The Importance and Challenge of Launch Environment Testing

A Senior Project

presented to

The Faculty of the Aerospace Engineering Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

Of the Requirements for the Degree

Bachelor of Science

By Christina Diaz

March 2012

The Importance and Challenge of Launch Environment Testing

Christina Diaz[1]
California Polytechnic State University, San Luis Obispo, CA, 93407

This report discusses the purpose and effect of environmental testing, particularly vibration, shock and acoustic tests, in the aerospace industry. Vibration, shock, and acoustic testing are methods of that are used to quantify and analyze the physical phenomenon of the launch environment on a payload or launch vehicle. The importance of innovation in testing and understanding of failures is crucial to a successful spacecraft mission. The advancement and precision of these testing methods is also explored in this report such as the invention of the 6 Degree of Freedom (DoF) vibration table and solutions to data acquisition issues recently discovered in the industry. A detailed overview of how standards particularly MIL-STD-810 have provided uniformity in the industry will also be discussed.

I. Introduction

ENVIROMENTAL testing has always been a necessity in regards to the survivability and reliability of space systems[1]. The lift and ascent environments during the launch phase of the mission dictate the structural design, as well as the intense thermal and operation requirements that may affect the payload and other mission critical equipment[2]. This environment poses great driving factors in a mission's architecture and must be considered. Since the launch of Sputnik in 1957, several satellites and launch vehicles have been subjected to the often unknown factors of the launch environment[1]. A true mission success can only be derived from accurate and methodical testing to prepare and ensure designers that the space system will be able to withstand such an environment. The goal of this senior project is to understand the reasons for each step of that process as well as bring together the importance of launch environmental testing and the challenges that spacecraft designers face in the extensive preflight tests encompassing acoustic, shock, and vibration environments.

II. Background

A. Launch Environment

Among all the space environments, the most treacherous is that of the launch environment[1]. Reaching loads of up to 20 g's, payloads and launch vehicles are required to be able to withstand over a 90 second window of multi-axial forces and pressures[1]. The launch environment spans from ground to 80 km, where most people acknowledge that our atmosphere ends and space begins, also known as the Karman Line. The launch environment is responsible for the most hazardous times of space mission, launch and reentry. Because of high speeds, altitudes, and pressures, molecules in the air behave violently[1]. Vibrations, shock, and acoustics are factors engineers must consider when designing and testing for mission success.

Loads, both static and dynamic, drive the structure of the payload. Loads can be aerodynamic or completely dependent on the acceleration and vibration[1]. It is a function of the total pressure placed on the launch vehicle (LV) moving through the Earth's atmosphere at a certain speed. This relationship between altitude and velocity of the ascent trajectory determine the pressure on the LV. Steady-state and dynamic loads are measured in g levels, or a factor of 9.806 m/s^2, the gravitational pull of the Earth. Designers must consider the axial and lateral g values in order to design the payload to survive the sum of steady state and dynamic accelerations in the axial and lateral directions[1].

When dealing with shock, pyrotechnics are sometimes used to separate the LV from the spacecraft or to deploy a certain component of the payload, for instance explosive bolts[5]. This event creates a shock wave that transmits throughout the entire structure. As with loads, it is measured in orders of g's and natural frequency, Hz[5].

The acoustic environment, another important factor to consider, is a function of the physical configuration of the launch vehicle, acceleration time history, and the configuration of the propulsion system[1]. Another source of

---

[1] Student, Aerospace Engineering, 6071 E Belen St. Long Beach 90815, and AIAA student member.

dynamic pressures and loading is derived from the intense acoustic pressure created by the mixing of exhaust gas with the ambient atmosphere[2]. Acoustic pressure begins when the main engine is ignited and usually lasts no longer than 10 seconds. The acoustic pressure created by the turbulent mixing of pressures creates a sound wave that is reflected onto the launch vehicle[2]. The magnitude of that reflected pressure varies on various factors from the engine thrust velocity to the LV's structural makeup. Once in flight, the LV 's speed will be increasing each second. At some point, the relative velocity between the vehicle and ambient environment create once again, turbulent pressures around the vehicle. This also must be considered.

