DRAFT

Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-61-TM–xx October 2014

Survivability, Structures, and Materials Department

Technical Memorandum

Shock and Drop Testing of Large Format Lithium Batteries

by

Alex Askari, Paul Jawlik

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Administrative Information

The work described in this report was performed by the Materials and Power Systems Branch (Code 616) of the Naval Surface Warfare Center, Carderock Division (NSWCCD). The work was funded by US Department of Transportation to study the dynamic loads experienced by large format batteries during transportation and evaluate whether the current UN/DOT 38.3 T4 shock test accurately represents transportation mechanical environments.

Summary

Under the sponsorship of US Department of Transportation, the Materials and Power Systems Branch, Code 616, of the Naval Surface Warfare Center Carderock Division was tasked to study the dynamic loads experienced by large format batteries during transportation and evaluate whether the current UN/DOT 38.3 T4 shock test accurately represents transportation mechanical environments. If the study found the current test not to be valid, code 616 was also tasked to propose criteria and methods for conducting shock test on large format batteries.

In this study, the effectiveness of the current UN/DOT 38.3 T4 shock test to replicate the dynamic forces experienced by lithium batteries during the course of transportation was investigated. It was determined that the fixed acceleration and pulse duration parameters defined in the test could induce responses in test items that are not representative of abuse conditions during transportation.

Next, the transportation mechanical environments were studied through the data that have been compiled from established sources within the NATO countries. These data are summarized the in Allied Environmental Conditions and Test Publications 200 (AECTP 200). The data collected in the AECTP 200 showed that the most severe shocks experienced by packages occur during mishandling scenarios mainly during drop events. Therefore, Procedure IV (Transit Drop) of MIL-STD-810G, Method 516.6 was recommended as a replacement test for the current T4 shock test.

The third phase of this study investigated data that had been collected by academia and industry on drop heights recorded for various packages during transportation. The goal was to compare the results with that of MIL-STD-810G. Reviewing these results showed that only a few studies have examined drop heights experienced by packages larger than 25 lbs. Furthermore, these studies indicated that the drop height suggested in MILD-STD-810G for objects less than 100 lb with their largest dimension less than 36” only simulates worst case scenarios. No conclusion can be drawn for other drop heights listed in MIL-STD-810G as very few independent studies have looked at objects heavier than 100lb.

The final phase of this study examined the shock profiles experienced by a large format lithium battery (35 lbs) when dropped from various heights and onto different surfaces. The intent was to record the shock profiles and compare them to profiles specified in the UN/DOT 38.3 T4 shock test. Testing found that the UN/DOT shock profiles could be recreated by setting the drop height to 11” and the drop surface to 2” of plywood, 2 rubber mats, and 1” foam. Additionally, the maximum inputted acceleration increased well above the maximum of the UN/DOT profile as drop height increased and drop-surfaces were made more rigid. The range of transmitted shock frequencies also expanded well beyond the UN/DOT profile as drop height

increased and drop surfaces were made more rigid. It should also be noted that during all drops, including heights up to 48”, there did not appear to be any damage to the battery.

Objectives

The test T.4 (shock test) specified by the UN manual of Tests and Criteria require large format batteries to be subjected to a half-sine shock of peak acceleration of 50 g and pulse duration of 11 ms. The objectives of this study were to:

1) Study the dynamic loads experienced by large format batteries during transportation and evaluate whether the current UN/DOT 38.3 T4 shock test accurately represents transportation environments
2) If the study found the current test not to be valid, propose criteria and methods for conducting shock test on large format batteries.

Introduction and Problem Statement

Batteries during the four modes of transportation (road, rail, air, and sea) experience a variety of dynamic forces. In general, these forces can be divided into two categories. The first category covers relatively infrequent, non-repetitive shocks encountered in handling. The most severe mechanical aspects of handling are usually associated with the shocks and transients arising from rough handling, and particularly from the materiel being dropped. The second group encompasses the forces that are experienced due to vibration and repeated shocks due to road surface imperfections. These forces result in dynamic deflections of battery components. Dynamic deflections and associated velocities and accelerations may cause or contribute to structural fatigue and mechanical wear of battery components.

Mechanical shock has the potential for producing adverse effects on the physical and functional integrity of all materials. In general, the level of damage is affected by both the magnitude and the duration of the shock. The current UN/DOT 38.3 T4 shock test calls for a 50g, 11ms half sine pulse to be applied to batteries heavier than 12kg to simulate impact forces experienced during transportation. There are two deficiencies associated with this test that need to be addressed. The first problem with T4 shock test is the fixed amplitude of the test. As shown in equation (1) the estimated peak acceleration of an object dropped from height d_1 depends on the surface area (A), weight (m), and modulus (E) of that object [1]. Therefore, batteries of different sizes and weights experience a wide range of accelerations during mishandling scenarios. As a result, a fixed amplitude acceleration test does not accurately capture the forces experienced by various batteries during mishandling mainly being dropped.

$$a = \sqrt{\frac{E\,A\,g\,\mathrm{d1}}{h\,m}}$$ Equation (1)

The second issue with the T4 shock test is the fixed 11ms pulse duration defined in the test. Pulse width of transients depends on material characteristics of the impact surface and the dropped object. The effect of pulse width on the response of batteries to drop loading can be further explained by examining the shock spectrum of these loads. The force exerted on dropped objects is a half-sine force pulse with the frequency of w_0 that can be defined in terms of the unit step function by the following equation [2]:

$$f(t) = F_0 \sin(w_0\ t)\,[\,u(t) - u\left(t - \frac{\pi}{w_o}\right)]$$ Equation (2)

Where the pulse duration is $t_0 = \pi/w_0$. The corresponding spectrum of the half sine pulse can be obtained by first taking the Laplace transform of $f(t)$ and then by setting $s = j\omega$. The end product is the amplitude density spectrum of the half-sine force pulse and it is represented by G_{hs} (w):

$$G_{hs}(w) = \frac{2F_0}{w_0}\left|\frac{\cos(\frac{\pi\,w}{2\,w_0})}{1-(\frac{w}{w_0})^2}\right|$$ Equation (3)

Equation 3 is plotted in Figure 1. The graph indicates that the half-sine force pulse does not excite the object at $(w/w_0) = (2k+1)$ where k is a real number bigger than one. In other words, the spectral content of the excitation energy has periodic peaks and notches in the frequency domain. All modes that coincide with the peaks of the frequency response function (FRF) will be preferentially excited, while the modes that coincide with the notches in the excitation FRF will not be excited. It is evident from the graph below that it is possible for some of the natural frequencies of an object not to be excited, if the objected is tested at a pulse width not consistent with what it experiences during mishandling.

