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Li-ion Battery Safety under High-Speed Impact: Diagnosis, Prognosis and Risk Mitigation

January 2025

Final Report



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16. Abstract Lithium-ion batteries (LIBs) are critical to the early adoption of electrified small aircraft because they can provide the required energy, power, and cycle life. However, safety is still a concern, especially in dangerous situations like aircraft crashes or operations in harsh conditions. If damaged, the battery can release stored energy fast, leading to a battery fire or thermal runaway (TR). Not much is known in the open literature about LIB behavior, when an electric aircraft powered by LIB crashes into hard surfaces like steel or concrete. This project determined the crash survivability of LIB cells when launched into a rigid steel surface with speeds ranging from 50 to 300 mph. At 300 mph, all pouch cells shattered into pieces whereas cylindrical cells either caught fire or were badly damaged. At 100 mph, all pouch cells caught fire while cylindrical cells flattened and lost voltage. Cells tested at 50 mph survived the impact with slight visible cell deformation. Based on a small data set generated in this project, University of Dayton Research Institute (UDRI) suggests significant additional work is needed, especially on materials that can protect LIB cells at a higher speed (>50 mph).					
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Acronyms

Acronym	Definition
Al	aluminum
Ah	ampere hour
COTS	commercial off-the-shelf
ED	battery-specific energy density
FAA	Federal Aviation Administration
Gr	graphite
IR	infrared
kN	kilonewton
LCO	lithium cobalt oxide
LFP	lithium iron phosphate
LIBs	lithium-ion batteries
LMO	lithium manganese oxide
NCA	lithium nickel aluminum cobalt oxide
NHTSA	National Highway Traffic Safety Administration
Ni	nickel
NMC	lithium nickel manganese cobalt oxide
ORNL, DOE	Oak Ridge National Laboratory
SOC	state of charge
SS	stainless steel
TMS	thermal management system
Ti	titanium
TR	thermal runaway
URDI	University of Dayton Research Institute

Glossary

Term	Definition
UL1642	Lithium Battery Standards
adiabatic	A process that occurs without the transfer of heat or mass between a system and its environment. No gain or loss of heat.
coulombic efficiency (C.E.)	$C.E. = \text{total discharge capacity} / \text{total charge capacity}$
Eluent	The liquid solvent in ion chromatography that transports the analytes through the separator columns and detectors of the ion chromatograph.
Tad	Tad – temperature reached by a cell when all its discharge energy is released as heat under adiabatic conditions.

Executive summary

Lithium-ion batteries (LIBs) are the most likely energy storage for next-generation electric aircraft due to their high energy density, power, cycle life, and low self-discharge. However, the high energy density and quick energy release ability of LIBs pose significant safety risks (fire and explosion) for aircraft when the battery is overheated, overcharged, or damaged due to impact or collision. Research has been conducted to understand the safety of LIB under operating and quasi-static impact conditions, but not under dynamic impact - especially under high-speed conditions, as can be experienced in flying aircraft collisions. The Federal Aviation Administration (FAA) funded this project (FAA-692M15-22-T-00017) to the University of Dayton Research Institute (UDRI) to study the battery damage behavior under high-speed impact conditions relevant to aircraft speed (50 to 300 mph). Broadly, the objective was to conduct testing of the commercial-off-the-shelf (COTS) batteries in different formats (e.g., pouch & cylindrical) and chemistry in fully charged conditions against rigid stainless steel, simulating crash scenarios between aircraft and hard surfaces. The study found that battery cells without structural protection can barely survive a collision on a stainless steel plate when the battery speed is 50 mph. At 300 and 100 mph, cells sustained either major damage or resulted in thermal runaway. Structural protection, which needs further optimization, was determined to protect battery cells up to 150 mph. Although data is limited, the information contained in this report is encouraging.

1 Introduction

Lithium-ion batteries (LIBs) are the most likely energy storage for next-generation electric aircraft due to their high energy density, power, cycle life, and low self-discharge (Joshi & et al., 2020). However, the high energy density and quick energy release ability of LIBs pose a significant safety risk (fire and explosion) for aircraft when the battery is overheated, overcharged, short-circuited, or damaged due to impact (Joshi & et al., 2020; Kermani & Sahraei; Feng & et al., 2020; Yang & et al., 2021). The battery-specific energy density (ED) should serve as the basis for the threat of TR as suggested by Lamb et al. (Lamb & et al., 2021) . Ryan et al. (Ryan, Xiao-Guang, & Chao-Yang, 2022) applied the concept of measuring adiabatic cell temperature (T_{ad}) to illustrate the threat of short-circuit for the major LIB chemistries, as shown in Figure 1 (Ryan, Xiao-Guang, & Chao-Yang, 2022). Figure 1a shows that the adiabatic temperature is achieved by cells of varying specific energy if 10 or 20% of energy is released as heat through short-circuit discharge in 25 °C ambient. Specific energy ranges are shown for common LIB cathodes when paired with a graphite (Gr) anode (LFP/LMO,] LCO, NCA, and NCM111 to NCM811). A battery system with ED <200 Wh/kg ((e.g., lithium iron phosphate (LFP)/lithium manganese oxide (LMO) or lithium cobalt oxide (LCO) cathodes with Gr anodes and organic liquid electrolyte)) with 20% energy release will increase system temperature below safe temperature (~160°C) and possess the low probability of TR. Additionally, LIB systems with higher ED (lithium nickel aluminum cobalt oxide (NCA) and lithium nickel manganese cobalt oxide (NMC) cathode chemistries) of 200 – 300 Wh/kg with 20% energy release during electrical shorting will push battery temperature (~240°C) to a high risk of TR. Figure 1b shows that, as the ED of the battery increases, the battery will afford to release either only a smaller fraction of energy stored or need a more robust thermal management system (TMS) to cool down the battery as heat is released during electrical shorting upon damage. The TMS for the commercial LIB systems is designed for regular operation and not for TR events. In a TR event, heat release is not only extremely high, but the heat release rate is rapid and beyond the cooling capability of TMS (Ryan, Xiao-Guang, & Chao-Yang, 2022).

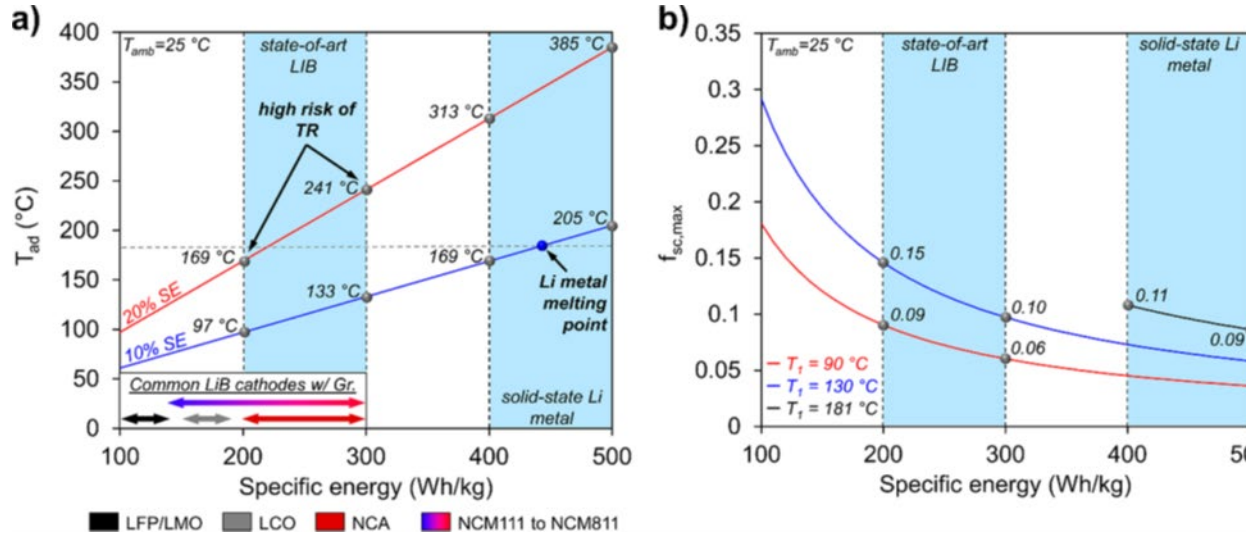


Figure 1. The threat of short-circuit for current and future batteries

Equation 1 offers a roadmap for safe battery design by considering the fundamental dependencies of the rate of temperature rise during short-circuit events, where ‘n’ is the discharge C-rate, ‘ED’ is the specific energy, and ‘Cp’ is the battery's specific heat capacity (materials) (Ryan, Xiao-Guang, & Chao-Yang, 2022). The rate of temperature in a battery increases with an increase in ‘n’ and ‘ED’ but adopting a strategy to reduce TR chances by reducing ‘n’ and ‘ED’ will significantly negate the battery's power and power delivery time.

$$dT/dt \propto nSE/cp \quad 1$$

Beyond LIB chemistry and their level of charge, the survivability of LIB toward mechanical damage and its safety depends on. but is not limited to, the types of cells (cylindrical vs. prismatic), cell casing used (metallic vs. plastic), and single-cell capacity ((Ampere hour (Ah)) of cells. Some basic parameters of typical battery cells that can be useful for electric aircraft power systems are shown in Table 1 (Peiyi & et al., 2020). As shown in Table 1, prismatic and pouch cells can be manufactured with a large capacity of up to 300 Ah. With the larger unit cell capacity of prismatic and pouch cells, the need for TMS becomes more stringent. Also, mechanically weak plastic cell casing makes pouch cells more susceptible to mechanical damage. However, the advantages of pouch cells over cylindrical and prismatic cells are less packaging weight, and cost. Yet. another advantage of using the pouch cell format is the dense packing of individual cells to build the battery modules. The dense packaging of cells to make battery modules is particularly significant for applications such as aircraft with space constraints. Regarding heat dissipation, a critical parameter to design thermal management to ensure battery

safety, a larger surface area, and a smaller cross-section thickness (thinner cells) such as in pouch cells can be advantage in facilitating faster heat dissipation but actual heat dissipation rates varies with cell formats and it's hard to prove a distinct advantage of one format over other as shown in (Figure 2, (Zheng, 2024)). Figure 2 shows temperature characteristics of LIBs with different formats under convective cooling conditions. Figure 2 (a & b) show temperature distribution and radial temperature distribution of an 18650 cell at the end of discharge at the end of 1C discharge and under different discharge rates respectively. Figure 2 (c) shows temperature distribution of a large cylindrical cell (diameter of 32 mm and length of 113 mm) at the end of a 70-A state of charge (SOC)-neutral pulse cycle. Figure 2 (d & e) show simulated and measured temperature distribution of a 20-Ah NMC pouch cell under 5-C discharge when $t = 250$ and 667 s, respectively. Figure (f & g) respectively show temperature distribution and 3D visualization of the temperature distribution of a prismatic cell at the end of 1C discharge.