B. Qualification Testing of Space Hardware

Flight hardware and systems are qualified through a series of environmental and operational tests that expose units to environments and scenarios that will be encountered in its lifetime[9]. This testing is a requirement for not only the whole spacecraft system, but also every individual part such as boom structures, electronic components, and space thruster motors. Engineers involved in the development of spacecraft need to understand the critical aspect of surviving certain environments. This time and cost often dictates a programs cost and schedule, which is made efficient through a global supply chain[9]. First governing program documents are often reviewed to determine which environmental tests will need to be conducted as well as verification and deployment tests[9]. With that, designs are developed to carry out the given tests with drawings, equipment specifications, software development plans, and ground support equipment. The units are then manufactured and assembled with component level hardware tested first. After integration, the spacecraft level test is performed as well as the evaluation of interface compatibility across subsystems[9]. After the system tests and evaluation tests are performed, the spacecraft is shipped to the launch site. Figure (1) depicts general spacecraft integration and testing flow.

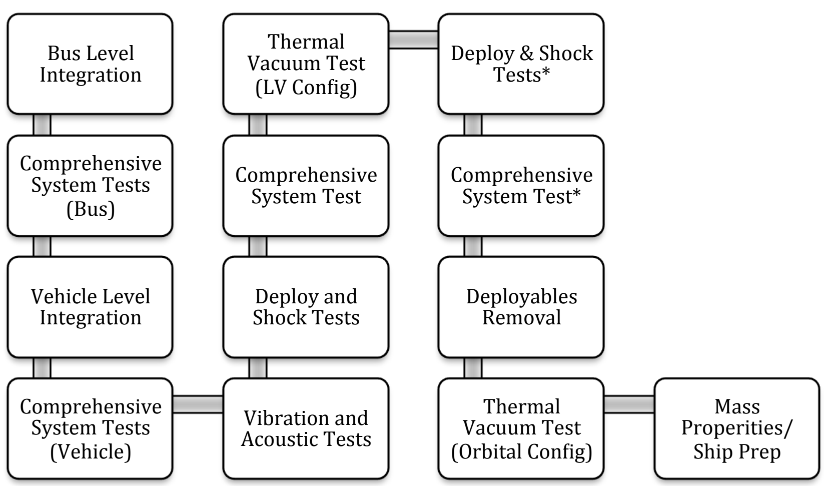

Figure 1: A typical spacecraft integration and testing flow diagram is shown. (* if required)[9]

As it is made clear in the figure above, all testing operations must be performed with quality and control. Everything is documented according to standard test procedures and the results of each step must reviewed before continuing along the flow down.

C. Vibration Testing

Vibration testing allows engineers to consider the vibratory displacements in a system due to various external and internal environments. It is accomplished by introducing an oscillatory force into a structure usually with a shaker. There are two typical vibration tests performed: random and sinusoidal[1]. Sinusoidal tests allow for one frequency to be tested at a time on a system, which is usually designed to examine the response of the test subject[3]. Random tests allow for multiple frequencies to be tested at a time, which is generally considered to replicate a more lifelike environment[1]. Usually vibration tests are run one axis at a time, in other words; only one axis of the structure is conducted despite most vibrations happening multi-axially. Figure 2 shows an example of a typical result from vibration test.

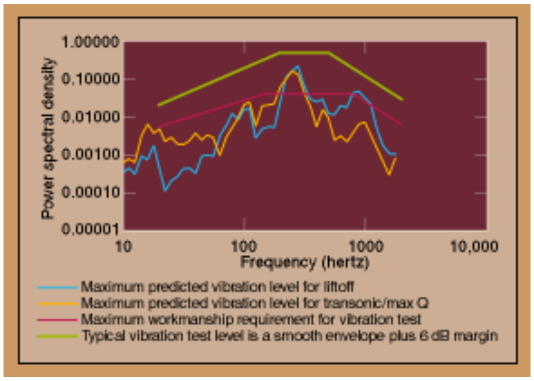

Figure 2: Typical vibration tests are plotted against frequency and power spectral density (PSD). PSD is how much power or signal is being derived from a specific frequency.[2]

As aforementioned, sine tests are used for the examination of the unit by looking at one specific frequency at a time. Low-level sine tests are usually performed before and after to look for performance changes in the unit under test (UUT). Performance changes could include frequency shifts or amplitude changes which would signify to the engineer and analysis that there is a change in the unit. A sine burst test tests the UUT for quasi-static loads to verify the strength of the structure. With these tests, limits are usually setup against a design margin, which is provided to the test engineer by the dynamic analyst as a precaution.

