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The Use of UL 1642 Impact Testing for Li-ion Pouch Cells

RYAN AALUND, (Member, IEEE), AND MICHAEL PECHT, (Life Fellow, IEEE)
Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD 20742, USA

Corresponding author: Ryan Aalund (raalund@umd.edu)

ABSTRACT The industry demand for high-capacity cells with a small footprint is a result of demands for improved products and new applications. However, this presents challenges in terms of safety. While standards, such as UL 1642, have been developed for battery safety assessment, including impact testing, this paper shows that cell manufacturers are facing difficulties with UL 1642 safety tests. This is leading to alterations in the test procedures, where 'golden samples' are tested, while production cells cannot pass the safety tests. This is a flaw in the process that is being accepted by UL. This paper reviews the UL 1642 standard and similar standards used in portable electronics, provides experimental support for the concerns, and presents recommendations.

INDEX TERMS Impact test, internal short circuit, Li-ion pouch cells, mechanical testing, safety, standards.

I. INTRODUCTION

All batteries carry a safety risk, and battery manufacturers are compelled to meet safety requirements. One safety issue is associated with impact testing. An impact test is a mechanical stress test to observe the reaction of Li-ion cell after a sudden and measured force. The observable unsafe reactions include explosions and fires. Impact testing is intended to determine the safe prevention of fire or explosion after a cell has been obstructed by an object [1], [2].

Sahraei *et al.* [3] explored complex loading scenarios that resulted in short circuits. The research provides a description of the behavior of each electrode/separator layer and how a resulting short circuit is developed. Lou *et al.* [4] conducted experiments on Li-ion pouch cells with indentation loads. Varying force levels were used to evaluate the evolution of anode and separator changes that result in a short circuit. Chung *et al.* [5] characterized failure patterns for varying mechanical loads at the cell level. The stated research advances understanding of internal short circuits in Li-ion cells, but the results also highlight an important gap; mechanically induced short circuits are multi-variant and the relationship between safety and mechanical integrity is not well defined.

Dynamic impact tests have been researched by Kisters *et al.* [6] and Chen *et al.* [7]. The experiments show that with minor mechanical deformation catastrophic failures will occur due to a multitude of underlying failure mechanisms. Other research has examined the effect of state of charge and sate of health [8], [9] on mechanical integrity.

In the existing body of work a common theme is that mechanically induced short circuits are of great concern and more effort is needed to understand the failures. The direction of research is gaining deeper understanding of what exactly is failing and how variances affect failures. However, the research has not evaluated the implications of their findings to the industry standards; for example, the minimum test thresholds available to assure safety, or the relationship between standards-based testing and the results uncovered during experimentation.

UL 1642, Standard for Safety Lithium Batteries, was the first standard, published in October 1985, with focus on the topic of Li-ion cell safety for both primary (non-rechargeable, e.g. lithium) and secondary (rechargeable, e.g. Li-ion) cells and batteries. Subsequent editions were released in November 1992, April 1995, and September 2005. The 5th and latest edition was released on March 13, 2012. These editions and revisions addressed emerging trends including prismatic and pouch cells. UL 1642 currently covers electrical, mechanical, environmental, and fire exposure tests; short circuit, abnormal charging, forced-discharge, crush, impact, shock, vibration, heating, temperature cycling, altitude simulation, and projectile test. The impact test is one of four mechanical tests required by UL 1642.

Many other standards have been introduced since UL 1642 was first published. Standards range from broad to

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application specific. For example, Ruiz *et al.* [10] reviewed standards specific to electric and hybrid electric vehicles. This paper focuses on UL 1642 because of its prominence in many applications and its evolution and current requirements with regards to impact tests. The paper overviews the standard and the impact test methods, and then explores the effectiveness of the tests. Experiments are presented which include cells designed specifically to comply with UL 1642, off-the-shelf cells, and custom cells with UL guidance.

