Lattice Energy LLC

Tesla Motors Model S battery had thermal runaway

What really caused the fiery October 1, 2013 incident?

Tesla's theory: event caused by metallic debris on road impaling battery

Theory has some issues: could it instead have been an internal field-failure?

Lewis Larsen

President and CEO
Lattice Energy LLC
October 16, 2013

October 1, 2013 - Kent, WA USA
Scene before arrival of firefighters

Tesla Motors Model S in flames

"Grow your tree of falsehood from a single grain of truth."

Czeslaw Milosz - poem 1946

October 1, 2013 - Kent, WA USA
Scene after arrival of firefighters

Fire now partially extinguished

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Contents

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Key takeaways

October 1, 2013 - Kent, WA USA
Scene just as firefighters arrived

Lattice comment:

If this mini-inferno is truly "controlled" then we are astounded.

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Key takeaways

Simplified timeline of selected events

Oct. 1, 2013: Tesla Motors Model S experienced battery thermal runaway and large fire involving at least one of the battery pack's modules; incident occurred in Kent, WA USA

Oct. 2, 2013: *Jalopnik* published first story about the fiery runaway and posted amateur video clip showing the car burning with 6' flames just before Kent firemen arrived on scene

Oct. 3, 2013: *Associated Press* reporter Mike Baker published an *AP* wire story about Tesla fire

Oct. 3, 2013: Later that day, *AP* reporters Mike Baker and Tom Krisher published follow-up story in which Tesla finally admitted that the large fire had begun in Model S battery pack

Oct. 3, 2013: At 1:00 PM, *Forbes* staff writer Hannah Elliott published an online story based on an interview with Tesla spokesperson, Elizabeth Jarvis-Shean, who also stated that Elon Musk would not be commenting publicly on the Tesla battery fire; while fact-checking for her story, Elliott was still unable to independently verify existence of: (1) "large metallic object" lying on road surface that Tesla claimed was run-over by driver and rotated upward, pierced the Model S battery pack, and triggered battery runaway and fire; and (2) WA DOT road crew that supposedly recovered the object

Oct. 4, 2013: Tesla CEO Elon Musk finally responded to press stories about Model S battery fire in a company blog post; outlined Tesla's battery impalement theory which they claim provides an explanation for mechanism that triggered the thermal runaway and fire

Oct. 16, 2013: As of today, existence of "large metallic object" and "road crew" have not been confirmed by any third parties; still many unanswered questions about the incident

Key takeaways

- ✓ On October 1, 2013, in Kent, WA USA while traveling down a 4-lane state highway during morning rush-hour, a Tesla Model S sedan experienced a battery thermal runaway and ensuing fire with 6-foot high flames that destroyed the front hood area of the vehicle
- ✓ To explain why its much-heralded battery safety systems were unable to prevent the occurrence of a potentially dangerous battery thermal runaway and fire that disabled and destroyed key parts of a full-sized vehicle within a span of several minutes, Tesla proposed a theory for the event. It explains the runaway as having been caused by the car's driver accidentally running over piece of road debris - "large metallic object" - that had been lying on the highway surface. In Tesla's theory, this hypothetical metal object somehow rotated upwards, slammed into the car's armored underbody with 25 tons of force, and then pierced a module in the car's battery pack, which triggered a thermal runaway and fire
- ✓ To date, Tesla has not provided any detailed explanation as to exactly how they estimated the object piercing force on battery pack's "armor plate" to be ~25 tons. Our investigation and calculations suggest that a 25 ton force would not likely pierce any truly armor-grade metals; on the other hand, if Model S' so-called "armor plate" is really composed of some type of soft metal or composite material, 25 tons would be sufficient energy for successful penetration
- ✓ Experimental data concerning 18650 nail penetration and crush tests shows that if violent thermal runaways occur in such situations, they frequently start within less than a second or two. That clearly was not the case in the October 1 incident, which had a surprisingly long event timeline that spanned at least 2 - 3 minutes, which happily enabled the driver to exit a potentially bad situation safely without injury. This lengthier timeline is not consistent with prior 18650 piercing/crush data or with massive instant damage posited in Tesla's theory

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Key takeaways

- ✓ Lattice's alternative theory for the October 1 model S runaway posits that: field-failure internal electrical short (whatever its proximate cause might truly be) occurred in a single 18650 cell that was located somewhere in first front module of vehicle's battery pack. This field-failure-triggered event caused catastrophic overheating of the affected cell, creating huge local temperature increase within a few seconds that wreaked havoc within the immediate module
- ✓ A small explosion could have occurred inside front battery module without breaching the armored pack; an unsuspecting, very surprised driver could have very easily misinterpreted a 'whomph' he would have felt with his body as an indication that the vehicle had run over some sort of object lying on the road (while admittedly speculative, this idea is plausible in view of fact that existence of claimed "large metallic object" has not yet been substantiated by Tesla)
- ✓ Importantly, propagation of field-failure-induced super-hot runaway conditions into adjacent cells ("thermal fratricide") within same battery pack module was slowed rather significantly by Tesla's multi-tier, very sophisticated battery safety system engineering discussed herein. The consequent retardation of thermal propagation between cells by safety features built into the battery pack lengthened the runaway event timeline by > 2 - 3 minutes, which was observed
- ✓ In this incident, Lattice believes a Model S battery pack encountered something very different from "garden variety" thermal runaways (see Appendix 1 for definitions and details) that Tesla's otherwise brilliant system safety engineering was designed to thwart. What occurred on Oct. 1 was very likely a much rarer, deadlier type of thermal runaway called a 'field-failure" (again, see Appendix 1). What distinguishes field-failures from 'ordinary' thermal runaways are vastly higher peak temperatures in conjunction with electric arc discharges; best that can be hoped-for under such circumstances is that a battery fails 'gracefully' without detonating, as on Oct. 1

Tesla Motors Model S:

