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# Technical Report

Title: KSC Engineering Review Board ELV-Pegasus-1999-03 Decision on Pegasus Captive Carry Random Vibration Testing Requirements

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## 1.0 Executive Summary

An Engineering Review Board (ERB) was convened by the Kennedy Space Center (KSC) Expendable Launch Vehicle (ELV) Project Office. This ERB recommended a new random vibration qualification testing guideline for NASA spacecraft riding on Pegasus launch vehicles. Part 1 of the ERB defined recommended design scenarios for Vandenberg Air Force Base (VAFB) missions, campaign missions or ferry missions. The VAFB or campaign mission design recommendation is one launch abort return to base followed by a successful launch attempt. The ferry mission design recommendation is ferry from VAFB to the remote launch site, one aborted launch, a ferry back to VAFB for service, a return ferry to the launch site, and one aborted launch attempt followed by a successful launch attempt. Part 2 of the ERB defined random vibration test durations for these scenarios. It is recommended that prototype spacecraft and prototype components be qualified by testing to the Pegasus maximum flight environment (MEFL) +3dB for a duration defined by the mission profile. A formula is provided for this purpose. It is also recommended that protoflight spacecraft and components be qualified by testing to the Pegasus MEFL+3dB for 75 seconds. The 75 seconds is a compromise between preserving hardware life and screening workmanship defects.

## 2.0 Introduction

The air launched Pegasus launch vehicle is unique from ground launched vehicles in that its primary random vibration environment is not derived from powered flight. Instead, the critical random vibration environment is seen during the captive carry under the Orbital Carrier Aircraft (OCA). Not only are the captive carry levels greater than powered flight levels, but the duration is also longer. For some missions this environment may exist for many hours as opposed to several minutes of powered flight.

Existing standards for spacecraft testing are based on ground launched vehicles (see Table 2.1). These standards are not consistent even within themselves, leading to a "to each his own" qualification approach. MIL-HDBK-340A tends to contain the strictest standards and the guidelines of that book (120 - 180 seconds of qualification testing) are not sufficient to demonstrate equivalent life of the Pegasus captive carry environment. Furthermore, none of the standards address protoflight testing in a fatigue/wear situation. Therefore, new qualification standards are required for the unique Pegasus environments.

| Qualification Standard for Spacecraft | Protoflight Level | Protoflight Duration (sec) | Prototype Level | Prototype Duration (sec) |
|---|---|---|---|---|
| KSC-SELVS | MEFL+3dB | 75 | NA | NA |
| NASA Standard | MEFL+3dB | 60 | MEFL+3dB | 120 |
| MIL-HDBK-340A (was MIL-STD-1540) | Envelop(MEFL, min level) + 3dB | 120 | Envelop(MEFL, min level) + 6dB | 120 |

Table 2.1: Comparison of Different Standards for Spacecraft and Vehicle Level Random Vibration Testing.

There are three launch options for Pegasus missions: VAFB, campaign, or ferry. A VAFB mission integrates the spacecraft to the Pegasus at VAFB and launches from VAFB. A campaign mission integrates the spacecraft to the Pegasus at a remote site and launches from that remote site. The VAFB and campaign missions are identical except for the integration and launch location. Therefore, the VAFB mission will be referred to as a campaign mission. The ferry mission integrates the spacecraft to the Pegasus at VAFB and then ferries the integrated Pegasus on the OCA to a remote launch site. For any option, the launch sequence consists of a short (typically 40 minutes) cruise to a drop point and then a few minutes of powered flight for the Pegasus.

Deriving a qualification random vibration test for Pegasus is complicated by several factors. First, there are the significant differences between a campaign and a ferry mission. Within each of these, there is the question of what the design-to profile should be. Unlike ground launched vehicles which can only fly once each mission, the Pegasus can have multiple launch attempts which make the exposure duration an uncertainty.

Second, there is the complication of the qualification philosophy of each spacecraft program. There are two distinct approaches for spacecraft: prototype and protoflight. Prototype programs have dedicated qualification units that are not for flight. In a prototype program the qualification unit demonstrates that the hardware can survive the flight environment with margin and then a flight unit is built that is given only an acceptance test to screen out workmanship defects. In a protoflight program the qualification unit is also the flight unit. Therefore, a balance must be struck between qualification testing and preserving hardware life.

