SPACE VEHICLE TESTING

A Master's Project

presented to

the Faculty of California Polytechnic State University,

San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Aerospace Engineering

by

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ABSTRACT

Space Vehicle Testing

Charlotte Ann Belsick

Requirement verification and validation is a critical component of building and delivering space vehicles with testing as the preferred method. This Master's Project presents the space vehicle test process from planning through test design and execution. It starts with an overview of the requirements, validation, and verification. The four different verification methods are explained including examples as to what can go wrong if the verification is done incorrectly. Since the focus of this project is on test, test verification is emphasized. The philosophy behind testing, including the "why" and the methods, is presented. The different levels of testing, the test objectives, and the typical tests are discussed in detail. Descriptions of the different types of tests are provided including configurations and test challenges. While most individuals focus on hardware only, software is an integral part of any space product. As such, software testing, including mistakes and examples, is also presented. Since testing is often not performed flawlessly the first time, sections on anomalies, including determining root cause, corrective action, and retest is included. A brief discussion of defect detection in test is presented.

The project is actually presented in total in the Appendix as a Power Point document.

Keywords: test, verification, software, hardware, anomaly

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APPENDIX A SPACE VEHICLE TESTING POWER POINT DOCUMENT

- A1. Requirements
- A2. Verification Methods
- A3. Test Philosophy
- A4. Test Objectives
- A5. Test Descriptions
- A6. Software Testing
- A7. Anomalies
- A8. Defect Detection in Test
- A9. Summary
- A10. Acronyms
- A11. Bibliography

Space Vehicle Testing

Charlotte Belsick

AERO 599

Master's Project

Fall Quarter 2012

Agenda

- Requirements
- Verification Methods
- Test Philosophy
- Test Objectives
- Test Descriptions
- Software Testing
- Anomalies
- Defect Detection in Test
- Summary

REQUIREMENTS

Where Do Requirements Come From?

- Established to assure that product performs as needed in the operational environments
 - Product performance
 - Margins
 - Proof of product development
 - Proof of product build
- Standard testing requirements are levied on the aerospace community
 - Function of type of product
 - Function of level of integration
 - Establishes environments
 - Provides preferred sequence
- Product specifications generated
 - Product performance with margin
 - Environments
 - Levied requirements

Typical Environment Requirements

Test \ Units	Electrical and Electronic	Antenna	MMA	Solar Array	Battery	Valve or Propulsion Component	Pressure Vessel or Component	Thruster	Thermal	Optical	Structural Components
Inspection	R	R	R	R	R	R	R	R	R	R	R
Specification Performance	R	R	R	R	R	R	R	R	R	R	R
Leakage	ER	—	R	—	R	R	R	R	R	R	R
Shock	R	ER	ER	ER	R	ER	ER	ER	ER	ER	ER
Vibration or Acoustic	R	R	R	R	R	R	R	R	R	R	ER
Acceleration	ER	ER	ER	ER	ER	ER	ER	ER	—	ER	ER
Thermal Cycle	R	ER	ER	ER	R	ER	ER	ER	ER	ER	ER
Thermal Vacuum	R	R	R	R	R	R	R	R	R	R	—
Climatic	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
Pressure	ER	ER	ER	ER	ER	R	R	R	R	R	R
EMC	R	R	R	R	R	ER	ER	ER	ER	ER	ER
Life	ER	ER	R	ER	R	R	ER	R	ER	ER	ER
Burst Pressure	—	—	ER	—	R	R	R	R	ER	—	—
Static Load	ER	ER	ER	ER	R	—	ER	—	—	—	R

All units fall into one or more of these categories

“R” = Required Test

“ER” = Evaluation required with technical rationale

“—” = No test required

Ensemble of environmental tests

Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E)

More Information is Available

- For each test the matrix points to the sections in MIL-STD-1540 for detailed requirements
- Associated standards referenced for additional information and application

Test \ Units	Electrical and Electronic	Antenna	MMA	Solar Array	Battery	Valve or Propulsion Component	Pressure Vessel or Component	Thruster	Thermal	Optical	Structural Components
Inspection	R	R	R	R	R	R	R	R	R	R	R
Specification Performance	R	R	R	R	R	R	R	R	R	R	ER
Leakage	Example: Associated requirements references for pressure testing (Section 2) AIAA S-080-1998 Space Systems-Metallic Pressure Vessels, Pressurized Structures and Pressure Components AIAA S-081-2000 Space Systems-Composite Overwrapped Pressure Vessels										
Shock											
Vibration or Acoustic											
Acceleration											
Thermal Cycle	R	ER	ER	ER	R	ER	ER	ER	ER	ER	ER
Thermal Vacuum	R	R	R	R	R	R	R	R	R	R	—
Climatic	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
Pressure	ER	—	ER	—	R	R	R	ER	ER	—	—
EMC	R	R	ER	ER	ER	ER	ER	ER	ER	ER	ER
Life	ER	ER	R	ER	R	R	ER	R	ER	ER	ER
Burst Pressure	—	—	ER	—	R	R	R	R	ER	—	—
Static Load	ER	ER	ER	ER	R	—	ER	—	—	—	R

“VEE” Diagram

Validation and Verification

- Product validation
 - Confirm that the as-built item can support the mission plan
 - Validation has an independent and/or user's perspective
 - “Build the **right** thing”
- Verification
 - Confirm that the as-built item can conform to the documented requirements
 - “Build the thing **right**”

Verification & Validation Objectively Show
That the Mission Can be Achieved

Validation

- Requirements validation
 - Assure requirements and flow down are what is intended and needed
- Product validation involves system level activity
 - Verification may be performed at lower level but need to assure entire product works as intended in the end state and after environments
- Non-flight validation
 - Assure tools are correct
 - Models, simulators, and test beds
- Must have the correct information for validation
 - Implied requirements are not acceptable

Validation is NOT Just for Software

Verification

- MUST! determine, plan and coordinate methods early
 - To establish scope of program
 - To establish expectations with suppliers and customer
 - Objectively show compliance that all requirements are fulfilled
 - Provide proof of concept
- Verification methods need to be executed, documented, and accepted
 - Prior to acceptance of incoming items and
 - Prior to customer delivery
- Verification method decisions should be made with quality of proof in mind

Guilty Until Proven Innocent

Did I Meet the Requirement?

There must be **necessary** and **sufficient** proof that the requirement **criteria** is met

- **Necessary** implies that the condition must be met before further evidence is supplied
- **Sufficient** implies that all appropriate proof is available
 - It is **necessary** that the solar array deploy properly to verify that the power system can provide adequate power to the vehicle, but it is not **sufficient**
 - Tolerances need to be stated to allow variance
- **Pass** implies that **all** required aspects are met
 - **Doing** a test or other verification activity is not the same as **passing** it
- **Fail** implies that **some** required aspects are not met
 - The requirement is not met if there is any aspect not met

Determine Criteria BEFORE Starting

VERIFICATION METHODS

Methods of Verification

Demonstration

Does it or doesn't it?

Inspection

Look at it

Analysis

Max velocity v , the velocity at burnout =
$$v = \sqrt{([T - M \cdot g] / k) * [1 - \exp(-2 \cdot k * \sqrt{([T - M \cdot g] / k) / M} * t)]} / [1 + \exp(-2 \cdot k * \sqrt{([T - M \cdot g] / k) / M} * t)]$$

where T = thrust t = burn time
 k = wind factors M = mass
 g = gravity acceleration

Do the math (dry lab it)

Test

Measure it

D I A T

Demonstration

- **Qualitative** proof of performance obtained by a successful completion of a pass/fail, go/no go, satisfactory/unsatisfactory or pathfinder event
- Preferred method when
 - A proof of concept in a simulated operational environment is required
 - An operator (i.e., human interface) is involved
- Often software requirements are verified by demonstrations
 - The actual software requirement is inferred to have been successful by virtue of demonstrating a higher level function

Note: This is different than deployment site demonstration / validation (aka "demval")

Qualitative Proof

Which Would You Chose?

Medium Fidelity Demo (The Practical)

Photo courtesy of Lockheed Martin

Low Fidelity Demo (The Start)

Photo courtesy of NASA

Photo courtesy of NASA

High Fidelity Demo (The Ideal)

Failures of Demonstration

- Satellite hits overpass during move damaging shipping container
 - Long time between pathfinder and satellite transport
 - Road repaved – decreased clearance by 2-inch
- Incorrect command sent to spacecraft causing 3 month mission outage
 - Demonstration performed with different personnel
- Boom caught on blanket thus unable to extend fully
 - Demonstration not performed with all blankets

Demonstrate With the Correct Fidelity

- Physical confirmation of hardware/software characteristics against design documents
- Preferred method when
 - Production standards and process control requirements are involved
 - Known or high risk design instabilities may exist
 - First article inspection (FAI)
 - Review of drawings, parts lists, scripts, etc

Note: Production “tests” and “checks” during manufacturing and assembly (such as nondestructive examinations) are classified as inspection

Physical Confirmation – Measurement

Failures of Inspection

- Inspection causes unplanned missile removal
 - Boroscope inadvertently trips rail cars due to difficult access
- Incorrectly applied thermal protection tape prevented stage separation stranding satellite in wrong orbit
 - What it said: Wrapping should be applied *within 0.5 inches* of the mounting bracket flange
 - What was meant: Wrapping should be applied *no closer than 0.5 inches*
- “Where’s Waldo” syndrome
 - Human eye is not perfect if data is cluttered or given too quickly
 - Lots of data increases odds of missing something
- Complacency can develop in the inspector

Need Clear and Doable Requirements

Inspection

Within 0.5"

As built

*No closer
than 0.5"*

As intended

Where's Waldo Syndrome

Analysis

$$\Phi v = \sqrt{[T - M \cdot g]}$$
$$F = ma \quad \sigma = P/a$$

Analysis

- Mathematical or logical treatment of data using appropriate models , simulation, calculations, etc. to reach conclusions that are not directly obtainable from measurements
 - **Need to validate the model**
- Preferred method when
 - A heritage (or sufficiently established) design or technology is used
 - A test or demonstration is impractical or impossible
 - The analytical method is of sufficient fidelity to reflect the specific requirement being verified
 - Verifying entire requirements “space” could result in damage to the hardware or software

Note: Analysis includes simulation and similarity

Mathematical Approach

Analysis

$$\Phi v = \sqrt{[T - M \cdot g]}$$
$$F = ma \quad \sigma = P/a$$

Failures of Analysis

- Network downlink capability
 - Analysis indicated system capable of this with bit error rate 1×10^{-6} or better
 - Validation test showed analysis off by 3 orders of magnitude or more
- Thermal hardware added at launch base
 - Thermal analysis performed early in the design life cycle
 - Design changes not adequately assessed
- Solid rocket motor nested too deep and destroyed spacecraft
 - Plume heating effects assumptions did not incorporate adequate design margin
 - Generic, rather than space vehicle specific, models used

Analysis Must Be Validated

Test

- Quantitative proof of performance obtained by measurement of a response to a defined stimulus under controlled conditions
- Preferred method
- Must test
 - A new (or sufficiently new) design, technology, or application
 - Workmanship defects exist that can only be discovered via testing
 - Many product to product interactions

The Overall Preferred Method

Failures of Test

- Satellite failure undetected during acoustic test
 - Passed unpowered acoustic test
 - Acoustic environment “shook” electronic package component loose
 - Only discovered during thermal vacuum test
- Box level test not perceptive enough to determine circuit inadequacy
 - Box successfully passed qualification and acceptance test
 - On-orbit (cascaded) failure showed components voltage/current higher than specification levels
- Critical telemetry and command (T&C) failover missed
 - Unit tests proved both T&C processors worked
 - System test proved they could nominally work together
 - Did not test failover to redundant side
 - Resulted in hung bus without anyway to recover during end to end test

Won't Find the Problem Unless You Test for It

When It Makes Sense to Combine Methods

- Some requirements can't be fully verified by one method due to inherent limitations in the method or constraints
 - Especially for high level requirements
- Analysis and Test are the most common methods combined to prove the whole
- Reality is inspection, demonstration, and test are done together all the time

Coupled Loads: Analysis + Test

Requirements Verification

Determine how to verify – requirement by requirement

Verification Process Rolls it All Up

TEST PHILOSOPHY

Why Do We Test?