D. Shock Testing

The purpose of shock testing is to allow engineers to quantize peak shock amplitudes in m/s^2 or g units. Usually having done so, engineers can now appropriately check their model and make legitimate decisions. Often, testing for just amplitude does not give accurate description to the damage potential on the unit[4]. With this in mind, frequency, shape, and duration of the shock pulse are also considered.

The basic concept behind a shock test is to introduce a transient physical excitation into a system. Often, especially in the aerospace industry, the shock response spectrum (SRS) is used to analyze a shock test. The SRS is a graphical representation of a transient acceleration input relative to how a single degree of freedom (SDOF) system would respond to such input[4]. SRS does not necessarily describe the shock pulse; however, it describes the effect of the pulse on a series of SDOFs, which can indicate the shock's potential for damage[4]. Figure 3 shows the results of a typical shock test.

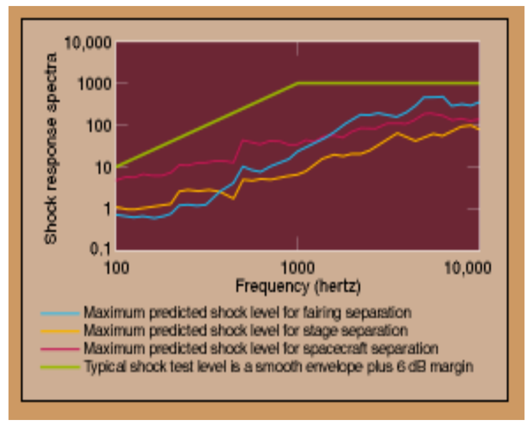

Figure 3: Results of a typical shock test look similar to this in that they are usually plotted in frequency vs. SRS[2].

Another way test engineers and analysts examine a shock response is through reviewing the time history of the shock response which is shown in Figure 4. Usually measured acceleration time histories are used to derive shock test requirements as well as other issues that may arise in testing, such as a loose component or errors in data acquisition[2].

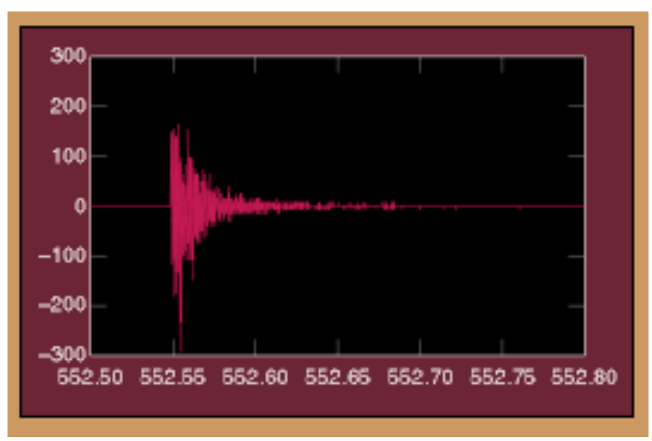

Figure 4: A typical acceleration time history is shown above. Note that it is visible to see the initial shock pulse, which then dampens, as time progresses in the graph[2].

E. Acoustic Testing

The goal of acoustic testing is to simulate the acoustic pressures expected during liftoff and ascent mission phases. Several components in both the launch vehicle and payload are sensitive to acoustic noise and must be testing to sure that any defects or failures are screened before system integration[2]. In a typical test, the hardware is placed in an acoustic chamber that has thick walls and a smooth interior surface that permits echoing. Loudspeakers are also positioned throughout the chamber, which will supply the needed acoustic energy while microphones will record and control the acoustic levels in the room[2]. Accelerometers will also be placed to detect vibration or motion in any of the critical components being tested. The results of the test will then be acquired and reviewed to see if they compare to the specifications of the dynamic analysts in order to assess their

qualification for flight. Figure 5 gives a typical acoustic test result, which as shown is plotted against 1/3 octave frequency, usually in Hertz, and sound pressure level, usually in decibels[2]. Due to the presence of accelerometers on the test article, low-level acoustic runs are also performed as a baseline calibration similar to the low level sine sweep in vibration tests. These tests give test conductors and analysts a comparison of runs, which make looking for frequency and amplitude shifts easier.