Overview of vehicle and systems

Lattice Energy LLC

Tesla Motors Model S: Overview of vehicle and systems

Basic functional organization of key system components


Image source: Tesla Motors


Electric motor seen from behind

Image credit: GT Carlot

Note: original Tesla images have been adapted by Lattice

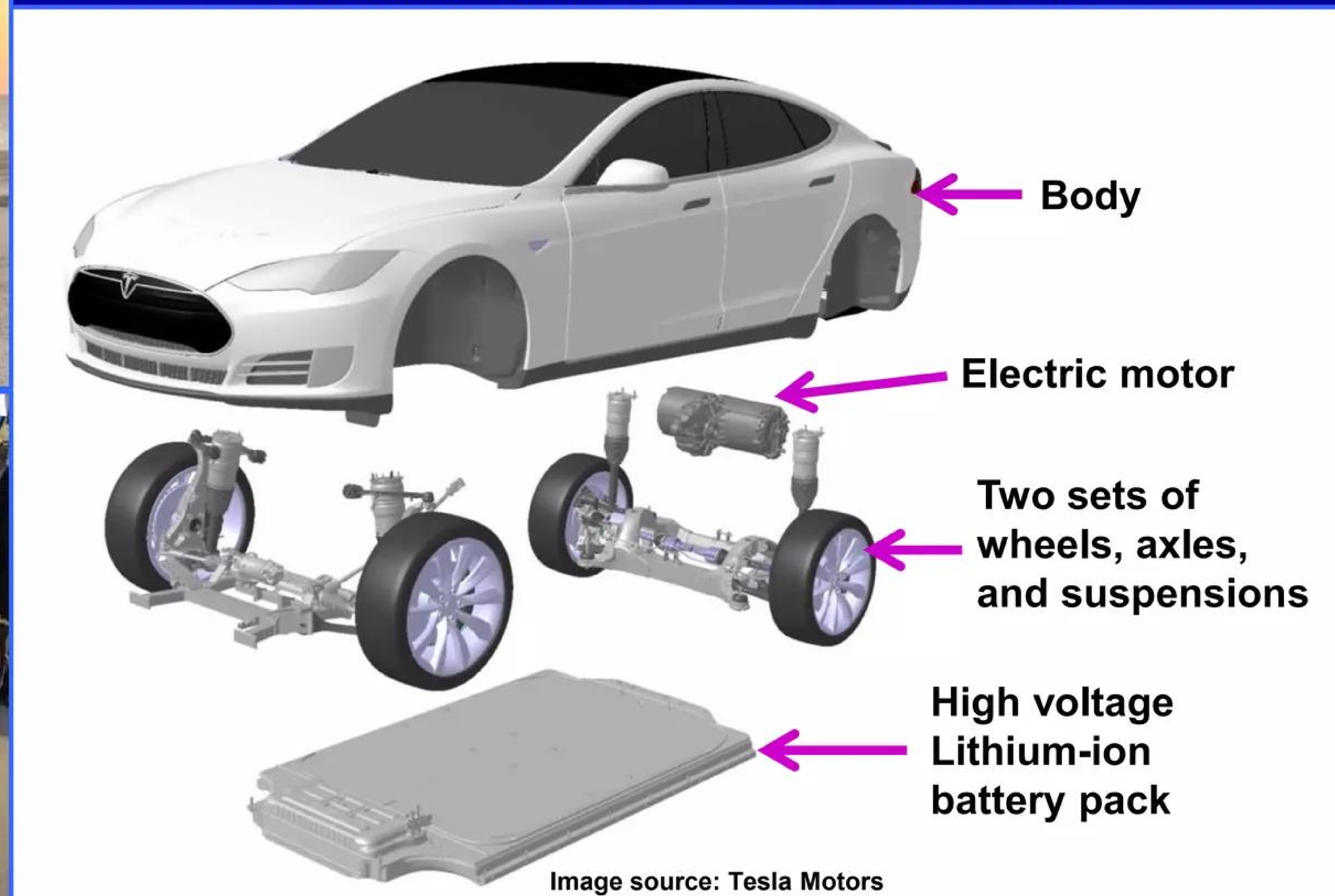


Image source: Tesla Motors

Tesla Motors Model S: Overview of vehicle and systems

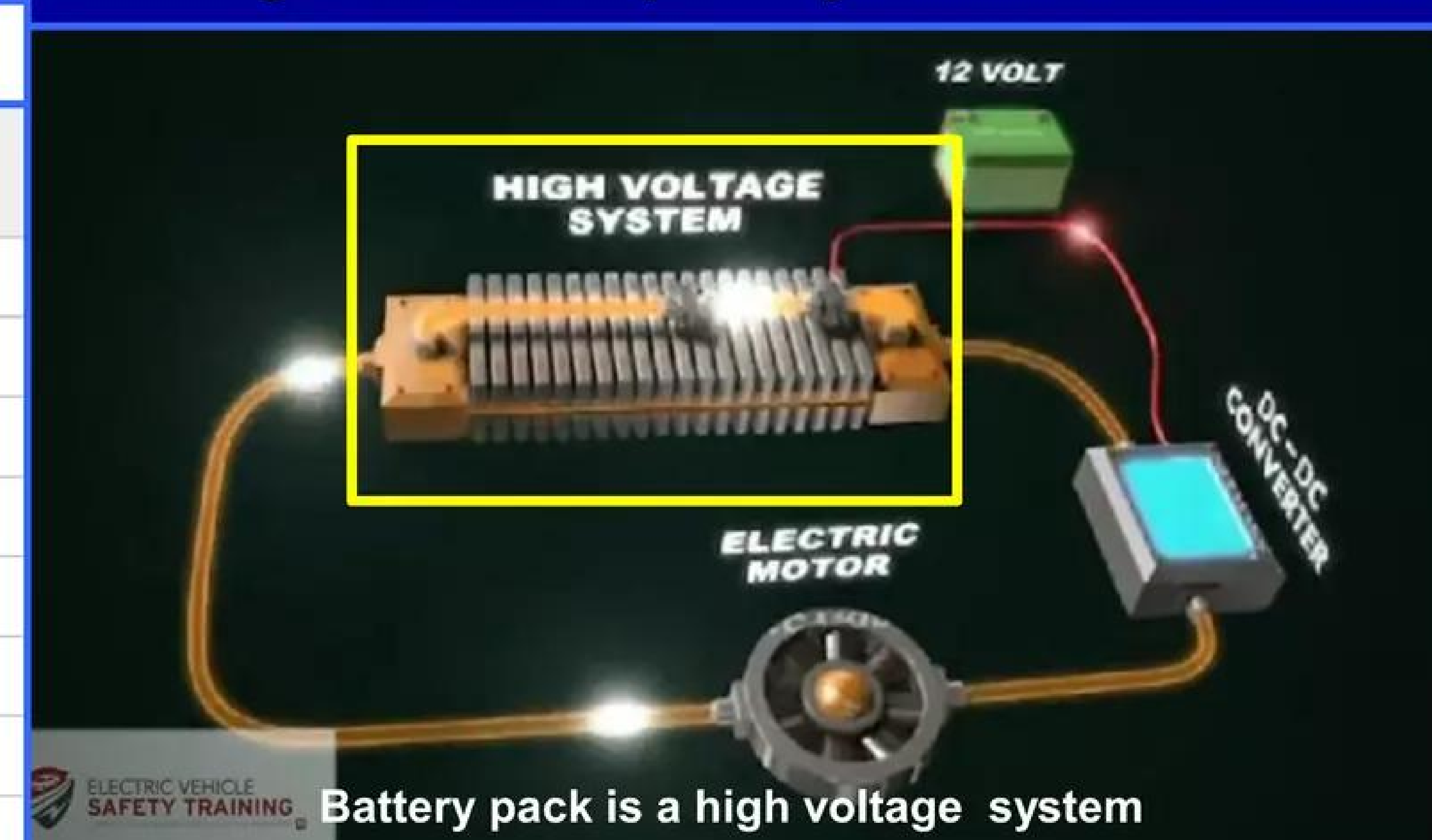
Battery pack integrates/controls up to ~7,000 Panasonic Li-based cells

Model S battery pack uses 18650As with NCA chemistry; that is, a Lithium nickel cobalt aluminum (NCA or chemically = $LiNiCoAlO_2$) cathode chemistry developed by Panasonic. The ~7,000 such batteries contained in a Model S pack contain specialized formulation of NCA and other unique characteristics that have been specifically optimized for EV applications (creating a so-called "automotive grade" 18650A cell). Please note this is not exactly the same as commodity 18650 battery cells that Panasonic manufactures and sells for the consumer retail market

Tesla employee grasping a Model A battery pack

Panasonic
NCR18650A (New High Capacity Model)
3.1 Ah
675 Wh/L
18.6 +0/-0.7 mm
65.2 +0/-1.0 mm
Approx. 44.5 g
3.6 V
4.2 V
11.2 Wh

High-level conceptual system schematic



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Tesla Motors Model S: Overview of vehicle and systems

Battery pack integrates/controls up to ~7,000 Panasonic Li-based cells

NHTSA opened-up interior of 60 kWh Model S battery during routine testing

Close-packed 18650 batteries are oriented vertically within 14 individual modules

Image shows upper surface of battery pack

Half of battery pack now exposed: shows 7 modules

Note: 85 kWh Model S battery pack differs: has 8 modules per side for total of 16

Tesla Motors Model S: Overview of vehicle and systems

Management system controls, monitors and optimizes battery operation

"The Tesla Roadster battery system"

Tesla Motors, August 16, 2006
G. Berdichevsky, K. Kelty, J.B. Straubel, and E. Toomre

"Multiple microprocessors within the ESS communicate via a CAN Bus, a robust automotive communication protocol. During normal vehicle operation and storage, the battery logic board communicates with the vehicle to initiate battery cooling, report state of charge, and signal battery faults. A fundamental element of the vehicle and battery pack safety design is the ability to electrically disconnect the high voltage of the pack from the rest of the car (by controlling two high voltage contactors) if any of number of adverse conditions are detected."

"Microprocessors, logic circuitry and sensors are continually monitoring voltages, currents and temperatures within the pack. These sensors also monitor inertia acceleration (e.g. to detect a crash) and vehicle orientation to the ground (e.g. to detect a rollover). Our battery packs also include smoke, humidity, and moisture sensors. If certain sensors exceed the specified range, then the high voltage contactors will immediately (within milliseconds) disconnect the high voltage of the battery pack from the car. In fact, the contactors are only closed (connected) when commanded and energized to do so. Without the proper commands these contactors will open."

Lattice comments:

- ✓ Battery management system (BMS) on Model S is further improved version of earlier BMS used on Tesla Roadsters
- ✓ Model S has integrated GPS; its BMS also has integrated two-way wireless data telemetry capabilities for key diagnostics, monitoring, and control parameters, as well as two-way Internet connectivity
- ✓ When it wishes, Tesla Motors has capability to remotely monitor location and key operating parameters of any of its vehicles that are traveling through areas with wireless communications services

Source URL: http://large.stanford.edu/publications/coal/references/docs/tesla.pdf

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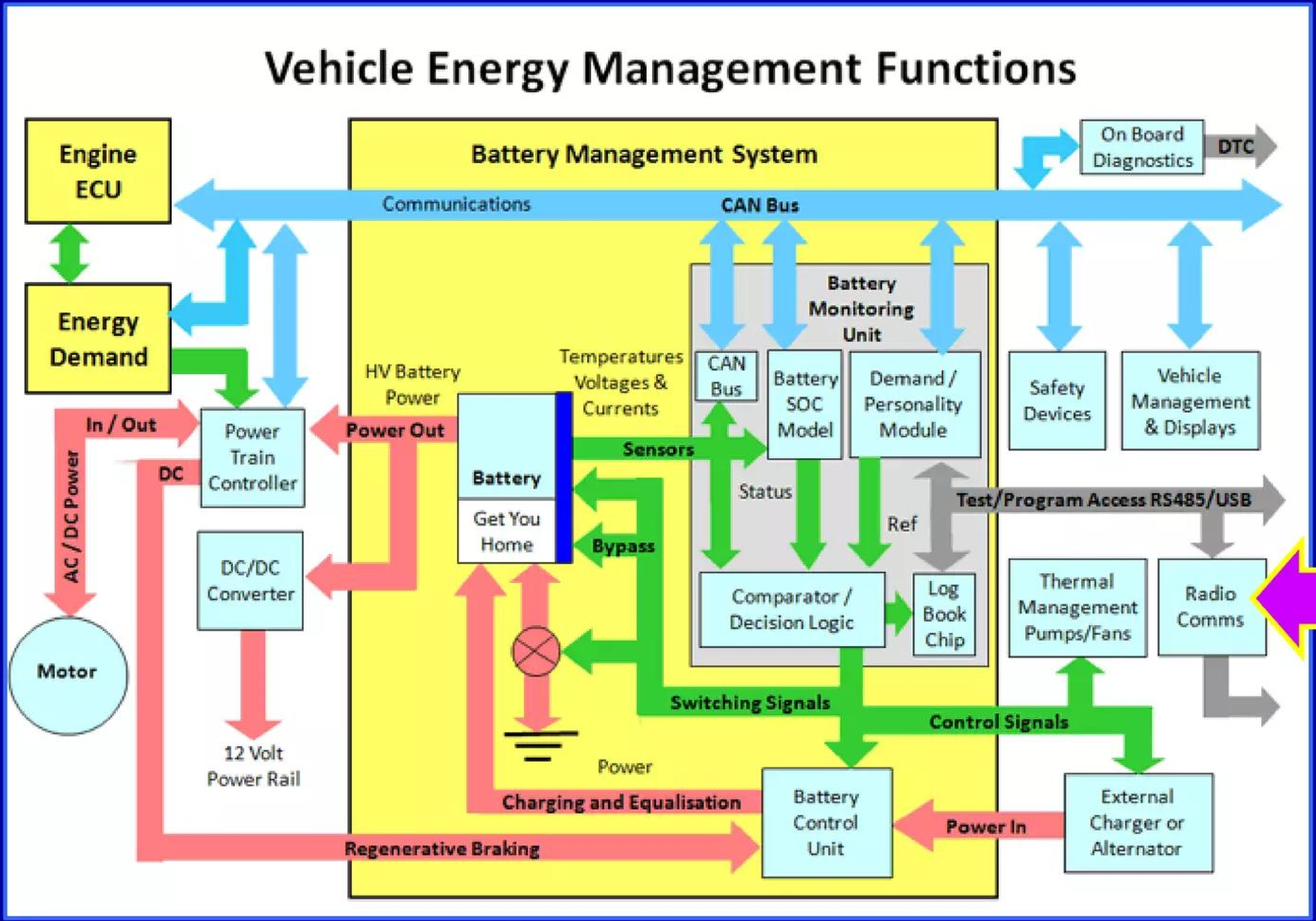
Tesla Motors Model S: Overview of vehicle and systems