- Product integrity
 - Validate design
 - Verify requirements
 - Understand performance and margin
 - Find defects before flight
 - Find the unknown unknowns
 - Assure workmanship
 - Create confidence
 - Certify readiness
- Systems getting increasingly complex
 - Interactions not easily modeled

**Need Thorough, Disciplined, Perceptive Test that
is Representative of Operations**

Test Philosophy

- Test philosophy is evolving
 - Industry is moving from low risk to “managed risk” atmosphere
 - Affordability
 - Perceptiveness
- Qualify and verify at lowest level
 - Screen defects before integrating into next higher assembly
 - Most perceptive testing
 - Lower repair cost
 - Not in single line flow
 - Minimize retest
- Next higher assembly
 - Validation of requirements
 - Verification and qualification of interfaces
 - Verification and qualification of performance and functionality

**Finding Defects Requires
Multiple Levels of Robust Testing**

Levels of Integration

- Part - single or joined pieces which are not normally subject to disassembly without destruction or impairment of the design use
 - Examples: resistor, integrated circuit, relay, roller bearing
- Subassembly/Unit - a functional item that is viewed as a complete and separate entity for purposes of manufacturing, maintenance, or record keeping containing two or more parts which is capable of disassembly or part replacement
 - Examples: printed circuit board with parts installed , gear train
- Subsystem – assembly of two or more functionally related subassemblies/units and may include interconnection items such as cables or tubing, and the supporting structure to which they are mounted
 - Examples: electrical power, attitude control, telemetry, thermal control, propulsion
- System - integrated set of subsystems capable of supporting an operational role in space
 - Examples: space vehicle, launch vehicle, ground station
- System of systems – integrated individual systems to achieve unique, unified, additional capabilities
 - Examples: Constellation including ground stations

Level of Integration

Unit

Subassembly

Part

System

Need Correct Verification at Correct Integration

Test Pyramid

- Test is a cumulative process
 - Build on previous testing to minimize failures at next higher level of assembly
- Verify workmanship and requirements at the lowest level possible
- Find failures at the lowest level possible where perceptiveness is the greatest
 - Focus on interfaces as move up the pyramid

Most Effective Test is at the Appropriate Level

Basics of Test

- What can be tested
 - Anything that can be instrumented to indicate state or numeric value of parameters: hardware, software, databases
- Provide the worst case and nominal conditions on the flight hardware and software
 - Understand limitations and impacts of non-flight articles
- Not everything can be tested but do the best you can
 - Decide what is NOT done and understand the associated risks and impacts
 - Supplement with other verification methods
- What can't be tested, tested well, or tested feasibly
 - Where the necessary conditions of the test are physically impossible or difficult to engineer without introducing too much uncertainty in the results or risk to the unit under test (UUT)
 - Where the ramifications of the test vastly exceed the nature of the test

Test Selection Process

Approach 1:

Start with all tests and delete when knowledge allows

Approach 2:

Start with minimum set and add as experience demands

- Dilemma – Cost and schedule impacts in either case may be prohibitive
- Considerations
 - Vibration: all units
 - Shock: if flight levels $> 0.8 \times$ frequency
 - Thermal vacuum: if high power and/or thermal dissipation
 - Thermal cycle: if low power and/or not sensitive to vacuum
 - Acoustic: if large surface
 - Leakage: only if pressurized/sealed
 - Pressure: if sealed and/or pressure vessel
 - Acceleration: only if function affected
 - EME: only on electrical
 - Life: only if cycled

*Which Approach is Wiser?
Which is Cheaper?*

Trust But Verify

Test Planning

- A good test program is one where the hardware performance is verified under fielded conditions
 - Development tests find breaking points
 - Qualification tests validate performance design margins
 - Acceptance tests validate hardware is free of workmanship defects and will perform under fielded conditions
- Decisions to be made
 - Desired performance margins
 - Desired tests to screen for workmanship defects
 - Validate performance before, during and/or after exposure

Test Planning (cont)

- Software test planning must be **incorporated** into system test planning during the earliest stages of the system life cycle
 - Levels of software and system integration for space and ground
 - Integration levels where requirements will be verified
- Software, hardware, and system test planning include planning for development or procurement of **necessary test resources**
 - Simulators, emulators
 - Test drivers, stimulators
 - Automated test execution tools
 - Automated Test Equipment (ATE)
 - Automated Ground Equipment (AGE)

Early and Thorough Test Planning is Essential

Development Tests

Tests conducted on representative articles to

- Validate/demonstrate the evolution of designs from the conceptual phase to the operational phase
 - New design concepts
 - Application of proven concepts and techniques to a new configuration
 - Technology insertion
 - Characterize engineering parameters, gather data
- Reduce risk involved in committing designs to the fabrication of qualification and flight hardware
 - Breadboard testing
 - Model validation
 - Validate test scripts and procedures
 - Investigate problems or concerns that arise after successful qualification
 - Engineering characterization tests and tests to validate qualification and acceptance procedures

Qualification Tests

- Demonstrate that the design, manufacturing process, and acceptance program produce mission items that meet specification requirements
- Validate the planned acceptance program including test techniques, procedures, equipment, instrumentation, and software
- Performed beyond maximum predicted environments (MPE) to provide margin
- A single qualification test item of a given design should be exposed to all applicable environmental tests
- Protoqualification tests (protoqual/protoflight)
 - Modified qualification (reduced margin) conducted on product which is considered to be available for flight
 - Saves costs but increases risk
 - Protoflight tests all units
 - Protoqual tests only the first unit; subsequent units tested at acceptance levels

Acceptance Tests

- Demonstrate the acceptability of each deliverable product
- Demonstrate conformance to subset of specification requirements
- Provide quality-control assurance against workmanship or material deficiencies
 - Intended to stress screen items to precipitate incipient failures due to latent defects in parts, materials, and workmanship
- Performed at MPE
 - Will not create conditions that exceed appropriate design safety margins or cause unrealistic modes of failure

Test Like You Fly (TLYF)

- There shall be no nominal activity will be performed in operation that hasn't been demonstrated in a flight-like manner on the ground
 - Don't want first occurrence of operation to be experienced in space
 - Test in same order and same conditions like it is used (flown)
- Recommended approach to verification and validation and associated risk decision making
 - Involves system engineers, hardware and software engineers, test creators, mission designers, operations personnel, and those charged with independent evaluation of design verification
- Provides a unique assessment process that focuses on determining the “mission-related” or “like you fly” risks associated with potential flaws in our space systems

Test Like You Fly !!

Not Like You Fly

- Frequently, it is not possible to test like you fly
- Those limitations (aka exceptions) are due to
 - Physics (can't be done)
 - Engineering (not practical to do)
 - Programmatic (philosophy, cost or schedule constraints)
- TLYF limitations shall be addressed with risk assessment and mitigation
 - Mitigation can be adjunct analyses, non-TLYF tests, etc.
 - Often mitigated by a “sum of the parts” approach
- Risk of doing test in a flight-like way must be weighed against the risk of missing flaws when doing it in a non-flight-like way (or not doing it at all)

Need to Understand the Risk and Impacts

Test Resources

- Test Articles
 - Preferably in matrix format, show key government and contractor resources
- Test Sites and Instrumentation
 - Ranges and national facilities
- Test Support Equipment
 - Special GSE that must be acquired
- Threat Systems/Simulators
 - Type and fidelity
- Test Targets and Expendables
 - Rockets, bombs, target characteristics, etc.
- Operational Force Test Support
 - Planes, ships, on-orbit assets already under assignment
- Simulations, Models and Testbeds
 - Computer driven simulators for hardware-in-the-loop type system testing
- Special Requirements
 - Any significant non-instrumentation capabilities and resources such as: unique geodesy products or restricted air/sea/landscapes
- Test and Evaluation Funding Requirements
 - Estimate, by fiscal year and appropriation line number
- Manpower/Personnel Training
 - Training requirements and limitations that affect test and evaluation execution
 - Human factors

**The Earlier You Determine Test Program Needs –
The Better**

Not for Flight Hardware: Brassboards, Engineering Units, Test Beds

- Brassboards
 - A circuit board or unit using flight equivalent, but not flight qualified, parts and assembly techniques
 - Used as functional and interface test article
- Engineering Unit
 - A flight equivalent, and possibly flight qualifiable, unit meant to be used as a test article in a test bed
- Test Beds
 - An electrical and signal flight equivalent assembly of a subsystem or satellite using brassboard units. May not be mechanically equivalent to satellite in layout
 - Used to perform initial subsystem and/or spacecraft hardware and software functional tests; validate test procedures for flight units; troubleshoot problems identified on flight spacecraft both during ground test and on-orbit operations
 - Stress testing
 - Off-nominal testing

**These Non-Flight Items Can Be Very Handy...
But Often First on the List to Be Deleted**

Maybe Not for Flight Hardware

- Structural test model
 - Form/fit precursor to flight model
 - Tested to qualification levels of vibration, shock, acoustic
 - Can be used to verify harness layout, interference paths, fit checks, etc.
- Simulators
 - Simulates specific conditions or the characteristics of a real process or operation
 - Potential development / anomaly investigation platform thereafter
- Qualification test hardware
 - Flight-like but highly stressed
 - Validate manufacturability and design concepts
 - Test to qualification levels for all environmental test
 - Potential development / anomaly investigation platform thereafter

Non-flight Hardware Can be Upgraded to Flight

Test Related Issues

- Minimal planning
- Don't understand the UUT
- Don't have documented steps
- Don't have clear criteria including tolerances
- Incorrect test article fidelity
- Test not perceptive enough
- Not Test Like You Fly
- Margins unknown or not understood
- All the modes and states are not known or addressed
- Not understanding impact of UUT vs flight configurations
- Environments or conditions not properly coupled

Unclear Unknown Undisciplined

TEST OBJECTIVES

Integration of Test

<i>Parts</i>	<i>Subassembly / Unit</i>	<i>Subsystem Integration</i>	<i>System: Payload & Vehicle Integration</i>	<i>System End-to-End</i>	<i>Pre-Launch Validation</i>
<ul style="list-style-type: none"> • Electrical • Thermal • Vibration • X-ray • Life • Leak • Radiation 	<ul style="list-style-type: none"> • Functional • Electrical • Mechanical • Software • Vibration • Shock • Burn-in • Temp cycle • Vacuum • Pressure/leak • EMI/EMC • Special 	<ul style="list-style-type: none"> • Functional • Interface Verification • Electrical • Signal • Pressure/leak • Hardware in-the-loop simulation • Software 	<ul style="list-style-type: none"> • Functional • Interface Verification • Electrical • Mechanical • Software • Acoustic • Vibration • Shock • Orbit Thermal-Vacuum • Pressure/leak • EMI/EMC • Special 	<ul style="list-style-type: none"> • Functional • Signal • RF • Electrical • Mechanical • Flight SW • Ground SW • Procedures • Databases • Data Analysis • Ops Concept 	<ul style="list-style-type: none"> • Functional • Electrical • Mechanical • Software • Pressure/leak • Install before flight • Remove before flight

Integration & Test Flow

- Performance Testing
 - Demonstrate electrical, optical, mechanical , and software of UUT satisfies specification requirements and tolerances
 - Demonstrates design margins and specification compliance for all pathways and modes
- Functional Testing
 - Assess operability of UUT within boundaries established by design requirements

