

Qualification of Electrical Ground Support Equipment for New Space Programs

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ABSTRACT

With the Space Shuttle program coming to an end, the National Aeronautics and Space Administration (NASA) is moving to a new space flight program that will allow expeditions beyond low earth orbit. The space vehicles required to comply with these missions will be carrying heavy payloads. This implies that the Earth departure stage capabilities must be of higher magnitudes, given the current propulsion technology. The engineering design of the new flight hardware comes with some structural, thermal, propulsion and other subsystems' challenges. Meanwhile, the necessary ground support equipment (GSE) used to test, validate, verify and process the flight hardware must withstand the new program specifications.

This paper intends to provide the qualification considerations during implementation of new electrical GSE for space programs. A team of engineers was formed to embark on this task, and facilitate the logistics process and ensure that the electrical, mechanical and fluids subsystems conduct the proper level of testing. Ultimately, each subsystem must certify that each piece of ground support equipment used in the field is capable of withstanding the strenuous vibration, acoustics, environmental, thermal and Electromagnetic Interference (EMI) levels experienced during pre-launch, launch and post-launch activities. The benefits of capturing and sharing these findings will provide technical, cost savings and schedule impacts information to both the technical and management community.

Keywords: Qualification; Testing; Ground Support Equipment; Electromagnetic Interference Testing; Vibration Testing; Acoustic Testing; Power Spectral Density.

1. INTRODUCTION

There are many risks associated with Space Flights design and development. Many of these risks are known, but some of them are unknown. New space programs have the benefit of learning from previous programs, but there are disadvantages. The new program requirements bring questions and problems that must be addressed using the best judgment possible. Building and performing multiple tests have proven to mitigate many unknowns. Test facilities play a vital role in the determination of limits to which both ground and flight hardware are tested. However, budget limitations may preclude from performing test on every single piece of hardware and software. Thus, engineering analysis and judgment are the next best level of conformance.

2. CLASSIFICATION OF HAZARD LOCATIONS

In accordance with the Occupational Safety and Health Administration (OSHA), the National Electrical Code (NEC) defines hazardous locations as those areas "where fire or explosion hazards may exist due to flammable gases or vapors, flammable liquids, combustible dust, or ignitable fibers or flyings." Table 2.1 classifies each of those categories¹.

CLASSES	GROUPS	DIVISIONS	
		1	2
I Gases, vapors, and liquids (Art. 501)	A: Acetylene B: Hydrogen, etc. C: Ether, etc. D: Hydrocarbons, fuels, solvents, etc.	Normally explosive and hazardous	Not normally present in an explosive concentration (but may accidentally exist)
II Dusts (Art. 502)	E: Metal dusts (conductive, and explosive) F: Carbon dusts (some are conductive, and all are explosive) G: Flour, starch, grain, combustible plastic or chemical dust (explosive)	Ignitable quantities of dust normally are or may be in suspension, or conductive dust may be present	Dust not normally suspended in an ignitable concentration (but may accidentally exist). Dust layers are present.
III Fibers and flyings (Art. 503)	Textiles, wood-working, etc. (easily ignitable, but not likely to be explosive)	Handled or used in manufacturing	Stored or handled in storage (exclusive of manufacturing)

The NASA's Kennedy Space Center (KSC) facilities and operational areas comply with these standards and classify its activities in accordance with the following categories:

- 1) Hazardous Location
 - A - Class 1 Div 1
 - B - Class 1 Div 2
 - C - Non-hazardous

Thus, when designing avionics, electrical, fluids, mechanical and pneumatic systems, personnel need to consider the worse environment to which their systems can be exposed. Hence, systems engineers must test and qualify their hardware to minimize the risk of failure.

3. QUALIFICATION METHODS

The NASA location at the Kennedy Space Center (KSC) in Florida, the agency designs, develops, integrates, tests, processes and operates the Ground Support Equipment (GSE) necessary to achieve safe Space Flight Readiness. Despite being aware of the numerous "unknowns" in the process's Life Cycle, it is understood that one way to mitigate and/or reduce the probability of failure of its GSE, is to perform multiple tests to the multiple systems. The location of use of each subsystem's assembly and components is predetermined based on the architectural design. Depending on the location, the environmental conditions and intensity experienced by similar components may be different. Therefore, in order to conduct sound engineering assessment, each component is ground tested to the specifications of its worse load environment. For example, similar components are used in two completely different environments, then such GSE component is qualified by testing to the more severe environmental load levels.