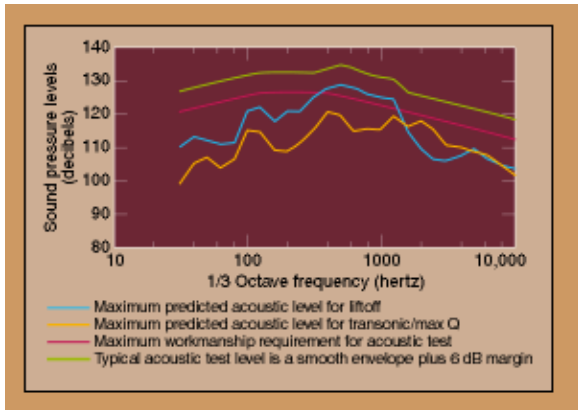

Figure 5: Typical acoustic test result shows the various acoustic levels for different mission and test phases. Note the frequency typically ranges from 30 to 10,000 Hertz[2].

III. Current Testing Methods

In order to provide uniformity for departments and agencies working with the United States Department of Defense, the United States Military Standard was created, specifically MIL-STD-810, also known as "Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests". This military standard specifies equipment's environmental design and testing limits to similar conditions it will experience in service. Also, the standards establish specific test methods that recreate the environmental effects the test item will experience. Despite it being mainly for military and government applications, MIL-STD-810 has been applied for commercial purposes as well. In terms of spacecraft and the dynamic launch environment, MIL-STD-810G, the newest update to the standard, addresses vibration, shock and acoustic tests criteria.

The standard is split into three main sections tailored with overall uniformity in mind. Part one describes management, engineering, and other technical roles in design and the environmental testing process. Part two describes specific testing methods and guidelines, however, they are not applied as strict routines that cannot be altered; however, some methods have established limits. The goal of part two of MIL-STD-810G is to generate the more accurate, realistic testing data possible. Lastly, the standard concludes with a plethora of realistic considerations that can assist in developing material that will perform reliably under environmental conditions in the areas of intended use.

IV. Innovations and Challenges in the Industry

The testing world moves forward as innovations are created and challenges are conquered. The following section discusses a few examples of the innovations and challenges that have been met throughout the years. The most important thing to note is that these innovations and challenges have propelled the testing world towards a unifying goal of simulating realistic lifetime conditions as efficiently and accurately as possible.

A. Development of the Simultaneous Multiaxis Vibration Table

Among one of the greatest difficulties in accounting for the vibration environment present during launch is the ability to account for multi-axial loads encountering the launch vehicle and payload. On a traditional vibration testing, only one axis can be tested at a time; however realistically speaking, vibration loads are happening simultaneous at launch. In order to account for this multiple degree of freedom systems had to have been design and created to appropriate test for this. Also, being able to supply the correct loads and being able to acquire data has been updated over the years.

Specifically the world of vibration tested began with mechanical shakers that were used for short stroke, nominal sinusoidal shaking as shown in Figure 6.[6] Frequencies were tested one at a time from 50 to 60 Hz[6]. In the 1950s,

testing standards specified three tests in the x, y, and z directions.[6] Interestingly enough even in today's industry, single axis tests are still performed, despite its underrepresentation of the real world environment.