Block diagram of functionality: generic EV battery management system



Wireless data telemetry and connectivity to Internet

Source URL: http://www.ddqcw.com/bbs/thread-76249-1-1.html

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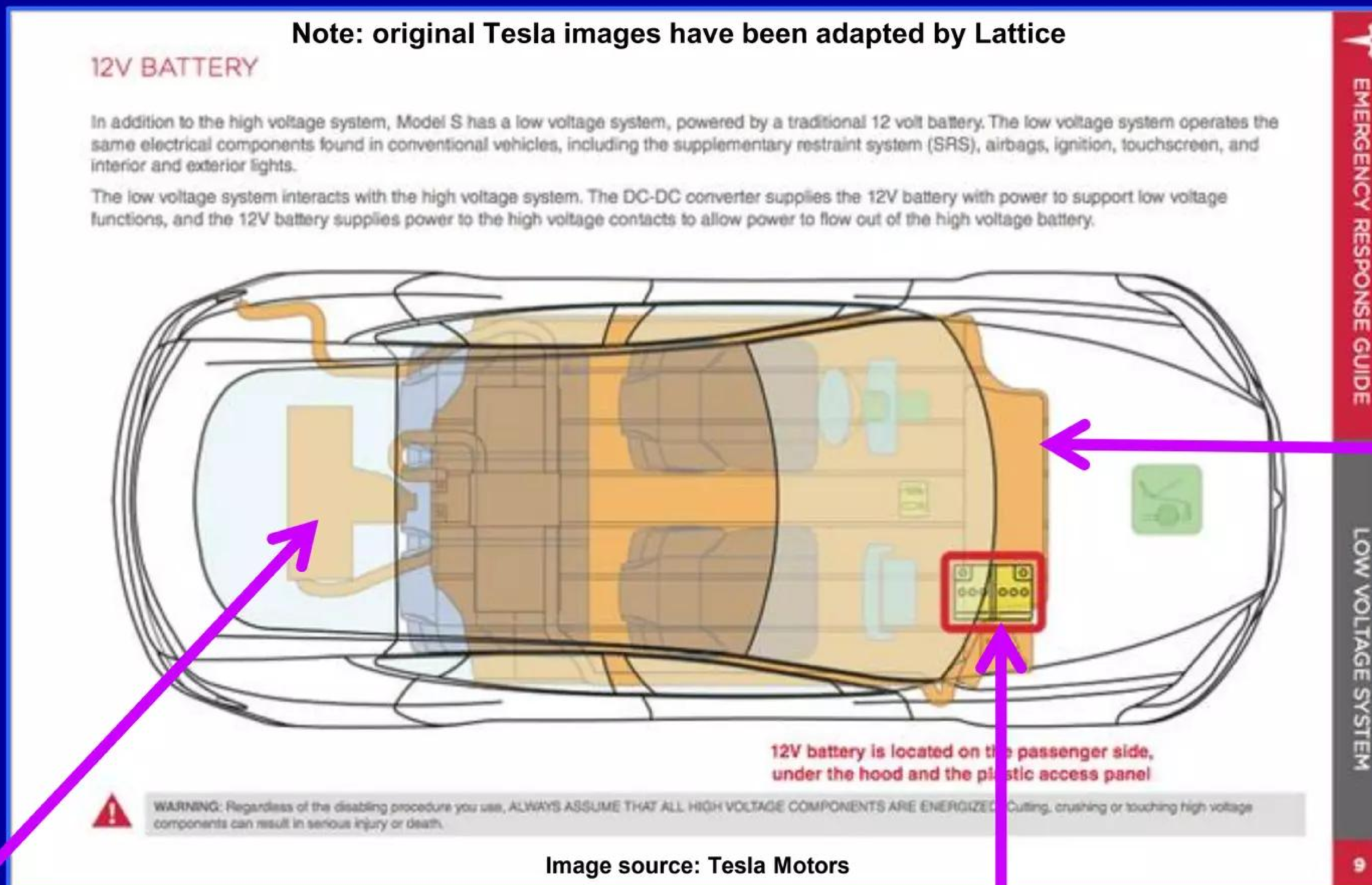
Tesla Motors Model S: Overview of vehicle and systems

Spatial locations: battery pack (orange color) and 12V lead-acid battery

Rear



High voltage battery pack – front leading edge

Front

Electric motor

12V battery

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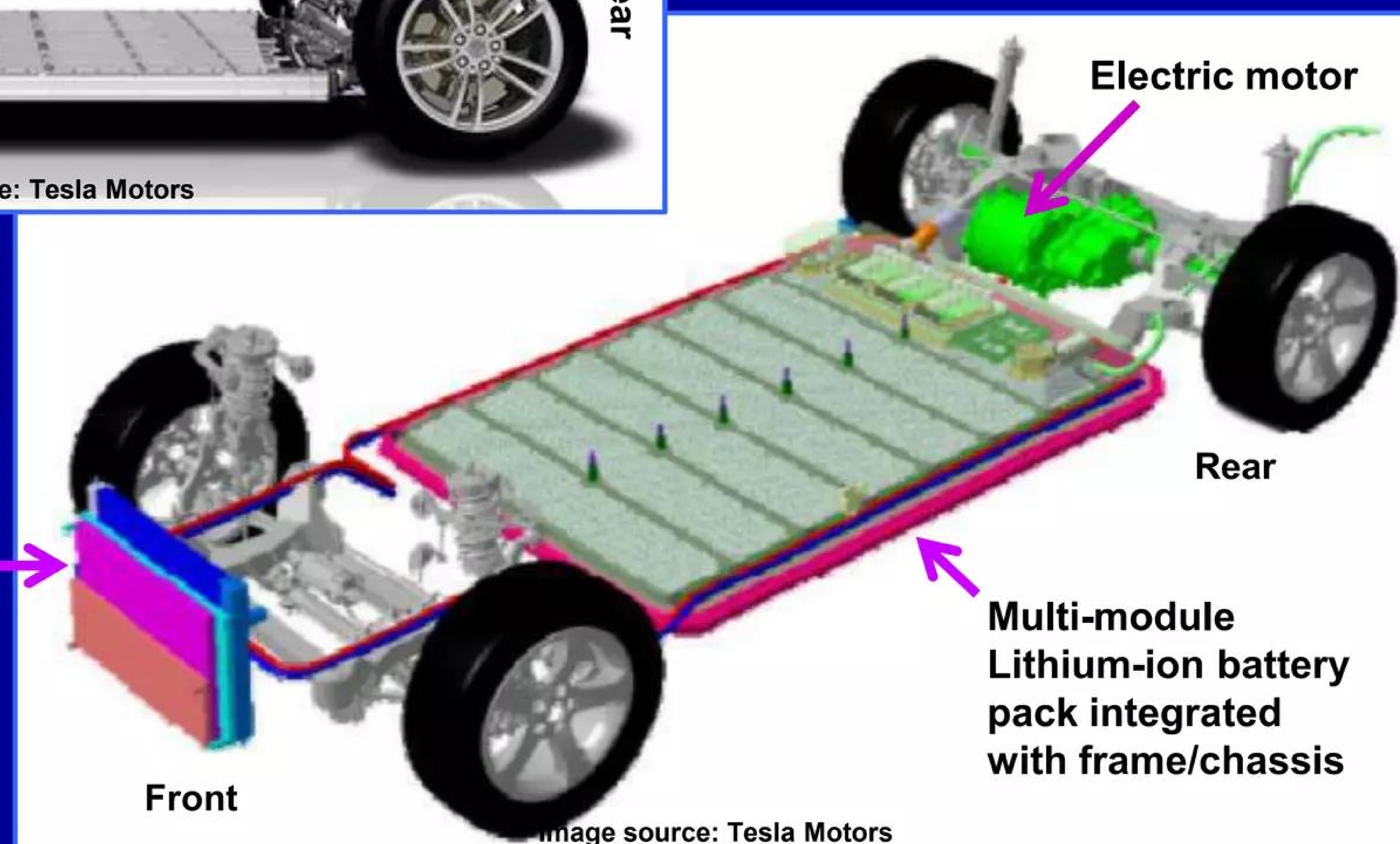
Tesla Motors Model S: Overview of vehicle and systems

Battery pack is tightly integrated with car's major structural components

Front radiator includes heat exchanger for battery pack's cooling system



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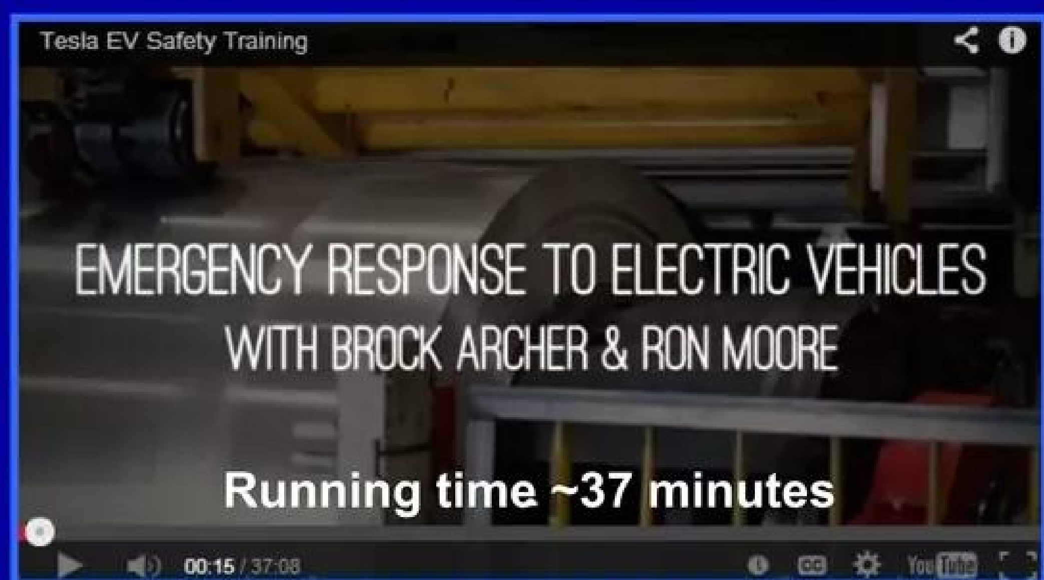
Tesla Motors Model S: Overview of vehicle and systems

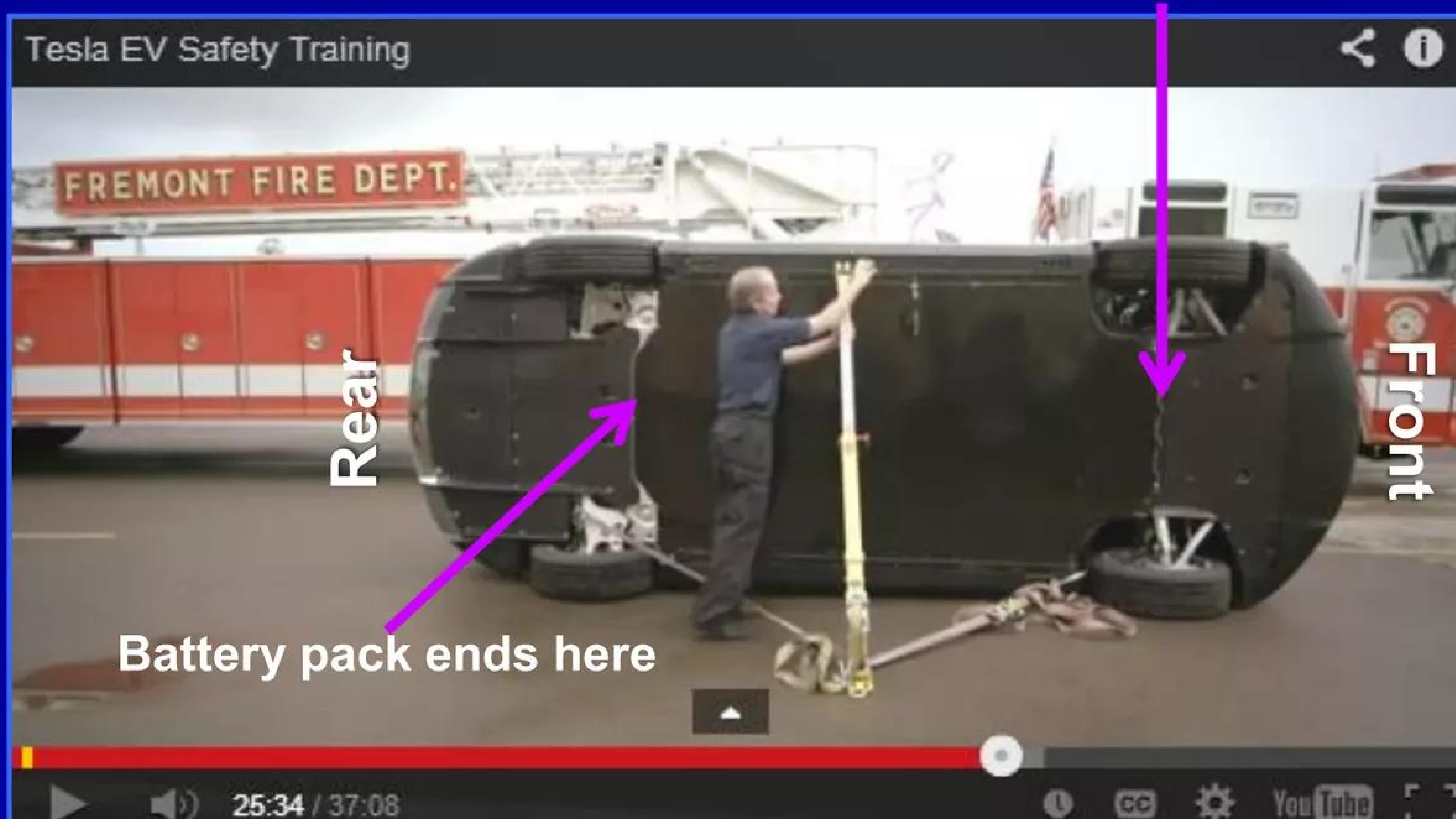
Company’s safety training video shows smooth underbody of vehicle