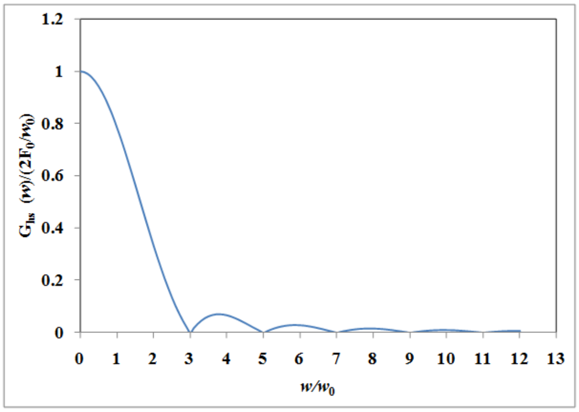

Figure 1- Amplitude Density Spectrum of Half-Sine Wave Pulse of Duration π/w_0 [2]

This report first discusses the current data and test procedures outlined in MIL-PRF-810G and supporting documents to offer an alternate test method to that of described in UN/DOT 38.3 T4 shock test. Subsequently, the studies that have been conducted by the academia and industry to characterize the transportation environment will be discussed. All the various road or vehicle related sources of excitation produce a composite of continuous (vibration) and transient (shock) motions at the payload. It should be noted that this paper only provides advice on testing procedures that simulate transient (shock) motions during transportation.

Transportation Mechanical Environments

The subsequent sections summarize the dynamic loads that may be experienced by objects during road transportation as outlined in the Allied Environmental Conditions and Test Publications 200 (AECTP200) [3] and the MIL-PRF-810G [4]. AECTP 200 describes environmental conditions and data that have been compiled from established sources within NATO countries.

Road Transportation

This section summarizes the mechanical environments, discussed in AECTP200, that may be experienced by materiel during road transportation. All the various road related sources of excitation produce at the payload a composite of continuous (vibration) and transient (shock) motions. This paper only provides recommendations on testing procedures to simulate transient (shock) motions during transportation.

Materiel Carried as Restrained Cargo:

The transients (or shocks) originating from the vehicle will originate from pot-holes and general discontinuities in the road surface. Due to the influence of the vehicle and its suspension system, the initial shock pulse will be followed by a rapid exponential decay. Even for the most severe shocks the amplitude of the response decays to insignificance within 2 or 3 cycles. The peak amplitudes of the transients appear to follow an approximately Gaussian distribution. The rate of occurrence and standard deviation will be influenced for a particular vehicle by velocity and road surface condition. Typical road surface induced transients for a 4 x 4 truck are shown in Figure 2. Responses were measured on the vehicle's load bed over the rear axle (see CATEGORY 242/1 of Reference [3]). The amplitude of transients experienced by restrained cargos is significantly lower than that likely to occur as a result of any mishandling i.e. being dropped. Therefore, for test purposes, it is reasonable to subject lithium batteries to test sceneries that simulate mishandling during transportation. These test procedures will be discussed in a separate section.

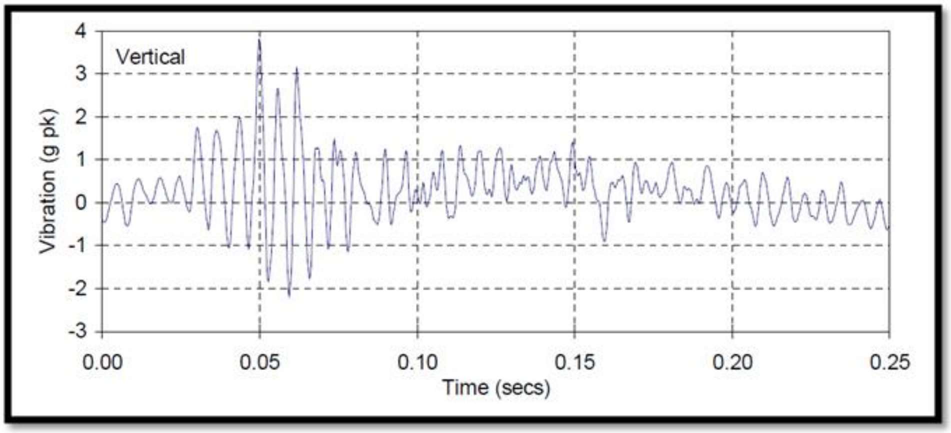

Figure 2- Transient responses experienced on a Bedford 4x4 truck on a good quality road [3]

Materiel Carried as Loose Cargo:

The motions originating from the payload bouncing on the cargo deck and jostling with neighboring cargo are usually, for test purposes, considered separately from the shocks or transients originating from the road surface. The reason for this is that the severity and characteristics of these shocks, as experienced by the payload, will be significantly different from the transients originating from the road surface. The transformation of the available kinetic energy into a shock pulse will depend upon the structural stiffness of the two impacting faces (the payload platform and the package). The stiffer the two impacting faces, the shorter duration the pulse and greater its amplitude. Typical wooden packages impacting a wood load platform may induce accelerations of around 40 g during carriage over rough roads (see CATEGORY 242/1 of Reference [3]). In general, the amplitude of the transients will be less severe than that likely to occur as a result of any mishandling i.e. being dropped. However, the payload may experience a number of such transients giving rise to possible medium cycle fatigue failure conditions.