The protoflight approach is very common. Because only one flight or flight-like unit needs to be built, the program costs are cheaper. Spacecraft hardware is one application where this approach is viable. Because spacecraft only need to survive for a very short rough ride, fatigue is rarely an issue. Once the spacecraft has survived the test environment, the probability of surviving the flight environment is high. However, the long duration Pegasus missions provide an added complication to the protoflight program.

This report summarizes a complete recommendation on how to qualify spacecraft for Pegasus missions. First, a series of design scenarios is developed based on the three types of missions. Then a qualification test philosophy is established based on both the prototype and protoflight approaches.

# 3.0 Design Scenarios

## 3.1 Possible phases of a Pegasus Launch

The possible phases of a Pegasus launch and their description are shown in Table 3.1. The key factors driving the random vibration environment are: take-off, cruise, landing and powered flight. The duration of the cruise phase is driven by the launch site: VAFB, Wallops Flight Facility (WFF), Cape Canaveral Air Force Station (CCAFS) or Kwajalein Missile Range(KMR).

## 3.2 Recommended Design Scenarios

One RTB per launch attempt was included in each mission design scenario. Note that the design scenarios do not encompass mission unique configurations which impact areas such as a launch recycle timelines or different launch box locations.

| Possible Phases of a Pegasus Launch | Description |
|---|---|
| Launch attempt | Take-off with 40 minute cruise[1] |
| Powered Flight (a.k.a. Launch) | Pegasus Stage 1, Stage 2, Stage 3 burns |
| Ferry from VAFB to launch site | Up to two take-offs, 2 landings and 9.67 hours of cruise (worst case)[1,2] |
| Return ferry from launch site to VAFB | Up to two take-offs, 2 landings and 8.67 hours of cruise (worst case)[1,2] |
| Launch Abort – Return to Base | 10 minute cruise with landing[1] |
| Launch Abort – Return to Alternate Site | Some cruise with landing[1] |
| Launch Recycle | 25 minute cruise |

Note 1: Take-off is take-off with 20 minute climb. Landing is 20 minute descent with landing.
Note 2: Cruise duration for a ferry to the launch site includes one hour to fly through the launch box for a telemetry flow test. The telemetry flow test is not performed on a return ferry to VAFB.

Table 3.1: Possible Phase of a Pegasus Launch

### 3.2.1 VAFB or Campaign Mission

These two mission design scenarios were combined into one recommendation since these two mission options have identical timelines for the random vibration environment experienced by the spacecraft. The design scenario recommended is one abort RTB followed by a successful launch attempt. This results in two take-offs, 1.5 hours of cruise, one landing and powered flight.

### 3.2.2 Ferry Missions

Two assumptions were made for ferry missions. The first assumption was that a return ferry to VAFB to demate the integrated launch vehicle from the OCA with a ferry flight back to the launch site should be included in any ferry mission design scenario because the probability of demating the integrated launch vehicle from the OCA is greater than zero. For example, any critical spacecraft or Pegasus item that fails and requires Payload Fairing (PLF) removal for access would necessitate a return ferry to VAFB and a demate. The second assumption was that if a return ferry was required to demate the integrated launch vehicle from the OCA then an additional RTB should be included in the design scenario. Therefore, the design scenario recommended is one ferry flight followed by one abort RTB, return to VAFB ferry, followed by a ferry flight back to the launch site, one abort RTB followed by a successful launch attempt.

3.2.2.1 Ferry Mission to CCAS or WFF

These two launch sites were combined into one design scenario since the identical timeline was applicable to either launch site. The design scenario results in six take-offs, 17.33 hours of cruise, 5 landings and powered flight.

3.2.2.2 Ferry Mission to KMR

It should be noted that as of October 12, 1999, the launch box for KMR had not been resolved. Thus, the cruise duration was based on NASA's HETE-2 mission worst case launch box. Furthermore, the ferry flight to KMR is done in two segments: VAFB to Hawaii and then from Hawaii to KMR.

The design scenario results in nine take-offs, 30.33 hours of cruise, eight landings and powered flight.

## 4.0 Qualification Test Durations

A set of test durations was developed to encompass any design scenario outlined in Section 3. Some of the key issues during development were variable design scenario's, fatigue equivalence, wear equivalence, workmanship screening, broadband non-stationary signals, and prototype vs. protoflight.