Table 1. Basic parameters of three typical battery cells

Manufacturer	Configuration	Geometry [mm]	Voltage [V]	Capacity [Ah]	Specific power [W/kg]	Weight [g]
Panasonic	cylindrical	18.5 (dia)×65.3(L)	3.6	3.2	120	48.5
Hitachi	prismatic	148×91×26.5	3.6	28	2300	720
Kokam	pouch	462×327×15.8	3.6	240	360	4780

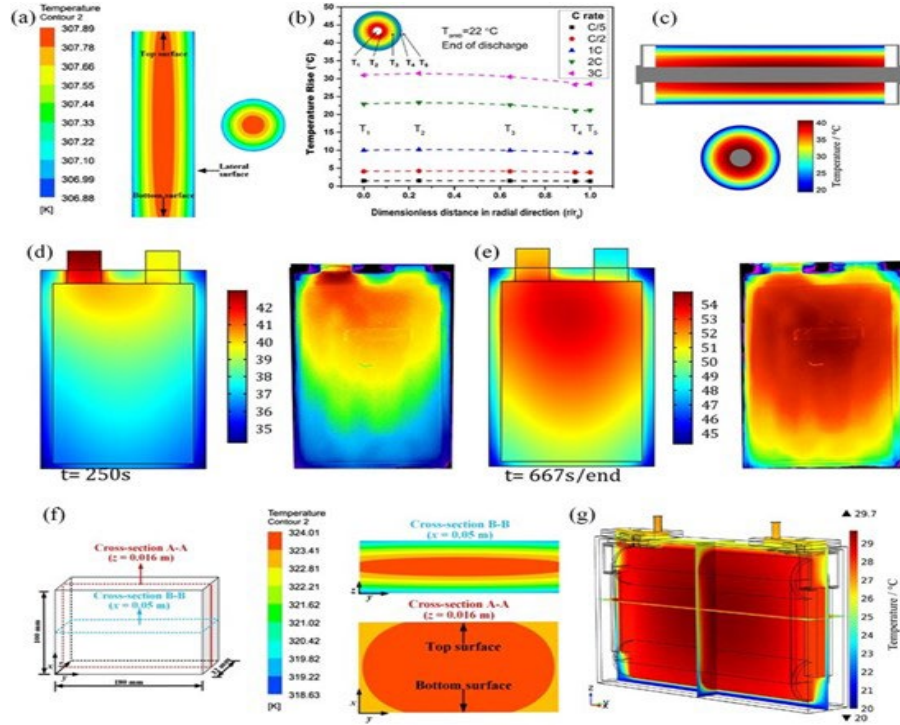


Figure 2. Temperature characteristics of Li-ion cells with different formats under convective cooling conditions.

Despite many advantages of pouch vs. prismatic/cylindrical cells in terms of packaging (cell casing) weight, the container of the battery must have the strength and rigidity necessary to resist the abuses (e.g., mechanical crush, impact, puncture, etc.) without resulting in a risk of fire. For instance, as per UL1642 guidelines, a battery must survive a 3000-pound (13 kN) load (32 mm diameter piston). UL1642 also suggests a projectile test, as the type of cell casing (metal-cylindrical or prismatic) vs. plastic/metal laminate (pouch) can generate different types of ejecta, in which no ejecta of a burning cell should escape a stainless steel mesh (25.4 mm opening, 0.43 mm wire diameter). In 2015, the Oak Ridge National Laboratory (ORNL), DOE published a review (Turner & et al., 2015) of “crash models for advanced automotive batteries” under a DOE project 2088-V805-14 for the National Highway Traffic Safety Administration (NHTSA). Some recent work that further advanced the understanding of the failure mechanism of Li-ion under loads includes but is not limited to (Yu & et al., 2021) studied failure under high transient impact employing a Machete (hammer) impact test system. Kister et al. studied the effect of different speed of mechanical load and failure scenarios of impacted Li-ion cells (Kisters & et al., 2017), and Ruiz et al. reviewed different abuse testing including mechanical testing (Ruiz & et al., 2018).

The above discussion suggests it may be necessary to develop damage-proof battery enclosures when using high-energy, high-power batteries with minimum safety concerns. The damage-proof battery enclosure should protect LIB under a high-speed collision or other mechanically damageable scenarios and add minimal weight to the overall battery system. To develop such a protective battery enclosure, we needed to understand the failure mechanism of LIB cells under high-speed projectile impact with and without a protective enclosure. The projectile tests conducted for this project were novel and different from the UL1642 projectile test described above. In the current project, a limited number of the projectile tests involved launching battery cells at aircraft speed and impacting on a steel surface at various angles, mimicking an aircraft crash. Note that a more detailed study is warranted to reach the most effective solution. For this project, we conducted high-speed projectile tests on two formats (pouch and cylindrical) and two LIB chemistries – lithium nickel manganese cobalt oxide (NMC) and LFP cathodes- from 300 mph to 50 mph. The results are summarized and discussed in this report.

2 Types of LIB cells and high-speed impact test procedure

This section provides details of tested LIB cells and high-speed impact test procedure.

2.1 Types of tested LIB cells for high-speed impact test survival

We anticipated that LIB with plastic pouch cell casing would be more vulnerable to impact damage than prismatic and cylindrical (steel or aluminum) cell casing. In this test, a fully charged (100% SOC) high-energy (energy = 250 Wh/kg, power = 300 W/kg) and high-power (energy = 100 Wh/kg, power = 500 W/kg) cells with plastic pouch and steel cylindrical cell casing were launched into a rigid steel plate using a compressed-gas gun. LCO/NMC and LFP cathodes constituted energy and power cells. The impact velocities varied between 50 mph and 300 mph to determine how the battery responds at increasing impact velocities. The battery cells were launched in these tests to hit the stainless steel target at 0 and 90 degrees. Response of LIB cells upon impact was recorded using a high-speed camera operating at a minimum framing rate of 10,000 frames/sec. Whenever the impact did not lead to cell TR or if the cell did not shatter into pieces, the temperature and voltage of the cell were stored for several months. After the allotted time, if voltage and temperature did not change, the cells were subjected to discharge to determine if the impact led to any forced discharge of the battery. If a forced discharge was detected, that may indicate a failure of internal cell components. Failure of internal cell components was characterized visually and using electrical characterizations.

Table 2 lists details of the tests completed for this project. Fully charged LIB cells with different chemistries (NMC and LFP), formats (pouch and cylindrical), and designs (energy and power) were tested at three different speeds (300, 100, and 50 mph). The tested cells confirmed their specified maximum charge capacities, corroborating that they were high-quality cells.

Noteworthy is that all the cells tested at 50 mph survived, which can provide confidence that if tests were conducted below 50 mph all cells would survive. We conducted a few tests on smaller pouch cells with 2Ah capacity but kept the speed of 100 mph the same. Test 11 demonstrates what can happen if smaller cells with similar LIB chemistry are impacted at the same speed as larger cells, as shown in test 7, for example.

Table 2. High-speed impact test variables

Test number	Cell capacity (Ah)	Cell type	Speed of impact (mph)	Impact angle (deg)
Test 1	5	NMC pouch (energy)	300	0
Test 2	4	NMC pouch (power)	300	0
Test 3	3.4	NMC 18650	300	0
Test 4	1.5	LFP 18650	300	0
Test 5	2x2	NMC pouch in Al box	300	0
Test 6	3.4	LFP 26650 (power)	100	90
Test 7	2x5	NMC pouch (energy)	100	90
Test 8	2x4	NMC pouch (power)	100	90
Test 9	3.4	NMC 18650 (energy)	100	90
Test 10	1.5	LFP 18650 (power)	100	90
Test 11	2x2	NMC pouch (energy)	100	90
Test 12	2x5	NMC pouch in Al box	100	90
Test 13	2x5	NMC pouch (energy)	50	90
Test 14	2x4	NMC pouch (power)	50	90

Test number	Cell capacity (Ah)	Cell type	Speed of impact (mph)	Impact angle (deg)
Test 15	3.4	NMC 18650 (energy)	50	90
Test 16	1.5	LFP 18650 (power)	50	90
Test 17	3.4	LFP 26650 (power)	50	90
Test 18	2x5	NMC pouch in Al box	50	90

2.2 High-speed impact test procedure

Figure 3 shows the impact test assembly. UDRI employed 4-inch to 7-inch bore compressed-gas guns (Figure 3a) to launch the batteries held by either a foam sabot (Figure 4) or the aluminum (Al) box into a rigid steel target (Figure 3b). Impact test assembly also includes Laser-Photodetectors to measure impact velocity, an HBM Data Acquisition System (16-bit recording at 1Mhz sampling rate), and Vision Research digital high-speed cameras Model V1611 and V2012 to record top, side, and front views of test articles before and after impact. The post-impact test temperature measurement was carried out using an infrared (IR) heat sensor.

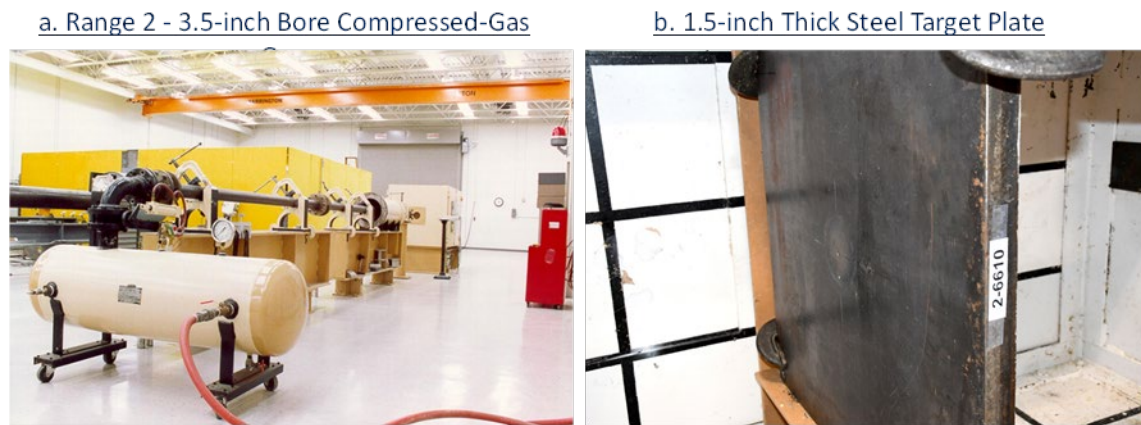


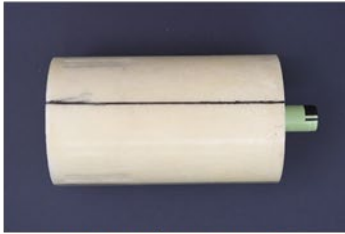
Figure 3. Impact test machine (a) and stainless steel target (b)

Figure 4 shows part of the test assembly that holds and accelerates battery cells to reach desired impact speeds and angles. Sabots, used to hold battery cells and provide acceleration, are made of polyurethane foam with different densities (4 or 6.6 lb/ft³). The sabot does not provide significant mechanical protection to the battery during impact. For every impact test, a new sabot was built.

Pouch and cylindrical cells cast in polyurethane foam with cell protruding



~4 lb/ft³ foam density



~6.6 lb/ft³ foam density

Launched in Sabot that is stripped away



Figure 4. Display of battery cells, aluminum box, polyurethane foam sabot

Other test variables included impact velocity (50, 100, and 300 mph) and impact angles (0 and 90 degrees). Each test was recorded with high-speed cameras (10,000 frames/sec) to examine the battery response during the impact. After the high-speed crash of the Li-ion cell, pictures of damage were captured, and the post-test battery conditions, such as temperature and fire, were recorded and discussed in the following sections.

3 Test results and discussion

This section provides results (impact resiliency) and discusses impact tests conducted on various LIB cells at different speeds and angles of impact.

3.1 Impact resiliency of LIB cells at 300 mph

Figure 5 shows the top of the battery cell (Task 1-Task 5) hitting the stainless steel target at 90 degrees. At 300 mph, none of the cells survived, as summarized in Table 3 and shown in Figures 6 to 10. Figure 6 (Test 1) shows the 5Ah energy pouch cells disintegrating into pieces and no fire was observed. A similar result was observed for 4 Ah power pouch cells, as shown in Figure 7 (Test 2).

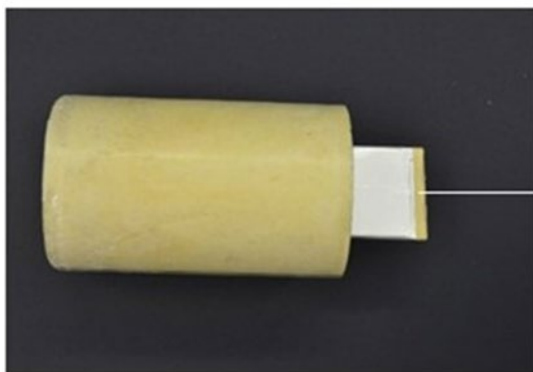


Figure 5. The top of the cell hit the stainless steel target at 90 degrees

Table 3. Summary of 300 mph impact tests (Test 1 – 5)

Shot No.	Test #	Battery ID	Battery type	Battery weight (g)	Battery pkg weight w/foam (g)	Impact velocity (ft/s)	Impact velocity (mph)	Results
2-6609	1	LiPo 725001 15 5Ah	NMC pouch, energy cell	79.85	140.13	433	295	Pouch disintegrated in multiple pieces no recorded temperature .
2-6610	2	PL-674513 5 4Ah	NMC pouch, power cell	86.15	145.32	441	301	Pouch disintegrated in multiple pieces no recorded temperature .
2-6612	3	18650 3.4Ah	NMC energy, cylindrical	45.46	146.85	396	270	Front half of battery crushed. Pin protrudes

Shot No.	Test #	Battery ID	Battery type	Battery weight (g)	Battery pkg weight w/foam (g)	Impact velocity (ft/s)	Impact velocity (mph)	Results
								out back of battery.
2-6613	4	18650 1.5Ah	LFP power, cylindrical	38.80	138.05	432	295	Front half of battery crushed.
2-6614	5	2Ah	2x NMC pouch enclosed in AL box	251.40	No Foam	452	308	Housing buckled. Edges of impacted cap broke off.

