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Safety of lithium batteries in transportation

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Abstract

UN Document ["Recommendations on the Transport of Dangerous Goods Manual of Tests and Criteria", 3rd Revised Edition, 1999] outlines a test plan that is fundamental to the classification for transport of lithium batteries with metallic lithium, lithium alloy or lithium-ion intercalation electrodes. The tests can be divided into two categories: safety tests (internal and external short circuit, forced-over-discharge, charge) and environmental tests (reduced pressure, thermal, vibration and shock). These safety tests are intended to assess known unsafe behavior in abusive circumstances.

This paper discusses the importance of environmental tests in the transport scenario and presents a discussion on how the existing safety tests provide only a false sense of security. Simple measures that prevent abuses in transport are suggested that would be more effective and ensure greater safety. A recent incident at Los Angeles International Airport (LAX), where lithium cells in transit were abused and caused to burn, is now cited by some regulators as proof that safety testing is required. This paper describes how that logic is flawed. Testing would not have prevented the LAX incident. Therefore, continued promotion of and focus on safety testing is working against the ultimate goal of improved safety in transport. This paper concludes that effective regulations should promote and maximize safe transportation of lithium batteries through environmental testing and the elimination of unsafe circumstances that enable lithium batteries to become a hazard in transport. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Specifications; Lithium batteries; Safety testing

1. Introduction

This paper continues on the theme of regulations for the transport of lithium batteries which began at the 21st International Power Sources Symposium with proposed amendments to UN ST/SG/AC.10/11: transport of dangerous goods — lithium batteries [2], presented in May 1999. It contained a brief history of the lithium battery transport regulations, many specific and general criticisms of the UN regulations, that have not substantially changed to-date, and many proposals for amending the regulations. Reference [2] holds up well after two more years of lithium battery safety debate and its contents will not be repeated here.

An amendment process is ongoing for a variety of reasons. The introduction of lithium-ion products as lithium batteries under the UN regulations is certainly a major factor. Our interest pre-dates that issue and concerns the value and appropriateness of specific tests and the overall test plan associated with the UN regulations. Writing about the amendment process is challenging as the issues under debate change frequently when many draft proposals are flying around. Private sector interests have one additional limiting constraint. Only national government representatives, with little or no direct technical knowledge or experience, may officially propose amendments, attend and vote on the amendments at the UN.

A working committee made up of dangerous goods officials from Canada, the United States, Great Britain, France, Germany and Japan have been officially debating amendments.

Current regulations rely heavily on the tests in the UN test plan to determine the transportation classification of a lithium battery. The practical use of tests is something that can be assessed. Review of the UN test methodology has provided little assurance that meeting the requirements of some tests would equate to transportation safety. One event has brought attention to the question of what constitutes a hazard for transporting lithium batteries. A lithium battery incident at Los Angeles International Airport (LAX) provides us with a case that illustrates how the current regulations fail to assure confidence in safe transport.

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Why lithium batteries are potentially hazardous in transport is no great mystery. Assuring safety during the transport of these products is the goal of the regulations.

2. Regulations

There are many aspects of dangerous goods transport regulations. UN regulations are recommendations to national authorities. Each nation retains its own authority over transport regulations, however, it makes sense to minimize differences from one nation to another in order to facilitate international shipping. Most nations either accept the UN recommendations as is, or re-publish them with specific national modifications introduced. Canada is an example of the former. The USA is an example of a country that re-publishes the UN recommendations. The Code of Federal Regulations, known as CFRs, contain their modified version of the UN Special Provisions. The Special Provisions outline the basic rules such as what is regulated, allowed sizes, and general instructions for packaging.

Each mode of transport — air, marine, road or rail for example, have international organizations which also parrot the UN regulations. These organizations and their members have real power since they can ultimately refuse to carry a shipment, regardless of the UN recommendations. Conversely, shipping a lithium battery is only a practical problem if a carrier will not accept the shipment, regardless of UN classification for shipment.

Air transport is generally the most restrictive. International Civil Airlines Organization (ICAO) and International Air Transport Authority (IATA) must be convinced of safety of lithium batteries submitted for air transport. Representatives from ICAO and IATA are following the amendment process and participating where appropriate.

