal and Propulsion Engineering Systems Section and the Reliability Engineering Office.

Note: *As an example, it might be acceptable to perform certain baseline tests at only the subsystem level if interactions between subsystems involving qualification and workmanship issues can be adequately addressed.*

7. Test Implementation Requirements

Information supporting test planning and documentation is presented in Appendix E, Test Planning and Documentation.

7.1 Test Activities

7.1.1 Steady State Determination

The thermal engineer shall establish and determine achievement of steady state conditions.

Note: *Temperature changes of less than 0.3°C/hour over 3 consecutive hours may be sufficient for hardware with time constants of less than 4 hours but may be inadequate for hardware with large thermal mass, e.g., filled propulsion tanks or cryogenic instruments. Similar considerations apply to periodically repeating transient behavior.*

7.1.2 Test Environment

Thermal influences from the environment experienced by the flight hardware system shall be simulated to bound environments consistent with worst-case hot and cold extremes.

Note: The flight hardware system experiences *heating from the environment that results from direct solar, planetary IR, planetary albedo, aero-braking, launch, and planet/moon surface operations. Acceptability of the design during launch and aero-braking is normally verified by analysis because of the brevity of exposure and the difficulties in simulating these environments during test.*

7.1.2.1 Solar Simulation

System level testing that employs solar simulation meets the following requirements:

The solar beam shall be checked for uniformity.

The solar beam variation shall be within ± 5% over the portion of the beam diameter illuminating the test article.

The beam shall be spot mapped with the test article in place to determine the local solar flux impinging on specific parts of the flight hardware system.

Notes: *The beam variation, coupled with the reflection/blockage picked up by the spot mapping, can result in local solar flux differences of +20%/-10% relative to a test chamber flux monitor measurement.*

A spectral measurement of the solar beam should be made so that a re-calculation of the solar absorptance can be made for all critical coatings/surfaces of the test article. (Absorptances under the solar simulator beam can be significantly different from those in space with the real sun.)

7.1.2.2 Planetary IR and Albedo Load Simulation

Effects of planetary IR and reflected solar pertinent to the thermal design shall be simulated during the STT.

Note: *Planetary IR and reflected solar effects are usually added together and the resulting flux imposed on the flight hardware system by quartz IR lamps or a heated black painted plate. Calculating the fluxes is easy, but getting the simulation correct is tough. It is important that calibration runs be made and the flux monitored by radiometers.*

7.1.2.3 Atmospheric Simulation

System level testing that requires atmospheric conditions shall be in the appropriate environment and pressure (e.g. GN_2 or CO_2 for Mars missions).

Note: *Simulating the environmental loads on a lander/rover on the surface of a planet/moon can be very difficult. More time will be spent on thermal modeling to distill down a meaningful worst-case hot and cold test configuration. An atmosphere, a difference in gravity, wind, etc. complicates the analyses and performing the test in an earth bound simulator that was designed to simulate space. However, the test configuration arrived at will require similar hardware: IR lamps, heater plates, direct solar, etc. Introducing an atmosphere other than nitrogen creates problems of freezing and sublimation that causes pressure spikes on pressure gages that require re-calibration or the purchase of a new gage. Because of the expense and difficulty of testing as you fly and flying as you test, compromises are likely.*

7.1.3 Test Instrumentation and Data Acquisition

7.1.3.1 Test Sensors

Temperature sensors shall be located to facilitate thermal model correlation and requirements verification.

Functional performance of flight temperature sensors shall be verified.

Note: *Document relevant temperature sensor specification (type, wire gage) and heater function (guard, warm-up, simulator, etc.). Document the maximum power (capability and/or allowable) for each heater.*

7.1.3.2 Data Acquisition Sampling Frequency

All temperatures, applied voltages, power, and currents shall be automatically recorded at a frequency commensurate with the objective of respective test phases.

The data used for control shall be sampled at a frequency that is suitable to the respective operation.

Note: *The recording (archiving) frequency for data storage is typically once per minute. The real time sampling frequency is at least twice per minute.*

7.1.3.3 Alarm Limits

Alarm limits shall be specified for all flight/test sensors and all other telemetry that is relevant to flight system safety.

Note: *Conservatively, yellow alarm limits are specified 5°C within the AFT range and red alarm limits are set at the AFT limits. For worst-case environmental and functional conditions, temperatures are not expected to exceed the AFT. During thermal design robustness demonstration, temperatures are not expected to exceed FA limits.*

7.1.4 Thermal Accommodations for Ground Support Equipment

The flight test article shall be thermally isolated from the test support hardware.

In an instrument test, flight hardware shall be used for the mechanical interfaces to a simulated S/C interface.

7.2 Post-Test Activities

Test data shall be correlated with the thermal model.