Test Objectives – Part

- Definition
 - Piece(s) not normally subject to disassembly without destruction or impairment of the design use
- Test Objective
 - Screen for workmanship and latent parts defects
 - Verify part specification performance

Start with Good Products

Test Objectives – Subassembly/Unit

- Definition
 - Unit containing two or more parts which is capable of disassembly or part replacement
- Test Objective
 - Verify workmanship and design
 - Verify subassembly/unit specification performance
 - Can have software and/or firmware
 - Perceptive testing at the subassembly level reduces repairs and saves schedule and cost
 - LMMS paper 1986, D. A. Smith reviewed 29 units
 - 82 Critical failures counted = Failure rate of 2.8 per unit
 - 59 of the 82 (72%) could have been detected at card level
 - Computer industry routinely screens populated boards for defects

Courtesy of NASA

Perceptive Part and Unit Tests Save \$\$

Unit Qualification Tests

Test \ Units	Electrical and Electronic	Antenna	MMA	Solar Array	Battery	Valve or Propulsion Component	Pressure Vessel or Component	Thruster	Thermal	Optical	Structural Components
Inspection	R	R	R	R	R	R	R	R	R	R	R
Specification Performance	R	R	R	R	R	R	R	R	R	R	ER
Leakage	ER	—	R	—	R	R	R	R	R	—	—
Shock	R	ER	ER	ER	R	ER	ER	ER	ER	ER	ER
Vibration or Acoustic	R	R	R	R	R	R	R	R	R	R	ER
Acceleration	ER	ER	ER	ER	ER	—	ER	—	—	ER	ER
Thermal Cycle	R	ER	ER	ER	R	ER	ER	ER	ER	ER	ER
Thermal Vacuum	R	R	R	R	R	R	R	R	R	R	—
Climatic	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER	ER
Pressure	ER	—	ER	—	R	R	R	ER	ER	—	—
EMC	R	R	ER	ER	ER	ER	ER	ER	ER	ER	ER
Life	ER	ER	R	ER	R	R	ER	R	ER	ER	ER
Burst Pressure	—	—	ER	—	R	R	R	R	ER	—	—
Static Load	ER	ER	ER	ER	R	—	ER	—	—	—	R

Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E) Table 6.3-1

Unit Acceptance Tests

Test \ Units	Electrical and Electronic	Antenna	MMA	Solar Array	Battery	Valve or Propulsion Component	Pressure Vessel or Component	Thruster	Thermal	Optical	Structural Components
Inspection	R	R	R	R	R	R	R	R	R	R	R
Wear-In	--	--	R	-	ER	R	--	R	--	--	--
Specification Performance	R	R	R	R	R	R	R	R	R	R	ER
Leakage	ER	ER	R	--	R	R	R	R	--	--	--
Shock	ER	ER	ER	--	ER	ER	--	ER	--	ER	--
Vibration or Acoustic	R	R	R	R	R	R	ER	R	--	R	ER
Thermal Cycle	R	ER	ER	ER	ER	ER	--	ER	ER	ER	--
Thermal Vacuum	R	R	R	R	R	R	ER	R	R	R	--
Proof Pressure	ER	--	ER	--	R	R	R	ER	--	--	--
Proof Load	--	ER	ER	--	ER	ER	ER	ER	ER	ER	R
EMC	ER	ER	--	ER	ER	ER	--	--	--	--	--

Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E) Table 6.3-2

Typical Unit Test Sequence

Unit Test Margins and Duration

Test	Qualification	Protoqualification	Acceptance
Shock ⁽¹⁾	6 dB above acceptance, 3 times in both directions of 3 orthogonal axes	3 dB above acceptance, 2 times in both directions of 3 orthogonal axes	Maximum predicted environment (MPE), once in both directions of 3 orthogonal axes
Acoustic ⁽²⁾	6 dB above acceptance for 3 minutes	3 dB above acceptance for 2 minutes	Envelope of MPE and minimum spectrum (Figure 6.3.6-1) for 1 minute
Vibration ⁽²⁾	6 dB above acceptance for 3 minutes in each of 3 axes	3 dB above acceptance for 2 minutes in each of 3 axes	Envelope of MPE and minimum spectrum (Figure 6.3.5-1) for 1 minute in each of 3 axes
Thermal Vacuum (non-electrical and non-electronic)	±10°C beyond acceptance for 6 cycles	±5°C beyond acceptance for 3 cycles	MPT for 1 cycle
Thermal Cycle or Thermal Vacuum Only	±10°C beyond acceptance for 27 cycles	±5°C beyond acceptance for 27 cycles	Envelope of MPT and minimum range (-24 to 61°C) for 14 cycles
Combined Thermal Vacuum and Thermal Cycle	±10°C beyond acceptance for 4 thermal vacuum cycles and 23 thermal cycles	±5°C beyond acceptance for 4 thermal vacuum cycles and 23 thermal cycles	Envelope of MPT and minimum range (-24 to 61°C) for 4 thermal vacuum cycles with minimum 2-hour hot operational dwell and 10 thermal cycles
Static Load	1.25 times the limit load for unmanned flight or 1.4 times limit load for manned flight, duration encompassing flight loading time	1.25 times the limit load for unmanned flight or 1.4 times limit load for manned flight, duration encompassing flight loading time	1.1 times the limit load
Pressure	Pressures as specified in Table 6.3.12-2 following acceptance proof pressure test	Pressures as specified in Table 6.3.12-2 following acceptance proof pressure test	1.1 times MEOP for pressurized structures; 1.25 times MEOP for pressure vessels; 1.5 times MEOP for pressure components. Other metallic pressurized hardware items per ANSI/AIAA S-080 and S-081
EMC	12 dB minimum, duration same as acceptance	6 dB minimum, duration same as acceptance	6 dB, 20 minutes at each space vehicle transmitter frequency for radiated susceptibility

⁽¹⁾ See Section 10.2.6 for additional information.

⁽²⁾ See Section 10.2.2 and 10.2.3 for units with effective duration greater than 15 seconds.

Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E) Table 6.3-3

Space Vehicle Subsystems Integration

It's the Sum of Many Parts

Test Objectives – Subsystem

- Definition
 - Assembly composed of functionally related units that perform one or more prescribed functions
- Test Objective
 - Verify interfaces and key performance parameters
 - Verify specification performance
 - Should have flight software and firmware
 - Access often limited at system level
 - Provide a more perceptive test than system level
- Typical Tests
 - Payload subsystem
 - Structural test assembly
 - Mechanical assemblies (e.g. antenna arrays)
 - Propulsion subsystem

Photo Courtesy of NASA

Follows System Level Approach and Test Flow

Subsystem Qualification

Test	Reference	Suggested Sequence	Payload Fairing	Structure	Bus	Payload / Instrument	Multi-Unit Module
Inspection	4.6	1, 11	R	R	R	R	R
Specification Performance ⁽¹⁾	7.3.1	2, 10	R	R	R	R	R
Static Load	7.3.2	3	R	R	R	R	R
Pressure <u>and Leak</u>	7.3.3	4	ER	ER	ER ⁽⁴⁾	ER	ER
Shock	7.3.6	7	-	ER	ER	ER	ER
Random Vibration or Acoustic	7.3.4 7.3.5	5	R	ER	ER	ER	ER
Thermal Vacuum	7.3.7	6	-	ER	ER	R	R
Separation and Deployment ⁽³⁾	7.3.8	8	R	R	R	ER	ER
EMC	7.3.9	9	-	-	R	R	ER
Mode Survey	7.3.10	Any	R	-	R ⁽²⁾	R ⁽²⁾	ER

R Required
ER Evaluation Required (See 6.3)

- (1) Specification performance tests shall be conducted prior to, during and following each environmental test, as appropriate
- (2) Mode survey testing is required for both the either at the Subsystem or the System level.
- (3) First motion testing of separable/deployable components required.
- (4) Required for propulsion subsystem

Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E) Table 7.3-1

Subsystem Acceptance

Test	Reference	Suggested Sequence	Payload Fairing	Structure	Bus	Payload	Multi-Unit Module
Inspection	4.6	1, 10	R	R	R	R	R
Specification Performance ⁽¹⁾	7.3.1	2, 9	R	R	R	R	R
Static Load	7.3.2	3	R ⁽²⁾	R ⁽²⁾	R ⁽²⁾	R	-
Pressure and Leak	7.3.3	4	-	-	R	R	R
Random Vibration or Acoustic	7.3.4	5	ER	-	-	ER	R
	7.3.5						
Thermal Vacuum	7.3.7	6	-	-	ER	R	R
Separation and Deployment ⁽³⁾	7.3.8	7	ER	-	ER	ER	ER
EMC ⁽⁴⁾	7.3.9	8	-	-	ER	ER	-

R Required

ER Evaluation Required (See 6.3)

(1) Specification performance tests shall be conducted prior to, during and following each environmental test., as appropriate

(2) Required for composite and bonded structures. Evaluation required for all other structures.

(3) First motion testing of separable/deployable components required.

(4) Required when there is less than 12 dB margin.

Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E) Table 7.3-2

Subsystem Level Margins and Durations

Test	Qualification	Protoqualification	Acceptance
Shock	1 activation of all shock-producing events; 2 additional activation of significant events	1 activation of all shock-producing events; 1 additional activation of significant events	1 activation of significant shock-producing events
Acoustic ⁽¹⁾	6 dB above acceptance for 3 minutes	3 dB above acceptance for 2 minutes	Envelope of MPE and minimum spectrum (Figure 6.3.6-1) for 1 minute
Vibration ⁽¹⁾	6 dB above acceptance for 3 minutes in each of 3 axes	3 dB above acceptance for 2 minutes in each of 3 axes	Envelope of MPE and minimum spectrum (Figure 8.3.7-1) for 1 minute in each of 3 axes
Thermal Vacuum	±10°C beyond acceptance for 8 cycles	±5°C beyond acceptance for 4 cycles	MPT for 4 cycles
Static Load ⁽²⁾	1.25 times the limit load for unmanned flight or 1.4 times limit load for manned flight, duration sufficient to record data	1.25 times the limit load for unmanned flight or 1.25 times limit load for manned flight, duration sufficient to record data	1.1 times the limit load for bonded, composite, or sandwich structures, duration sufficient to record data
Pressure and Leak ⁽³⁾	1.1 times MEOP for pressurized structures; 1.25 times MEOP for pressure vessels; 1.5 times MEOP for pressure components. Pressure testing followed by leak testing at MEOP. Other metallic pressurized hardware items per AIAA S-080 and S-081	1.1 times MEOP for pressurized structures; 1.25 times MEOP for pressure vessels; 1.5 times MEOP for pressure components. Pressure testing followed by leak testing at MEOP. Other metallic pressurized hardware items per AIAA S-080 and S-081	1.1 times MEOP for pressurized structures; 1.25 times MEOP for pressure vessels; 1.5 times MEOP for pressure components. Pressure testing followed by leak testing at MEOP. Other metallic pressurized hardware items per AIAA S-080 and S-081
EMC	12 dB minimum, duration same as acceptance	6 dB minimum, duration same as acceptance	6 dB minimum, 20 minutes at each space vehicle transmitter frequency for radiated susceptibility

⁽¹⁾ See 10.2.3 for subsystems with effective duration greater than 15 seconds.

