Random Vibration Testing Of Hardware

A Tutorial Presentation to Microgravity Science Division's Project Managers Working Group

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Agenda

- Course Objectives
- Executive Summary
- History of Vibration Standards
  - Test Standards
  - ERB
- Background
  - Types of Programs
  - Types of Testing
- NASA-STD-7001 and SARG
- Workmanship
  - Introduction
  - History
  - Value
  - Exceptions
- Stowage
  - History and ERB
  - Flowchart
  - Expectations
  - Stress Analysis

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Course Objectives

- Provide the Microgravity Science Division's Project Managers with the background and understanding relative to current GRC Engineering practices regarding vibration testing of space-flight hardware.
- Present and clarify SARG wording and flowcharts
- Improve mission assurance and reduce flight risk by proper implementation of such recommendations.

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Executive Summary

- Engineering (7700/7800) ERB was held in July 2000 to set GRC's policy relative to random vibration testing.
- As a result of the ERB:
  - NASA-STD-7001 "Payload Vibroacoustic Test Criteria" was accepted as governing document and incorporated into updated SARG document.
  - Additional wording added to SARG emphasizing:
    - the value and need for workmanship testing
    - the special case of soft stowed hardware
  - Safety and Assurance Directorate (SAAD, formerly OSAT) participated in ERB and is in agreement with the ERB decisions

Executive Summary (2)

- NASA-STD-7001/SARG sets overall policy for random vibration testing (protoflight, qualification, acceptance and workmanship) of flight hardware.
- Two types of hardware programs:
  - Prototype Program: Dedicated test and flight hardware sets
    - Qualify design with margin above expected environment
    - Accept flight hardware relative to expected environment and workmanship quality
  - Protoflight Program: Only one hardware set
    - Test and fly the same hardware
    - Inherently riskier

Executive Summary (3)

- Random vibration workmanship testing, in a hard-mounted test configuration, is a widely-utilized, successfully proven method of screening electrical and mechanical products for flaws and hidden defects.
  - Applicable to components weighing less than 50 kg (110 lbs.)
  - Magnitude (6.8 Grms) screening level:
    - Not based on expected flight (launch) environment
    - Based on sufficiently rigorous threshold level to find defects
    - Does not cause acceptable hardware to fail
  - Uncovers defects not found by thermal screening.
  - Usually enveloped with other flight-based test levels.
    - Often drives test specifications for STS environments thereby becoming a design driver.

Executive Summary (4)

- For Hardware flown in soft stowage (foam):
  - There is still great value in screening electrical and mechanical products for workmanship defects
  - Launching in foam does NOT waive requirement for hard-mounted workmanship testing
  - Allowances are made for "vibration-sensitive" hardware
    - But do not declare hardware vibration-sensitive just to avoid hard-mounted workmanship testing of under-design components
  - Clarify SARG "stowed components" wording and flowchart to original intent:
    - Qualify Stowage Design
    - Workmanship Testing of Hardware

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Test Standards

- Vibration test requirements generally governed in past (pre-1993) by combination of:
  - GEVS (NASA GSFC) General Environmental Verification Specification for STS & ELV Payloads, Subsystems, and Components
  - SPAR (NASA GSFC) Standard Payload Assurance Requirements
  - MIL-STD-1540 (Air Force) Test Requirements for Launch, Upper Stage and Space Vehicles
  - Contractor practices

Test Standards (2)
Development of Lewis Standards

- SAGE (Standard Assurance Guidelines for Experiments) effective January 1993.
  - Based on GEVS and SPAR documents
- LMI (Lewis Management Instruction) 8070.2 effective March 1993.
- SARGE (Standard Assurance Requirements and Guidelines for Experiments) effective April 1996.
  - Reference made to LMI 8070.2

Test Standards (3)
Development of Agency-wide Standards

- In early 1993, NASA initiated concerted effort to develop Agency-wide standards for hardware verification.
- “The exchange of flight hardware in multicenter projects mandates that qualification and acceptance test practices be consistent across the agency” (Dan Mulville/former NASA Chief Engineer)
- GRC (McAleese/Hughes) participated on Vibroacoustics Standards Panel in 1993-1994.
- NASA-STD-7001 “Payload Vibroacoustic Test Criteria” effective June 1996.

Test Standards (4)
Status at GRC in 2000

- SARGE document points to defunct LMI.
  - LMI 8070.2 eliminated in February 1998, per request of Risk Management Office/8100 (formerly OSAT), as part of Government Performance Review action to eliminate duplications of standards.
- Engineering and OSAT involvement and direction varied greatly from project to project.
- Many decisions made "real-time" in vibration lab by Project Manager, SDL personnel or "last-minute" Engineering consulting.

ERB #2000-001

- Cancellation of LMI 8070.2 created void in random vibration test requirements for GRC space-flight hardware.
- NASA-STD-7001 “Payload Vibroacoustic Test Criteria” was now available as the new standard to judge flight worthiness of GRC space-flight hardware.
- On July 13, 2000 a 7700/7800 ERB # 2000-001, “Adoption of Random Vibration Test Standards for Microgravity Space-Flight Hardware,” was held.
  - Joint recommended proposals were made by Engineering (B. Hughes/7735) and OSAT (G. Kelm/0510) and accepted by ERB (J. Taylor, D. Gauntner and K. Adams).
  - Microgravity Science Divsion personnel (A. Otero, J. Koudelka) did attend and participate in the ERB meeting.

