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
Charlotte Ann Belsick
December 2012
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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
ACKNOWLEDGMENTS

I’d like to thank Bruce Arnheim, The Aerospace Corporation, for his counsel and guidance and Ron Moore, Lockheed Martin Space Systems Company, for his advice in the development of this project. I would also like to thank Michael Belsick, Lockheed Martin Space Systems Company for his relentless reminders, reviews, and support without which this project would still be work in process.
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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
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

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<th>Antenna</th>
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*All units fall into one or more of these categories*

*“R” = Required Test*

*“ER” = Evaluation required with technical rationale*

*“=” = No test required*

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

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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

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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
“VEE” Diagram

Operational Requirements ➔ Operational Validation
Concepts, Architecture, Validation Plans ➔ System Validation
System Requirements and Verification Plans ➔ System Verification
Subsystem Requirements and Verification Plans ➔ Subsystem Verification and Validation
Assembly Requirements and Verification Plans ➔ Assembly Verification and Validation
Subassembly Requirements and Verification Plans ➔ Subassembly Verification and Validation
Components Design and Verification Plans ➔ Component Verification
Fabrication, “Code to”, and “Build to” documentation

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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
  - 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

– **Sufficient** implies that all appropriate proof is available

– **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 =

\[
v = \sqrt{\left[ T - M \cdot g \right] / k} \cdot \left[ 1 - \exp(-2k \cdot \sqrt{(T - M \cdot g) / k}) \right] / \left[ 1 + \exp(-2k \cdot \sqrt{(T - M \cdot g) / k}) \right]
\]

where

- \( T \) = thrust
- \( t \) = burn time
- \( k \) = wind factors
- \( M \) = mass
- \( g \) = gravity acceleration

*Do the math (dry lab it)*

**Test**

Measure it

DIAT
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”)*
Which Would You Chose?

**Medium Fidelity Demo**  
(The Practical)

Photo courtesy of Lockheed Martin

**Low Fidelity Demo**  
(The Start)

Photo courtesy of NASA

**High Fidelity Demo**  
(The Ideal)

Photo courtesy of NASA
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*
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**

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Pictures courtesy of The Aerospace Corp Crosslink©
Where’s Waldo Syndrome
• 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*
Failures of Analysis

- Network downlink capability
  - Analysis indicated system capable of this with bit error rate $1 \times 10^{-6}$ 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
• **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
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

Diagram showing the process of coupled loads analysis and testing, with steps including:
- Mass Properties
- Stiffness Properties
- Damping Properties
- LV Structural Dynamic Model
- SV Structural Dynamic Model
- Coupled SV/LV Loads Analysis Dynamics Model and Response Recovery Equations
- Solve Equations of Motion
- Test

Flowchart with connections to drawings and vehicle launch and space operations.
Determine how to verify – requirement by requirement

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<td>3.8.3.3</td>
<td>Operate over temperature range -15C to 45C</td>
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</table>
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

Reference MIL-HDBK-340 and DOD-HDBK-343
Belsick AERO 399 Master Project
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 x 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

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
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

<table>
<thead>
<tr>
<th>Parts</th>
<th>Subassembly / Unit</th>
<th>Subsystem Integration</th>
<th>System: Payload &amp; Vehicle Integration</th>
<th>System End-to-End</th>
<th>Pre-Launch Validation</th>
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<td>• Ground SW</td>
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<td>• Leak</td>
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- Functional
- Interface Verification
- Electrical
- Signal
- Pressure/leak
- Hardware in-the-loop simulation
- Software
- Functional
- Interface Verification
- Electrical
- Signal
- Pressure/leak
- Hardware in-the-loop simulation
- Software
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- Signal
- RF
- Electrical
- Mechanical
- Signal
- Mechanical
- Flight SW
- Ground SW
- Procedures
- Databases
- Data Analysis
- Ops Concept
- 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

**Part**
**Subassembly/Unit**
**Assemble**
**Test**
**Selloff**

**System**
**Integrate**
**Test**
**Selloff**
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

Perceptive Part and Unit Tests Save $$

Courtesy of NASA
# Unit Qualification Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Units</th>
<th>Electrical and Electronic</th>
<th>Antenna</th>
<th>MMA</th>
<th>Solar Array</th>
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<th>Pressure Vessel or Component</th>
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Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E) Table 6.3-1
# Unit Acceptance Tests

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

Inspection → Wear-in (Acceptance) → Specification Performance → Leak → Shock

Acoustic or Random Vibration → Acceleration (Qualification) → Leak → Thermal Cycle → Thermal Vacuum

Climatic (Qualification) → Pressure → Leak → EME → Life (Qualification)