⁽²⁾ Refer to AIAA S-110-2005 and TOR-2003(8583)-2894

⁽³⁾ Refer to TOR-2003(8584)-2895, SMC-S-005, and SMC-S-006

Test Objectives – System

- Definition
 - Composite of equipment, skills, and techniques capable of performing or supporting an operational role
 - Includes all operational equipment, related facilities, material, software, services, and personnel required for its operation
- Test Objective
 - Verify interfaces and key performance parameters
 - Validate operational capabilities
 - Validate specification requirements
 - Functional and performance tests
 - Will have flight software and firmware
 - Environmental tests

Courtesy of Lockheed Martin

Usually the 1st Time It All Comes Together

Preferred System Test Sequence

System Qualification

Test	Section	Suggested Sequence	Launch Vehicle	Upper-stage Vehicle	Space Vehicle
Inspection	4.6	1, 13	R	R	R
Specification Performance ⁽¹⁾	8.3.1	2, 12	R	R	R
Pressure/Leakage	8.3.2	3, 7, 10	R	R	R
EMC ⁽²⁾	8.3.3	4 or 11 ⁽²⁾	R	R	R
Shock	8.3.4	6	R	R	R
Acoustic or Random Vibration ⁽³⁾	8.3.5	5	ER	R	R
	8.3.6				
Thermal Balance	8.3.7	8	--	ER	R
Thermal Vacuum	8.3.8	9	--	ER	R
Mode Survey	8.3.9	Any	ER	ER	R

R Required

ER Evaluation Required

⁽¹⁾ Electrical and mechanical specification performance tests shall be conducted prior to, during and following each environmental test, as appropriate.

⁽²⁾ EMC testing, sequence 4 or 11, shall be conducted when there are radiated emission requirements below 10 dBuV/m or there is a requirement on passive intermodulation levels.

⁽³⁾ Vibration can be used in place of acoustics for vehicle weights under 180 kilograms.

Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E) Table 8.3-1

System Acceptance

Test	Reference Paragraph	Suggested Sequence	Launch Vehicle	Upper-stage Vehicle	Space Vehicle
Inspection	4.6	1, 12	R	R	R
Specification Performance ⁽¹⁾	8.3.1	2, 11	R	R	R
Pressure/Leak	8.3.2	3, 7, 9	R	R	R
EMC ⁽²⁾	8.3.3	4 or 10	ER	ER	ER
Shock	8.3.4	6	ER	ER	R
Acoustic or Vibration ⁽³⁾	8.3.5 8.3.6	5	ER	R	R
Thermal Vacuum	8.3.8	8	--	R	R

R Required

ER Evaluation Required

⁽¹⁾ Electrical and mechanical specification performance tests shall be conducted prior to, during and following each environmental test as appropriate.

⁽²⁾ EMC testing (sequence 4 and 10) required when there is less than 12 dB margin.

⁽³⁾ Vibration can be used in lieu of acoustics for vehicles under 180 kg.

Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E) Table 8.3-2

System Level Margins and Durations

Test	Qualification	Protoqualification	Acceptance
Shock	1 activation of all shock-producing events; 2 additional activation of significant events	1 activation of all shock-producing events; 1 additional activation of significant events	1 activation of significant shock-producing events
Acoustic ⁽¹⁾	6 dB above acceptance for 3 minutes	3 dB above acceptance for 2 minutes	Envelope of MPE and minimum spectrum (Figure 6.3.6-1) for 1 minute
Vibration ⁽¹⁾	6 dB above acceptance for 3 minutes in each of 3 axes	3 dB above acceptance for 2 minutes in each of 3 axes	Envelope of MPE and minimum spectrum (Figure 8.3.7-1) for 1 minute in each of 3 axes
Thermal Vacuum ⁽²⁾	±10°C beyond acceptance for 8 cycles	±5°C beyond acceptance for 4 cycles	MPT for 4 cycles
Proof Pressure	1.1 times MEOP for pressurized structures; 1.25 times MEOP for pressure vessels; 1.5 times MEOP for pressure components. Other metallic pressurized hardware items per AIAA S-080 and S-081.	1.1 times MEOP for pressurized structures; 1.25 times MEOP for pressure vessels; 1.5 times MEOP for pressure components. Other metallic pressurized hardware items per AIAA S-080 and S-081.	1.1 times MEOP for pressurized structures; 1.25 times MEOP for pressure vessels; 1.5 times MEOP for pressure components. Other metallic pressurized hardware items per AIAA S-080 and S-081.
EMC	12 dB minimum, duration same as acceptance	6 dB minimum, duration same as acceptance	6 dB minimum, 20 minutes at each space vehicle transmitter frequency for radiated susceptibility

⁽¹⁾ See 10.2.3 for units with effective duration greater than 15 seconds.

⁽²⁾ See Note 10.1.1 if vehicle thermal cycle testing is performed.

Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E) Table 8.3-3

Test Objectives – System End-to-End

- Test Objective
 - Verify space vehicle and ground intersegment interface
 - Should include space vehicle flight and operations qualified software
 - Validate telemetry processing, command capability, and communication between the space vehicle through the ground receiving network to mission processing
 - Functional uplink, downlink
 - Timing
 - Communication
 - Launch rehearsal to validate procedures and training
 - Typically last electrical test at the launch site
- Common issues
 - Antenna polarity
 - Crypto key mismatch
 - Network timing and protocol

Courtesy of Integrated Ocean Observing System

Simple Test that Avoids Potential Fatality

Test Objectives – Pre-Launch

- Demonstrate readiness of the hardware, software, personnel, procedures, and mission interfaces to support launch and the program mission
 - Assure readiness for space vehicle integration with the launch vehicle and launch facility
 - Verify that no changes have occurred in vehicle parameters as a result of handling and transportation to the launch base
 - Demonstrate interface compatibility
 - Assure readiness to launch
 - Demonstrate successful integration of the launch and space vehicles with the launch facility
 - Demonstrate compatibility exists between the integrated vehicle hardware and software, ground equipment and software, and within the entire launch and on-orbit system (end-to-end)

Courtesy of NASA

Perform Before and After Shipment to Launch Site

Typical Pre-Launch Flow

- Precursors to launch processing
 - Launch vehicle dynamics analysis
 - LV adapter fitcheck and deployment
 - LV electrical interface checkout
 - Mass properties
- Mechanical fit checks and alignments
- Electrical tests
 - In stowed position
 - Ideally end to end using antenna feed couplers, otherwise hardline
 - End to end functionality and launch sequence check (all copper paths)

Make Sure You Leave the Vehicle in its Final Launch Configuration!!

Test Objectives – On-Orbit

- To initialize and verify functional integrity of the space vehicle following launch
 - Demonstrates space vehicle operating as designed
 - Demonstrates ground systems are ready to support mission operations
 - Demonstrates Mission data can be distributed to the planned users
- Three major phases
 - Initialization and checkout
 - Operations and maintenance during normal operations
 - Anomaly response
- Continuing debate
 - Checkout only one string or also redundancy string?

Courtesy of NASA

**Must Demonstrate Patch Capability Prior to Launch –
Just in Case**

Typical On-Orbit Testing Flow

- Lasts anywhere from 30 days to 2 years

L + 5 Days*

Installation
Functional Checks
Calibration

L + 60 Days*

Satellite Subsystem/Payload Characterization
Interface and Performance Validation
Further calibration and Database Updates

L + 90 Days*

Mission Scenarios
Effectiveness Suitability
Mission Certification

*Timelines vary for each program according to complexity and problems encountered after launch

Test Descriptions

Test Configuration Issues

- What flight products are not included?
- What non-flight products are included?
- How will you handle missing hardware and software?
 - Mass model? Engineering unit? Simulator?
- What functional performance parameters will be monitored during a test?
 - How will you monitor the performance parameters?
 - Telemetry? Is sample rate adequate?
 - Hardwire?
- When are abbreviated functional tests acceptable?
 - Which functional parameters constitute an abbreviated functional test?
- Will tanks be loaded?
 - With what? What about cryogenic fluids?
 - Will operating pressures be used?

Understand and document test configuration

Wear-in/Burn-in

Purpose: Propagate latent infant mortality defects and to assure smooth and consistent performance

Wear-in

- Test Requirements
 - Number of cycles: 15 or 5% of the total number of expected cycles during service life
 - Post environment test
- Test Challenges
 - Perform prior to other tests
- Configuration
 - Applies to moving mechanical assemblies and propulsion devices (e.g., thrusters and valves)

Burn-in

- Test Requirements
 - Minimum 200 hours powered-on at high temperature
 - Last 100 hours error free
- Test challenges
 - Perform during thermal testing – may need to allow for the additional hours
- Configuration
 - Applies to electronic assemblies

Fail Criteria: Does not perform as expected

Performance Test

- Purpose
 - Verify electrical, optical, and mechanical performance with/without applied environments
- Test Requirements
 - Voltages, impedances, frequencies, pulses, waveforms,
 - Alignment, pressure, torque angle damping, etc
- Configuration
 - Bread board
 - Brass board
 - Flight quality
- Test Challenges
 - Breakout boxes
 - Telemetry rate (perceptiveness)
 - Simulators for companion signals
- Fail Criteria
 - Outside specified performance parameters

IT FAILED!

What about the case where performance is off nominal but within limits?

It's Performance, Not Functional Test!

Specification Performance Test (Subsystem and System)

- Verifies/validates mechanical and electrical performance of vehicle
 - Utilizes flight products including software
 - Includes mechanical deployments
- Performed before and after environmental exposures
 - Abbreviated test often performed between environments for risk mitigation

Photo courtesy of ESA

**Initial Performance Test Finds, the
Greatest Number of Defects (& Escapes)**

Hardware Environmental Exposure

Environment	Manufacturing	Handling, Shipping, & Storage	Part	Unit	Subsystem	AI&T	System	LV Integration	Launch	On-Orbit	Deorbit	Examples of Specific Environment
Climatic	R	Y	B	B	B	R	B	R	R		R	Salt spray, dust, humidity
Electromagnetic	Y	Y	B	B	B	B	B	B	R	R	R	Backup generator
Mechanical	Y	Y	B	B	B		B		R	R	R	Shock, vibration, acoustics
Natural Space			B							R	R	Radiation
Pressure-Ambient	Y	Y	B	B	B	Y	B	Y	R	R	R	Normal variation in barometric pressure
Structural Loading	Y	Y	B	B	B		B	R	R	R	R	Gravity, aero, thermal, thrust, maneuver
Thermal	Y	Y	B	B	B	Y	B		R	R	R	Temperature variations, cycling
Vacuum			B	B	B		B					

Y Process induced environment

B Test induced environment

R Actual or natural environment

Welding, soldering, X-Ray inspection

Shaker shock, Tvac, EMI/EMC,

LV induced vibration, on-orbit radiation

Ref: TOR-2006(8546)-4591 Space Vehicle Test and Evaluation Handbook, Table 4.3-1

Dynamic Test

- Purpose
 - Demonstrate ability of the system to meet performance requirements during and after exposure to the mission dynamic environment and to demonstrate design margin at qualification
- Test Types
 - Vibration: Typically part and unit level
 - Acoustic: Typically system level and large structure unit level
 - Shock: All levels
- Test Challenges
 - Very high test levels, greater than 100 g_{rms}
 - Tests must be split up into frequency bands
- Helpful Hints
 - Abbreviated pre- and post-environment tests typically performed
 - Prefer to perform powered on and monitored
 - Perform before thermal testing
 - Done in the order of launch exposure
 - Has a higher test effectiveness – will find more failures before launch

Dynamic Environments During Launch and Ascent

Ground Processing Environments May Set the Limits

Dynamic Testing – It's a Big Frequency Range

Dynamic Tests Do Not Cover the Same Frequency Range

Vibration Test

- Purpose
 - Workmanship screening
 - Product specification
 - Random
 - Sine amplitude
 - Sine sweep
- Test Requirements
 - Test tolerance bands
 - Large table with hydraulic actuators (covers 2-100 Hz)
 - Large table with magnetic coil and armature (covers 20-2000 Hz)
- Configuration
 - Unit – Flight, powered, functionally exercised