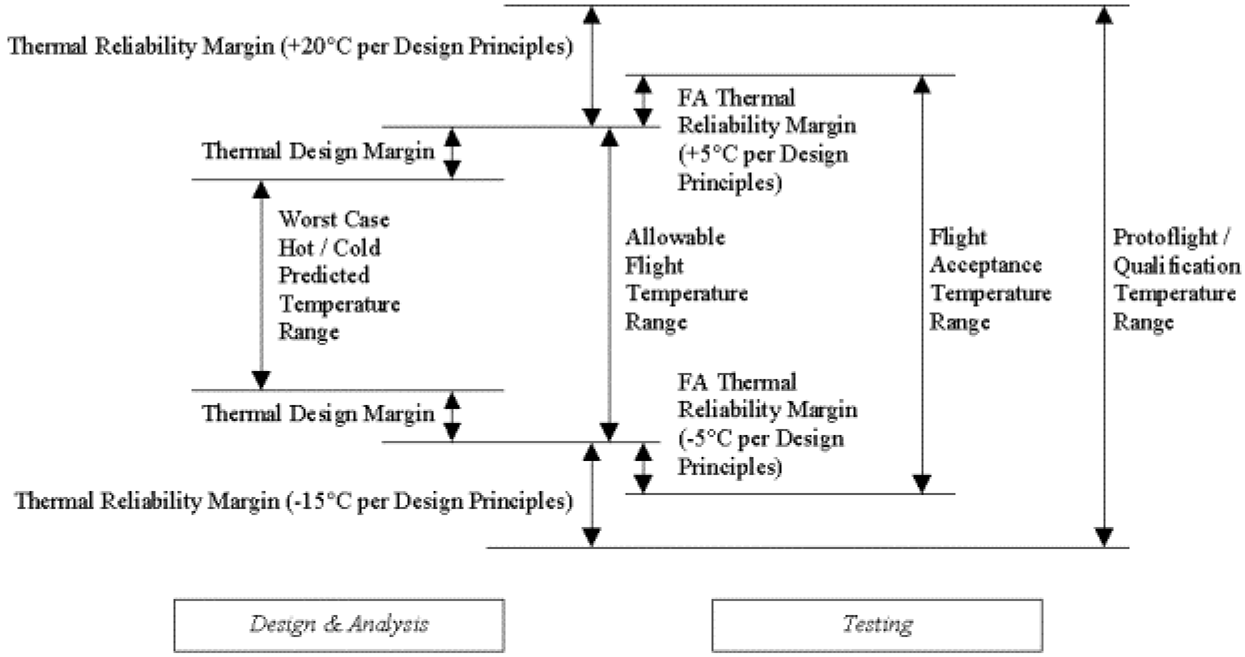
Flight predictions shall be updated using the correlated model.

A complete report of the STT and its results shall be released.

Note: *Thermal model correlation consists of identifying discrepancies between predicted and observed test temperatures, and adjusting thermal model parameters to minimize these discrepancies.*

Appendix G, Sample Table of Contents for STT Test Report outlines the subject matter to be addressed in the test report.

Appendix A: Temperature Range Definitions



Appendix B: EM/TCM/TDM Design Guidelines

The EM/TCM/TDM is expected to comply with the following fidelity requirements:

1. Flight-like chassis or housing that can be expected to attain the same average steady state temperature (± 3°C) as the flight unit given identical boundary conditions

    - Flight-like fit and form attributes (mechanical interfaces, thermal blanket interfaces, and cable access and egress)
    - Conforms to Mechanical Interface Control Documents
    - Flight-like material thickness, thermal conductivity, and surface thermo-optical properties
    - Thermal mass

2. Flight-like cabling (internal and external) and connectors

3. Flight-like heaters installed at locations that represent dissipations for:

    - Operating power
    - Non-operating power
    - Supplementary power
    - RHU/RTG simulators
    - Wire gauge selected such that losses in lead wires are negligible

Appendix C: ETRR Guidelines

1. The location of the ETRR should be near the facility where the testing will be performed

2. The review board, as part of the review, should perform a walkthrough of the test facility

3. The ETRR should take place no later than 60 days prior to the start of environmental testing

4. Objectives of the ETRR:

    - Ensure that required hardware, software, personnel, facilities are/will be available and prepared to support the upcoming tests
    - Ensure that adequate flight system and facility contingency plans are/will be in place, including safety procedures for personnel, hardware and facilities
    - Confirm that the test timeline addresses environmental requirements verification and incorporates required test article configuration changes at the various test environments
    - Verify test article readiness, assess test article waiver impacts, and establish concurrence from the engineering community
    - Identify any additional constraints against proceeding to the Environmental Test Phase

Appendix D: Sample Table of Contents for STT Plan

6.0 Pre-Test Bake-out and Phases

- 6.1 Pre-Test Bake-out
- 6.2 Phase 1
- 6.3 Phase 2
- 6.4 Test Timeline and Power Mode Matrix

7.0 Test Procedure

- 7.1 Nominal
- 7.2 Contingency (Facility Failures, etc.)