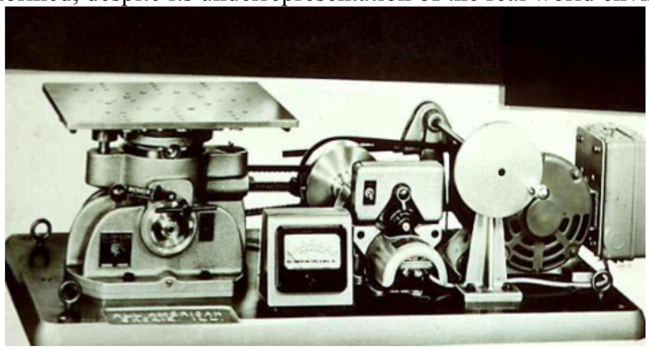

Figure 6: An example of an All-American direct drive mechanical shaker is shown above.[6]

As the number of failures increased, the development of a longer stroke, electrohydraulic shaker was developed. Also, simulating other hardware required testing at higher frequencies, commonly 2000 Hz, led to the development of today's electrodynamic shakers as shown in Figure 7.[6]

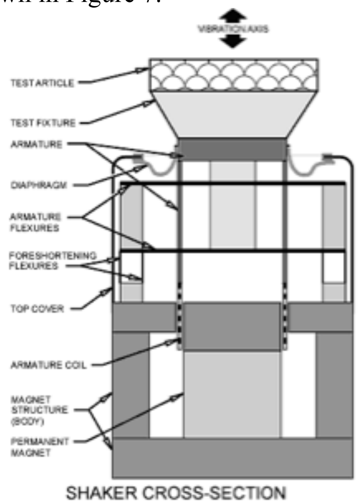

Figure 7: Typical components of an electrodynamic vibration shaker are shown above.[6]

Because the still progressive failure rate, researchers believed simultaneous multiaxis testing would be effective. According to Wayne Tustin of the Equipment Reliability Institute in Santa Barbara, California, MIL-STD-810G will be able to better define dynamic testing by accounting for much more realistic testing environment.[6]

Essentially, by being able to analyze flight hardware or engineering models on a more realistic platform, engineers would be able to create a much more dynamic, accurate testing environment to ensure higher reliability and performance.

B. Data Acquisition Challenges and Successes

Perhaps one of the most interesting errors in testing history was an issue that had occurred at an Independent Test Facility (ITF) that alerted several major aerospace companies of a data system issue. The Space Quality Improvement Council (SQIC) sponsored by Aerospace Corporation had been issued an alert by the ITF that there was a potential error of under testing parts, including flight hardware, caused by the data acquisition system settings the ITF had used for a pyro-shock testing[7]. The upset led to a series of investigations by a Tiger Team, whose goals were to assess how much the incident had affected parts, mitigate any immediate consequences, understand and control the cause, as well as insure this would not happen again[7]. From the results, it was found there was a potential under test due to aliasing. Aliasing is caused by an improper sample rate for signal content during digital acquisition. The original test setup that the ITF had used was a sample rate of 250,000 samples per second with a default two-pole filter at 100,000 Hertz[7]. There was an optional 20 KHz filter that was available; however, it

was not used. In order to see how much the hardware was under tested mass models were used and simultaneously from the original test set up a retest setup was used with an external 20 KHz six pole filter on a 16 bit data system[7]. The sampling rate was 250,000 samples per second. Figure 8 and 9 show similar results of what the Tiger Team saw.

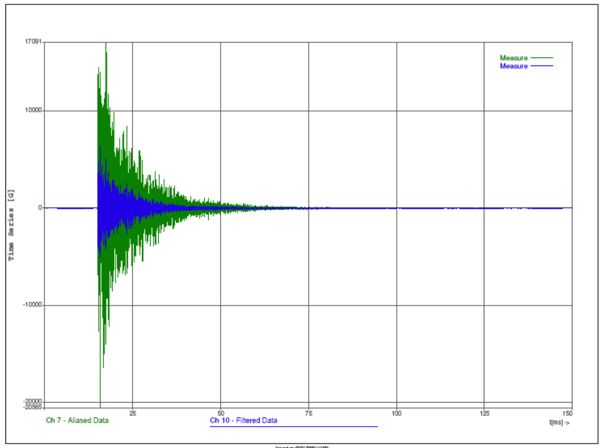

Figure 8: A comparison of the time history of the original test set up and retest setup.[7]