Source URL for online training video: http://boronextrication.com/2013/03/tesla-ev-safety-extrication-training-video/

Very smooth, turbulence-free underbody makes significant contribution to car’s very low drag coefficient (Cd) of ~0.24

Battery pack begins right here



- ✓ Video was produced to help first responders at EV road accidents, especially the firefighters, to be aware of key issues with EV electrical systems that are not found on IC engine cars: e.g., high-voltage components and wiring; safely disconnecting the battery subsystem; locations where structural cuts can be made safely; etc.
- ✓ Note the relatively smooth surface of car’s underbody
- ✓ Integrated “armor plate” protects entire battery pack from impacts originating from underneath the vehicle
- ✓ Vehicle upended here is a new Tesla Motors Model S

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Tesla Motors Model S: Overview of vehicle and systems

Company can collect remote telemetry data on systems in near-real-time


February 13, 2013

A Most Peculiar Test Drive

By Elon Musk, *Chairman, Product Architect & CEO*

TAGS: ENGINEERING / ELECTRIC / MODEL S /

318 comments

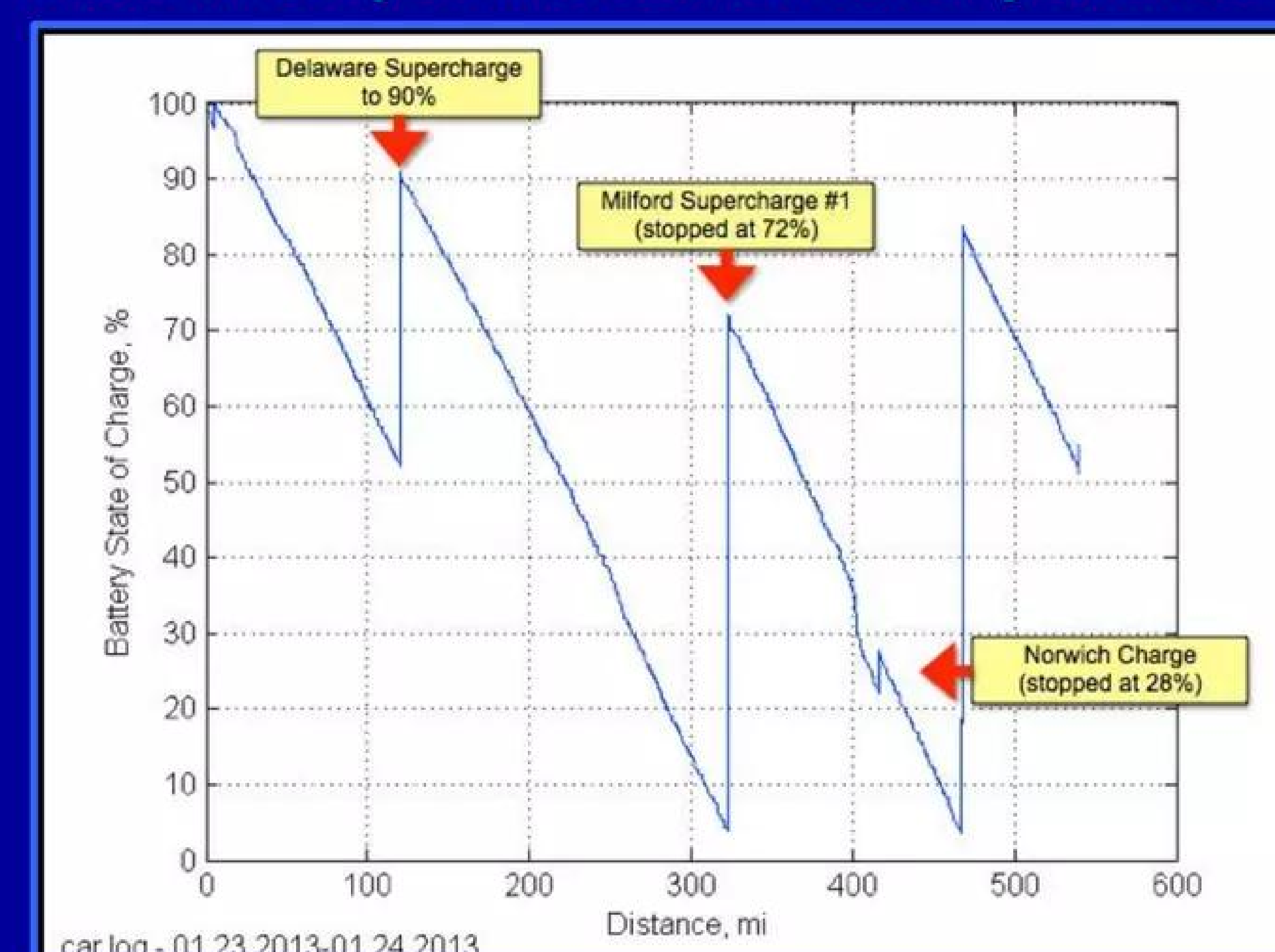
Lattice comments:

- ✓ **Earlier in 2013, Tesla criticized results of a Model S media test drive that were claimed and reported by journalist John Broder in a *New York Times* article**
- ✓ **Used wireless vehicle telemetry data as evidence to dispute Mr. Broder's claimed test drive results**

Quoting excerpts directly from Mr. Musk's post:

"After a negative experience several years ago with *Top Gear,* a popular automotive show, where they pretended that our car ran out of energy and had to be pushed back to the garage, we always carefully data log media drives. While the vast majority of journalists are honest, some believe the facts shouldn't get in the way of a salacious story. In the case of *Top Gear*, they had literally written the script before they even received the car (we happened to find a copy of the script on a table while the car was being 'tested'). Our car never even had a chance … The logs show again that our Model S never had a chance with John Broder …"

Example of remote telemetry data used against Broder; caption in Musk's post read, "Vehicle Logs for Media Drive by John Broder on January 23 and 24"



Source URL: http://www.teslamotors.com/blog/most-peculiar-test-drive

Tesla Motors Model S: Overview of vehicle and systems

Description: Android smartphone app interacts with car's onboard systems

The Tesla Model S Beta app puts Model S owners in direct communication with their cars anytime, anywhere. With this app, owners can:

- **Check charging progress in real time and start or stop charge**
- **Heat or cool Model S before driving - even if it's in a garage**
- **Locate Model S with directions or track its movement across a map**
- **Flash lights or honk the horn to find Model S when parked**
- **Vent or close the panoramic roof**
- **Lock or unlock from afar**

Known issues with the Tesla Model S Beta app include occasional UI glitches.

Source URL = https://play.google.com/store/apps/details?id=com.teslamotors.tesla&hl=en

Oct. 1, 2013: Tesla Model S

had battery thermal runaway

Oct. 1, 2013: Tesla Model S had battery thermal runaway

Incident occurred in Kent, WA after exiting 4-lane state highway #167

abc NEWS

Source URL: http://abcnews.go.com/US/wireStory/tesla-stock-tumbles-model-catches-fire-20450475

Tesla Stock Tumbles After Model S Catches Fire

SEATTLE October 3, 2013 (AP)

By MIKE BAKER Associated Press

AP

Shares of electric car company Tesla sank more than 6 percent Wednesday after an Internet video showed flames spewing from one of the company's vehicles near Seattle.

Quoting directly: The incident happened Tuesday after 8 a.m. as the driver was traveling southbound on state Route 167 through Kent, said Trooper Chris Webb of the Washington State Patrol. The driver stated that he believed he had struck some metal debris on the freeway, so he exited the highway and the vehicle became disabled.

The driver told authorities he began to smell something burning and then the vehicle caught fire. Firefighters needed several attempts to extinguish the flames because the blaze kept reigniting, Webb said. A trooper who responded to the scene was unable to locate any objects on the roadway, but Department of Transportation workers did observe some debris near the scene.

Continuing quote: Webb said there was too much damage from the fire to see what damage the debris may have caused.

The automobile site Jalopnik.com posted photos of the blaze that it says were taken by a reader, along with a video. The video shows the front of the Tesla Model S in flames.

In a statement issued Wednesday, Tesla said the fire was caused by "substantial damage" to the car when the driver hit a large metal object in the road. The flames, the company said, were contained to the front of the $70,000 vehicle due to its design and construction.

"All indications are that the fire never entered the interior cabin of the car. It was extinguished on-site by the Fire Department," the statement said.

Oct. 1, 2013: Tesla Model S had battery thermal runaway

Flames are already ~6 feet high; firefighters are just arriving on scene

Image below: freeze-frame from amateur video of incident shows entire front-end of Tesla Model S completely engulfed in flames

Toe of fireman's boot

Incident video source URL: http://www.youtube.com/watch?feature=player_embedded&v=q0kjl08n4fg

Oct. 1, 2013: Tesla Model S had battery thermal runaway

Firefighters have now cut into the hood area; still trying to control fire

Source URL: http://jalopnik.com/this-is-what-fiery-tesla-model-s-death-looks-like-1440143525

Incident video source URL: http://www.youtube.com/watch?feature=player_embedded&v=q0kjl08n4fg

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Oct. 1, 2013: Tesla Model S had battery thermal runaway

Update of AP story which ran earlier that day

Source URL: http://www.king5.com/news/local/Tesla-stock-tumbles-after-Model-S-catches-fire-near-Seattle-226207191.html

Local News

Tesla stock tumbles after Model S catches fire near Seattle

Credit: YouTube

by MIKE BAKER / Associated Press
Posted on October 2, 2013 at 2:52 PM
Updated today at 4:19 PM

SEATTLE - Shares of electric car company Tesla sank more than 6 percent Wednesday after an Internet video showed flames spewing from one of the company's vehicles near Seattle.

Quoting: The incident happened Tuesday after 8 a.m. as the driver was traveling southbound on state Route 167 through Kent, said Trooper Chris Webb of the Washington State Patrol. The driver stated that he believed he had struck some metal debris on the freeway, so he exited the highway and the vehicle became disabled.

The driver told authorities he began to smell something burning and then the vehicle caught fire. Firefighters needed several attempts to extinguish the flames because the blaze kept reigniting, Webb said. A trooper who responded to the scene was unable to locate any objects on the roadway, but Department of Transportation workers did observe some debris near the scene.

Webb said there was too much damage from the fire to see what damage the debris may have caused.

The automobile site Jalopnik.com posted photos of the blaze that it says were taken by a reader, along with a video. The video shows the front of the Tesla Model S in flames.