II. UL 1642

Li-ion battery[1] safety testing is required by certain regulatory bodies. Underwriter's Laboratory is recognized for developing safety standards and to perform safety testing as a Nationally Testing Laboratories. UL 1642 covers primary (non-rechargeable) and secondary (rechargeable) lithium batteries for use as power sources in products. These batteries contain metallic lithium, or a lithium alloy, or a lithium-ion, and may consist of a single electrochemical cell or two or more cells connected in series, parallel, or both, that convert chemical energy into electrical energy by an irreversible or reversible chemical reaction. The requirements cover lithium batteries intended for use in technician-replaceable (5 g or less of metallic lithium) or user-replaceable (4 g or less of metallic lithium with no more than 1 g in each cell) applications [11]. The requirements are intended to reduce the risk of fire or explosion when lithium batteries are used in a product. The final acceptability of these batteries is dependent on their use in a complete product that complies with the requirements applicable to such a product. The requirements are also intended to reduce the risk of injury to persons due to fire or explosion when user-replaceable lithium batteries are removed from a product and discarded. Qualifying for certification requires meeting the pass criteria for each test individual test in the suite of tests.

UL 1642 is a standard that includes mechanical impact testing. An impact test is a mechanical stress test in which a hard object, such as a steel rod, is placed on the test sample and a weight is dropped onto the steel rod. The test intends to observe the reaction of the test sample and see if unsafe reactions including explosions and fires arise. Impact testing has become increasingly difficult to pass as cell capacity has increased. The following changes to the impact test show a history of modifications made to accommodate the changing market.

On June 23, 2015, UL released a revision to UL 1642, Edition 5. The UL 1642 revision affects only the impact test. This revision is the second recently made to the standard to clarify the implementation of specific mechanical tests as they are applied to prismatic and pouch/polymer Li-ion cells.

The latest UL 1642 revision aligns with other Li-ion battery standards, which have varying requirements for impact testing. The UN Manual of Tests and Criteria (UN 38.3) requires crush testing on prismatic and pouch Li-ion batteries instead of impact testing, but impact testing is required for Li-ion cells. IEC 62133 Second Edition does not include any impact testing for Li-ion cells.

On August 24, 2018, a bulletin was issued from UL's Collaborative Standards Development System (CSDS) regarding UL 1642. The bulletin proposed for preliminary review and comment only the following change: "For Preliminary Review Only: Addition of a new test requirements for soft-case pouch cell for a Narrow Bar Crush Test or Dent Test instead of the Impact Test" [12]. The proposed changes would replace the cell impact test for a crush test in the case of a pouch but maintain the impact test for prismatic cells. The crush test will involve a steel bar applying 53 Mpa for five minutes on the top 25 mm of the cell.

III. IMPACT TEST

There are many guidelines and standards for impact testing. The UL 1642 Impact Test is conducted in a steel chamber or other fireproof box. The sample cell is placed on a flat surface inside the chamber. A 15.8 ± 0.1-mm steel rod is placed perpendicular across the sample. A 9.1 ± 0.46-kg weight is dropped from a height of 610 ± 25-mm onto the sample. Five samples are tested, each sample will be subjected to one drop each. The test is passed if none of the samples result in a fire or explosion after impact.

The UN Manual of Tests and Criteria (UN 38.3) has an impact test requirement for primary and secondary cells. The impact test setup for UN 38.3 on cells is set up the same as UL 1642. The test is set up in a steel chamber or other fireproof box. Ten samples are tested, each sample will be subjected to one drop each. Five of the samples are charged to a state of 50% capacity. The other five samples are aged, discharged from 100% to 0% and charged to 50% before testing. The test is passed if none of the samples result in a fire or explosion and the cell temperature does not exceed 170°C after impact.