Random vibration testing has four main purposes:

1. Uncovering fatigue failure modes
2. Uncovering mechanical and electrical equipment wear failure modes
3. Subjecting the test article to peak loads
4. Uncovering workmanship defects

Numbers 1 and 2 above are valid concerns. However, the equations for fatigue and wear equivalence are such that wear equivalence bounds fatigue equivalence. In other words, wear equivalence requires a longer test duration than does fatigue equivalence. Therefore, in the analysis, mechanical and electrical equipment failure scaling laws are used. Because Pegasus spacecraft must designed for large static or low frequency loads, associated with axial thrust and vehicle dynamics, the random vibration environment cannot, and is not intended to, demonstrate peak loads. Workmanship screening remains a valid purpose and is considered extensively. The focus in deriving qualification tests is mechanical and electrical equipment wear and workmanship.

## 4.1 Pegasus Phases of Flight

As with any launch vehicle, Pegasus goes through several phases of flight. Each of these is sufficiently different to warrant treating them differently. The Pegasus phases of flight are shown in Table 3.1. Not all of these phases are used for every flight. For example, for a VAFB campaign, only a launch attempt followed by powered flight may be needed. However, designing for this optimistic scenario is not recommended (described in Section 3).

Because of the variability and non-stationary nature of each of the phases in Table 3.1, the phases are further broken down into components (or building blocks). Test durations may be derived for each of these components. Then equivalent durations may be formed for each of the phases.

The key components from which all phases are derived are: ascent, cruise, descent, and powered flight. It is interesting to note that of the four components, ground launched vehicles only have the last.

## 4.2 Wear Equivalence for the Key Flight Components

Pegasus flight data was considered from six missions. These missions were considered because they met several criteria:

1. All were flights after the OCA ascent flight restrictions were imposed. This changed the random vibration environment during this phase of flight.
2. All were Pegasus XL vehicles rather than standard or hybrid vehicles. All future missions will be in this configuration.
3. No external modications existed that could have changed the environment in a non-standard way. Ducting has been the most common external modification.

This resulted in data from 5 1/2 flights being available. These flights were: STEP-4, TRACE, SNOE, SWAS, WIRE (1/2), and TERRIERS. For each of these, the X, Y, and Z axes from captive carry data and Stages 1-3 powered flight data were analyzed. From this data test equivalence durations were derived. This data is not shown here for proprietary reasons.

The processing strategy used was as follows:

- Spacecraft test levels were assumed to be SELVS-KSC[1] maximum expected flight level (MEFL)+3dB. These levels are also those in the Pegasus User's Guide[2]. These levels are shown in Figure 4.1
- Each flight was processed separately to determine equivalent durations for that flight. For each flight an ascent, a cruise, a powered flight, and a descent (when available) test duration was derived.

