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A Teardown Study of Flood-Damaged Electric Vehicles

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16. Abstract

In 2022 Hurricane Ian struck Florida's Gulf Coast with high winds, storm surges, and flash floods causing catastrophic loss. Extensive saltwater-flooding resulted in electric vehicle (EV) fires, creating an increased burden on hurricane emergency response efforts. In support of improved hurricane preparedness and the National Highway Traffic Safety Administration's mission to advance vehicle safety, this report documents the teardown study performed on 10 exemplar EVs. With assistance from Florida's State Fire Marshal's office and the Pipeline and Hazardous Materials Safety Administration, these EVs were bought at auction in Florida and taken to a teardown facility in Auburn Hills, Michigan. These EVs had varying degrees of floodwater damage. Study objectives were to develop and document assessment methodology to estimate potential fire occurrence in flood-damaged EVs; develop and document mitigation measures to reduce the risks during damaged EV transportation; determine root causes of EV fires resulting from saltwater damage; perform teardown analysis with recorded observations; and identify failure modes contributing to water infiltration and indicators of mechanical or fire-related damage within the battery pack.

Eight of the 10 EVs showed varying degrees of water penetration in the high-voltage power distribution enclosure (e.g., the "penthouse") or in the battery pack. Manufacturing intolerances, improper component installations, and component malfunctions seem to contribute to ingress of water.

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Table of Contents

List of Figures

List of Tables

List of Acronyms

BMS	battery management system
CAN	controller area network
EDS	electrical distribution system
EV	electric vehicle
HV	high voltage
IEC	International Electrotechnical Commission
INL	Idaho National Laboratory
IP	ingress protection
ISO	International Organization for Standardization
kWh	kilowatt hour
LED	light-emitting diode
LiB	lithium-ion battery
LV	low voltage
OBC	on-board charger
OEM	original equipment manufacturer
PCBA	printed circuit-board assembly
PDU	power distribution unit
PHEV	plug-in hybrid electric vehicle
PPE	personal protective equipment
SAE	Society of Automotive Engineers (name formally changed to SAE International in 2006)
SNL	Sandia National Laboratories
SOC	state-of-charge
SOP	standard operating procedure
VOC	volatile organic compound

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Introduction

The energy storage capacity of battery packs within light-duty consumer electric vehicles is substantial, spanning from a few 10s of kWh to approximately 200 kWh (Kane, 2021; Zhang et al., 2022). This significant reservoir of energy, referred to as "stranded" energy Zhang et al., 2022) when the EV is immobilized in an unknown state, presents formidable challenges. Whether resulting from collision damage or natural disasters such as hurricanes, this stranded energy has significant safety implications, affecting consumers, emergency responders, and recovery personnel. The presence of unknown stranded energy further complicates EV handling, transportation, storage, repair, and ultimate disposal strategies (Carey et al., 2023; Gutman et al., 2022). This complexity adds additional layers of logistic intricacies and cost considerations to the management of such EVs in compromised states.

Hurricane Sandy in 2012 first brought the saltwater-immersion issue to public attention when 16 Fisker Karma plug-in hybrid EVs caught fire in a New Jersey port after flooding (Motor Trend Staff, 2012). EV adoption has increased significantly since that event. New EV sales in 2022 made up to 10% of all new cars sold worldwide and 7.5 percent in the United States (BloombergNEF, n.d.; Boston, 2023; Mihalascu, 2023). BloombergNEF (n.d.) forecasts EV sales to make up 23 percent of total U.S. passenger car sales in 2025 and 51 percent percent by 2030. Florida saw a 7 percent EV share of passenger car sales in the first half of 2023 and is also the most hurricane-affected State (Mihalascu, 2023). Surges from recent hurricanes in Florida have revealed that seawater-flooded EVs pose major safety concerns to passengers, emergency responders, and recovery personnel Gutman et al., 2022).

In 2022 Hurricane Ian affected thousands of EVs to various degrees—600 were estimated to be total losses. There were 21 water-damaged EVs reported to have caught fire (Thampan, 2023; Zukowski, 2023). In several instances fire erupted while the affected EVs were being towed on flatbed trailers (Gutman et al., 2022; Cerullo, 2023; Hogan, 2022). Hurricane Idalia in 2023 also caused several EVs to catch fire, although these numbers were lower than those after Hurricane Ian (Cerullo, 2023). This was partly due to a relatively weaker hurricane as well as pre-emptive efforts by Florida fire departments to raise public awareness of the need to move EVs to higher ground. Besides hurricanes, other scenarios could also cause an EV to flood in saltwater although those incidents may not happen frequently. For instance, an incident was reported in 2019 where a boat on a boat ramp dragged a PHEV down into the saltwater (Jiang, 2019). The underside of the EV burst into flames shortly after being removed from the saltwater. Another recent boat ramp incident in Hollywood, Florida, resulted in an EV fire while the EV was submersed in saltwater (Townley, 2023). In general, saltwater-submerged EVs have been reported to ignite spontaneously, either immediately after immersion or up to several weeks following it (Hogan, 2022; Townley, 2023).

These field incidents show that an EV submerged in saltwater and its stranded energy have distinct safety concerns. SAE International, Sandia National Laboratories, and the International Organization for Standardization have recommended practices to perform saltwater-immersion testing of lithium-ion batteries to assess the abuse-response and evaluate worst-case scenarios of saltwater battery-immersion. They include SAE J2464 (SAE International, 2009), SNL's recommended practices for abuse testing rechargeable energy storage systems (Orendorff et al., 2017), and ISO 6469-1 (2019). There are variations as to how they recommend the saltwater-immersion-test should be conducted. For instance, among the three tests, the salinity of water may vary from 3.5 to 5 percent by weight, depth of immersion may vary from full submersion

(SAE International, SNL) to 1 m (ISO), the soak-time may vary from a minimum of 2 hours up to until the point that any visible reactions have stopped, and the post-immersion observation time may vary from none to up to 2 hours (Rask et al., 2021).

Saltwater battery-immersion tests and relevant data are rare in the open literature. In 2021 Rask et al. (2021) reported an exploratory study evaluating the abuse-response of automotive batteries from 8.8 to 60 kWh, including some of the testing protocols discussed above. The Rask et al. study gave insights into differences across testing procedures discussed above. They find that (1) Saltwater intrusion can de-energize or discharge a battery pack, and the primary reactions associated with it may end within an hour. Rask et al. observed no issue (arcing, underwater fire, etc.) while the battery packs were immersed in saltwater. (2) The salinity of water matters (i.e., lower salinity or brackish water containing <3.5 percent salinity leads to a slower discharge of battery packs), leaving a pack with high-energy content if enough time is not provided for full discharge. (3) A shorter immersion time (e.g., 15 to 20 minutes in their study) results in an unstable battery with high-energy content, which could potentially go into thermal runaway later.

Most modern EVs have large battery packs of up to about 200 kWh (Kane, 2021; Zhang et al., 2022). Besides field observations involving the natural disasters discussed above, the abuse-response of these large battery packs when submerged in saltwater is largely unknown in a controlled environment. The battery packs in EVs are typically designed to avoid explosions caused by high pressure (i.e., the battery packs have venting strategies to avoid creating high-pressure conditions if batterys go into thermal runaway). At the same time, it is reasonable to assume EV battery packs, with their ancillary components, maintain some level of watertightness. Clearly, a key objective is to avoid water ingress without creating a high-pressure environment that would lead to an explosion during a thermal-runaway event. The ingress protection code, defined by the International Electrotechnical Commission under IEC 60529 standard, defines different ratings that inform the protection of an enclosure against dust, accidental contact, and water (IP Code, 2023; IEC, 1976; Bisenius, 2006). For instance, IPX7 and IPX8 are relevant to an EV flooding scenario. An IPX7 rating indicates the presence of no harmful quantity of water upon immersing an enclosure up to 1 meter for 30 minutes (IP Code, 2023; IEC, 1976). An IPX8 rating is relevant to continuous immersion scenarios and is more stringent than IPX7. An IPX8-rated enclosure must sustain a depth of at least 1 meter, up to 3 meters for a time duration in agreement with the manufacturer.

Saltwater-submersion abuse-test response data of modern EV battery packs, as outlined in SAE J2464, SNL, and ISO 6469-1 standards, remains conspicuously unavailable for public access. Even if such data was accessible, the challenge lies in correlating it with real-world EV flood scenarios, given the substantial disparities in flood conditions concerning depth, salinity, and duration compared to controlled abuse-response tests. Moreover, the design of EV battery packs, their built-in subsystems, and their IP methods vary distinctly across original equipment manufacturers, adding an additional layer of unknowns between laboratory tests with standalone battery packs and in-field fire incidents involving entire EVs. Compounding this challenge, IP ratings for EVs and their battery packs are seldom found in the open literature. Various online sources vaguely suggest IP ratings, typically falling in the range of IPX5 to IPX7, without explicitly referencing specific OEMs (Taylor, 2023; Autotrader, 2020; Gaton, 2018). Making clear whether EV OEMs execute leak tests as part of their production quality assurance and control processes, equivalent to recommended practices, codes, or real-world conditions, is equally elusive. Even if one assumes all EVs possess IPX7 ratings, this still falls short of replicating genuine real-world scenarios, such as Hurricane Ian, characterized by water surges exceeding 15 feet over extended durations (Chasing, 2022). Consequently, comprehensive understanding of how saltwater submersion affects EV and battery pack safety, as well as the underlying causes of fires in post-immersion scenarios, remain conspicuously absent. Therefore, a critical imperative exists to meticulously assess various EVs and battery packs under realistic flood conditions, with a view to understanding in detail the failure modes and mechanisms that cause catastrophic events. It may also be necessary to revisit relevant standard testing procedures and ratings to ensure alignment with evolving real-life circumstances, ultimately benefiting consumers, emergency responders, insurance carriers, and other stakeholders. Thorough understanding of the root causes of battery failures or fires in post-immersion scenarios could also guide EV OEMs and battery pack developers in formulating effective mitigation strategies for failsafe.

The United States frequently contends with flooding associated with hurricanes, and the growing prevalence of EVs in coastal regions has introduced additional complexities regarding the impact of these recurring storms on EV battery safety, thereby influencing appropriate handling procedures. These concerns come from the inherent uncertainties about new EV technology when confronted with hurricanes. To mitigate these uncertainties, comprehensive and meticulous controlled testing, validation, and postmortem analyses are imperative, with focus on realistic system configurations and scenarios, particularly saltwater flooding. In this context, EVs that have survived hurricanes (i.e., were inundated by floodwaters but did not ignite) assume pivotal roles in understanding the root causes of potential failure or fire incidents.

This study gives early insights into battery failure modes that might have contributed to fires or establishes correlation with post-hurricane fire occurrences, such as those in Hurricanes Ian or Idalia. Further, postmortem and teardown examination of hurricane-affected EVs hold immense value in assessing vulnerabilities of modern EVs and battery packs in real-world saltwater-flooding scenarios. This teardown study also has valuable guidance for enhancing battery pack designs to enhance their resilience in flooding conditions. Additionally, this teardown study can inform development of improved protocols and standards for controlled testing.

This study was performed by the U.S. Department of Energy’s Idaho National Laboratory in collaboration with Munro & Associated, Inc., on behalf of the National Highway Traffic Safety Administration.

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Hurricane Ian and Flood-Damaged EV Samples

Hurricane Ian was a Category 5 hurricane struck southwestern Florida from September 23 to October 1, 2022 (Hurricane Ian. 2023; Bucci et al., 2023). The Florida State Fire Marshal's office estimated 3,000 to 5,000 EVs were affected; 600 were deemed to be total losses. Additionally, 21 EV fires were associated with Hurricane Ian (Thampan, 2023; Zukowski, 2023).

Table 1 lists EVs chosen for the teardown study, which were sourced from various auction and storage sites in Florida. Figure 1 visually illustrates the approximate flood levels, indicating the extent of flooding experienced by these EVs. Following Hurricane Ian, these EVs remained at these sites until they were acquired in early July 2023 and transported to Munro & Associates' facility in Auburn Hills, Michigan, from July to August 2023 for the teardown examination. The actual teardown study was conducted in August and September 2023 under the supervision and guidance of INL.

Table 1. Flood-damaged EVs selected for the teardown study

EV	Vehicle Make, Model and Year	Auction Site
V1	Tesla Model Y, 2022	IAA[1] Clewiston Site 749, 3005 County Road 835, Clewiston, FL 33440
V2	Tesla Model Y, 2022	
V3	Tesla Model 3, 2020	
V4	Porsche Taycan, 2022	Copart,[2] 2601 Center Road, Fort Pierce, FL 34946-7502
V5	Lucid Air Grand Touring, 2022	IAA West Palm Beach, 14344 Corporate Rd S, Jupiter, FL 33478
V6	Tesla Model X, 2017	Copart 10175 U.S. 17, Arcadia, FL 34269
V7	Tesla Model X, 2020	
V8	Tesla Model X, 2017	
V9	Tesla Model S, 2018	
V10	Tesla Model 3, 2018	

[1] IAA Holdings, LLC [Insurance Auto Auctions Corp], Westchester, IL, is a Ritchie Bros. Auctioneers company focusing on marketing and sale of total-loss, damaged, and low-value vehicles, with sites in 170 countries.
[2] Copart, Inc., headquartered in Dallas, Texas, is a major international vehicle auction company.

Figure 1. Ten flood-damaged EVs, showing the approximate flood-line represented by the dashed line

Vehicle Transportation

To enable the teardown and inspection, the EVs had to be transported from Florida to Munro's Auburn Hills, Michigan, facility. The transport was coordinated through a third-party vehicle-transport company, Assured ES[3] with specific expertise (handling, towing, recovery, spill response, etc.) in moving EVs and delicate/hazardous EVs per local, State, and Federal guidance.

The EVs were transported using a flatbed trailer, two or three EVs per trip, as shown in Figure 2. To assess the state of the battery pack before and after loading, as well as during transport, a dynamic monitoring system, based on temperature and a handheld flammable gas monitoring device, was used, as shown in Figure 3 to Figure 5. The dynamic monitoring system consisted of four thermocouples per EV, each mounted to the underside of the battery, dividing the pack into four temperature zones, and wired to an early-warning computer display, as shown in Figure 4, which provided an audio and visual alert for the transport driver. The dynamic monitoring system was installed prior to the EVs being loaded onto the transport trailer in Florida, and the system remained in an active and monitoring state while the EVs were in transport to the teardown location in Michigan. As part of this scheme, the front-most EV in each transport had a fifth thermocouple to measure ambient air temperature as a dynamic reference for all the EVs in transport. The driver's display, as shown in Figure 4(a), allowed for an adjustable offset from the ambient reference temperature, above which a warning would be issued for any of the four battery pack temperature zones defined by the four thermocouples. An offset of 10°C from ambient was chosen as the threshold for the warning. Any genuine thermal event would naturally lead to a significantly higher temperature differential. This threshold represents the lowest level at which the team felt comfortable, ensuring the warning system would not experience unnecessary trips. The audible warning is a spoken message identifying which temperature zones are too high. A Bluetooth speaker with a laptop in the driver's compartment ensured the audible alert was loud enough for the driver to hear over the engine and road noise. The visual warning alert, as displayed in Figure 4(b), was a simulated LED that transitioned from green to red, along with a textual message identifying which sensor was registering the temperature as too high.

The flammable gas monitoring system, based on the Renesas[4] SGAS711 flammable gas sensor, was given to Munro by INL to scan the surroundings of the EVs before, after, and intermittently, during transport. This gas sensor has been shown to detect H_2, CO, and volatile organic compounds (VOCs), which was verified in limited laboratory settings. The gas sensor kit was later arranged to a handheld probe using 15 VDC input power, as shown in Figure 5. The handheld gas probe was used to confirm that no off-gas leaking was present before and after loading and intermittently during transport of the EVs.

Additionally, thermal/infrared imaging and a gas sensor were used to observe the state of the battery packs before transport. Thermal/infrared imaging can detect local hotspots indicating any abnormal issues in the battery. Out of an abundance of caution, EVs were left stationary while being monitored on the trailer for at least an hour, prior to commencing transport. This was performed to ensure the loading process did not destabilize the battery pack in any way.

[3] Assured Emergency Services, Waterford, MI.
[4] Renesas Electronics Corporation, Tokyo, Japan.

Figure 2. EVs loaded onto a transport trailer, ready for transport

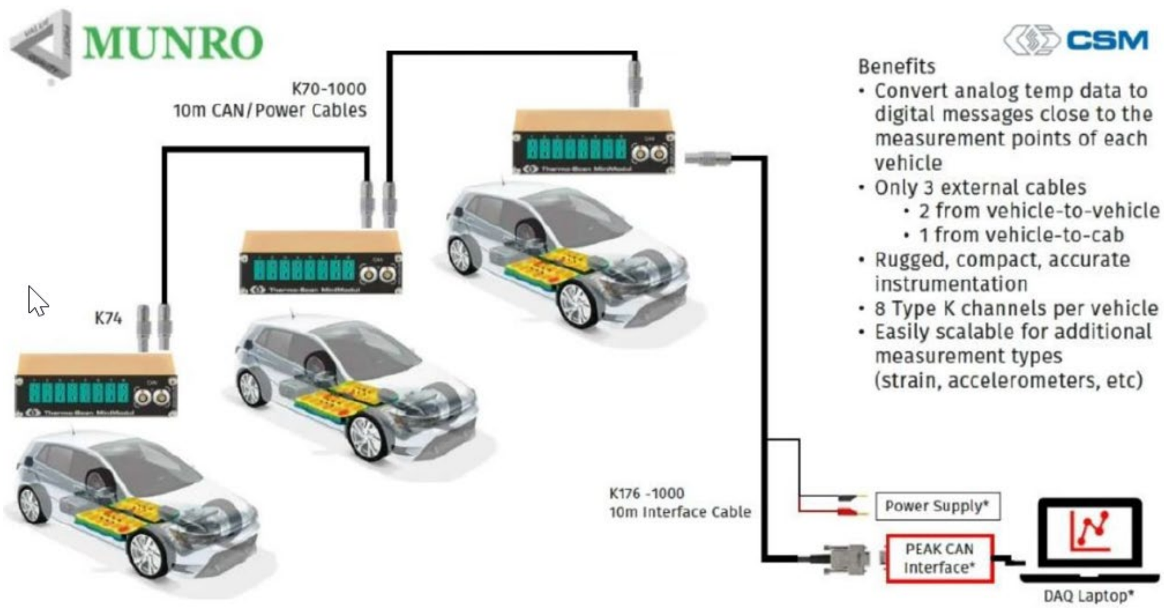

Figure 3. Transport-instrumentation layout, showing the daisy-chain components. Image courtesy of CSM Products, Inc., makers of the instrumentation devices that were used for each transport trip.

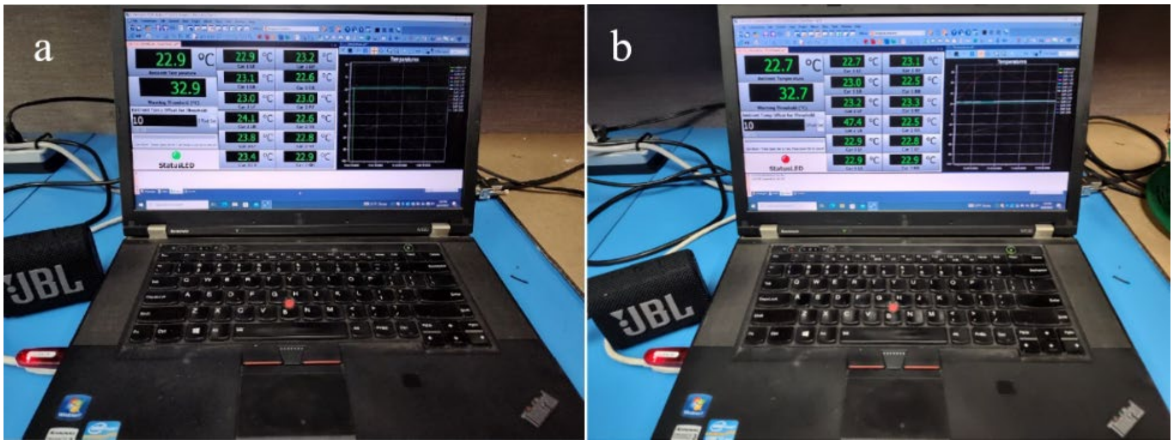

Figure 4. (a) The normal driver display for the three EVs in transport, showing a green LED warning light in the bottom left corner of the screen. (b) The driver display for an emulated high-temperature warning (i.e., a red LED light warning in the bottom left corner).

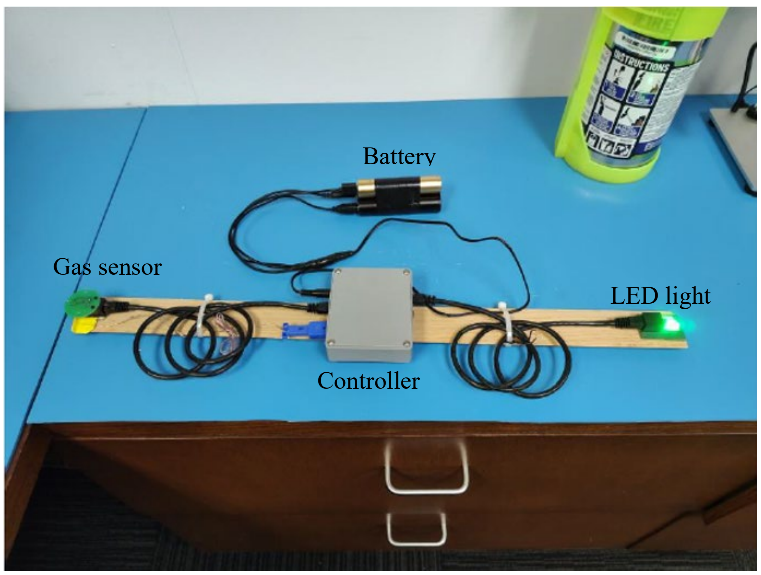

Figure 5. Handheld battery off-gas sensor

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Onsite Preparation and Pack Removal

To remove the high-voltage battery pack from the vehicle, it was necessary to ensure the state of the EV was safe. Hence, upon arrival the high- and low-voltage systems were prepared and checked appropriately. An internally developed standard operating procedure established by Munro was followed for the preparation and removal of the HV battery pack, which included the following steps.

1. Severing the HV interlock/cut loop
2. Disconnection of the 12-volt battery system
3. Removing the underbody shields
4. Disconnecting cooling lines and draining the cooling system
5. Disconnecting the HV connectors and cables
6. Verifying the status of the battery contactors
7. Covering the HV connectors
8. Removing the fasteners and lowering the pack.

Proper HV personal protective equipment was worn during the full duration of the teardown. This PPE included Honeywell Salisbury Class 0 rubber gloves with leather over protectors to protect against electric-shock hazards and eye protection to safeguard against injury due to arc flash with a full face-shield for any operations that had heightened levels of arc flash potential. The teardown was conducted by trained personnel. All Munro personnel assigned to the project were certified in Munro's Level 1 HV training, followed Munro's SOP for HV teardowns, and for those working directly with HV, were certified in Munro's Level 2 HV training as well. In addition to preparing for pack removal, the Munro team also prepared the EVs to allow the INL team to attempt to extract any possible controller area network bus diagnostic information prior to teardown. This consisted of applying an external, 12-volt power source (current-limited to 30 A) to power the LV system after the HV cut loop had been severed and the 12-volt battery had been disconnected. Once the battery packs were removed, they were moved to a separate area for further disassembly and review, and the EV shell was taken out of the building for temporary storage.

While the 12-volt systems were operational in some of the EVs, a few of them (e.g., V8 and V10) did not show continuity in the LV systems due to saltwater-induced damage and corrosion. As a result, the electrical frunk release could not be activated through the compromised 12-volt circuitry by applying external power. Hence, those frunks were forcibly opened to gain access.

Figure 6 shows the top view of the packs after their removal from the EVs. A visual examination of the exterior of the packs showed some similarities in their design and overall architecture. For instance, irrespective of model year, Tesla Models 3 and Y shared a similar pack design/architecture. On the other hand, the Tesla Models S and X shared a different pack design/architecture. Porsche and Lucid had additional distinctions in their respective pack designs/architectures as well. Hence, the packs were grouped into four categories, as shown in Table 2. Different pack design attributes and distinctions are covered in the respective pack design discussions in Key Observations. Respective teardown video links are included in Table A-1 in Appendix A.

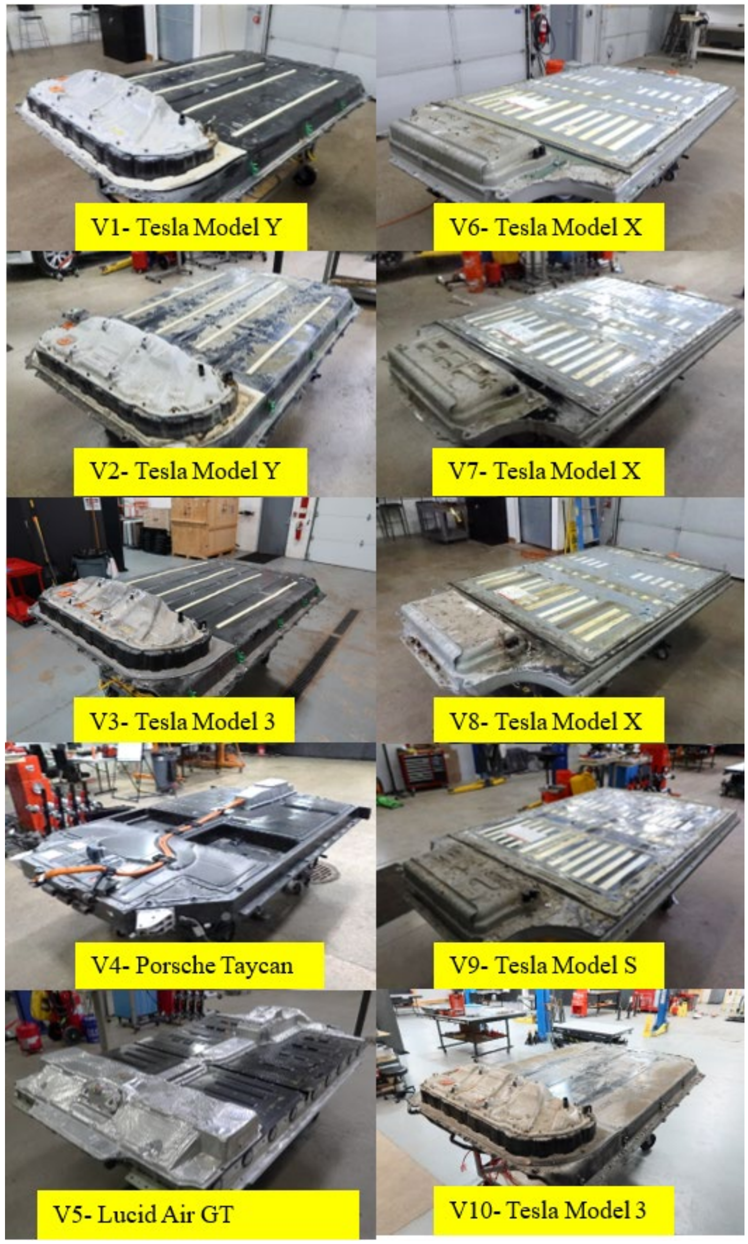

Figure 6. Top view of the packs after being removed from the EVs

Table 2. Grouping of pack designs based on commonalities in their designs

Pack Design	Vehicle Number	Vehicle Make and Model
1	V1, V2, V3, and V10	Tesla Models 3 and Y
2	V6, V7, V8, and V9	Tesla Models S and X
3	V5	Lucid Air Grand Touring
4	V4	Porsche Taycan

Pack Design

Pack Design 1: Tesla Models 3 and Y

Exterior

As shown in Figure 7, the battery pack consists of a primary tray and lid enclosure with the lid painted black, which contains the HV modules, and a separate "penthouse" module mounted to the top rear of the pack. The penthouse lid, as indicated in Figure 7(b), has a reusable gasket attached to it with special fasteners, as shown in Figure 7(a), for easier service of the components it contains. Key exterior components of the penthouse are identified in Figure 8(a). The penthouse contains components of the power distribution system, such as the main contactors, the pyro-fuse, and other fuses, as well as the HV controller for the main battery management system board, the on-board charger, and the DC-DC converter, as shown in Figure 8(a). By removing the rear seat and some brackets, the lid can be removed without removing the entire battery pack from the EV.

Figure 7. Pack Design 1 penthouse: (a) penthouse lid and (b) underside of penthouse lid, showing the reusable gasket

A liquid-applied urethane perimeter seal was positioned between the main lid and the primary tray of the pack enclosure. It was necessary to use an oscillating cutting tool to cut through the liquid-applied seals, as shown in Figure 8(b), while monitoring through an infrared camera to watch for abnormal temperatures. All 10 EVs in this study used liquid-applied urethane seals that required the oscillating cutting tool to get through. This pack design has two moisture-activated vents located on the rear-right and rear-left sides of the battery pack, as shown in Figure 8(c). The moisture-activated vents were mounted through the bottom of the tray into the interior of the penthouse module. Pack Design 1, consisting of Tesla Model 3 and Y, also featured two vent assemblies attached to the rear-left and rear-right sides via threaded fasteners with a seal against the pack tray, as shown in Figure 8(c). Each vent assembly has a Gore[5] vent, a pressure diaphragm, and a pressure-blowout patch. Ventilation was directed outward on either side with a

[5] W. L. Gore & Associates, Inc., Tokyo, Japan.

stamped cover over the top of the vents. Cooling-port connections to the pack were all connected externally to the primary tray at the front and rear, with two external front-to-rear interconnecting pipes, on both the passenger's side and driver's side, as observed in Figure 8 (d–e).