For, prismatic and pouch battery packages, there is a crush test instead of an impact test. This may be because there is an assumption that all cells used in battery packages will have met the cell requirement. UL has a similar methodology of testing between UL 1642 and UL 2054, Standard for Safety Household and Commercial Batteries. UL 2054 maintains tests at a battery level for Li-ion batteries deferring single cell testing to UL 1642 [13].

The UN38.3 crush test method requires a battery to be crushed between two flat surfaces. The crushing force shall be applied to the widest side. The crushing is to be gradual (1.5cm/s). Crushing continues until the first of three options is reached; (1) The applied force reaches 13kN, (2) the voltage of the cell drops by at least 100mV, or (3) the cell is deformed by 50% or more of its original thickness. When the criteria are met to stop crushing the press is released. The criteria to pass UN38.3 requires the external temperature does not

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[1] A cell is a single encased electrochemical unit consisting of one positive and one negative electrode that exhibits a voltage differential across the two terminals. A battery is one or more cells electrically connected. By safety organization standards, even a single cell with the addition of terminals, a protective circuit, and the connector would qualify as a battery. However, transport organizations, such as FedEx, consider a single cell battery a cell and not a battery [27].

exceed 170°C and there is no disassembly and no fire during the test and within six hours after the test.

IEC 62133-2 First Edition does not include any impact testing for Li-ion cells or battery packs but does include a crush test for cells. The IEC 62133 crush test is the same test method as UN38.3 but with a different stop criterion. The applied force threshold is the same at 13kN. The crushing force will also stop if the voltage of the cell drops to 1/3 the original open-circuit voltage.

Impact testing is a form of mechanical abuse that results in an internal short circuit. The mechanism that leads to an internal short circuit is complex, as stated by Fang *et al.* [14] a basic Li-ion cell has four scenarios in which a short can occur, i.e., short between the two current collectors, the short between the active materials of the two electrodes, the short between the anode active material and the aluminum collector, and the short between the cathode active material and the copper current collector. The effect is not the same for each of the various combinations of internal short circuits. Through modeling and experimental validation, it has been shown that the short circuit between the aluminum collector and the negative electrode produce the highest heat generation [14], [15]. Therefore, this combination leads to the most dangerous internal short circuit.

However, an impact test is not specific to one type of internal short circuit. And mechanical abuse tests must be considered more broadly in application. Sahraei *et al.* [3], Kisters *et al.* [6], Wierzbicki and Sahraei [16], Sahraei *et al.* [17], [18], and Zhang *et al.* [19] have linked deformation caused by mechanical abuse testing to internal short circuits. Using a finite element model, the occurrence of an internal short circuit is predicted with regards to the breaking force and displacement of the cell. The internal short circuit is the result of a broken electrode leading to failure of the separator material. Concerning Li-ion pouch cells specifically, Hao *et al.* [20] modeled how an internal short circuit is created by mechanical abuse. Though the failure mechanism is corroborated through modeling and experimentation across multiple research groups, there is lack of consensus on appropriate tests for confirming the safety relating to mechanical abuse. Lamb and Orendorff [21] performed two variations of mechanical abuse methods (mechanical blunt rod testing and nail penetration) on Li-ion cells of different constructions, the experimentation showed that the results were dependent on the test conditions, concluding that mechanical abuse testing is most useful when correctly representing the field use case. Location and electrode fracture pattern create additional variance on how the failure propagates within the cell [22].

With an emphasis on safety, it is widely accepted that mechanical abuse testing is necessary. Therefore, it is understood protecting against internal short circuits is necessary for the successful production of safe Li-ion pouch cell batteries. The inconsistent requirements called out for mechanical abuse tests across the numerous safety standards is rooted in the lack of consensus on what specific types of mechanical abuse will be experienced in the field. Impact testing is a plausible stress that could be experienced in a field application.