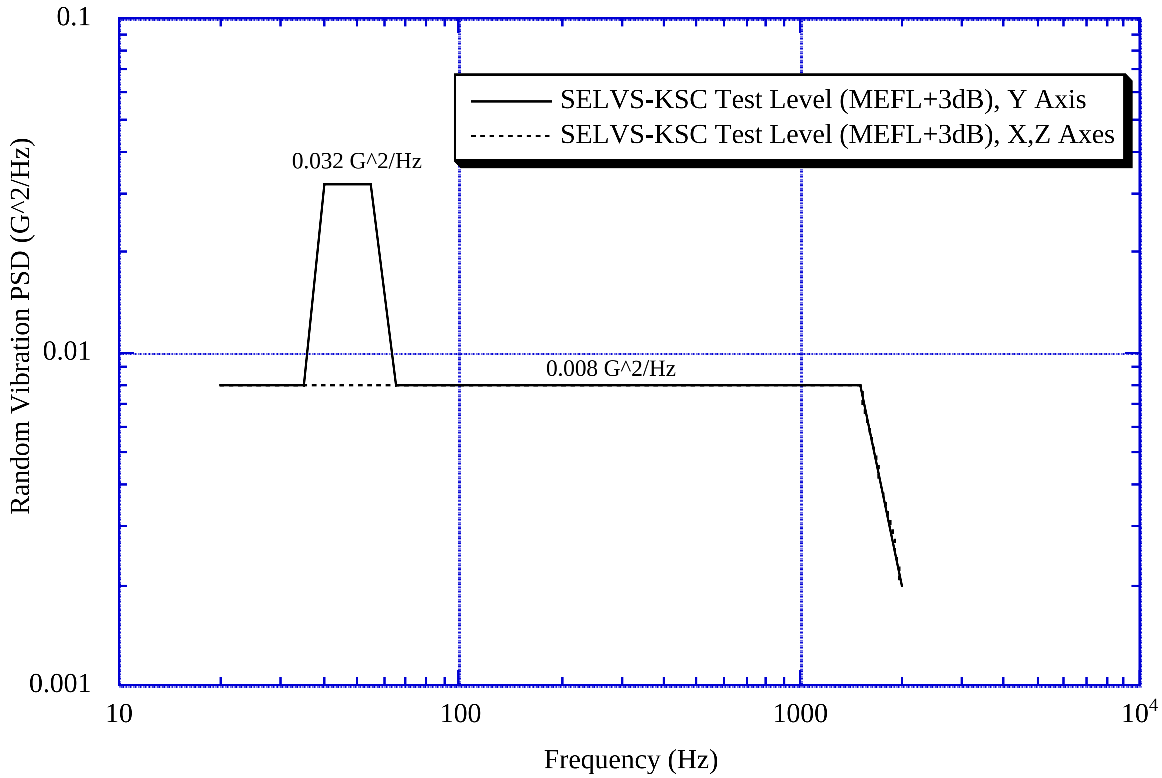


Figure 4.1: Pegasus Spacecraft Interface Random Vibration Test Environment

- For each flight, the vibration data was available as a set of power spectral densities (PSD's) for each one minute or each 3 minutes of flight. Therefore, equivalent durations were found for each minute (or 3 minutes) of flight. Then, for each component of each flight, an equivalent duration was found for each frequency band by adding up the individual durations for each minute (or 3 minutes) of that component (Equation 1). This processing approach removes the smearing or averaging due to the non-stationary aspects of the data.

  i = mission, j = flight time, k = frequency band, T = test duration

$$T_{i,j,k} = t_j * \left( \frac{\text{Flight PSD Level}_{i,j,k}}{\text{Test PSD Level}_k} \right)^2 \qquad (1)$$

- The test duration for each segment of flight (e.g. ascent) is found by selecting the frequency band that has the largest equivalent test duration:

$$T_{\text{segment},i} = \max_k \left( \sum_{j=\text{segment times}} T_{i,j,k} \right) \qquad (2)$$

- Now, equivalent test durations exist for each component of each flight. Statistics are used across all flights to find the overall P95/50 value for each component of flight:

$$T_{segment} = P95/50\{T_{segment,i}\} \tag{3}$$

- Descent is assumed equal to ascent. Because only two flights of data existed for this and these two sets of data differed so greatly, the assumption was made to treat a descent as equivalent in test time to an ascent.
- The test durations for a phase of flight is defined by combining the appropriate components times. Because the frequency content of the various components is different, the combination to segment durations is not additive.
- Finally, the test durations were doubled to account for the variability in the wear life of components. Others have suggested as much as a factor of 4 is needed to cover the uncertainty, but a factor of 2 was selected here as a balance between the worst case and no variation.

The results from the above data analysis are shown in Tables 4.1 and 4.2.

## 4.3 Prototype Hardware Testing

Prototype hardware represents a qualification unit not intended for flight. An equivalent flight unit will be built after the qualification unit has passed all testing. It is expected that few spacecraft will be prototype, but that some new or risky components will be prototype. The previously derived durations have been based on the spacecraft interface. However, the spacecraft interface environment is transferred to the assembly and component level. Therefore, the durations derived are applicable to assemblies and components. The test magnitude for these items will be determined at their interface to the main structure.

Prototype hardware shall be qualified by:

- Defining a design scenario (per Section 3)
- Building a test duration from the building blocks of Table 4.2.
- A minimum time of 120 seconds is required per NASA-STD-7001.[3]
- Test levels shall be MEFL+3dB with a tolerance of ±3dB. The MEFL for the spacecraft and its components will be different.

| COMPONENT | EQUIVALENT TEST TIME (SEC) |
|---|---|
| Ascent | 11 |
| Cruise (per hour) | 12 |
| Descent | 11 |
| Powered Flight | 6 |

Table 4.1: Test equivalence durations for the Pegasus launch sequence components

| SCENARIO BUILDING BLOCK | BUILDING BLOCK | TEST EQUIVALENCE | TEST EQUIVALENCE |
|---|---|---|---|

| | COMPONENTS | BASES (SEC) | (SEC) |
|---|---|---|---|
| Successful launch attempt | ascent<br>+ 40 min cruise*<br>+ powered flight | 11<br>+ 8<br>+ 6 | 25 sec |
| Ferry | ascent<br>+ x hours cruise<br>+ descent | 11<br>+ 12x<br>+11 | 22+12x sec |
| Aborted launch attempt | ascent<br>+ 50 min cruise*<br>+ descent | 11<br>+ 10<br>+ 11 | 32 sec |

*These cruise times are typical. These may be used or mission specific values may be computed.