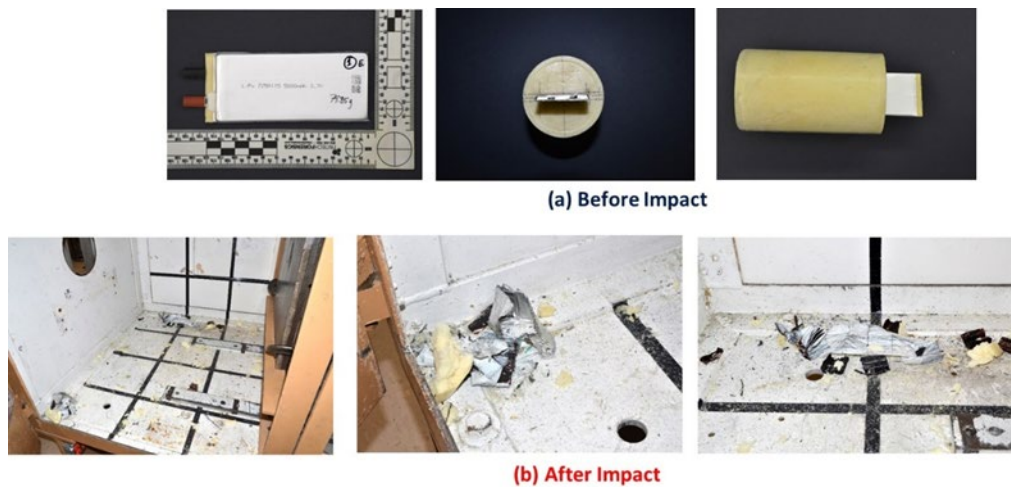


Figure 6. Fully charged Li-ion cells before (a) and after (b) crash (300 mph)

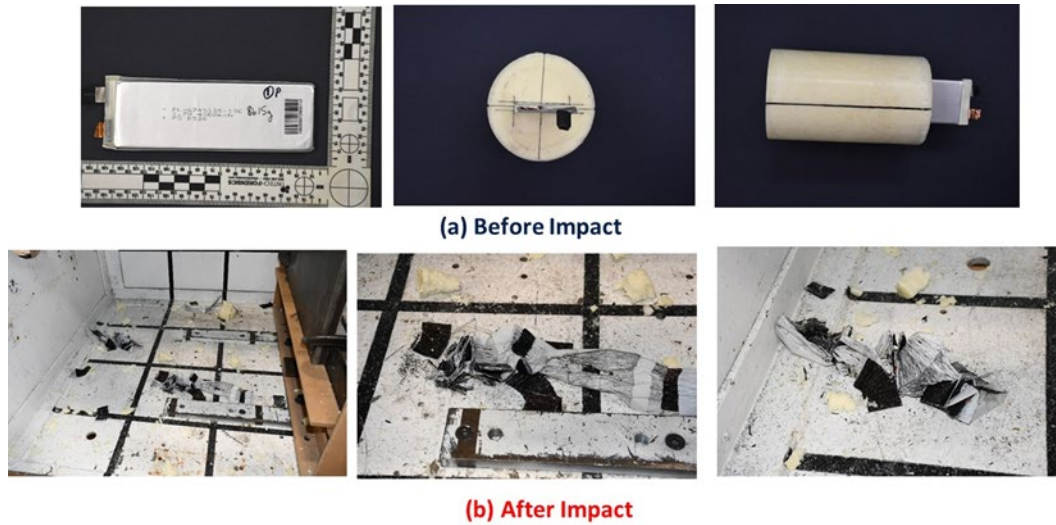


Figure 7. Fully charged Li-ion cells before (a) and after (b) crash (300 mph)

Cylindrical cells (Figure 8 and Figure 9) showed different behavior than pouch cells (Figure 6 and Figure 7) primarily due to differences in case material. The former used stainless steel, and the latter used plastics. Figure 8 (Test 3) shows that most parts of the high-energy cylindrical 18650 cell (NMC, cathode) and the internal rod used as electrode current collector upon 300 mph impact at stainless steel remained together. They became a source of cell shorting and battery fire (TR). A temperature of more than 900°C was recorded on the burning NCR 18650 cell.

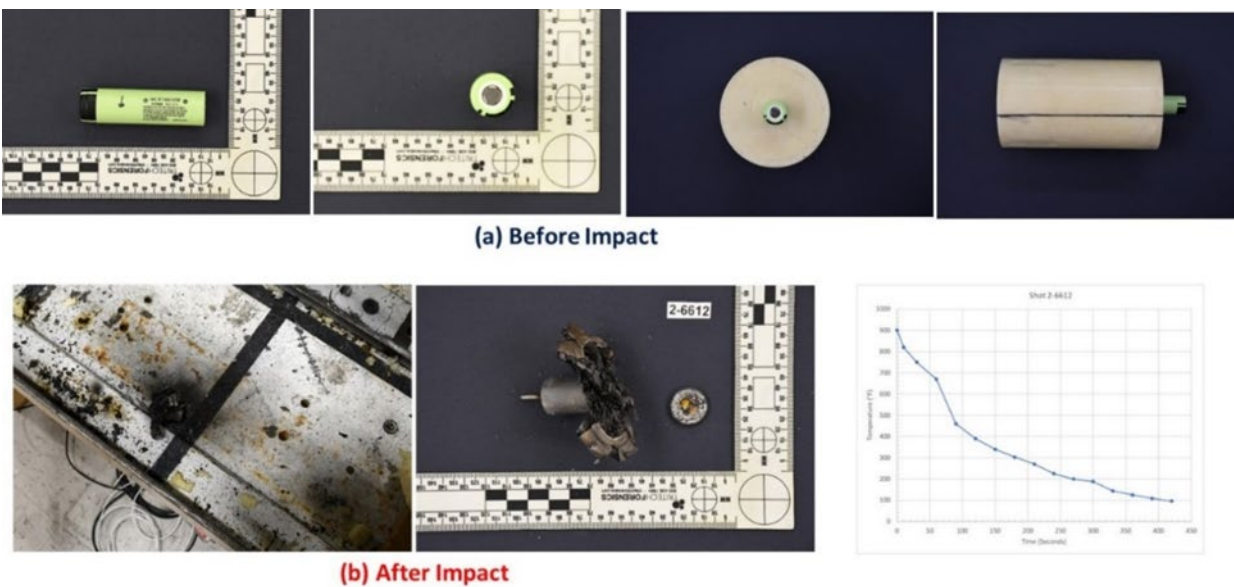


Figure 8. Fully charged Li-ion cells before (a) and after (b) crash (300 mph)

Figure 9 (Test 4) shows similar cell component damage on the power cylindrical cell (LFP, cathode) as observed for the NMC 18650 cell. Still, the lack of a metallic rod as an electrode current collector in the LFP cell may have avoided electrical shortening and battery fire. The maximum temperature observed in the case of LFP cells was just above 250°C.

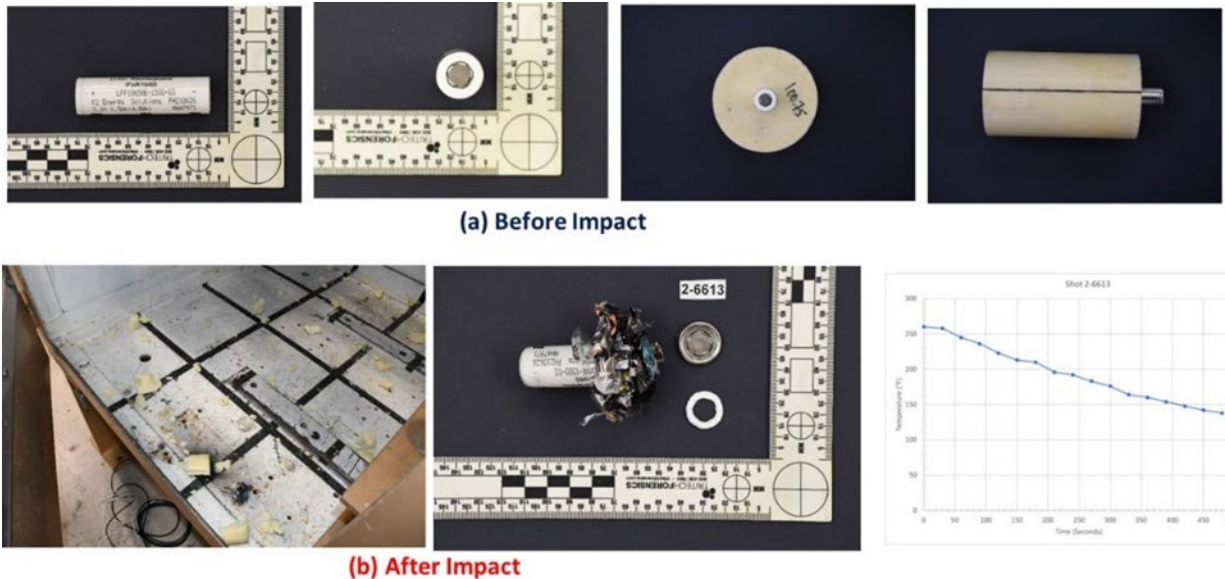


Figure 9. Fully charged Li-ion cells before (a) and after (b) crash (300 mph)

After observing the full destruction of cells when they crashed at 300 mph, we decided to test cells enclosed in an aluminum box with a wall thickness of 2.5 mm for extra protection to prove the relevance of using a secondary enclosure. Figure 10 demonstrates that the aluminum box provides crash protection to pouch cells, but the cells are still damaged. The maximum temperature observed was 215°C, but there was no battery fire.

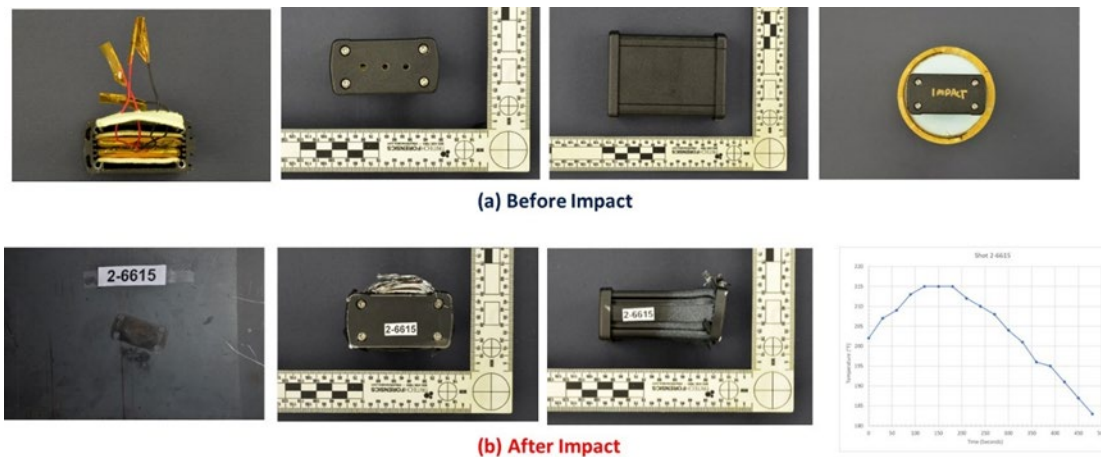


Figure 10. Fully charged two pouch Li-ion (Al box) before (a) after (b) crash (300 mph)

3.2 Impact resiliency of LIB cells at 100 mph

Figure 11 shows the side of the battery cell (Test 6 - Test 18) hitting the stainless steel target at 0 degrees. At 100 mph (Test 7 - Test 12; Table 3), the “large format pouch” cells ((5 Ah energy cell (Test 7) and 4 Ah power cell (Test 8)) caught fire after hitting the target. Small format pouch cells (2 Ah – Test 11) survived the impact. All cylindrical cells (Test 6, 9, and 10) did not catch fire, but the cell casing was damaged to varying degrees, as summarized in Table 4.