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Oct. 1, 2013: Tesla Model S had battery thermal runaway

Oct. 2 @ 7:40 PM EDT: International Business Times excerpts fire report

Excerpts from accident report by Regional Fire Authority of Kent, Washington USA

Short Report:
VEH ON FIRE
<08:19:31>NAM: EMMERT, STEVE/PSRBY TXT: BLK SEDAN .. OCCUP'T IS OUT .. WSP ADVISED
<08:20:20>BRIAN/PSBY PHO: [redacted] CON: N TXT: RP STATES IS AN ELECTRIC VEH - UNK HOW STARTED - APPEARS DRIVER DID GET OUT - BLOCKING END OF SB RAMP AND WB WILLIS
2013100108
<08:20:33>NAM: CARLSON,ROB/DRIVER PHO: [redacted] CON: O TXT: RP IS DRIVER, STATES IS ELECTRIC VEH..NOT OCCUPIED
<08:20:33>LOC: S WASHINGTON AV/W WILLIS ST ,KEN NAM: STAFFORD, RAY/PSBY PHO: [redacted] TXT: UNK IF OCC'D.... ..
<08:20:36>, PSBY REPORTING SAME: HELL, RON [redacted]
<08:37:08>,#10/01/13 08:36:51 TO FD24 FROM CR07:WSP IS CALLING FOR A TOW. AND THANKS!
<08:20:22>,OTHER CALL SAYS 100FT WEST OF 167 ON WILLIS ..BLK TESLA CAR FLAMES FROM ENGINE
<08:22:11>, PSBY REPORT SAME: COLEMAN, MARY [redacted], NO NEW INFO
B71<08:22:42>,1 CAR ON FIRE...W WILL AT END OF OFF RAMP
B71<08:23:40>,OFF RMP FROM SB 167 TO WILLIS WILL BE BLOCKED
E71<08:24:08>,WSP UPDATED
B71<08:25:28>,LOCATE DRIVER PLEASE
B71<08:26:51>,MSG LEFT ON DRIVERS VM
B71<08:29:09>,ON OFFRAMP.. GREEN CAR W/LADDER ON IT
B71<08:35:37>,HIT SOMETHING ON FREEWAY...XWALK ON WILLIS BLOCKED
<08:37:13>, PER WSP, THEY WILL CALL TOW
B71<09:09:51>,ROB CARLSON, 2710 107 AVENUE SE, BELLEVUE 98004
B71<09:10:43>091043, '12 SSIG TESLA, ***0489 LAST 4 OF VIN #
B71<09:20:17>,DRIVER STATED THAT HE HIT AN OBJECT IN THE HOV LANES OF SB 167. THE CAR STARTED TO RUN POORLY AND HE PULLED OFF THE FREEWAY. THE CAR STARTED TO SMOKE AND CAUGHT FIRE. NON INJURY.

E71
Incident
13:46:40 Wednesday, October 2, 2013
KF0201 - Galassi, Scott A
CPT
1

E71, E76, and B71 responded to a car fire at Highway 167, South bound off ramp to Willis St. B71 arrived on location and reported a car fire. E71 arrived on location and blocked West bound traffic on Willis Street. E71 found a medium sized sedan that appeared to have an engine compartment fire. E71 pulled an attack line and extinguished the fire. E71 had to break the driver's side window to gain access to the interior of the vehicle. The Fire appeared to be extinguished then re-ignited underneath the vehicle. E71 then attempted to extinguish with water. The application of water seemed to intensify the fire activity. E71 then applied dry chemical extinguisher to extinguish the fire. The application of the dry chemical extinguisher put down the majority of the fire.

The vehicle's driver stated that he had struck some kind of object on the freeway. He stated that he then began to have problems with the vehicle and pulled off the freeway.

E71 could not access the portion of the vehicle that was still burning. E71 had to dismantle the front end of the vehicle to gain access to the burning material. E71 found what appeared to be a battery pack in the front end of the vehicle that continued to burn. E71 had to puncture multiple holes into the pack to apply water to the burning material in the battery.

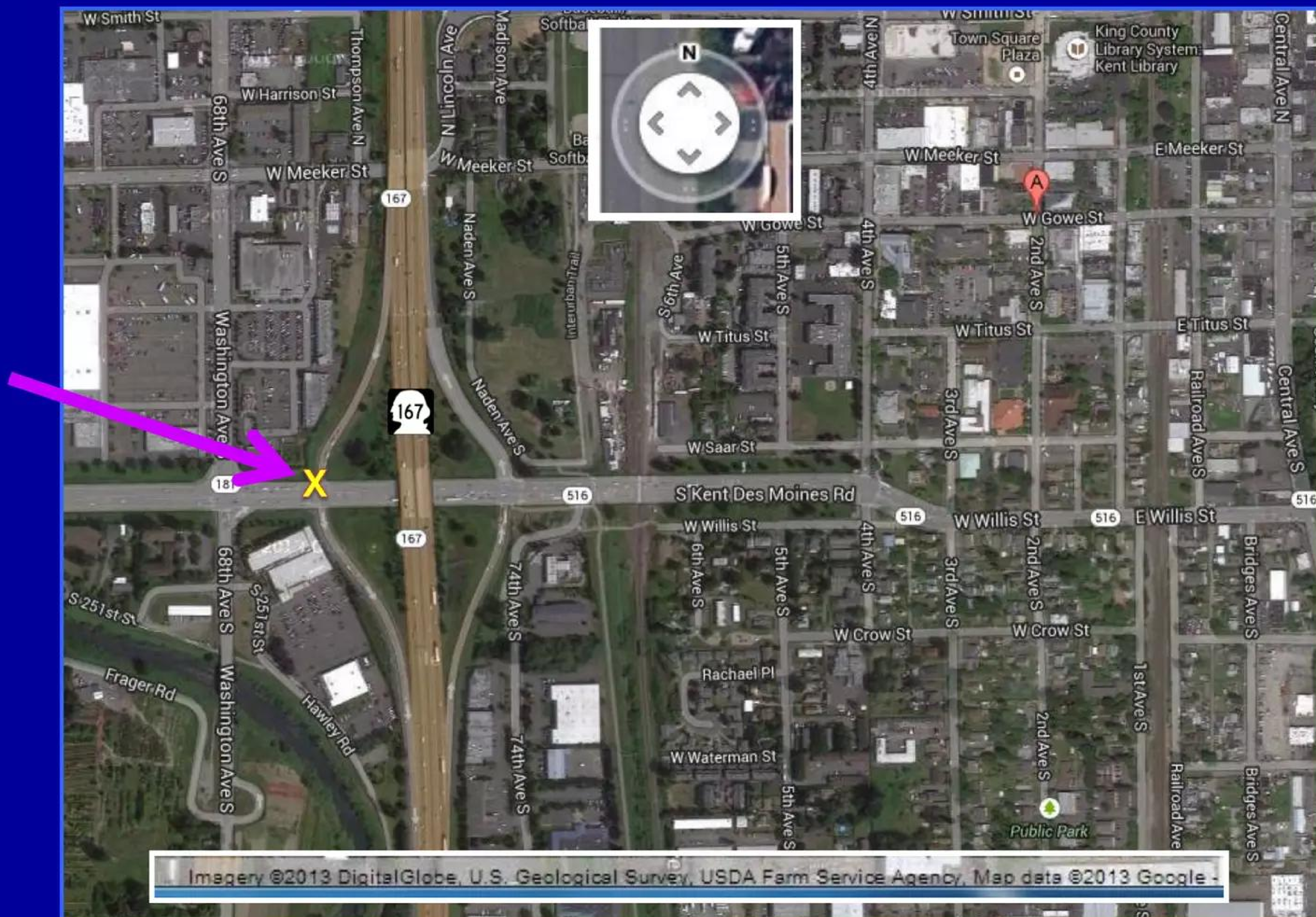
E71 then used a high lift jack to expose the undercarriage of the vehicle, in an attempt to completely extinguish the battery pack. E71 discovered that there was no access to the battery from the undercarriage. E71 then used a circular saw to cut an access hole into front structural member to apply water to the battery pack. E71 completely extinguished the fire. E71 went back into service.

Source: http://www.ibtimes.com/tesla-model-s-driver-hits-object-hov-lane-near-kent-washington-car-smokes-catches-fire-lithium

Lattice Energy LLC

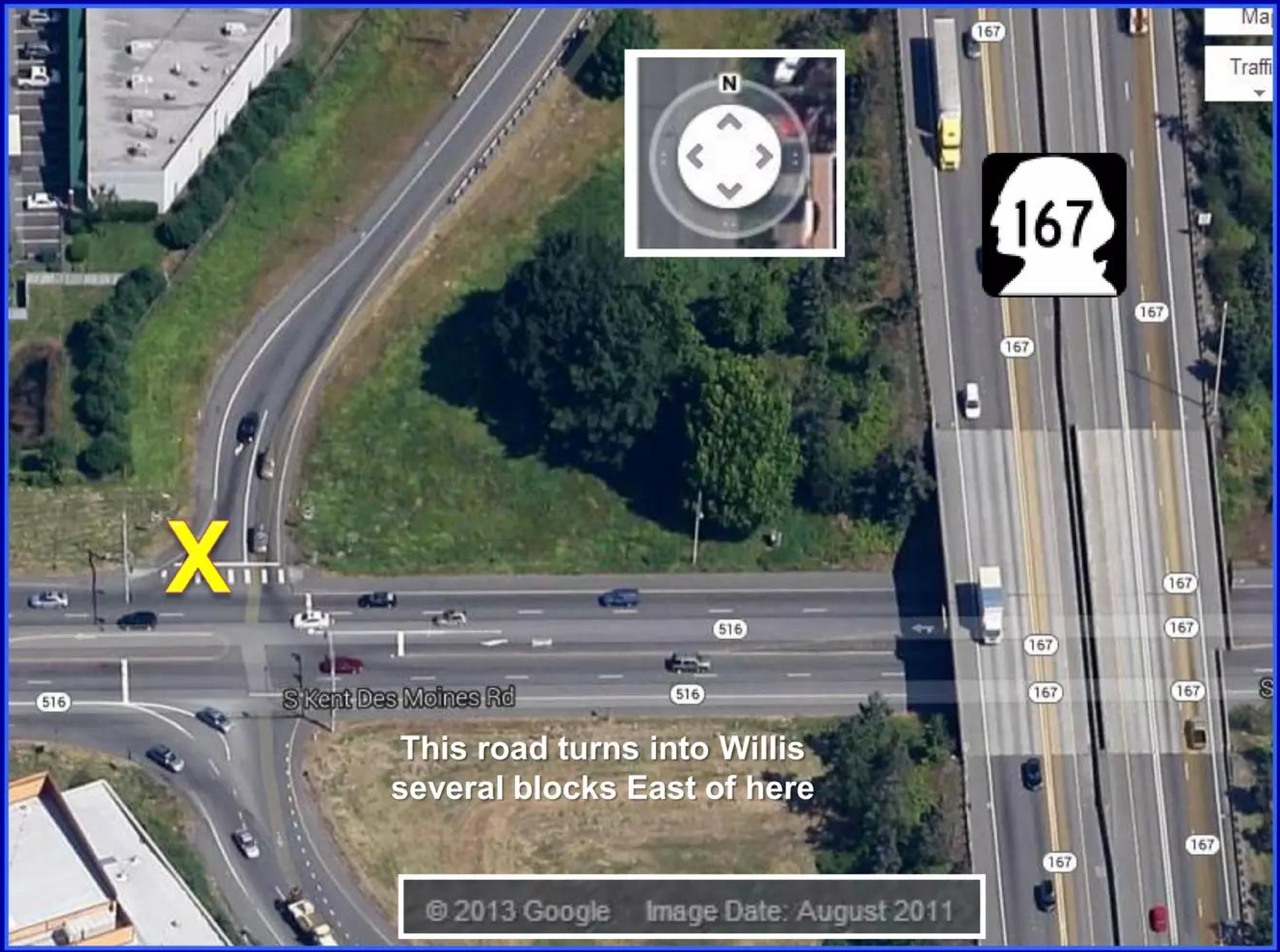
Oct. 1, 2013: Tesla Model S had battery thermal runaway