Picture courtesy of The Aerospace Institute

Vibration Test (cont)

- Test Challenges
 - Duration effects fatigue life
 - Life demonstrated during qualification
 - Which axis first
 - Fixture resonance
 - Penalty testing
- Fail Criteria
 - Fails performance test during or after exposure
 - Fails deployment test after exposure
 - Structure cracks or yields, torque relaxed
 - Parts fall off
- Helpful Hints
 - Unit should be powered
 - Perform before thermal testing

Photo courtesy of NASA

Power-on Vibration Tests Are Preferred Workmanship Tests

Acoustic Test

- Purpose
 - Product specification
 - Can defer to higher level of assembly
 - When risk of failure is low
 - Don't defer solar arrays and large antennas
 - To ensure pressure loading survival for low mass to area hardware
- Test Requirements
 - Reverberant chamber - large concrete box with air or nitrogen horns
 - Test Setup and Instrumentation
 - Pretest shaping runs
 - Microphone locations
 - Data quality checks
 - Overtest protection
- Configuration
 - Launch Configuration (stowed)
 - Power-on
 - MIL-HDBK-340A requires at least all hardware on during ascent

Pictures courtesy of The Aerospace Corp Crosslink©

Acoustic Test (cont)

- Test Challenges
 - Spectrum levels and duration, test tolerance bands
 - Minimum stress screening level
 - Number and placement of control microphones
 - Inspection or tests to validate unit passed test
- Pass Criteria
 - No power intermittents observed during exposure
 - No parts fell on floor
 - Structure intact - subsequent deployments nominal
 - Subsequent ambient functional or thermal test passed
- Helpful hints
 - Typical antenna failures are at supports and laminate debonds
 - Typical solar array failures are cracked glass, laminate debonds, circuit lifting

Courtesy of European Space Agency

Shock Test

- Purpose
 - Product specification
 - Qualification test susceptible units (ex. TWTAs, gyros)
 - High frequency events such as deployments and separations for system
- Test Requirements
 - Test methods
 - Plate (hanging or on table) struck by hammer or ram
 - Beam struck by hammer
 - Vibration shaker
 - Multiple times in each axis
 - Amplitude with test tolerance criteria
 - Test fixturing used to minimize interference of response spectrum
 - Flight representative

Shock Test (cont)

- Configuration
 - Power on and monitored
 - High resolution needed
 - Relay chatter detection
- Test Challenges
 - Which units are susceptible
 - Coverage by random environment
 - Test Setup and Instrumentation
 - Pretest shaping runs
 - Test tolerance bands
 - Accelerometer locations
 - Data quality checks
 - Overtest protection
- Fail Criteria
 - Structural cracks and yielding
 - Power interrupts
 - Fail post test functional or deployment
 - Parts fall off

Photo courtesy of Dayton T. Brown, Inc

Shock Test (cont)

- Shock Test Criteria
 - Peak g response from 100 to 10000 Hertz
 - Or actual firing of explosively actuated devices or clamp band hardware (staging, separation, deployment releases)
 - Impulse time history must be < 20 msec
 - Damage potential
 - $\text{Velocity} > 50 \text{ in/sec} = 0.8 \times \text{frequency}$
- Helpful Hints
 - Unit test should precede vibration test
 - System test should precede acoustic test
 - Typically identifies design deficiencies
 - Components too close to shock source
 - Inadequate deployment clearances
 - Breaks in wires, seals or crystals
 - Relay chatter

Thermal Tests

- Purpose
 - Demonstrates performance at or near maximum and minimum predicted temperatures
 - Survival temperatures
 - Operational temperatures
 - Detects material, process and workmanship defects
 - Emphasis on mounting, cabling, connectors, and component and subsystem interactions
 - Higher quality parts do not reduce need for thermal cycling test
 - A significant percentage of unit thermal cycling failures are parts related
 - Verification of flight thermal control subsystem

Photo courtesy of ESA

Source of Thermal Environments

Thermal Tests (cont)

- Test Requirements
 - Ambient pressure or vacuum
 - Temperature extremes and range
 - Operation/non-operation profile
 - Dwell at temperature extremes
 - Number of cycles
 - Temperature transition rate
 - Powered on or off
 - Functional tests hot and cold
 - Cold and hot starts
 - Survival heater check out
 - Redundant instrumentation
- Configuration
 - Flight software
 - On-orbit configuration

Thermal Tests (cont)

- Physics of failure
 - Plastic strain/thermal expansion mismatch/ fatigue expressed by Coffin Manson/ Miners rule/ temperature - time related degradation
 - Detection can be significant to 20 cycles thermal tests
- Helpful Hints
 - Perform after vibration
 - Vibration defects may precipitate in the thermal tests
 - Start thermal testing at temperature above ambient (bake and dry out)
 - End TVac at temperature higher than ambient
 - A significant percentage of unit thermal failures are parts related

Survival and Turn-On

- Verifies that the unit can survive extreme environments and operating conditions and subsequently perform within specification over a narrower environmental range
- Functions as part of the stress-screening process
- Demonstrates that the unit is well-designed, has good parts and materials, and is properly produced
- Demonstrates that the unit has survival and turn-on capability for anticipated and contingent environments
 - Anticipated extreme environments
 - Cold condition following transfer orbit
 - Hot condition (possible operational)
 - Contingent extreme environments
 - Satellite damage or loss of attitude control or communication during ascent or transfer orbit
 - Safemode conditions
 - Failed heater or inadvertent operational mode

Powered On or Off During Transition?

- MIL-STD-1540E requirements
 - Unit on during transitions
 - Cycle through operational modes
 - Monitor perceptive parameters for failures and intermittents
 - Cold start/Hot start
- Failure rates during screening doubled with the units powered on*
- IES guidelines recommends conducting thermal cycling tests with the power on
- Conclusion
 - Screen is more effective with the UUT powered on
 - More flaws are precipitated into failures
 - Failures are easier to detect

Significant Risk Trade to Test Without Power

*Ref: K. L. Quart and I. Wong. Proceedings IEEE Reliability and Maintainability Symposium, IEEE, New York,

Vacuum or Ambient Pressure?

Test Objectives	TVac	Thermal Cycle
Flight-like Environment	x	
Orbital Performance	x	
Thermal Control	x	
Arcing	x	
Multipacting/Corona	x	
Material Outgassing	x	
Sensitivity to conduction	x	
Electrical Intermittence	x	x
Latent Defects/Failure Propagation	x	x
Thermal Stress Effects	x	x
Hardware Integration Verification	x	x
Faster thermal transition rates		x

Thermal Vacuum is Not
the Same as Thermal Cycle

Thermal Vacuum

- Vacuum environment
- Qualification
 - More cycles and larger temperature extremes
 - Additional instrumentation
 - Design objective and thermal balance emphasis
- Thermal control subsystem verification
 - Achieve thermal equilibrium at both hot and cold temperatures
 - Check emissivities of key surfaces and insulation blankets
 - Check thermal conductance values (internal gradients)
 - Check heat pipe and louver performance
 - Primary and redundant thermostat/heater circuits:
 - Activation commands and control authority verified
 - Temperature control established, hot spots, cold spots, gradients determined
 - Verify propulsion subsystem thermal performance

Photo courtesy of STFC

Thermal Balance Test

- Qualification test to validate analytic thermal model
- Demonstrates and verifies the thermal control hardware and design in vacuum environment
- Typically three to eight mission phases simulated
 - Cold phase, hot phase, heater verification, confirmation phase, transient phases
 - Worst case combinations of seasons, equipment duty cycles, solar angles and eclipse conditions
 - Exercise all important heat flow paths and response of temperature-sensitive and mission critical equipment
- Thermal vacuum environment simulated with heat load techniques and chamber cold wall

Photo courtesy of Astrium

Leak Test

- Purpose
 - Demonstrates the capability of pressurized components and hermetically sealed units to meet the specified design leakage rate requirements
- Hardware types
 - Sealed electronic boxes
 - Propulsion systems
 - Pressure vessels
- Test Challenges
 - Combined environments (temperature+vibration+pressure)
 - Referee fluid/helium
 - Contamination
 - Validation method
- Helpful Hints
 - Differential pressure beyond MEOP
 - Perform between environments

Test for Leaks Early and Often

Pressure Test

- Purpose
 - Unit: demonstrate structural margin
 - Subsystem/Vehicle: demonstrate flow, pressure and leakage rate within specification
- Environment
 - Design burst pressure: Product of the maximum expected operating pressure (MEOP) and a burst factor
 - MEOP: highest gage pressure that an item in a pressurized subsystem is required to experience during its service life
- Configuration
 - Proof pressure: $1.1-1.5 \times \text{MEOP}$ for 5 minutes
 - Pressure cycle: 4 times expected cycles or 50 cycles
 - Burst pressure: $1.25-5.0 \times \text{MEOP}$ (non-flight UUT)
- Fail Criteria
 - Bursts, permanent deformation, proper torquing, adequate regulation, etc
 - Leakage at MEOP

Photo courtesy of The Aerospace Corporation

Propulsion Pressure and Leak

- Purpose
 - Demonstrate that propulsion subsystem meets specified flow, pressure, and leakage rate requirements
- Proof pressure performed before and after environmental exposure
- Look for contamination, proper torquing, adequate regulation

Photo courtesy of AMSAT-DL, Wilfried Gladisch

EME Tests

- Purpose
 - Hardware functions together in intended electromagnetic environment and is not source of interference
 - Demonstrates satisfactory electrical and electronic equipment operation in conjunction with the expected electromagnetic radiation from other subsystems or equipment
- Configuration
 - Flight configuration
 - Uses all possible operational modes
 - First system test is to verify requirement, 2nd test is to verify workmanship through environments leading to final flight configuration

Photo courtesy of NASA

EME Tests (cont)

- Test Types
 - Electromagnetic Interference (EMI)
 - Electromagnetic Compatibility (EMC)
 - Radio Frequency Interference (RFI)
 - Radiated energy: through the air
 - Conducted energy: along wires
- EME test families
 - Radiated emissions and susceptibility (RE, RS)
 - Conducted emissions and susceptibility (CE, CS)
 - Power quality
 - Electrostatic discharge (ESD)

Photo courtesy of General Dynamics

EME Tests (cont)

- Fail Criteria
 - Inability to command
 - Loss of data
 - Uncommanded response
 - Bad housekeeping data
 - Loss in signal:noise margin
- Helpful Hints
 - Use development tests to identify issues and inject into the design => don't patch
 - 7 of 10 units don't meet original requirements
 - Cost for discovery at next level factor of 8
 - 1 in 10 spacecraft fail EMC at system level
 - Pay particular attention to weaker units
 - Best solution is a good design

Photo courtesy of NOAA and NASA

Follow Design Guidelines – Check Early if Critical

Life Test

- Purpose
 - Detect wearout, drift, or fatigue-type failure modes or performance degradation
 - Exercise a unit through its cycle, stroke, or rotation during appropriate environment
- Test Requirements
 - Pressurized structure/vessels duration: 50 cycles or 4 times predicted operating life or service cycles
 - For structure not vibration qualified: 4 times life
 - Other UUT: 2 times predicted operating life or service cycles
- Environment
 - Ambient, thermal, and vacuum to evaluate wearout and drift failure modes
 - Pressure, thermal, and vibration to evaluate fatigue-type failure modes

Life Testing

- Configuration
 - Flight quality
 - Coupons made with the same process
- Helpful Hints
 - Qualification test
 - Special tests
 - Battery charge/discharge
 - Solar cell performance
 - Bearings

Bearing Under Test Aerospace Lab Ops

Photo courtesy of Aerospace Corporation

A Real World Example of Problems from Unit Environmental Tests

- Taken from a non-developmental (i.e., later in the block build) vehicle
 - Shows that even late vehicles have unit problems
- Shows the kinds of events that correspond to the failures and delays
 - Good visual for various readiness reviews

Power Supply

PN 35069-7 SN 2 (1 of 6)

▲Planned Events

▼Unplanned Events

Test Anomalies:

D

TAR 0502 - Unit Failed
Standby Power Test.
Error in slice A.
Tester Wiring. No
Overstress to the UUT.
Repaired the Tester.
Repeated Test.