Burst Pressure (Qualification) → Static Load (Qualification) → Specification Performance → Inspection
### Unit Test Margins and Duration

<table>
<thead>
<tr>
<th>Test</th>
<th>Qualification</th>
<th>Protoqualification</th>
<th>Acceptance</th>
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<tbody>
<tr>
<td><strong>Shock</strong></td>
<td>6 dB above acceptance, 3 times in both directions of 3 orthogonal axes</td>
<td>3 dB above acceptance, 2 times in both directions of 3 orthogonal axes</td>
<td>Maximum predicted environment (MPE), once in both directions of 3 orthogonal axes</td>
</tr>
<tr>
<td><strong>Acoustic</strong></td>
<td>6 dB above acceptance for 3 minutes</td>
<td>3 dB above acceptance for 2 minutes</td>
<td>Envelope of MPE and minimum spectrum (Figure 6.3.6-1) for 1 minute</td>
</tr>
<tr>
<td><strong>Vibration</strong></td>
<td>6 dB above acceptance for 3 minutes in each of 3 axes</td>
<td>3 dB above acceptance for 2 minutes in each of 3 axes</td>
<td>Envelope of MPE and minimum spectrum (Figure 6.3.5-1) for 1 minute in each of 3 axes</td>
</tr>
<tr>
<td><strong>Thermal Vacuum</strong></td>
<td>±10°C beyond acceptance for 6 cycles</td>
<td>±5°C beyond acceptance for 3 cycles</td>
<td>MPT for 1 cycle</td>
</tr>
<tr>
<td><strong>Thermal Cycle or Thermal Vacuum Only</strong></td>
<td>±10°C beyond acceptance for 27 cycles</td>
<td>±5°C beyond acceptance for 27 cycles</td>
<td>Envelope of MPT and minimum range (−24 to 61°C) for 14 cycles</td>
</tr>
<tr>
<td><strong>Combined Thermal Vacuum and Thermal Cycle</strong></td>
<td>±10°C beyond acceptance for 27 thermal vacuum cycles and 23 thermal cycles</td>
<td>±5°C beyond acceptance for 27 thermal vacuum cycles and 23 thermal cycles</td>
<td>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 1.1 times the limit load</td>
</tr>
<tr>
<td><strong>Static Load</strong></td>
<td>1.25 times the limit load for unmanned flight or 1.4 times limit load for manned flight, duration encompassing flight loading time</td>
<td>1.25 times the limit load for unmanned flight or 1.4 times limit load for manned flight, duration encompassing flight loading time</td>
<td>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 6 dB, 20 minutes at each space vehicle transmitter frequency for radiated susceptibility</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>Pressures as specified in Table 6.3.12-2 following acceptance proof pressure test</td>
<td>Pressures as specified in Table 6.3.12-2 following acceptance proof pressure test</td>
<td>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 6 dB, 20 minutes at each space vehicle transmitter frequency for radiated susceptibility</td>
</tr>
</tbody>
</table>

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

Belsick AERO 399 Master Project
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

Follows System Level Approach and Test Flow
# Subsystem Qualification

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

- **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

<table>
<thead>
<tr>
<th>Test</th>
<th>Reference</th>
<th>Suggested Sequence</th>
<th>Payload Fairing</th>
<th>Structure</th>
<th>Bus</th>
<th>Payload</th>
<th>Multi-Unit Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection</td>
<td>4.0</td>
<td>1, 10</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Specification Performance&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>7.3.1</td>
<td>2, 9</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Static Load</td>
<td>7.3.2</td>
<td>3</td>
<td>R&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>R&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>R&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>R</td>
<td>-</td>
</tr>
<tr>
<td>Pressure and Leak</td>
<td>7.3.3</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Random Vibration or Acoustic</td>
<td>7.3.4</td>
<td>5</td>
<td>ER</td>
<td>-</td>
<td>-</td>
<td>ER</td>
<td>R</td>
</tr>
<tr>
<td>Thermal Vacuum</td>
<td>7.3.7</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>ER</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Separation and Deployment&lt;sup&gt;(3)&lt;/sup&gt;</td>
<td>7.3.8</td>
<td>7</td>
<td>ER</td>
<td>-</td>
<td>ER</td>
<td>ER</td>
<td>ER</td>
</tr>
<tr>
<td>EMC&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td>7.3.9</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>ER</td>
<td>ER</td>
<td>-</td>
</tr>
</tbody>
</table>

- **R** Required
- **ER** Evaluation Required (See 6.3)

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

<sup>(2)</sup> Required for composite and bonded structures. Evaluation required for all other structures.