Google maps image on 167 southbound exit ramp in Kent, WA USA



Oct. 1, 2013: Tesla Model S had battery thermal runaway

Higher-resolution Google image of 167 down ramp: X marks location



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Oct. 1, 2013: Tesla Model S had battery thermal runaway

Google Earth view of corner where Model S runaway car burned

Lattice Energy LLC

Oct. 1, 2013: Tesla Model S had battery thermal runaway

Oct. 3: Tesla finally admits that EV's battery was involved in fire

Source URL: http://abcnews.go.com/US/wireStory/tesla-stock-tumbles-model-catches-fire-20450475

APNewsBreak: Tesla Says Car Fire Began in Battery

SEATTLE October 3, 2013 (AP)

By MIKE BAKER and TOM KRISHER Associated Press

A fire that destroyed a Tesla electric car near Seattle began in the vehicle's battery pack, officials said Wednesday, creating challenges for firefighters who tried to put out the flames.

Company spokeswoman Liz Jarvis-Shean said the fire Tuesday was caused by a large metallic object hitting one of the battery pack's modules in the pricey Model S. The fire was contained to a small section at the front of the vehicle, she said, and no one was injured.

Quoting directly: In an incident report released under Washington state's public records law, firefighters wrote that they appeared to have Tuesday's fire under control, but the flames reignited. Crews found that water seemed to intensify the fire, so they began using a dry chemical extinguisher.

After dismantling the front end of the vehicle and puncturing holes in the battery pack, responders used a circular saw to cut an access hole in the front section to apply water to the battery, according to documents. Only then was the fire extinguished.

The incident happened as the Tesla's driver was traveling southbound on state Route 167 through the Seattle suburb of Kent, said Trooper Chris Webb of the Washington State Patrol. The driver said he believed he had struck some metal debris on the freeway, so he exited the highway and the vehicle became disabled.

Continuing quote: The driver, who did not return a phone call seeking comment, told authorities he began to smell something burning and then the vehicle caught fire.

Firefighters arrived within 3 minutes of the first call. It's not clear from records how long the firefighting lasted, but crews remained on scene for 2 1/2 hours.

Tesla said the flames were contained to the front of the $70,000 vehicle due to its design and construction.

"This was not a spontaneous event," Jarvis-Shean said. "Every indication we have at this point is that the fire was a result of the collision and the damage sustained through that."

There was too much damage from the fire to see what damage debris may have caused, Webb said.

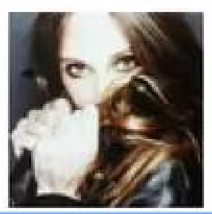
The automobile website Jalopnik.com posted photos of the blaze that it says were taken by a reader, along with a video.

Oct. 1, 2013: Tesla Model S had battery thermal runaway

Oct. 3: *Forbes* still can't verify existence of metallic object or road crew

Forbes

Source URL: http://www.forbes.com/sites/hannahelliott/2013/10/03/the-tesla-fire-is-a-textbook-pr-problem-and-they-should-fix-it/



Hannah Elliott, Forbes Staff
I cover the fun stuff: High-end cars, watches, fashion and culture.
+ Follow (858) Follow 234k

BUSINESS | 10/03/2013 @ 1:00PM | 5,335 views

The Tesla Fire Is A Textbook PR Problem - And They Should Fix It

+ Comment Now + Follow Comments

By now most Tesla-watchers have seen the footage of the flaming Model S in Seattle.

Quoting directly from *Forbes*:

Tesla has been mostly quiet on this front, releasing only this official response to the press:

"The fire was caused by the direct impact of a large metallic object to one of the 16 modules within the Model S battery pack. Because each module within the battery pack is, by design, isolated by fire barriers to limit any potential damage, the fire in the battery pack was contained to a small section in the front of the vehicle."

Oct. 1, 2013: Tesla Model S had battery thermal runaway

Oct. 3: *Forbes* still can't verify existence of metallic object or road crew

Source URL: http://www.forbes.com/sites/hannahelliott/2013/10/03/the-tesla-fire-is-a-textbook-pr-problem-and-they-should-fix-it/

Further quoting directly from *Forbes*:

Earlier today I spoke with Elizabeth Jarvis-Shean, Tesla's director of global communications, and while she described the mechanics of the accident to me (again, the official word is that the driver hit something big that punctured the battery pack and caused the fire, which was contained by Tesla technology) she was unable to answer some key questions I had.

Namely: What was the object? How was something so big able to apparently disappear from the site of the alleged crash? What recourse does the driver have under his ownership contract in terms of replacing his vehicle? Will Tesla replace it or refund him the $50,000-plus he paid for it?

These were the answers I got to those and similar questions: "I can't really speak to that." "I can't comment." "I don't know at this point."

Oct. 1, 2013: Tesla Model S had battery thermal runaway

Oct. 3: *Forbes* still can't verify existence of metallic object or road crew

Source URL: http://www.forbes.com/sites/hannahelliott/2013/10/03/the-tesla-fire-is-a-textbook-pr-problem-and-they-should-fix-it/

Further quoting directly from *Forbes*:

Tesla founder Elon Musk would not be commenting directly on the fire, she said.

This to me seems like an error. Wouldn't it be smarter in the long run to be actively up-front with the public and with journalists about just how exactly the company plans to respond to negative media coverage?

Wouldn't it be better to say, "We are doing this, this and this" to fix the problem and calm anxiety about the cars?

It has been a full day and a half since the accident – enough time to come up with more than two sentences emailed to journalists.

Oct. 4: Tesla released its theory of Model S battery runaway

Oct. 4: Tesla released its theory of Model S battery runaway

TESLA
MODEL S   MODEL X   SUPERCHARGER   ENTHUSIASTS
BLOG   CUSTOMER STORIES   PHOTOS & VIDEOS   EVENTS   FORUMS

BLOG

October 4, 2013

Model S Fire

By Elon Musk, *Chairman, Product Architect & CEO*

TAGS: CORPORATE / MODEL S /

0 comments

Two e-mails were published in Tesla's blog along with Mr. Musk's post; in an e-mail sent to the owner of the damaged Model S, Mr. Jerome Guillen, VP of Sales and Service for Tesla, further elaborated on Tesla's explanatory theory about the battery runaway as follows:

"All indications are that your Model S drove over large, oddly-shaped metal object which impacted the leading edge of the vehicle's undercarriage and rotated into the underside of the vehicle ('pole vault' effect). This is a highly uncommon occurrence."

Continuing Mr. Guillen's remarks:

"Based on our review thus far, we believe that the Model S performed as designed by limiting the resulting fire to the affected zones only. Given the significant intensity of the impact, which managed to pierce the 1/4 inch bottom plate (something that is extremely hard to do), the Model S energy containment functions operated correctly. In particular, the top cover of the battery provided a strong barrier and there was no apparent propagation of the fire into the cabin. This ensured cabin integrity and occupant safety, which remains our most important goal."

Screen-capture image - first paragraph in his Oct. 4 blog post:

Earlier this week, a Model S traveling at highway speed struck a large metal object, causing significant damage to the vehicle. A curved section that fell off a semi-trailer was recovered from the roadway near where the accident occurred and, according to the road crew that was on the scene, appears to be the culprit. The geometry of the object caused a powerful lever action as it went under the car, punching upward and impaling the Model S with a peak force on the order of 25 tons. Only a force of this magnitude would be strong enough to punch a 3 inch diameter hole through the quarter inch armor plate protecting the base of the vehicle.

In this post, Mr. Musk further added that, " … our battery pack is … divided into 16 modules with firewalls in between."

Source: http://www.teslamotors.com/blog/model-s-fire

Oct. 4: Tesla released its theory of Model S battery runaway

Published copies of Oct. 3 e-mails with Robert Carlson to support theory

On Oct 3, 2013, at 12:29 PM, Jerome Guillen wrote:

Dear Mr. Carlson:

I am the VP of sales and service for Tesla, reporting directly to Elon Musk, Tesla's CEO.

I am sorry to hear that you experienced a collision in your Model S 2 days ago. We are happy that the Model S performed in such a way that you were not injured in the accident and that nobody else was hurt.

I believe you have been in contact with Justin Samson, our service manager, since the accident. We are following this case extremely closely and we have sent a team of experts to review your vehicle. All indications are that your Model S drove over large, oddly-shaped metal object which impacted the leading edge of the vehicle's undercarriage and rotated into the underside of the vehicle ("pole vault" effect). This is a highly uncommon occurrence.

Based on our review thus far, we believe that the Model S performed as designed by limiting the resulting fire to the affected zones only. Given the significant intensity of the impact, which managed to pierce the 1/4 inch bottom plate (something that is extremely hard to do), the Model S energy containment functions operated correctly. In particular, the top cover of the battery provided a strong barrier and there was no apparent propagation of the fire into the cabin. This ensured cabin integrity and occupant safety, which remains our most important goal.

We very much appreciate your support, patience and understanding while we proceed with the investigation. Justin keeps me closely informed. Please feel free to contact me directly, if you have any question or concern.