LEGEND			
☝	First Acceptance Test	Other Work In Progress	⌚
😊	Good Acceptance Test	Last Unit Invasion	👤
☝	Good Acceptance Retest	Last Accept Test/Completed Unit	🚩
☝	Failed Acceptance Test/Rework	Insignificant Unplanned Events	D

Note: Shadowed Boxes Represent Significant Unplanned Events

Power Supply

PN 35069-7 SN 2 (2 of 6)

LEGEND			
☝	First Acceptance Test	Other Work In Progress	⌚
😊	Good Acceptance Test	Last Unit Invasion	👤
✌	Good Acceptance Retest	Last Accept Test/Completed Unit	🏠
☞	Failed Acceptance Test/Rework	Insignificant Unplanned Events	D

Note: Shaded Boxes Represent Significant Unplanned Events

Notes :

1. See FRB 21045 for Detailed Analysis and Corrective Action.

Power Supply

PN 35069-7 SN 2 (3 of 6)

Test Anomalies:

- ☒ TAR 0525 - Unit Wouldn't Power on. Test Cable Not Seated. No Overstress to the UUT. Cable Reseated. Test Repeated.
- ☒ TAR 0526 - Erroneous Current Reading. Tech Misinterpreted the Procedure. No Overstress to the UUT. Test Continued.

LEGEND	
	First Acceptance Test
	Good Acceptance Test
	Good Acceptance Retest
	Failed Acceptance Test/Rework
	Other Work In Progress
	Last Unit Invasion
	Last Accept Test/Completed Unit
	Insignificant Unplanned Events

Note: Shadowed Boxes Represent Significant Unplanned Events

Power Supply

PN 35069-7 SN 2 (4 of 6)

Test Anomalies:

- ☒ TAR 0533 - Distorted Wave Forms. Tester Problem. No Overstress to the UUT. Repaired Tester. Continued Test.
- ☒ TAR 0537 - During TC#3 the Wrong Redundancy was on. Tech Error. No Overstress to the UUT. Repeated TC#3.

Test Anomalies:

- ☒ TAR 0553 - Side "A" Section Failed to Command on. Test Equipment Anomaly. No Overstress to the UUT. Test Repeated.
- ☒ TAR 0586 - Unit Failed Temp Output Test. Two Test Cables Miswired. Reworked Cables. No Overstress to the UUT. Test Repeated.

LEGEND			
 	First Acceptance Test	Other Work In Progress	 D
	Good Acceptance Test	Last Unit Invasion	
	Good Acceptance Retest	Last Accept Test/Completed Unit	
	Failed Acceptance Test/Rework	Insignificant Unplanned Events	

Note: Shadowed Boxes Represent Significant Unplanned Events

Power Supply

PN 35069-7 SN 2 (5 of 6)

▲ *Planned Events*

▼ *Unplanned Events*

LEGEND			
<div>☺</div> <div>☺</div> <div>☺</div> <div>☺</div>	First Acceptance Test	Other Work In Progress	<div>⌚</div> <div>☞</div> <div>🚩</div> <div>D</div>
	Good Acceptance Test	Last Unit Invasion	
	Good Acceptance Retest	Last Accept Test/Completed Unit	
	Failed Acceptance Test/Rework	Insignificant Unplanned Events	

Note: Shadowed Boxes Represent Significant Unplanned Events

Power Supply

PN 35069-7 SN 2 (6 of 6)

▲ *Planned Events*

▼ *Unplanned Events*

Recap

Functional, Vibration, Thermal Cycling, Thermal Vacuum

- Total test time: 8/22 - 10/9 = 7 weeks
- # Vibration test/retests = 2
- # Thermal cycle test/retest=2
- # partial retests = 5

LEGEND	
	First Acceptance Test
	Good Acceptance Test
	Good Acceptance Retest
	Failed Acceptance Test/Rework
	Other Work In Progress
	Last Unit Invasion
	Last Accept Test/Completed Unit
	Insignificant Unplanned Events

Note: Shadowed Boxes Represent Significant Unplanned Events

SOFTWARE TESTING

Software is an Integrated Subsystem

- Flight software should be treated as an integrated subsystem
 - Often thought of as independent subsystem – *it isn't!*
 - Resides on hardware in different subsystems
 - ex., GN&C, comm, TCS, payload, EPS
 - Avionics is condensing boxes into cards and cards are condensing into chips
 - Lots of software and hardware interfaces
 - Need (new) agile and thorough systems engineering and verification techniques and tools
- Incremental builds
 - Build and test is not complete until the final build
 - Identify subset of requirements for each build
 - Need to test software developed in current build with other software developed in previous builds

“Software has become the last refuge for fixing problems”

– Steve Jolly, MRO Program Manager

All Software has Bugs

- It costs more to fix bugs the later they are discovered
 - ex., ~10x more to fix a bug in the coding phase than the requirements phase
- Requirements – not coding – is a major source of software errors
 - Poorly stated, ambiguous
 - Changing/creeping
 - Nonfunctional
 - Omitted
- Peer reviews and product evaluation required prior to testing
 - Formal process
 - Come prepared
 - Document results

Flight Software Failures

- Satellite loses ground contact after several hours
 - An ACS software sign error kept the spacecraft from pointing at the Sun
 - Cause: lack of end-to-end testing
- Launch vehicle delivers satellite to wrong orbit
 - Entered flight control parameter order of magnitude smaller than test parameter
 - Cause: testing was not performed with the flight software

“Reducing the frequency of testing to cut costs should be avoided. Many recent launch vehicle failures and mission mishaps could have been prevented had testing not been shortchanged.”

“...inadequate reviews, poor risk management and insufficient testing/verification were each found in six of eight separate mission failure investigations.”

Report on Project Management in NASA. March 13, 2000

Simulators and Test Beds

- Flight-like hardware
 - Simulate hardware interfaces
 - Simulate signal interfaces
 - Simulate orbital condition
- Flight software and databases
- Test software and databases
- Used to verify potential degrading requirements
 - Scenarios
 - Negative testing
 - Stress testing
 - Off nominal testing
 - Contingencies
- Understand
 - Differences
 - Limitations
 - Test specific responses
- Validate simulator/test bed
- Control the configuration
 - Treat like it is flight
- Document anomalies

**Validated and Configuration Controlled Simulators
and Test Beds are Critical**

Software Verification – NOT Just Test

- All verification methods need to be utilized
 - Do not rely on (and wait for) testing to identify the bugs
 - Cannot perform 100% testing
 - Space software is complex and run in interdependent environments
 - Time and money run out before all testing can be performed
- Prioritize test objectives and optimize test procedures for important and critical tests
 - Good risk analysis skills essential
 - Critical requirements/tests
 - Safety – failure leads to hazard of system or personnel
 - Security – failure leads to breach of system security
 - “ility” – failure adversely affects dependability, reliability, maintainability, availability
 - Other mission critical requirement – failure adversely affects Key Performance Parameter (KPP)

Software Test Preparation

- Preparation for test
 - Multi-discipline review of test cases and test procedures
 - Recommend engineering tests on functionally equivalent units and/or dry run (informal test) prior to performing run for record

*“Although programmers, testers, and programming managers know that code must be designed and tested, many appear to be unaware that tests themselves must be designed and tested – designed by a process no less rigorous and no less controlled than that used for code.”**

- Test case
 - Inputs
 - Environments
 - Traceability to requirements and design information
 - Execution details (ex., procedure)
 - Expected results and success criteria
 - Potential hardware risks/issues and appropriate actions to take
 - Configuration controlled

* Boris Beiser, SW Testing Techniques 2nd edition

Tests Shall Be

- Repeatable
 - Identical hardware and software should generate identical results
- Complete
 - Objective evidence of compliance to allocated requirements, design elements, and coverage criteria
- Configuration controlled
 - Software input and output products (ex. databases), environments (ex., test equipment), procedures, scripts, and test cases
- Independent
 - After unit level, test must be independently conducted (someone other than the developer of the code)

Test Thoroughly at the Correct Levels

Definitions for Software Testing

- Blackbox testing – requirements based testing
 - Tester focuses on requirements and has no knowledge of internal structure
 - aka functional testing
- Branch testing – every instruction in each conditional statement
- Graybox testing – mixture of whitebox and blackbox testing
 - Functional testing where tester has sufficient knowledge of software's structure to drive testing to focus on critical and “hard to reach” paths
 - aka mixed testing
- Negative testing – show something is not met or doesn't work
 - Outside of normal or “illegal” input
- Nominal testing – uses normal parameters
 - aka positive testing

Definitions for Software Testing (cont)

- Performance testing – focused on requirements related to system execution and speed
- Path testing – every set of conditional statements or branches
- Regression testing – retest of previously tested software after a change to ensure (still) performs as it should
- Scenario based testing – demonstrate operational capabilities and functions based on the concept of operations for nominal and off-nominal conditions
 - Clear what stimulus and response of interest are
- Stress testing – uses simulated levels at and beyond limits
 - ex., ranges, rates, workload
- Whitebox testing – code based testing
 - Tester has knowledge of software's structure
 - NOT debugging

Software Testing

Software Unit Testing

- Purpose
 - Single compilation element which performs low level function, subfunction, or task
 - Verifies source code modules perform as designed
- Test cases shall cover (at a minimum)
 - Unit design including correct execution of all statements and branches
 - All error and exception handling
 - All software unit interfaces including limits and boundary conditions
 - Start-up, termination, and restart
 - All algorithms
- Test legacy reuse software if
 - Modified reuse software units
 - Track record indicates potential problems
 - Even if not modified
 - Critical reuse software units
 - Even if not modified
- Perform on simulators and test hardware by software developer

Software Unit Integration and Testing

- Purpose
 - Integrate 2 or more software units and test to make sure it works as intended
 - Testing against the software design
 - Whitebox testing of logical paths through software, boundary testing, and error handling
- Test cases shall cover (at a minimum)
 - Correct execution of all interfaces between software units including limit and boundary conditions
 - Integrated error and exception handling across the software units
 - All end-to-end functional capabilities
 - All allocated software requirements
 - Performance testing including operational input and output data rates and timing and accuracy requirements
 - Stress testing including worst-case scenarios
 - ex., fault tolerance, fail over, data capture and reporting
 - Resource utilization measurement
 - ex., CPU, memory, storage, bandwidth
- Perform on target hardware in configuration close to operational by software developer
- All reuse software including modified and unmodified legacy reuse and COTS shall undergo unit integration and testing

Software Item Qualification Testing (SIQT)

- Purpose
 - Demonstrate that software item requirements have been met
 - Blackbox testing, demonstrating operational functionality, proper input acceptance and output generation, and data integrity
- Test cases shall cover (at a minimum)
 - Verification of all software requirements under operation environment conditions
 - ex., operational data constants, operational input and output data rates, operational scenarios, target hardware configurations
 - Verification of all software interface requirements using actual interfaces or high-fidelity simulation
 - Verification of all software specialty engineering requirements including software reliability requirements and fault detection, isolation, and recovery
 - ex., supportability, testability, dependability/reliability/maintainability/availability, safety, security, human systems integration
 - Stress testing including worst-case scenarios
 - Resource utilization measurement
- Perform on target hardware as close as possible to the operational target hardware in operational configuration
 - Independent verification and validation (IV&V)
 - Performed by a software test organization independent of the developers
- All software requirements shall be verified by SIQT regardless of new, reuse, or COTS