At issue is the logic behind current regulations. Every lithium cell or battery type within the scope of Special Provision 188 or 230 must be tested to the UN test plan before it can be classified and before it can be shipped. There are other conditions to be met, but this evaluation focuses on the tests in the test plan.

3. The limited value of testing

The data generated by any test are directly related to the design and specific parameters of the test. For example, a charge test at a given current informs us of the behavior of the sample under test at that one current. If the test is specified at a certain temperature, then we also learn about the behavior at that certain temperature. We are left with a number of uncertainties. We are not certain if the sample is representative of all similar products. Therefore, we perform multiple tests. But we are still uncertain if the group of cells tested is representative of all lots produced. We do not know if products produced earlier or later than the test lot are identical to the test lot or if changes have been made to materials or procedures without a change to the model number. The UN tests allow a very broad scope of change to a product before requiring re-test. We do not know how minor changes might affect the test results.

Practical considerations such as cost, time and the destructive nature of the tests (which means all products cannot be tested) force us to ignore the uncertainties.

Chief among the uncertainties is how do these products behave at other charge currents? Most cell and battery tests and test plans are attempting to determine the safety of the products when operating normally in their application. The limits of performance within the application are defined by the limits of the product to operate safely and can be determined from the specifications published by the manufacturer of the cell. This could also mean that certain performance-limiting devices are incorporated into the cell, battery or equipment. It, therefore, makes better sense to design a test, for example the charge test, where the charging current is specified to be within the manufacturer's specified operating limit or below the operation of a fuse or positive temperature coefficient (PTC) device.

But how relevant is this to the transport scenario? If cells in shipment become loose and can operate in uncontrolled combinations with each other, it is possible that charging of a cell will occur, just as short circuits, forced discharges and crushing are likely to occur. It is likely that any such accidental charging current will exceed the tested limit and the manufacturer's specification. Any value of the limited testing regime has disappeared.

If the decision to ship these products was based upon such test results, then the test results have misled us.

Could a charge test be devised that would be all encompassing? No doubt an extreme test could be applied, however, with lithium cells and batteries the test results would likely be violent and appear to prove the point that lithium cells and batteries cannot be shipped safely. This would be incorrect logic.

There is a safe means to transport a lithium cell or battery with respect to the risk of charging. Simply stated, charging must be prevented from occurring during transport. Just as cells and batteries are equipped with current limiting devices to ensure they operate in their applications within manufacturer's specified limits, cells and batteries during transport must be effectively prevented from charging. The low cost solution to this puzzle is effective, not necessarily expensive. It is packaging. Packaging must be considered as a performance-limiting device. Exactly the same argument can be made for forced discharge testing of cells.

Unfortunately, the UN test plan contains certain tests that are designed for assessing safety within limits that do not correlate to the possibilities of an unlimited transport accident. These tests provide information that is limited by the design of each test. Most test conditions can be considered only as a single point on a multi-dimensional spectrum (combinations of voltage, current, temperature and pressure) of possible transport accident conditions. What is proven regarding safe transportation from each test is dwarfed by what is ignored. When considering transport accident possibilities, the spectrum is nearly infinite.

If a potentially dangerous circumstance, such as charging, short circuit, forced discharging or crushing, can be prevented, then is that not preferable to limited testing that attempts to "prove" that the dangerous circumstance can be safely tolerated?

Some have argued that since existing tests are conducted at the extreme limits of allowed performance, the tests are, therefore, testing beyond what may reasonably be expected under normal conditions of transport [3]. This is an example of the incorrect logic that is applied to lithium battery transportation safety testing. In fact, the existing tests fall far short of simulating the spectrum of possible transport accident possibilities regardless of how harsh they are. They cannot possibly anticipate or simulate all possible accident conditions. Hence, such performance tests are more accurately referred to as limited tests throughout this document.