Rail Transportation

This section addresses the mechanical environments that may be experienced by packages during rail transportation. It should be noted that the information contained in reference [3] relates mainly to payloads transported on the UK rail network. However, the ride characteristics of mainland European and North American trains are largely similar to those in the UK [3]. The dynamic environment experienced by a payload transported by rail can be considered to consist of continuous excitations that arise during motion along the track and transient excitations that mainly arise during switching operations. This report only covers the transient excitations that occur during rail transportation. With the exception of switching shocks in the longitudinal axis, the dynamic responses arising from rail transportation are generally less severe than those for road transportation (see reference [3] LEAFLET 242/2). The switching shock magnitude is dependent upon impact speed, buffering equipment characteristics and the total mass of the wagons involved. The maximum reported acceleration in reference [3] for switching operations is 15 g for traditional loose coupled wagons. The amplitude of the transients experienced during rail transportation will be less severe than that likely to occur as a result of any mishandling i.e. being dropped. Therefore, the shock test severities associated with transportation by rail are encompassed by those associated with mishandling.

Air Transportation

This section addresses the mechanical environments that may be experienced by packages during air transportation. The section considers air transportation by fixed wing jet aircraft, fixed wing propeller aircraft and rotary wing aircraft. The environments experienced by packages, when carried as a payload within transport aircraft, depend on the type of transport aircraft used, ie: whether the transport aircraft is a fixed wing jet aircraft, a fixed wing propeller aircraft or a rotary wing aircraft [3]. The dynamic excitations experienced by equipment carried as payload arise predominantly from aerodynamic sources, power plan sources, jet plume effects, propellers, and action of main rotor blades and gear boxes depending on the type of transport aircraft. The extent to which excitations may be generated by these sources depends upon the flight conditions mainly take-off, climb, cruise, and landing [3]. A variety of vibration excitations are experienced during different flight stages. However, transient excitations (shock) are only experienced during landing and can attain a two g peak in the case of fixed wing propeller aircraft. Typical landing shocks for a fixed wing propeller aircraft are shown in Figure 3. Similar to road and rail transportation, the amplitude of the transients experienced during air transportation will be less severe than that likely to occur as a result of any mishandling i.e. being dropped. Therefore, the shock test severities associated with transportation by air are encompassed by those associated with mishandling.

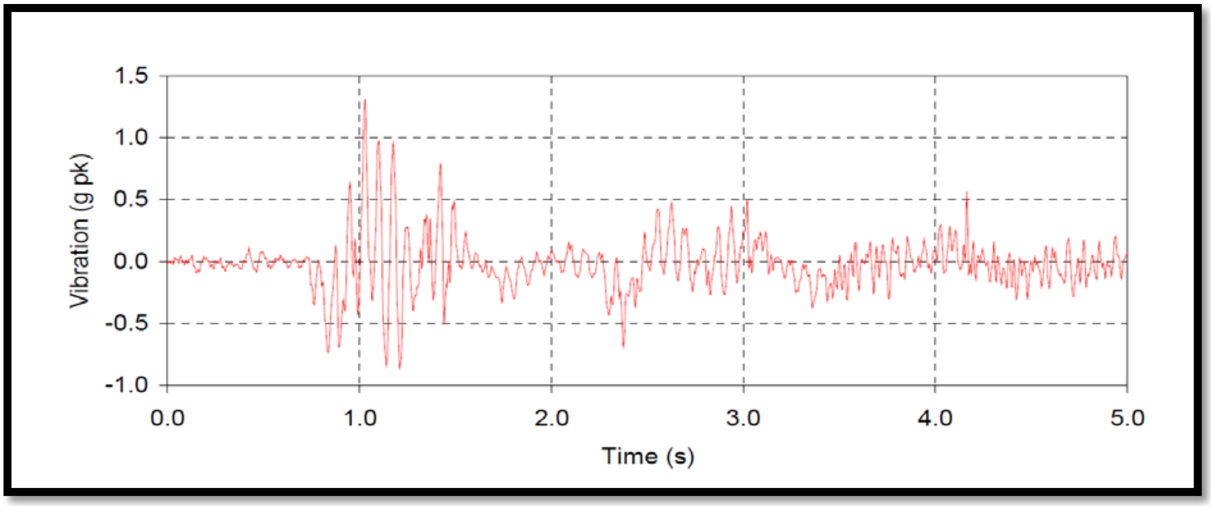

Figure 3- Propeller transport aircraft landing shock

Sea Transportation

This section addresses the mechanical environments that may be experienced by packages during sea transportation. The dynamic excitations, experienced by a payload during transportation by ship are mainly continuous vibratory motions. The continuous motions are principally vibrations arising from propulsion equipment and auxiliary machinery. However, the focus of this paper is on transients that are usually associated with adverse sea states. Higher sea states can give rise to transitory motions arising from waves impacting (or slamming) the ships' hulls. The actual payload would not experience these excitations directly but rather indirectly though the dynamic responses of the ship's hull (natural frequencies are in the 2-5 Hz region). The consequence of this is that the payload, in effect, experiences mainly quasi-static loading rather than dynamic motions. The quasi-static inertia loadings are usually of such low magnitude as not to cause any concern. In general the quasi-static loadings due to handling exceed those of sea transportation.

Handling

This section addresses the mechanical environments that packages are subjected to during handling. The most severe mechanical aspects of handling are usually associated with the shocks and transients arising from rough handling, and particularly from the materiel being dropped. Such events may cause local structural damage and internal fractures. As discussed in the preceding sections, the transients arising from rough handling are more severe than the dynamic loads experienced by packages in different modes of transportation. Considering the deficiency of the current T4 shock test in UN/DOT 38.3 manual, MIL-STD-810G drop testing is a more realistic method to simulate the dynamic loads experienced during mishandling scenarios. Procedure IV (Transit Drop) of reference [4] Method 516.6 is intended to determine if the test item is capable of withstanding shocks normally induced by loading and unloading of materiel from a transportation platform, or other elevated surface. The suggested drop heights for this test are summarized in Table 1. We recommend replacing the current T4 shock test with the transit drop test as described MIL-STD-810G.