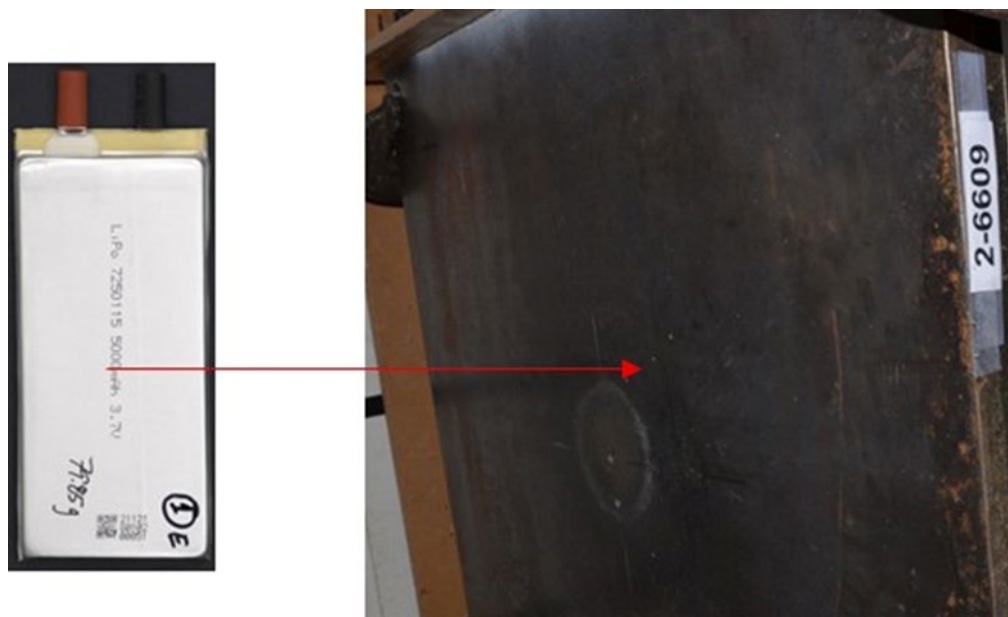


Figure 11. The body of the cell hit the stainless steel target at 90 degrees

Table 4. Summary of 100 mph impact tests (Test 6 – 12)

Shot No.	Test #	Battery ID	Battery type	Battery weight (g)	Battery pkg weight w/foam (g)	Impact velocity (ft/s)	Impact velocity (mph)	Results	Max temp (C°) – after impact
2-6682	6	26650 3.4Ah	LFP Energy, cylindrical (red)	86.43	146.41	173	118	Battery was RF after test; no temperature recorded. Battery flattened one side. 0.896” post-test. Battery ends cracked - liquid coming from cracks.	RT
5-3745	7	5Ah	2x NMC pouch (baseline) energy	170.24	427.73	178	121	Battery smoking/ glowing red	-1100 °C

Shot No.	Test #	Battery ID	Battery type	Battery weight (g)	Battery pkg weight w/foam (g)	Impact velocity (ft/s)	Impact velocity (mph)	Results	Max temp (C°) – after impact
								after shot.	
5-3749	8	4Ah	2x NMC pouch (baseline) power	178.66	418.65	172	117	Battery started smoking after shot/flames ignited. Started to record temp – 2 min after shot/fire went out.	-600 °C
2-6685	9	18650 3.4Ah	NMC Energy cylindrical (green)	45.71	148.21	172	117	Battery was RT after test no temperature recorded. Battery flattened on	RT

Shot No.	Test #	Battery ID	Battery type	Battery weight (g)	Battery pkg weight w/foam (g)	Impact velocity (ft/s)	Impact velocity (mph)	Results	Max temp (C°) – after impact
								one side 0.72” pretest 0.620” posttest.	
2-6686	10	18650 1.5Ah	LFP Power, cylindrical (white)	38.82	132.96	170	116	Projectile popped out of sabot. Battery was RT after shot but was warm when retrieved from chamber. Started recording temperature 13 min after test. Battery	RT

Shot No.	Test #	Battery ID	Battery type	Battery weight (g)	Battery pkg weight w/foam (g)	Impact velocity (ft/s)	Impact velocity (mph)	Results	Max temp (C°) – after impact
								flattened on one side 0.632” posttest.	
2-6692	11	2Ah	2x NMC pouch (baseline)	87.25	236.19	169	115	Battery was RT after test no temperature recorded. No visible damage on battery	RT
5-3747	12	5Ah	2x NMC pouch enclosed in AL box	379.96	620.75	185	126	Battery was RT after test no temperature recorded. Battery popped out	RT

Shot No.	Test #	Battery ID	Battery type	Battery weight (g)	Battery pkg weight w/foam (g)	Impact velocity (ft/s)	Impact velocity (mph)	Results	Max temp (C°) – after impact
								at sabot slightly hit corner then hit flat. Box endcaps cracked; box is compromised and bent.	

Figure 12 (Test 6) shows the after-impact damage on the LFP 26650 cylindrical cell. The battery was RT after the test, and no temperature was recorded. However, the battery flattened on one side (0.896"), and the impact cracked open a portion of the casing that allowed liquid electrolyte to emanate from the cracks. After some time, the cell dried and became nonfunctional, but there was no battery fire. A similar observation was recorded (Figure 13 and Figure 14) for 18650 cylindrical cells (NMC – Test 9 and LFP – Test 10).

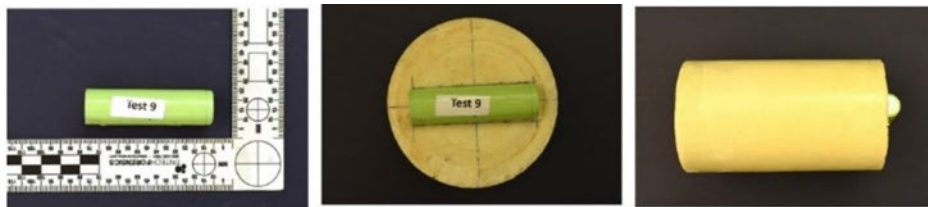


(a) Before Impact

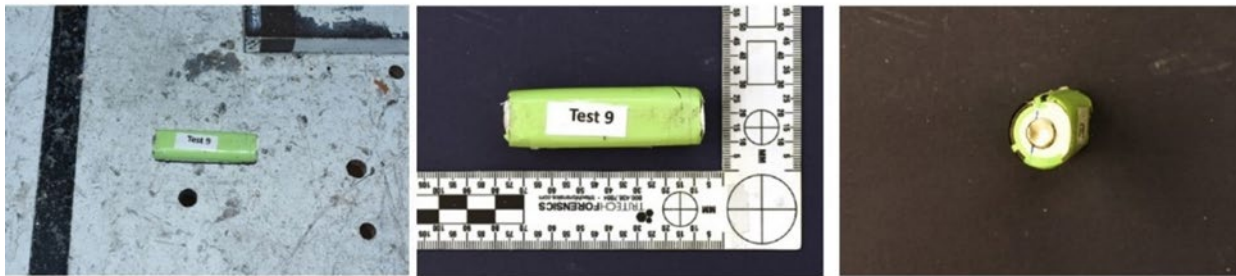


(b) After Impact

Figure 12. Fully charged LFP 26650 slightly flattens after crash (100 mph)



(a) Before Impact



(b) After Impact

Figure 13. Fully charged NCR 18650 slightly flattens after crash (100 mph)

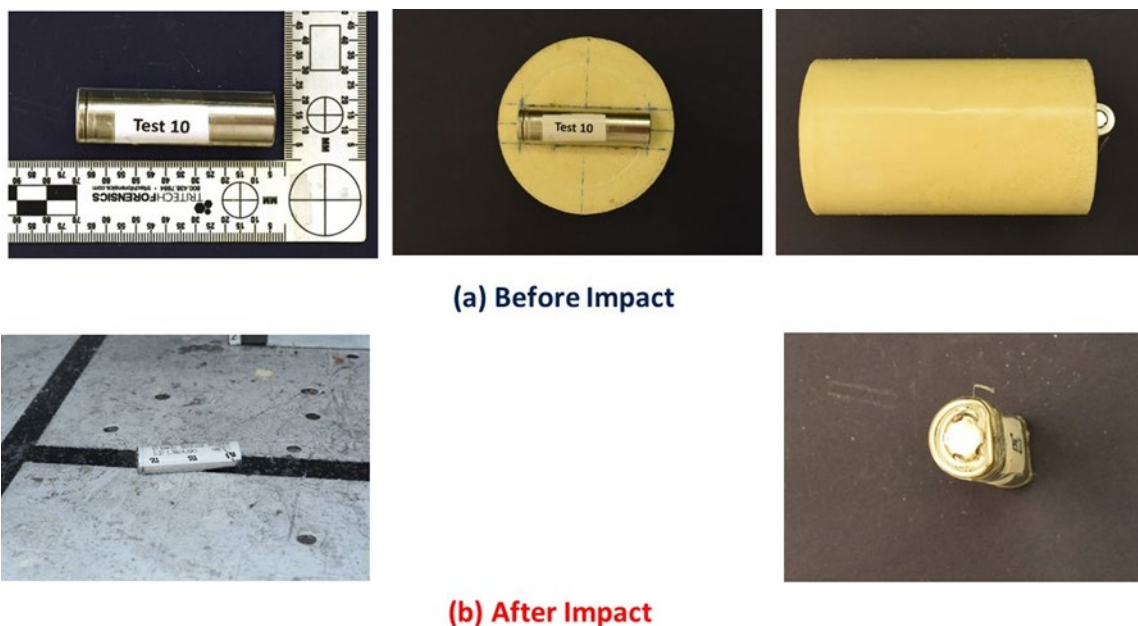


Figure 14. Fully charged LFP 18650 slightly flattens after crash (100 mph)

Figure 15 (Test 7) and Figure 16 (Test 8) show the after-impact battery fire damage on the fully charged large format 5 Ah energy and 4 Ah power cells, respectively. However, the small format pouch cell (2Ah) (Test 11), as in Figure 17, survived the 100 mph crash. Results from Figure 15, Figure 16, and Figure 17 suggest that larger format cells are more susceptible to crash damage, but more work must be completed to confirm this conclusion. Irrespective of cell format, real-life battery design needs secondary protection to ensure crash safety. We confirmed the need for secondary protection by crashing large format cells (5 Ah energy cell) enclosed in a 2.5 mm wall-thick Al box (Test 12). 5Ah cells enclosed in an Al box survived a 100 mph crash at stainless steel, as shown in Figure 18 and Table 4. There was slight damage to the Al box but no damage to the enclosed battery.