There are budgetary constraints when complying with this testing methodology. Component qualification testing can become very expensive very quickly. To obtain the best test results, each test must be conducted independently from other tests. Each test may require different personnel skill set, different test equipment and different facilities. A secondary concern is experienced when the system's design personnel is supporting the Qualification Testing phase, instead of supporting another project's phase such as design, development, procurement, assembly, analysis, functionality testing, integration, verification and validation. Additionally, there is a possibility that the GSE under testing may not be approved for use in the field. The GSE units that underwent qualification tests can only be used in the field if a panel of experts determines that there is no risk associated with using a unit that underwent thru a Qualification Test.

There are no set sequences for testing GSE, only suggested sequences¹¹. It may be a matter of resources availability or the determination to conduct test to destructive limits. Ideally, all tests are performed using the same set of GSE components and all components survive all tests. The flowchart depicted in Figure 3.1 shows a typical sequence of events that should be considered during subsystems' component qualification of GSE for new Space Programs.²

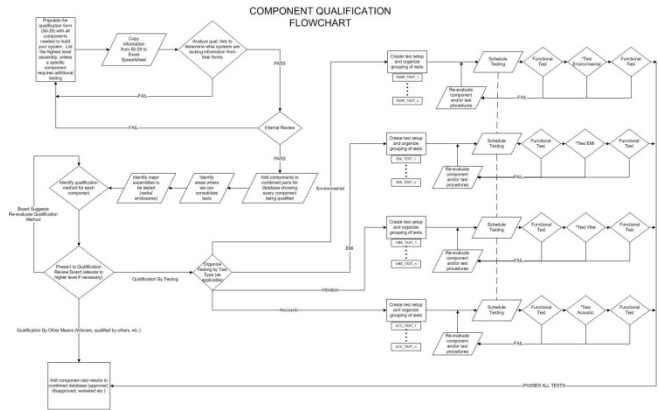


Figure 3.1: Component Qualification Flowchart of Electrical Ground Support Equipment.

Typical methods of qualification³ defined in KSC-STD-G-0003 include, but are not limited to:

- a) Qualification by Testing
- b) Qualification by Similarity
- c) Qualification by Legacy (Prior Qualification)
- d) Qualification by Usage and Analysis
- e) Qualification by Higher Level Assembly Testing

For the purposes of this paper, the main tests considered are: Environmental, Electromagnetic Interference (EMI), Vibration and Acoustics testing. Each test, along with some general test requirements, is described in the following sections.

3.1 Vibration / Acoustic Testing

Although the Vibration and Acoustic tests should be performed independently, for the purposes of this paper it was decided to categorize them together. The four (4) levels below categorize the location where the hardware is installed. Here are the levels:

Vibration/Acoustic Level

- A - Mobile Launcher, around exhaust well, no shock mount
- B - Mobile Launcher, Launch Umbilical Tower
- C - Mobile Launcher, Shock Mounted or minimal grms
- D - Launch Pad

Thus, hardware is ground tested to the highest “worst” levels exposed according to its installed location. Another test design consideration relates to the operational scenarios of each system. Some systems such as Communication and Tracking require being operational before, during and after a space vehicle launch. However, some systems (such as Sound Suppression Water) are not required to be operational after the space vehicle has cleared the launch tower.

The KSC-NE-8764 Volume I – entitled “Crew Launch Vehicle (CLV) Mobile launcher solid rocket motor exhaust plume induced environment Acoustic and Vibration” document depicts the Vibration and Acoustic environment in the near and far field during lift-off⁴. The closer to the exhaust well, the higher the Grms levels experienced by the hardware. The metric of “grms” is typically used to specify and compare the energy in repetitive show vibration systems⁵.