SW/HW Integration & Testing

- Purpose
 - Integrate software items with interfacing (target) hardware and software items and test for all aspects of system-wide and system architectural design
 - Includes non-developmental software (e.g., COTS, reuse) and developed software
 - All reuse software including modified and unmodified legacy reuse and COTs shall undergo software/hardware integration and testing
 - Whitebox testing of the software/hardware design
- Test cases shall cover (at a minimum)
 - Correct execution of all SW-to-SW and SW-to-HW interfaces including limit and boundary conditions
 - Integrated error and exception handling
 - End-to-end functional capabilities
 - All allocated software requirements
 - Performance testing including worst-case scenarios
 - Start-up, termination, restart
 - Fault detection, isolation, and recovery handling
 - Resource utilization measurement
- Perform on target hardware in configuration close to operational
 - Include actual ground equipment
 - Performed by independent element/segment/system integration team(s) with support from software and hardware IPTs
 - Hardware and software are pretested separately to find and eliminate errors

Software System Qualification Testing

- Purpose
 - Demonstrate system requirements have been met
 - Uses already qualified software and hardware
 - Testing represents mission-like conditions as closely as possible
 - Blackbox testing against the prime/critical item, element, segment, and system requirements
 - Includes software item and software interface requirements
- Test cases shall cover (at a minimum)
 - Requirements in the system specification, segment specifications, and all other levels of requirements between the system and segment specifications and the software requirements in the specification tree including interface requirements at all levels
- Perform on operational target hardware in operational configuration
 - Performed by independent element/segment/system integration team(s) with support from software and hardware IPTs
- Process
 - Dry run system test cases and procedures to ensure they are complete and accurate
 - Update system test cases and procedures
 - Perform “run for record” test

Definitions for Software Anomalies

- Defect – flaw in system or software product that is discovered through inspection process
 - Note: residual defects not discovered can lead to faults, failures, and anomalies
- Fault – flaw in system or software product that is discovered through a test process
- Failure – inability of a system or component to perform its required functions within specified performance requirements
- Anomaly – any condition that deviates from expectations based on requirements specifications, design documents, user documents, standards ,etc, or someone’s perception or experience
 - Anomalies may be found during, but not limited to, review, test, analysis, compilation, or use of software or applicable documentation

Software Anomaly Classification by Severity

Severity	Applies if a problem could:
1	<ul style="list-style-type: none">a. Prevent the accomplishment of an operational or mission essential capabilityb. Jeopardize safety, security, or other requirement designated “critical”
2	<ul style="list-style-type: none">a. Adversely affect the accomplishment of an operational or mission essential capability and no work-around solution is knownb. Adversely affect technical, cost, or schedule risks to the project or to life cycle support of the system, and no work-around solution is known
3	<ul style="list-style-type: none">a. Adversely affect the accomplishment of an operational or mission essential capability but a work-around solution is knownb. Adversely affect technical, cost, or schedule risks to the project or to life cycle support of the system, but a work-around solution is known
4	<ul style="list-style-type: none">a. Result in user/operator inconvenience or annoyance but does not affect a required operational or mission essential capabilityb. Result in inconvenience or annoyance for development or maintenance personnel, but does not prevent the accomplishment of those responsibilities
5	Any other effect

Ref: SMC-S-012 Software Development for Space Systems – Appendix C

Common Mistakes

- Inadequate software test planning
 - Need to develop new agile and thorough methods
- Inadequate (or no) unit testing by the software developers
 - Latent errors in code are sent to unit integration
- Insufficiently tested or untested modules are promoted
 - Error isolation and correction is impossible
 - Perceptiveness problem
- Integration tests fail to uncover errors
 - Prove what's known, not test for what isn't
 - Test cases are written to show that the software works, but do not provide sufficient error testing
 - Need negative testing
- Software qualification not performed on target hardware configuration
 - Requirement verification may be invalid, especially performance requirements
- Software qualification performed after delivery
- No regression testing of requirements verified in previous builds

Pieces of the Puzzle

- Exponential Growth in Flight Software
 - software development can exceed hardware development time
 - Qualification takes even longer

Flight and Payload Software Equivalent Lines of Code (KSLOC)

Software Deliveries Now on Critical Path in Space Vehicle Development

Pieces of the Puzzle

- Potential exponential growth in flight software related anomalies
 - In test
 - In flight

It's Better to Find Them in Test than in Flight!

Exponential Growth In Flight Software - Now on Critical Path

Which Means Exponential Growth In Flight Software Anomalies - In test - In flight

Survey of best military software contains 5 defects/KSLOC, suggests 5% manifest into anomalies

Need to Develop and Use Different Practices

Pieces of the Puzzle

- On-orbit anomaly histories show software related anomalies can and do damage space systems
 - Effective testing minimizes the anomalies encountered in flight

Year Ranges
 1981 to 1985
 1986 to 1990
 1991 to 1995
 1996 to 2000
 2001 to 6/03

Exponential
Growth In
Flight Software
- Now on Critical
Path

Which Means
Exponential
Growth In
Flight Software
Anomalies
- In test
- In flight

On-orbit Anomaly
Histories Show
Software
Anomalies Can
Damage
Space Systems

Pieces of the Puzzle

- Effective system level testing means using the fully integrated flight system including qualified flight software
 - Would you test without the flight computer?
- Understand and validate the simulators and test beds

Pieces of the Puzzle

- Thermal vacuum is the closest environment test to flight-like
 - Test Like You Fly
 - Escapes
 - 42% of the failures in TVac were escapes from previous tests*
 - Thermal control subsystem
 - Thermal control dependencies can only be checked during thermal testing
 - Temperature dependent hardware
 - ex., cryo payloads

You Can't Develop SW in a Vacuum but You Should Test it in One

Pieces of the Puzzle

- Software related failures can occur at temperature
 - Effective testing minimizes the anomalies encountered in flight
 - Hardware/software interfaces
 - Timing
 - Timing can be thermally dependent
- Factory thermal anomaly data corroborates software failures

Final Flight Software Should be Used in TVac

Pieces of the Puzzle

- Anomaly data shows HW/SW interface issues are key
 - Can no longer design and develop independently
 - Research shows increased chance of flight failure with units being reworked after SV TVac

Pieces of the Puzzle

- More complex code
 - More bugs
 - Harder to find
 - Takes longer to develop
 - Increased chance that final software will not be ready by system test

Exponential Growth In Flight Software
- Now on Critical Path

Which Means Exponential Growth In Flight Software Anomalies
- In test
- In flight

Effective System Means the Test Using Entire System including Software

Anomaly Data Shows HW/SW Interface Issues Are Key

On-orbit Anomaly Histories Show Software Anomalies Can Damage Space Systems

Thermal Test is the Closest Test to Flight-Like Testing
- TLYF
- E escapes
- Thermal Ctl S/S

Software Related Failures Can Occur at Temperature
- HW/SW Interfaces
- Timing

More complex
– Increased chance SW won't be ready by system test

Pieces of the Puzzle

- Need to consider each case
 - Programmatics
 - Modularity
 - Software complexity
 - Mission criticality
 - Software development process including thoroughness of checkout and verification
 - Reuse vs modified

Pieces of the Puzzle

- Effective testing minimizes the anomalies encountered in flight
 - Set up the test program and test at the correct levels
 - Use the entire flight system (especially software)
 - Understand, validate, and control the simulators and test beds

The Choice is Ours

Pieces of the Puzzle

Our decisions create our destiny

ANOMALIES

Stuff Happens

- All hardware has flaws
- All software has bugs
- All interfaces (hardware to hardware, hardware to software, and software to software) have flaws beyond the individual elements
 - Standard interfaces aren't
- Plan for anomalies – plan contingencies
- Design analysis frequently assumes ideal conditions
 - Real life isn't ideal
- We may all speak English, but we don't speak the same language

Murphy's Law Applies

Results Are Different than Expected

You have an anomaly!

S top what you are doing

W rite down the anomaly

A ssess the situation

T roubleshoot methodically to determine root cause

- Do **NOT** break configuration without consulting a wider audience
- Understand consequences of activities
- Get a wider look at the problem, potential causes, and consequences

P revent the problem from occurring again

Stop, Think, THEN Do

Anomaly Flow

Anomaly Indicators in Data

- What the data tells you
 - Out-of-limits
 - States
 - Trends
 - Oddities (out of family)
- The data won't tell you what you need to know if it is...
 - Missed
 - Data gathered but not analyzed
 - Neglected
 - Out of family but within specification
 - "It only happened once"
 - Explained away
 - It must be a power glitch or noise; nothing in the flight product can explain it (but neither can the test product)
 - Most of the observables explain it

Out of Family Data Needs to be Understood

Anomaly Tracking Issues

- Data and anomalies need to be tracked across the life cycle
 - Vendor
 - Factory
 - Launch site
 - On-orbit
- Ownership of the process is an issue
 - Many jurisdictions and systems/tools
 - Quality, Test, Software Engineering, Hardware Engineering, Manufacturing, Reliability, Operations, etc
 - No commonality and little overlap
 - Fully closed loop process is essential

Document It – Can't Address if Not Known

**Kelly McGee and Alex Rubin, Failure Data Capture Tool: The Quest for an Open Standard, 20th Aerospace Testing Seminar*

Five Common Mistakes

- Sign errors
- Last-minute configuration mix-up
 - Every vehicle has late changes – often difficult to verify
 - Non-flight item removal, database update, harness mating, bracket installation, etc.
- Inability to cope with a computer hang-up
 - Ensure the system can gracefully handle software glitches
- Misbehaving circuit protection devices
 - Fuses, circuit breakers, and similar devices are hardware counterparts of fault management algorithm
 - Often inadvertently “designed to blow”
- Pyro safety deficiency
 - Pyros impart large and irreversible shocks to the system
 - Flying debris, post-firing shorts and structural shocks can cause damage

What is Root Cause

- Root cause is
 - The actual or true agent(s) that cause a failure, anomaly, problem, or concern
 - The underlying cause that led to the occurrence of the **failure mechanism**
 - Preventing failures from reoccurring means discovering **ALL of the root causes**, not just the first cause you can identify
- Root Cause is known when
 - All of the observed symptoms can be explained based on the physical description of the system
 - No symptoms remain unexplained
- If root cause is not known, there is associated risk

It May Not be A Single Root Cause

Root Cause Analysis

- *Root cause analysis* consists of
 - Investigation (includes troubleshooting)
 - Analysis
 - Decision (includes preventative actions)
- If you don't get to the root cause you may fix the immediate problem, but not the rest of what needs fixing
 - Root cause will give you clues on where you may have other problems you haven't stumbled across yet
 - We can spend a lot of time, effort, and money chasing solutions that merely mask the symptoms without diminishing the real problems
- Root cause is derived at the final or lowest level of analysis and is usually contained within the process, design, or workmanship parameters of the failed item

Ask WHY Multiple Times

Jefferson Memorial – the Importance of Why

Root Cause Analysis Tools

- Decision Drawing / Logic Drawing
 - Tree diagrams in which the selection of each branch requires some type of logical decision be made
 - Causal Factor or Fault Tree / Event Tree
 - Tree diagrams in which the selection of each branch requires the actions and conditions that were necessary and sufficient for a given consequence to have occurred
 - Cause-and-Effect / Fishbone / Ishikawa diagrams
 - Cause and effect diagram organized into a structure similar to that of a fishbone
- Problem → Effect → “fish head”

Created by Kaoru Ishikawa for Quality Management

Use the Tools to Help Get Root Cause

Corrective Action

- There are two levels of corrective action
 - Disposition: **Product** Restoration
 - Fix the product with the anomaly
 - Preventative: **Process** Restoration
 - Make sure the anomaly doesn't happen again
- Consider the “siblings”
 - Look for and fix related products subject to the same root cause, even if they haven't “broken” yet