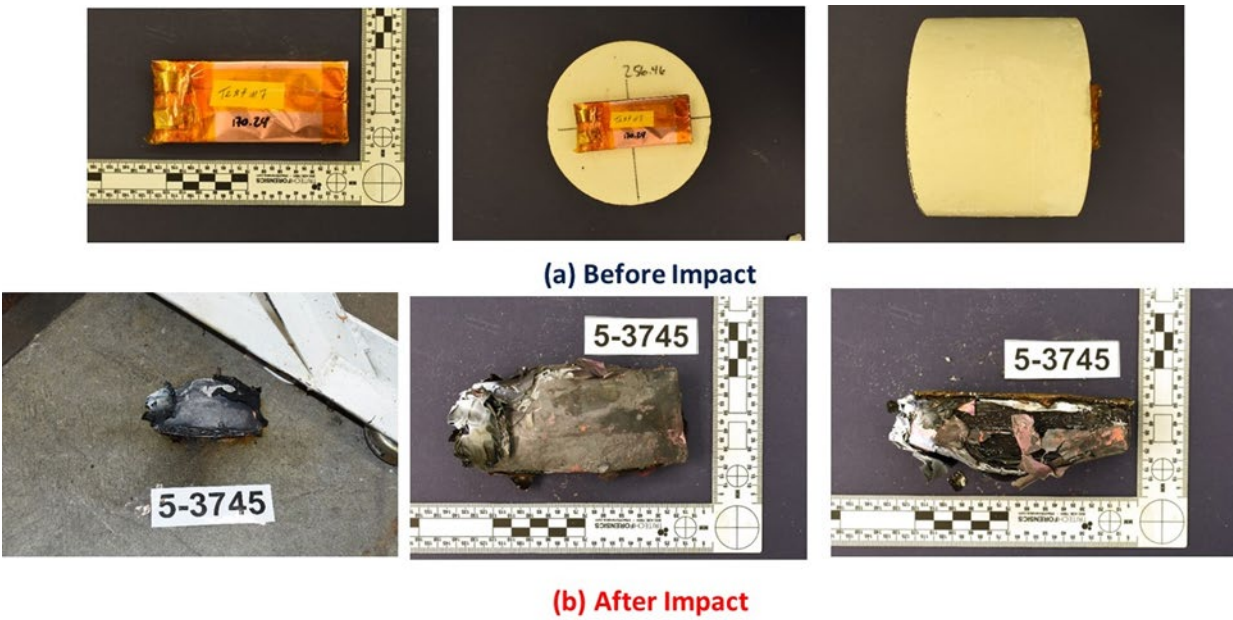


Figure 15. Fully charged 5Ah energy pouch cells caught fire after crash (100 mph)

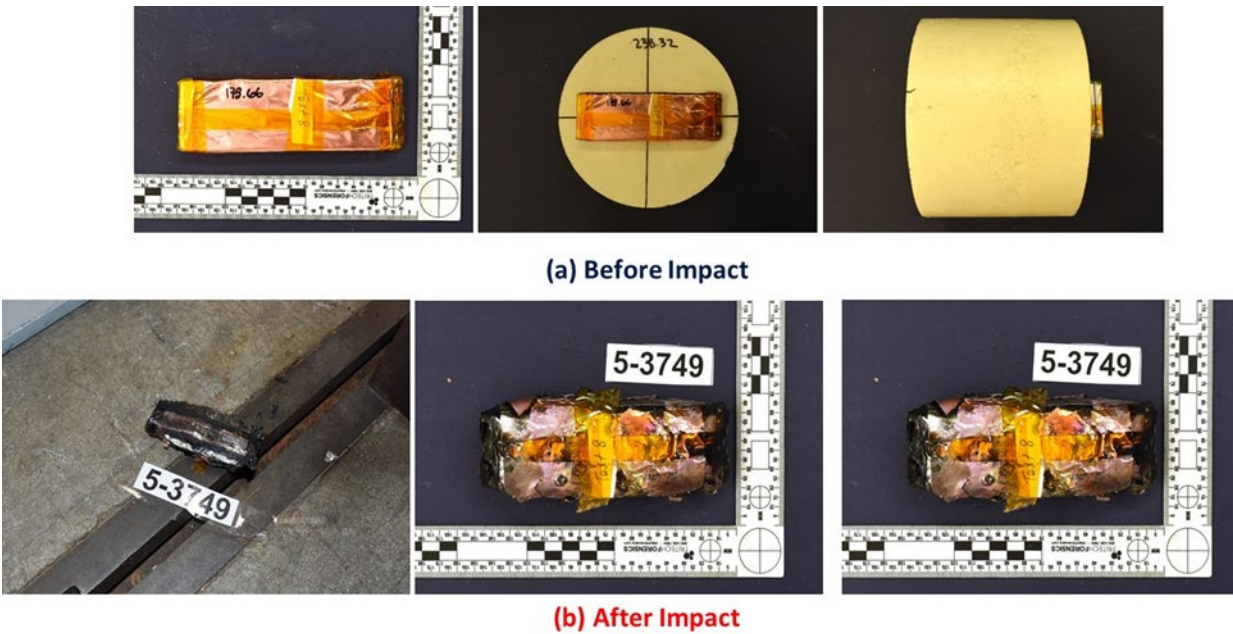


Figure 16. Fully charged 4Ah power pouch cells caught fire after crash (100 mph)

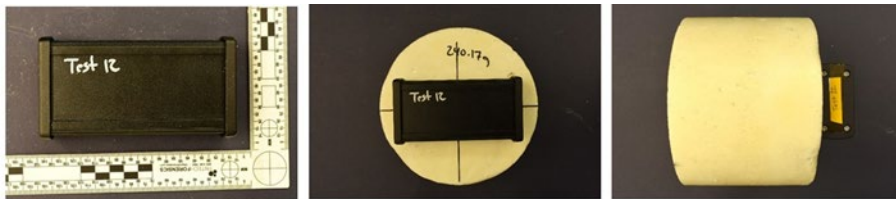


(a) Before Impact

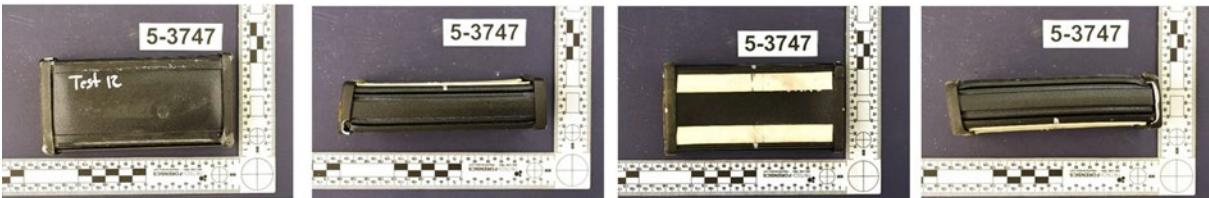


(b) After Impact

Figure 17. Fully charged 2Ah energy pouch cells after crash (100 mph)



(a) Before Impact



(b) After Impact

Figure 18. Fully charged 5Ah energy pouch cells enclosed in Al box after crash (100 mph)

3.3 Impact resiliency of LIB cells at 50 mph

At 50 mph (Test 13 – Test 16; Table 5), all the cells in large format pouch, cylindrical cells, and pouch cells enclosed in the Al box survived except for some minor bending of Al enclosures, flattening of cylindrical cell case and bending of pouch cells. The physical observations and the

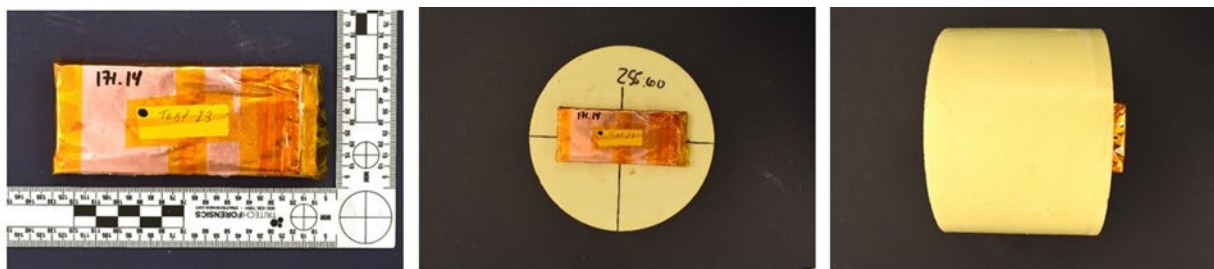
visuals of test results for Tasks 13 – 18 are shown in Figure 19, Figure 20, Figure 21, Figure 22, Figure 23 and Figure 24, showing that the crash with 50 mph at stainless steel may not damage cells to the extent that leads to a battery fire. However, minor electrical shorting or electrolyte leakage is possible if the cell casing is damaged and loss of electrochemical performances, which was confirmed through post-impact test electrochemical characterization.

Table 5. Summary of 50 mph impact tests (Test 13 – 18)

Shot No.	Test #	Battery ID	Battery type	Battery weight (g)	Battery pkg weight w/foam (g)	Impact velocity (ft/s)	Impact velocity (mph)	Results	Max temp (C°) – after impact
5-3746	13	5Ah	2x NMC pouch (baseline) Energy	171.14	428.18	77	52	Battery slightly bent. Battery was RF after test; no temperature recorded.	RT
5-3750	14	4Ah	2x NMC pouch (baseline) Power	179.02	431.88	70	48	Battery was RT after test no temperature recorded. No visible damage on battery.	RT
2-6687	15	18650 3.4Ah	NMC Energy cylindrical (Green)	45.89	145.81	65	44	Battery was RT after test no temperature recorded.	RT

Shot No.	Test #	Battery ID	Battery type	Battery weight (g)	Battery pkg weight w/foam (g)	Impact velocity (ft/s)	Impact velocity (mph)	Results	Max temp (C°) – after impact
								Battery flattened on one side 0.725” pretest 0.683” posttest .	
2-6688	16	18650 1.5Ah	LFP Power, cylindrical (White)	38.37	138.29	65	44	Battery was RT after test no temperature recorded. Battery flattened on one side 0.715” pretest 0.675” posttest .	RT
2-6689	17	26650 3.4Ah	LFP power, cylindrical (Red)	86.48	147.87	68	46	Battery was RT after test no temperature recorded. Battery flattened on one	RT

Shot No.	Test #	Battery ID	Battery type	Battery weight (g)	Battery pkg weight w/foam (g)	Impact velocity (ft/s)	Impact velocity (mph)	Results	Max temp (C°) – after impact
								side 1.032” pretest 0.971” posttest .	
5-3748	18	5Ah	2x NMC pouch enclosed in AL box	379.91	618.59	83	57	Battery was RT after test no temperature recorded. Al box slightly bent.	RT



(a) Before Impact



(b) After Impact

Figure 19. Fully charged 5Ah energy pouch cells survived after crash (50 mph)

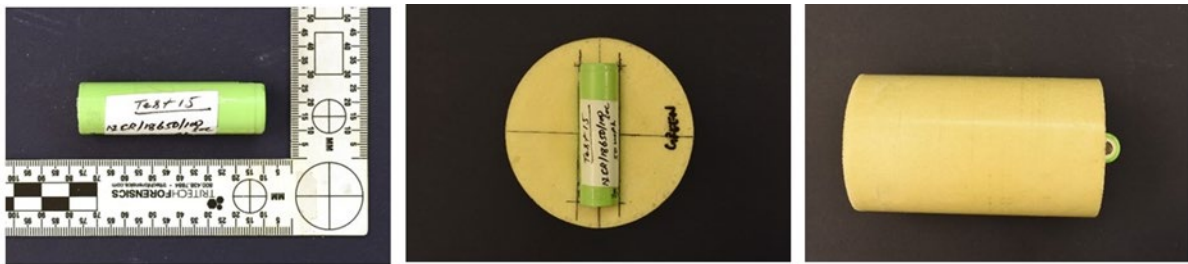


(a) Before Impact



(b) After Impact

Figure 20. Fully charged 4Ah power pouch cells survived after crashing (50 mph)



(a) Before Impact



(b) After Impact

Figure 21. Fully charged NCR 18650 was almost unaffected after crash (50 mph)



(a) Before Impact



(b) After Impact

Figure 22. Fully charged LFP 18650 was almost unaffected after crash (50 mph)



(a) Before Impact



(b) After Impact

Figure 23. Fully charged LFP 26650 was almost unaffected after crash (50 mph)