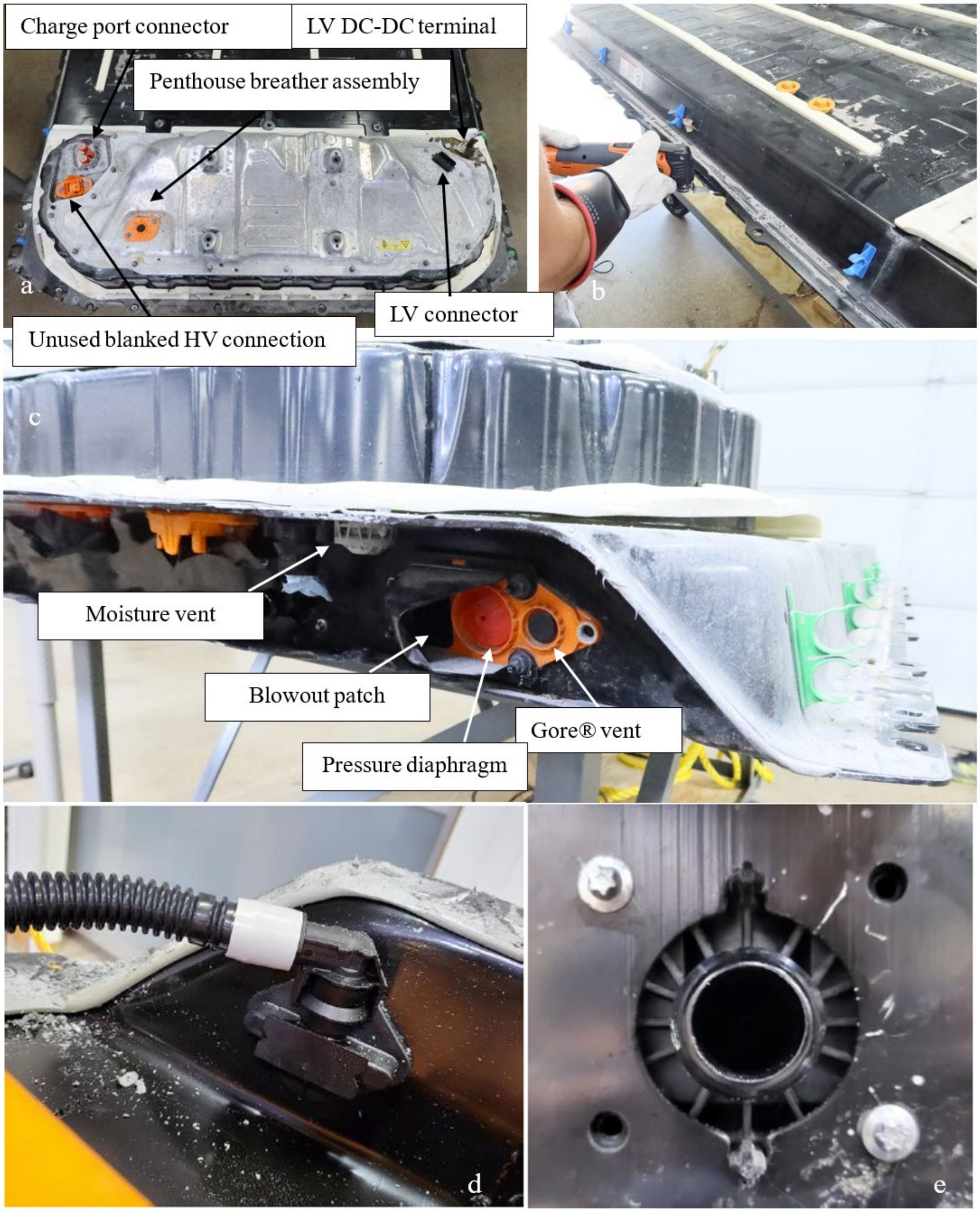

Figure 8. (a) Pack penthouse and its components, (b) use of the oscillating tool, (c) different vents, (d) front coolant port exterior, and (e) rear coolant port exterior

Interior

The interior of the penthouse compartment was sealed from the rest of the battery pack, as shown in Figure 9. This compartment contained all serviceable components for easy access under the rear passenger seat of the vehicle. It also had a moisture-sensing drain valve to vent any liquid, such as from any potential coolant leak, from the pack.

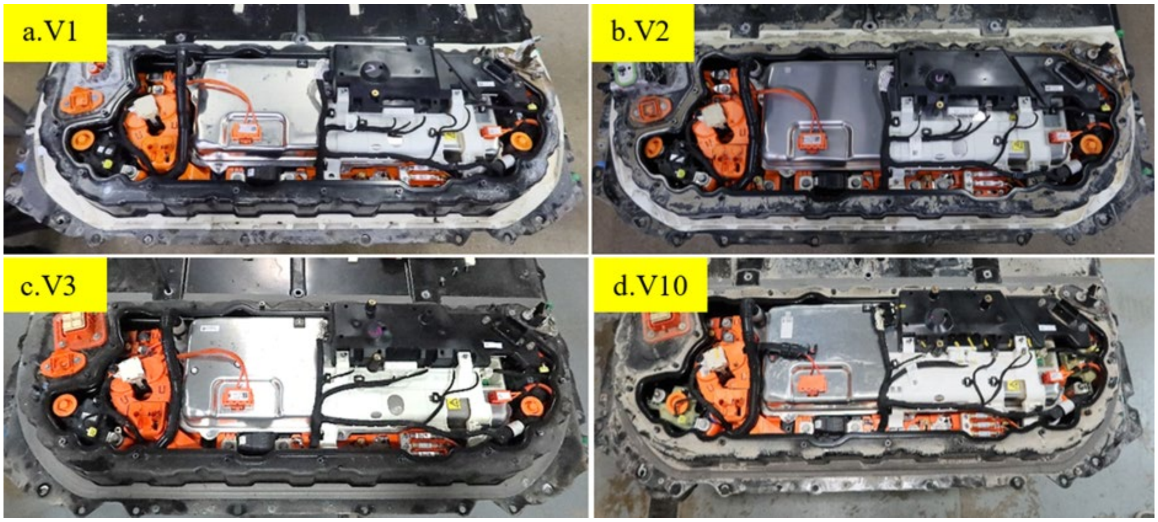

Figure 9. Open penthouse assembly, showing the key components

Figure 10 shows the battery pack after removing the penthouse enclosure and pack lid. Each pack consisted of 96 serially connected cell groups. Two peripheral modules, Modules M1 and M4, had 23 serially connected cell groups, while two center modules, Modules M2 and M3, had 25 serially connected cell groups. Each cell group consisted of 46 cylindrical cells in parallel, with each cell sized 21 mm in diameter and 70 mm long (2170). This pack configuration is 96s46p accordingly.

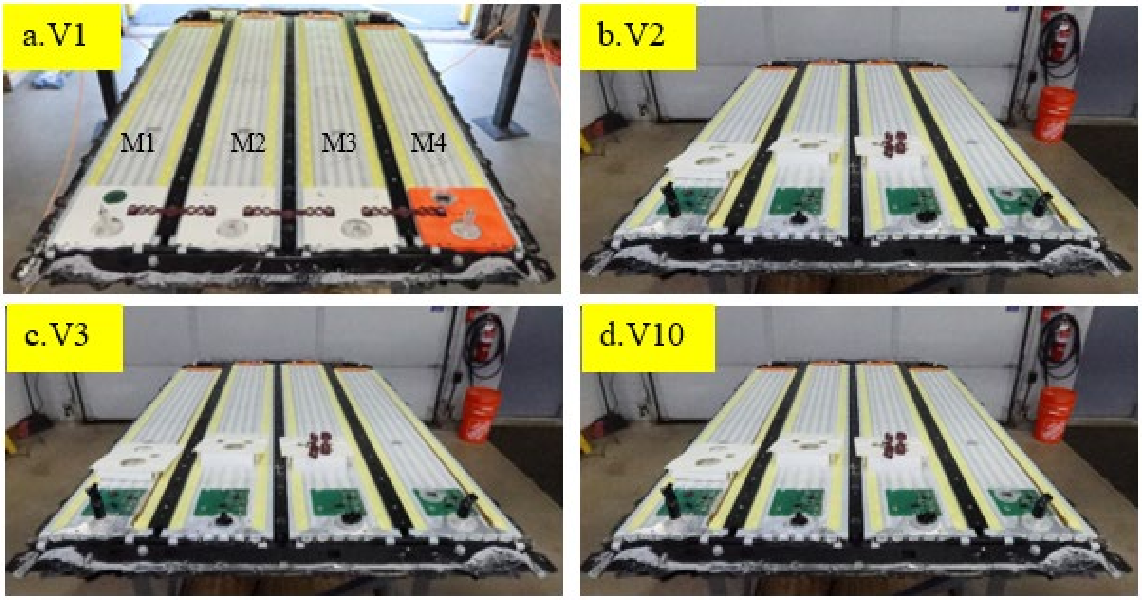

Figure 10. Battery pack after removing the pack lid and penthouse assembly

Pack Design 2: Tesla Models S and X

Exterior

This battery pack was relatively simple to remove because it was designed for easy EV installation and removal. All electrical and cooling connections were designed to require no additional effort than to remove the battery-mounting fasteners and drop the pack. This means the normal latches holding the electrical connectors together that one might expect are not present, such that the pack being bolted in is the effective latch for each connector. The cooling ports on the battery had integrated check valves that closed automatically when the pack was removed to minimize coolant loss, thus eliminating the cumbersome draining process normally required for pack removal.

Figure 11 shows the overhead view of Pack Design 2, with the major components identified. A plastic sheet was installed onto the top of the pack with what appeared to be a butyl bead as a perimeter seal. This plastic sheet was intended to prevent moisture from entering the top of the pack through the numerous fastener openings it covers, as well as to protect the HV battery from moisture (Tesla, 2020). This plastic sheet was basically a secondary seal, with each fastener already individually sealed. The battery cover and fastener arrangement for Pack Design 2 was much different in design from Pack Design 1. This pack cover was nearly flat, in contrast to Pack Design 1, requiring more fasteners, especially between modules, and creating more potential leak paths from the fasteners than were present in the Pack Design 1—hence, the need for the plastic sheet.

Pack Designs 1 and 2 from Tesla both have a penthouse assembly atop the main pack. Pack Design 2 had the penthouse toward the front of the vehicle, whereas Pack Design 1 had the penthouse on the rear of the pack. At the top point of the penthouse, three of the four packs with this design type had a vent, as shown in Figure 11. The fourth pack in the group, which came from V7, had the most recent Model X year (2020) design, and did not have this vent.

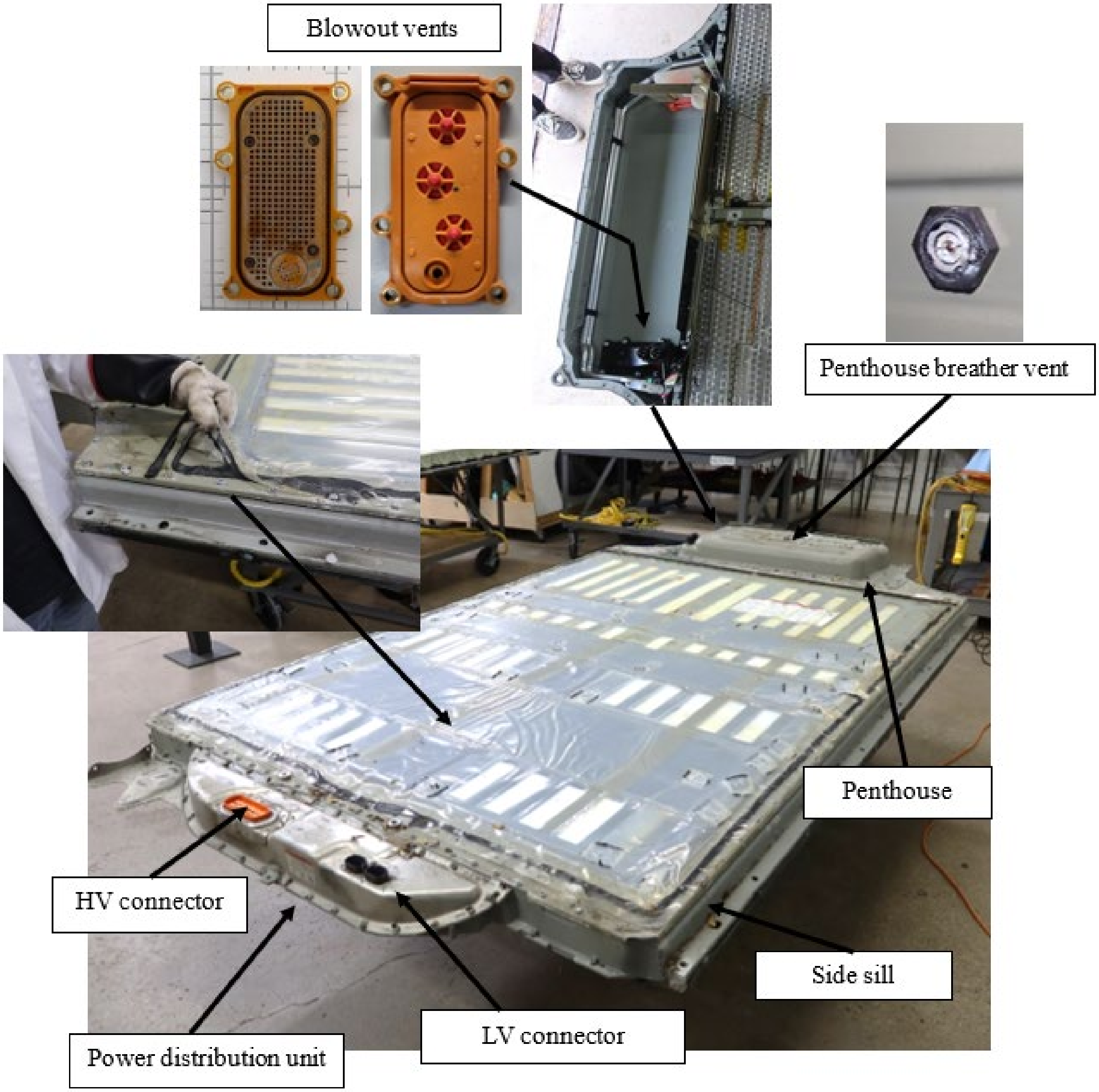

Figure 11. Pack Design 2 overhead view with major component descriptions

Interior

Several pressure vents lay along both side sills of the pack. The compartments for each battery module, except for the two closest to the penthouse, had a pressure vent assembly, as shown in Figure 12. Each module compartment vent assembly had two actual vents and four dummy vents (plugs) for a total of six holes in the side sill per compartment. The plugs could easily be converted into vents, if needed, for additional vent capacity, but this feature was apparently not needed. However, this left four additional holes to be sealed per applicable module compartment, creating several unnecessary potential leak paths that could have been avoided.

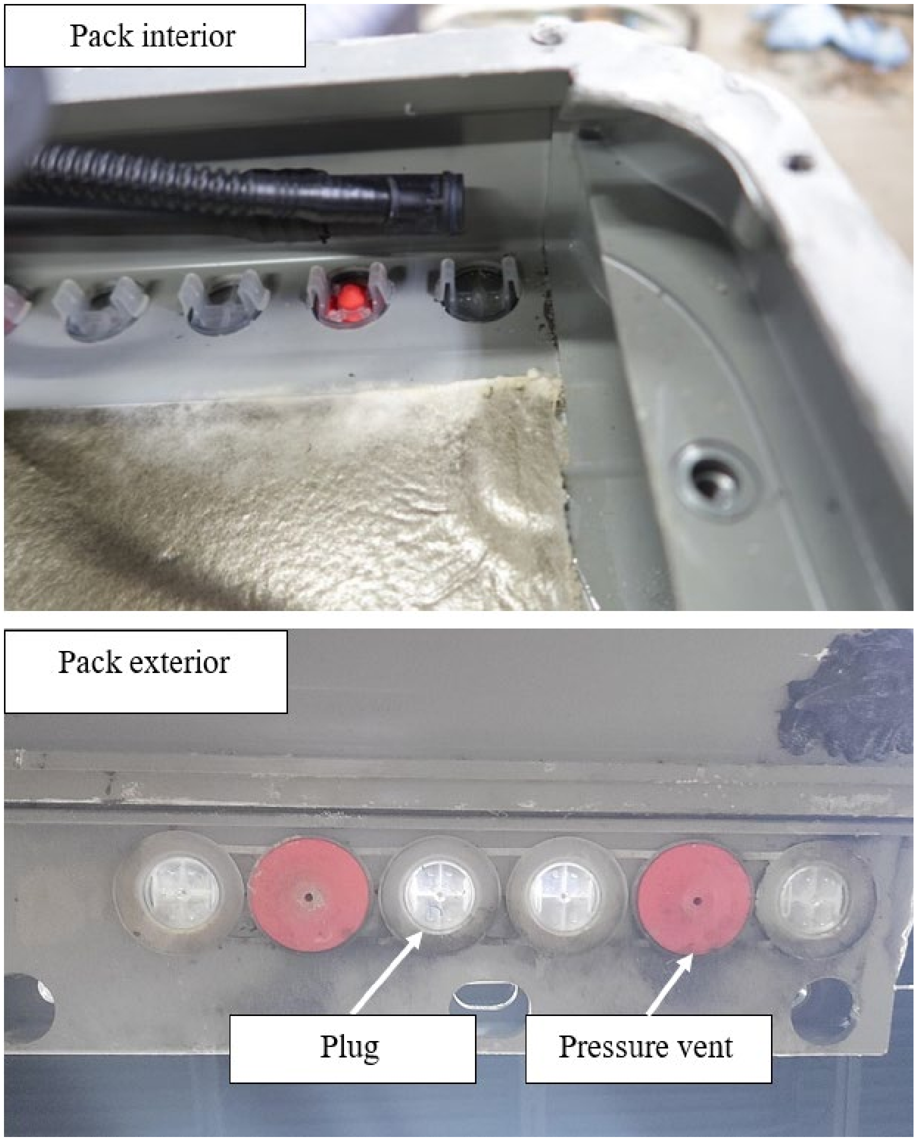

Figure 12. Vents and vent hole plugs along the side sill of the battery pack, which is an arrangement that is unique to Pack Design 2.

Unlike Pack Design 1 from Tesla, the penthouse in Pack Design 2 contained optional battery modules (for extending range), vents, cooling pipes, busbars, and a pyro-fuse that is replaceable from the underside of the vehicle. Contactors and other normally serviced components in Pack Design 2, such as the main BMS, were instead housed in another compartment at the rear of the pack called a power distribution unit, which is shown in Figure 13.

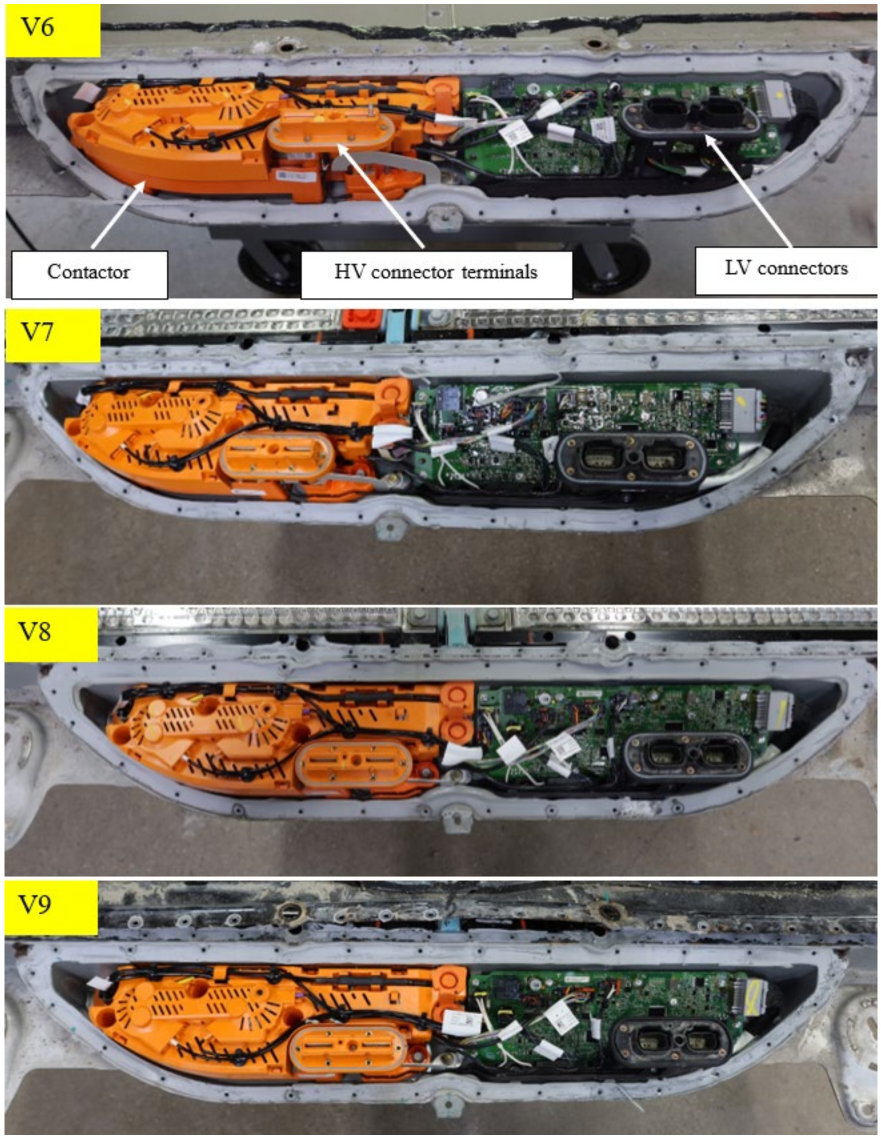

Figure 13. PDU of Pack Design 2

The Pack Design 2 module size and arrangement varies distinctly from Pack Design 1, which was used in Tesla Models Y and 3, as observed in Figure 14. Unlike Pack Design 1, shown in Figure 10, which had four larger modules, Pack Design 2 consisted of up to 16 smaller modules with different packaging strategies. The standard range V6 and V8 EVs consisted of 14 modules, whereas the extended-range V7 and V9 EVs consisted of 16 modules, as shown in Figure 14.

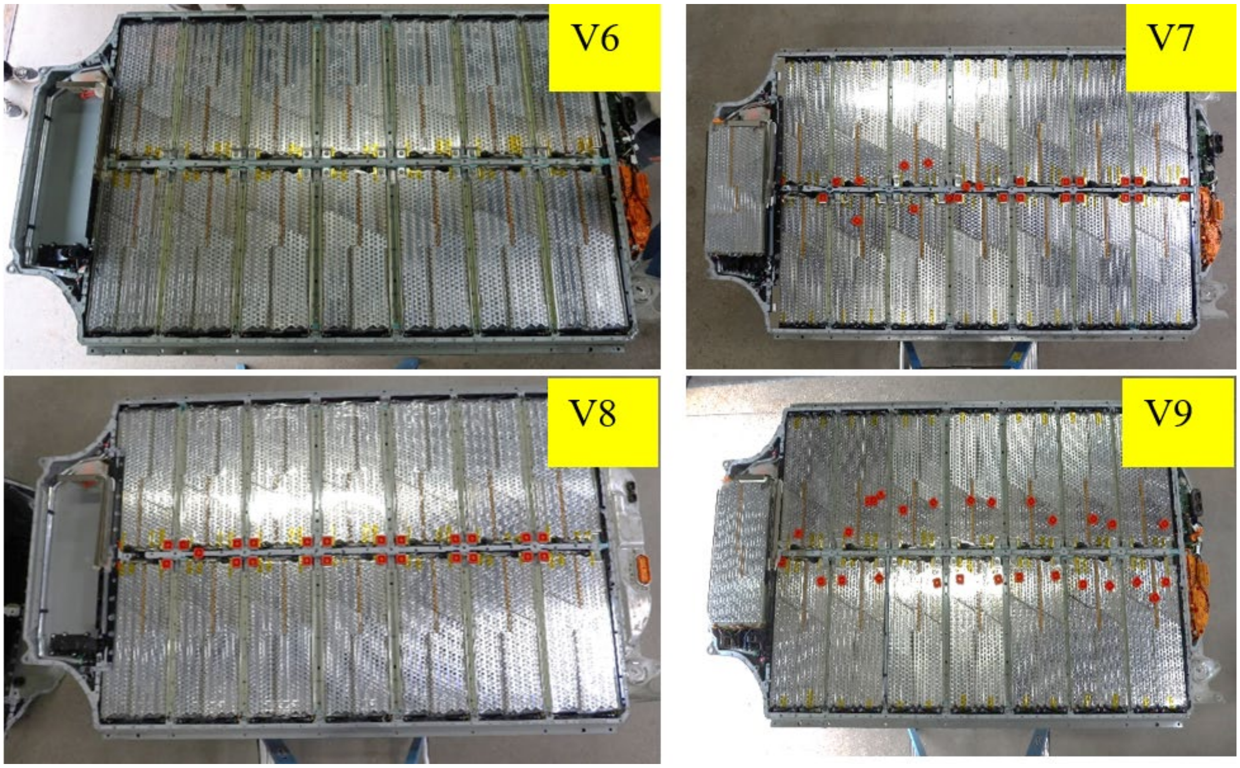

Figure 14. Main battery compartment of Pack Design 2. The V6 and V8 models have 14 modules, while the V7 and V9 models have 16 modules.

Pack Design 3: Lucid Air Grand Touring

Exterior

Pack Design 3 consisted of a Lucid Air Grand Touring battery pack with two housings inside the main lower pack for what might be called a dual-penthouse arrangement, as shown in Figure 15. Each penthouse had a small removeable subcover, made of sheet-molded compound, for access to the easily serviceable PDU components within. The PDU also had several Gore breather vents. The battery lid was attached by means of a sealant and fasteners connecting to the lower metal frame.

This pack design appeared to have an extraordinary pressure-release vent-valve capacity (e.g., 18 large vents, 9 per side sill), until one considers their dual purpose, as evident in Figure 15. These pressure vents consisted of an injection-molded base that is attached to the side sill extrusion via liquid-applied adhesive and a flexible diaphragm that is pressed into the base. The valves not only release pressure from the pack during a thermal event, but by removing the silicone inner section of the valve, each also can be used for access to the internal-module busbar fasteners.

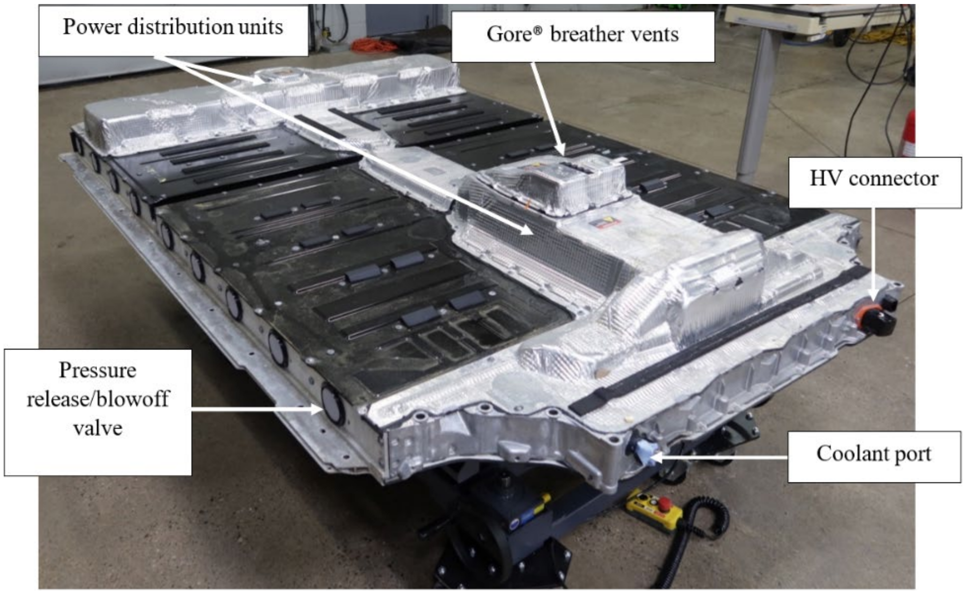

Figure 15. Exterior of Pack Design 3, Lucid Air Grand Touring

Interior

As shown in Figure 16, each internal battery module had 10 serially connected cell groups of 30 parallel cells each, for a total of 300 cells per module, which are represented as 10s30p. Nineteen modules resided in the main/lower battery compartment, with three additional modules located in the penthouses above for a total of 22 modules with a pack configuration of 220s30p.

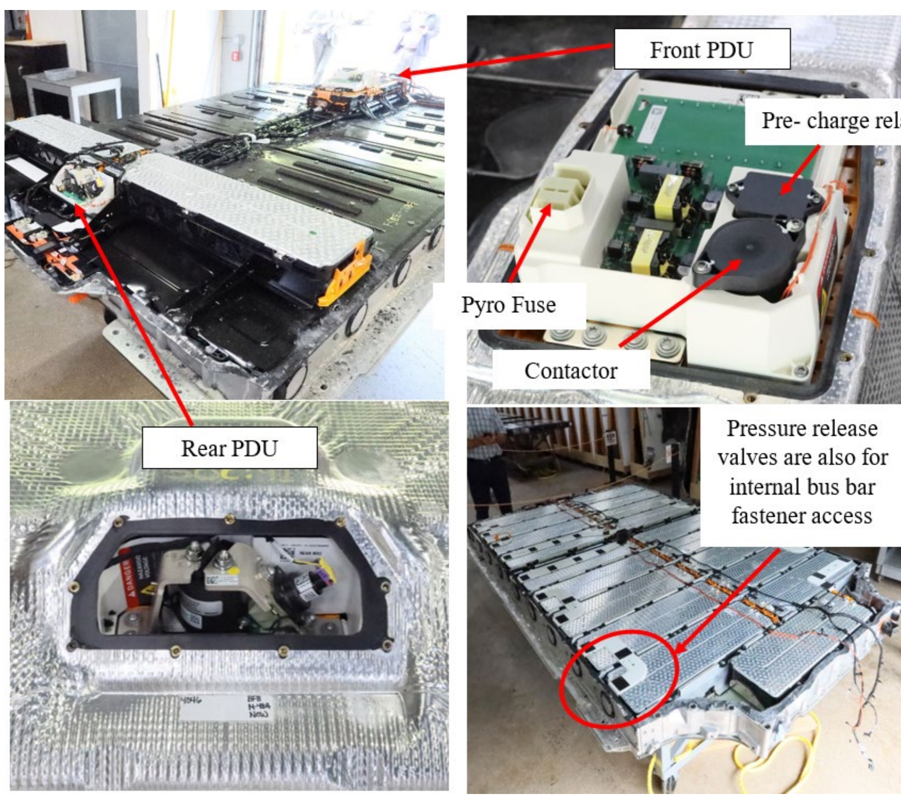

Figure 16. Pack Design 3 interior views

Pack Design 4: Porsche Taycan

Exterior

As shown in Figure 17, Pack Design 4 consisted of a primary tray and lid enclosure that contained the HV modules with a separate penthouse compartment mounted to the top rear of the pack, which housed the power distribution system components, such as the main contactors, pre-charge circuitry, fuses, and BMS. The penthouse module/PDU was fastened to the top of the HV battery pack using a combination of strategies to seal the fasteners and prevent environmental contamination of the pack interior. The penthouse was a removable and separate enclosure, sealed from the main battery pack for easier service of the components it contains. The battery module housing was constructed from an aluminum-extrusion welded to cast-aluminum endcaps. Welds were cut through with a Dremel to remove the endcaps from both sides and access the current collectors.