Fix the Root Cause –
Don't Just Keep the Product Moving

Retesting After Disposition

- Retests must be performed to re-establish qualification, protoqualification and acceptance of reworked flight hardware, software, associated interfaces, and related interactions
 - Rework and retest need the same system engineering perspective and risk evaluation as original design, manufacturing, and test
- Decisions to be made
 - How much performance and environmental retest is needed
 - What was invalidated by troubleshooting and disposition
 - What conditions are the retests
 - Environments, cycles, etc
 - What additional reviews and oversight are needed
 - Understand the risks and impacts

Verification is NOT Complete Until Test Passes

Retest Considerations

- Hardware retest approach should be conservative
 - Vibration before thermal at unit level
 - Longer burn-in for high failure rate hardware
- Suggested minimum unit retesting
 - Random vibration: three axes
 - Thermal vacuum/thermal cycle: three cycles
 - Repeat invalidated tests
 - Repeat associated functional and/or performance tests
 - Hardware changeout following System Test
 - Penalty test plus normal retest
- Space vehicle retesting based on program risk assessment
 - Extent and impact of R&R assessed on case-by-case basis
 - Assess residual risk of NOT retesting as part of decision process
- Unit pedigree traceability system provides valuable insight
 - Track cumulative reworks / retests
 - Calculate fatigue equivalence vs. margins
 - Identifies potentially high risk hardware

Retest Considerations (cont)

- Risks
 - Not uncovering a 2nd (or 3rd) defect that was masked by the original
 - Introducing new problems and secondary damage
 - Cumulative Stress
 - What defects will be missed if the retest is less robust than the original test in which the problem was detected?
 - Out of sequence activities tend to be less rigorous than first build
- Heavy rework / late installation items increase risk of failure
 - Heavy rework/retest
 - 3X greater chance of infant mortality failure
 - Late installation: After vehicle TVac
 - Late installation often bypasses critical tests
 - Heavy + Late causes increased flight anomalies
 - Three times greater infant mortality rate
 - Rework introduces less predictable failure modes

Conditions That May Drive Retest

- Test anomalies
- Requirements change
- Change in flight environments
- Rework of previously tested hardware
- Change in materials or build processes

Retest Guidance from MIL-HDBK-340A

- Amount of disassembly and reassembly
 - "If hardware required considerable disassembly/reassembly, previous tests have likely been invalidated, even if repairs are relatively simple."
- Quantity and complexity of disconnects/reconnects
 - "A repair requiring soldering or welding involves risk of damage to surrounding hardware which could invalidate previous tests."
- Access to inspect
 - "If a repair can be inspected locally in the same manner as it was inspected during original manufacture, considerable confidence in its adequacy can be obtained."
 - " ... a repair which does not allow the same degree of inspection .. Has invalidated previous tests."

DEFECT DETECTION IN TEST

Defect Detection - Overview

- The same defect can be found using more than one type of test/environment
 - Leaky seals found in thermal vacuum, leak, and electromagnetic testing
 - Shorted part found in performance, dynamic, thermal, and electromagnetic testing
- Chose verification method with correct perceptiveness at the correct level of integration
- Understanding the failure modes is key to downsizing

All Products have Defects
The Challenge is to Find the Critical Ones!

Defect Attributes/Trends

Qualification vs Acceptance Failures

IUS Program by Test Type

Performance Tests are Often the First Opportunity

HW Defects Identified by Qualification Tests

Potential Failure Mechanism	Primary Qualification Tests to Identify Failure Mechanism									
	Functional	Vibration or Acoustic	Shock	Thermal Cycle	Thermal Vacuum	Acceleration	Leakage	Proof and Burst Pressure	EMI/EMC	Life
Mounting broken/loose	X	X	X			X			X	
Broken part		X	X	X	X					
Shorted part	X	X			X				X	
Defective part	X	X		X	X				X	
Defective board	X	X		X	X				X	
Broken/shorted/pinched wires	X	X		X	X				X	
Defective/broken solder	X	X		X	X				X	
Contamination		X	X	X	X					
Leaky gaskets/seals/RF					X		X		X	
Incorrect wiring/routing design	X	X							X	
Relay/switch chatter		X	X						X	
Adjacent circuit board contact		X	X						X	
Premature wearout		X								X
Electromagnetic interference									X	
Insufficient design margin	X					X		X	X	
Corona discharge/arcing					X					
Inadequate tiedown of tubing/wiring		X				X			X	
Inadequate thermal design				X	X					
Brittle material failure			X							
Inadequate fatigue life		X		X						X

HW Defects Identified by Acceptance Tests

Potential Failure Mechanism	Primary Acceptance Tests to Precipitate Failure									
	Functional	Wear-in	Vibration or Acoustic	Shock	Thermal Cycle	Thermal Vacuum	Leakage	Proof Pressure	Proof Load	EMI/EMC
Parameter drift	X		X		X	X				
Electrical intermittants - Solder joints - Loose joints - Connectors			X	X	X	X				X
Latent defective parts	X		X	X	X	X				
Parts shorting			X							
Chafed/pinched wires			X							X
Adjacent circuit board contact			X	X						
Parameters changing due to deflections		X			X	X				X
Loose hardware			X	X						X
Moving parts binding		X				X				
Leaky gaskets/seals					X	X	X			X
Lubricants changing characteristics		X			X	X				
Material embrittlement				X	X	X				
Outgassing/contamination			X	X		X				
Degradation of electrical or thermal insulation						X				X
Corona discharge/acrcing						X				X
Defective pressure vessels								X		
Structural defects									X	
Defective wiring	X									X
Defective tubing						X				

SUMMARY

Summary

- Verification (and validation) testing shall be traced to the requirements
- Understand difference between validation and verification
 - Validation – Build the **right** thing
 - Verification - Build the thing **right**”
- Pick the correct verification method for the requirement– D I A T
 - Verification method decisions should be made with quality of proof in mind
 - Verify and validate at the correct level – most cost and schedule efficient
 - Ensure that the method addresses all key characteristics and an appropriate set of the variable space
 - Where feasible, select test as the verification method of choice
 - Determine pass/fail criteria BEFORE starting
 - Understand fidelity for demonstration and analysis

**Validate, Verify, and Find and Fix Defects
BEFORE Flight**

Summary

- Requirements verification process rolls it all up to provide proof that the final requirements have been met

- Determine how to verify – requirement by requirement
 - Find all the “T” and establish the test program

Summary

- Test is a cumulative process
 - Pyramid test philosophy
 - Most effective test is at the appropriate level
- Establish and execute an effective test program early
 - Keep the big picture in mind
 - Understand the programmatics
 - May require additional upfront commitment and new software development methods
 - Identify hardware and software resources needed
- Choose the right test approach for your program
 - All tests are valuable
 - Removing tests is a function of Program risk tolerance
 - It's always a balance of risk

Summary

- There are a number of different environmental tests
 - These tests are the foundation of a successful test program
 - Understand and decide “why” and “what” test is before starting
 - Test Like You Fly
- Software growth is posing a risk to the critical path
 - Software is not a stand alone system
 - Increase in failures and escapes both during system test and on-orbit
 - Need to start qualification program early
- Execute planned and integrated software test program
 - Peer reviews and product evaluation required prior to testing
 - Use the software test process
- Understand limitations and differences of simulators and test beds
 - Configuration management is essential

Summary

- S W A T all anomalies
 - Stop what you are doing
 - Write down the anomaly
 - Assess the situation
 - Troubleshoot methodically to determine root cause
 - Do NOT break configuration without consulting a wider audience
- Pursue anomalies to root cause
 - Prevent the problem from occurring again
- Defects and errors are inherent in systems and manufacturing
 - Proper problem identification, root cause determination and appropriate resolution are critical
 - Rework and re-test need to be accomplished with the same perspectives and risk evaluation as the original design, manufacturing and test flow

BACK-UP

Acronyms

ABI	Advanced Baseline Imager
ABL	Airborne Laser
ACS	Attitude Control Subsystem
ACTS	Advanced Communications Technology Satellite
AFSCN	Air Force Satellite Control Network
AGE	automated ground equipment
AI&T	assembly, integration, and test
AIAA	American Institute of Aeronautics and Astronautics
AIM	Aeronomy of Ice in the Mesosphere
aka	also known as
ANSI	American National Standards Institute
ATE	automated test equipment
C&DH	command and data handling
CE	conducted emission
CFE	radiated susceptibility
CIV	critical ionization velocity
CNOFS	Communication Navigation Outage Forecasting System
CO2	carbon dioxide
Comm	communication
ConOps	concept of operations
CONTOUR	Comet Nucleus Tour
COTS	commercial off-the-shelf
CPU	central processing unit
CS	conducted susceptibility
CS	cold start

DSCS	Defense Satellite Communications System
DIAT	demonstration inspection analysis test
DS1	Deep Space 1
EMC	electromagnetic compatibility
EME	electromagnetic effects
EMI	electromagnetic interference
EPS	Electrical Power Subsystem
ESA	European Space Agency
ESD	electrostatic discharge
EUV	extreme ultraviolet
FAI	first article inspection
FCM	flow control manifold
FF	full functional
FR	frequency response
Gaia	Global Astrometric Interferometer for Astrophysics
GFE	government furnished equipment
GMI	GPM Microwave Imager
GN&C	guidance, navigation and control
GOES	Geostationary Operational Environmental Satellite
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GSE	ground support equipment
HED	hall effect device
HS	hot start
HST	Hubble Space Telescope

Acronyms

HW	hardware
I&T	integration and test
ICD	interface control drawing
IEEE	Institute of Electrical and Electronic Engineers
IES	Illuminating Engineering Society
IEU	Interface Electronics Unit
IR	infrared
IRU	inertial reference unit
ISS	International Space Station
IUS	inertial upper stage
IV&V	independent verification and validation
KPP	key performance parameter
KSLOC	thousands software equivalent lines of code
LCU	load control unit
LMMS	Lockheed Martin Missiles and Space (aka Lockheed Martin Space Systems Company)
LV	launch vehicle
MEOP	maximum expected operating pressure
MGS	Mars Global Surveyor
MIRI	Mid InfraRed Instrument
MMA	moving mechanical assembly
MPE	maximum predicted environment
MPT	maximum predicted temperature
MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration
NiH ₂	Nickel Hydrogen

P/L, PL	payload
PIM	passive intermodulation
PLF	payload fairing
PN	part number
PWA	printed wiring assembly
QC	quality control
R Vib	random vibration
R&R	remove and replace
RCA	root cause analysis
RCS	Reaction Control Subsystem
RE	radiated emission
RF	radio frequency
RFI	radio frequency interference
RS	radiated susceptibility
S	stabilize
S/B	should be
S/C	spacecraft
S/S	stabilize and soak
SIQT	software item qualification testing
SN	serial number
SPR	software problem report
SRM	solid rocket motor
SRS	shock response system
SV	space vehicle
SW	software
T&C	telemetry and command

Acronyms

TAR	test anomaly report
TC	thermal cycle
TCS	Thermal Control Subsystem
TERRIERS	Tomographic Experiment using Radioactive Recombinative Ionosphere EUV and radio Sources
Thermal Ctrl S/S	Thermal Control Subsystem
TLYF	test like you fly
TP	test procedure
TT&C	telemetry, tracking, and control
TV	thermal vacuum
TVac	thermal vacuum
TWINS	Two Wide-Angle Imaging Neutral-Atom Spectrometers
TWTA	traveling wave tube amplifier
UHFFO	Ultra High-Frequency Follow-On
UUT	unit under test
Vib	vibration
Xe	Xenon

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