Table 1- Transit drop test (Table 516.6-VI of MIL-STD-810G)

Weight of Test Item and Case, kg (lb)	Largest Dimension, cm (inches)	See Notes	Drop Height, cm, (inches)	Number of Drops
Under 45 (100) Manpacked or transportable	< 91 (36)	a, d	122 (48)	Drop on each face, edge, and corner. Total of 26 Drops
	≥ 91 (36)	a, d	76 (30)	
45 to 90 (100 to 200) Inclusive	< 91 (36)	a	76 (30)	Drop on each corner. Total of 8 Drops
	≥ 91 (36)	a	61 (24)	
90 to 450 (200 to 1000) Inclusive	< 91 (36)	a	61 (24)	
	91 to 152 (36 to 60)	b	61 (24)	
	> 152 (60)	b	61 (24)	
Greater than 450 (1000)	No limit	c	46 (18)	Drop on each bottom edge and bottom face or skids. Total of 5 Drops.

Drop Heights recorded by other Organizations

Over the past several decades, various organizations have examined the shock environment experienced during shipping and handling processes. Unfortunately, they have often not covered the relationship between package weight and equivalent drop height. The reasons for this are not entirely clear, but are likely due to cost: many of the studies indicated that shipping packages a statistically significant amount of times is a costly process. This cost generally increases with package weight, therefore a limited number of studies have examined package sizes larger than 25 lbs. Nevertheless, analyzing and collecting the existing data in a central document is a valuable step towards evaluating the shock environment likely to be experienced by a large format battery.

One of the earliest and most influential efforts to examine the shipping and handling environment was a U.S. Department of Agriculture report written by Ostrem and Godshall in

1979 [6]. The report, titled "An Assessment of the Common Carrier Shipping Environment", analyzed existing shock, vibration, temperature, and humidity data. Although many studies have been performed since the report, it still represents a valuable source for drop-height data. It is important to keep in mind, however, that the instrumentation used during the time of the study was inferior to that used in later decades and the data should be used with caution.

The results of the two studies covered in Ostrem and Godshell, along with the MIL-STD-810G drop height, are shown in Figure 4. The first study examined drop heights experienced by 25 lb packages and the second study drop heights experienced by 43 lb packages. For the 25 lb packages, ~95% of all drops were below the 48" MIL-STD-810G drop height (for objects weighing less than 100 lbs) demonstrating the appropriateness of the standard for this weight. The 48" height was a more aggressive value for the 43 lb packages as over 99% of drops occurred below the 48" MIL-STD-810G value. That being said, it was not unreasonably high as there were still some drops in excess of the 48".

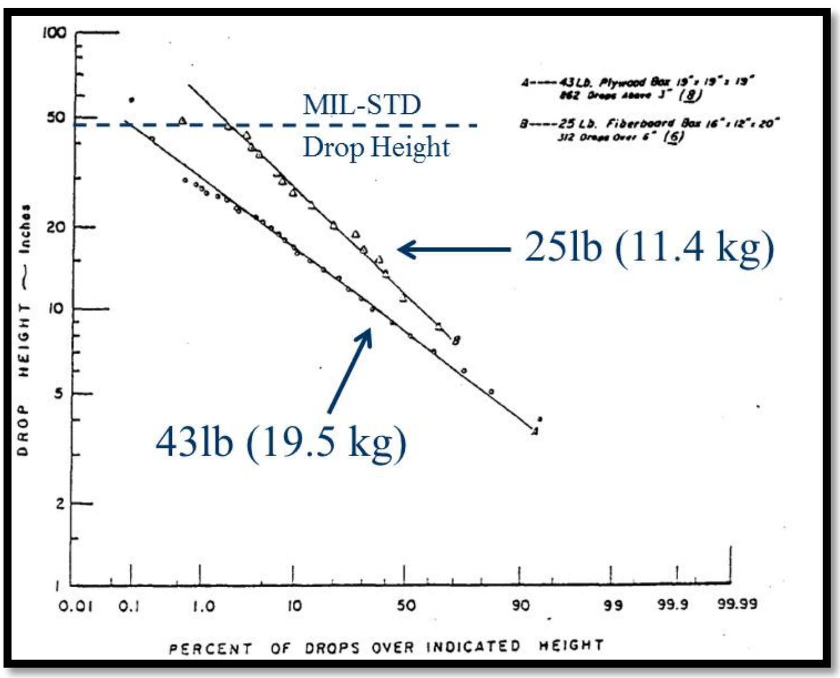

Figure 4- Percent of drops over given heights for 43 lb and 25 lb packages [6].

A later study by Singh and Voss examined the equivalent drop heights experienced by 20 lb, 30 lb, and 45 lb packages in domestic shipping environments [7]. Over 95% of all drops were below 30" for the 20 lb packages, 24" for the 30 lb packages, and 26" for the 45 lb packages. The corresponding maximum drop heights for these packages were 42", 41", and 30" respectively for the 20 lb, 30 lb, and 45 lb packages respectively. This indicates that the MIL-

STD-810G drop height may be too aggressive if the 95% drop height is used as a test parameter, but is more reasonable if the maximum drop height is considered.

In 1999, a consortium of private high-tech companies (HP, Intel, Lexmark, among others) performed the "MADE Study" (Measurement and Analysis of the Distribution Environment) [8]. This study explored the equivalent drop heights of 25 lb packages in the domestic shipping environment. The results are shown in Figure 5. The study showed that 95% of the drops were less than 22", but 0.25% of the drops were above 48".