When evaluating Overall Sound Pressure Levels (OASPL) both the Mean (50% Confidence Level) and the Specification (97.7% Confidence Level) values must be considered. The Power Spectral Density (PSD) analysis of most legacy space vehicles are publicly available. Therefore, for ground acoustic testing of new space vehicles, it is acceptable to scale down (or up) the Octave Band Sound Pressure Levels (OBSPL) levels of previous space vehicles to determine the expected acoustic levels of the new space vehicle. Predicting these values is critical to ground testing requirements verification and validation. Additionally, the search for test facilities may be limited if the required test levels are abnormally high.

To determine the Sound Pressure Level (SPL) Spectrum we use a logarithm representation of the given frequency:

$$\text{Thus, } \text{SPL}(f) = 10 \text{ Log}_{10} \text{S}(f) \quad [\text{units: dB, re: } 2 \times 10^{-5} \text{ Pascals (Pa)}] \quad (1)$$

where S(f) is the square of the pressure ratio $\{ p_{rms}^2 / p_{ref}^2 \}$

Then the Overall Sound Pressure Level (OASPL) states that the total energy contained in the spectrum⁶ is given by:

$$E = \int \text{S}(f) df \quad (2)$$

which is then integrated over all resolved frequencies⁷. Then the OASPL becomes:

$$\text{OASPL} = 10 \text{ Log}_{10} (E) \quad [\text{units: dB}] \quad (3)$$

If we use as reference 0 [dB] or 2×10^{-5} Pa, then the OASPL can be calculated follows⁶:

$$\text{OASPL} = 10 \text{ Log} \{ p_{rms}^2 / p_{ref}^2 \} \quad (4)$$

$$\text{Equation (4) can be re-written as } \text{OASPL} = 20 \text{ Log} \{ p_{rms} / p_{ref} \} \quad (5)$$

where $p_{rms}^2 = \sum_k p_k^2$ and p_{ref} is ostensibly the audible limit of the human ear

A typical calculation at different Octave bands given its Sound Pressure level is shown in Table 3.1 below⁷.

Table 3.1 Sound Pressure levels at various Octave bands

Octave Band	Sound Pressure Level (SPL) (dB) Ref: 0 [dB] = 2×10^{-5} (Pa)	Sound Pressure p_k^2 (Pa^2)
31.5	124	1.005×10^3
63	130	4.000×10^3
125	135	1.265×10^4
250	139	3.177×10^4
500	134	1.005×10^4
1000	128	2.524×10^3
2000	124	1.005×10^3
4000	120	4.000×10^2
8000	116	1.592×10^2
	$p_{rms}^2 = \sum_k p_k^2$	6.356×10^4
Overall Sound Pressure Level (OASPL)	$\text{OASPL} = 10 \text{ Log} \{ p_{rms}^2 / p_{ref}^2 \}$	142 [dB]
Overall Sound Pressure Level (OASPL)	142	

The Voyager I spacecraft mission was launched from Cape Canaveral Air Force Station in Florida on a Titan IIIE / Centaur vehicle⁸ in September 5, 1977. Figures 3.1(a) and Figure 3.1(b) show the configuration of each spacecraft.

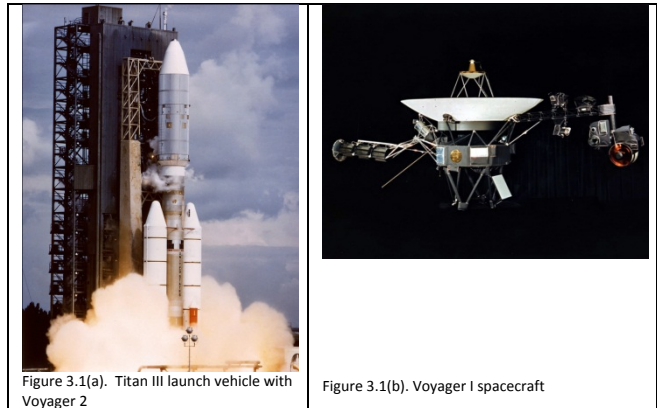
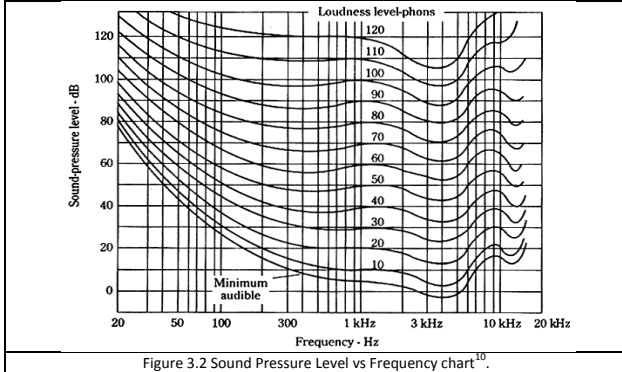