IV. UL TEST RESULTS AND EXPERIMENTATION

First, a custom cell designed for a medical device has been examined. Two manufacturers submitted samples to UL for testing and certification. Ten cells from each manufacturer are submitted specifically to comply with UL 1642 impact test. For the first manufacturer, the third cell tested failed due to fire. The separator inside the cell was cut in half resulting in a thermal runaway, which resulted in a fire. The second manufacturer passed testing at the third-party test site and was certified. Investigation into why one manufacturer was able to pass and the other failed uncovered the motivation of this paper and further investigation of the current state of the industry, the history of the UL 1642 standard, and how current manufacturing leaders are meeting the requirements of the standard. An experiment was performed to examine the results of impact testing on three market available manufacturers of similar Li-ion cells. Five samples from each manufacturer were submitted for testing. An impact test was performed on each manufacturer's cell until a cell failed. All manufacturers failed to meet the pass criteria. The final experiment considers guidance provided by the cell manufacturer for passing impact testing once the first experiment failed. This requires modifications to the electrolyte. The effect of electrolyte change is discussed further.

Two custom cells were developed and intended to meet UL 1642 requirements. The first custom cell has a capacity of 2.6Ah and has a Lithium cobalt oxide (LCO) chemistry. The custom cell being evaluated had size constraints that resulted in physical dimensions of 31mm X 90mm X 8.5mm. Common practice in Li-ion cell manufacturing is to reduce the inert material to leave more space for positive and negative electrodes [23]. The inert material is the separator, which functions as the mechanism preventing internal shorts. Reducing the thickness of the separator can increase the capacity of a cell when constrained by dimensions. However, a thinner separator weakens the defense against internal short circuits which are liable to result in fires and explosions [24]. The second cell developed was equivalent dimensionally but has a lithium nickel manganese cobalt oxide (NMC) chemistry and capacity of 2.4Ah.

Both went through UL 1642 testing; the first at a South Korean test site, the second at a Chinese test site. The first manufacturer's cells failed the impact test and was given conditional approval. Conditional approval requires the failed test must be met in a specified amount of time. Each test series of UL 1642 has designated samples, and 10 samples are required for impact testing. UL test teams in Korea recommended submitting mechanical test samples with the flame-retardant additive. The other test samples did not have to contain the flame-retardant additive. Another suggestion was to wait for the next revision of UL 1642, which will include language for narrow bar impact testing on soft pouches.

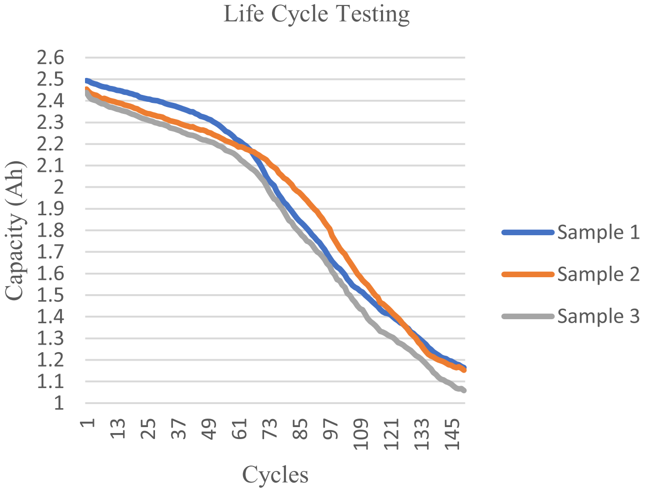


FIGURE 1. Capacity impact of flame-retardant additive.

The flame-retardant additive solution was rejected due to negative impact on performance.

Fig. 1 shows the greater than 50% capacity reduction in only 150 cycles at charge and discharge rate of 0.5C. Requirements for this design, met by the non-flame-retardant variation, maintained 80% capacity after 500 cycles with the same charge and discharge rate.