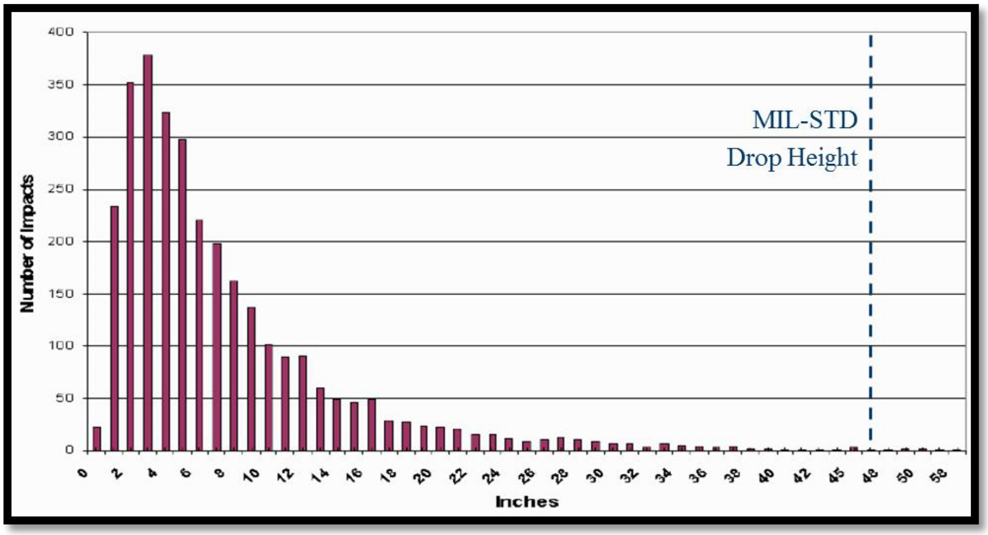

Figure 5- Number of impacts at various drop heights for a 25 lb package as recorded in the MADE Study [8]. The original graph has been modified to show the MIL-STD-810G drop height applicable to the package

In 2001, Singh et al. performed one of the few contemporary studies that examined shock experienced by heavier objects [9]. The study shipped 46 lb, 72 lb, and 140 lb packages a total of 48 times to three separate locations in the United States. All shipments were made by ground delivery. They found that 95% of all drops were below 34", 32", and 22" for the 46 lb, 72 lb, and 140 lb packages respectively. These values, along with the applicable MIL-STD-810G drop heights, are summarized in Table 2. Note that the MIL-STD-810G drop height is 30" for the 72 lb package instead of 48". This is because the 72 lb package had a dimension longer than 36" and therefore has a lower associated drop height. The MIL-STD-810G drop height also drops for the 140 lb package as it falls into the 100 lb – 200 lb range.

Table 2 Drop heights from [9].

Package Weight (lb)	95% Drop Height (in)	MIL-STD-810G Drop Height (in)
46	34	48

72	32	30
140	22	30

A final study, performed by Russell and Kipp, examined the shocks experienced by 27.5 lb packages shipped between several locations in Europe [10]. In total 57 one-way shipments were made. The highest drop recorded was 42" and 95% of all drops were less than 24". Based on these numbers, the MIL-STD-810G drop height may be too aggressive.

The same study also reviewed existing drop literature including Ostrem and Godshall's 1979 report. As part of the review, the study included a graph from the report that plots drop height as a function of weight for three levels of probability (see Figure 6). Added to the graph are the MIL-STD drop heights. These drop heights tend to be more aggressive than the other shock curves and indicate that the MIL-STD-810G drop heights might represent worst-case scenario events.

It should be mentioned, however, that it is unclear if this graph was made by Russell and Kipp based on information in the report's text or possibly taken from an appendix, but efforts to locate the graph in the Ostrem and Godshall report have not been successful. The graph is still included here as it contains potentially valuable information, but should be treated with caution until its source can be verified.

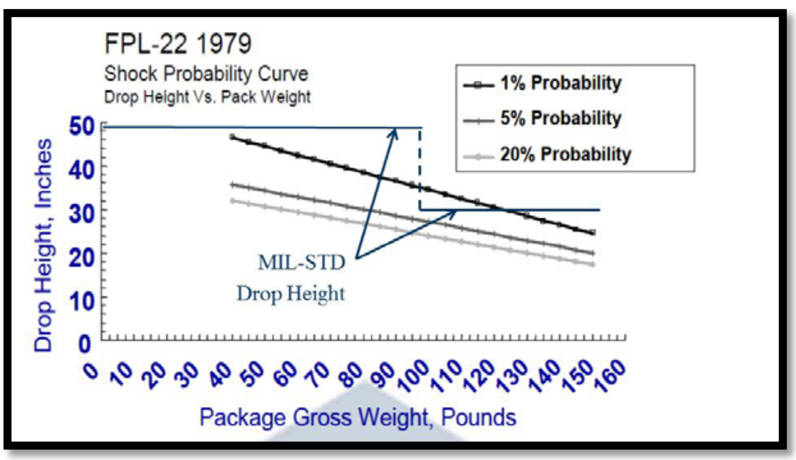

Figure 6- Drop height as a function of weight for three different probability levels. Taken from [10]. The original graph has been modified to show the applicable MIL-STD-810G drop heights

Drop Testing of a Large Format Battery

This phase of the study examined drop testing a 110 Amp-hour (A-hr), 35 lb., lithium-ion battery manufactured by Valence Technology (Model #: U24-12XP). The first set of drops was used to iteratively find a drop height and surface combination needed to create the 11 ms, 50-g shock pulse as specified in the UN/DOT 38.3 T4 shock test. This was done to provide a sense of drop-conditions needed to replicate the UN/DOT shock profile. Next the battery was dropped from the same height, but onto different surface-types and last the battery was dropped onto the same surface, but from increasing heights.