Figure 3.1(a). Titan III launch vehicle with Voyager 2

Figure 3.1(b). Voyager I spacecraft

It is very important to observe that the values of Table 3.1 can be used as a guide to scale (up or down) acoustic levels of new space launch vehicles in the perimeter of its launch platform. It should be noted that the value of OASPL is greater than any individual sound pressure level in the specification, because it represents an intensity of the spectrum as a whole.⁹ Therefore, when designing ground acoustic and vibration tests, the test team must:

- a) Estimate the Average Sound Pressure Levels (SPL) for each location. Typical test locations are as close as the Mobile Launch Tower (MLT) and as far as 15,000 ft (Far Field) from the MLT.
- b) Consider the various frequencies at each of those locations. Typical Octave Band Center Frequencies range from 2 Hz – 8,000 Hz. See Figure 3.2 for a generic SPL vs Hz chart.



3.1.1 Vibro-Acoustic Test Level Requirements

Sound Pressure Levels of Heavy lift vehicles can surpass higher than normal limits. For these extreme cases, testing are conducted at facilities that can reach levels over 130 dBs and that can fit full racks, enclosures and the entire spacecraft if possible. The OASPLs values below⁴ were taken from the Saturn V and the Space Shuttle program:

- 1) (Ref. KSC-NE-8764, Appendix A-3)
 - a) ML Base “except vicinity” (away) of Exhaust Hole
 - i. Mean Overall Acoustic Sound Pressure Level (OASPL) @ 50% Confidence Level = 141.7 dB.
 - ii. Specification (OASPL) @ 97.7% Confidence Level = 147.2 dB.
- 2) (Ref. KSC-NE-8764, Appendix A-5)
 - a) ML Base, Compartments around (internal/near) exhaust well
 - i. Mean Overall Acoustic Sound Pressure Level (OASPL) @ 50% Confidence Level = 150.4 dB.
 - ii. Specification (OASPL) @ 97.7% Confidence Level = 161.9 dB.
 - iii. [\[Ref. KSC-NE-8764 Appendix A-7\] “Induced Environment Acoustic and Vibration”](#)
 - b) ML Tower – All Levels
 - i. Mean Overall Acoustic Sound Pressure Level (OASPL) @ 50% Confidence Level = 165.6 dB.
 - ii. Specification (OASPL) @ 97.7% Confidence Level = 170.5 dB.

3.1.2 Test duration:

- 1) ([Ref. KSC-STD-164B, p.22](#)) “Environmental Test Methods for GSE Standard...”
 - a) Time: minimum test is 10 seconds.
 - b) For each additional launch, add 5 seconds.
 - c) Do not exceed 3 minutes.
 - d) 3 minutes = 100 launches.
 - e) Assumptions: => 10s + 5s*(5 launches – 1st test launch) = 30seconds.
Therefore, for 36 launches, the maximum length of a test at any particular frequency is calculated as follows:
10s + 5s*(35 launches – 1st test launch) = 180seconds = 3 minutes (MAX)

3.1.3 Vibration Test Setup

Accelerometers and other sensors are placed in strategic locations throughout the hardware considered for testing. Ideally, racks, enclosures and panels are tested at least twice; once with no contents (empty configuration) and then loaded. Additionally, sensors are moved from test to test, to ensure the critical areas are considered as hardware experiences different effect at different locations under different loads. Figures 3.1.3(a) and 3.1.3(b) depict a typical test configuration. The hardware is to be tested in the expected operational configuration. Therefore, if dampers are included in the installation design, then it must be tested as such.



Figure 3.1.3(a): Placement of accelerometers in an empty enclosure.