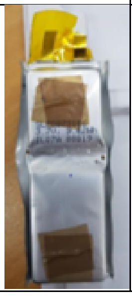
When providing samples of the second cell to the test site in China, the vendor-provided altered samples for impact testing. The samples are modified cells that have been altered from the original design by including a flame-retardant additive, specifically to help pass impact tests. While investigating why the first manufacturer failed the impact test and the second manufacturer passed, it was discovered altered samples were used by the second manufacturer. The manufacturer of the second cell responded to inquiry into cell alteration that this was part of the cell manufacturer's standard practice of developing cells that must meet UL 1642.

UL appears to be aware of Li-ion cell manufacturers difficulty in complying with impact test requirements, as is evident in their acceptance of altered samples being accepted for testing. It is reasonable to believe that UL is coerced by manufacturers to provide a means to achieve compliance; this scrutinizes the move to crush tests rather than impact tests. As the impact test has become more difficult to pass, the impact test requirement has been either reduced in scope or outright abandoned.

A. EXPERIMENT 1: CUSTOM CELL FOR MEDICAL DEVICE

Impact testing was explored in the laboratory, instead of third-party test sites. The first experiment ran was to repeat the UL 1642 impact test on the first custom cell, see Impact Test (section III) above for a detailed description of the test setup. Three samples were instrumented with a thermistor and submitted for impact testing. The samples failed impact testing, as they did while tested by UL. Table 1 shows the results of the impact test; beginning open circuit voltage (OCV), maximum recorded temperature, and photos after testing.

TABLE 1. Custom cell impact test results.

MEASUREMENT	Sample 1	Sample 2	Sample 3
Open Circuit Voltage V	4.173	4.174	4.170
Maximum Temperature °C Top / Bottom	106.9 / 114.2	120.9 / 96.8	122.5 / 367.8
Photo after impact			

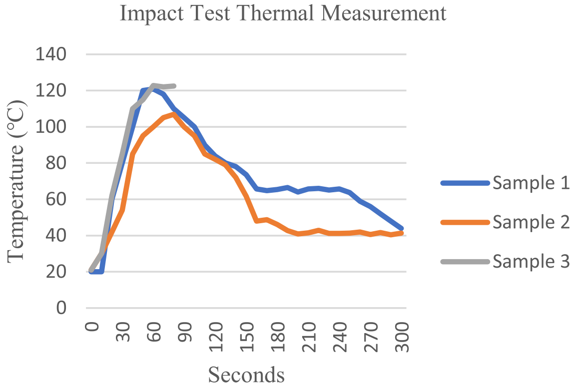


FIGURE 2. Thermal response during impact test.

The impact test damages the separator which can create a short circuit within the cell. The thermal event is result of the short circuit. Samples 1 and 2 begin to experience an increase in temperature, but the temperature begins to cool when case temperature is approximately 120°C. The separator for this sample is a single layer polyethylene. With excessive heat the separator will shut down through a process of closing it pores due to melting. Polyethylene has a melting point of 130°C. Fig. 1 plots the external temperature data points of the top side thermistor of all three samples. Sample 3 stopped recording once the fire melted the Kapton tape.

B. EXPERIMENT 2: OFF-THE-SHELF

The custom cell results and feedback from the UL test team led to research into off-the-shelf cells. Three cells with similar capacity and dimensions were tested to the same criteria. Five samples of each off-the-shelf cell were tested. All three cell vendors failed at least one of the five samples.

The first five samples have a capacity of 2Ah and total energy of 7.7-watt-hours (Wh). The chemistry of the cell is NMC. The second set of samples have a capacity of 2.35 Ah and total energy of 9Wh. These cells are also NMC. The final samples have a capacity of 3Ah and 11.5 Wh of total energy. All samples are single cell batteries.