Table 4.2: Test equivalence durations for the Pegasus mission scenario building blocks.

## 4.4 Protoflight Hardware Testing

Protoflight hardware represents a single unit intended for qualification and flight. It is expected that most spacecraft will be protoflight and some components may also be protoflight. Protoflight qualification must balance between demonstrating survivability and protecting remaining life. Protoflight qualification only proves that the test article was able to endure the flight environment, not that it still can.

Protoflight hardware shall be qualified using:

- Test levels equal to MEFL+3dB with a tolerance of ±3dB. The MEFL for the spacecraft and its components will be different.
- A test duration of 75 seconds. This duration is derived for workmanship screening and is constant regardless of design scenario. A discussion on this follows.

No literature exists on protoflight testing for long duration events. This is not surprising as protoflight qualification, which erodes hardware life, does not make sense in a long duration fatigue or wear environment. In spite of this, NASA spacecraft programs continue to use this technique independent of the launch vehicle environment.

The philosophy established by this report is that protoflight testing for a long duration environment should be a workmanship screen. Testing for the full flight equivalent duration does not prove anything about the existing life remaining. Therefore, to maximize the life remaining, the test duration should be such that most defects are uncovered without sacrificing extended life.

Much literature exists on workmanship screening (also called stress screening). However, the space industry uses installation, manufacturing, and inspection techniques that differ from common practice. Therefore, much of the database of knowledge is not applicable. Fortunately, there is data from the military, which uses standards similar to NASA. Three references, all of which focus on 'black box' components, are discussed next.

MIL-STD-810E[4] entitled "Environmental Test Methods and Engineering Guidelines" suggests that 5-10 minutes of testing at MEFL should be used for stress screening/defect screening. In this way, 75% of defects found. This is equivalent to 75-150 seconds at MEFL+3dB

NAVMAT P-9492[5] entitled "Navy Manufacturing Screening Program" claims that 80% of workmanship defects are in black-boxes. Therefore, workmanship screening focuses on components. This reference states that 5 minutes at a level similar to that of MIL-HDBK-340A minimum component levels is the duration that is maximally efficient at uncovering defects without excessive wear (see Figure 4.2). This is equivalent to 75 seconds at MIL-HDBK-340A + 3dB.

RADCTR-86-149[6] entitled "Environmental Stress Screening" uses a huge database of military hardware failures in the field to determine that 15 minutes at MIL-HDBK-340A minimum levels uncovers 75% of defects. This is equivalent to 225 seconds at MIL-HDBK-340A + 3dB. While the database size of this study is significant, it is not as controlled as the NAVMAT study.

Based on the above studies, a duration of 75 seconds was selected for maximum efficiency in protoflight testing. This assumes the curves in Figure 4.2 as minimum levels for component testing. This assumes the Pegasus MEFL+3dB curve for spacecraft level testing (Figure 4.1). The justification for this last point is made through analogy to MIL-HDBK-340A. As shown in Figure 4.2, the NAVMAT and MIL-HDBK-340A component levels are similar. While the NAVMAT paper does not list a spacecraft level specification, MIL-HDBK-340A does. It is assumed that the MIL-HDBK-340A minimum spacecraft levels and minimum component levels are consistent. Therefore, 75 seconds at the MIL-HDBK-340A minimum spacecraft level is best for environmental stress screening. Figure 4.3 shows that the Pegasus MEFL+3dB levels are similar to the MIL-HDBK-340A minimum levels. Therefore, 75 seconds at the Pegasus MEFL+3dB is the spacecraft protoflight qualification duration.