ERB Summary

- The ERB #2000-001 decisions were:
  - (1) ERB agreed that NASA-STD-7001 should be utilized by 7700/7800 as the new standard to judge flight worthiness of GRC space-flight hardware, with respect to random vibration.
  - (2) ERB agreed that NASA-STD-7001 should replace reference to LMI 8070.2 in an updated SARGE document, in the vibroacoustics section of the SARGE.
  - (3) ERB recommends to OSAT that it incorporates the attached suggested SARGE wording into the updated SARGE.
    - ERB package contained additional wording on the value of workmanship testing and the testing of stowed hardware.
- Safety and Assurance Directorate (SAAD/8000, formerly OSAT) were in total agreement with the decisions of the ERB.
  - OSAT implemented ERB recommendations into the updated SARG.
  - Strongly believes in the need and value of workmanship testing.

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Background
Types of Hardware Programs

- Prototype (Qualification)
  - There are 2 sets of hardware: Qualification and Acceptance
  - Qualification hardware is dedicated for testing and is not intended for flight.
- Protoflight
  - There is 1 set of hardware which is exposed to all testing and is also intended for flight.
  - Protoflight program incurs higher risk (than prototype program), as tradeoff for lower cost and shorter schedule.
    - Higher risk includes:
      - Protoflight hardware sees higher environments than acceptance flight hardware
      - No (qualification) test demonstrated fatigue life
      - No hardware development program

Background
Types of Vibration Testing

- Qualification (Prototype program)
  - Performed on dedicated test hardware (produced by same drawings, materials, tooling, manufacturing processes, inspection methods and level of personnel competency as used for flight hardware)
  - Test demonstrates, with margin (~ P99%), the design adequacy of the hardware for its intended mission use.

Background
Types of Vibration Testing (2)

- Acceptance (Prototype program)
  - Performed on flight hardware (built in accordance with a design that has been qualified)
  - Test demonstrates satisfactory performance of flight hardware and systems relative to the expected (~ P95%) environment and to reveal inadequacies in workmanship and material integrity
  - Flight acceptance hardware includes follow-on hardware, flight spares and reflight hardware (that are identical in design and material configuration to the qualified article).

Background

Types of Vibration Testing (3)

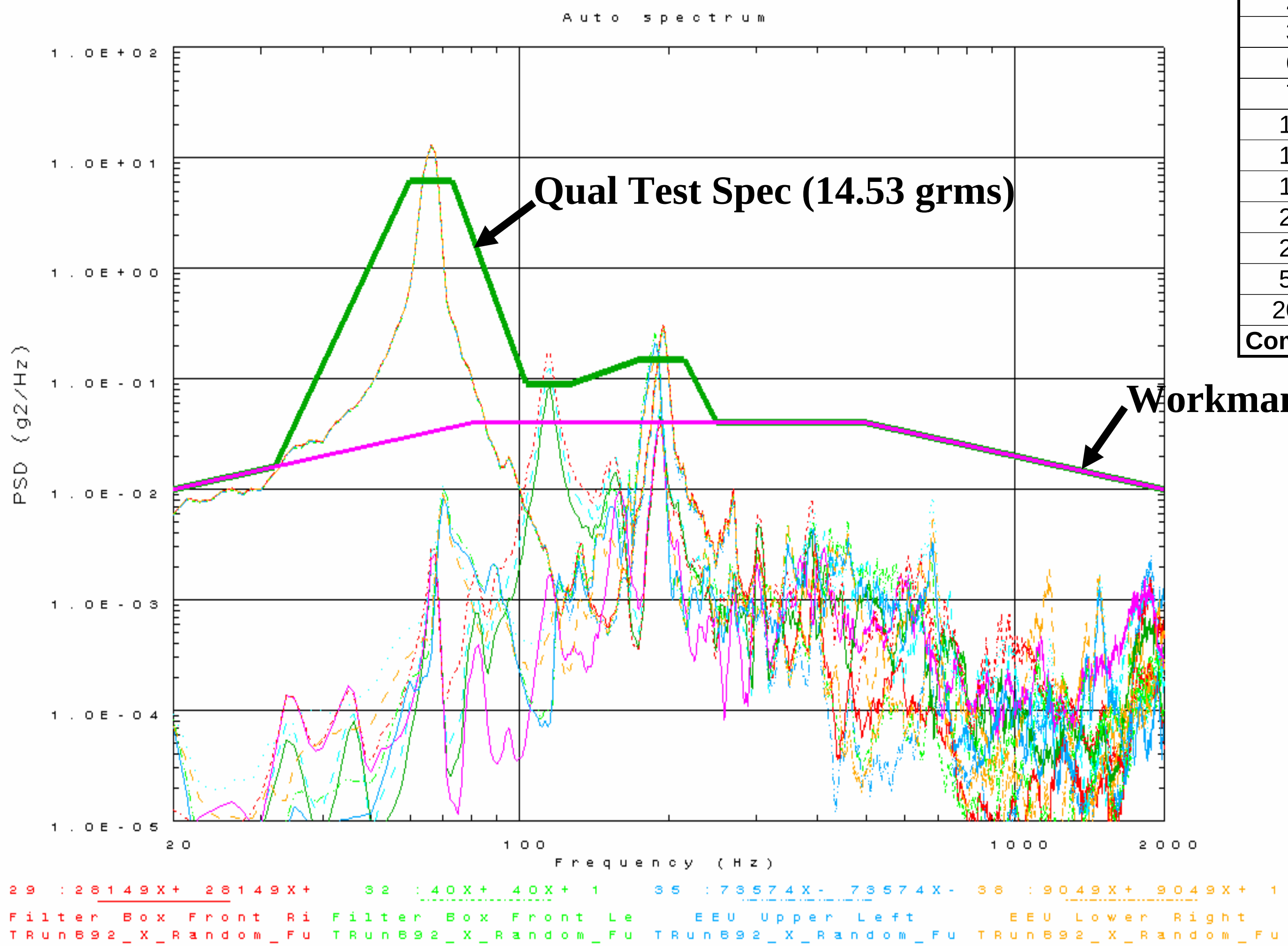
- Protoflight program
  - Performed on flight hardware of a new design (where dedicated test hardware for prototype testing does not exist).
  - Test serves purpose of both prototype/qualification and flight acceptance test (assess design adequacy of hardware with margin (~ P99%), demonstrate satisfactory performance of flight hardware relative to expected environment, and reveal inadequacies in workmanship and material integrity).
  - Combines design qualification test levels and flight acceptance test durations.