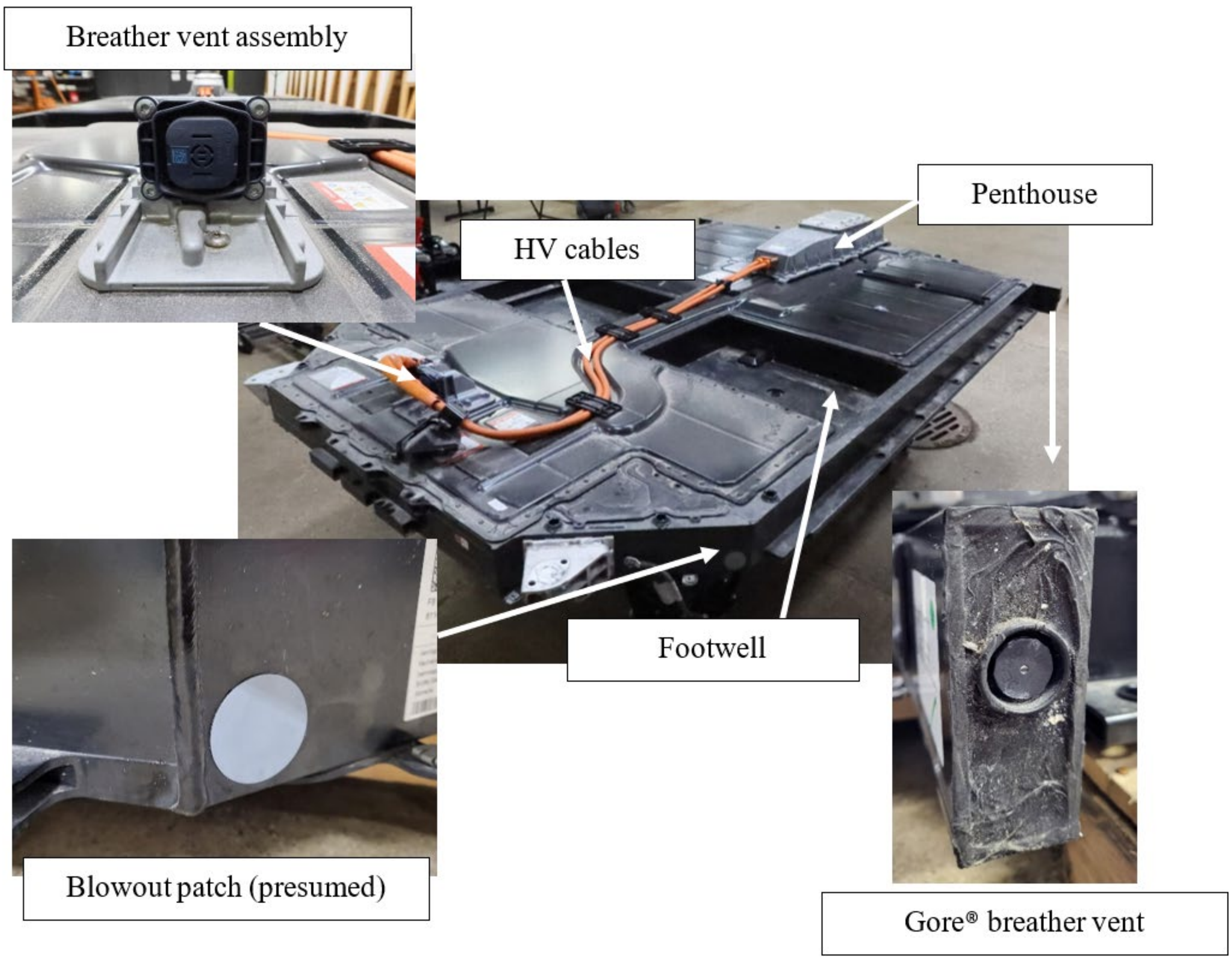

Figure 17. Exterior of the V4 battery pack with key components identified

The Porsche Taycan featured a series of breather vents and what appeared to be blowout patches on the battery pack exterior, as displayed in Figure 17. Gore breather vents were installed on the ends of the tray extrusions at the front-right and front-left sides of the pack. At the rear-right and rear-left, circular adhesive-backed patches were found, which presumably act as pressure-blowout valves as gases are directed through the cells of the extruded walls of the tray. At the top rear of the pack was a large breather assembly housing a membrane within a cast-aluminum and injection-molded housing, which was attached to the lid via threaded fasteners with an injection-molded seal.

Interior

Figure 18 shows the key components of the penthouse interior, which included the fuse, contactor, pre-charge resistor, pre-charge relay, etc. The pack consisted of 28 battery modules, as shown in Figure 19. The pouch cells were arranged in a 6s2p configuration in each module, for a total of 168s2p or 336 cells. Each corner of the pack had a compartment housing the cooling system components that are serviceable without needing to access the HV areas of the pack.

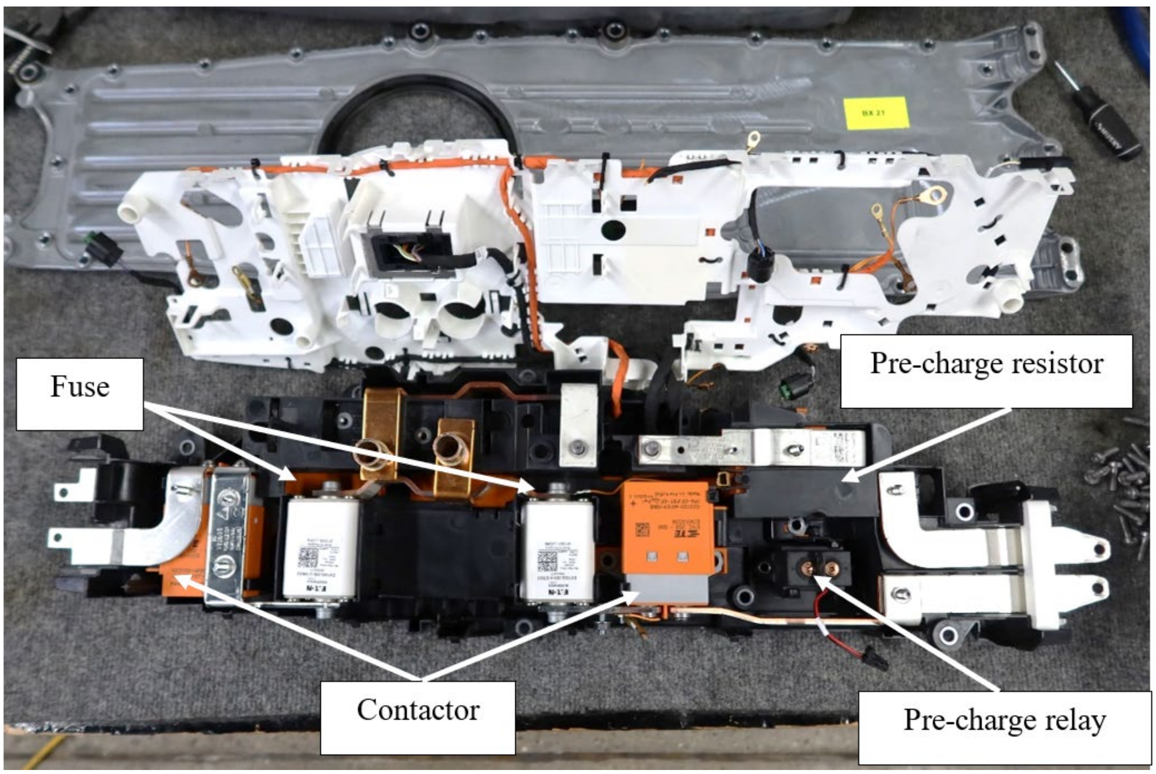

Figure 18. Penthouse assembly interior of Pack Design 2

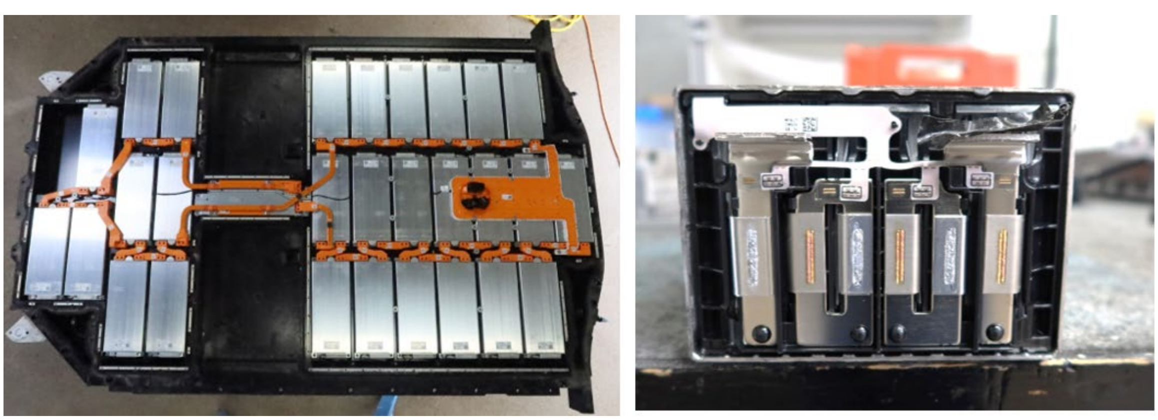

Figure 19. Battery compartment interior, showing the entire battery pack (left) and module (right) with the end-wall removed

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Key Observations

The damage to the interiors of the EVs varied depending on the level of water immersion they experienced. The water intrusion resulted in visible water marks, debris, sediment, and mold/mildew in areas including seats, sills, floor, and instrument panel. In one case (V1), there was a notable presence of fecal matter within the cabin due to the prolonged presence of rodents in that vehicle.

The HV battery casings were exclusively positioned beneath the EVs, and the battery compartments appeared to have been fully submerged in water. This was evident from dried water patterns, the presence of sand and silt, corroded fasteners, and signs of corrosion and pitting on the exterior metal components. In a few instances, such as was discovered in EVs V4 and V5, the raised penthouse attached to the top of the battery compartment appeared to have been partially submerged as well.

The submersion status of the LV battery varied based on the flood-line indicated in Figure 1. Some LV batteries were fully submerged, some partially, and others remained unaffected by the saltwater. For detailed information about the location, chemistry, and submersion status of the 12-volt batteries, please refer to Table 3.

Table 3. 12-volt battery location, chemistry, and state of submersion

Vehicle Number	Vehicle Make, Model and Year	12-Volt Battery Number, Location, and Chemistry	State of Submersion
V1	Tesla Model Y, 2022	One, under wiper cowl, LiB	Partial
V2	Tesla Model Y, 2022	One, under wiper cowl, lead-acid battery	Full
V3	Tesla Model 3, 2020	One, under wiper cowl, lead-acid battery	Full
V4	Porsche Taycan, 2023	One, under wiper cowl, lead-acid battery	No submersion
V5	Lucid Air dream, 2022	Two, under rear passenger seat, in right rear wheel well, both lead-acid batteries	Partial
V6	Tesla Model X, 2017	One, under wiper cowl, lead-acid battery	No submersion
V7	Tesla Model X, 2020	One, under wiper cowl, lead-acid battery	No submersion
V8	Tesla Model X, 2017	One, under wiper cowl, lead-acid battery	Full
V9	Tesla Model S, 2018	One, under wiper cowl, lead-acid battery	Full
V10	Tesla Model 3, 2018	One, under wiper cowl, lead-acid battery	Full

Distinct corrosion was observed throughout the EVs where salty or brackish water submersion was experienced, which may have compromised proper functionality. This included the metal frames, battery pack exterior, LV systems and harnesses, HV charging connectors, fasteners, etc. Figure 20 shows selected areas from different EVs where saltwater immersion resulted in corrosion.

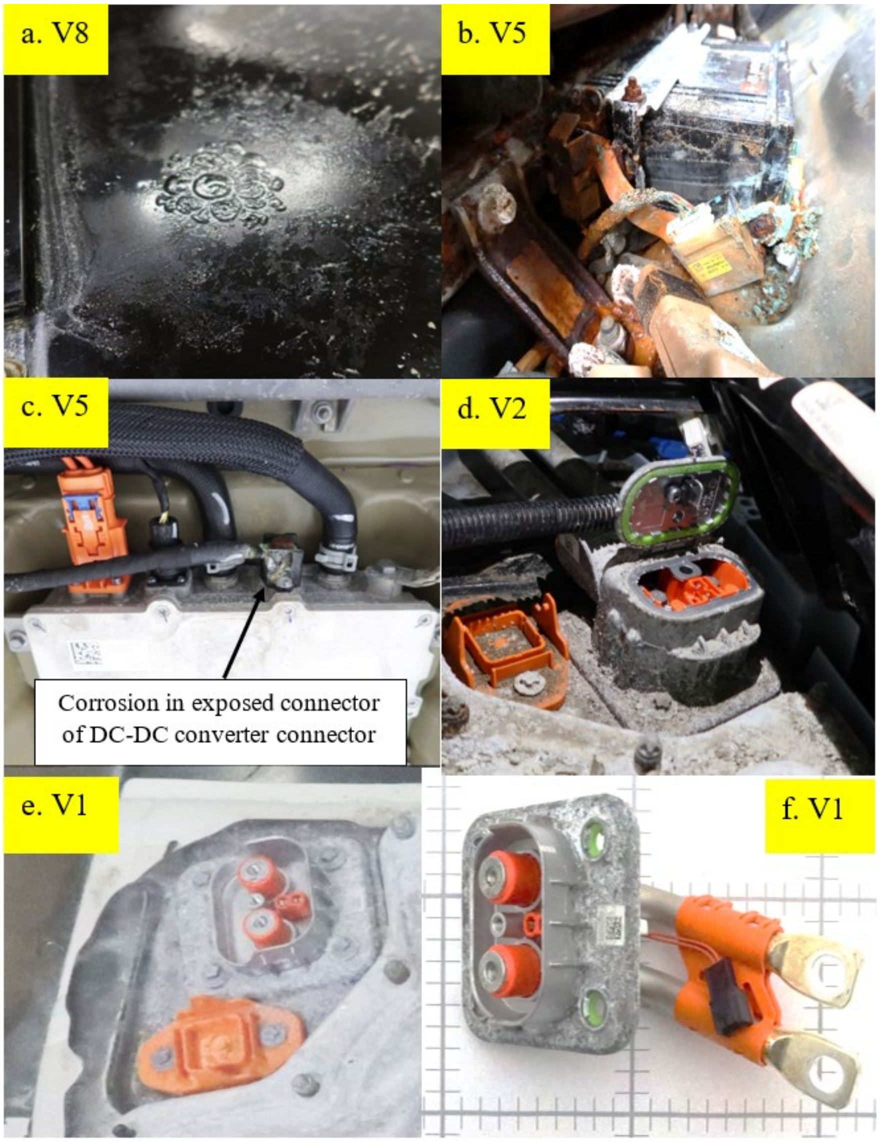

Figure 20. (a) Areas of corrosion were observed on the battery lid surface of V8. (b, c) The primary 12-volt battery and surrounding components located under the second-row passenger seat cushion exhibited excessive amounts of corrosion in V5. (d) The corrosion on the exterior of the same connector of V2 was so severe the two halves could not be separated without causing damage to the connector and surrounding components. (e, f) The on-board penthouse charging connector showing distinct corrosion outside for V1; the interior showed no corrosion.

Pack Design 1: Tesla Models 3 and Y (Vehicles V1, V2, V3, and V10)

This design group included two Tesla Model Y (V1 and V2) and two Tesla Model 3 (V3 and V10) EVs. Pack Design 1 consisted of a primary tray and lid enclosure that contained the HV modules with a separate penthouse compartment mounted to the top rear of the pack, which contained the power distribution components (main contactors, pre-charge circuitry, pyro-fuse, BMS, etc.), as well as the OBC and DC-DC converter. Key observations related to water submersion and their related effects for Pack Design 1 are discussed below.

Penthouse

As noted earlier, Tesla HV batteries feature a penthouse module that contains a combined OBC and DC-DC converter, in addition to the power distribution system (i.e., contactors, fuses, etc.). These HV components were connected directly to the battery module terminals via busbars and contactors. The removable stamped-aluminum lid of the penthouse featured a liquid-applied closed-cell urethane seal that was secured to the lid with threaded fasteners. The lid had a Gore breather assembly installed at the top, as identified in Figure 21(a).

As shown in Figure 21, the exterior cover of the penthouse showed signs of submersion resulting in various levels of corrosion in all four EVs in this design group. The front-right corner of the penthouse compartment featured two exposed terminals linking the DC-DC converter output to the LV system electrical distribution system, as shown in Figure 22. The LV DC-DC converter terminals were exposed on the penthouse and, as a result, exhibited particularly severe corrosion. For EVs V1 and V2, the positive-side terminal was corroded to an extent that the fastener could not be removed; the cable terminal had to be severed instead. Submersion in salty or brackish water with or without the DC-DC converter turned on could result in galvanic activity that caused this corrosion.

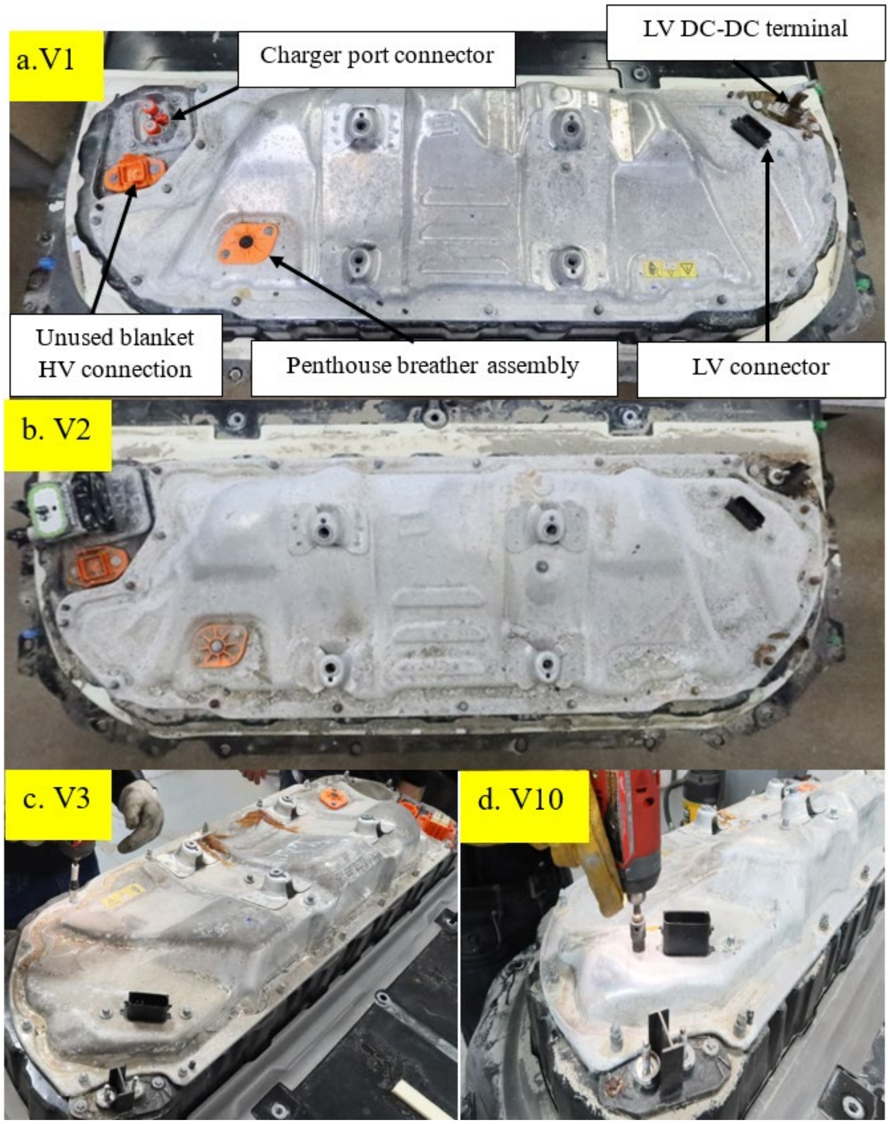

Figure 21. Penthouse exterior cover showing distinct saltwater-induced corrosion

Figure 22. The front-right corner of the penthouse compartment shows two exposed terminals linking the DC-DC converter output to the LV system EDS.

The underside of the penthouse lid cover in EVs V1 and V2 displayed dried residue of a liquid, which suggested either condensation or some degree of water ingress into the area, as observed in Figure 23(a–b). In the case of V1, these areas were mostly concentrated around the penthouse breather vent and the LV communication connector, as illustrated in Figure 23(a). Notably, there was no visible evidence of water ingress or corrosion, so it is plausible the marks observed on the underside of the penthouse lid in V1 were due to condensation, rather than actual water penetration.

In the case of V2, more noticeable watermarks were evident on the underside of the lid. An approximately 1 cm area near the LV communication connector silicone seal showed signs of corrosion, as indicated in Figure 23(b). This suggests that some level of water ingress was likely.

However, EVs V3 and V10 did not display any signs of dried residue of a liquid in the underside areas of the penthouse cover, as illustrated in Figure 23(c) and Figure 23(d), respectively.

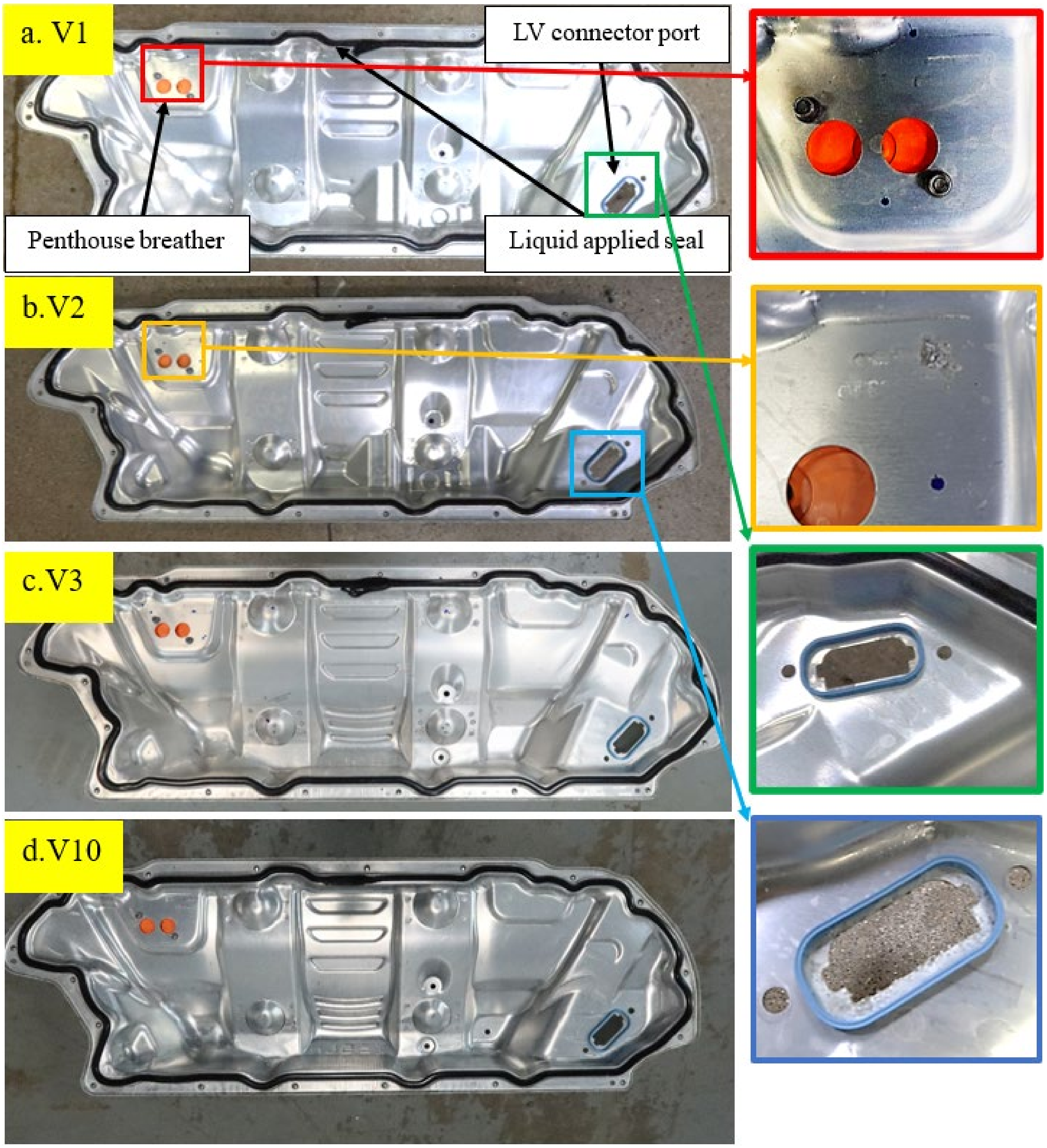

Figure 23. Undersides of the penthouse covers for Pack Design 1

Figure 24(a–b) shows the inside of the penthouse with the key components identified. During the preparation stage of HV battery removal, there was no voltage measured at the external HV connectors or charge port for all the EVs in this group, which verified the contactors were in an open state and functioning as expected. Upon inspection of the interior of the penthouse for EVs V1, V2, and V10, no signs of water ingress were observed, and no damage to the contactors was noted; therefore, removal and further analysis of the contactors was deemed unnecessary. The ceramic and pyrotechnic fuses within the penthouse of these three EVs remain intact, suggesting the HV battery pack did not experience an overvoltage or overcurrent event prior to teardown. Continuity of the squib in the pyrotechnic fuse was verified with a digital multimeter. The current shunt was intact and showed no signs of corrosion or damage.

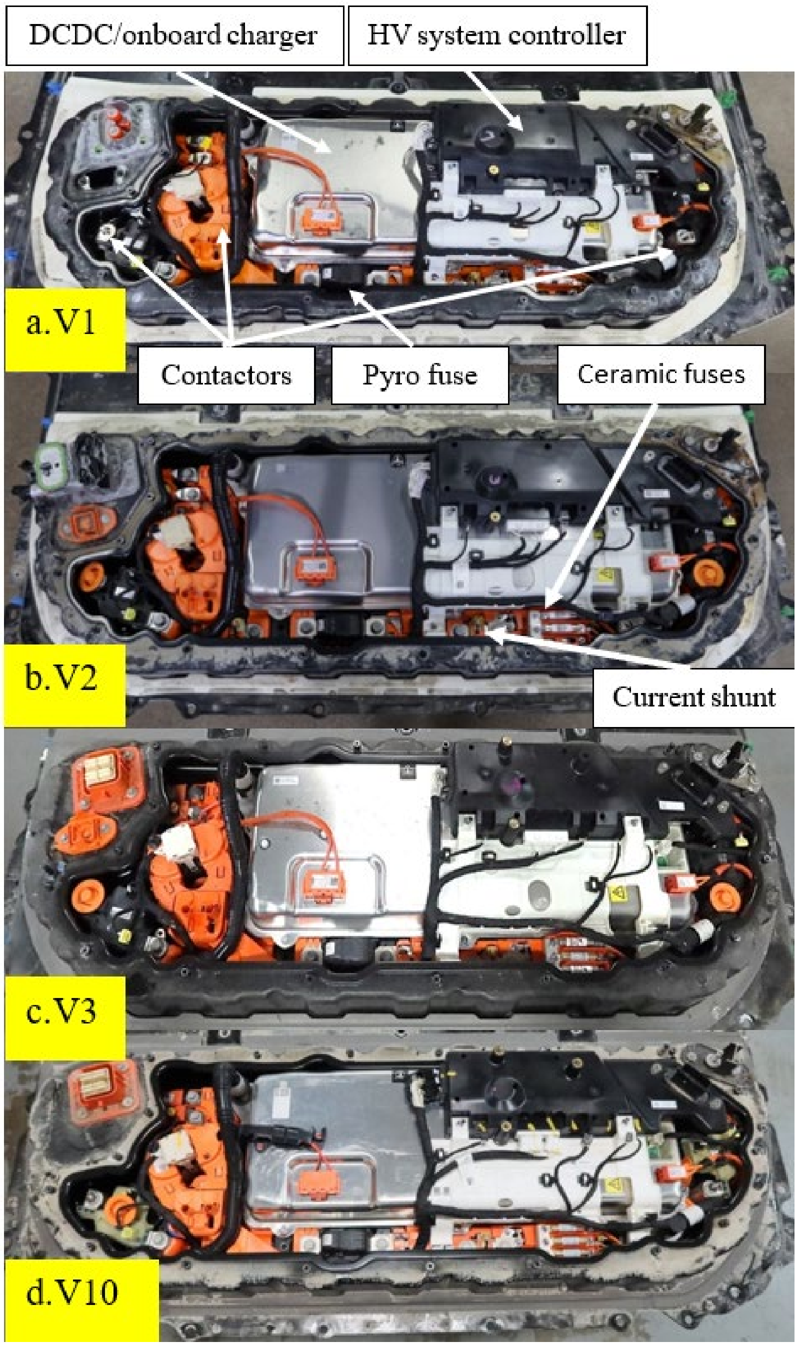

Figure 24. Top view of the penthouse after removing the lid

However, clear signs of deterioration and contamination was observed, including the presence of water and water stains, in both the penthouse and various subcomponents of V3, as depicted in Figure 25. Figure 25(a) shows evidence of water residue and contaminants on the penthouse floor, while Figure 25(b) reveals the presence of water on the contactor connector. Furthermore, corrosion was identified in areas such as the busbar connections, connectors, the uncoated aluminum housing of the charger/inverter module, and elsewhere, as illustrated in Figure 25(c–g). It is important to note the open-circuit (normal) tests and pyro-fuse triggers for the contractors were found to be functional. However, given these observations, it is possible that some of the components within the penthouse may not be able to operate correctly in their current state.