The environmental exposure tests make sense when determining transport safety. Finite limits are known for the temperature exposure that products in transport will see. The atmospheric pressure limits are known. Appropriate vibration and shock tests can be developed that accurately simulate the various modes of transportation. These tests must continue to be applied and require review to assure accurate simulations of real transport experience. Tests for vibration, shock and temperature currently in force are less than adequate simulations of the real transport environment extremes.

There is still great confusion about the internal short circuit test. The current edition of the UN test plan, ST/SG/AC.10/11/Revision 3 (1999), has amended this test to read: each cell is deformed until the open circuit voltage drops abruptly or is reduced to at least one third, or until a maximum force of 1000× the weight of the cell, but not less than 10 kN, is applied. The choice of three optional test endpoints (OCV drop, voltage drops to 1/3 OCV or 10 kN applied force) shows clearly the confusion between an internal short circuit test or a crush test. The two OCV-related test endpoints define this as an internal short circuit test. The applied force endpoint redefines this as a crush test — albeit one entitled an internal short circuit test.

Regardless, the test proves almost nothing about the transport safety of a cell design if the test operator chooses to end the test when the OCV changes abruptly (and most do). Everything tested will likely pass, and yet the sample cell under test is potentially dangerous if crushed beyond the point of an abrupt change in voltage. The result is a product being transported that is still a potential hazard in a transport accident if it is crushed. If the test is conducted to the applied force rule and a fire or worse is the result, it may be ruled unsafe to transport. This would be equally twisted logic. The product would be entirely safe to transport so long as it is not crushed in the process.

The danger due to the development of an internal short circuit is real, and so is the danger due to crushing. Internal short circuits that, by design of the cell or battery pack, can pose a risk to safe transportation can be identified with appropriate vibration and shock testing. Artificially, crushing a cell can create an internal short circuit but it does not simulate the type of internal short circuit that has historically been a transportation problem. The existing UN test plan does evaluate the possibility of an internal short circuit for battery packs (a short circuit within the pack external to the cells). Once again we have a situation where the safety of a product in transport is based upon data from a poorly designed, limited test. Once again, would it not be superior to prevent cells and batteries from being crushed during transport? Attention to packaging would be all that is necessary to prevent crushing.

4. The LAX incident

Two years ago, the motivation of some for amending the transport regulations was driven by the fact that the existing regulations did not allow for large batteries such as electric vehicle batteries. Regulators appeared to be ignorant of the poor quality of the existing regulations and, therefore, approached the amendment problem by dealing almost solely with the definitions of scope in the Special Provisions. Cosmetic changes to the test plan were suggested to accommodate the mass and size of the larger batteries and have now been incorporated into Revision 3 (1999) of the UN test plan [1].

Focus has now turned to more fundamental questions of transport safety. On 28 April, 1999, a fire destroyed freight, including lithium batteries, on two aircraft cargo pallets at the Northwest Airlines cargo facility at LAX. The pallets had been taken off an inbound passenger-carrying flight from Osaka, Japan. The aircraft was a Boeing 747, operated by northwest airlines as flight 0026. The US National Transportation Safety Board's (NTSB's) investigation of this incident revealed that lithium batteries likely present a serious fire hazard to air transportation required immediate attention. [4] This incident now commonly referred to as the LAX incident was investigated by the NTSB and resulted in the issuance of Safety Recommendations A-99-80 through 84 [4].

The events of that day are captured on an airport security video for all to see.[1] Essentially, two pallets, one containing 100 000 primary lithium cells (Sanyo CR2 Li/MnO_2), the other containing 20 000 more of these primary cells and some rechargeable cells as well, were abused many times by the fork-lift truck operators as they moved them around an outdoor cargo area of the airport. Abuse occurred over a period of hours resulting in a fire that could not initially be put out with the portable fire fighting equipment at hand and

[1] Both the RSPA and NTSB have copies of this airport security video.

was only extinguished when a fire truck arrived and doused the pallets with a large volume of water. Details are available online from the NTSB report [4] and the subsequent Advisory Notice put out by the Research and Special Programs Administration (RSPA), DOT [5].