Background
Types of Vibration Testing (4)

- Workmanship (often combined with other tests when appropriate)
  - Performed to identify latent defects and manufacturing flaws in electrical, electronic, electromechanical and mechanical hardware at the component level.
    - Testing at a higher assembly level, such as Subsystem/Package level testing, is acceptable in lieu of component level testing.
    - Testing at a lower assembly level may be done to establish early confidence.
  - Component defined as a functional subdivision of a subsystem and is generally a self-contained combination of items performing a function necessary for the subsystem's operation. (Examples: card-cage assembly, DC-DC converter, camera, laser driver, fluid bottles, transmitter, gyro package, actuator, battery).
  - Care should be exercised not to apply workmanship testing to highly sensitive optical components and sensors that could be damaged.

Combining Workmanship with Flight-Based Test Level

(Example: FCF Component Qualification Test Specification)



FREQ(Hz)	PSD(G^2/Hz)
20.0	0.010
32.0	0.016
60.0	6.250
73.0	6.250
103.0	0.090
127.0	0.090
175.0	0.150
215.0	0.150
250.0	0.040
500.0	0.040
2000.0	0.010
Composite	**14.53 grms**

Background
Levels of Assembly
(from GEVS & SARG)

- Payload (space experiment, loaded rack, spacecraft)
- Subsystems/Packages (fluid supply, experimental, video processing, avionics and diagnostics packages, attitude control, electrical power subsystems, instruments)
- Components (card-cage assembly, DC-DC converter, camera, laser driver, fluid bottles, transmitter, gyro package, actuator, battery)
- Assembly (power amplifier, gyroscope)
- Subassembly (wire harness, loaded printed circuit boards)
- Parts (resistor, capacitor, relay, nut, bolt, valve)

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NASA-STD-7001*/SARG**
Advantages of Utilization

- GRC is now consistent with Agency direction and on firm foundation.
  - Streamline intercenter programs
- GRC project office has clear, consistent direction, in the form of a flight-proven engineering practice, prior to any vibration testing.
  - NASA-STD-7001 applies to Classes A, B and C Payloads (Class D Payloads may utilize test tailoring) as defined by NPR 8705.4 Risk Classification for NASA Payloads.

*NASA-STD-7001 “Payload Vibroacoustic Test Criteria”, June 21, 1996

**SARG “Space Assurance Requirements and Guidelines”, GRC-M0510.002 Rev C, December 1, 2003

NASA-STD-7001/SARG
Advantages of Utilization (2)

- Vibration testing expectations of EDD are consistent and known, which if properly followed, should eliminate issues during pre-ship review process by EDD and SAAD.
- Project adherence to test standards should increase probability of detecting workmanship or other defects on the ground, improve hardware reliability in space and enhance overall probability of achieving a successful mission.

GENERAL REQUIREMENTS
TEST ENVIRONMENTS AND TEST DURATIONS

Table 3.4.8-1
Executive Summary of NASA-STD-7001 Verification Test Requirements[3]

Type of Test Hardware	Test Level[1,2]	Test Duration
Prototype:		
Qualification:		
Single Mission	MEFL + 3 dB	2 minutes per axis
Multiple (N) Reflights:	MEFL + 3 dB	2 + 0.5N minutes per axis N= Number of reflights
Flight Acceptance:	MEFL - 3 dB	1 minute per axis
Protoflight:	MEFL + 3 dB	1 minute per axis

Notes:

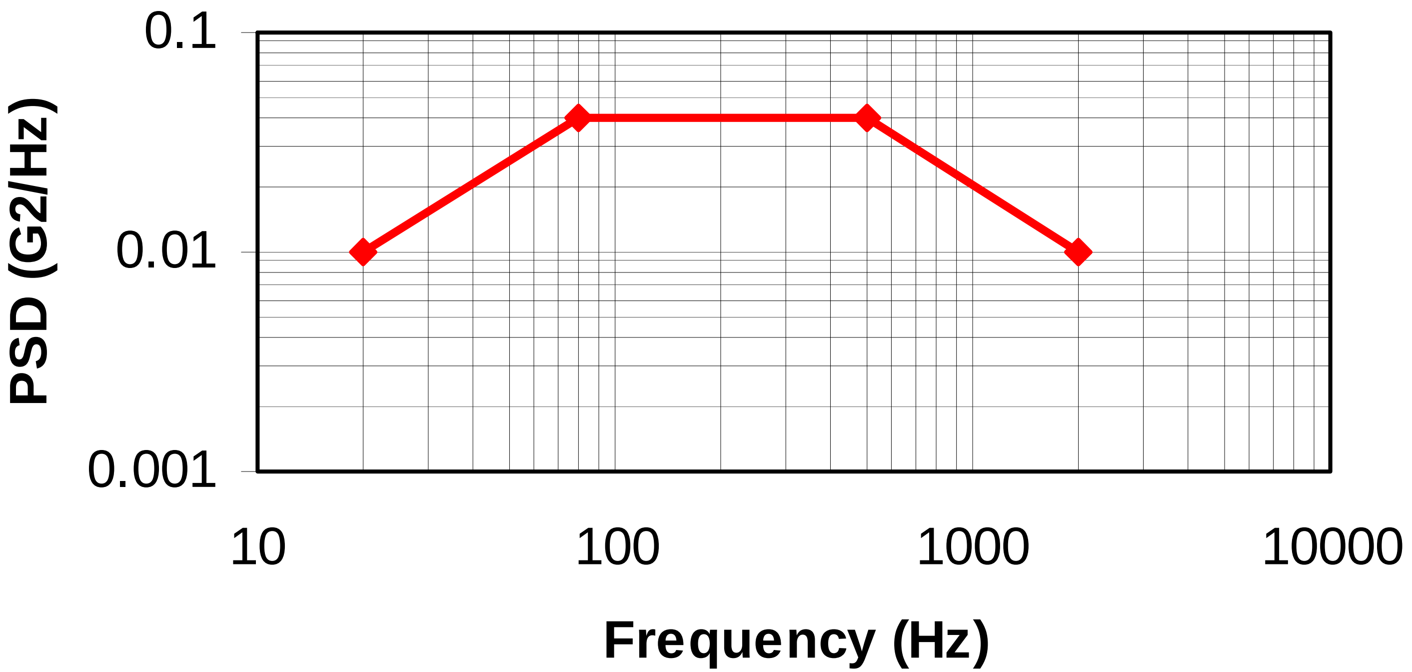
1. Maximum Expected Flight Level (MEFL) defined as 95%/50% Probability Level.
2. A minimum workmanship random vibration test specification (of 6.8 Grms) shall be imposed on electrical, electronic, and electromechanical components weighing 50 kg (110 lbs.) or less. This spectrum is given in Table 3.4.8.1.1-1.
3. Check the parent document for current test levels.

Flight-Based Test Levels

- Flight-based test levels are often based on available flight (or ground test) data.
  - Probability/Confidence (P/C) Level = mean + (k)(sigma)
    - Where the "k factor" is a statistical table lookup value based on the preferred probability (P) level, the preferred confidence (C) level, and number of flight observations (N).
  - The flight-to-flight variability is characterized via a log-normal distribution.
- Maximum Expected Flight Level (MEFL) is defined by NASA-STD-7001 to be statistically the P95%/50% level (95% probability with 50% confidence)
  - P95/50 Interpretation: There is a 50-50 chance of one exceedence of the P95/50 spectrum level in 20 flights.
  - P95% = mean + 1.64 sigma (i.e. k=1.64 for N = infinity)
  - It is often assumed for aerospace vibe data that 1 sigma = 3 dB
- Prototype Qualification = MEFL + 3 dB (roughly ~ P99%)
- Prototype Acceptance = MEFL – 3 dB (roughly ~ P74%)
- Protoflight = MEFL + 3 dB (roughly ~ P99%)