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

<sup>(4)</sup> 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

<table>
<thead>
<tr>
<th>Test</th>
<th>Qualification</th>
<th>Protoqualification</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shock</td>
<td>1 activation of all shock-producing events; 2 additional activation of significant events</td>
<td>1 activation of all shock-producing events; 1 additional activation of significant events</td>
<td>1 activation of significant shock-producing events</td>
</tr>
<tr>
<td>Acoustic</td>
<td>6 dB above acceptance for 5 minutes</td>
<td>3 dB above acceptance for 2 minutes</td>
<td>Envelope of MPE and minimum spectrum (Figure 6.3.6-1) for 1 minute</td>
</tr>
<tr>
<td>Vibration(2)</td>
<td>6 dB above acceptance for 3 minutes in each of 3 axes</td>
<td>3 dB above acceptance for 2 minutes in each of 3 axes</td>
<td>Envelope of MPE and minimum spectrum (Figure 6.3.7-1) for 1 minute in each of 3 axes</td>
</tr>
<tr>
<td>Thermal Vacuum</td>
<td>±10°C beyond acceptance for 8 cycles</td>
<td>±5°C beyond acceptance for 4 cycles</td>
<td>MPT for 4 cycles</td>
</tr>
<tr>
<td>Static Load(2)</td>
<td>1.25 times the limit load for unmanned flight or 1.4 times limit load for manned flight, duration sufficient to record data</td>
<td>1.25 times the limit load for unmanned flight or 1.25 times limit load for manned flight, duration sufficient to record data</td>
<td>1.1 times the limit load for bonded, composite, or sandwich structures, duration sufficient to record data</td>
</tr>
<tr>
<td>Pressure and Leak(3)</td>
<td>1.1 times MEOP for pressurized structures; 1.25 times MEOP for pressurized 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</td>
<td>1.1 times MEOP for pressurized structures; 1.25 times MEOP for pressurized 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</td>
<td>1.1 times MEOP for pressurized structures; 1.25 times MEOP for pressurized vessels; 1.5 times MEOP for pressurized components. Pressure testing followed by leak testing at MEOP. Other metallic pressurized hardware items per AIAA S-080 and S-081</td>
</tr>
<tr>
<td>EMC</td>
<td>12 dB minimum, duration same as acceptance</td>
<td>6 dB minimum, duration same as acceptance</td>
<td>6 dB minimum, 20 minutes at each space vehicle transmitter frequency for radiated susceptibility</td>
</tr>
</tbody>
</table>

(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

Ref: TR-2004(8583)-1 Rev A (MIL-STD 1540E) Table 7.3-3
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

1. **Instrument with Accelerometers and Thermocouples, Flight and Non-flight**
   - Payload Module I&T
   - Bus Module I&T
   - Antenna Assemblies I&T

2. **Space Vehicle Integration**
   - Pressure/Leak
   - Shock Testing
   - Acoustics Testing
   - Pre-Acoustics Preparation

3. **Initial Specification Performance Test**
   - Pressure/Leak
   - EMC/EMI Testing

4. **Thermal Cycle Testing**
   - Thermal Balance/Vacuum Testing
   - Pressure/Leak
   - EMC/EMI Validation (RE & PIM)

5. **Final Specification Performance Test**
   - End-to-End Testing
   - Post-Environment Integration

6. **Final Assemblies I&T**
   - RF Compatibility/Launch Base Rehearsal Testing
   - Pre-shipping Test

7. **Launch Site Preparations**
   - Transportation To Launch Site
   - Launch Base Post-ship and Pre-Launch Tests

8. **Launch Operations**
   - Mass Properties Testing
   - Storage

9. **On-Orbit Operations**
   - Launch Operations
   - On-Orbit Operations

Belsick AERO 399 Master Project
## System Qualification

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

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

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

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

<table>
<thead>
<tr>
<th>Test</th>
<th>Qualification</th>
<th>Protoqualification</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shock</td>
<td>1 activation of all shock-producing events; 2 additional activation of significant events</td>
<td>1 activation of all shock-producing events; 1 additional activation of significant events</td>
<td>1 activation of significant shock-producing events</td>
</tr>
<tr>
<td>Acoustic</td>
<td>6 dB above acceptance for 3 minutes</td>
<td>3 dB above acceptance for 2 minutes</td>
<td>Envelope of MPE and minimum spectrum (Figure 6.3.6-1) for 1 minute</td>
</tr>
<tr>
<td>Vibration</td>
<td>6 dB above acceptance for 3 minutes in each of 3 axes</td>
<td>3 dB above acceptance for 2 minutes</td>
<td>Envelope of MPE and minimum spectrum (Figure 8.3.7-1) for 1 minute</td>
</tr>
<tr>
<td>Thermal Vacuum</td>
<td>±10°C beyond acceptance for 8 cycles</td>
<td>±5°C beyond acceptance for 4 cycles</td>
<td>MPT for 4 cycles</td>
</tr>
<tr>
<td>Proof Pressure</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
</tr>
<tr>
<td>EMC</td>
<td>12 dB minimum, duration same as acceptance</td>
<td>6 dB minimum, duration same as acceptance</td>
<td>6 dB minimum, 20 minutes at each space vehicle transmitter frequency for radiated susceptibility</td>
</tr>
</tbody>
</table>