Figure 3.1.3 (b): Instrumented enclosure ready for vibration testing.

3.1.4 Acoustic Test Setup

Microphones and other sensors are placed in strategic locations throughout the hardware considered for testing. Ideally, racks, enclosures and panels are tested at least twice; once with no contents (empty configuration) and then loaded. Additionally, sensors are moved from test to test, to ensure the critical areas are considered as hardware experiences different effect at different locations under different loads. Figures 3.1.4(a) and 3.1.4(b) depict a typical test configuration. The hardware is to be tested in the expected operational configuration. Therefore, if sound isolators are included in the installation design, then it must be tested as such.

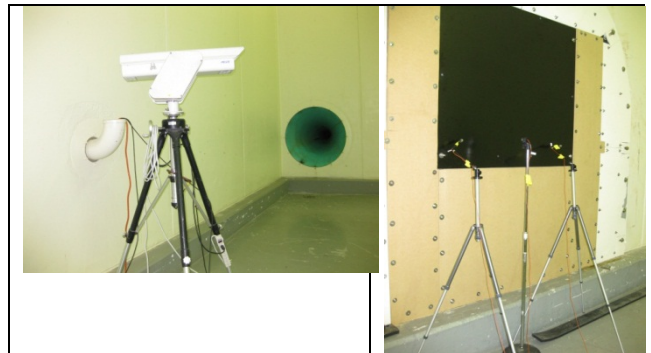


Figure 3.1.4 (a): Camera and cables feed from Test facility to Control room at the Johnson Space Center Acoustic Test Facility.

Figure 3.1.4(b): Audio sensors mounted over a wall panel prior to testing.

3.2 Environmental Testing

Qualification testing of both ground support equipment and flight hardware is expected to be performed in accordance to the exposed/induced environment where it will be used. There are many variables to each test condition, but for the purposes of this paper, the three environmental scenarios are considered.

The following Environmental Control Levels are defined in KSC-STD-164 (except EMI, acoustic, vibration, explosion and lift-off blast)¹¹:

- A - Outdoor, extended temperature (-25C to +85C, Humidity, Rain, Icing, Fungus, Salt fog, Sand and Dust)
- B - Outdoor (0 to +70 C, Humidity, Rain, Icing, Fungus, Salt fog, Sand and Dust)
- C - Indoor (0 to +60 C, Humidity)
- D - Climate Controlled

3.3 Electromagnetic Interference Testing

Whether or not the GSE will be used or installed near the Mobile Launch Tower, Electromagnetic Interference (EMI) Tests are performed during equipment qualification testing. EMI, also called radio frequency interference or RFI is a disturbance that affects an electrical circuit due to either electromagnetic induction or electromagnetic radiation from an external source¹². Signals can be affected by EMI leaks. Proper cable connections play a huge role in minimizing signal disturbance. Although, there is not a set way on the order of qualification testing, it is advisable to conduct EMI qualification test after a vibration test has passed inspection. Cables connections may come loose after a strenuous motion test, thus an EMI leak might not be detected if the EMI qualification test was performed prior to the Vibration and/or Acoustic test.

4. REPORTS

It is recommended to capture all pertaining component qualification information in a database¹³. There may be multiple stakeholders that benefit from efficient reporting tools. For example, subsystems engineers, test design engineers, test conductors, budget analysts, logistics control, configuration management, travel coordinators and even managers benefit from the collected data.

Figure 4.1 below shows a one page report that includes assembly information for components used and tested by various subsystems and their expected location of use. The expected test levels correspond to the Hazard Location, Vibro-Acoustic location and its Environmental control levels.

Component	Assembly	SubAssembly	Subsystem	Installation Need Date	Test Method	Test Results	Test Status
0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001
0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001
0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001
0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001	0001-00000001

Figure 4.1: One page report of component qualification test information.

5. CURRENT AND FUTURE DEVELOPMENTS

The next step in the component qualification testing of the new space program is to be able to conduct functional tests using the equipment as configured in the design documents. The component qualification test board will play a critical role as they will decide which methods are acceptable to qualify the new costly electrical ground support equipment. Concurrently, Mechanical, Fluids systems are having similar decisions about their Ground Support Equipment.

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