The exact cause of the fire may never be known. Once the packaging integrity was destroyed, it could have started by any of the following mechanisms: crushing of cells, short circuiting of cells, charging or forced discharging. It really does not matter. It is clear that the fork-lift trucks sufficiently damaged the packaging allowing cells to move into contact with each other. Many fell out of the pallet altogether.

This incident caught the attention of regulators. The primary lithium cells that caught fire were not dangerous goods by definition of Special Provision 188 (and 49CFR173.185) due to the small amount of lithium per cell. They were not required to be tested to the UN test plan. As a result of the specific language of the regulations, there was no requirement for the shipment to be identified as lithium batteries and, therefore, handlers were unaware of the nature of their cargo. It was clearly demonstrated that lithium cells contain flammable materials and can burn. It was also demonstrated that it is very difficult to extinguish them. These and other serious issues have been raised by the NTSB. The RSPA, working with industry, ICAO and IATA are required to address the NTSB's concerns for safe lithium battery transportation by air.

In the meantime, several lessons learned from the incident can be described that relate to the UN test plan. It is our opinion that the Sanyo CR2 cell, had it been applied to the UN test plan, would have passed all of the tests. This opinion arises from experience with other similar products, not specifically the CR2 involved at LAX, which has not been tested by our laboratory. As suggested in the preceding discussion on the limited value of testing, the circumstances of those cells in the LAX transport accident were uncontrolled. Once packaging integrity was destroyed, cell combinations were possible which may have produced uncontrolled high voltages or high currents. There was a completely different thermal environment than the test laboratory. There were unknown mechanical pressures introduced from the shear mass of products on each pallet. Therefore, an individual cell may have been subjected to a crushing force once it was unprotected. The NTSB have recommended the DOT should consider the testing requirements for lithium batteries in the United Nations ''Recommendations on the Transport of Dangerous Goods Manual of Tests and Criteria'' [1]. Therefore, it is timely to note that the existing test plan would not have prevented the LAX incident. It is also important to note that the shipment had traversed the Pacific Ocean in the belly of a Boeing 747 without incident before the packaging was damaged. How far from safe transport was this shipment?

It is interesting to note that the fire at LAX was extinguished only when a fire truck arrived that could deliver a sufficiently large volume of water to cool the burning pallet. This course of action was taken without fire-fighters knowing that the pallet contained lithium batteries. It was, purely by coincidence, the correct course of action. The success of applying large volumes of water to lithium battery fires was established in the UK over 10 years ago [6] and is generally known within the primary lithium battery industry. The UK study pointed out that the flammable electrolytes are the major contributor to a lithium battery fire and that lithium metal itself makes only a minor contribution. As such, speed is essential in stopping the fire, and the solvent fires would present no special problem to fire-fighters.

5. Safe transport of lithium batteries

Some regulators take the view that lithium batteries are inherently unsafe. For example, when referring to primary lithium batteries that power automated external defibrillators, the US Department of Transport's Federal Aviation Administration stated: safety of these batteries is stressed because extremely energetic materials are used in lithium cells and they are not intrinsically safe [7]. In time, this position will hopefully change to agree with the natural behavior of lithium batteries. With any battery, lithium or otherwise, it is safe to assume that under standard temperatures and pressures they are safe if not operating. To be viable as a commercial product, they must remain safe when operating within the design limits. It is in the manufacturers' interest to ensure this is true. It can be reasonably determined by applying such standard testing as outlined by UL, the IEC or others. Safety problems only arise when an unsafe circumstance occurs. Lithium batteries have existed long enough for us to understand these circumstances well. Lithium batteries must not be exposed to temperatures, pressures, mechanical shocks or vibrations beyond their design limits. Therefore, testing to environmental limits makes sense and must be continued as there is a safety benefit from continuing vigilance.