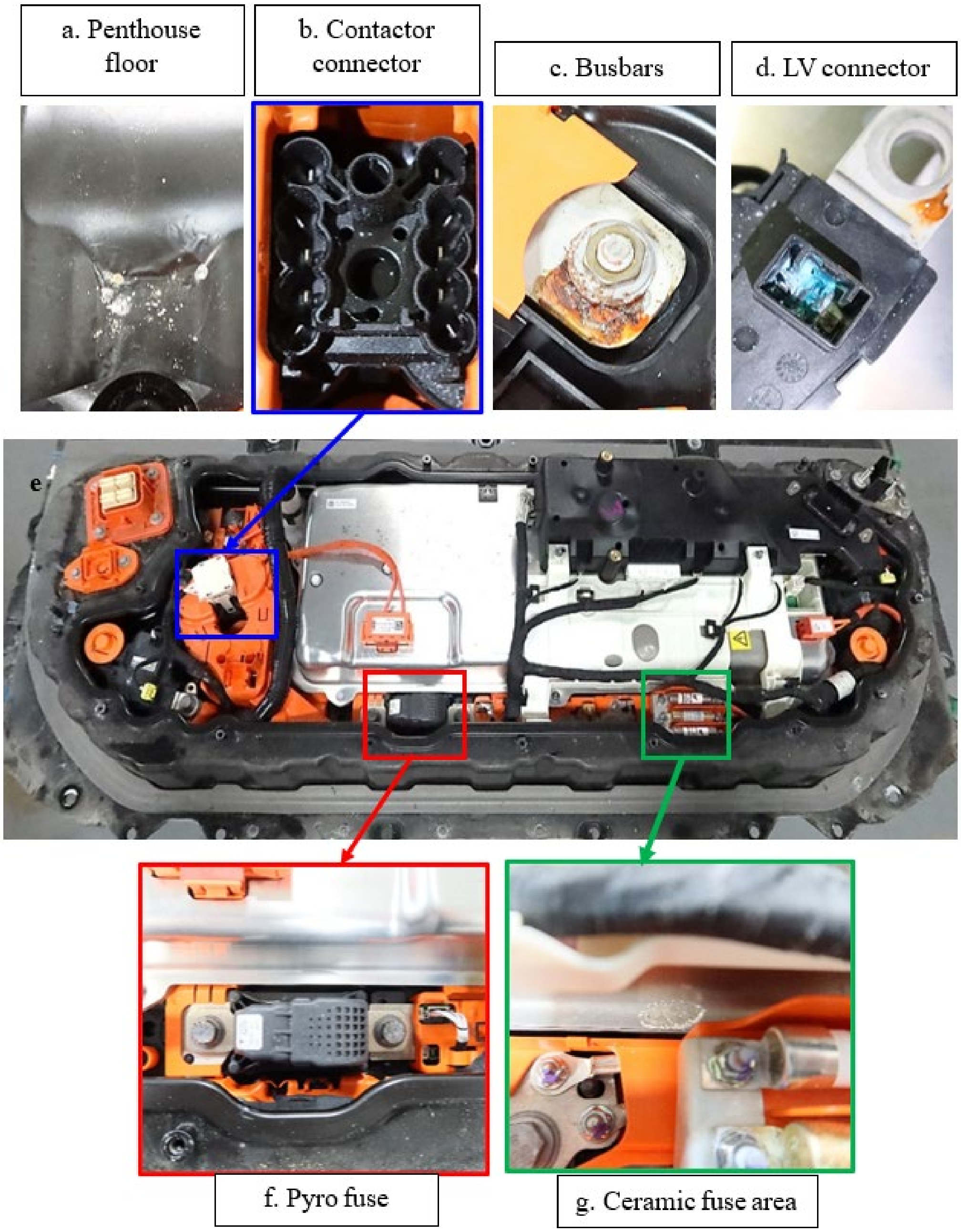

Figure 25. The internals of the penthouse of V3. The presence of water, water marks and residues, contaminations, and corrosion are highlighted in the figure insets.

Penthouse Interface Seals

Figure 26 shows that the areas at the tops of the battery modules interfacing with the penthouse and the electronics within feature circular gaskets for sealing between the penthouse and the module space. Corrosion and contamination observed on the surfaces of these sealed areas, which were exposed to the penthouse space of vehicle V3, as indicated in Figure 26, are most likely due to the water ingress revealed in Figure 25. Moreover, one of the gaskets appears to have failed, with some surface corrosion noted around the terminal bus plate of Module 1, as observed in Figure 26(c–d). It is very possible the exposure and corrosion on the BMS printed circuit-board assemblies have incurred some form of damage that would negatively affect their function.

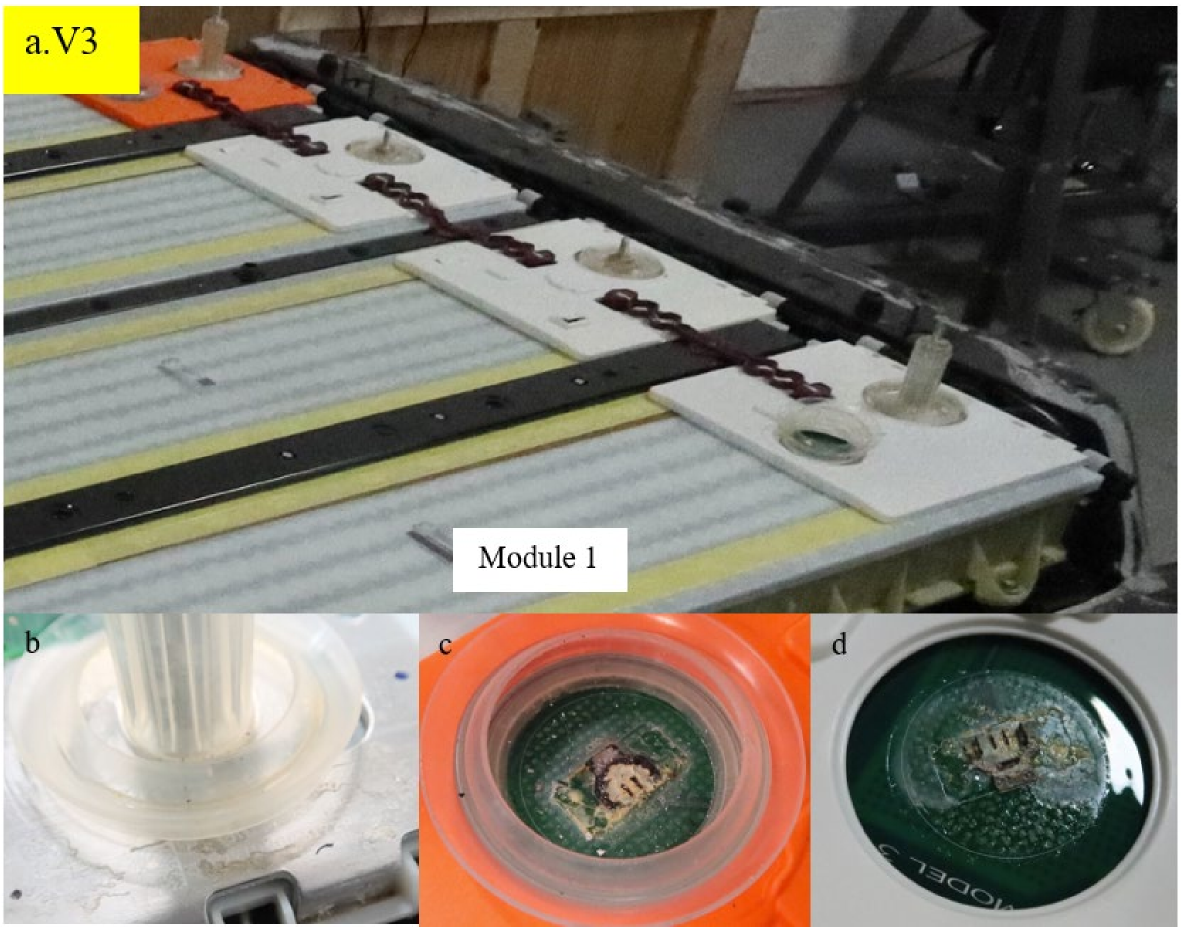

Figure 26. Penthouse interface seals of vehicle V3

Penthouse Moisture Vent or Flood Port

Two moisture-activated vents, or “flood ports” in Tesla nomenclature, are located on the rear-right and rear-left sides of the battery packs in Pack Design 1, mounting through the bottom of the tray into the interior of the penthouse compartment. In these vents, cellulose-based wafers are stacked around a central shaft held closed by a spring that expands in the presence of moisture, thus compressing the spring and opening the vent. In general, the exterior portion of this moisture vent showed signs of debris from the submersion of the EVs in Pack Design 1. For the V1, V2, and V10 EVs, the sealed, interior portion of the vent appeared to be clean, suggesting the seal prevented intrusion into the pack, as indicated in Figure 27(a–c). For V3, both vents were observed to have been activated and stuck open, as shown in Figure 27(d–e). Additionally, the O-rings of the vents appeared to be intact and uncompromised. While it is difficult to determine whether these vents failed in some way and allowed water intrusion into the penthouse space or they merely operated as intended and only opened due to exposure to water within the penthouse from another source, they would present a point of ingress if at least one of the two are either flawed or activated due to exposure to water from the outside of the pack. Note that the Tesla service manual implies there is a first and second design of this port, along with a retrofit procedure.

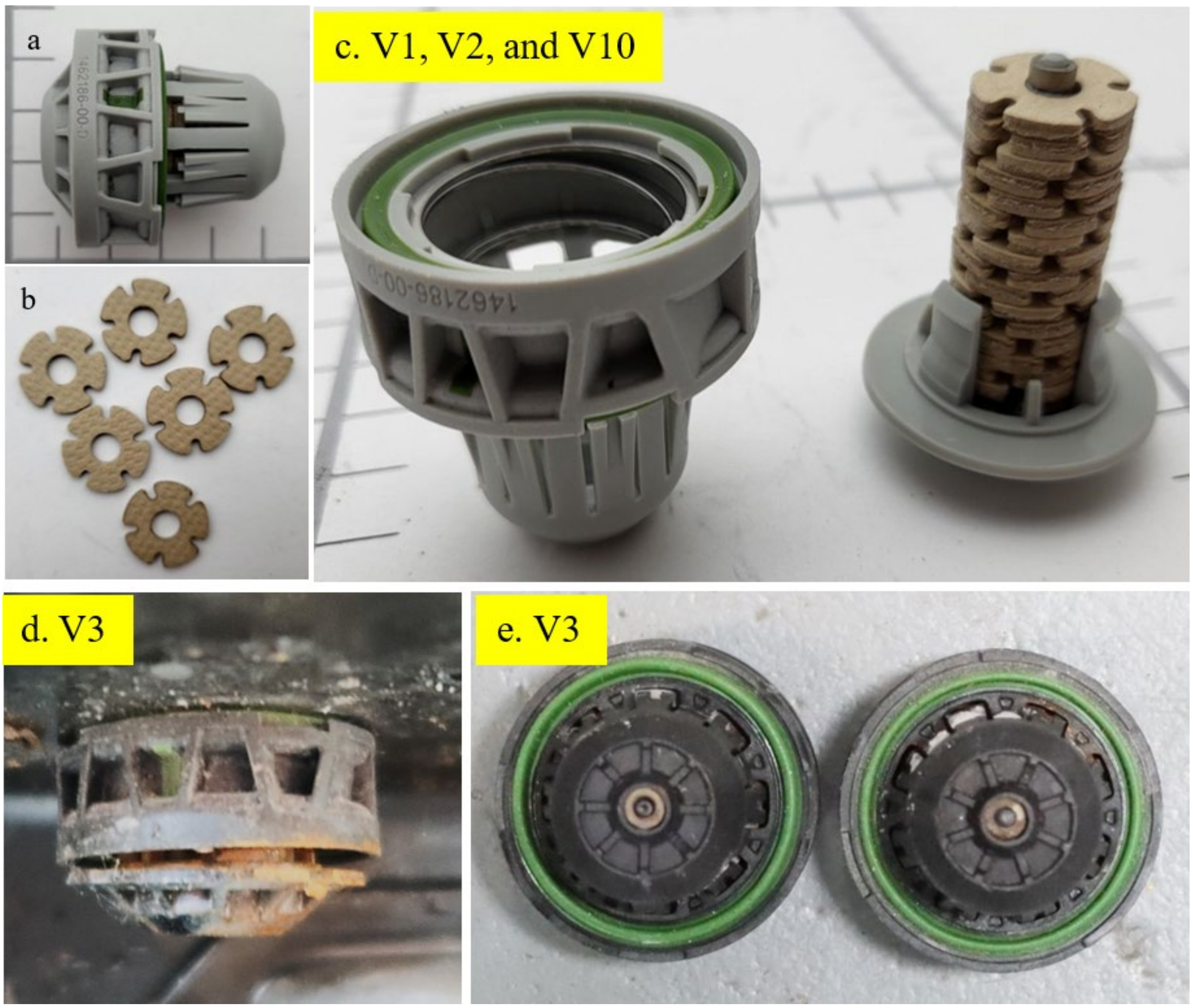

Figure 27. Penthouse moisture vents of Pack Design 1

Battery Pack Vent Assembly

Pack Design 1, which is common to Tesla Models Y and 3, featured two vent assemblies attached to the rear-left and rear-right sides of the main battery pack via threaded fasteners with a seal against the pack tray, as shown in Figure 28. As identified in Figure 28(a), each side employed a Gore vent, a pressure diaphragm, and a pressure-blowout patch. Ventilation was directed outward on either side with a stamped cover over the top of the vents. An examination of the exterior and interior of the vent assemblies for all EVs in this design group showed no sign of seal failure or water ingress through any component of the vent assembly. Two fasteners appeared to have been removed from each vent assembly as a running change, likely to reduce cost, but there was no evidence that seal efficacy was compromised as a result.

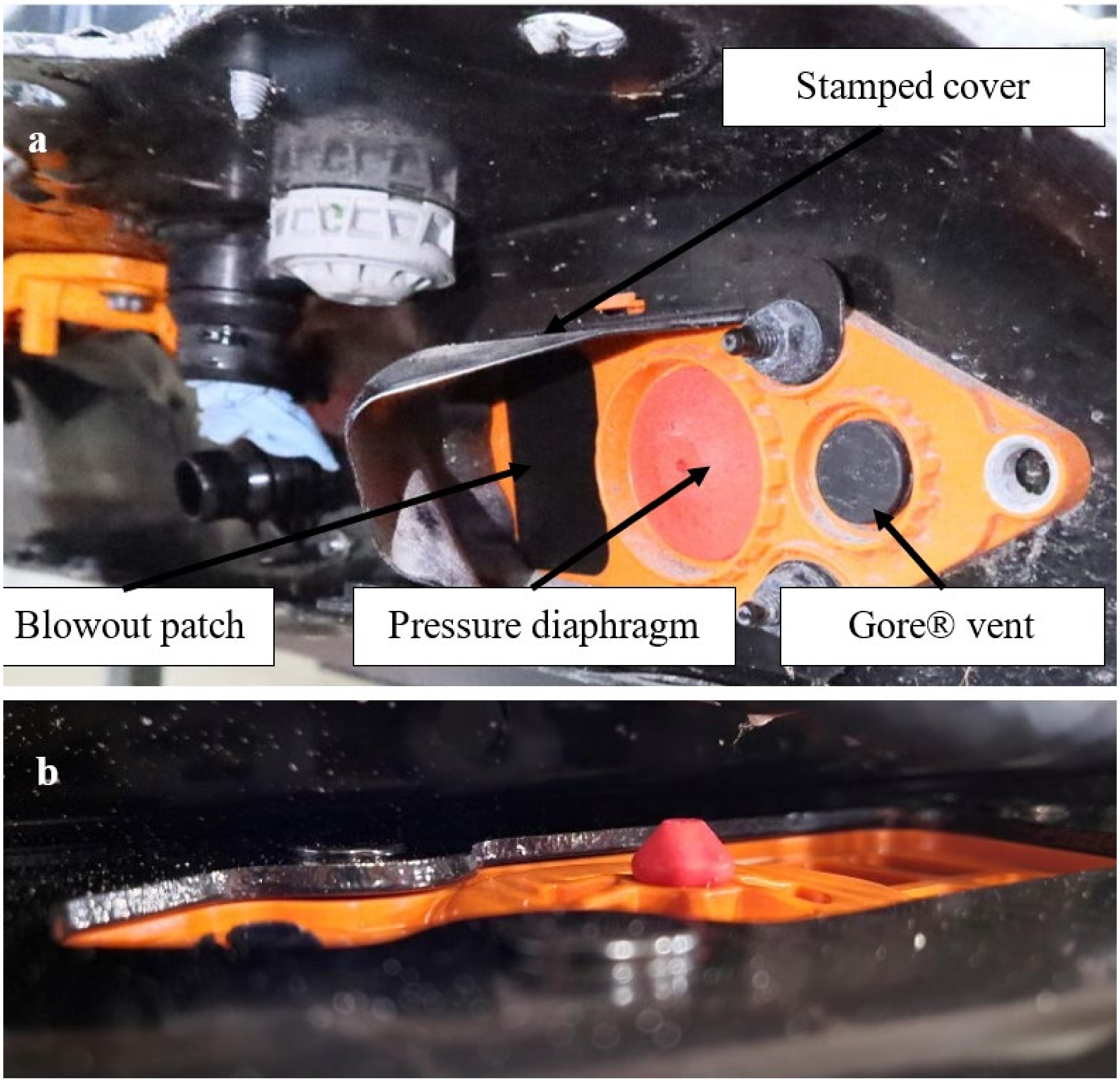

Figure 28. Battery pack vent assembly of Pack Design 1:
(a) vent assembly exterior, and (b) vent assembly interior

Connectors

The HV battery penthouse compartment featured an LV communication connector port close to the DC-DC converter of the LV terminals, as shown in Figure 29(a). The male connector on the penthouse, as observed in Figure 29(a), mated to a female connector on one of the vehicle's LV harnesses, as observed in Figure 29(b), to communicate battery-diagnostic information. A single seal was present on the interior of the female connector, as shown in Figure 29(b). Figure 29(a) shows the interior, sealed area of the LV communication connector on the penthouse of V1 that exhibited what appeared to be the dried residue of water intrusion and remnants of light corrosion or contamination surrounding the bases of several pins. Similar corrosion was discovered on the corresponding terminals of the EV wire harness, as shown in Figure 29(b). No melting was observed on the connector terminals or pins—only powdery white sediment appeared to be present. Although no apparent issues with communication were observed, increased levels of corrosion could eventually affect EV operation due to potentially impaired EV to battery communication. This issue was not observed in EVs V2, V3, and V10.

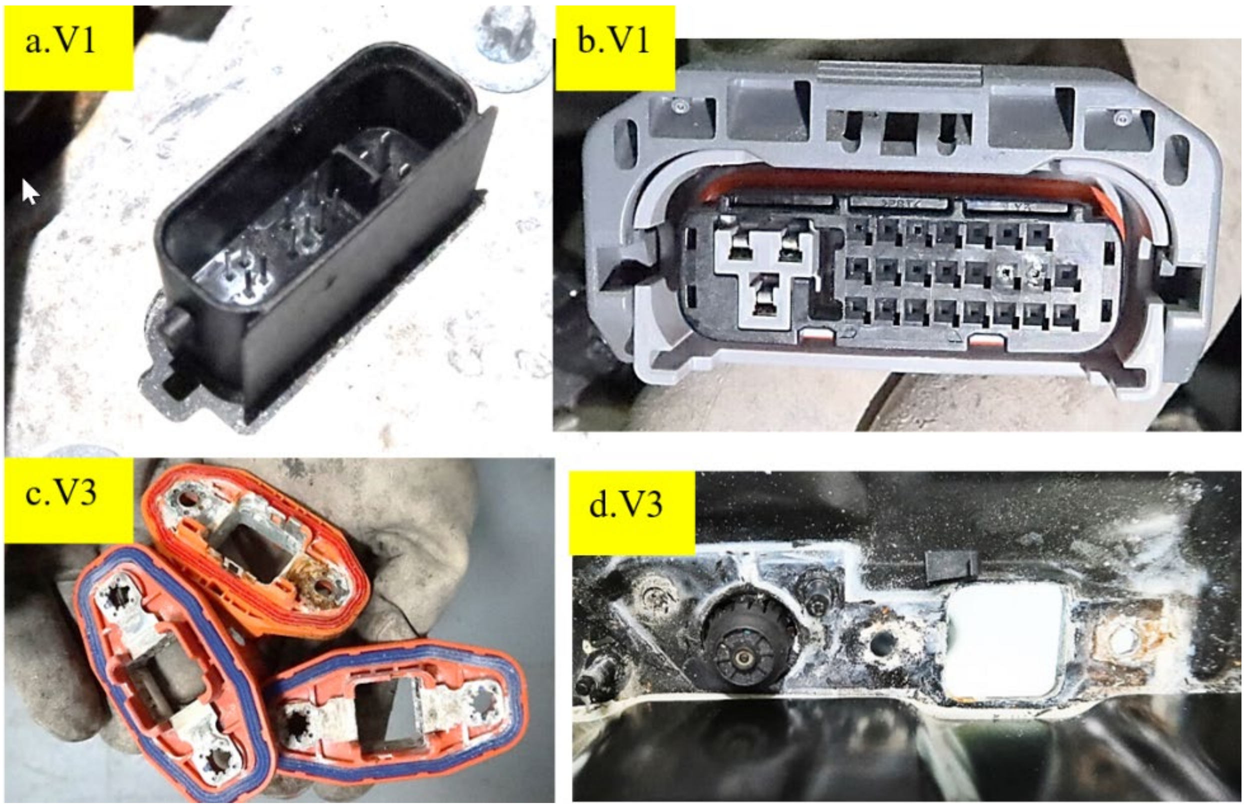

Figure 29. (a–b) LV communication connector of V1. (c–d) HV connector of V3

In the case of Vehicle V3, a significant degree of corrosion was evident on the HV connectors located in the electronics penthouse, as depicted in Figure 29(c–d). Additionally, the internal surface of the pack, where these connectors are mounted, exhibited substantial contamination, as shown in Figure 29(d). These observations suggest the HV connectors in Vehicle V3 may have served as a potential entry point for water, allowing for water intrusion into the vehicle.

It is worth noting that, in the other three EVs within this Pack Design Group, the HV connectors remained unaffected and did not exhibit signs of compromise.

Pack Lid Seal

The liquid-applied pack lid seal for Vehicles V1, V2, and V3 retained their integrity, successfully deterring any water intrusion. However, water, residue, and contaminants were observed on the pack floor under Module 4 of Vehicle V10, as shown in Figure 30(a). This water and contaminant intrusion did not appear to contact the cells at any point although the lower outboard mount fasteners of the module exhibited light corrosion, as observed in Figure 30(b). The apparent point of ingress was determined to be a void or gap in the liquid-applied lid-perimeter seal at a complex curve near the front-right corner, as shown in Figure 30(c–d), possibly due to trapped air and/or inadequate clamping load prior to curing of the seal.

Figure 30. Observation inside the V10 battery pack:
(a) water residue (note smear) underneath battery module, (b) corroded module fastener, (c) defective appearance of the lid seal, and (d) air pockets in another area of the seal, which did not result in ingress (bottom right)

Coolant Port

Tesla Models Y and 3, grouped into Pack Design 1, featured four coolant ports—two at the front and two at the rear—for the supply and return of the ethylene-glycol coolant to thermally manage the battery pack, as shown in Figure 31. Each coolant port was attached with threaded fasteners and seals against the interior face of the pack tray. An examination of the exterior and interior of the coolant ports showed no sign of seal failure or water ingress for any of the EVs in Pack Design 1. Two fasteners appeared to have been removed from each coolant port as a running change, likely to reduce cost, but there was no evidence that seal efficacy was compromised as a result.

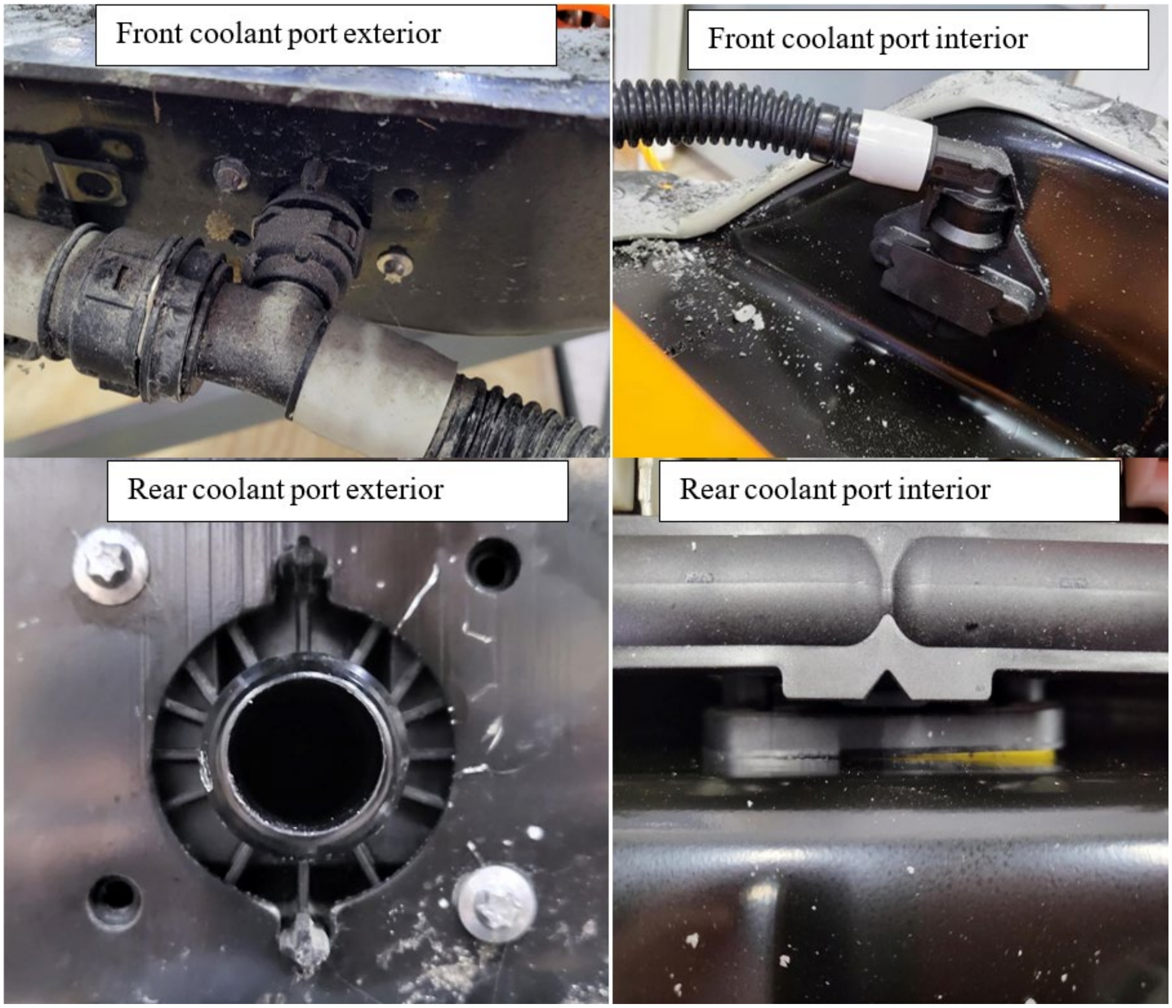

Figure 31. Representation (V1) coolant port of Pack Design 1

12-volt Battery

The 12-volt battery for this pack design was located under the wiper cowl. Vehicle V1 had a LiB while the other EVs had conventional lead-acid batteries to supply LV power. As shown in Figure 32, the V1 Li-ion battery was at least partially submerged, as evidenced by the corrosion present on the surface of the cast-aluminum housing. The voltage reading from the main external terminals at the time of removal was 0.026 V. A control board was located under the cast-aluminum lid covering the four prismatic Li-ion cells within the battery. The prismatic cell voltages measured 0.612, 0.407, 0.277, and 0.409 V, or 1.7 V total.

Such an LV reading indicates this LiB reached a state of over-discharge, likely through the submersion of the LV terminals on the HV battery pack penthouse. Given the low state of charge, it is highly unlikely this battery could be safely recharged or used again, but it does not appear to have failed in a catastrophic manner nor does it appear to be responsible for any damage to its neighboring components. The 12-volt battery interior did not display signs of water ingress, as shown in Figure 32, suggesting that, despite submersion, the connector seal was uncompromised. The switching components on the PCBA and the disparity in the voltages measured at the external terminals and directly from the cells suggest the 12-volt battery possesses the capability to open the circuit between the main external connector and the prismatic cells within the housing, which would theoretically allow the battery to self-protect against a short-circuit or abuse conditions.

Snapshots of the 12-volt lead-acid batteries are presented in Figure 33, which provides evidence (marks, debris, sediment, etc.) of full submersion. The terminals of all these batteries showed heavy corrosion. These LV batteries measured (~0.05 V) as severely drained but did not appear to have failed in a catastrophic manner or to be responsible for any damage to neighboring components.