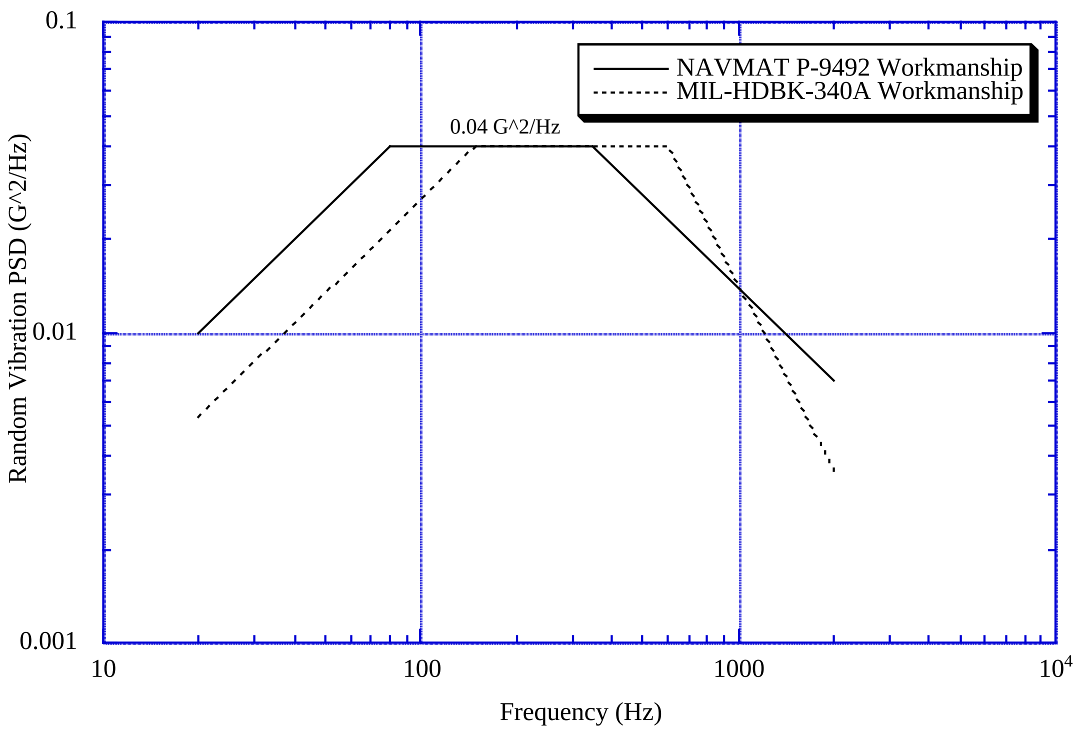


Figure 4.2: Comparison of the NAVMAT optimal screening level versus the MIL-HDBK-340A minimum component level. Both curves are 6.1 g's RMS.