For all tests the battery was instrumented with several thermocouples to measure changes in temperature during drop events – one for each side of the battery except the bottom. Voltage was also measured. To measure accelerations inputted to and experienced by the battery, three accelerometers were mounted to the test apparatus. The first was attached to an aluminum base plate that the battery was securely mounted to. This accelerometer measured the shock inputted to the battery and was compared to the shock values specified in the UN/DOT test series. The remaining two accelerometers were attached to the top surface of the battery and measured the response accelerations. These accelerations are specific to the material and construction of the object being dropped.

The battery mounted to the aluminum plate was placed into a remotely-operated drop apparatus that could be raised or lowered to a desired height. Various surfaces were placed under the battery assembly to replicate potential drop surfaces. All drops took place in an isolated test container designed to contain extreme lithium battery failure events such as fires and case-ruptures. This was deemed necessary in case one of the drops significantly damaged the battery and led to a thermal runaway event. All measurements were performed in a separate laboratory space. All drops were video recorded. Pictures of the set-up are shown in Figure 7.

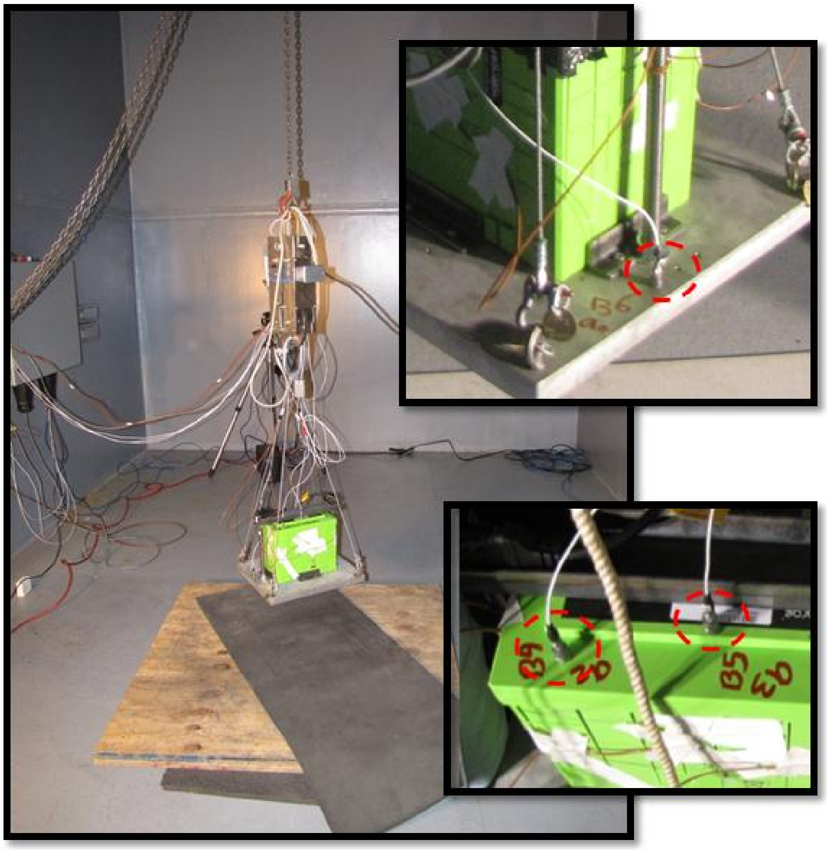

Figure 7. Battery drop-test set-up. The three accelerometers mounted to the base-plate and battery are circled in red.

The first set of drops was performed to find a drop-height/surface combination that closely replicated the 50 g, 11 ms UN/DOT profile. As there are theoretically infinite combinations that could create this profile (although limited between drop heights of 5" and 24"), this test was performed to determine experimentally whether at least one such combination could be created in the laboratory. As can be seen in the shock profile of Figure 8, dropping the battery assembly from a height of 11" onto a surface consisting of 2" of plywood, 2 rubber mats, and 1" of foam was one such combination. Also shown in Figure 8 is the frequency spectrum of the inputted shock pulse. The spectrum indicates that there was a peak excitation frequency around 50 Hz, but that frequencies died out after about 150 Hz.

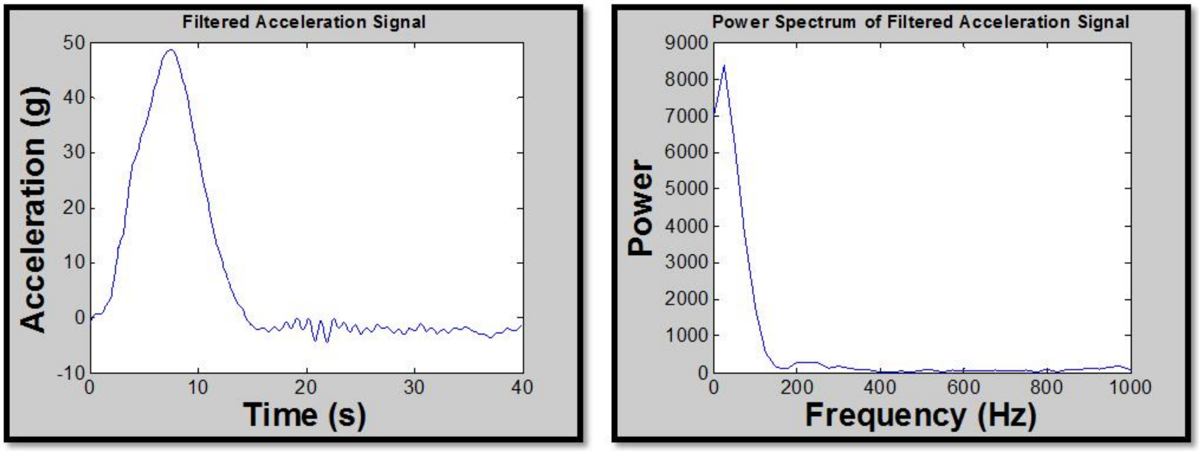

Figure 8. Input acceleration and frequency spectrum for an 11” drop onto 2” of plywood, 2 rubber mats, and 1” of foam.