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

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)

Perform Before and After Shipment to Launch Site

Courtesy of NASA
Typical Pre-Launch Flow

- **Precursors to launch processing**
  - Launch vehicle dynamics analysis
  - LV adapter fitcheck and deployment
  - LV electrical interface checkout
  - Mass properties

- **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)

- **Mechanical fit checks and alignments**

---

**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?

Must Demonstrate Patch Capability Prior to Launch – Just in Case

Courtesy of NASA
Typical On-Orbit Testing Flow

- Lasts anywhere from 30 days to 2 years

**Deployment Timeline**

- **Launch**
- **First Contact**
- **Bus Initialization & Transfer Orbit Operations**
- **Deployments**
- **Payload Initialization**
- **Payload Calibration & Handover to Operations**

**Timelines (in days)**

- **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’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

<table>
<thead>
<tr>
<th>Environment</th>
<th>Manufacturing</th>
<th>Handling, Shipping, &amp; Storage</th>
<th>Part</th>
<th>Unit</th>
<th>Subsystem</th>
<th>AI&amp;T</th>
<th>System</th>
<th>LV Integration</th>
<th>Launch</th>
<th>On-Orbit</th>
<th>Deorbit</th>
<th>Examples of Specific Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climatic</td>
<td>R</td>
<td>Y</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>R</td>
<td>B</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>Salt spray, dust, humidity</td>
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<tr>
<td>Electromagnetic</td>
<td>Y</td>
<td>Y</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>Backup generator</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Y</td>
<td>Y</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>R</td>
<td>R</td>
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<td>R</td>
<td>R</td>
<td>Shock, vibration, acoustics</td>
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<tr>
<td>Natural Space</td>
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<td>B</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>R</td>
<td>Radiation</td>
</tr>
<tr>
<td>Pressure-Ambient</td>
<td>Y</td>
<td>Y</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>Y</td>
<td>B</td>
<td>Y</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>Normal variation in barometric pressure</td>
</tr>
<tr>
<td>Structural Loading</td>
<td>Y</td>
<td>Y</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>Gravity, aero, thermal, thrust, maneuver</td>
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<tr>
<td>Thermal</td>
<td>Y</td>
<td>Y</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>Temperature variations, cycling</td>
</tr>
<tr>
<td>Vacuum</td>
<td></td>
<td></td>
<td>B</td>
<td>B</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Welding, soldering, X-Ray inspection</td>
</tr>
</tbody>
</table>

- **Y**: Process induced environment
- **B**: Test induced environment
- **R**: Actual or natural environment

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
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

Power-on Vibration Tests Are Preferred Workmanship Tests

Photo courtesy of NASA
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
    • Overetest 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
    • Velocity> 50 in/sec = 0.8 x 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

<table>
<thead>
<tr>
<th>Event</th>
<th>Heating Source</th>
<th>Cooling Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Factory Build/Transportation</td>
<td>Ambient Temperature, Electronics</td>
<td>Convection, Air Conditioning</td>
</tr>
<tr>
<td>2 Launch Pad</td>
<td>Ambient Temperature, Electronics</td>
<td>Convection, Air Conditioning</td>
</tr>
<tr>
<td>3 Initial Ascent</td>
<td>Fairing Temperature</td>
<td>Convection</td>
</tr>
<tr>
<td>4 Payload Fairing Jettison</td>
<td>Solar, Free-Molecular Heating, Earth IR, Albedo</td>
<td>Space Environment</td>
</tr>
<tr>
<td>5 Transfer Orbit, Park Orbit</td>
<td>Solar, Earth IR, Albedo, Electronics</td>
<td>Space Environment</td>
</tr>
<tr>
<td>6 On-Orbit</td>
<td>Solar, Earth IR, Albedo, Electronics</td>
<td>Space Environment</td>
</tr>
</tbody>
</table>
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