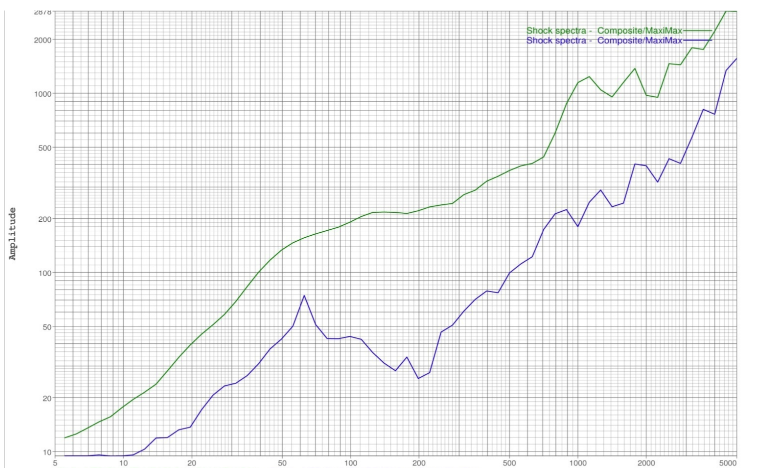

Figure 9: A comparison of the original and retest[7]

In retrospect, this event was a serious significant under test of various components which could have caused catastrophic effects. Despite this setback, the aerospace industry has seamlessly moved from analog data acquisition systems to digital acquisitions system. Before tape decks were used to record tests with the issue that tape desks could only hold so much data and thus need to be replaced or rerecorded. Now, digital systems are used which have become the center of processes and validation prior before running a test. Software such as M+P has been developed to automate what used to be done in the analog world. Financially, digital acquisitions systems have saved testing centers significant amount in costs as well as removing the human element of the testing process. In the industry, time is money and as facilities are driven to meet demanding test schedules, digital data acquisition systems help tremendously.

C. Energy Based Measurements for Shock Testing

Another current development in the realm of shock testing is using energy-based parameters to characterize the shock environment of a unit. A consideration in the shock-testing world is that the aerospace industry does not place as much precedence on funding for shock as the seismic, geotechnical world. Sandia National Laboratory began to investigate and implement the ideas in the geotechnical world to address and correct limitations they found with using solely SRS as a form of shock environment representation[8]. According to Sandia, the SRS has been widely used in industry however it is equally faced with various issues. Energy metrics, as Sandia research, was a

way of modeling the probabilistic risk of a unit in that environment. The technical foundation of energy metrics is that they offer better physical significance in terms of failure criteria and a better mathematical model. It also allows for clearly frequency resolution and it has been found to have a direct connection to the engineering damage parameters that could be used to simulate the structural response of the unit. With that being said, energy based metrics are not a perfect science, but rather another alternative to quantifying dynamics of a system. It also allows for the incorporation of uncertainties as well as a way to assess and quantify multi-axis environments, which would yield a more realistic response. In other words, energy metrics are another way of looking at the data.

Energy metrics are derived from a base-excited system such as a mass and damper system. The relative coordinate frame is defined and an equivalent system is creased now with the force excited. Work of the system is then calculated then with further analysis the final equation is

With further research, energy metrics is derived as,

$$\frac{m\dot{z}^2}{2} + \int c\dot{z}^2\,dt + \int f_s\dot{z}\,dt = -\int m\ddot{x}\dot{z}\,dt \tag{1}$$

where this can be easily seen as the general energy balance of the system. This applies to any base excitation system and note solely a shock response system. With this energy balance, relative energies of both single degree of freedom and multiple degree of freedom systems can be found. Also using an absolutely coordinate system, absolute energies include general rigid body dynamic motion and only consider deformation of the system, which is desirable in the shock world. Energy metrics can also be normalized for mass and plotted against frequency, similar to the typical SRS plot as shown in Figure 10.