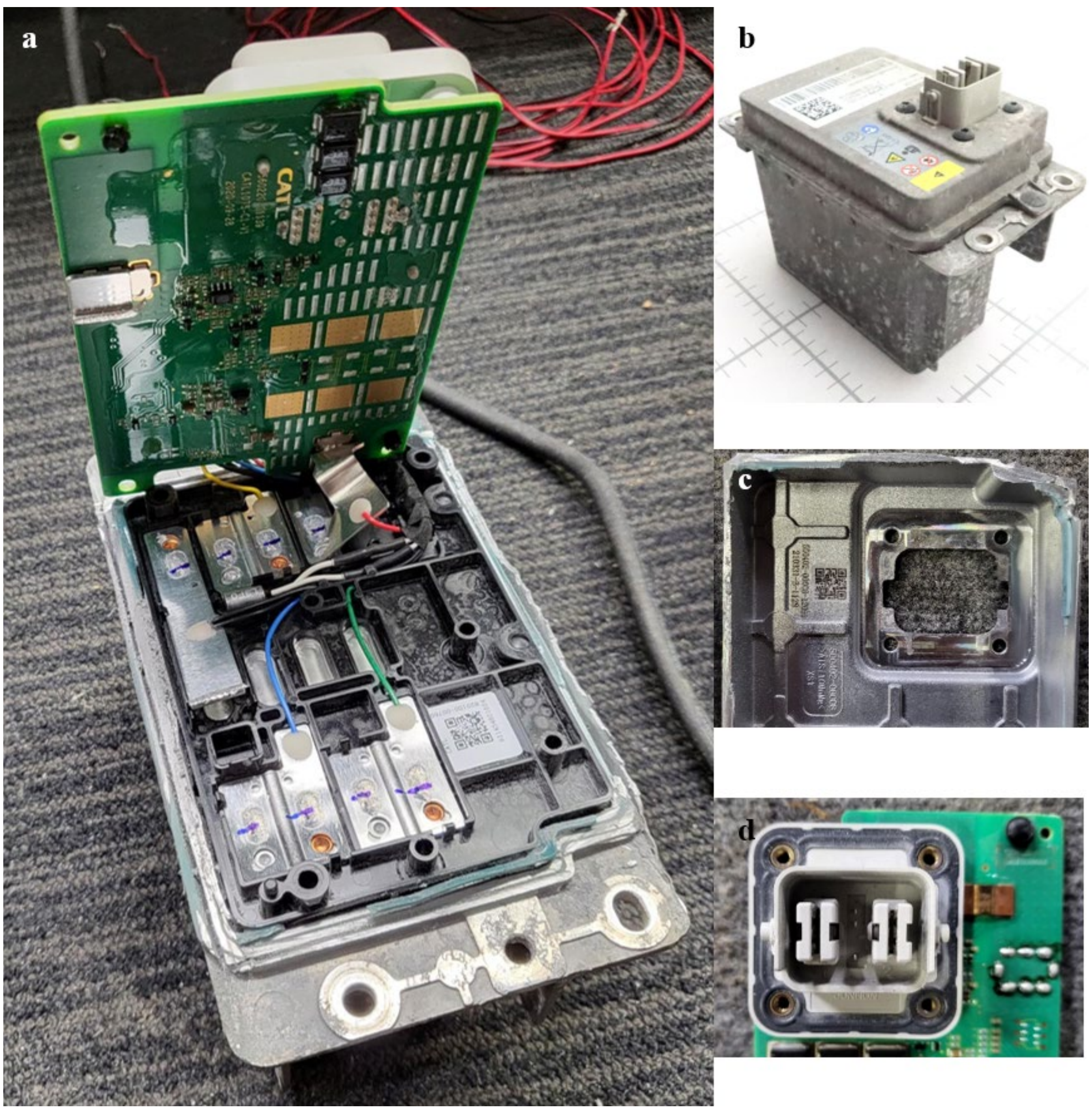

Figure 32. Dissection of LV battery of Vehicle V1

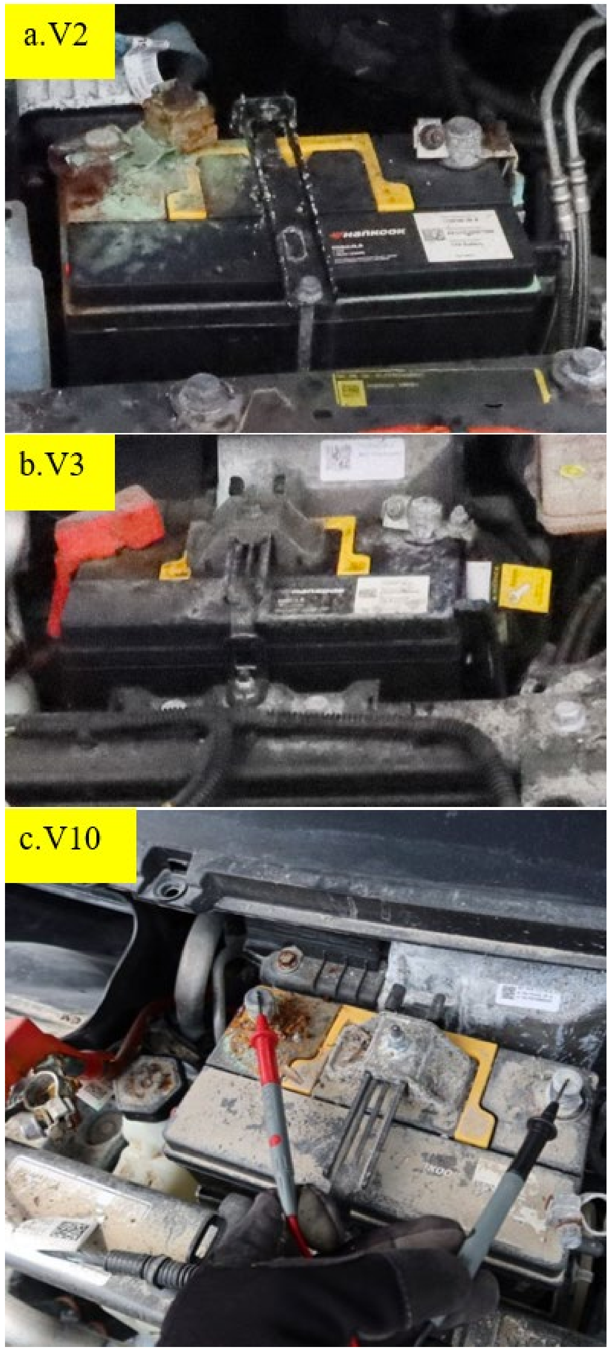

Figure 33. LV battery of V2, V3, and V10

Battery Pack

Pack-level voltage measurement was taken from the main positive and negative terminals inside the penthouse immediately following penthouse cover removal, as shown in Figure 34(a). The main battery compartment of Pack Design 1 contained four battery modules, as identified in Figure 34(b). Module-level voltage measurements were taken at the positive and negative terminals of each module. Modules 1 and 4 consisted of 23 cell groups each while Modules 2 and 3 contained 25 cell groups each. The voltage measurement of those cell groups were taken through the BMS cell group taps indicated in Figure 34(c).

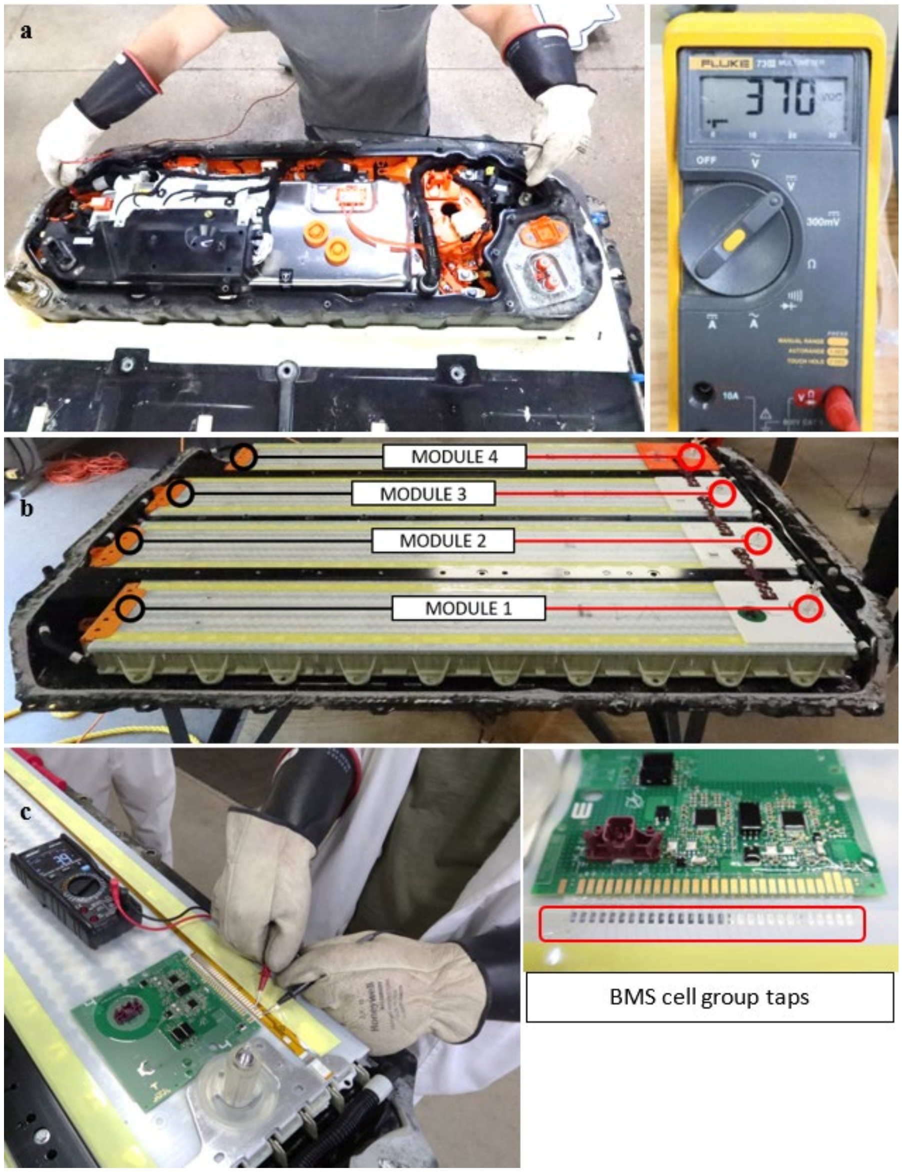

Figure 34. Inside of battery pack and measurement strategy:
(a) pack voltage measurement through penthouse terminals, (b) module arrangement within a pack, and (c) cell group voltage measurement through BMS taps

Table 4 presents the measured pack, module, and cell group voltages. In general, the pack retains HV even after more than 10 months of storage. Figure 35(a) shows a representative open battery with the modules identified. Except for V3, the maximum cell group voltage variation remained within 14 mV. Module 3 of V3, as shown in Figure 35(b–d), measured 3 V lower than the identical Module 2. Cell group voltage testing revealed Cell Group 11 within Module 3 of V3 measured 1.06 V (i.e., severely over-discharged) vs. the average cell group voltage of 3.91 V. Module 3 was removed to inspect the floor area directly underneath, as observed in Figure 35(b–c). The floor of this module space revealed neither any sign of water intrusion nor sign of damage, as shown in Figure 35(b). The over-discharged Cell Group 11 was consequently located, and the surrounding materials removed. No evidence of any physical damage was found, as shown in Figure 35(c). The absence of any evidence of water-induced damage indicates probable manufacturing- or age-related issues within Cell Group 11 resulting in higher self-discharge during the extended period of storage following the flood event in the absence of charging.

Table 4. Measured pack, module, and cell group voltages of Pack Design 1

Vehicle	Pack Voltage, V	Module 1 Voltage/Cell Group Spread, V	Module 2 Voltage/Cell Group Spread, V	Module 3 Voltage/Cell Group Spread, V	Module 4 Voltage/Cell Group Spread, V
V1	370	88.60/3.85 ±0	96.25/3.85 ±0	96.25/3.85 ±0	88.55/ 3.8 5±0
V2	381	91.30/3.97 ±0	99.30/3.97 ±0	99.30/3.97 ±0	91.30/ 3.97 ±0
V3	383	91.80/3.99 ±0.014	100.70/4.03 ±0.013	97.70/3.91 ±0.581	92.80/ 4.04 ±0.011
V10	392.6	94.10/4.09 ±0.002	102.20/4.09 ±0.005	102.1/4.08 ±0.006	94.20/4.10 ±0.004

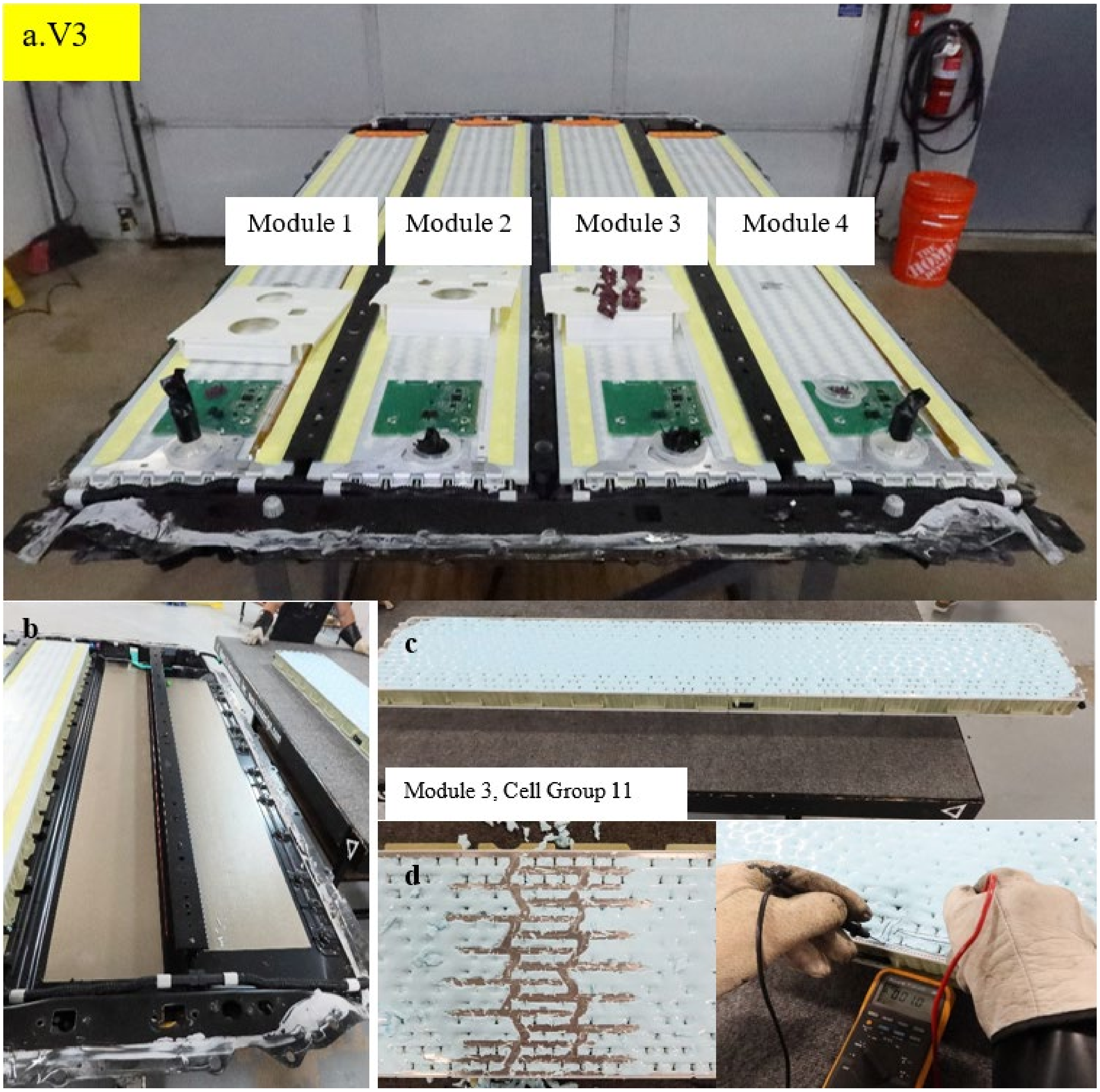

Figure 35. Vehicle V3 battery pack:
(a) open battery pack showing the four modules, (b) the battery pack after removing Module 3 and 4, (c) Module 3 isolated, and (d) Module 3, Cell Group 11. Module 3 compartment has no ingress evidence. Bond-wire encapsulation was removed from Module 3 for bond-wire and current collector inspection after LV reading on Cell Group 11

Summary on Pack Design 1

Pack Design 1, which encompassed the Tesla Models 3 and Y, exhibited several vulnerabilities to ingress, including the electrical connectors, vents, flood ports, and seals.

In the case of Vehicle V10, identified as a Tesla Model 3, evidence suggests ingress occurred in the main battery compartment due to a potential insufficiency in the application of sealant between the base and the lid. This insufficiency appears to have transpired at a complex curve near the front-right corner, possibly attributed to the entrapment of air and/or inadequate clamping pressure prior to seal curing.

Vehicle V2, a Tesla Model Y, also displayed indications of ingress into the penthouse compartment, primarily stemming from the breather vent and blue LV connector seals.

The LV connector used in Vehicle V1, another Tesla Model Y, exhibited signs of pin corrosion due to water ingress.

Vehicle V3, identified as a Tesla Model 3, revealed evidence of the presence of water and water-induced corrosion or contamination within the penthouse compartment and across various components. Furthermore, one of the two internal circular gaskets responsible for sealing between the penthouse and module space experienced a failure although it should be noted this was an internal leak and can be considered a secondary consequence of submersion. Both flood vents/ports within Vehicle V3 were found to have either failed or been activated although it remains unclear whether this activation was a causative factor or a consequence of ingress; nevertheless, they represent potential pathways for leakage. Importantly, the HV connectors on the pack of Vehicle V3 appear to have likely contributed to its ingress following exposure to flooding conditions.

Pack Design 2: Tesla Models S and X (Vehicles V6, V7, V8, and V9)

Pack Design 2 included three Tesla Model X (V6, V7, and V8) and one Tesla Model S (V9) EVs. This pack was relatively simple to remove because it was designed for easy EV installation and removal. All connections required no additional effort than to remove the battery-mounting fasteners and drop the pack. Key observations related to the impact of flood damage are elucidated below.

Adhesive-bonded Plastic Sheet

As noted earlier, unlike Pack Design 1 that includes Tesla Models 3 and Y EVs, the battery pack used in Pack Design 2 employed an adhesive-bonded plastic cover on top of the main battery compartment, probably as an added layer of safety from any water intrusion. This plastic cover is exclusively present on all battery pack lids in Pack Design 2 as well, but the penthouse and PDU are uncovered. A liquid-applied sealant is present on every fastener located underneath the plastic cover.

In general, all pack exteriors in this group were covered in sediment and debris, indicating full submersion. For Vehicle V6, the plastic sheet was able to retain its integrity. However, the plastic cover in the remaining EVs (e.g., V7 to V9) failed to retain their integrity, as shown in Figure 36–Figure 38. Standing water was evident on the pack exterior, both on top of and underneath the plastic lid cover. Adhesive beads were penetrated by water, allowing water across the barrier. The lid did employ an environmental coating to minimize degradation from corrosion. However, a multitude of areas with corrosion or failed environmental coatings are noted across the entirety of the lid exterior, as evidenced by "bubbling" of the lid coating, and most likely caused by the trapped water compromising the coating. This corrosion also extended to several fasteners exhibiting a rusty appearance.

Despite the numerous exterior areas showing corrosion, the interior-facing underside of the lid exhibited no signs of corrosion, contamination, or damage, and the pack interior likewise had no evidence of such, as shown in Figure 36 **to** Figure 38. It is possible the corrosion could compromise the sealing around the fasteners and/or the lid material itself and allow water and contaminant intrusion into the pack interior in the future, but this would conceivably take a long time.

Vehicles V6 and V7 were submerged just above the rocker-panel whereas Vehicles V8 and V9 were fully submerged. The undamaged plastic lid cover in V6 and the failed lid covers in V7 to V9 do not sufficiently show a correlation between plastic cover failure and submersion depth. However, failure of the plastic covers for both V8 and V9, which were fully submerged, may indicate this failure mode becomes more likely with a higher depth of water submersion.

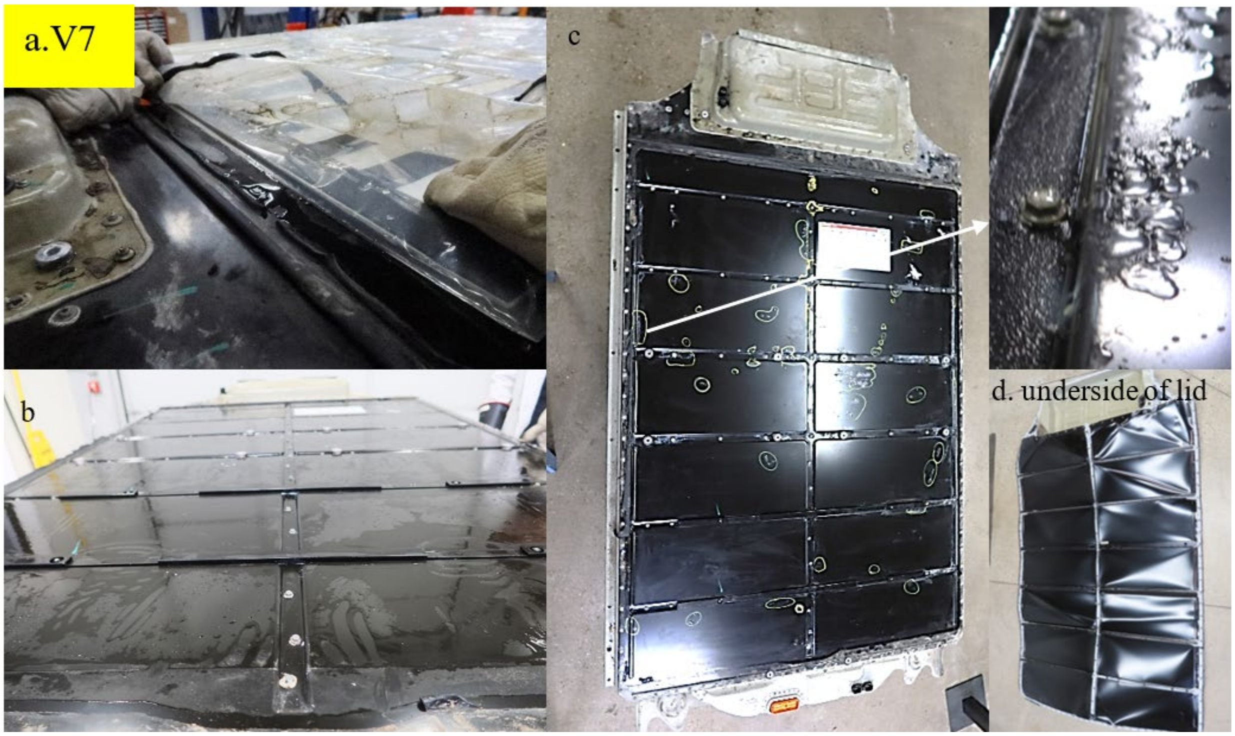

Figure 36. V7 battery pack after removal from the vehicle:
(a) V7 battery pack exterior showing failed plastic cover, (b) water underneath plastic cover, (c) marked corroded areas, and (d) corrosion free lid underside

Figure 37. V8 battery pack after removal from the vehicle:
(a) water underneath plastic cover, (b) salt residue near a fastener, (c) marked corroded areas, and (d) corrosion free lid underside

Figure 38. V9 battery pack after removal from the vehicle:
(a) V9 battery pack exterior showing failed plastic cover, (b) water underneath plastic cover, (c) corrosion in the fastener area, (d) marked corroded areas on the exterior of the lid, and (e) salt residues at the exterior of the lid. The underside of the lid was observed to be corrosion free.

Penthouse Breather Vent

As discussed earlier, the HV battery for this pack design had a raised penthouse section, as observed in Figure 39(a). For this pack design and in an extended-range model, this section of the pack housed extra battery modules, as shown in Figure 39(b–e). A mechanical breather vent sat on the lid in the center of the penthouse of V6, V8, and V9, as shown in Figure 39(b–c, and e). Vehicle V7 did not have a breather vent. This mechanical breather vent is a two-part assembly with an injection-molded nut fastening to the vent body from inside the pack to secure it to a lid, as observed in Figure 39 (a and inset). The penthouse of V6 and V8 were empty, as they housed standard range 75 kWh battery packs. Vehicles V7 and V9 consisted of extended-range 100 kWh battery packs and contained two extra battery modules in the raised, penthouse section, as shown in Figure 39.

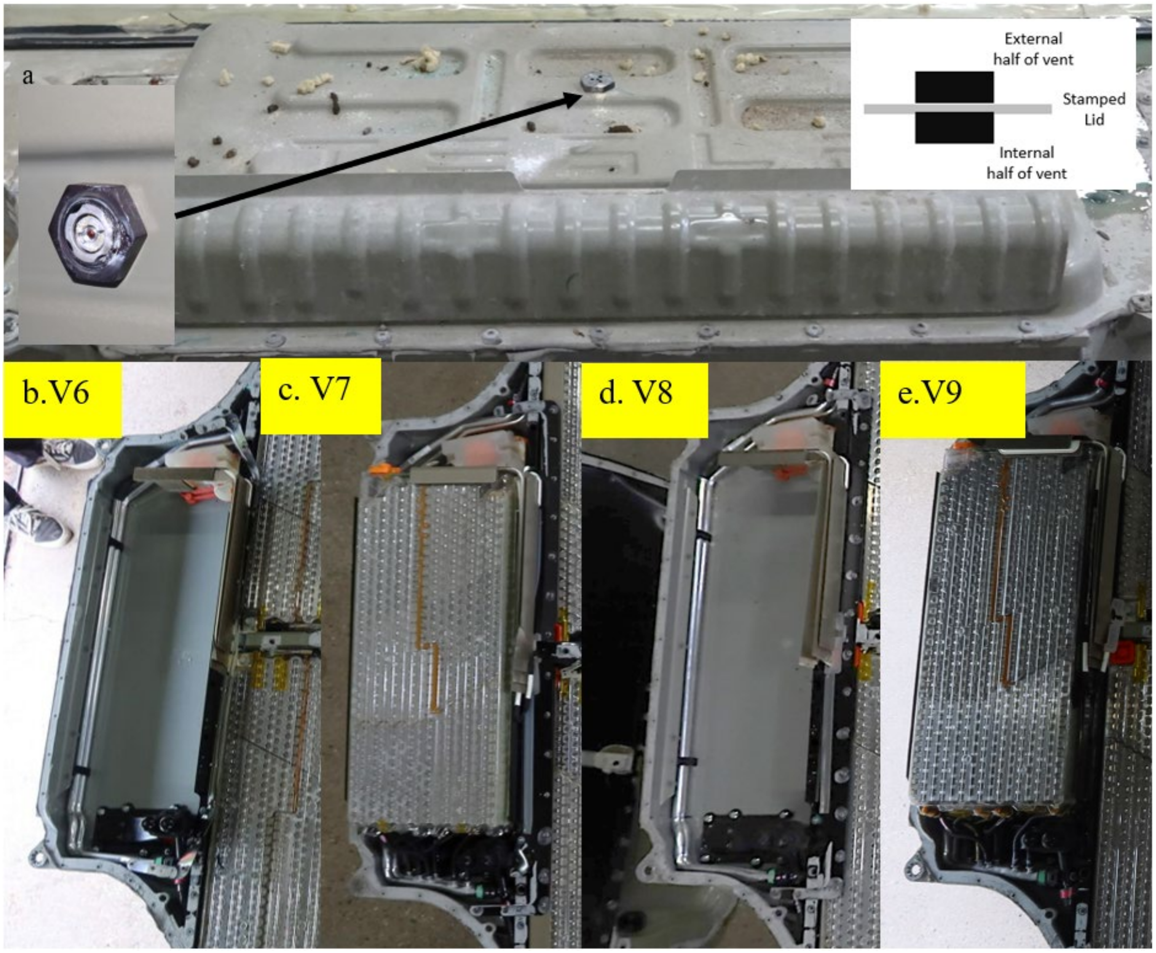

Figure 39. (a) Penthouse breather vent located at the center of lid, and (b), (c), (d) and (e) top view of the penthouse enclosure upon removing the lid. Vehicle V7 did not have a breather vent.

Water ingress and contaminants were observed on the floor of the penthouse space of V6, and V8, directly below the breather vent on the lid, as observed in Figure 40(c) and Figure 41(c), respectively. Examination of the V6 vent revealed a compromised section of the O-ring, as shown in Figure 40(a–b), which aligns with visible witness marks on the retaining nut of the vent on the pack interior, suggesting the compromised seal was responsible for the ingress of water. In this specific V6 battery pack, less risk potential was evident due to the absence of battery modules directly underneath the leaking breather vent; however, were this an extended-range battery, this water intrusion would have fallen directly on the top of the additional battery modules.

The pyrotechnic fuse inside the Model X battery, as shown in Figure 41(d and e), is physically located at the front-right of the pack and electrically located in the middle of the 14 modules. The pyrotechnic fuse is contained within an injection-molded housing containing an injection-molded seal that is compressed against the interior of the pack floor. Figure 41(d and e) shows the presence of sediment deposits exclusively on the interior side of the pyrotechnic fuse, suggesting the source of the liquid that came into contact with the seal is somewhere inside the pack penthouse. Hence, it is likely the liquid may have originated from the vent in the penthouse area of the lid.

For the V8 pack, the penthouse breather vent O-ring was uncompromised, as shown in Figure 41(a), which suggests that an internal failure of the vent itself is responsible for the water intrusion. A large number of water marks and contaminants surrounding the pyro-fuse housing are observed in Figure 41(b). Corrosion is evident on one of the pyro-fuse busbars, as shown in Figure 41(d), all presumably due to the penthouse vent failure. The water intrusion was sufficient to contaminate and corrode one of the pyro-fuse busbars and would presumably present a severe failure risk, as observed in Figure 41(d).