# Vacuum or Ambient Pressure?

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

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
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 x MEOP for 5 minutes
  – Pressure cycle: 4 times expected cycles or 50 cycles
  – Burst pressure: 1.25-5.0 x MEOP (non-flight UUT)

• Fail Criteria
  – Bursts, permanent deformation, proper torquing, adequate regulation, etc
  – Leakage at MEOP
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 Compatability (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)
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

Follow Design Guidelines – Check Early if Critical

Photo courtesy of NOAA and NASA
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:
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

Note: Shadowed Boxes Represent Significant Unplanned Events
Power Supply
PN 35069-7 SN 2 (2 of 6)

8/23/90
Ambient Functional Test
TP 2007105

8/23/90
8 Thermal Cycles
TP 2007106

8/27/90
Replaced Fuse F4 & Transistors Q10, Q11, & Q12
TP 2007107

Test Anomalies:
TAR 0515 - During TC#1 @ -11° F the Voltage Between J2B-1 and J2B-2 was -1.21VDC S/B +5.4 to +5.6VDC.¹

Findings:
Shorted Transistor Q11 and Blown Fuse F4. Possible Stress to Q10 & Q12.

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

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

Note: Shadowed Boxes Represent Significant Unplanned Events
Power Supply
PN 35069-7 SN 2 (3 of 6)

8/27/90
Ambient Functional Test
TP 2007109

8/28/90
1 Axis Vibration Test
TP 2007109

8/29/90
Ambient Functional Test
TP 2007109

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)

8/30/90
8 Thermal Cycles
TP 2007109

9/14/90
Ambient Functional Test
TP 2007110

9/16/90
Thermal Vacuum Test
TP 2007111

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
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 (5 of 6)

Isolation Test
TP 2007112

Ambient Functional Test
TP 2007105

Unit Conditionally Accepted

Planned Events
Unplanned Events

<table>
<thead>
<tr>
<th>LEGEND</th>
</tr>
</thead>
<tbody>
<tr>
<td>🎉 First Acceptance Test</td>
</tr>
<tr>
<td>😊 Good Acceptance Test</td>
</tr>
<tr>
<td>😊 Good Acceptance Retest</td>
</tr>
<tr>
<td>🐮 Failed Acceptance Test/Rework</td>
</tr>
</tbody>
</table>

Note: Shadowed Boxes Represent Significant 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
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 that 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 Beiszer, SW Testing Techniques 2nd edition
Tests Shall Be

• Repeateable
  – 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)
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
• Performance testing – focused on requirements related to system execution and speed
• Path testing – every set of conditional statements of 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

Unit Testing
Confirms that source code performs as designed

Unit Integration Testing
Verifies interfaces of integrated SW perform as designed

Software Item Qualification Testing (SIQT)
Verifies software requirements
Includes nominal, negative, and scenario-based testing

Software/Hardware Integration Testing
Integrates SW with the target HW
Test for all aspects of system-wide and system architectural design

System Qualification Testing
Verifies software requirements with mission-like conditions as closely as possible

On-Orbit Checkout/Testing
Executed when 1st placed in operation to checkout system to determine working properly
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

<table>
<thead>
<tr>
<th>Severity</th>
<th>Applies if a problem could:</th>
</tr>
</thead>
</table>
| 1        | a. Prevent the accomplishment of an operational or mission essential capability  
          b. Jeopardize safety, security, or other requirement designated “critical” |
| 2        | a. Adversely affect the accomplishment of an operational or mission essential capability and no work-around solution is known  
          b. 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        | a. Adversely affect the accomplishment of an operational or mission essential capability but a work-around solution is known  
          b. 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        | a. Result in user/operator inconvenience or annoyance but does not affect a required operational or mission essential capability  
          b. 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!

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
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
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

Software is playing a much more critical role in our mission success

More complex
- Increased chance SW won’t be ready by system test
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

- Increased chance SW won’t be ready by system test

More complex
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 - Stop what you are doing
W - Write down the anomaly
A - Assess the situation
T - Troubleshoot 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

✔ Prevent the problem from occurring again

Stop, Think, THEN Do
Anomaly Flow

Anomaly Detected → Interrupt Test → Document Anomaly And Activities

Limited Troubleshooting (NO Config Change)

Failure Review Board → Determine Root Cause

Fix Root Cause

Disposition Product → Retest

Continue 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

*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”

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
Defect Attributes/Trends

Notes:
1. Total data set is 166 items.
2. Any given defect may have more than one attribute