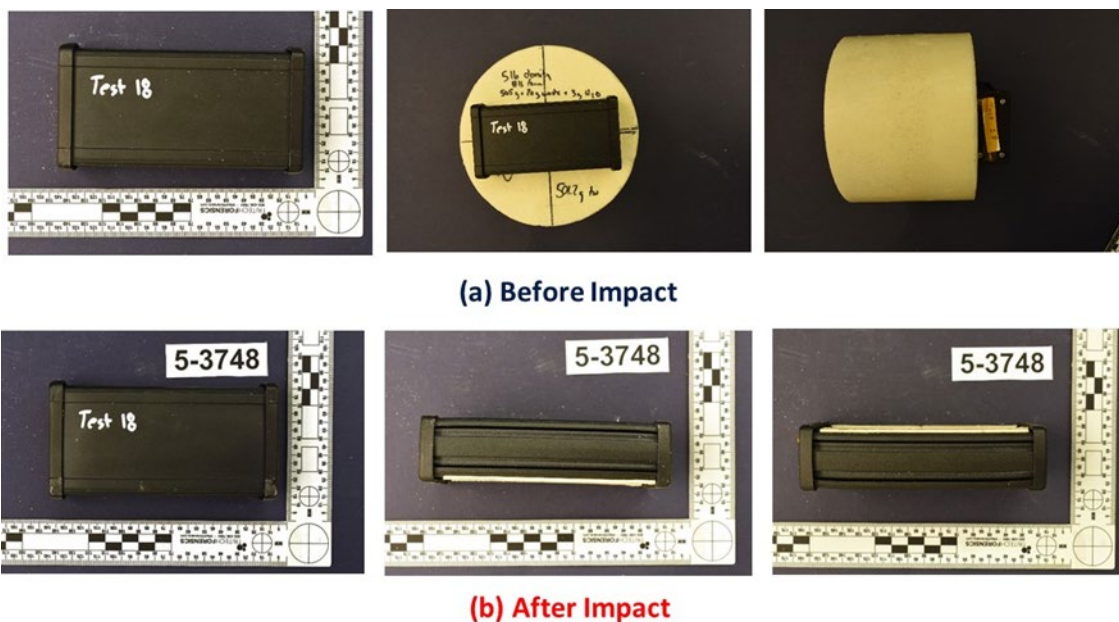
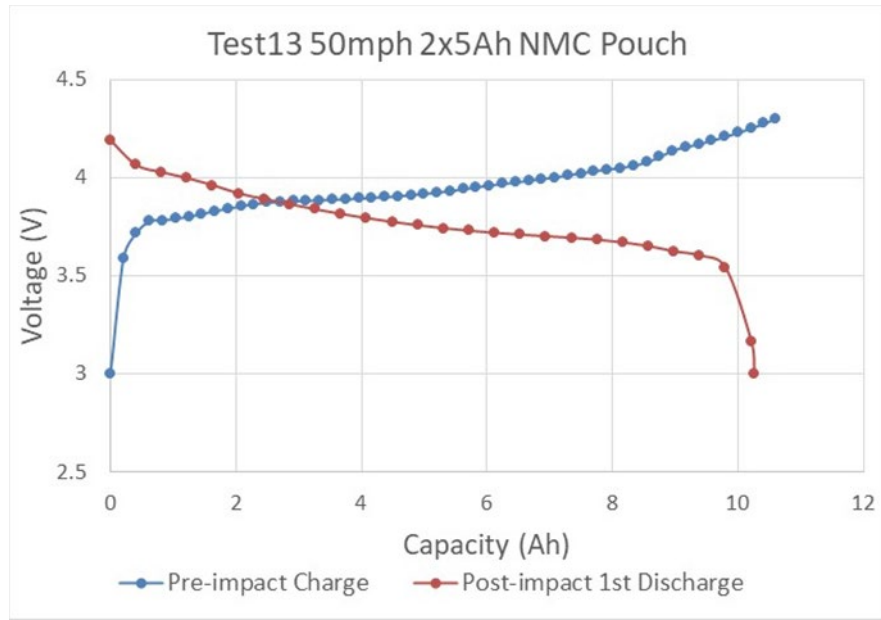


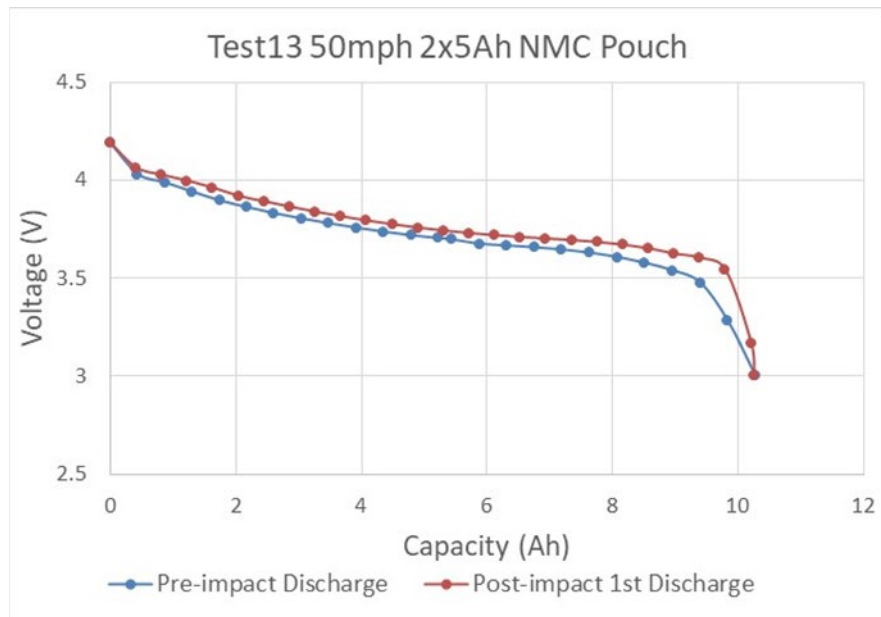
Figure 24. Fully charged 5Ah energy pouch cells (Al box) not affected after crash (50 mph)

The initial post-impact electrochemical test results on some cells are provided in this section (Figure 25, Figure 26, and Figure 27). However, the results, both physical damage/chances of battery fire and loss of electrochemical performances, can vary with the size of the battery pack, cell chemistry, level of charge, cell aging, etc. More research is needed to conclude the accuracy of these assumptions. The cell crash survivability at 50 mph may also suggest that these cells will likely pass the a 50ft drop test as the end speed of cells crashing into a target can be roughly 30 mph.

Figure 25 shows that a fully charged (100 SOC) energy cell stack (2x5Ah) has comparable pre-impact and post-impact (50 mph) cell capacities. The cell did not lose capacity after impact, indicating no physical damage to cell components.



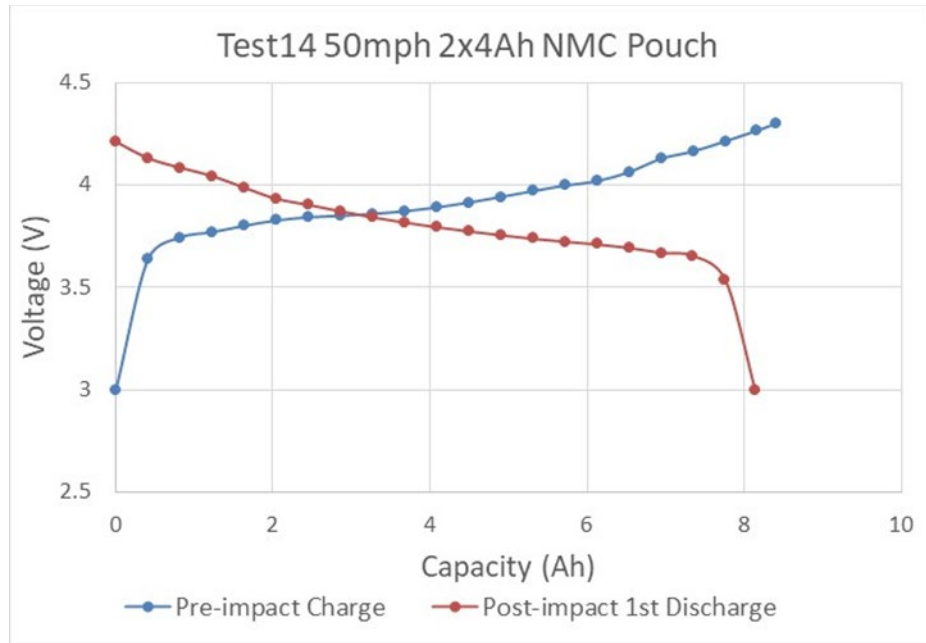
(a)



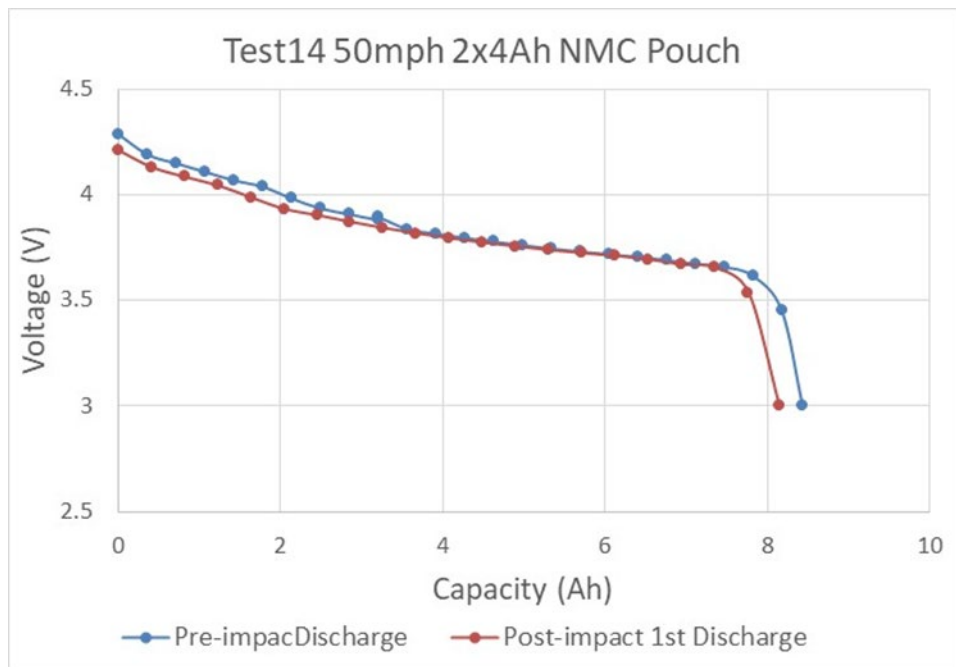
(b)

Figure 25. (a) Pre/post-impact discharge capacity (b) pre/post discharge 2 stacked cells

A similar result was obtained for a fully charged (100 SOC) power cell stack (2x4Ah) (Figure 26). This indicates that energy pouch cells (2x2Ah) survived a 50 mph impact on stainless steel in terms of physical and electrochemical damages.



(a)



(b)

Figure 26. (a) Pre/post-impact discharge capacity (b) pre/post discharge 2 stacked cells

As expected, fully charged energy cells enclosed in the Al box were also unharmed (Figure 27). Long-term cycling of these cells and cells from all other tests that did not catch fire has been completed, and the results are shown in the next section.

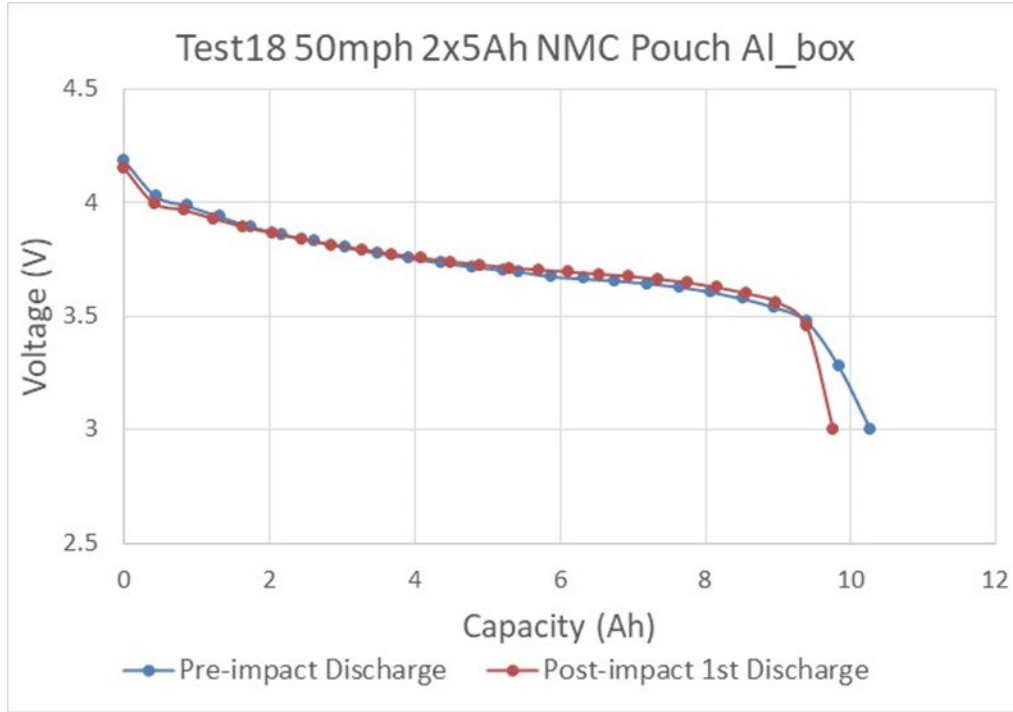


Figure 27. (a) Pre/post-impact discharge capacity (b) pre/post discharge stacked cells (Al box)

4 Post-impact testing electrical behavior of survived LIB cells

This section presents cell post-impact test features and the next steps in research and development to ensure battery safety for electric aircraft applications.