These results provided a semi-quantitative measure of the conditions needed to replicate the UN/DOT shock profile: the exact drop-height was known, but the exact material properties of the different surface materials were not. The purpose of this test, however, was only to provide a sense for what conditions replicate the UN/DOT profile and then to use these conditions as a baseline from which other drops are compared.

The next series of drops consisted of dropping the battery from the same 11” height but onto different surfaces. In addition to the 2” of plywood, 2 rubber mats, and 1” of foam surface, two other surfaces were investigated: 2” of plywood and ½” of steel. The results are shown in Figure 9 and demonstrate that as the surface becomes more rigid, the maximum amplitude and range of inputted frequencies significantly increase. The 2” plywood resulted in a maximum acceleration of roughly 130 g’s and frequencies that extended out to 1,000 Hz. The ½” steel was even more severe with a maximum acceleration approaching 500 g’s and frequencies extending onwards 2,000 Hz. This data clearly confirms that the distribution of the drop energy in the frequency domain heavily depends on the pulse duration and the amplitude of the input pulse.

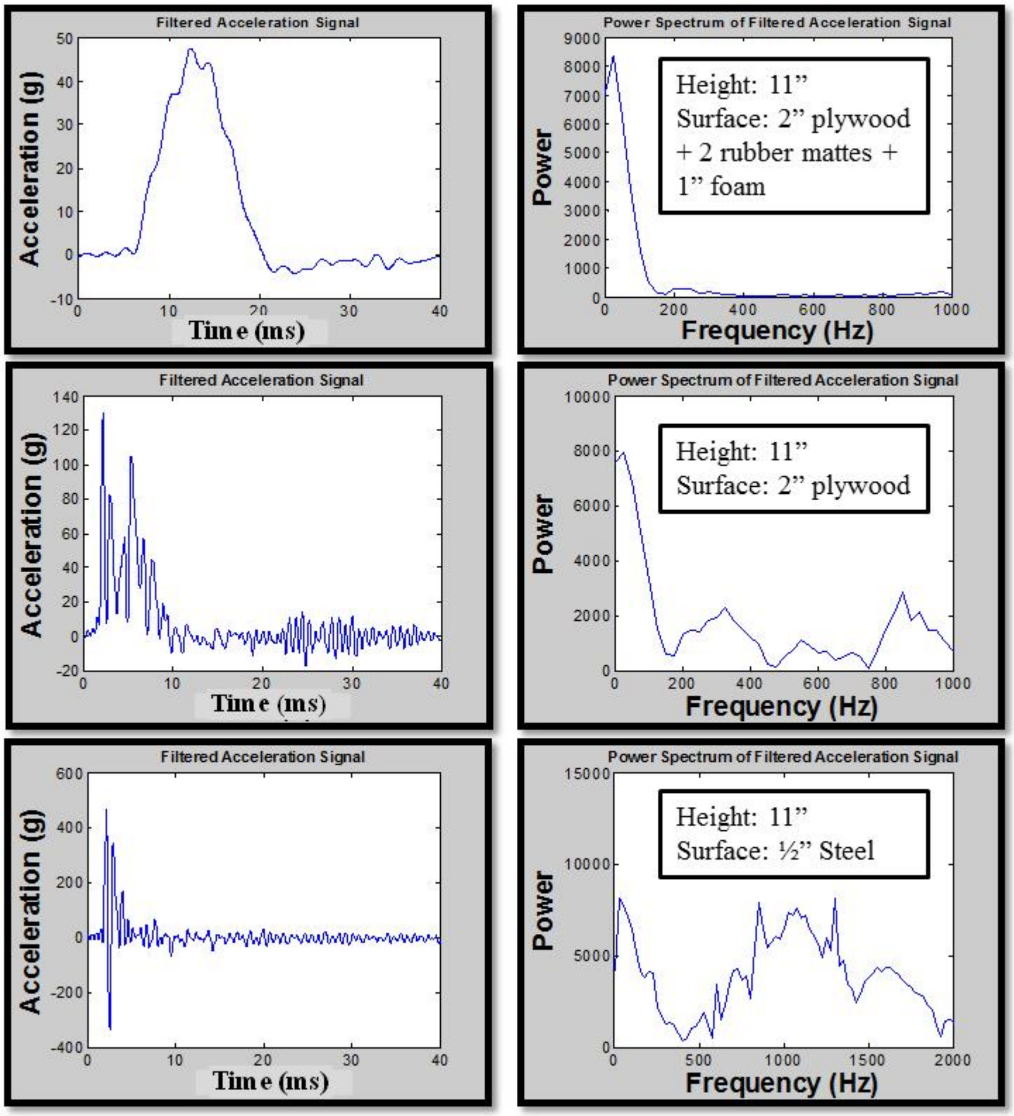

Figure 9. Acceleration and frequency inputs to 11" drops on three different surfaces.

The final test was a series of drops from increasing heights onto the same surface. Drop heights were 24", 36", and 48" and the surface was 2" of plywood. The results of the drops are shown in Figure 10. As can be seen in the graphs, as the drop height increased, the maximum acceleration and range of inputted frequencies also increased. At 24" for example, the maximum acceleration was around 225 g's with frequencies extending to 1,000 Hz, but at 48" the maximum acceleration was just over 800 g's with frequencies extending to 5,000 Hz. This test illustrates that increasing the drop height not only increases the amount of energy transferred to a given object, but that energy is transferred at larger accelerations and higher frequencies.