Most Frequent Attributes

Root Cause Summary

Design 36%
Mfg, Assy, I&T 25%
Induced 12%
Software 11%
Workmanship 9%
Unknown 7%

Belsick AERO 399 Master Project
Qualification vs Acceptance Failures

Test Environment

Performance Tests are Often the First Opportunity
# HW Defects Identified by Qualification Tests

<table>
<thead>
<tr>
<th>Potential Failure Mechanism</th>
<th>Functional</th>
<th>Vibration or Acoustic</th>
<th>Shock</th>
<th>Thermal Cycle</th>
<th>Vacuum</th>
<th>Acceleration</th>
<th>Leaking</th>
<th>Proof and Burst Pressure</th>
<th>EMI/EMC</th>
<th>Life</th>
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</thead>
<tbody>
<tr>
<td>Mounting broken/loose</td>
<td>X</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>Broken part</td>
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<tr>
<td>Shorted part</td>
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<tr>
<td>Defective part</td>
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<td>Defective board</td>
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<td>Broken/shorted/pinched wires</td>
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<tr>
<td>Defective/broken solder</td>
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<tr>
<td>Contamination</td>
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<tr>
<td>Leaky gaskets/seals/RF</td>
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<td></td>
<td>X</td>
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<tr>
<td>Incorrect wiring/routing design</td>
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<td>Relay/switch chatter</td>
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<tr>
<td>Adjacent circuit board contact</td>
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<td>Premature wearout</td>
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<tr>
<td>Electromagnetic interference</td>
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<td>Insufficient design margin</td>
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<tr>
<td>Corona discharge/arcing</td>
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<tr>
<td>Inadequate tiedown of tubing/wiring</td>
<td>X</td>
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<tr>
<td>Inadequate thermal design</td>
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<tr>
<td>Brittle material failure</td>
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<tr>
<td>Inadequate fatigue life</td>
<td>X</td>
<td>X</td>
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</tr>
</tbody>
</table>
# HW Defects Identified by Acceptance Tests

<table>
<thead>
<tr>
<th>Potential Failure Mechanism</th>
<th>Primary Acceptance Tests to Precipitate Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Functional</td>
</tr>
<tr>
<td>Parameter drift</td>
<td>X</td>
</tr>
<tr>
<td>Electrical intermittants</td>
<td></td>
</tr>
<tr>
<td>- Solder joints</td>
<td></td>
</tr>
<tr>
<td>- Loose joints</td>
<td></td>
</tr>
<tr>
<td>- Connectors</td>
<td></td>
</tr>
<tr>
<td>Latent defective parts</td>
<td>X</td>
</tr>
<tr>
<td>Parts shorting</td>
<td>X</td>
</tr>
<tr>
<td>Chafed/pinned wires</td>
<td>X</td>
</tr>
<tr>
<td>Adjacent circuit board contact</td>
<td>X</td>
</tr>
<tr>
<td>Parameters changing due to deflections</td>
<td>X</td>
</tr>
<tr>
<td>Loose hardware</td>
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<tr>
<td>Moving parts binding</td>
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<tr>
<td>Leaky gaskets/seals</td>
<td>X</td>
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<tr>
<td>Lubricants changing characteristics</td>
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<tr>
<td>Material embrittlement</td>
<td>X</td>
</tr>
<tr>
<td>Outgassing/contamination</td>
<td>X</td>
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<tr>
<td>Degradation of electrical or thermal insulation</td>
<td>X</td>
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<tr>
<td>Corona discharge/acrcing</td>
<td>X</td>
</tr>
<tr>
<td>Defective pressure vessels</td>
<td>X</td>
</tr>
<tr>
<td>Structural defects</td>
<td>X</td>
</tr>
<tr>
<td>Defective tubing</td>
<td>X</td>
</tr>
</tbody>
</table>

Belsick AERO 399 Master Project
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— DIAT
  – 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

<table>
<thead>
<tr>
<th>Rqmt #</th>
<th>Spec Para</th>
<th>Requirement</th>
<th>Verif Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>73</td>
<td>3.6.2.1</td>
<td>Compatible with launch vehicle</td>
<td>D/A</td>
</tr>
<tr>
<td>92</td>
<td>3.8.3.3</td>
<td>Operate over temperature range -15C to 45C</td>
<td>T</td>
</tr>
</tbody>
</table>

• 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 programmatic
  – 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
The summary contains the following points:

- 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

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABI</td>
<td>Advanced Baseline Imager</td>
</tr>
<tr>
<td>ABL</td>
<td>Airborne Laser</td>
</tr>
<tr>
<td>ACS</td>
<td>Attitude Control Subsystem</td>
</tr>
<tr>
<td>ACTS</td>
<td>Advanced Communications Technology Satellite</td>
</tr>
<tr>
<td>AFSCN</td>
<td>Air Force Satellite Control Network</td>
</tr>
<tr>
<td>AGE</td>
<td>automated ground equipment</td>
</tr>
<tr>
<td>AI&amp;T</td>
<td>assembly, integration, and test</td>
</tr>
<tr>
<td>AIAAA</td>
<td>American Institute of Aeronautics and Astronautics</td>
</tr>
<tr>
<td>AIM</td>
<td>Aeronomy of Ice in the Mesosphere</td>
</tr>
<tr>
<td>ANS1</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>ATE</td>
<td>automated test equipment</td>
</tr>
<tr>
<td>C&amp;DH</td>
<td>command and data handling</td>
</tr>
<tr>
<td>CE</td>
<td>conducted emission</td>
</tr>
<tr>
<td>CFE</td>
<td>radiated susceptibility</td>
</tr>
<tr>
<td>CIV</td>
<td>critical ionization velocity</td>
</tr>
<tr>
<td>CNOFS</td>
<td>Communication Navigation Outage Forecasting System</td>
</tr>
<tr>
<td>CO2</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>Comm</td>
<td>communication</td>
</tr>
<tr>
<td>ConOps</td>
<td>concept of operations</td>
</tr>
<tr>
<td>CONTOUR</td>
<td>Comet Nucleus Tour</td>
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<tr>
<td>COTS</td>
<td>commercial off-the-shelf</td>
</tr>
<tr>
<td>CPU</td>
<td>central processing unit</td>
</tr>
<tr>
<td>CS</td>
<td>conducted susceptibility</td>
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<tr>
<td>CS</td>
<td>cold start</td>
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<tr>
<td>DSCS</td>
<td>Defense Satellite Communications System</td>
</tr>
<tr>
<td>DIAT</td>
<td>demonstration inspection analysis test</td>
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<tr>
<td>DS1</td>
<td>Deep Space 1</td>
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<tr>
<td>EMC</td>
<td>electromagnetic compatibility</td>
</tr>
<tr>
<td>EME</td>
<td>electromagnetic effects</td>
</tr>
<tr>
<td>EMI</td>
<td>electromagnetic interference</td>
</tr>
<tr>
<td>EPS</td>
<td>Electrical Power Subsystem</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ESD</td>
<td>electrostatic discharge</td>
</tr>
<tr>
<td>EUV</td>
<td>extreme ultraviolet</td>
</tr>
<tr>
<td>FAI</td>
<td>first article inspection</td>
</tr>
<tr>
<td>FCM</td>
<td>flow control manifold</td>
</tr>
<tr>
<td>FF</td>
<td>full functional</td>
</tr>
<tr>
<td>FR</td>
<td>frequency response</td>
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<tr>
<td>Gaia</td>
<td>Global Astrometric Interferometer for Astrophysics</td>
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<tr>
<td>GFE</td>
<td>government furnished equipment</td>
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<tr>
<td>GMI</td>
<td>GPM Microwave Imager</td>
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<tr>
<td>GN&amp;C</td>
<td>guidance, navigation and control</td>
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<td>GOES</td>
<td>Geostationary Operational Environmental Satellite</td>
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<tr>
<td>GPM</td>
<td>Global Precipitation Measurement</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GSE</td>
<td>ground support equipment</td>
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<tr>
<td>HED</td>
<td>hall effect device</td>
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<tr>
<td>HS</td>
<td>hot start</td>
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<tr>
<td>HST</td>
<td>Hubble Space Telescope</td>
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## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>HW</td>
<td>hardware</td>
</tr>
<tr>
<td>I&amp;T</td>
<td>integration and test</td>
</tr>
<tr>
<td>ICD</td>
<td>interface control drawing</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
</tr>
<tr>
<td>IES</td>
<td>Illuminating Engineering Society</td>
</tr>
<tr>
<td>IEU</td>
<td>Interface Electronics Unit</td>
</tr>
<tr>
<td>IR</td>
<td>infrared</td>