4.1 Post-impact features of LIB cells

Table 6 lists the tests conducted in the project with pass or fail remarks. Pass indicates the impact condition in which the cell, after impact, was able to cycle as a standard battery cell. Fail indicates the impact condition that led to permanent cell damage; either the cell went to TR or fractured in pieces or became nonfunctional due to internal damage or electrical connections. At 300 mph impact at a stainless steel target:

1. all pouch cells were shredded in pieces,
2. NMC 18650 cylindrical cells ended in TR, and
3. LFP 18650 cylindrical cells were severely damaged (labeled as fail).

At 100 mph, impact at a stainless steel target, cylindrical cells (NMC and LFP) were physically damaged but did not end in TR. However, both energy (5 Ah) and power (4 Ah) pouch cells went into TR. In a similar condition, a smaller pouch cell (2 Ah) survived and cycled for 100

cycles as a normal cell (Figure 28). At a 50 mph impact, none of the cells ended in TR; cylindrical cells suffered minor visible physical damage but could not be cycled, which may be due to some internal damage or electrical connections.

Table 6. List of tests conducted in this project with their post-impact cycling condition

Test #	Cell capacity (Ah)	Cell type	Speed of impact (mph)	Impact angle (deg)	Post-impact cycling condition
Test 1	5	NMC pouch (energy)	300	0	Fail
Test 2	4	NMC pouch (power)	300	0	Fail
Test 3	3.4	NMC 18650	300	0	Fail
Test 4	1.5	LFP 18650	300	0	Fail
Test 5	2x2	NMC pouch in Al box	300	0	Fail
Test 6	3.4	LFP 26650 (power)	100	90	Fail
Test 7	2x5	NMC pouch (energy)	100	90	Fail
Test 8	2x4	NMC pouch (power)	100	90	Fail
Test 9	3.4	NMC 18650 (energy)	100	90	Fail
Test 10	1.5	LFP 18650 (power)	100	90	Fail
Test 11	2x2	NMC pouch (energy)	100	90	Pass
Test 12	2x5	NMC pouch in Al box	100	90	Pass
Test 13	2x5	NMC pouch (energy)	50	90	Pass
Test 14	2x4	NMC pouch (power)	50	90	Pass
Test 15	3.4	NMC 18650 (energy)	50	90	Fail
Test 16	1.5	LFP 18650 (power)	50	90	Fail

Test #	Cell capacity (Ah)	Cell type	Speed of impact (mph)	Impact angle (deg)	Post-impact cycling condition
Test 17	3.4	LFP 26650 (power)	50	90	Fail
Test 18	2x5	NMC pouch in Al box	50	90	Pass

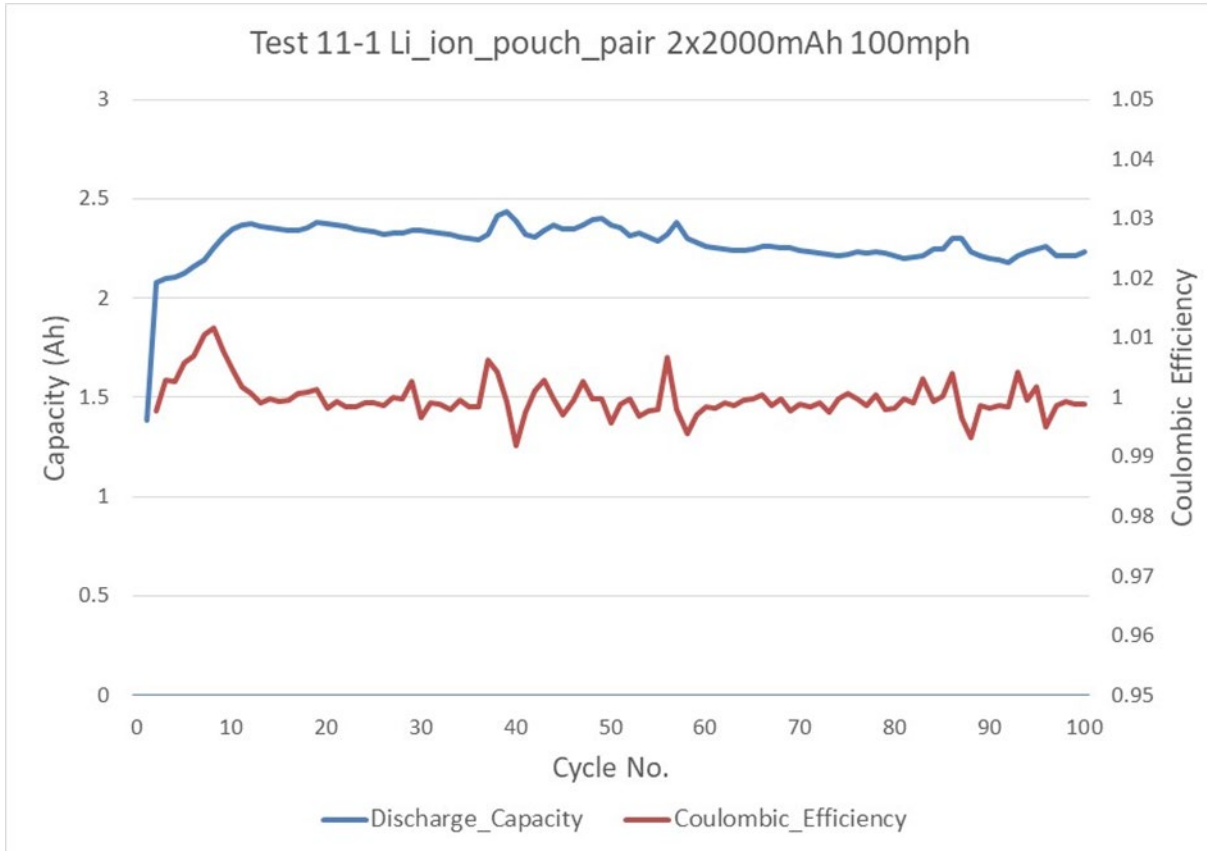


Figure 28. Post-impact discharge capacity/coulombic efficiency – 2 Ah NMC pouch cell launched at SS target (50 mph)

All pouch cells were satisfactory and could cycle as normal cells (Figure 29, Figure 30, Figure 31, Figure 32, and Figure 33), though energy cells (Figure 29) showed signs of fast cell capacity decay that may be due to some internal stress caused by impact. Energy cell (5 Ah) enclosed in an Al box projected at stainless steel at a speed of 50 mph cycled like a standard cell confirming the need for a protective enclosure to ensure battery safety. The need for protective enclosure is further exemplified through additional work in the next section.

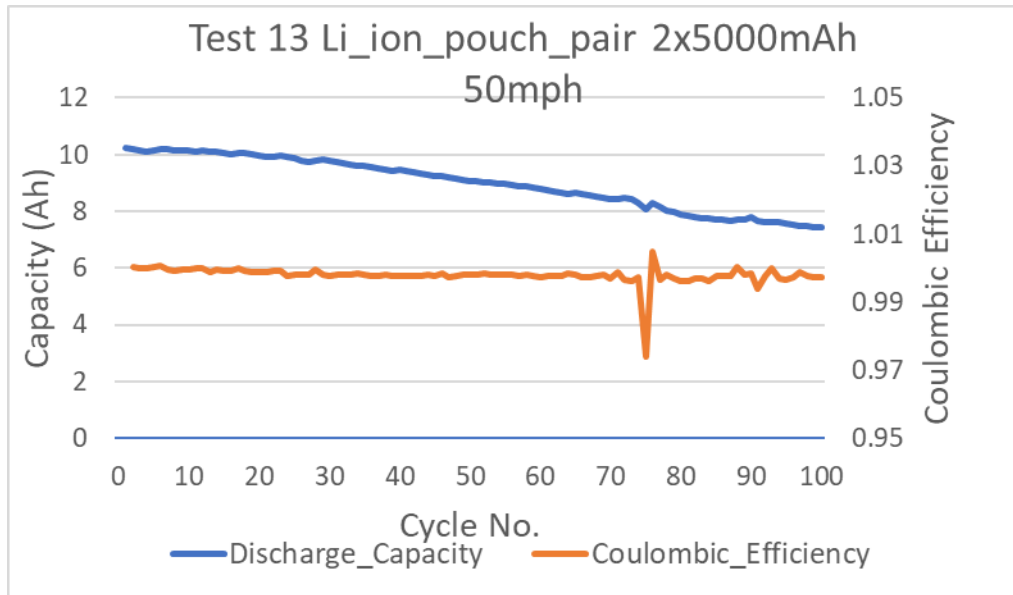


Figure 29. Post-impact discharge capacity/coulombic efficiency – 2 5Ah NMC pouch (energy) cell launched at SS target (50 mph)

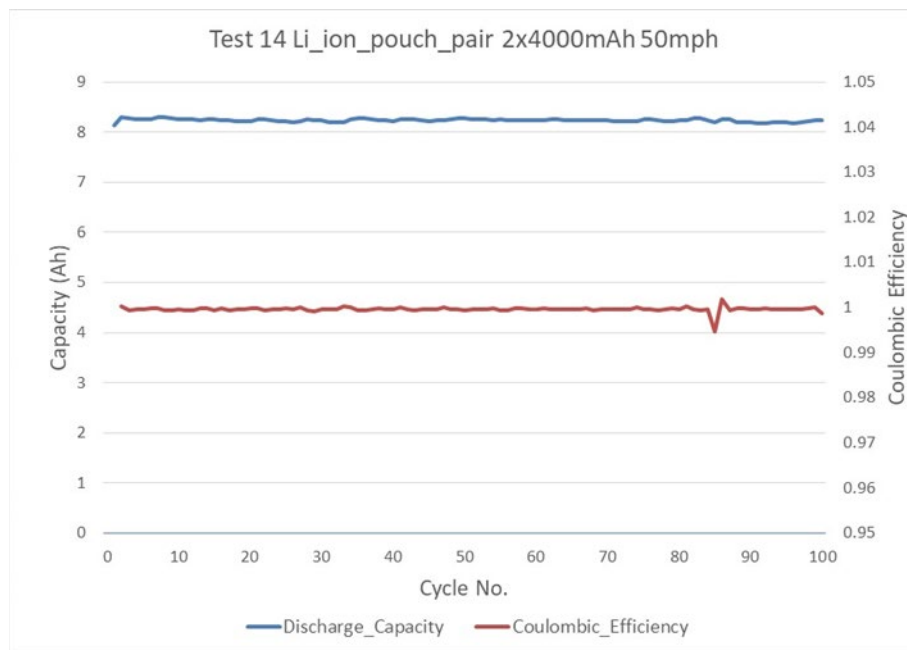


Figure 30. Post-impact discharge capacity/coulombic efficiency – 2-4Ah NMC pouch (power) cells launched at SS target (50 mph)