Best regards,
Jerome Guillen I VP, WW sales and service

From: robert Carlson
Sent: Thursday, October 03, 2013 12:53 PM
To: Jerome Guillen
Subject: carlson 0389

Mr. Guillen,

Thanks for the support. I completely agree with the assessment to date. I guess you can test for everything, but some other celestial bullet comes along and challenges your design. I agree that the car performed very well under such an extreme test. The batteries went through a controlled burn which the internet images really exaggerates. Anyway, I am still a big fan of your car and look forward to getting back into one. Justin offered a white loaner--thanks. I am also an investor and have to say that the response I am observing is really supportive of the future for electric vehicles. I was thinking this was bound to happen, just not to me. But now it is out there and probably gets a sigh of relief as a test and risk issue-this "doomsday" event has now been tested, and the design and engineering works.

rob carlson

Note: in above e-mail, Robert Carlson, owner of the runaway Model S, revealed:

"I am also an investor [in Tesla] and…"

Source: http://www.teslamotors.com/blog/model-s-fire

Oct. 4: Tesla released its theory of Model S battery runaway

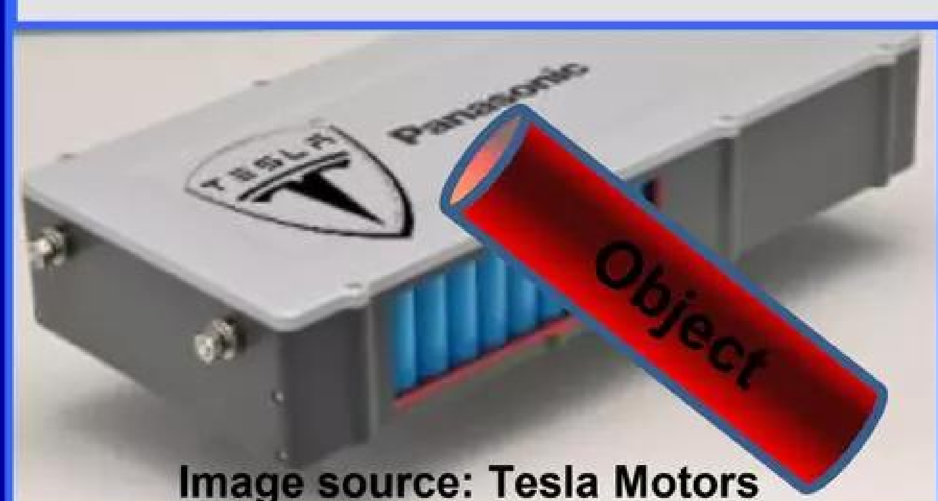
Graphical summary: metallic object's hypothesized point-of-impact

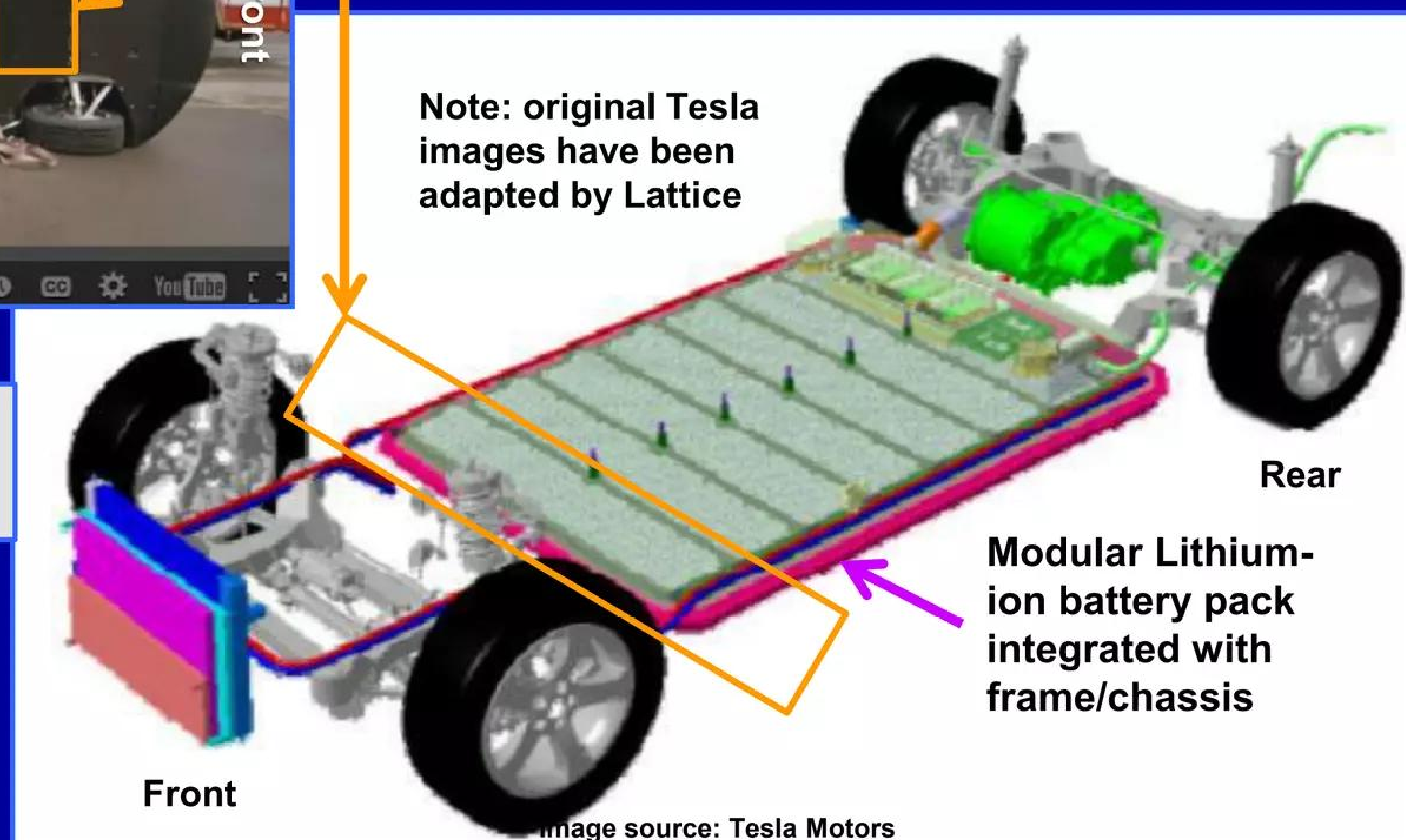
Battery pack begins right here

Battery pack ends right here

Tesla's theory of event posits that a "large metallic object" struck the leading front edge of battery pack, damaging the first module in the very front; impact occurred somewhere in the area delineated by orange rectangular boxes

3" dia. "large metallic object" would have pierced multiple 18650A battery cells and shorted electrical wiring locally





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Oct. 4: Tesla released its theory of Model S battery runaway

Summary of key points in their explanation of what caused the event

- ✓ According to an account provided by driver of the Model S: at highway speed the vehicle accidentally ran-over a piece of debris ("large metallic object") that had been lying on the state roadway #167 surface; problems with car operation began shortly thereafter
- ✓ Tesla then hypothesized that purported "large metallic object" had perhaps fallen-off some kind of truck; further claimed that WA "DOT road crew" had supposedly found and "recovered" a piece of debris at some point in time after the runaway incident that supposed "DOT road crew" believed to be the culprit object that caused battery fire
- ✓ Tesla theorized that as this debris was being run-over, the purported "large metallic object" rotated through an arc ("pole vault effect") and punched a "3 inch hole" through a "¼ inch thick armor plate" that protects the car's entire battery pack from possibly damaging impacts coming from direction of road surface underneath vehicle
- ✓ Tesla further theorized that it was this violent piercing of a metallic object into the first module (out of a total of 16) located at the front leading edge of the battery pack that was the proximate cause for the ensuing battery thermal runaway and blazing vehicle fire; Tesla then estimated it would take a force of "25 tons" to punch-through "armor"
- ✓ Tesla claimed runaway conflagration was limited and confined to first (fatally pierced) module in the battery pack as a result of Tesla's unique safety engineering features

Will theorized 25 ton impact force pierce battery's armor?

Lattice Energy LLC

Will theorized 25 ton impact force pierce battery's armor?

Process is analogous to use of punches and dies in metalworking

"Large metallic object" is punch; "armor plate" = sheet stock being punched

Nothing precisely equivalent to a rigid supporting die present in Tesla battery pack

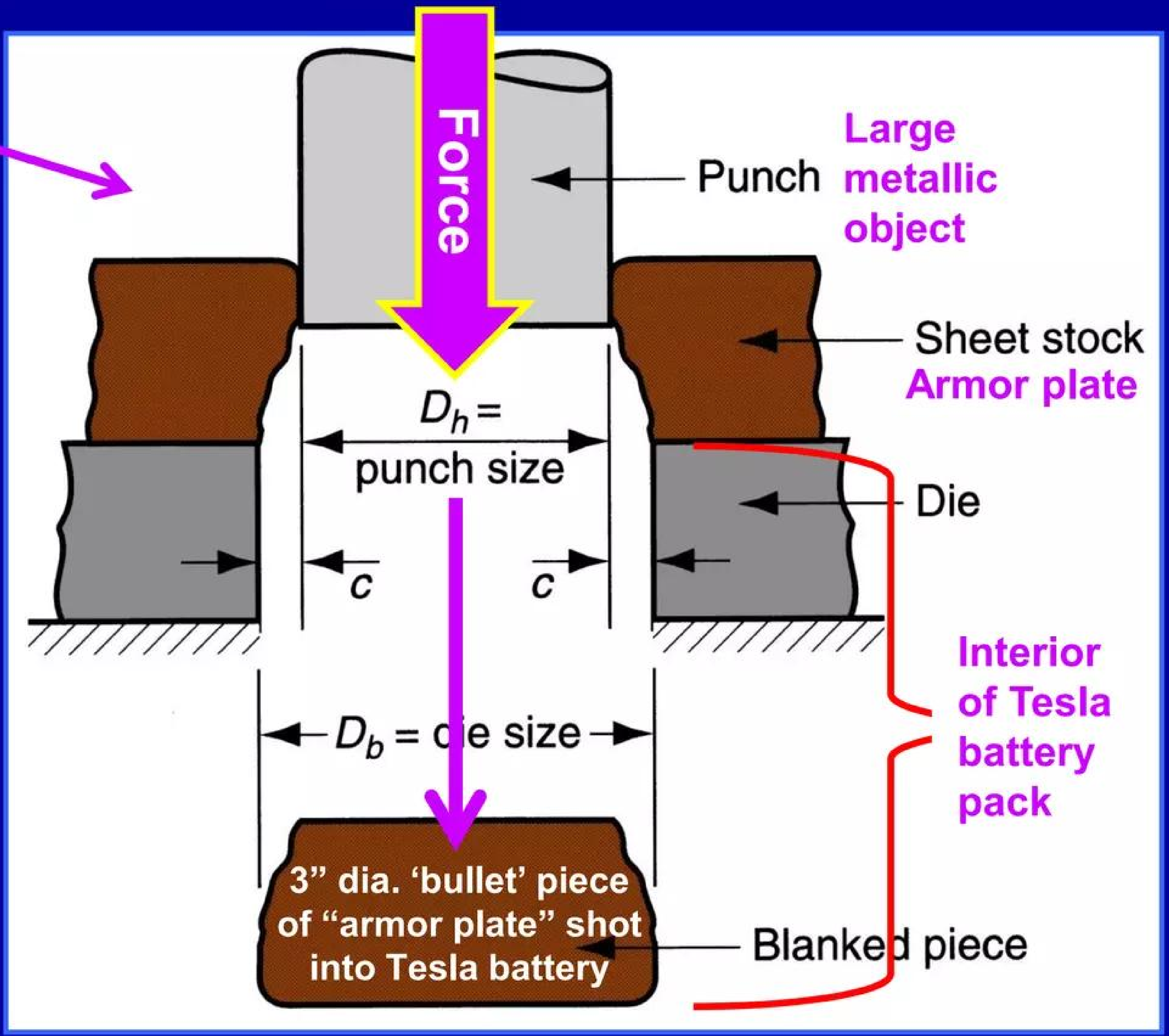
NC STATE UNIVERSITY
ise EDWARD P. FITTS DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

Fig. 20.6 is adapted

Course:

ISE 316 - Manufacturing Processes Engineering

Note: nothing precisely equivalent to a rigid supporting die is present in Tesla battery pack. So as "large metallic object" (= punch) is piercing the protective "armor plate" (= "sheet stock" in Figure to right) it will experience elastic bending 'give' prior to punch-through because Tesla's "armor plate" is probably ductile, flexible metal. In practical terms, this means that the amount of real-world force that would be required to punch a ~3" diameter hole through the Tesla battery pack's "armor plate" is likely to be larger than what we calculate with pure shear-force formulas used herein. Our estimated force thus probably conservative; perhaps lower by as much as ~20%