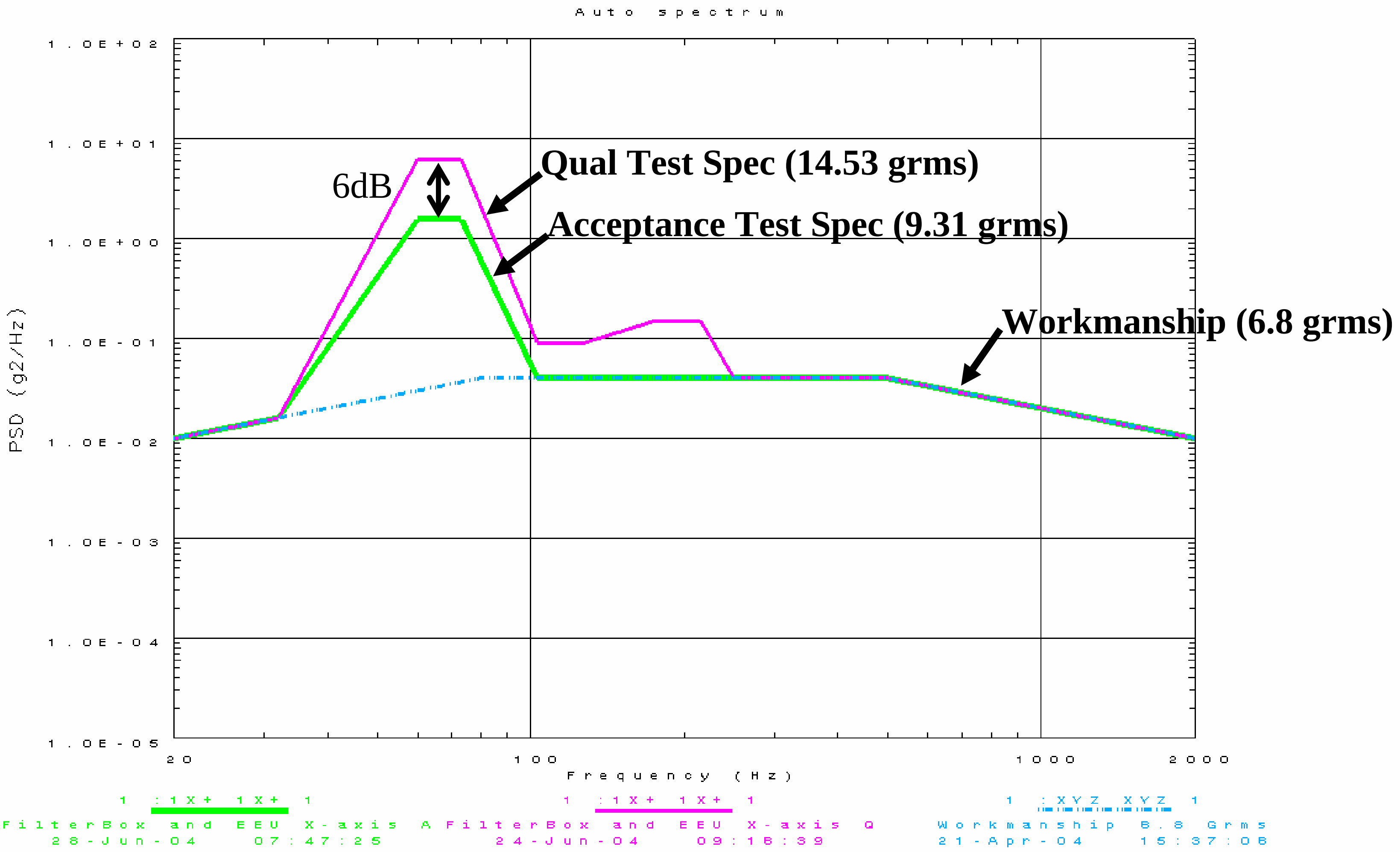
WORKMANSHIP TEST LEVELS

NASA-STD-7001
Workmanship Random Vibration Test Specification
for hardware weighing < 50 kg



Frequency (Hz)	PSD (G2/Hz)
20	0.01
80	0.04
500	0.04
2000	0.01
Composite	**6.8 Grms**

Test Specification Methodology
Example: FCF Component Test Specifications



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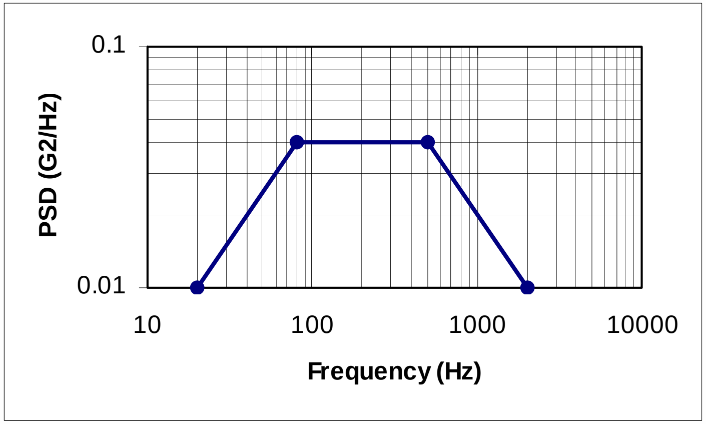
Workmanship Introduction

- A minimum workmanship random vibration test specification shall be imposed on electrical, electronic, electromechanical, mechanical components and mechanisms weighing less than 50 kg (110 lbs.).
- When the expected flight environment is very benign, the combined test is often driven by the workmanship test levels.
  - This is often the case for experiments flown on Shuttle.
  - Combining tests saves the program budget and schedule.
- "True" workmanship test screening is conducted in a hard-mounted test configuration. That is, the 6.8 Grms level is inputted directly into the component.
  - Workmanship input into a soft stowage container does not accomplish goals of screening hardware for defects.

Workmanship Introduction (2)

- Workmanship random vibration testing can uncover both mechanical and electrical/mechanical types of faults.
  - Workmanship vibe can detect defects not detectable by thermal screens such as loose contact, debris, loose hardware and mechanical flaws.
  - Random vibration workmanship excites multiple modes/resonances therein detecting defects not found in sine vibration or thermal.
- It is important to test with sufficient amplitude and frequency range to uncover the defects.