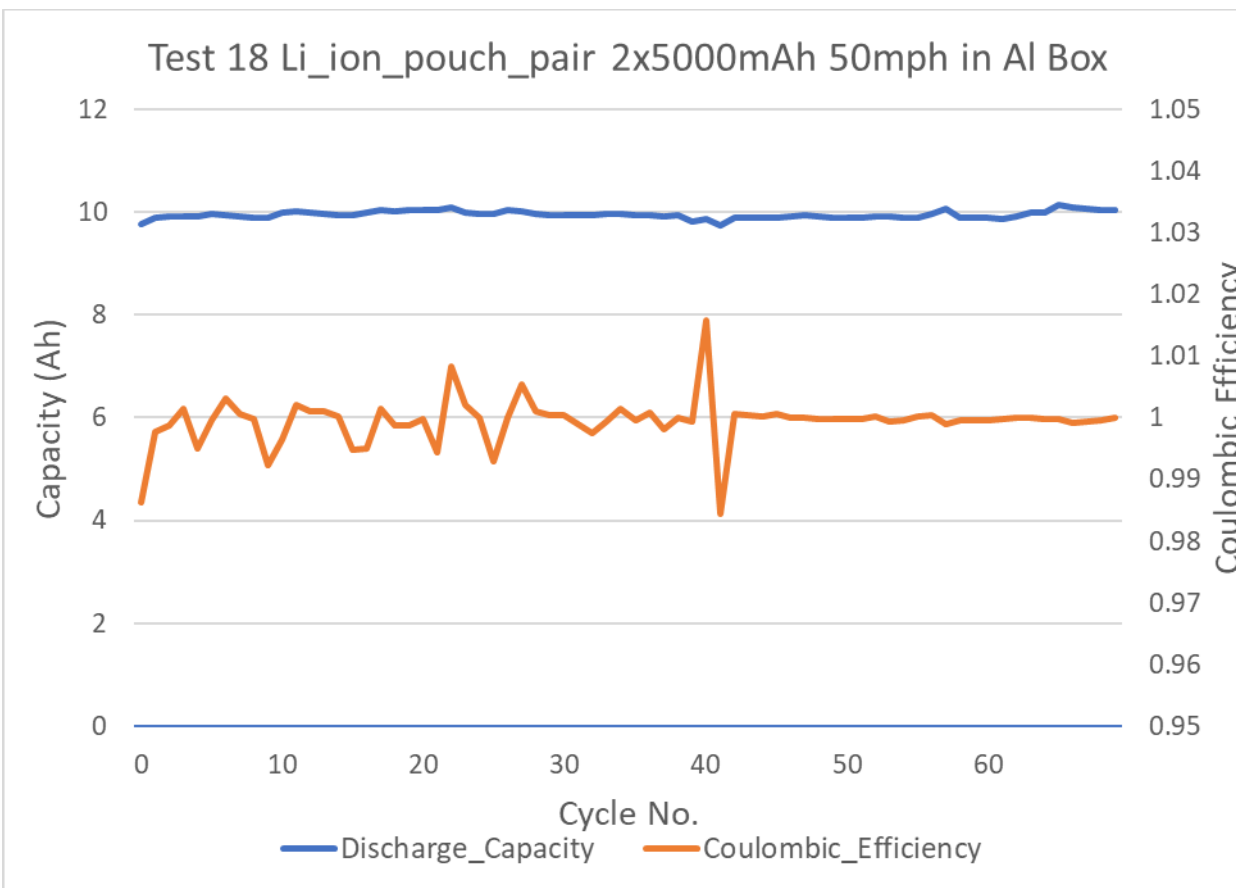


Figure 31. Post-impact discharge capacity/coulombic efficiency – 2-5Ah NMC pouch (energy) cells (Al box) launched at SS target (50 mph)

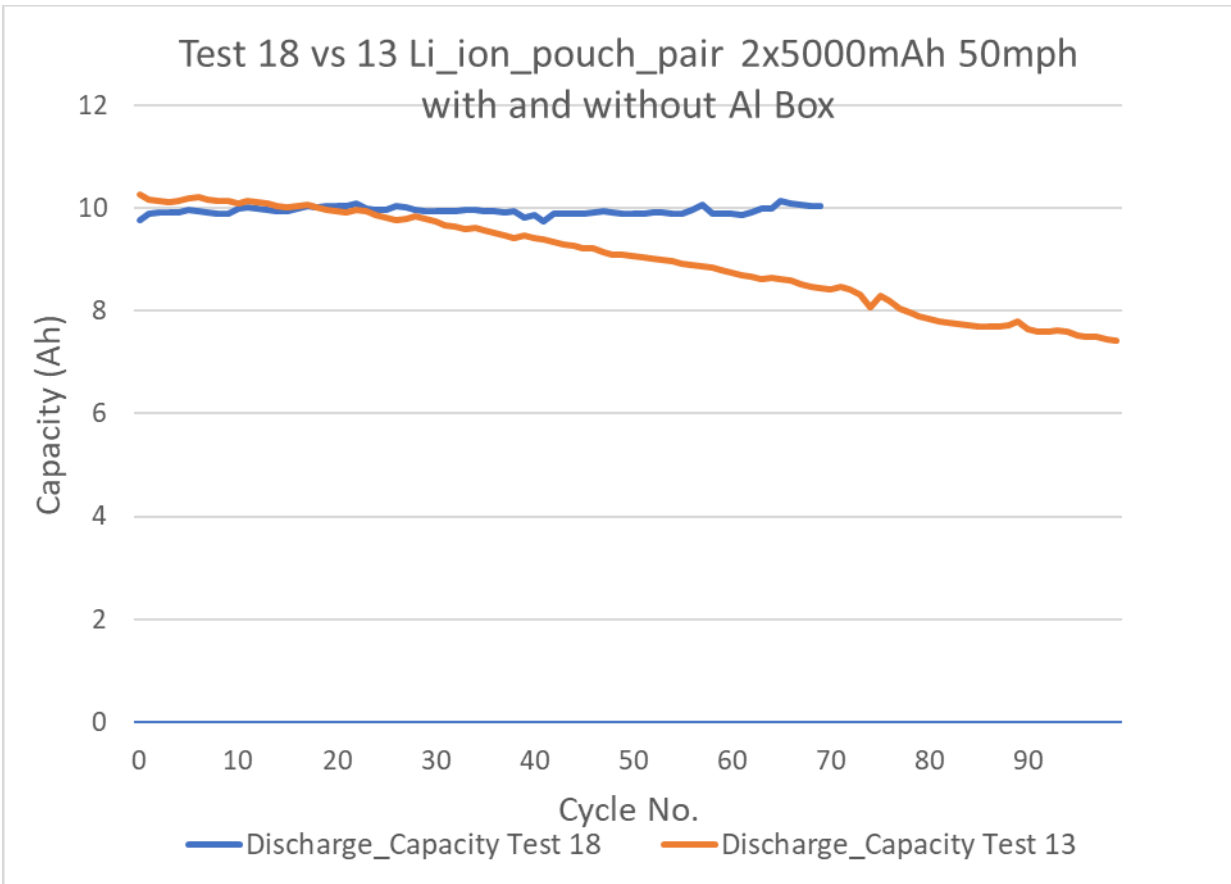


Figure 32. Post-impact discharge capacity/coulombic efficiency – 2-5Ah NMC pouch (energy) cells launched at SS target (50 mph)

4.2 Next step

The previous section supports the facts that LIB cells only survive an impact without a protective enclosure when they hit a hard surface like stainless steel at 50 mph. However, real-world applications such as electric aircraft may require cells to survive when impacted at different surfaces and at much higher speeds (>50 mph). Research and development efforts must be directed toward finding protective material/s (metal, plastic, composite, or their combination) that ensure battery safety in case collision speed increases beyond 50 mph. Figure 33 provides an example in which a 1 mm thick titanium (Ti) plate protects a two-cell stack of energy cells (2x5Ah parallel connected) when the stack hits stainless steel at 150 mph speed. Both energy and power cells, when projected at stainless steel at 100 mph, ended in TR. A 1 mm Ti provides TR protection and keeps cells electrochemically robust when impact speed is 150 mph. More work is needed to optimize Ti thickness and explore metals such as Al, stainless steel (SS), nickel (Ni), etc., in combination with different shock-absorbing materials such as plastics or composites.

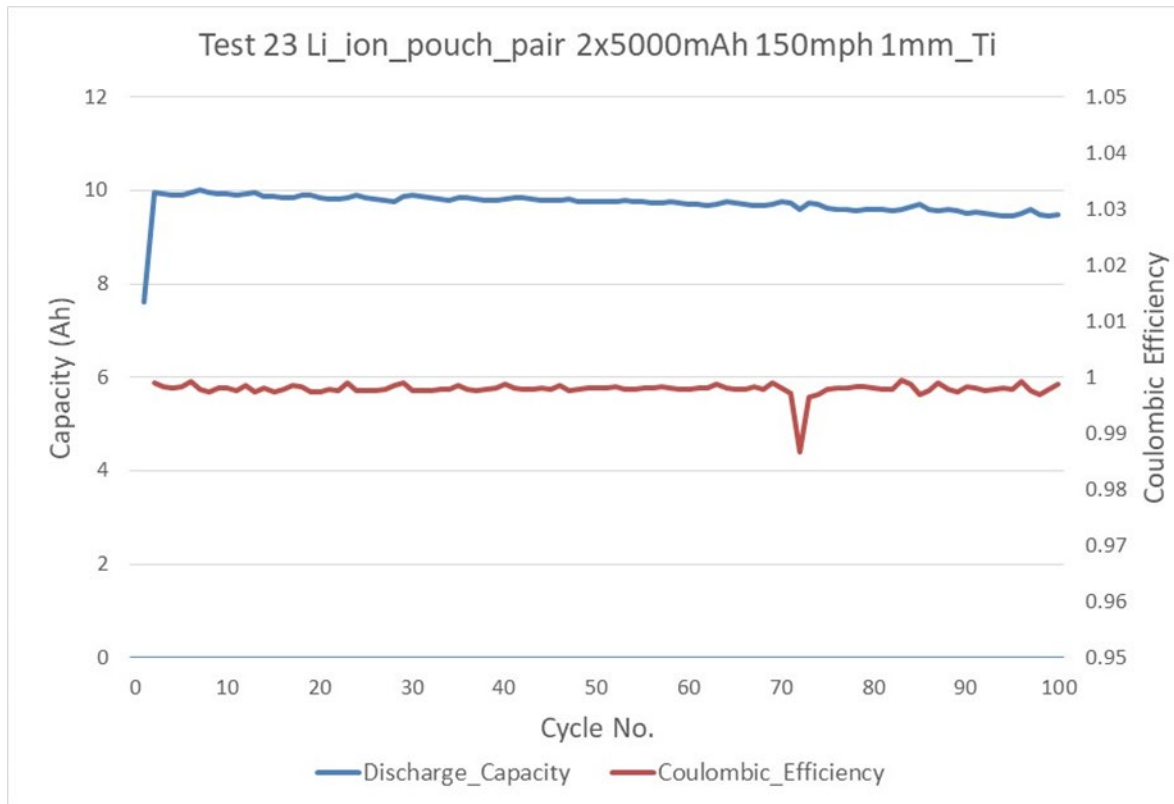


Figure 33. Post-impact discharge capacity/coulombic efficiency – 2x2Ah NMC pouch (energy) cell (1 mm Ti sheet) to SS target (150 mph)

5 Conclusions

In this project, experimental research was conducted to understand the safety of LIB cells under high-speed collision conditions, as can be experienced in flying aircraft collisions. UDRI studied the battery cell damage behavior under high-speed impact conditions relevant to aircraft speed (50 to 300 mph). Tests were conducted on LIB cells with two formats (pouch and cylindrical) and chemistry (NMC and LFP cathodes), which were commercial-off-the-shelf (COTS). All tests were conducted when cells were fully charged against fixed, rigid stainless steel targets. We found that battery cells without structural protection can barely survive a collision on a stainless steel plate when the battery speed is 50 mph. At 300 and 100 mph, cells sustained either significant damage or resulted in thermal runaway. Structural protection involving a 1 mm Ti sheet, which needs further optimization, was determined to protect battery cells up to 150 mph. However, beyond this project's scope, the plastic, carbon composite, and other metal boxes should be tested to determine and select secondary boxes for total protection from high-speed impact crashes. UDRI recommends more elaborate tests to determine the proper structural protection to ensure battery safety in electric aircraft.

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