</tr>
<tr>
<td>IRU</td>
<td>inertial reference unit</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>IUS</td>
<td>inertial upper stage</td>
</tr>
<tr>
<td>IV&amp;V</td>
<td>independent verification and validation</td>
</tr>
<tr>
<td>KPP</td>
<td>key performance parameter</td>
</tr>
<tr>
<td>KSLOC</td>
<td>thousands software equivalent lines of code</td>
</tr>
<tr>
<td>LCU</td>
<td>load control unit</td>
</tr>
<tr>
<td>LMMS</td>
<td>Lockheed Martin Missiles and Space (aka Lockheed Martin Space Systems Company)</td>
</tr>
<tr>
<td>LV</td>
<td>launch vehicle</td>
</tr>
<tr>
<td>MEOP</td>
<td>maximum expected operating pressure</td>
</tr>
<tr>
<td>MGS</td>
<td>Mars Global Surveyor</td>
</tr>
<tr>
<td>MIRI</td>
<td>Mid InfraRed Instrument</td>
</tr>
<tr>
<td>MMA</td>
<td>moving mechanical assembly</td>
</tr>
<tr>
<td>MPE</td>
<td>maximum predicted environment</td>
</tr>
<tr>
<td>MPT</td>
<td>maximum predicted temperature</td>
</tr>
<tr>
<td>MRO</td>
<td>Mars Reconnaissance Orbiter</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NiH₂</td>
<td>Nickel Hydrogen</td>
</tr>
<tr>
<td>P/L, PL</td>
<td>payload</td>
</tr>
<tr>
<td>PIM</td>
<td>passive intermodulation</td>
</tr>
<tr>
<td>PLF</td>
<td>payload fairing</td>
</tr>
<tr>
<td>PN</td>
<td>part number</td>
</tr>
<tr>
<td>PLF</td>
<td>payload fairing</td>
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<tr>
<td>PWA</td>
<td>printed wiring assembly</td>
</tr>
<tr>
<td>PWA</td>
<td>printed wiring assembly</td>
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<tr>
<td>Q/C</td>
<td>quality control</td>
</tr>
<tr>
<td>R Vib</td>
<td>random vibration</td>
</tr>
<tr>
<td>R&amp;R</td>
<td>remove and replace</td>
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<tr>
<td>RCA</td>
<td>root cause analysis</td>
</tr>
<tr>
<td>RCS</td>
<td>Reaction Control Subsystem</td>
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<tr>
<td>RE</td>
<td>radiated emission</td>
</tr>
<tr>
<td>RF</td>
<td>radio frequency</td>
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<tr>
<td>RFI</td>
<td>radio frequency interference</td>
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<tr>
<td>RS</td>
<td>radiated susceptibility</td>
</tr>
<tr>
<td>S</td>
<td>stabilize</td>
</tr>
<tr>
<td>S/B</td>
<td>should be</td>
</tr>
<tr>
<td>S/C</td>
<td>spacecraft</td>
</tr>
<tr>
<td>S/S</td>
<td>stabilize and soak</td>
</tr>
<tr>
<td>SIQT</td>
<td>software item qualification testing</td>
</tr>
<tr>
<td>SN</td>
<td>serial number</td>
</tr>
<tr>
<td>SPR</td>
<td>software problem report</td>
</tr>
<tr>
<td>SRM</td>
<td>solid rocket motor</td>
</tr>
<tr>
<td>SRS</td>
<td>shock response system</td>
</tr>
<tr>
<td>SV</td>
<td>space vehicle</td>
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<td>SW</td>
<td>software</td>
</tr>
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<td>T&amp;C</td>
<td>telemetry and command</td>
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## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>TAR</td>
<td>test anomaly report</td>
</tr>
<tr>
<td>TC</td>
<td>thermal cycle</td>
</tr>
<tr>
<td>TCS</td>
<td>Thermal Control Subsystem</td>
</tr>
<tr>
<td>TERRIERS</td>
<td>Tomographic Experiment using Radioactive Recombinative Ionosphere EUV and radio Sources</td>
</tr>
<tr>
<td>Thermal Ctrl S/S</td>
<td>Thermal Control Subsystem</td>
</tr>
<tr>
<td>TLYF</td>
<td>test like you fly</td>
</tr>
<tr>
<td>TP</td>
<td>test procedure</td>
</tr>
<tr>
<td>TT&amp;C</td>
<td>telemetry, tracking, and control</td>
</tr>
<tr>
<td>TV</td>
<td>thermal vacuum</td>
</tr>
<tr>
<td>TVac</td>
<td>thermal vacuum</td>
</tr>
<tr>
<td>TWINS</td>
<td>Two Wide-Angle Imaging Neutral-Atom Spectrometers</td>
</tr>
<tr>
<td>TWTA</td>
<td>traveling wave tube amplifier</td>
</tr>
<tr>
<td>UHFFO</td>
<td>Ultra High-Frequency Follow-On</td>
</tr>
<tr>
<td>UUT</td>
<td>unit under test</td>
</tr>
<tr>
<td>Vib</td>
<td>vibration</td>
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<tr>
<td>Xe</td>
<td>Xenon</td>
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Belsick AERO 399 Master Project
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