History of Workmanship

- Random vibration workmanship testing is one of the primary ways to uncover flaws or defects in materials and production.
  - Mercury/Gemini/Apollo studies
  - Grumman Aerospace studies (1973)
  - Navy Manufacturing Screening Program (NAVMAT P-9492, 1979)
  - Hughes Aircraft/Air Force Environmental Stress Screening (RADC-TR-86-149, 1986)
  - "Random Vibration in Perspective" W. Tustin and R. Mercado, 1984
  - "Vibration Analysis for Electronic Equipment" D. Steinberg, 1988, Wiley-Interscience
- Thermal cycling screening is also highly recommended.
- JPL, Aerospace Corporation, Lockheed Martin, and NASA centers have a long history of using workmanship testing to uncover design and workmanship flaws.

History of Workmanship Testing (2)
At NASA GRC

- Workmanship testing has long been utilized and valued at NASA GRC:
  - General Environmental Verification Specification (GEVS) for STS and ELV Payloads, Subsystems, and Components, NASA GSFC, January 1990.
  - Lewis Management Instruction (LMI) 8070.2, March 19, 1993
  - NASA-STD-7001, June 21, 1996
  - Space Assurance Requirements and Guidelines (SARG), GRC-M0510.002, Revision C, December 1, 2003.
- Workmanship testing has been utilized for many Microgravity Science Division projects to verify the workmanship/assembly of hardware:
  - CM-1, CM-2, PCS, FCF utilize workmanship as part of screening of electro-mechanical components including: manual valves, cameras, circuit boards, mass flow controllers, pressure switch, relays, pressure transducers, pressure regulator, solenoids, power supplies, digital data recorder, gas chromatograph, recirculation pumps.

History of Workmanship (3)
Current DOD Requirements

- MIL-STD-1540E ("Test Requirements for Launch, Upper-Stage, and Space Vehicles" January 31, 2004)
  - Standard was officially released June 2004
  - Minimum random vibration workmanship spectrum required for acceptance testing
    - 6.9 Grms, 0.04 g^2/Hz plateau extended from 150 to 800 Hz
    - Plateau upper frequency raised to capture the higher resonances of today's smaller PCB cards
  - Note: Units mounted on shock or vibration isolators require vibration qualification testing in two configurations:
    - Unit mounted with isolators (qualify for flight environment)
    - Unit hard-mounted without isolators present (qualify for future acceptance level testing (that includes minimum workmanship))

History of Workmanship (4)
Current DOD Requirements

- MIL-STD-810F ("DOD Test Method Standard for Environmental Engineering Considerations and Laboratory Tests" January 1, 2000)
  - "The minimum integrity test is intended to provide reasonable assurance that materials can withstand transportation and handling including field installation, removal, and repair."
  - "Vibration levels and durations are not based on application environments. Rather, experience has shown that material that withstands these exposure functions satisfactorily in the field, and that material tested to lower levels does not. These exposures are sometimes called "junk level" tests."
  - Use care with delicate materials.
  - Maximum test weight should be 36 kg (80 lb).
  - Minimum integrity test is 7.7 Grms, 0.04 g^2/Hz plateau from 20 to 1000 Hz.

Value of Workmanship
Types of Defects Detected
(from NASA GSFC)

- Loose electrical connections
- Loose nuts, bolts, etc.
- Relay/switch chatter
- Physical contaminants (loose foreign matter)
- Cold solder joints and solder voids
- Incomplete weld joints
- Close tolerance mechanisms
- Defective piece parts
- Improperly crimped connections
- Wire defects
- Insufficient clearance
- Shrinkage of or too soft potting material
- Wire fatigue failure due to routing
- Loose or missing mounting hardware
- Excessive valve leakage or closure

Value of Workmanship (2)
Sample from Aerospace Corporation
(from component failure database of space vehicles)

CAUSE CATEGORY	CAUSE CODE	CAUSE DESCRIPTION
part	unknown	QUAD. TRANSISTOR FAILURE P/N 10166599-1.
workmanship	intermittent	MPC-CONNECTOR IN FL4 BROKEN DURING INSTALLATION. WAS INTERMITTENT IN VIBRATION.
test	overtest	VIB EQUIPMENT UNABLE TO CONTROL ALL VIB LEVELS IN THE REQUIRED SPECTRUM.
workmanship	rework	HANDLING ERROR DUE TO DESIGN OBSTRUCTION.
workmanship	pinched wire	ASSEMBLERS WRENCH PINCHED WIRE DUE TO POSITION OF TEST EQ.
workmanship	cable/connector	DEFECTIVE CANNON CONNECTORS.
design	[NULL]	UNEXPLAINED ANOMALY
part	process	BROKEN CORE INSIDE L207 VARIABLE INDUCTOR.
workmanship	solder	SOLDER BALL-ORIGIN UNKNOWN.
workmanship	vibration stress	RATTLING AMPLIFIED VIBRATION
workmanship	contamination	A GOLD FLAKE LODGED ON GOLD WIRE BONDING DIE & OUTPUT PAD.
workmanship	strain relief	INADEQUATE STRESS RELIEF ON LEADS.
workmanship	contamination	LARGE PARTICLE OF GOLD/TIN SEALING MATERIAL IN CAVITY OF U6, A QUAD DRIVER, LDC 8412, ON THE -104-02 BOARD.
workmanship	contamination	CONDUCTIVE PARTICLE IN Q8 (2N3997)
part	short	C37, P/N 10383504-1, ON MULT ASSY, SHORTED TO SHIELD.
workmanship	solder	SOLDER CONNECTION AT FL3 FILTER (MPC) & Q3 HAD CRACKED LEAD.
workmanship	handling	HAIRLINE CRACK IN ROD RESISTOR R21. DUE TO HANDLING.
part	unknown	CERAMIC CAP C7, R06 STYLE, KEMET, LDC 8146C, LOCATED ON THE A21 PWB, HAD EXCESSIVE LEAK CURRENT.
workmanship	torque	IMPROPERLY TORQUED DUMMY LOAD CONNECTION ON SYNTH. L2.
workmanship	vibration stress	LOOSE COVER.