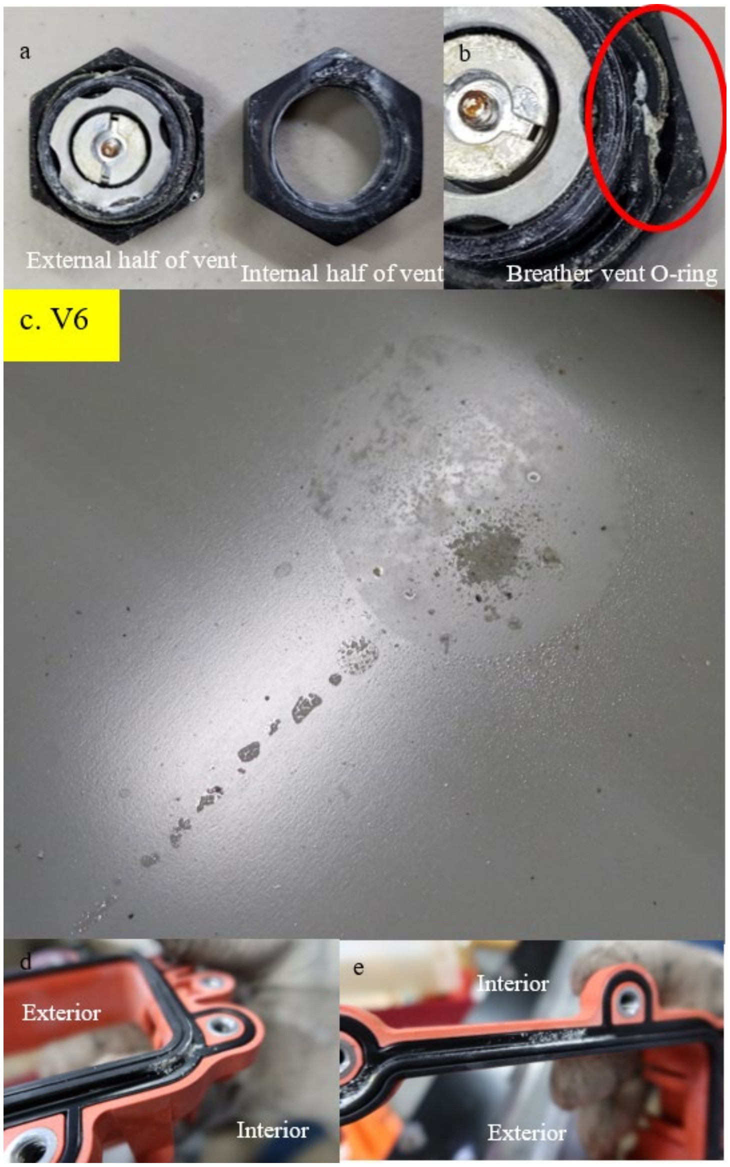

Figure 40. Vehicle V6 penthouse components:
(a) exterior and interior of the penthouse breather vent, (b) compromised breather vent O-ring, (c) water marks and contaminants on the battery penthouse floor, directly underneath the breather vent, and (d, e) sediments on the pyrotechnic fuse

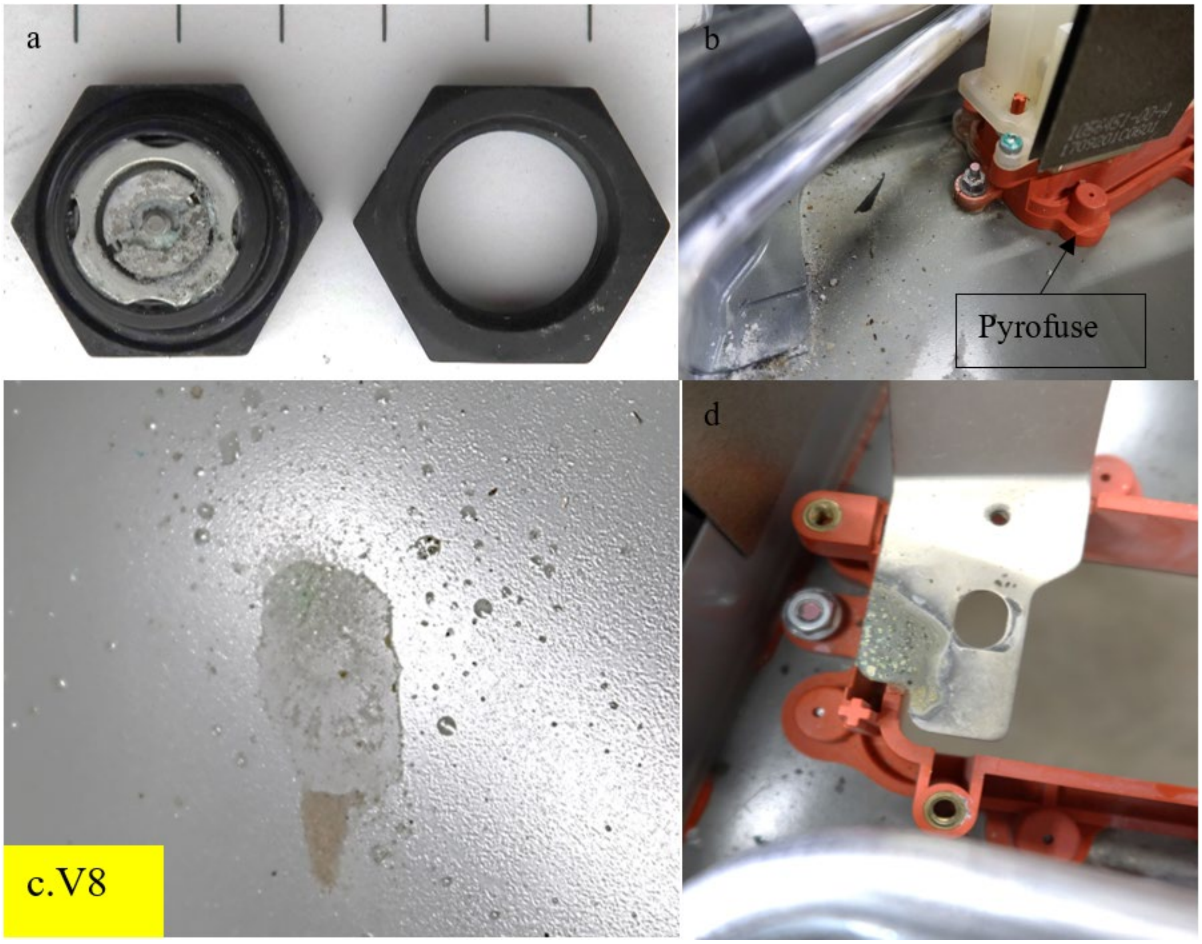

Figure 41. Vehicle V8 penthouse components:
(a) penthouse breather vent, (b) water marks and contaminant surrounding pyro-fuse housing, (c) water marks and contaminants on the battery penthouse floor, directly underneath the breather vent, and (d) corrosion on the pyro-fuse busbar.

Evidence of distinct water ingress and contaminants was also observed on the interior face of the penthouse lid, as shown in Figure 42(a), and on the floor of the penthouse space of V9, as indicated in Figure 42. Examination of the breather vent revealed an intact and uncompromised O-ring, which suggests an internal failure of the vent itself is responsible for the water intrusion, as observed in Figure 42(b).

The penthouse compartment for this pack contained two battery modules placed one on top (M9) of another (M8). The lower battery module (M8) underneath the breather vent within the penthouse space measured a mere 0.40 to –0.45 V, indicating severe over-discharge and an inability to function. Though also contaminated and corroded, the upper module (M9) voltage measured normal, in-line with the remainder of the modules; therefore, it is presumed the water intrusion flowed over the upper module and left it unaffected in comparison to the lower module (M8), which dwelled in the accumulated water. The penthouse floor area also shows distinct signs of corrosion, contamination, and mold, as shown in Figure 42(d and e).

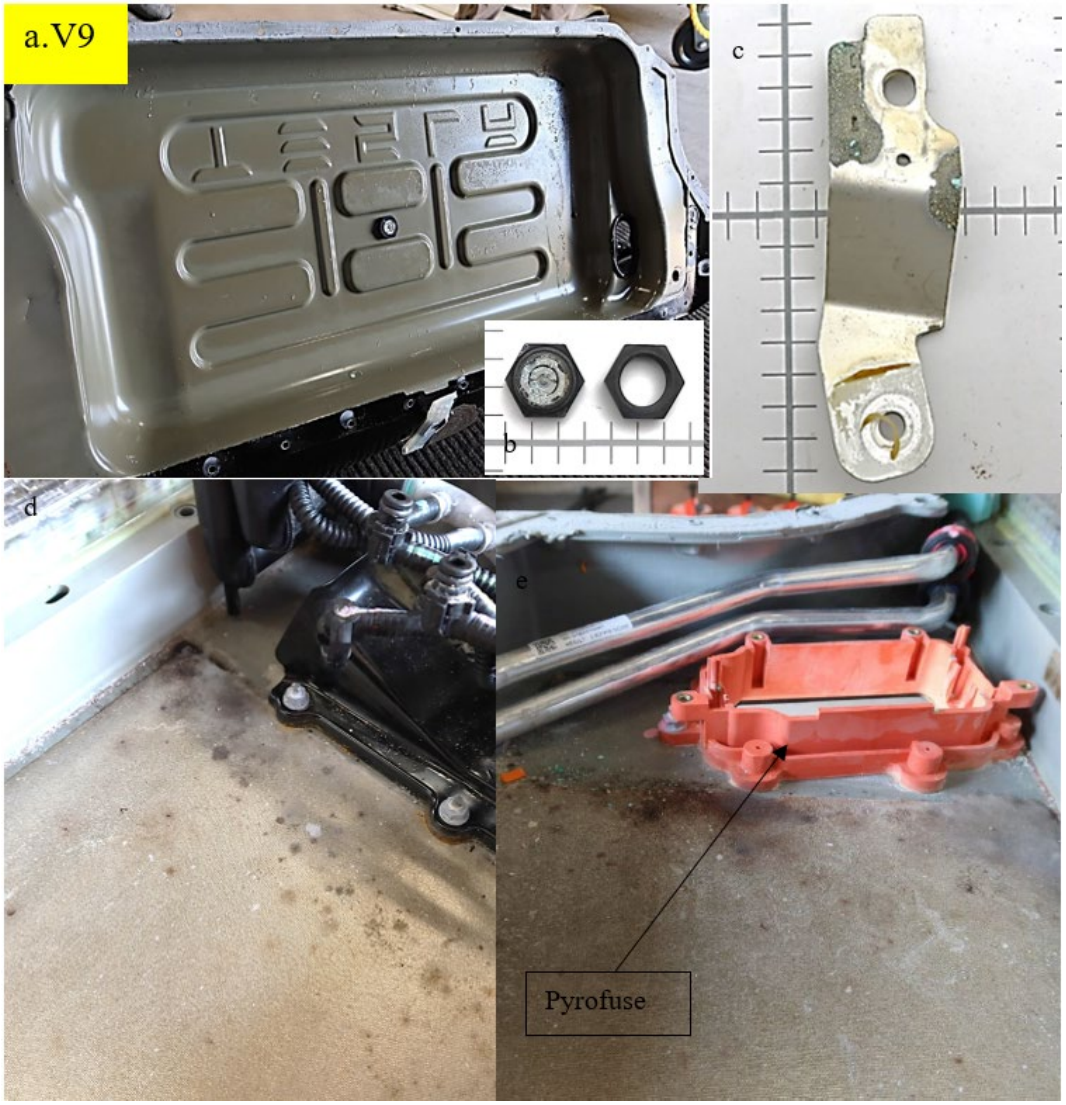

Figure 42. Vehicle V9 penthouse area:
(a) interior face of penthouse lid, covered in condensation, (b) heavily corroded vent, (c) corrosion on the pyro-fuse bus bar, and (d, e) water marks, contaminants, and mold on battery penthouse floor

Battery Pack Vent Assembly

Pack Design 2 featured a vent assembly at the front-left of the pack, as shown in Figure 42(a), to direct gases outward in the event of thermal runaway. The vent contained a stamped cover on the interior, which sat atop the injection-molded vent body. The vent body used an O-ring seal around the perimeter housed in an injection-molded vent assembly, which compressed against the interior of the pack floor. The vent housed three pressure diaphragm blowout valves and a Gore breather valve.

Upon removal of the V6 vent, sediment deposits were observed in a localized area of the O-ring seal, as indicated in Figure 42(b–d). The sediment was present on both sides of the seal, as shown in Figure 42(c), suggesting a breach had occurred. Given the proximity of the breach exclusively to one of the studs used to fasten the vent to the pack, it is possible that insufficient fastener torque resulted in a local reduction in compressive force on the seal, causing this localized leak. The vent assemblies of Vehicles V7, V8, and V9 were all uncompromised.

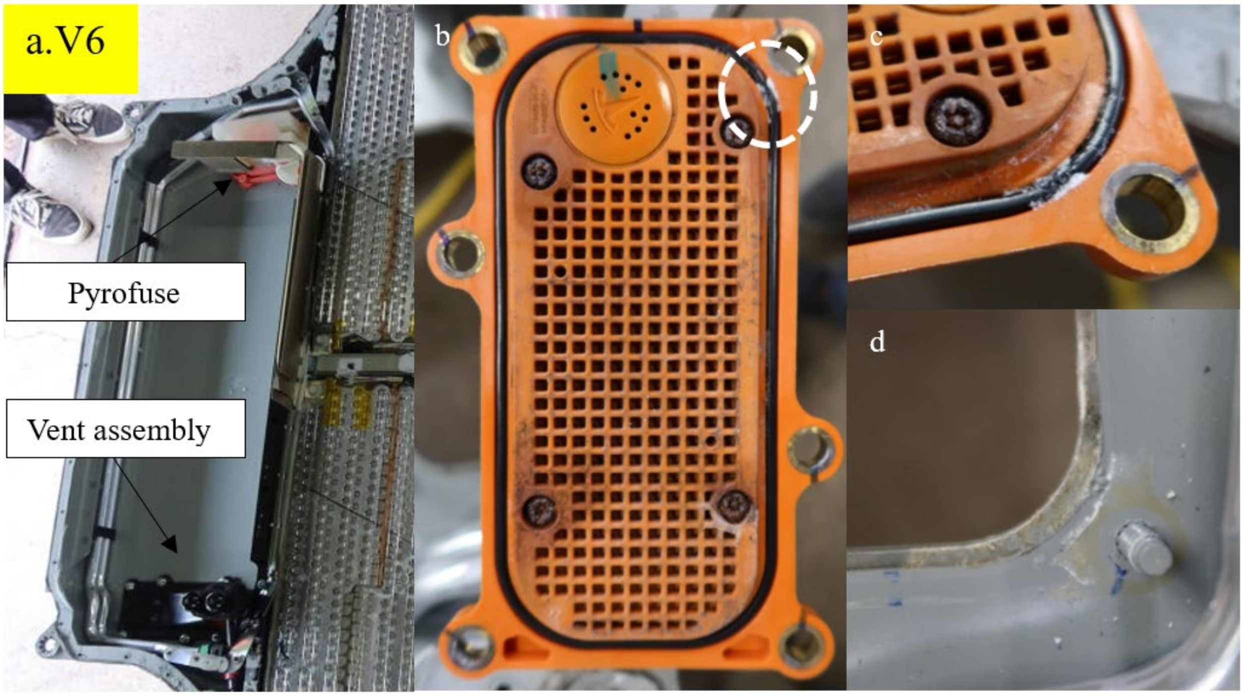

Figure 43. A representative (V6) vent assembly of Pack Design 2: (a) location of vent assembly, (b) interior side of the vent assembly with identified location of sediment, (c) sediment on vent seal, and (d) witness marks inside pack.

Outboard Vents and Plugs

As shown in Figure 44(a–c), the rear-right area of the V8 interior battery pack displayed small amounts of standing water along with corrosion, contamination, and what appeared to be mold across the mica sheet located underneath battery modules M1 and M2, as observed in Figure 44(a). The areas underneath and adjacent to two modules at the rear-right of the pack were examined to better understand the failure mode, which resulted in the observed water ingress, as shown in Figure 44(a). The side sills of the battery pack for this design group featured snap-in pressure vents and vent hole plugs, each of which seal against the battery pack tray with an O-ring, as indicated in Figure 44(d–e). Close examination of the interior side of the vents revealed certain instances where the retaining features of the snap-in vent bodies appear to have failed, resulting in the vent or vent plug becoming unseated in its hole, thereby compromising the integrity of the O-ring and allowing water ingress. Not every component had been unseated from the interior, as shown in Figure 44(d–e); rather, the exterior faces of the other compromised vents revealed slight misalignment that may have contributed to a compromised O-ring seal.

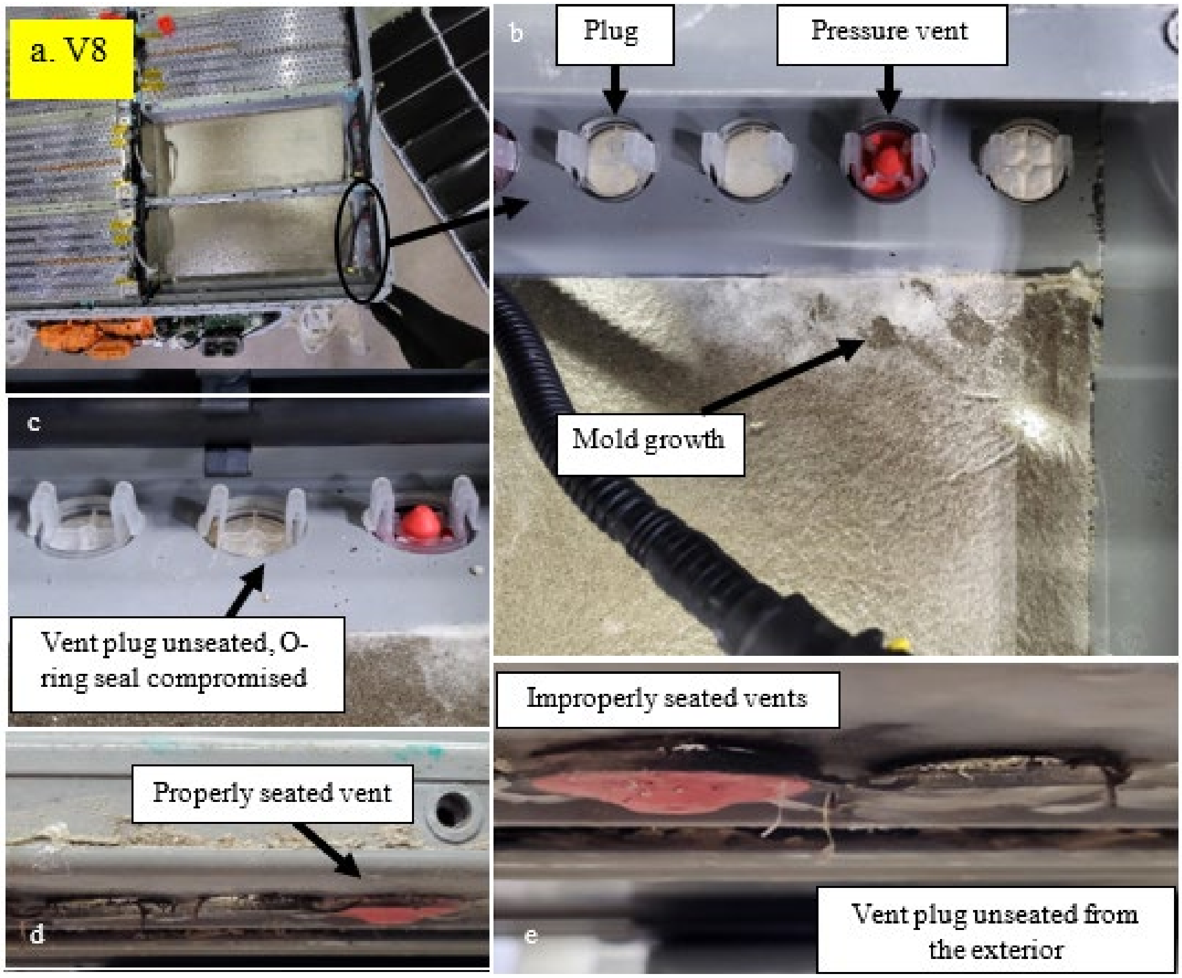

Figure 44. Evidence of water ingress in main battery pack of V8 through the side sill pressure plug:
(a) removed battery modules showing the location of side sill pressure vent and plugs; (b) close-up showing the pressure vent and plugs and mold growth; (c) unseated vent plug from interior; (d) a properly seated vent; and (e) a vent that no longer appears to be seated

For Vehicle V9, several module spaces within the battery pack displayed signs of water contamination—water, water marks, sediment/residue, and/or mold—as pointed out in Figure 45. The outboard side sill vents and plugs showed varying degrees of contamination and may be a primary source of water intrusion within the non-penthouse area of the V9 pack, as observed in Figure 45(a–d). Close examination of the interior side of the vents revealed no obvious signs of failure, such as damage; however, several plugs/vents did not sit perfectly flush against the exterior surface of the pack, which may indicate the O-ring seals are inadequate to provide a proper seal by themselves if a plug/vent becomes even slightly unseated. Damage to one of the outer "shields" covering the plug/vent area was also observed, but this damage appeared to be limited to the shield itself. There was no obvious correlation between the damaged shield and potentially failed plugs/vents. The combination of saltwater exposure and rusting followed 10 months of storage, which may have caused some of the vents or plugs to come loose over time.

The outboard side sill vents and plugs were found to remain uncompromised for Vehicles V6 and V7.

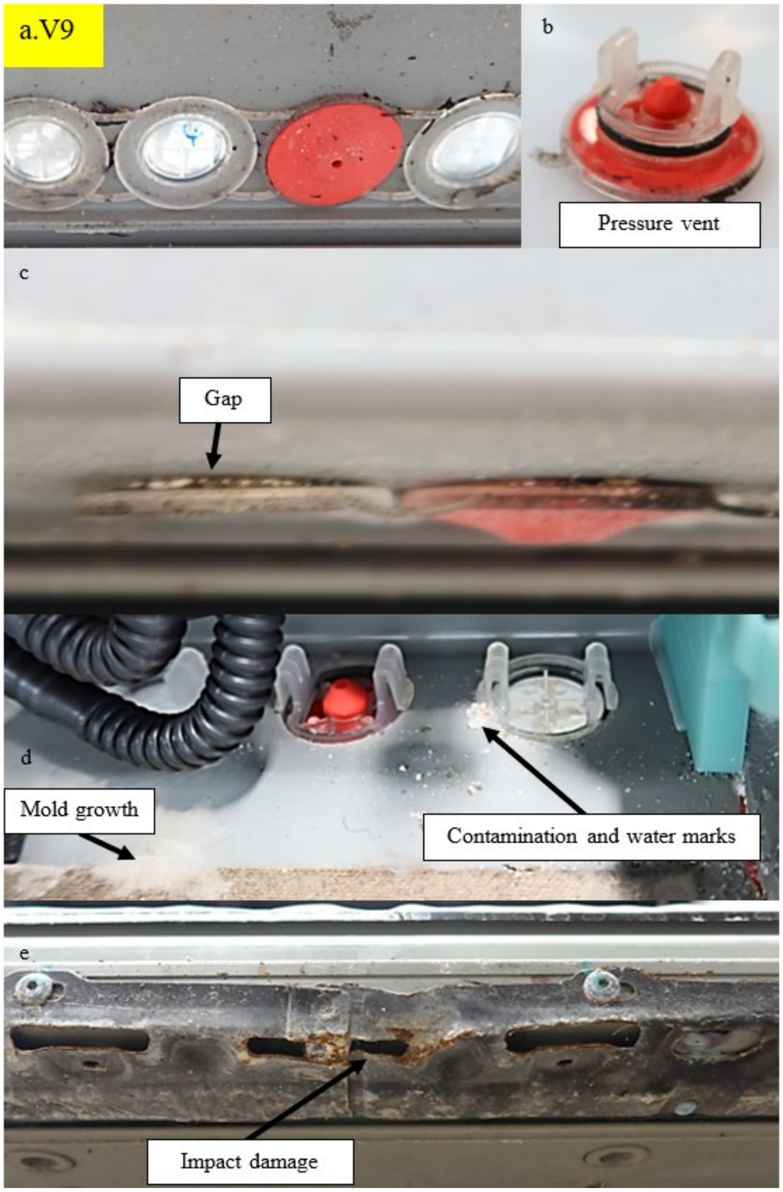

Figure 45. Evidence of water ingress in the main battery pack of V9 through the side sill pressure plug:
(a) side sill pressure vent and plugs; (b) close-up showing the pressure vent; (c) gap in the outboard plug; (d) contamination, watermark, and mold growth near the outboard pressure vents and plugs; and (e) impact damage

Pack and Module Voltage

Figure 46 displays the exposed battery packs, featuring the modules. The module size and arrangement in Pack Design 2 (e.g., Tesla Models S and X) varied distinctly from Pack Design 1 (e.g., Tesla Models Y and 3), as observed in Figure 34. Unlike Pack Design 1, which had four larger modules, Pack Design 2 consisted of up to 16 smaller modules with different packaging strategies. The standard range Vehicles V6 and V8 consisted of 14 modules, whereas the extended-range Vehicles V7 and V9 housed 16 modules. Table 5 lists the measured pack and module voltages and their variations. Like before, the pack-level voltage measurement was taken from the main positive and negative terminals inside the PDU immediately following cover removal. Module-level voltage measurements were taken at the positive and negative terminals of each module.

Table 5. Measured pack and module voltages of Pack Design 2

Vehicle	Pack Voltage, V	Average Module Voltage± St. Dev. /Maximum Spread, V
V6	305.6	21.82 ±0.0445/0.18
V7	298.9	18.68 ±0.027/0.12
V8	346.3	24.72 ±0.028/0.11
V10	396.6	23.04 ±5.83/24.12

Pack voltage varied between 298.9 and 396.6 V for this group of EVs. For Vehicles V6, V7, and V8, the module voltages were consistent, deviating by at most 0.18 V (maximum-minimum module voltage) and 44.5 mV, 1σ standard deviation. For Vehicle V9, the voltage of Module M8, which was located underneath module M9, measured 0.44 V; hence, it created a wider spread of 24.12 V and a standard deviation of 5.83 V. Both Modules M8 and M9 were located directly underneath the failed penthouse breather vent, which caused water ingress (see earlier discussion in Penthouse Breather Vent). The lower battery module within the penthouse, M8, measured a mere 0.4 V and showed evidence of prolonged and severe water contamination, as indicated by the large amounts of corrosion and residue throughout the module, as observed in Figure 46. Hence, Module M8 may be nonfunctional, unsafe, and completely unsuited for operation. The source of the water exposed to this module would appear to be the breather vent on the top of the penthouse lid, which resided directly above both M8 and M9. Given that M8 is located at the bottom of the pack, water likely collected and caused a short, which discharged the module. Though also contaminated and corroded, the upper module M9, as indicated in Figure 47, measured voltage in-line with the remainder of the modules; therefore, it is presumed the water intrusion flowed over the upper module and left it unaffected relative to the lower module, which dwelled in the accumulated water.

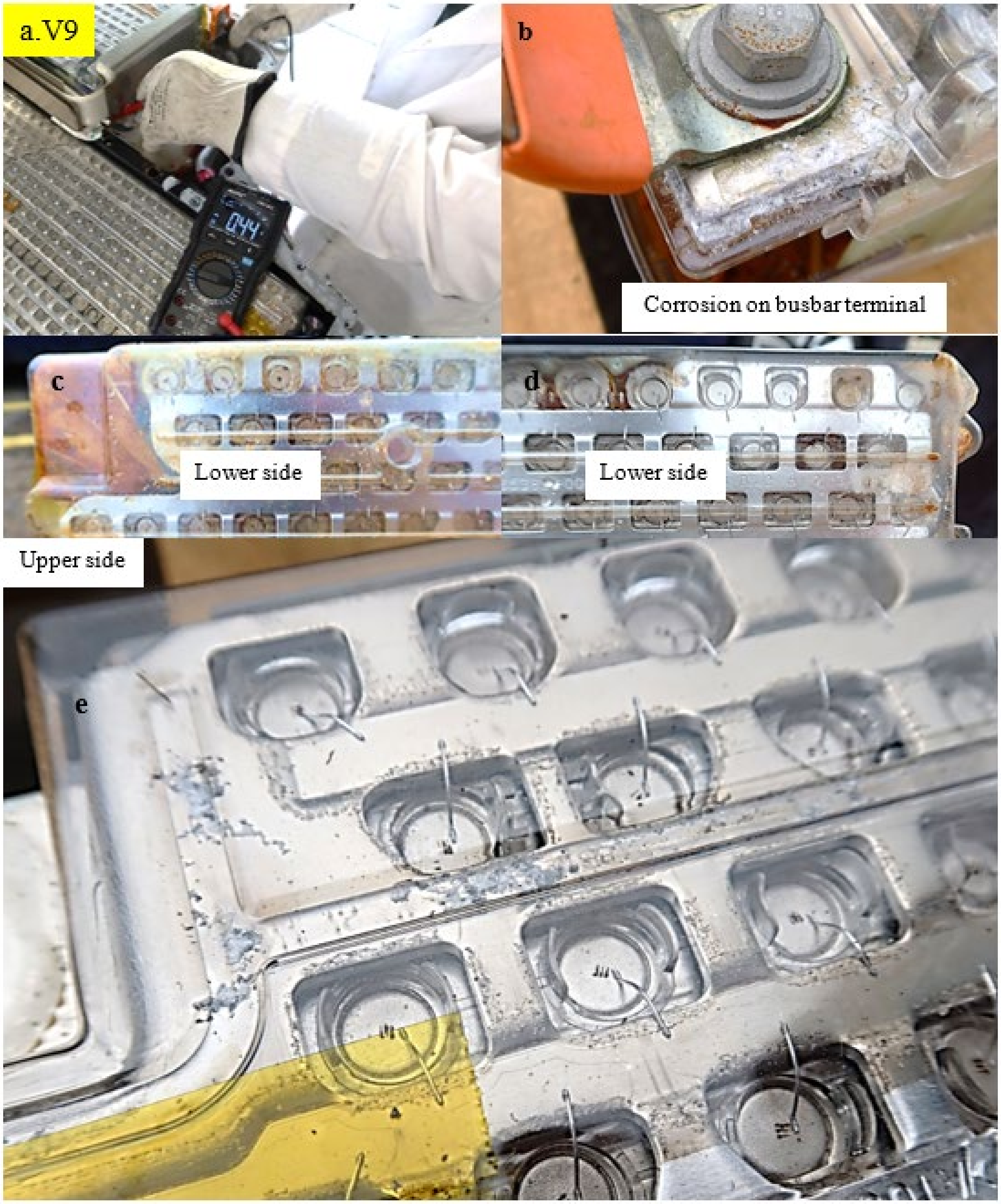

Figure 46. Vehicle V9, module M8 (the lower module in the penthouse): (a) module voltage measurement; (b) corroded busbar terminal; (c), (d) corrosion, contamination, and residue on lower side of module M8; and (e) corrosion on upper side of module M8

Figure 47. Vehicle V9, module M9 (i.e., the upper module in the penthouse), showing watermarks, contamination, and corrosion

Isolation Fault Within Battery Pack

While testing for isolation faults by measuring the HV connector and module-to-chassis voltages, various abnormal results were observed. Munro expected the voltages to be below 1.0 V, or any higher voltage ramping down to less than 1.0 V within a few seconds using only the input impedance of the voltmeter as a load. Any exceptions were investigated for probable cause. The observed voltages here were (i) a measurement of 0.55 V between the external HV terminals with the contactors open, as shown in Figure 48(a); (ii) a measurement of 218.6 V, which is more than half of the entire nominal pack voltage between battery module M1 to the battery chassis prior to busbar removal, as shown in Figure 48(b); and (iii) a measurement of 3 to 9 V from the individual modules to the battery chassis after the busbars had been removed. Hence, Vehicle

V9, a Tesla Model S battery pack, featured isolation faults between each module and the battery chassis, as evidenced by the above measurements.