8.0 Pre-Test Temperature Predictions

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11.0 Test Responsibilities and Reports

12.0 Test Control

- 12.1 Environmental Control
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- 12.3 Contamination Control
- 12.4 Pre-Test and Post-Test Integrity Checks

APPENDICES

- A. Allowable Flight and Pre-Launch Temperature Requirements
- B. Thermocouples and Test Heaters: Data Acquisition Requirements
- C. Thermocouple Installation Requirements
- D. Flight Temperature Transducer Table
- E. Test Heater Installation Requirements
- F. Diagrams of Thermocouple, Flight Temperature Transducers, and Test Heater Locations
- G. List of Data Acquisition Parameters
- H. List of MLI Lay-ups, Areas, and Masses
- I. List of Flight Hardware System Thermal Control Coatings
- J. List Of Acronyms

Appendix E: Test Planning and Documentation

The following planning and reporting milestones are strongly recommended:

Event	Timing
Preliminary STT Concept	Thermal PDR
STT Preliminary Plan Peer Review	4 Weeks Prior to Thermal CDR
Preliminary STT Plans	Thermal CDR
Preliminary STT Plan Release	2 Weeks Prior to ETRR
Preliminary STT Plan Summary	ETRR
STT Final Plan Peer Review	6 Weeks Prior to STT Start
STT Final Plan Project Review	4 Weeks Prior to STT Start
STT Final Plan Sign-off	2 Weeks Prior to STT Start
STT Preliminary Results Presentation	1 Week After STT End
STT Final Test Report Peer Review	10 Weeks after STT End
STT Final Test Report Release	3 Months After STT End

The test documentation owners and test flow are shown below:

Document(s)	STT Test Plan	STT Test Matrix	ATLO STT Test Procedure	STT Preliminary Results Presentation	STT Final Test Report
What	Appendix D	Test: -coordination -time line -pass criteria	Functional test Procedural info	T/C design changes P/FRs Unexpected/ unexplained	Appendix G
Who	T/C Engineer	T/C Engineer	ATLO Engineer	T/C Engineer	T/C Engineer
When	ETRR – 2 weeks	ETRR – 2 weeks	STT – 2 weeks	STT + 1week	STT + 3 month

time

Appendix F: Test Environment Considerations

In thermal testing values for the simulation of certain environmental conditions are commonly accepted. These values are given here for reference:

Vacuum for deep space simulation:	$\leq 1\text{x}10^{-5}$ Torr
Chamber wall for deep space simulation:	$\leq -180^{\circ}$C
Solar constant:	$= 1367.5 \pm 4$ W/m^2

A good vacuum chamber will achieve a stable pressure between 10^{-5} Torr and 10^{-7} Torr. This is a long way from the hard vacuum of space but adequate. Pressures in the 50 to 5 x 10^{-4} Torr range can cause arcing of high voltage items and 10^{-4} Torr pressures usually signals a chamber leak or extreme out-gassing by the test article or support hardware. During pump-down and back-fill, consideration needs to be given to turning off high voltage items.

Thermally, space is perfectly black and at a temperature of - 270°C. Chamber shrouds are not perfectly black and typically operate near the boiling point of liquid nitrogen (-195.85°C) and are usually run between -180°C and -185°C to minimize liquid nitrogen usage. For a test article operating at room temperature, its radiation potential is reduced by 1% due to the wall temperature being at -180°C rather than -270°C.

The size of the chamber has a large effect and the “black” shroud has a decrease in emittance with a decrease in temperature. For a high emittance test article, whose area is 0.3 of the chamber area, the reduction in radiation interchange factor is 4% for a chamber shroud with an emittance of 0.8. The flight hardware system thermal model will pickup the difference in the chamber to space temperature results, but all other parameters being equal, cooler hardware temperatures should result for flight.

Direct solar simulation is routine and is done with xenon lamps and a collimating system like the JPL 25’ Space Simulator. Quartz IR lamps, locally configured to the application, can also impose an equivalent heat load. Either way, the flux will be measured and monitored by a radiometer. Reflection off of the chamber floor shroud can be significant.

Consider simulating the additional absorbed solar loading resulting from degradation of thermo-optical properties (increase in solar absorptance) by using a higher solar irradiance level, if the impact to the rest of the flight hardware system is acceptable.

Appendix G: Sample Table of Contents for STT Test Report

10.0 Spacecraft Thermal Model Correlation

11.0 Design Modifications

11.1 Design Deficiency Description

11.2 Post-Test Design Changes

11.3 Design Verification Matrix

11.4 Problem Failure Reports (PFRs)

12.0 Conclusions and Recommendations

13.0 References

APPENDICES

A. Test Log Excerpts

B. Thermocouple, Heater, Flight Transducer and Blanket Tables

C. Thermocouple/Flight Transducer/Heater Location Figures

D. Temperature Plots

E. Flight Transducer Correlation

F. Thermal Design Validation

G. Facility Anomalies