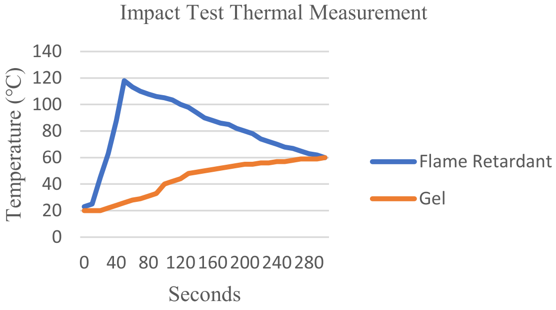


FIGURE 3. **Thermal response of altered samples.**

Failure analysis on all failing cells led to the same results: Damage to the separator, which results in a short-circuit, that generates a localized heat source, when combined with enough state of charge result in an exothermic event. The hot surface and ambient air and lithium result in fire or explosion [25].

The results are the same as the custom designed cells. The similarities highlight the weak points; a single layer separator, capacity greater than 2Ah, single pouch Li-ion cell. Future experiments will isolate these variables to understand their effect on the failure.

C. EXPERIMENT 3: UL INFLUENCED CUSTOM CELL

There have been two proposed changes to the makeup of the cell; gel electrolyte or flame-retardant additive to electrolytic. The gel electrolyte is not a widely used practice, so only one sample was constructed for testing. The flame-retardant additive is more accessible, and samples were made for both impact testing and characterizing. Both corrective actions pass the impact test. Thermal measurement during the impact test for an added flame-retardant and gel electrolyte cell can be found in Fig. 3. The flame-retardant variant reacted like the other samples. The flame-retardant limits the ability to create a thermal runaway, thereby providing an opportunity for the separator shut down to function properly. The gel electrolyte has a unique response, the temperature does not have the same temperature spike. Instead, the gel remains more stable after impact. Note Fig. 3 ends at 300 seconds, per UL test protocol, but after 30 minutes the samples with gel electrolyte were back to ambient temperature.

However, the use of gel electrolyte is not common practice in most cell manufacturing facilities. The cost of a cell will increase with the use of a gel electrolyte. Further evaluation must be done on the feasibility of gel electrolyte. The flame-retardant variations were characterized. There was a reduction in the available capacity, discharge rate, and capacity retention. Capacity loss was so severe, see Fig. 1.

Through testing, it has been determined that impact testing pass criteria cannot be met with Li-ion pouch cells with capacities greater than 2Ah. The available corrective actions are not practical for field applications. Flame-retardant additive to the electrolyte harms performance. A gel electrolyte is impractical with regards to maintaining a low cost. Widespread adoption of gel electrolyte would drive costs lower, however, more testing is needed to understand performance impact.

V. CONCLUSION

This paper provides evidence that UL China and South Korea are violating the trust of the industry by both practicing and endorsing the practice of circumventing the proper impact testing of batteries. One should never use a modified battery, that is not intended for the market and made solely for the purpose of passing a test. Testing a modified battery, such as one with a different electrolyte, whether gel or with an additive, to pass the test, has no relevance for the safe concerns of customers.

Rather than continuing to take the current approach, which is to modify products or the tests to meet industry capabilities, of a safety standard should be considered. For example, it is probable that end users will induce an impact to a battery when they dispose of a battery, or a product having a battery. The purpose of these standards is to protect the consumers.

Another issue is the impact test itself. The current impact tests mentioned pertain to new cells. However, cells will change with life cycle environmental and operational conditions, and may incur a reduction in capacity, lithium dendrite growth, and swelling. These changes can influence impact testing and should be considered in the test plan. More research is needed to determine the effect of cell age on the impact test. This is critical for the assessment of safety in disposal.

Li-ion technologies are outpacing the standards put in place to guide them and assure their safety and efficacy. It is unreasonable to think the industry would slow down to allow the standards to dictate tempo at which technologies advance, which means more emphasis must be placed on forward-looking standards development. A potential method to bridge the gap between worst-case scenario safety testing and application is the use of a warning label identifying that the impact test was not performed, and there are risks to the consumers.