Value of Workmanship (3)

- Aerospace Corporation's database shows that ~ 80% of all of their component failures for space vehicles are due to workmanship quality and assembly issues.
- The demonstration of survivability to workmanship levels is even more important to GRC today due to:
  - The more prevalent usage of COTS hardware
  - The longer-durations required for ISS missions
  - Lack of crew time and up-mass
- It is more cost effective to the Project to identify defects at lower levels of assembly.
- It is better to identify incipient defects during ground testing than in flight or on orbit.

We all want to achieve success on-orbit!

Workmanship Exceptions

- Exceptions to workmanship testing might include true "vibration-sensitive" components such as:
  - mirror assemblies
  - alignment critical devices
  - optical hard drives
- Being an under-designed component does not justify a declaration of hardware as being "vibration-sensitive."
- For exceptions, hardware developer needs to provide to GRC the confidence and/or vendor test data that demonstrates sufficient workmanship.
- Launching in soft stowage (i.e. foam) does **not exclude** the hardware from hard-mounted workmanship testing.

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Stowed Hardware: History

- Testing of stowed hardware (i.e. launched in foam) is "new" at GRC. How should we test stowed hardware?
- Discussions were held with Aerospace industry:
  - NASA GSFC
  - NASA MSFC
  - Aerospace Corporation
  - JPL
  - Boeing
- There was/is overwhelming technical consensus that stowed hardware still needs to be exposed to workmanship vibration levels.
  - Benefit in verifying its quality and workmanship.
  - Note: The foam-attenuated levels are not sufficient to screen the workmanship quality.

Stowed Hardware: ERB

- As a result of the ERB #2000-001, a GRC Engineering policy was established to meet the goals of workmanship testing of stowed hardware:

  (1) Test verify, via qualification/protoflight level testing, that the package design can survive launch loads with margin.

  - Qualify flight package design with hardware in a stowed configuration test.
  - This also verifies that the stowed hardware can survive the launch environment.

  (2) Test verify, via hard-mounted workmanship testing, that the hardware has adequate workmanship.

  Workmanship test hardware in hard-mounted configuration

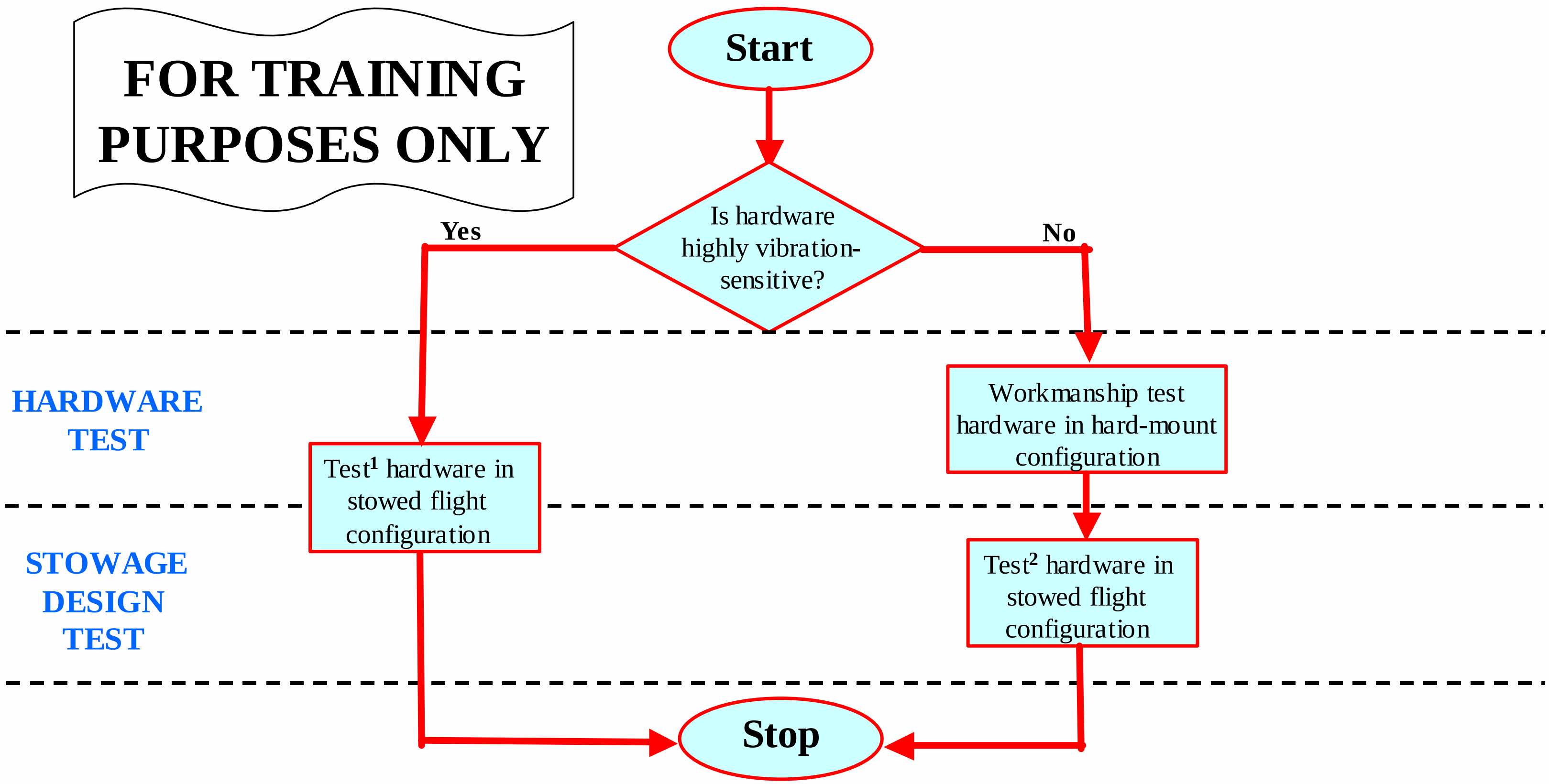
  - Screen out assembly flaws and hidden defects (that could still occur despite stowed package protection during launch).
  - Exceptions provided for "vibration-sensitive" hardware