Figure 48. V9 battery pack:
(a) measuring the external HV terminals with the contactor open; (b) measuring the voltage between battery module M1 and the battery chassis; (c) water on the floor of the module cavity; and (d) mold along the center spine of the tray

Note, in various areas in and around each module, liquid water was observed because of the ingress, as was corrosion on various 18650 battery cells, as observed in Figure 48(c, d) and Figure 49 This cell corrosion appeared to be consistent with damage due to electrolyte leakage (Wang et al., 2022; Bubbico et al., 2018). The front of the pack used aluminum tubing to carry ethylene glycol coolant to the main inlet/outlet ports on the pack lid, as shown in Figure 49(a). Corrosive crystalline material was observed on the aluminum tubes, which contacted the pack tray, as shown in Figure 49(a, b). Continuity measurements revealed a loss of isolation within each module between the 18650 battery cells and the extruded aluminum cooling channel. The aluminum cooling channel weaves through the cells in a serpentine path with a thin layer of thermally conductive adhesive between the cooling channel and the battery cells to improve surface contact and heat-transfer properties, as shown by the schematic in Figure 49(e). Given that some battery cells were corroded, and the damage appeared consistent with electrolyte leakage, a hypothesis can be made that the electrolyte degraded the adhesive layer between the battery cells and the cooling channel, thereby enabling electrical conductivity from the cells through the cooling channels and the coolant fluid itself to the pack chassis. This observed conductivity could also have been from normal manufacturing tolerances that might have allowed some cell connections to the cooling tube to have lower resistance than others due to the thickness variation in the adhesive. These isolation faults were deemed to be of sufficiently high resistance to be deemed safe and, probably, not in violation of FMVSS 305 (>500 Ω/V) (49 CFR Part 571, 2017).

Figure 49. Image showing the impact of water damage that may have contributed to an isolation fault in Vehicle 9:
(a) aluminum coolant tube at front of pack, (b) corrosion build up between aluminum coolant tubes and pack chassis, (c) corrosion on current collectors because of ingress, (d) corrosion on battery cell, and (e) cell-cooling arrangement

Connectors (LV and HV)

The HV battery featured two LV connectors for communication with the rest of the vehicle, as shown in Figure 50. Each connector had a seal against the lid in addition to seals within the connector housings themselves. The body-side female connector employed a snap-fit feature that would normally lock the mating connector in place if used as an in-line connection in a conventional wire harness. Given that the HV battery is designed to drop vertically from the EV without having to manually disengage coolant or electrical connections, this snap-fit feature is effectively unused in this application. The snap-fit feature serves as positive assurance that a connection has been made and will also ensure the seal around the terminals achieves sufficient compression.

Upon examination of the LV connectors after dropping the pack, significant corrosion was noted around several pins, in addition to one of the pins having been broken off in the corresponding female body-side connector, as observed in Figure 50. CAN communication was still possible, even with the observed damage. The lack of a snap-fit mechanism to ensure proper installation depth for the LV connector is likely the mechanism by which the water was able to enter the connector and cause the observed corrosion on the pins and terminals. The compression of the LV connector seal depends on the installation of the entire HV battery pack. This failure mode was not observed in the remaining EVs in this design group.

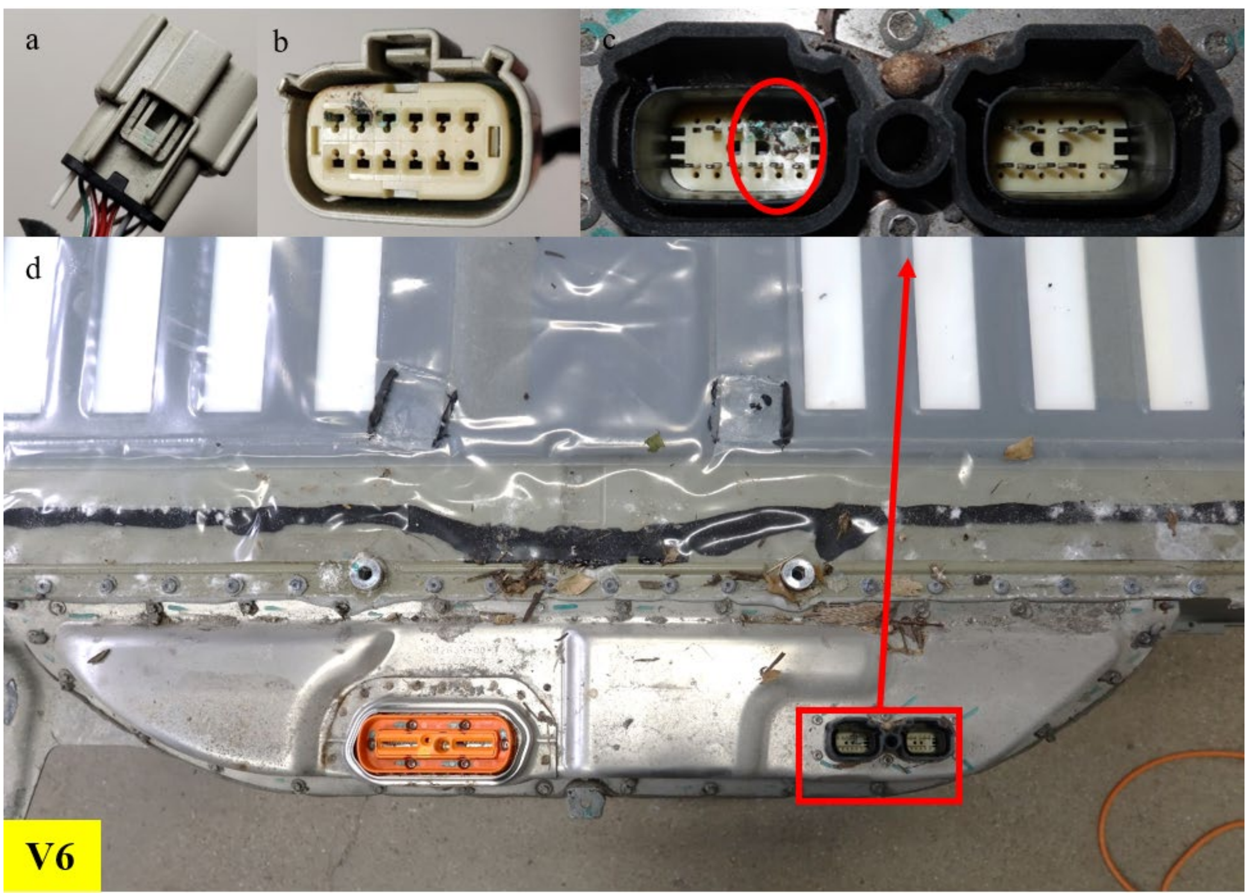

Figure 50. Image showing LV connector of Pack Design 2 (or V6)

Both the Tesla Model X and Model S battery packs are designed for "pack swapping," allowing for simple removal of the HV battery from the EV body. To facilitate this, the coolant connections, LV connectors, and HV terminals on the battery pack all mate with a corresponding connector on the body as the pack is installed, requiring no operators to make connections with cables or tubes. Corrosion was noted inside one of the battery pack HV terminals upon removal from the vehicle (V9), as observed in Figure 51. Examination of the body-side HV terminal connector showed signs of corrosion on the corresponding terminal blade, with no corrosion noted on the other blade. The corroded terminal blade displayed white deposits around the base where it protruded from the injection-molded connector housing, suggesting the ingress originated somewhere on the body-side HV harness and crept along the conductor, eventually making its way into the HV battery connector.

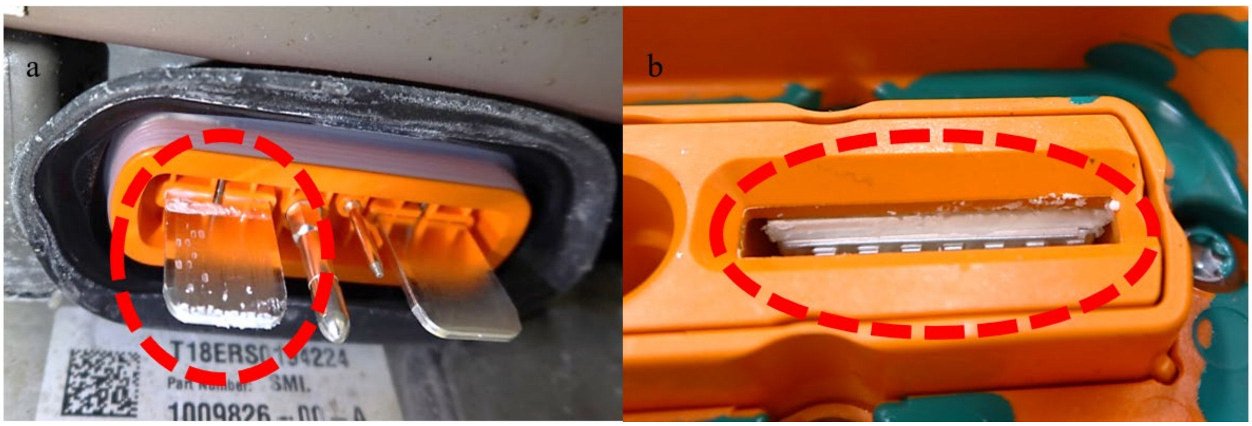

Figure 51. Ingress in HV terminal of vehicle V9

Power Distribution Unit

Upon removal of the power distribution lid for Vehicle V7, a portion of the sealant bead remained adhered to the lid and exposed an area of corrosion on the mating surface of the tray structure, as indicated in Figure 52. Although spanning the full width of the mating surface, no evidence of water intrusion or corrosion was observed on or below the power distribution components. It is most probable that at an undetermined point in time—most likely during the flood event—the coating of the tray structure adjacent to this sealing surface became damaged and then allowed corrosion to begin, progress, and creep under the sealant bead, eventually compromising the complete width of the sealing surface. Judging by the lack of corrosion or contamination within the interior space, it is most likely the corrosion progressed after the flood and during storage at a vehicle scrapyard. This corrosion prevents proper sealing and may render the pack unfit for service. This failure mode was not observed in the other EVs of this group.

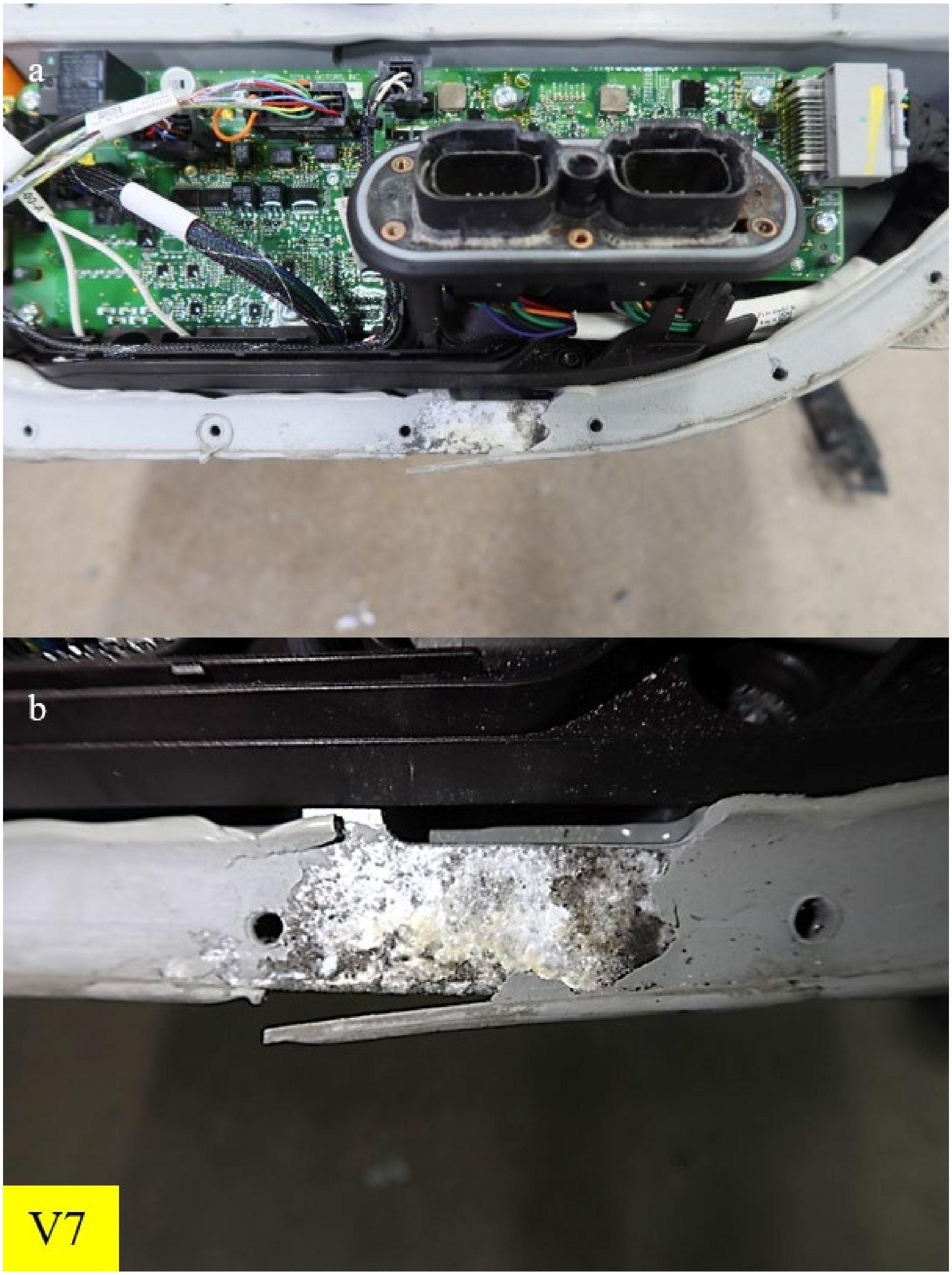

Figure 52. Corrosion on PDU-lid sealant-mating surface

Summary on Pack Design 2

Pack Design 2, composed of the Tesla Models S and X, exhibited a higher susceptibility to water ingress relative to Pack Design 1, which included the Tesla Models 3 and Y.

In each pack within Pack Design 2 (e.g., Tesla Model X Vehicles V6 and V8 and Tesla Model S V9), equipped with the upper penthouse vent, failure modes and pathways associated with this vent were identified, leading to the intrusion of water into the penthouse area. Vehicle V9, a Tesla Model S, experienced the most-significant impact due to vent failure, along with one of its penthouse modules failing in a non-destructive manner. Conversely, Vehicle V7, a Tesla Model X, did not feature this vent, resulting in the absence of ingress within the pack's penthouse area.

Furthermore, the adhesive-bonded sheet in Pack Design 2, intended to enhance flood damage resistance, failed in three instances (i.e., V7–V9) out of the four EVs in this design group. These failures resulted in the trapping of sufficient water to create noticeable corrosion across the entirety of the exterior lid surface. Over time, this corrosion has the potential to degrade the integrity of the pack.

The outboard snap-in pressure vents and vent hole plugs situated at the main battery compartment were identified as another vulnerability for water ingress in two of the four EVs in this group (e.g., Tesla Model X Vehicle V8 and Tesla Model S Vehicle V9). This led to the presence of standing water beneath several modules, which resulted in visible corrosion, contamination, and mold growth. A closer examination of the interior side of the vents revealed instances where the retaining features of the snap-in vent bodies had failed, potentially causing the vent or vent plug to become unseated in its hole, thereby compromising the integrity of the O-ring and permitting water ingress. Additionally, Vehicle V9 (e.g., a Tesla Model S) displayed minor isolation faults between each module and the battery chassis, as indicated by the measurements that were conducted.

In one specific case, the sealant bead near the PDU of Vehicle V7 (e.g., a Tesla Model X) exhibited severe corrosion, and it detached while the PDU was being removed. This detachment likely stemmed from corrosion effects on the metallic surface beneath the sealant bead due to water submersion. Like Pack Design 1, EVs within Pack Design 2 also exhibited water ingress through both the LV and HV connectors, as observed in Vehicles V6 and V7.

Pack Design 3: Lucid Air Grand Touring (V5)

Pack Design 3 consisted of a 2022 Lucid Air Grand Touring EV, designated as V5. The level of flooding experienced by this vehicle, as determined by the flood-line, was established at the height of the rocker panels at the bottom of the doors, as illustrated in Figure 1. This was corroborated by the evidence of water intrusion into the cabin underneath the second-row seats. Physical inspection of the EV interior and exterior revealed minimal debris or evidence of water, with the only notable indication of ingress being the significant corrosion on the primary 12-volt battery under the second-row seats. Other key observations are listed below.

Severe Corrosion Surrounding Primary 12-volt Battery

Lucid's primary 12-volt lead-acid battery is located underneath the second-row seat cushion, as observed in Figure 53(a–b), with a secondary/auxiliary battery in the trunk area, as indicated in Figure 53(c–d). The negative terminals and the LV harnesses for both batteries were found to be disconnected. There is no cover or sealing strategy for the 12-volt battery, leaving it totally exposed underneath the seat.

The primary 12-volt battery and the surrounding components, located under the second-row passenger seat cushion, exhibited excessive amounts of corrosion. Paper towels were left in this space, suggesting the EV may have become wet from sitting in a large amount of sea/floodwater, submerging the battery. Dark water stains on the seat cushion indicate a water level that would have fully submerged the 12-volt primary battery.

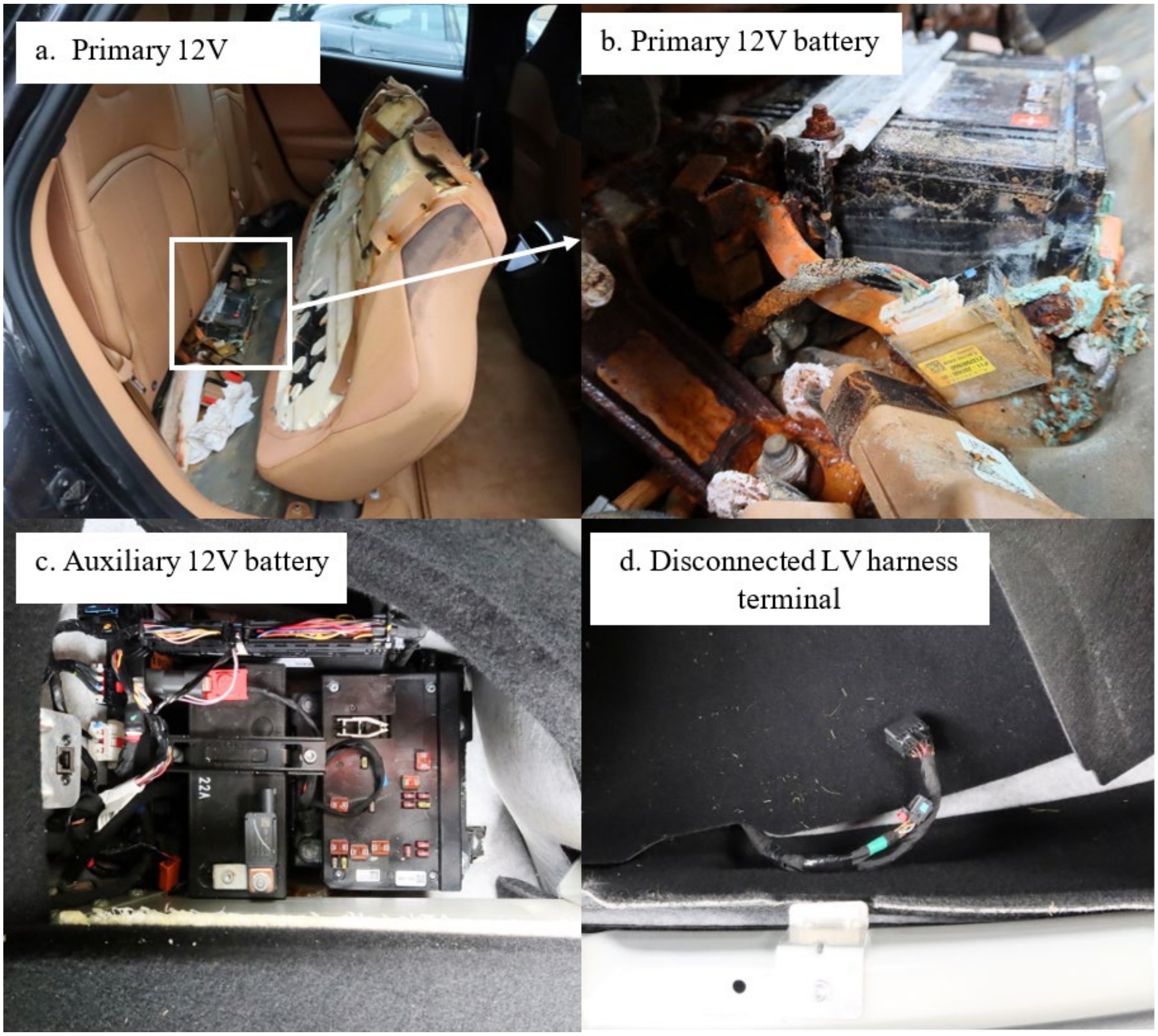

Figure 53. (a, b) 12-volt primary lead-acid battery underneath the second-row seat cushion, showing the disconnected negative terminal. (c, d) Auxiliary 12-volt lead-acid battery in trunk space, showing the disconnected negative terminal and LV harness.

Power Distribution Unit

Despite the water submersion and the water marks and corrosion observed on some of the aluminum components of the tray within the tray structure, none of the internal electronics (e.g., contactors, pyrofuses, etc.), busbars, or battery modules showed any trace of water or visible damage, nor did they exhibit any unusual results during inspection and testing, as indicated in Figure 54.

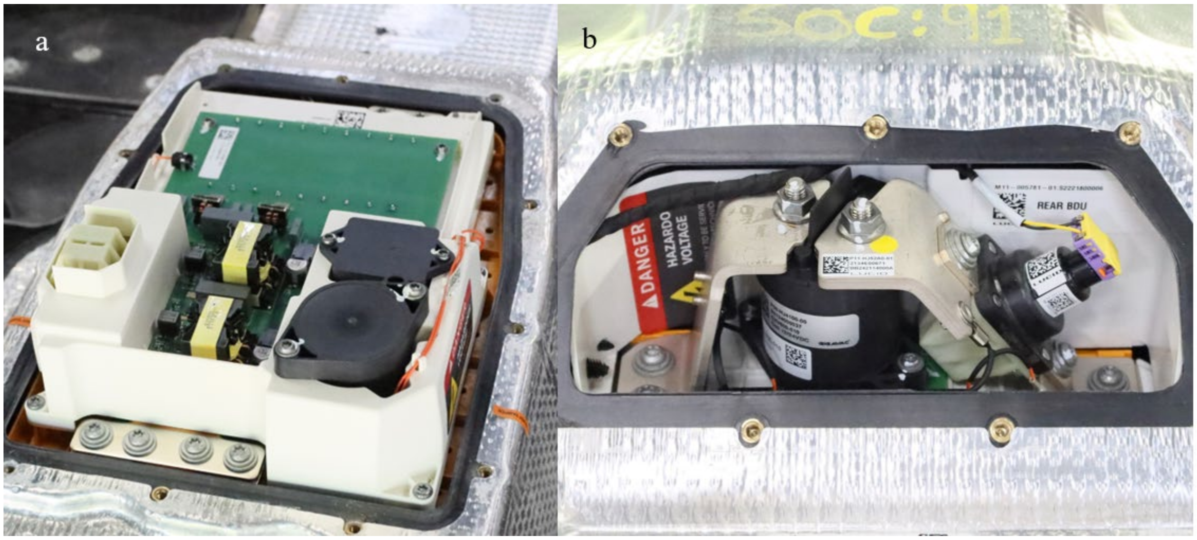

Figure 54. PDU of Pack Design 3: (a) front PDU and (b) rear PDU

Blowoff Valves and Breather Vents

For this pack design, the side sill diaphragm-type pressure vents provided access to the busbar fasteners on the modules, as shown in Figure 55. These pressure vents consisted of an injection-molded base attached to the side sill extrusions via a liquid-applied adhesive and flexible diaphragm pressed into the base. None of the 18 pressure vents lost integrity due to water submersion. The breather vents on top of the PDU, as shown in Figure 55(c), also retained integrity against water submersion.

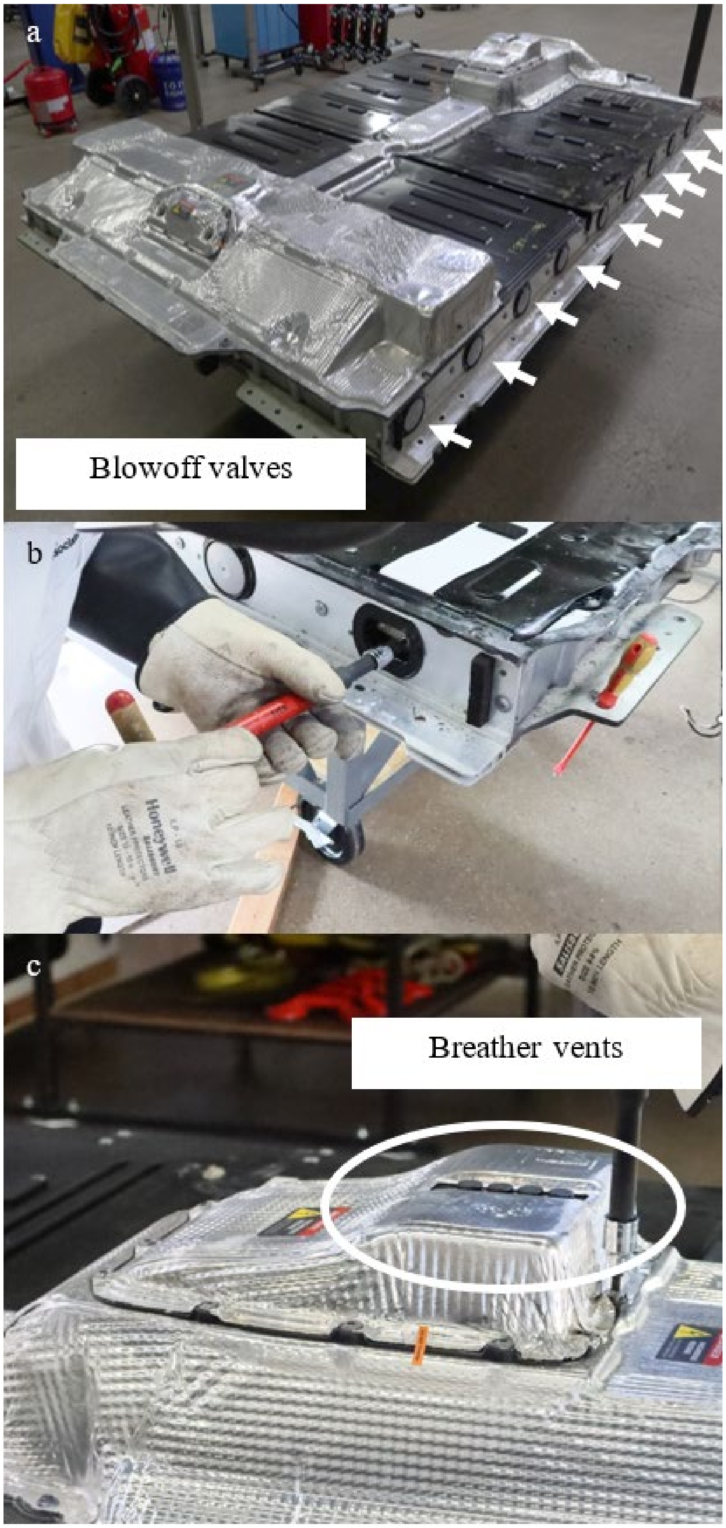

Figure 55. Lucid Air Grand Touring battery pack venting mechanisms: (a) 18 blowoff valves, (b) access of module busbars through the vents, and (c) breather vents

Water Intrusion Found Within Pack Interior

Upon lid removal, a small amount of standing water was discovered within the front-left corner of the pack interior. Upon removing the battery modules, additional standing water was observed below two additional modules, as shown in Figure 56. Further inspection of the battery tray structure and components revealed no damage, corrosion, or contamination of the battery modules or electronics; however, corrosion and contamination were observed on the lid and tray cross beam around the leak source, which could be due to a flawed lid-fastener seal.