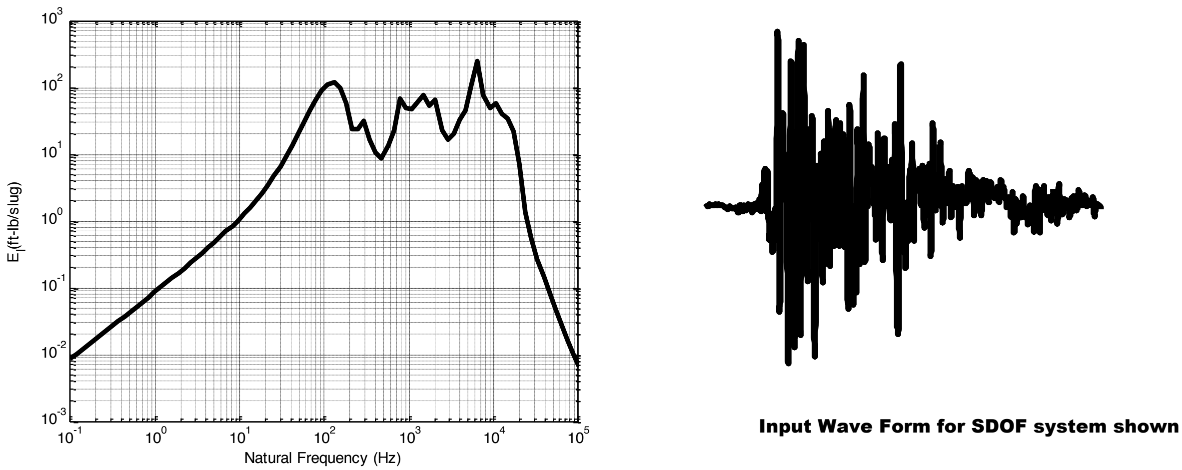

Figure 10: A typical input energy spectrum is shown, mass normalized for a single degree of freedom system. According to Sandia National Laboratory, they used input energy spectra as the basis for their shock waveform synthesis.

Using energy metrics and their fundamental purpose above, it is clear to see that it another innovative way to look and approach a dynamic system. With further research and implementation, energy metrics and input energy spectrum plots are another plausible form of verification and validation for shock testing.

D. Importance of Innovation and Challenges

Innovation and challenges created and faced bring the necessary change to restructure the testing world and provide new insight to the spacecraft design process. With the current state of the aerospace industry, innovations and challenges can in fact help industry reach low-cost, efficient, reliable solutions to better test spacecraft and flight components. With that being said, these challenges and successes bring together lessons learned.

V. Lessons Learned

Throughout the development of testing, lessons have been learned with innovation and failure. From the examples shown in this paper and the development and update of MIL-STD-810, it is clear to see the importance of uniformity, but most importantly, adaptation to new testing methods and solutions. Speaking specifically about the data acquisitions problems that happened in the industry, it is clear to see how issues such as cost, reliability, and

mission assurance can be compromised easily with bad testing methods or even carelessness. Interestingly enough, MIL-STD-810 does not include guidelines on data acquisition issues that may arise such as aliasing and misleading test results. As technology improves, reliance on computer and data systems becomes stronger and stronger. With that being said, MIL-STD-810 will eventually need to include the issues that engineers and technicians can run into when testing.

From observations at a testing facility, it is important to note the importance of not overlooking quality and understanding the roles and responsibilities of each person. For several instances, the issue is in fact, not technical, but rather stemmed from miscommunication and poor group dynamic. It is key to hold test briefings before conducting a test so everyone is on par with who is responsible for what and to address safety concerns. It is also important that each engineer and technician do not overlook the personal quality of his or her work. Various test facilities place importance on making sure every discipline is represented during a test such as program management, systems engineering, manufacturing, and quality assurance.

In terms of actual flow down, technical overviews, engineering models, processes, and requirements drive environmental testing. Technical overviews, or rather proposals, preliminary deign review, critical design review and floor pre-test briefings allow for clarity and understanding of the testing scenario and design itself. Pre-test briefings also allow for understanding of the testing requirements as dictated by the analyst and MIL-STD. It allows for engineers and technicians to interpret and understand what is expected from the test. Engineering models allow engineers to understand the structural response as well as other parameters prior to actually doing a flight hardware test. This allows for design flaws to be pointed out relatively early to avoid time delays or even unaccounted expenses. Prior to testing, it also crucial the measurement system and sensors are validated and calibrated for accuracy, precisions, sample rate, and system performance. Failure to do so can confound a test and cause for serious implications in scheduling. Sensors become the fundamental part of testing in that it is crucial for accelerometers, cables, and channels for example to be as accurate as possible to allow for real accurate data.