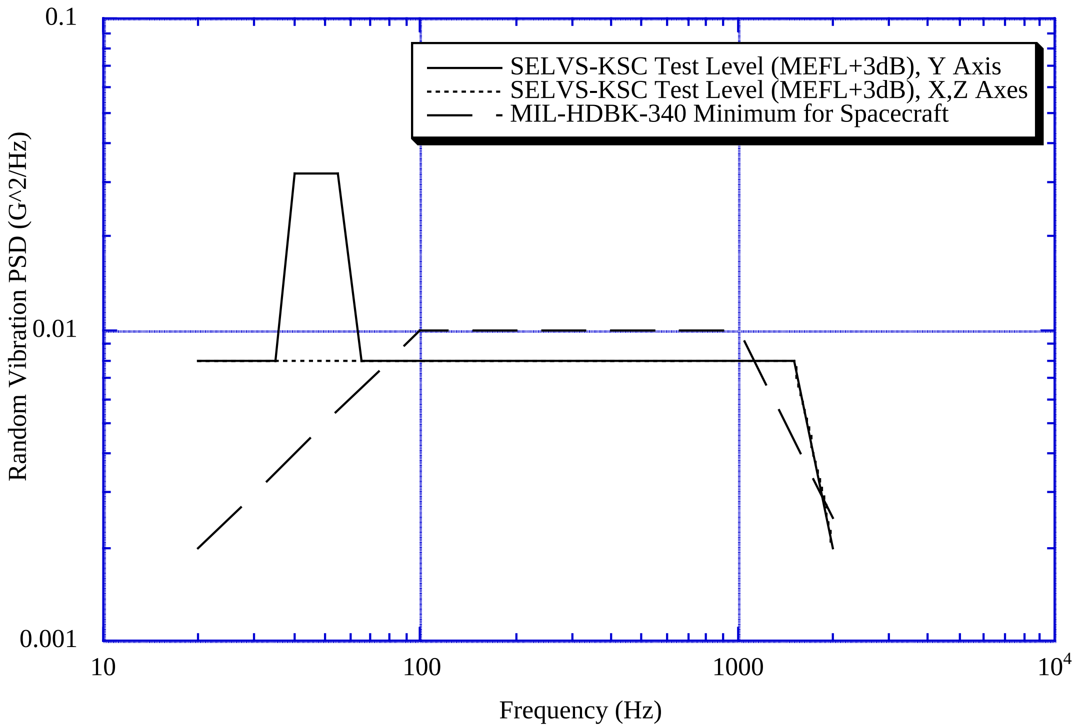


Figure 4.3: Comparison of the MIL-HDBK-340A minimum spacecraft test level versus the Pegasus MEFL+3dB test level. Both curves are 3.8 g's RMS.

It must be noted that the 75 second duration deviates from the NASA standard of 60 seconds for protoflight hardware. This is appropriate since the NASA standard is based on ground launched vehicles which see their maximum environment for a few seconds. Also, the NASA standard is intended to show the spacecraft the full environment with margin. This is not the intent in the wear driven Pegasus environment.

Finally, it must be noted that the data that exists and is referenced above all relates to 'black boxes', not structure. As noted in the NAVMAT study, 80% of defects are in the black boxes. Also, fatigue equivalence durations are much shorter than wear equivalence durations. Therefore, the choice of 75 seconds based on black boxes is appropriate for all hardware.

## 4.5 Examples of Test Durations

Example 1: VAFB launch and Any Campaign

The project should design for one abort and then a successful launch
= 1 aborted launch attempt + 1 successful launch attempt
= 32 + 25 = 57 sec < 120 sec
Therefore: Prototype duration = 120 seconds
Protoflight duration = 75 seconds

Example 2: KSC Ferry Mission

The project should design for ferry VAFB to KSC, 1 abort, ferry KSC to VAFB, ferry VAFB to KSC, 1 abort, and a successful launch.

= 2 aborts + 2 6-hr ferry's + 1 5-hr ferry + 1 successful launch
= 2*32 + 2*(22+12*5.33) + (22+12*4.33) + 25 = 64 + 172 + 74 + 25 = 335 sec

Therefore: Prototype duration = 335 seconds ~ 5.5 minutes
Protoflight duration = 75 seconds

Example 3: KMR Ferry Mission

The project should design for ferry VAFB to KMR, 1 abort, ferry KMR to VAFB, ferry VAFB to KMR, 1 abort, and a successful launch.

= 2 aborts + 2 11-hr split ferry's + 1 10-hr split ferry + 1 successful launch
= 2*32 + 2*(22+12*4.33+22+12*5.33) + (22+12*4.33+22+12*4.33) + 25
= 64 + 320 + 148 + 25 = 557 sec

Therefore: Prototype duration = 557 seconds ~ 9 minutes
Protoflight duration = 75 seconds

# 5.0 Summary and Conclusions

A new random vibration qualification test duration has been developed, as a function of mission profile, for spacecraft launched on a Pegasus. Mission design scenarios have been identified. Prototype and protoflight hardware has been addressed. The new specification is flexible for the various mission profiles available to the Pegasus launch vehicle. The flexibility of the new specification does not penalize simple campaign missions and it does not under-test complex ferry missions.

Changes to mission timelines (such as launch recycle), standard flight profile, or the external configuration of the Pegasus or the L-1011 (such as a vent stack) will need to be studied for a mission unique qualification requirement.

# 6.0 References


1. Orbital Sciences Corporation, "Small Expendable Launch Vehicle Services (SELVS) Kennedy Space Center (KSC) Performance Requirements and Capabilities", NAS10-99005, January 20, 1999.
2. Orbital Sciences Corporation, "Pegasus User's Guide", September 1998.
3. NASA, "Payload Vibroacoustic Test Criteria", NASA-STD-7001, June 21, 1996.
4. Department of Defense, "Environmental Test Methods and Engineering Guidelines", MIL-STD-810E, July 14, 1989.
5. Department of the Navy, "Navy Manufacturing Screening Program", NAVMAT P-9492, May 1979.
6. Rome Air Development Center, "Environmental Stress Screening", RADC-TR-86-149, September, 1986.