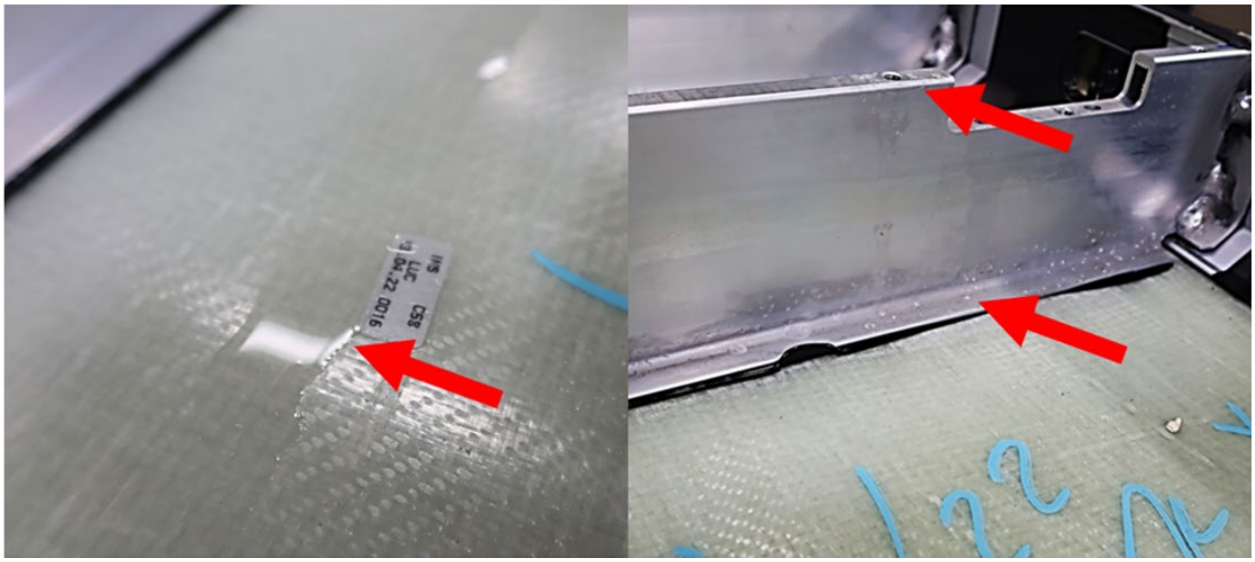

Figure 56. Inspection of the battery tray revealed locations with water collected on the floor plate below the modules and corrosion/water marks on a crossbeam.

The water ingress source is marked with red on both the lid and the tray in Figure 57, and the probable path of water ingress inside the pack is marked with blue arrows. Close-up images of the three locations where water pooled inside the pack are provided, numbered to align with the top-down view of the pack.

The failed lid-fastener seal, shown in Figure 57**,** appears to include a manufacturing shortcoming, and not damage caused by the flooding or otherwise; therefore, it is likely the sealing of this battery pack was compromised at the time of its assembly. Given the location of the current collectors on the bottom of the battery modules and their being covered by a polymer sheet, but otherwise unsealed from the pack interior, it is reasonable to assume they are at a high risk of shorting out should the level of water intrusion reach them (~1 cm).

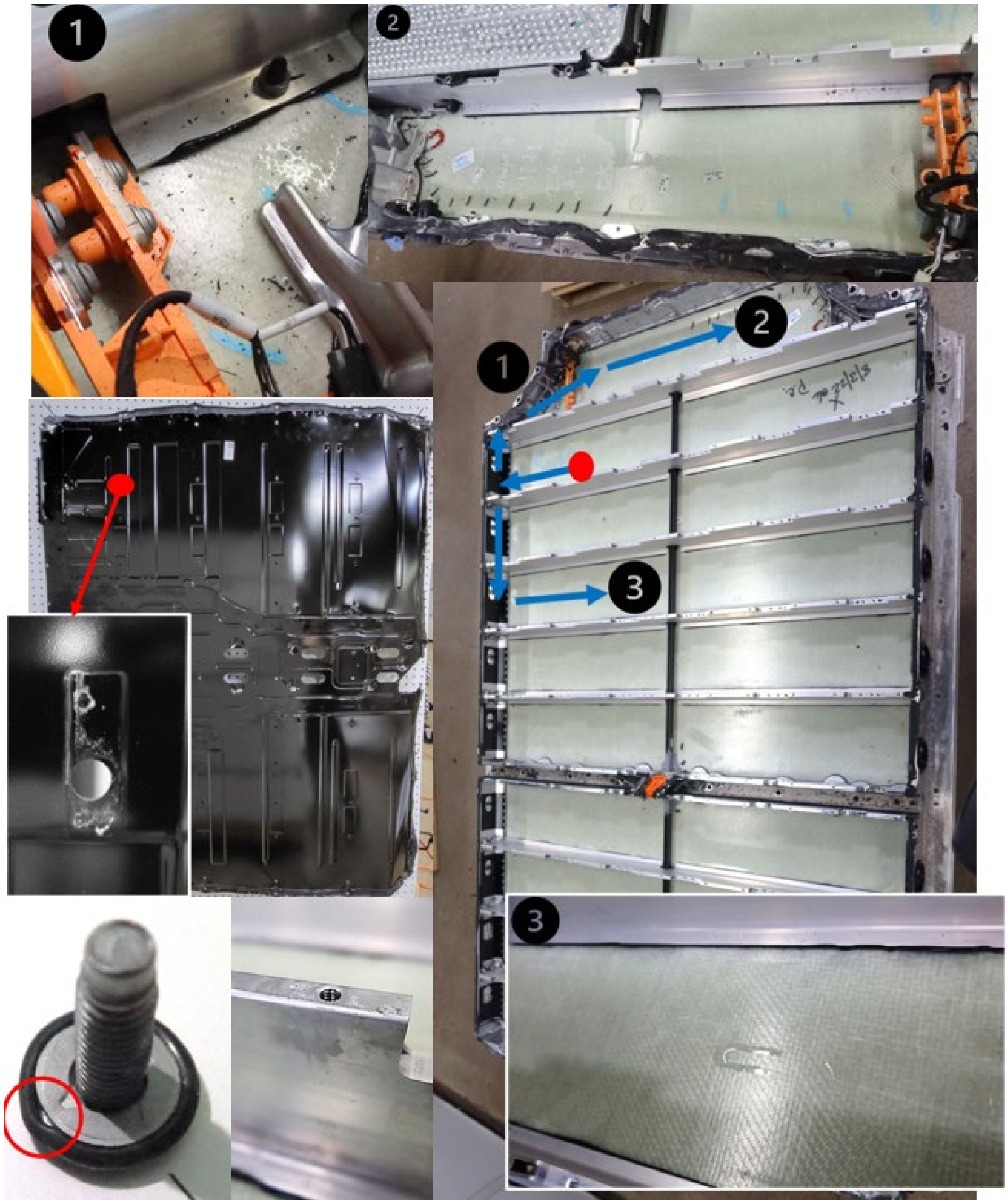

Figure 57. Locations of water contamination within the pack interior. The water ingress source is marked with red on both the lid and the tray, and the probable path of water ingress inside the pack is marked with blue arrows.

Pack and Module Voltage

Figure 58 shows the pack and module voltage being measured. Pack voltage was measured to be 889 V, seemingly congruent with markings on the pack exterior that denoted 91 percent state-of-charge, as observed in Figure 58(a). Module-level voltages were consistent without any significant variation, as observed in Table 6, indicating that none of the modules had shorted out or otherwise been damaged by water ingress.

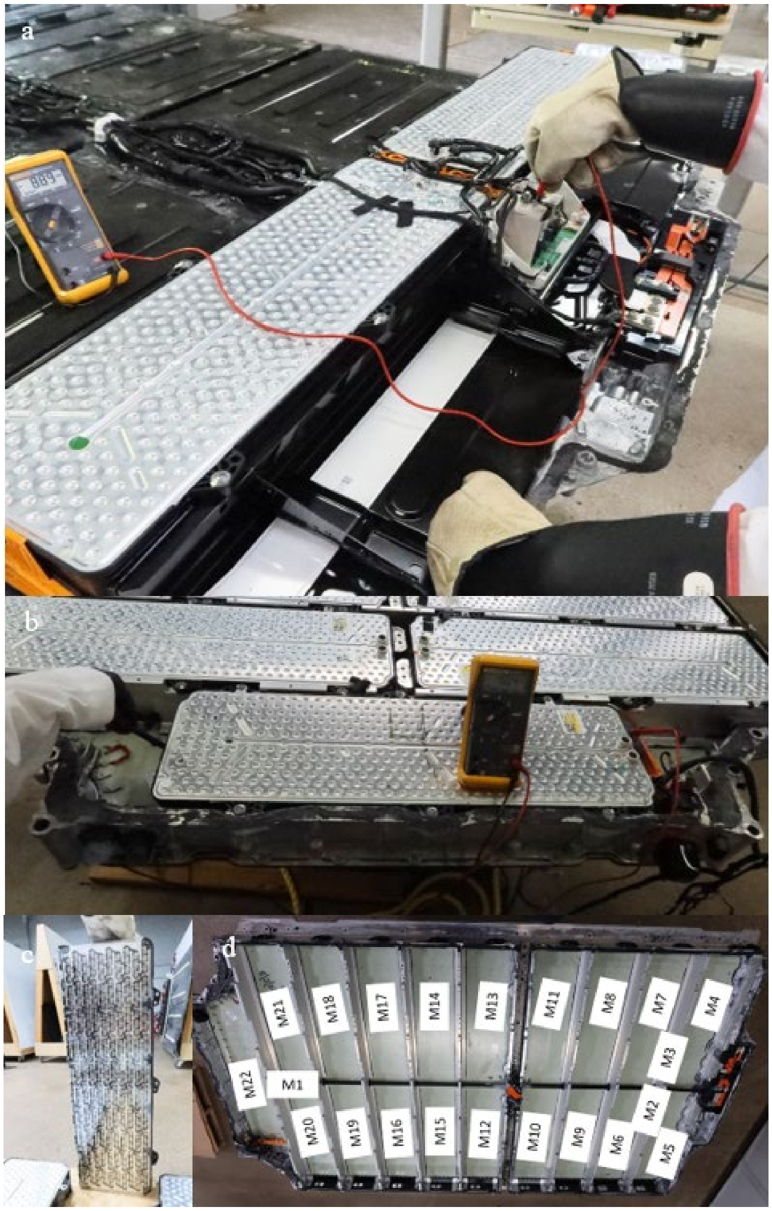

Figure 58. Pack and module voltage measurement of Lucid Air Grand Touring vehicle: (a) Pack-level voltage measurement, (b) module-level voltage measurement, (c) current collector (underside) of battery module, and (d) labeled modules

Table 6. Measured pack and module voltages of Pack Design 3, a Lucid Air Grand Touring vehicle

Vehicle	Pack Voltage, V	Module Voltage/Maximum Spread, V
V5	889	40.4±0.0/0.0

Pack Design 3 Summary

The failure of the lid-fastener seal, leading to the intrusion of water into the battery pack compartment, appears to be rooted in a manufacturing issue, rather than damage resulting from flooding or other external factors. This implies the integrity of the battery pack's sealing was likely compromised during the assembly process.

The location of the seal failure atop the pack suggests the entry of contaminants, such as dust and water in significant quantities, would be improbable unless the pack or EV were completely submerged. In a submersion scenario, such a flaw would pose an immediate and tangible threat to the sustained operational functionality and safety of the system.

Pack Design 4: Porsche Taycan (V4)

This vehicle, as-received, had photo identification that it had been flooded up to the rocker-panel, at the floor-level of the cabin, as observed in Figure 1. Visual inspection of the interior and exterior of the EV revealed minimal debris or evidence of water, suggesting the flood-line height was insufficient to allow ingress to the cabin interior. Visual inspection of the exterior of the HV battery pack confirmed that most of the exterior was submerged at some point, given the sediment in the second-row footwell cavities in the pack. However, the penthouse module on the top front of the pack showed no signs of corrosion, suggesting it had remained above the flood-line. Other observations are discussed below.

12-Volt Battery

The Porsche Taycan 12-volt battery was located at the front-right of the EV under a trim panel. The charge port and HV battery cables were located next to the 12-volt battery, where they were connected to the HV power distribution modules, such as the DC-DC converter and OBC. Given the location of the 12-volt battery and the low height of the flood-line, the 12-volt terminals displayed no observable corrosion, as shown in Figure 59.

Figure 59. (a) 12-volt battery location and (b) 12-volt battery terminals, showing no corrosion

Electronics Penthouse Fastener Seal

The penthouse module/PDU, as shown in Figure 60**,** was fastened to the top of the HV battery pack using a combination of strategies to seal the fasteners and prevent environmental contamination of the pack interior. One of these strategies was the use of square-cross-section O-rings around the fastener holes, and this was combined with the application of a grease.

An inspection of the penthouse upon removal of the penthouse revealed that one of the O-rings appeared to have been installed improperly, as evidenced by a displaced and crushed O-ring and a small witness area in the grease applied around the flawed O-ring, as observed in Figure 60. Although no contamination was observed within the pack interior, it is possible that this could have become a leak path if the submersion had reached above the pack lid for an extended period. Saltwater contamination within the pack interior could result in a potentially dangerous failure.

Figure 60. Possible assembly flaw found on the fastener seal of the electronics penthouse

Venting Strategy

The Porsche Taycan employed a series of breather vents and what appeared to be blowout patches on the battery pack exterior, as shown in Figure 61. Gore breather vents were installed to the ends of the tray extrusions located at the front-right and front-left sides of the pack. Circular adhesive-backed patches were located at the rear-right and rear-left of the pack, which presumably act as pressure-blowout valves when gases are directed through the cells of the extruded walls of the tray. At the top rear of the pack was a large breather assembly, which housed a membrane within a cast-aluminum and injection-molded housing attached to the lid via threaded fasteners with an injection-molded seal.

The seal integrity of the large breather assembly at the top rear of the pack was not found to be compromised, and no signs of ingress were noted on the underside of the lid in this area. The breather vents at the front of the pack and the (presumed) blowout patches at the rear were installed to the extruded sections that form the perimeter of the pack tray. The interiors of the extruded sections were used as a path for off-gassing and are not directly exposed to the module area inside the pack. No evidence suggested that either the blowout patches or breather vents were compromised and allowed water ingress.

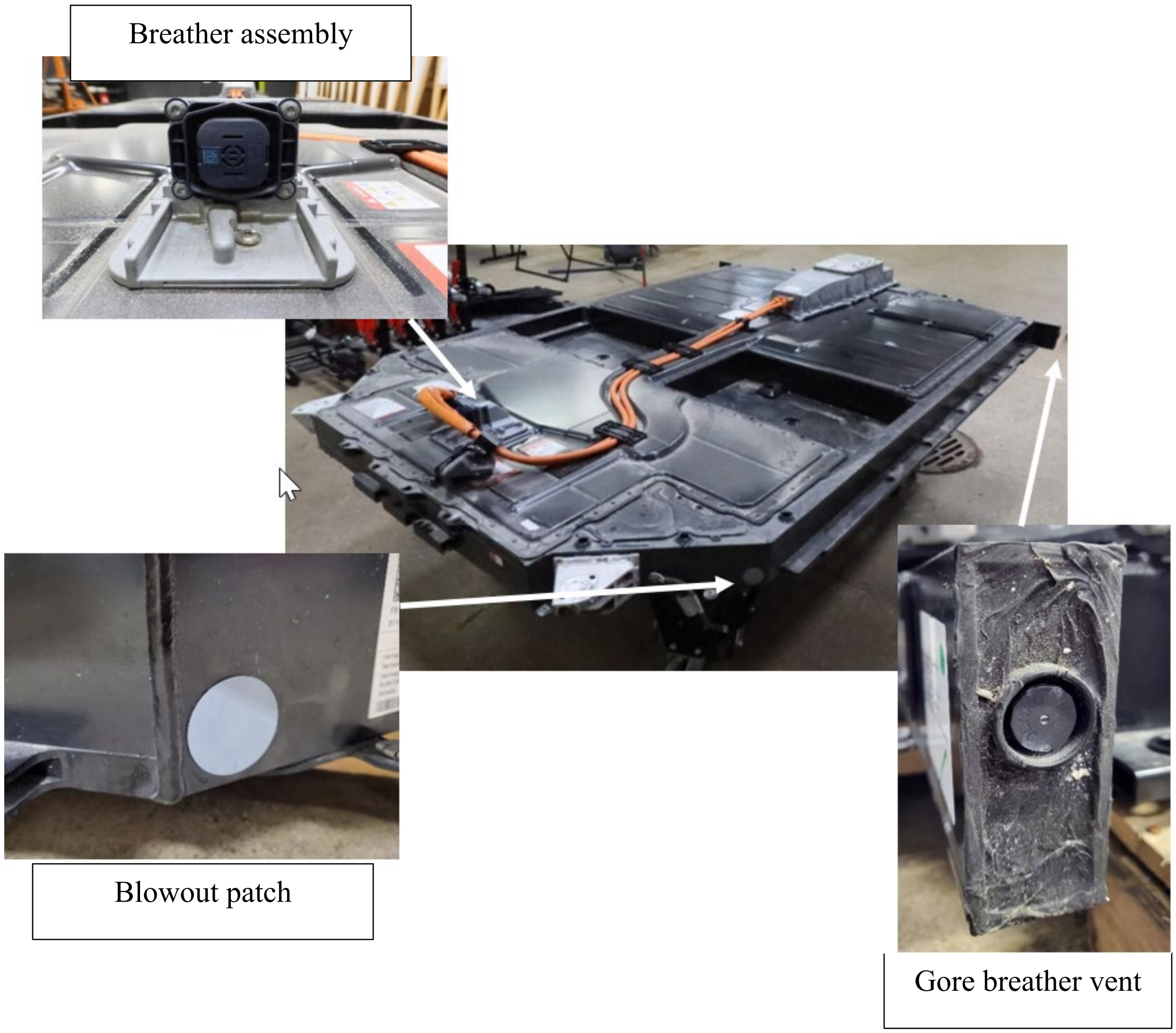

Figure 61. Porsche Taycan pack-venting strategy

Battery Pack

After the lid was removed, voltage checks were conducted to ensure everything fell within the expected and normal ranges. Next, the internals were inspected. No signs of corrosion or contamination were observed within the battery pack interior, as shown in Figure 62. Pack-level voltage was measured following the removal of the penthouse module. Two additional modules were taken out for further disassembly to obtain the cell group voltages. Module-level voltage measurements were taken upon the removal of the lid, prior to the removal of the busbars. Modules 1 and 17 were chosen due to their locations at the opposite ends of the pack, as indicated in Figure 62. Cell group voltages were obtained from the current collectors inside the module. The cells were arranged in a 2p6s configuration; therefore, six cell groups were measured per module.

Figure 62. Porsche Taycan battery pack external and internal views with measurements being completed

During an inspection of the pack interior, no contamination or corrosion was discovered within. The mid-pack fuse was found to be unbroken. No damage to any modules was observed. The module-level voltage delta was measured at 0.09 V between the highest and lowest measurements, as shown in Table 7. No damage was observed within the HV battery pack interior to suggest that water ingress occurred at any point. The pack voltage corresponded to an SOC of ~5 percent, which indicates either that the SOC of the pack was at that level during the time of flooding, or it experienced a higher rate of self-discharge relative to other packs evaluated in this study.

Table 7. Measured pack and module voltages of Pack Design 4, a Porsche Taycan vehicle.

Vehicle	Pack Voltage, V	Average Module Voltage± St. Dev. /Maximum Spread, V
V4	548	19.58±0.023/0.09 Module 1 Cell Group: 3.26 ±0.007/0.02 Module 17 Cell Group: 3.25±0.005/0.01

Main Battery Pack Terminals

The Porsche Taycan houses all power distribution components inside the penthouse module/PDU. The PDU interfaces with the main positive and negative terminals protruding from the battery pack lid when installed, as observed in Figure 63. The PDU base featured a circular seal that sits between the battery pack lid and the PDU, which encapsulated the main battery terminals.

The PDU seal around the main battery terminals showed no signs of ingress; however, the flood-line noted on the EV exterior indicated the likelihood the seal was only partially submerged. The integrity of this seal is critical to the safety of the pack, given that, even at this vehicle's 5 percent SOC, there was still a 548-volt potential across these two terminals. Should any water ingress have occurred, a short between these terminals would have been possible.

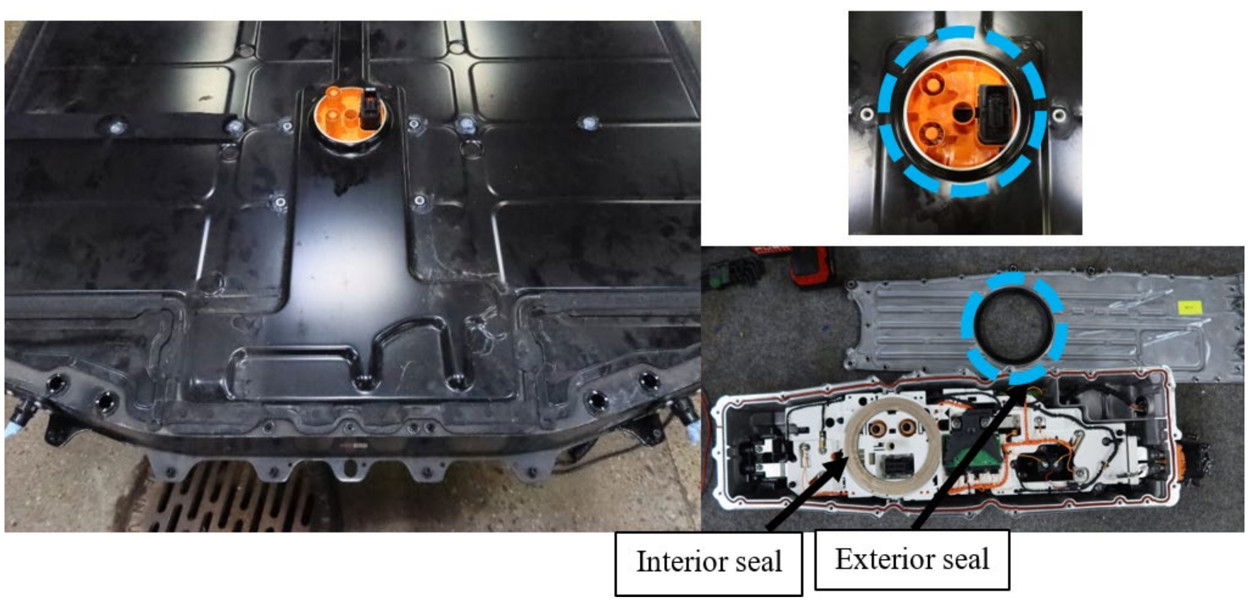

Figure 63. Image showing the location of the main battery terminals underneath the penthouse.

Pack Design 4 Summary

Despite the partial submersion of the battery pack and the presence of visible sediment covering most of the external surface of the pack, no indication of water ingress or corrosion within the interior of the pack was observed. Furthermore, the penthouse module situated atop the pack did not exhibit any sign of submersion, as determined by the height of the flood-line and the absence of corrosion on the module's housing.

Upon the removal and inspection of the penthouse, it was evident that one of the O-rings had been installed incorrectly. This was substantiated by the displacement and deformation of the O-ring, along with the presence of a small, marked region in the grease surrounding the faulty O-ring.

While there were no indications of contamination within the interior of the pack, it is conceivable that this incorrectly installed O-ring could have potentially served as a point of leakage if the submersion had persisted and reached a level above the pack lid, particularly over an extended duration.

A comprehensive examination of critical components within the penthouse module, including the current shunt, pyro-fuse, and contactors, revealed no anomalies or irregularities. Additionally, areas with a higher likelihood of water ingress, such as vents, coolant ports, and electrical connectors affixed to the pack through threaded fasteners and featuring injection-molded seals, were meticulously inspected and showed no indication of water intrusion.

EV Disposal

Following extraction of the battery packs from the EVs, they were allocated to various institutions for additional testing and training endeavors. Specifically, one of the EV shells (V1) underwent pedestrian testing at the NHTSA Vehicle Research and Testing Center. The remaining nine EV shells were returned to INL to facilitate training sessions for law enforcement personnel and emergency responders. The batteries are designated for recycling and transportation as Class 9 hazardous materials to the recycler, with packaging adhering strictly to the guidelines established by the Pipeline and Hazardous Materials Safety Administration.

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Report Summary

This study contributes to hurricane preparedness by investigating the inspection and transportation procedures for flood-damaged EVs, as well as the resultant damage and safety hazards associated with EV saltwater immersion. While the assessment of the safety and stability of stored energy in stranded EVs is an evolving area of research and development, our activity employed a protocol for examination and transportation that facilitated the safe transport of 10 EVs damaged by saltwater exposure. These techniques, when deemed suitable, could be applied to manage similar incidents in the future.

In this study, 10 EVs were subjected to evaluation. Among them, 8 EVs exhibited varying degrees of water intrusion (V2- 2022 Tesla Model Y, V3- 2020 Tesla Model 3, V5- 2022 Lucid Air Grand Touring, V6- 2017 Tesla Model X, V7- 2020 Tesla Model X, V8- 2017 Tesla Model X, V9- 2018 Tesla Model S, and V10- 2018 Tesla Model 3), observed either within the penthouse compartment or the battery pack. Specifically, 5 EVs (V5- 2022 Lucid Air Grand Touring, V6- 2017 Tesla Model X, V8- 2017 Tesla Model X, V9- 2018 Tesla Model S, and V10- 2018 Tesla Model 3) showed evidence of water infiltration into the primary battery pack compartment. It is important to note that the 2022 Porsche Taycan, which did not show any indication of water intrusion, was only partially submerged, specifically avoiding submersion of the penthouse. Consequently, full submersion at greater depths might have resulted in water ingress.

It is imperative to acknowledge that water infiltration into the pack penthouse containing serviceable power electronic components, and into the primary pack compartment, which houses the batteries, can lead to markedly distinct performance and safety ramifications compared to the main battery pack. Consequently, the tolerance for water ingress in these compartments may vary. For example, a certain level of water ingress into the penthouse may be deemed acceptable and predominantly affect the functionality of the battery pack. However, the same degree of ingress may or may not be permissible for the primary battery compartment, where the risk of a short-circuit—potentially initiating a thermal-runaway event and causing extensive damage to the vehicle—is present. Information regarding the permissible levels of water ingress into modern EV battery packs was not found in the open literature. Therefore, it is not feasible to comment on the severity of the ingress observed in this teardown study.

The teardown analysis of 10 EVs affected by Hurricane Ian has unveiled several significant findings:

- Potential pathways were identified for water ingress into the battery packs, arising from possible manufacturing imperfections, improper component installations, and component failures.
- Nevertheless, it can be affirmed that the volume of water permeating both the pack and penthouse compartments was inadequate to precipitate any catastrophic events involving the batteries of these EVs.
- Flood-damaged EVs are susceptible to corrosion and mold proliferation, posing safety hazards if these EVs continue to be operational.

To mitigate the risk of catastrophic EV fire incidents resulting from saltwater flooding, a potential solution is to prevent water ingress into the battery packs. A comparison between Pack Design 1 (in Tesla Model 3 and Y) and Pack Design 2 (in Tesla Model S and X) reveals that

Pack Design 2 had a greater number of potential water-entry points, making it less resistant to water ingress. This underscores the significance of battery pack design considerations to mitigate the effects of flood damage. Both the engineering design of the battery pack and the quality-control measures in component assembly can influence the probability of water ingress.

Critical component-corrosion failures, including those in battery modules, have the potential to render the battery pack nonoperational or unsafe. When liquid water infiltrates a battery pack, it creates a higher-moisture environment, accelerating corrosion in various components of the battery pack. This phenomenon was observed in Vehicles V6, V8, and V9 (Tesla Models S and X). Over time, such corrosion can compromise the performance, lifespan, and safety of the vehicle. In instances where damaged EVs remain in operation, the risk of failure may increase over time.

Although this teardown study provided insights into contemporary EV damage when exposed to saltwater-flooding, a root cause and failure mechanism related to field fire incidents was not identified. Identifying such factors would necessitate controlled tests involving EVs and battery packs under realistic flood conditions with extensive instrumentation, which was beyond the scope of this study. Alternatively, the failure mechanism could be determined through a fire origin and cause analysis of a saltwater-immersed EV. Regardless, no post-fire EVs with sufficient evidence for examination and reconstruction were made available during the study.

However, it is possible that EVs experiencing catastrophic failures due to saltwater immersion may have similar water ingress paths identified in this study. These leakage paths may have contributed to battery thermal runaway.

It was beyond the scope of this study to evaluate the relevance of existing immersion-testing protocols and standards to hurricane-induced flooding. The depth and duration of flooding (e.g., Hurricane Ian had as high as 15 feet of flooding for longer than 12 hours) differ from the testing protocols such as those outlined by United States Advanced Battery Consortium, LLC and SAE J2464, which cover full submersion of a battery pack for up to 2 hours, and IP rating standards (e.g., IPX7 covering a 3 ft, 3 in. submersion of a battery pack for 30 minutes). Additionally, this document does not provide guidance on non-destructive production-line-equivalent battery pack liquid leak tightness tests found in SAE J3277 (SAE International, 2022)

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Appendix A: Video File Links to Flood-Damaged EV Teardown

Table A-1. Teardown video file link of flood-damaged EVs

Vehicle #	Make, Model and Year	Teardown Video File Link
1	Tesla Model Y, 2022	https://youtu.be/IY7F0ucqwPw
2	Tesla Model Y, 2022	https://youtu.be/9g12cyxuJHU
3	Tesla Model 3, 2020	https://youtu.be/eo3EJDb3xSU
4	Porsche Taycan, 2022	https://youtu.be/gJsHJyFHZjQ
5	Lucid Air Grand Touring, 2022	https://youtu.be/c7UPb0TvZ0A
6	Tesla Model X, 2017	https://youtu.be/LVpCNcAlgtw
7	Tesla Model X, 2020	https://www.youtube.com/watch?v=N-VKWjUvRjA
8	Tesla Model X, 2017	https://youtu.be/-7hUIDZnvFU
9	Tesla Model S, 2018	https://youtu.be/_dDsLDvtWh0
10	Tesla Model 3, 2018	https://youtu.be/QMjzriCVu50

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