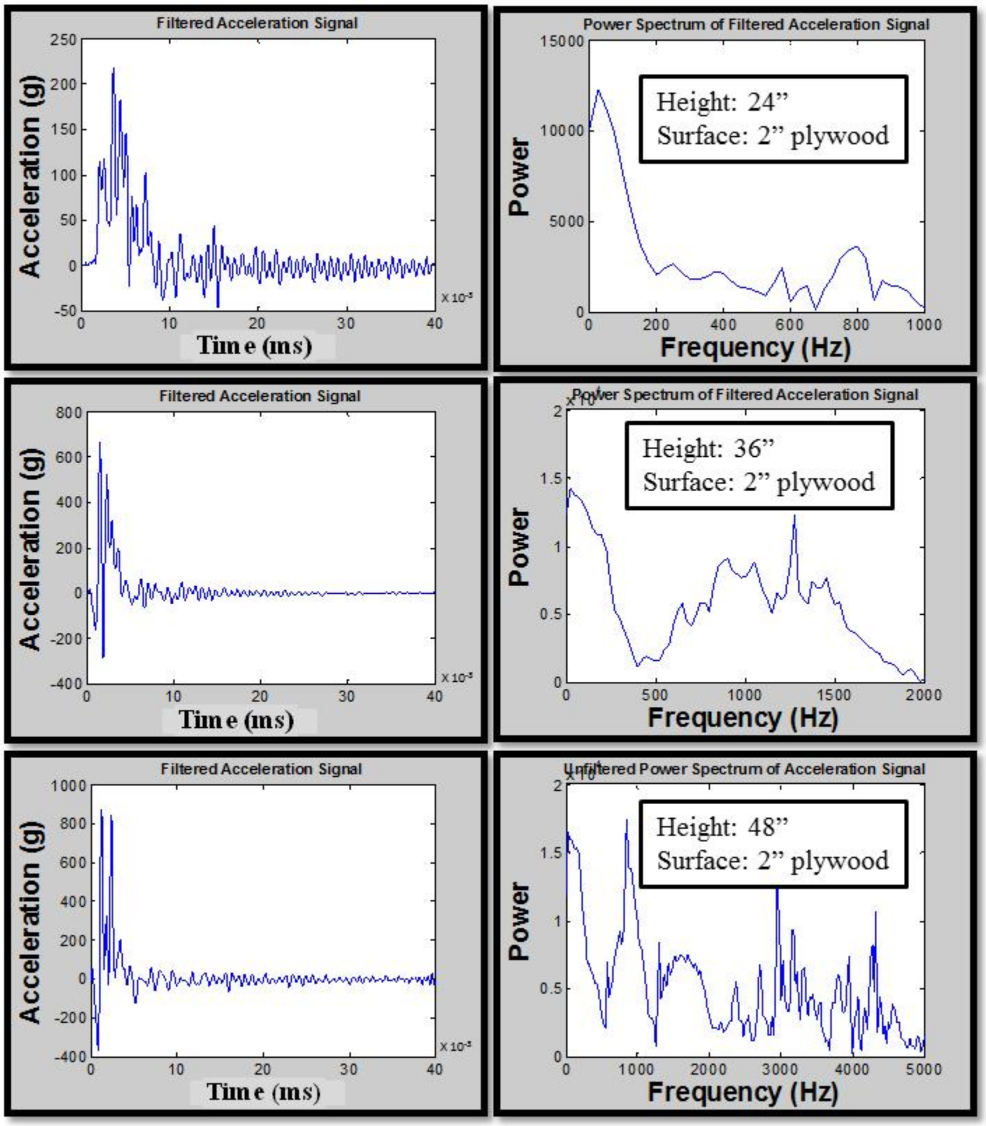

Figure 10. Accelerations and frequencies of drops onto 2" of plywood from 24", 36", and 48".

Overall the drop tests indicated that the 50 g, 11 ms shock test, although appealing from a repeatability standpoint, is not representative of mishandling scenarios mainly during drop events. Therefore, drop testing may prove an effective method for verifying shock resistance of lithium batteries. The positives and negatives of drop testing and using the 50 g, 11 ms shock test are summarized in Table 3.

Table 3. Positives and negatives of drop testing and the 50 g, 11 ms shock test.

Drop	50 g, 11 ms Shock
Encompasses all the dynamic forces experienced during transportation	Not universally representative of transportation environment for every battery design
Simpler test apparatus	Economically impractical for large format batteries
Repeatability is an issue	Repeatability makes it more attractive from a regulatory stand point
Further research is needed to define proper test parameters such packaging and drop height	

Conclusions

In this study, the effectiveness of the current UN/DOT 38.3 T4 shock test to replicate the dynamic forces experienced by lithium batteries during the course of transportation was investigated. It was determined that the fixed acceleration and pulse duration parameters defined in the test could induce responses in test items that are not representative of abuse conditions during transportation.

Next, the transportation mechanical environments were studied through the data that have been compiled from established sources within the NATO countries (AECTP200). These data showed that the transient excitations (shock) experienced by restrained packages transported by a Bedford 4x4 truck on a good quality road can attain a four g peak. Similarly, in the case of air transportation, transient excitations (shock) are only experienced during landing and can attain a two g peak in the case of fixed wing propeller aircraft. In sea transportation packages typically experience quasi-static loading rather than dynamic motions. The quasi-static inertia loadings are usually of such low magnitude as not to cause any concern. Furthermore, these data showed that with the exception of switching shocks in the longitudinal axis, the dynamic responses arising from rail transportation are generally less severe than those for road transportation. The maximum reported acceleration for switching operations was 15 g for traditional loose coupled wagons. The data in AECTP200 also indicated that the transients arising from rough handling are more severe than the dynamic loads experienced by packages in different modes of transportation.

Considering the deficiency of the current T4 shock test in UN/DOT 38.3 manual, it was determined that MIL-STD-810G (Procedure IV of Method 516.6) drop testing was a more realistic method to simulate the dynamic loads experienced during mishandling scenarios.

The last phase of this study investigated the data that had been collected by the academia and industry on drop heights recorded for various packages during transportation. The goal was to compare the results with that of MIL-STD-810G. Reviewing these results showed that only a few studies have examined drop heights experienced by packages larger than 25 lbs. These studies indicated that the drop height suggested in MILD-STD-810G for objects less than 100 lb with their largest dimension less than 36" only simulates worst case scenarios. No conclusion can be drawn for other drop heights listed in MIL-STD-810G as very few independent studies have looked at objects heavier than 100lb.

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