Most importantly though, with what was aforementioned, the follow through and documentation of a test is crucial to testing efficiency and success. Tests should follow the test procedure in order to demonstrate the unit or spacecraft with behave accordingly during its lifetime. On top of this comes the requirement to review and interpret the test results thoroughly. With this, roles and responsibilities of the measurement engineer and dynamics engineer come into play. It is their responsibility to review the data and compare the results to the theoretical finite element model. With this verification, the production of a test report with fully document the testing of the unit and ultimately the system. Any deviations from the initial sequence should be documented thoroughly as well.

VI. Conclusion

The importance of environmental testing is clear. Testing allows a deeper understanding of a unit or spacecraft's operational life as well as issues that may be encountered. Testing also helps spacecraft designers and operators to thoroughly understand not only the reliability of the system, but its efficiency. With the concept of "test like you fly," environmental testing solidifies the understanding of the launch environment from unit to unit. Because of the importance of this simulation, developments and changes are being made to create a more realistic test environment. With these challenges and innovations, a deeper understanding of the space and launch environment will follow as well as the development of more reliable, qualified units and spacecraft.

Among one of the most obvious benefits of testing is the financial aspect. Environmental testing allows for the ability to understand a unit's performance before launch and if the performance is not as expected, mitigation and redesign can occur. Despite the possibility of redesign or extra mitigation costing money, it is significantly less than having a mission or unit fail once in orbit. Because of this substantial benefit, innovation and exponential progress has been made in the testing world to allow for a more realistic testing platform. From moving to a digital data philosophy to rethinking how parameters are measured, environmental testing will continue to grow and help make stronger, more efficient, longer lasting, and higher performing spacecraft in the aerospace industry.

Acknowledgements

The author would like to thank Northrop Grumman Aerospace Systems for the opportunity to work in the environmental test facility Summer 2011. The author would also like to thank the entire Northrop Grumman Aerospace Systems environmental testing and measurements team for helping her learn the fundamentals and importance of testing in the aerospace industry. The author would also like to recognize and thank Andy Pokk, Terry Barone, and Kyle Hinkle for their guidance on writing this senior project.

References

[1] Tribble, Alan C. *The Space Environment: Implications for Spacecraft Design*. Princeton, NJ: Princeton UP, 1995. Print.

[2] "Environmental Testing for Launch and Space Vehicles." *The Aerospace Corporation*. Web. 31 Oct. 2011. <http://www.aero.org/publications/crosslink/fall2005/02.html>.

[3] "Deep Space 1: Vibration Qualification Testing." *Vibration Testing, Dynamic Signal Analysis and Measurement Data Acquisition: M+P International*. Web. 31 Oct. 2011. <http://www.mpihome.com>.

[4] Irvine, Tom. "SRS Tutorial." *Vibration Data*. Web. 31 Oct. 2011. <http://www.vibrationdata.com/>.

[5] Hughes, William, and Anne McNelis. "Pyroshock Environments Characterized for Spacecraft Missions: Hughes, William O. : Free Download & Streaming : Internet Archive." *NASA Technical Documents Archive*. NASA. Web. 31 Oct. 2011. <http://www.archive.org/details/nasa_techdoc_20050194723>.

[6] Tustin, Wayne. "MIL-STD-810G Will Better Define Dynamic Tests." Equipment Reliability Institute, Santa Barbara, California. *2007 Spacecraft and Launch Vehicle Dynamic Environments Workshop*.

[7] Hoan, Chuck. "Pyro-shock Aliasing Issues with Outside Lab." *Northrop Grumman Aerospace Systems*, 2011.

[8] Edwards, Tim. "Energy Based Metrics for Characterizing Shock Environments." Sandia National Laboratory, NISA, 2011.

[9] Lee, Daniel. "Integration and Test." *Space Mission Engineering: The New SMAD*. By James Richard. Wertz, David F. Everett, and Jeffery John. Puschell. Hawthorne, CA: Microcosm, 2011. Print.