Stowed Hardware: ERB (2)

- All hardware must still be tested to its flight-based stowed configuration environment (qualification, acceptance, protoflight) unless it has already seen larger test levels via hard-mounted workmanship testing.
- For typical STS payload environments, particularly those utilizing stowed configurations (i.e. foam), the hard-mounted workmanship test is very likely to result in the hardware seeing vibration levels higher than what it will see in stowage (during launch or stowed qualification test).
  - Therefore, the **random vibration workmanship test loads may become a design driver.**
    - As stated in SARG
    - As stated in “Guidelines for Loads on Items Soft-Stowed in Bags or Lockers,” NASA JSC memorandum, ES2-02-049, V.A. Fogt, January 7, 2003.

Stowed Testing Flowchart

(Applicable for typical STS payload environments)



NOTES:

1) Hardware test to the envelop of workmanship and flight-based environment. Flight-based environment is dependent on hardware program (protoflight OR qualification & acceptance).

2) Stowage design test to the envelop of workmanship and qualification/protoflight/(acceptance) flight-based environment. This stowage test is not required, unless it is needed to:

(a) Qualify a "new" stowage design, or
(b) Determine sufficiency of stowage packaging, or
(c) Qualify (or accept) hardware relative to stowed flight environment, if "all" stowed hardware has not already been exposed to higher test levels via the hard-mounted workmanship testing

Stowed Hardware: Expectations

- For "Non-Vibrational-Sensitive" hardware:
  - Perform workmanship test of the hardware in its hard-mounted configuration
    - This test verifies the workmanship quality of the hardware
    - (This also tests hardware to levels greater than it will see in stowed flight configuration, verifying that stowed hardware can survive launch.)
  - Perform qualification/protoflight level test (including envelope with workmanship), of the hardware in its stowed configuration
    - This test qualifies the stowage design
    - Only perform this test to:
      - Qualify a "new" stowage design, or
      - Determine sufficiency of stowage packaging (i.e. required inches of foam, etc.), or
      - Qualify (or accept) hardware relative to stowed flight environment, if "all" stowed hardware has not already been exposed to higher test levels via the hard-mounted workmanship testing

Stowed Hardware: Expectations (2)

- For "Vibration-Sensitive" hardware:
  - Perform Flight-based (Protoflight or Qualification and Acceptance) level (including envelope of workmanship) test of the hardware in its stowed configuration.
    - Verifies that vibration-sensitive hardware will survive the launch environment
    - Qualifies stowage design
  - In order to increase the mission assurance of vibration-sensitive hardware, the Project Manager may choose to perform additional confidence-building test of workmanship such as:
    - Component hard-mounted workmanship test using:
      - reduced test-tailored levels, durations, axes
      - notching at resonances
      - force-limiting control
    - Lower level of assembly hard-mounted workmanship testing

Stress Analysis of Stowed Hardware

- Stress analysis is only required for safety-critical stowed hardware**(*)**. Such hardware must be designed for the following load cases:
  - Liftoff/landing quasi-static loads
  - Pressure loads for pressurized hardware
  - Thermal loads
  - Appropriate hard-mounted workmanship random test load (response of hardware from test input, where 1 sigma random test input load = 6.8 Grms)
- For non-safety critical hardware, the hardware must be designed for the appropriate random load seen in the hard-mounted workmanship test.

References:

1. "Guidelines for Loads on Items Soft-Stowed in Bags or Lockers," NASA JSC memorandum, ES2-02-049, V.A. Fogt, January 7, 2003.
2. "Structural_Verification of Safety Critical Stowed Hardware," NASA GRC memorandum from 7740/Charles L. Denniston to 7700/John D. Taylor, January 26, 2004.

***** - Hardware stowed for launch which the crew can not adequately inspect (by means of sight or feel) to verify safe access on-orbit.