Finally, certain industries have regulatory bodies that demand the use of specific standards. For example, medical devices must meet the Food and Drug Administration (FDA) guidelines. International Standard Medical Electrical Equipment (IEC 60601-1 Ed. 3.1) requires secondary lithium batteries comply with IEC 62133. Additionally, the FDA has two recognized consensus standards for battery safety; UL 1642 and UL 2054 [26]. Consensus standards are standards recognized by the FDA for use in evaluating medical devices before they are approved for market entry. The FDA's Center for Devices and Radiological Health (CDRH) believes that conformance with recognized consensus standards can support a reasonable assurance of safety and/or effectiveness for many applicable aspects of medical devices. In the case of medical devices using batteries, manufacturers can use proof of compliance with UL 2054 and UL 1642 as evidence of a device's safety and effectiveness. However, UL does not review their standards based the medical industry needs.

Revisions to the standards are continuing to occur based on manufacturer input. A safety risk emerges as the standards requirements are diluted for ease of passing by the manufacturer. In the specific case of impact testing, the safety of the cell is dependent on the medical device housing, operational environment, and the probability of an impact incident. UL 1642 does not offer enough flexibility to test cells in a more applicable manner. The end results could either be too strict, for instance failing a cell that will be placed in an aluminum housing, or not strict enough, impact to any area of the cell is just as likely. The variance in applicability should be of concern to the medical community, and to the broader public.

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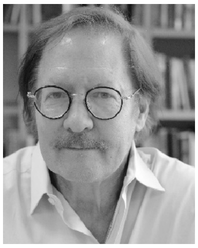
RYAN AALUND received the B.S. degree in electronics engineering technology and the M.S. degree in electrical engineering from DeVry University, in 2006 and 2013, respectively. He is currently pursuing the Ph.D. degree in reliability engineering with the University of Maryland, College Park, MD, USA.

From 2004 to 2008, he was an Electrical Engineer in the field of aerospace and defense. From 2008 to 2012, he worked as a Manufacturing and Test Engineer in the fields of aerospace, defense, and computer vision. From 2012 to 2018, he worked as a Reliability Engineer for Amazon Web Services and Amazon Prime Air. Since 2018, he has been a Principal Engineer and the Director of the Product Integrity for a medical device company. His research interests include accelerated life testing, system reliability theory, and prognostics and health management systems.

Mr. Aalund's awarded patents are in the field of prognostics and health management systems and accelerated life testing.



MICHAEL PECHT received the B.S. degree in physics, the M.S. degree in electrical engineering, and the M.S. and Ph.D. degrees in engineering mechanics from the University of Wisconsin. He is currently a Professor in applied mathematics and mechanical engineering with the University of Maryland. He is also the Director of the Center for Advanced Life Cycle Engineering (CALCE), which is funded by over 150 of the world's leading electronics companies at more than U.S. $6M/year. He has published more than 25 000 citations and more than 70 H-index. He is also a Professional Engineer, an ASME Fellow, an SAE Fellow, and an IMAPS Fellow. He served as the Editor-in-Chief of IEEE ACCESS, for six years, the IEEE TRANSACTIONS ON RELIABILITY, for nine years, and *Microelectronics Reliability*, for sixteen years. He has also served on three U.S. National Academy of Science studies, two U.S. Congressional investigations in automotive safety, and as an expert to the U.S. FDA. He has written more than 20 books on product reliability, development, use and *Supply Chain Management*. He has also written a series of books of the electronics industry in China, Korea, Japan, and India. He has written over 700 technical articles and ten patents. In 2015, he was awarded the IEEE Components, Packaging, and Manufacturing Award for visionary leadership in the development of physics-of-failure-based and prognostics-based approaches to electronics reliability. He was also awarded the Chinese Academy of Sciences President's International Fellowship. In 2008, he was awarded the highest reliability honor, the IEEE Reliability Society's Lifetime Achievement Award. In 2010, he received the IEEE Exceptional Technical Achievement Award for his innovations in the area of prognostics and systems health management.