Safety behavior of lithium batteries when operating can be eliminated as a transportation issue if they are not operating during transport. This can be assured with effective packaging that isolates cells and batteries. Therefore, it becomes irrelevant how a cell or battery behaves when short circuited, forced discharged, or charged. Crushing can be eliminated by effective packaging and reasonable handling. Internal short circuiting, either within a cell or external to a cell but within a battery pack can be ruled out as a transport risk with appropriate vibration and shock testing of sufficient severity and duration. These issues were addressed in the last paper [2]. Tests within the UN test plan for short circuit, charge, forced discharge and internal short circuit fall far short of simulating the enormous range of possible accident circumstances. However, if the focus of regulators would change to address prevention of these unsafe circumstances during transport, then the ''performance'' tests are simply not necessary. If cells and batteries are prevented from engaging in these operations during transport, assessing how they behave while operating is irrelevant. Eliminating these unsafe circumstances from the transport experience would provide far more assurance of safety to equipment and personnel.

The challenge for regulators should not be the design of new or improved tests. Regardless of effort or good intentions, performance tests can only provide limited information relevant to safety in transport. Such limited safety assurance does not compare well to effective prevention of operation and prevention of abuse. Defining the transportation environment accurately so that suitable performance-limiting packaging and handling requirements can be defined and stated clearly would yield greater assurance of safe transport. Using the LAX incident as an example, one lesson learned was that abuse inflicted on the pallets by forklifts must be taken into account as a possible experience the packaging must bear without losing its performance-limiting characteristics. This type of abusive handling is undesirable but difficult to eliminate and should be expected to occur [8].

How far from safe transport was the LAX shipment? It is difficult to say with certainty, but from descriptions of the packaging involved, which was clearly inadequate, it is likely that the very serious incident could have been prevented by only a very small, and possibly inexpensive, change to the packaging. Double boxing might have been enough. Stronger cell isolation in two directions instead of one might have been enough. A number of low cost, readily available solutions might have prevented the loss of packaging integrity and, therefore, prevented the cells from spilling freely and, therefore, preventing the fire.

The DOT is correct when it says that lithium batteries contain extremely energetic materials and, therefore, it is important that carriers and handlers know what they are carrying. When shipments of lithium batteries are so identified, handlers and carriers must then be sufficiently knowledgeable to act responsibly. International, national and modal regulations should provide more guidance to the shipper on the environment and other relevant circumstances of transport than they currently do, so that a shipper can select adequate packaging to survive the journey. Shippers have to understand that the packaging is more than a containment system, but also a cell or battery performance-limiting system that must remain intact during the entire trip. Shippers need more accurate guidance than is currently available to them in order to make their shipments safe.

It is obvious that lithium batteries should be identified as such, regardless of size. There is on-going debate as to how to accomplish this. Suggestions to consider:

1. include a warning on the packaging stating that the packaging integrity is critical to safety of the lithium batteries within; and
2. any damage to the packaging should disqualify the shipment from continued transport until repaired or re-packed to the original condition. Such ideas are more easily suggested than implemented in this multi-lingual world of international transport. However, such warnings would serve to remind shippers, handlers, and carriers of the essential requirement for packaging integrity. If the LAX shipment had been attended to after the first forklift abuse, perhaps the fire would not have started. Unfortunately, the pallets were abused over and over by the forklift operators who were oblivious to the contents.

Cells and batteries shipped in equipment are covered under UN Special Provision 231. Normally, an installed battery is isolated by an "off" switch, but not always. The same principles of safety as stated above must apply to cells and batteries in equipment. The same requirements for environment tolerance including temperature, pressure, shock and vibration must all be evaluated through testing. There are many instances where cells and batteries installed in equipment are operating at micro-ampere current levels to power clocks or maintain memory. Historically, these levels of current have not presented a safety problem. There should be continued allowance for very low current operation. There are safety circuitry requirements in these instances, such as effective current limiting devices and diodes, that must be employed in these applications.

6. Conclusion

Regulators can assure safe lithium battery transport by introducing into regulations measures that prevent exposure to unsafe circumstances during transport. Effective packaging, not necessarily expensive packaging, that isolates cells and batteries and prevents operation, including abusive circumstances that can be encountered, is essential. Respectful, knowledgeable handling requires identification of package contents. Environmental testing should be continued and reviewed for accurate transport simulation. Regulations should include sufficient guidance for shippers to determine effective packaging for a particular shipment.

Ultimately, the lithium battery transport systems should operate based upon a respect for the highly energetic materials used in lithium batteries instead of a fear of them.

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