Source (download MS-PowerPoint of Chapter 20 in ISE 316 – Fig. 20.6: http://tinyurl.com/kreyhw9

Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force from Tesla's data using a standard formula

Source URL = http://www.wisc-online.com/

Quoting: **"Wisc-Online is a digital library of Web-based learning resources called 'learning objects'. The digital library of objects has been developed primarily by faculty from the Wisconsin Technical College System (WTCS) and produced by multimedia technicians whom create the learning objects."**

Have developed a useful learning module titled, "Calculating force for punching"

Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force = F from Tesla's data using a standard formula

Calculating Force for Punching

Terminology: the term "shear strength" means ~ same thing as 'tensile strength"

$$F = \pi d \times t \times \sigma$$

Here's an example. The most common formula multiplies the tensile strength of the material to be punched by the hole circumference (or hole perimeter) by the material thickness. It is expressed as:

$$\begin{aligned} F &= \overset{\pi}{(3.1416)}\overset{d}{0.25} \times \overset{t}{0.25} \times \overset{\sigma}{50{,}000} \\ F &= 9817.48/2000 \quad \text{(Divide by 2000 to convert to pounds.)} \\ F &= 4.9 \text{ tons} \end{aligned}$$

Users calculate the tonnage required to punch holes in a specific base metal. The formula to be used is provided along with the tensile strength for various metals. A calculator is required.
Author(s): Dave Hoffman

F = Force in pounds (in tons if divided by 2000)
π = Pi (3.1416)
d = Diameter of ounch
t = Thickness of metal
σ = Material shear strength

Source URL = http://www.wisc-online.com/Objects/ViewObject.aspx?ID=FAB1302

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Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force = F from Tesla's data using a standard formula

Tesla did not specify composition of ¼" thick "armor plate" that was pierced

Was "armor" composed of some type of steel or perhaps aluminum alloys?

Besides dimensions d and t, calculated force strongly depends on tensile strength σ of punched material

Terminology: the term "shear strength" means the same thing as 'tensile strength"

$$F = \pi d \times t \times \sigma$$

d = diameter of punched hole in inches

t = thickness of metallic sheet being punched-through measured in inches

σ = shear = tensile strength expressed in pounds per square inch (psi)

$$F = \overset{\pi}{3.1416} \times \boxed{d} \times \boxed{t} \times \boxed{\sigma}$$

F = Force (tons)

(Note: Enter number as decimals. Round final answer to one decimal point.)

Shear Strength	Material
	Aluminum
10,500	Soft
20,000	2024-0
32,000	6061-T6
49,500	Brass
26,500	Copper
68,000	Inconel
20,000	Magnesium
60,000	Monel
37,000	Nickel
50,000	Steel – Low
70,000	Medium
112,000	High
60,000	Low Alloy
	Stainless –
72,000	Austentic
60,000	Ferritic
80,000	Martensitic
100,000	Tool Steel
200,000	Spring Steel

Assumptions: relying, on Tesla's public statements, we will simply assume that hole punched though car's "armor plate" by the "large metallic object" was roughly circular and ~3" in diameter

Source URL = http://www.wisc-online.com/Objects/ViewObject.aspx?ID=FAB1302

Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force from Tesla's data using a standard formula

Assume that Tesla's ¼" thick armor plate composed of ferritic stainless steel

Result: calculated force necessary to pierce armor = 70.1 tons

$$F = \pi d \ x \ t \ x \ \sigma$$

d = 3.0" t = 0.25" σ = 60,000 (psi)

Armor plate material assumed to be ferritic stainless steel which is a strong, very corrosion-resistant metal

F = 3.1416 x 3.0 x 0.25 x 60,000

F = 70.1

(Note: Enter number as decimals. Round final answer to one decimal point.)

Shear Strength	Material
	Aluminum
10,500	Soft
20,000	2024-0
32,000	6061-T6
49,500	Brass
26,500	Copper
68,000	Inconel
20,000	Magnesium
60,000	Monel
37,000	Nickel
50,000	Steel – Low
70,000	Medium
112,000	High
60,000	Low Alloy
	Stainless –
72,000	Austentic
60,000	Ferritic
80,000	Martensitic
100,000	Tool Steel
200,000	Spring Steel

Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force from Tesla's data using a standard formula

Now assume that Tesla's ¼" thick armor plate composed of soft Aluminum

Result: calculated force necessary to pierce armor = 12.4 tons

$$F = \pi d \times t \times \sigma$$

d = 3.0" t = 0.25" σ = 10,500 (psi)

Armor plate material unrealistically assumed to be just soft Aluminum that is light and corrosion-resistant

F = 3.1416 × 3.0 × 0.25 × 10,500

F = 12.4

(Note: Enter number as decimals. Round final answer to one decimal point.)

Shear Strength	Material
	Aluminum
10,500	Soft
20,000	2024-0
32,000	6061-T6
49,500	Brass
26,500	Copper
68,000	Inconel
20,000	Magnesium
60,000	Monel
37,000	Nickel
50,000	Steel – Low
70,000	Medium
112,000	High
60,000	Low Alloy
	Stainless –
72,000	Austentic
60,000	Ferritic
80,000	Martensitic
100,000	Tool Steel
200,000	Spring Steel

Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force from Tesla's data using a standard formula

Now assume Tesla's ¼" thick armor plate is composed of stronger Aluminum

Result: calculated force necessary to pierce armor = 37.7 tons

$$F = \pi d \times t \times \sigma$$

d = 3.0"   t = 0.25" σ = 32,000 (psi)

Armor plate material realistically assumed to be 6061-T6 Aluminum that is harder and corrosion-resistant

F = 3.1416 × 3.0 × 0.25 × 32,000

F = 37.7

Shear Strength	Material
	Aluminum
10,500	Soft
20,000	2024-0
32,000	6061-T6
49,500	Brass
26,500	Copper
68,000	Inconel
20,000	Magnesium
60,000	Monel
37,000	Nickel
50,000	Steel – Low
70,000	Medium
112,000	High
60,000	Low Alloy
	Stainless –
72,000	Austentic
60,000	Ferritic
80,000	Martensitic
100,000	Tool Steel
200,000	Spring Steel

(Note: Enter number as decimals. Round final answer to one decimal point.)

Lattice Energy LLC

Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force from Tesla's data using a standard formula

Let's examine a real-world commercial version of stronger Aluminum 6061-T6

Mechanical Properties

Hardness, Brinell	95	95	AA; Typical; 500 g load; 10 mm ball
Hardness, Knoop	120	120	Converted from Brinell Hardness Value
Hardness, Rockwell A	40	40	Converted from Brinell Hardness Value
Hardness, Rockwell B	60	60	Converted from Brinell Hardness Value
Hardness, Vickers	107	107	Converted from Brinell Hardness Value
Ultimate Tensile Strength	310 MPa	45000 psi	AA; Typical
Tensile Yield Strength	276 MPa	40000 psi	AA; Typical
Elongation at Break	12 %	12 %	AA; Typical; 1/16 in. (1.6 mm) Thickness
Elongation at Break	17 %	17 %	AA; Typical; 1/2 in. (12.7 mm) Diameter
Modulus of Elasticity	68.9 GPa	10000 ksi	AA; Typical; Average of tension and compression. Compression modulus is about 2% greater than tensile modulus.
Notched Tensile Strength	324 MPa	47000 psi	2.5 cm width x 0.16 cm thick side-notched specimen, K_t = 17.
Ultimate Bearing Strength	607 MPa	88000 psi	Edge distance/pin diameter = 2.0
Bearing Yield Strength	386 MPa	56000 psi	Edge distance/pin diameter = 2.0

Source: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6

Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force from Tesla's data using a standard formula

Now assume that Tesla's ¼" thick armor plate is composed of ASM Aluminum

Result: calculated force necessary to pierce armor = 47.1 tons

$$F = \pi d \times t \times \sigma$$

d = 3.0" t = 0.25" σ = 40,000 (psi)

Armor plate material more realistically assumed ASM 6061-T6 Aluminum that is stronger and corrosion-resistant

F = 3.1416 × $\boxed{3.0}$ × $\boxed{0.25}$ × $\boxed{40{,}000}$

F = $\boxed{47.1}$

(Note: Enter number as decimals. Round final answer to one decimal point.)

Assumption: Tesla' s "armor plate" is instead composed of higher- strength ASM Aerospace 6061-T6 Aluminum sheets

Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force from Tesla's data using a standard formula

Now assume that Tesla's ¼" thick armor plate is composed of medium steel

Result: calculated force necessary to pierce armor = 82.5 tons

$$F = \pi d \times t \times \sigma$$

d = 3.0" t = 0.25" σ = 70,000 (psi)

Armor plate material now is assumed medium-strength steel; stronger but less corrosion-resistant vs. Aluminum

F = 3.1416 x $\boxed{3.0}$ x $\boxed{0.25}$ x $\boxed{70,000}$

F = $\boxed{82.5}$

Shear Strength	Material
	Aluminum
10,500	Soft
20,000	2024-0
32,000	6061-T6
49,500	Brass
26,500	Copper
68,000	Inconel
20,000	Magnesium
60,000	Monel
37,000	Nickel
50,000	Steel – Low
70,000	Medium
112,000	High
60,000	Low Alloy
	Stainless –
72,000	Austentic
60,000	Ferritic
80,000	Martensitic
100,000	Tool Steel
200,000	Spring Steel

(Note: Enter number as decimals. Round final answer to one decimal point.)

Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force from Tesla's data using a standard formula

Let's examine ATI Defense commercial version of steel used in military armor

ATI 500-MIL®
High Hard Specialty Steel Armor

INTRODUCTION

ATI 500-MIL® High Hard Specialty Steel is wrought Ni-Cr-Mo specialty steel for armor plate. The balanced composition of the alloy lends itself to excellent toughness relative to other "high-hard" alloys while maintaining ballistic resistance that meets the MIL-DTL-46100E standard. The alloy's high toughness results in good blast properties.

Due to the processing practices utilized for ATI 500-MIL® steel, residual stresses are low; and plate exhibits minimal distortion after mechanical cutting. Thermal cutting may produce some distortion, but this typically will be much less than would be seen for liquid-quenched materials.

MECHANICAL PROPERTIES

Typical mechanical property data for ATI 500-MIL® specialty steel is included below. This data represents an average of results for 0.275 in. (7 mm) and 0.199 in. (5 mm) plate.

HARDNESS
Steel will re-harden in the 477 to 534 BHN range.

FLATNESS
ATI 500-MIL® specialty steel exceeds the flatness requirement referenced in section 3.2.8.3 of the MIL-DTL-46100E specification per ASTM A6.

TENSILE PROPERTIES (at room temperature)

Tensile Strength:	260,000 psi (1792 MPa)
Yield Strength:	150,000 psi (1034 MPa)
Elongation:	13%

Source: http://www.atimetals.com/Documents/ati_500-mil_tds_en.pdf

Lattice Energy LLC

Will theorized 25 ton impact force pierce battery's armor?

Wisconsin Technical College System (WTCS) has online resources

Can calculate required force from Tesla's data using a standard formula

Now assume Tesla's ¼" thick armor plate is composed of military-grade steel

Result: calculated force necessary to pierce armor = 176.8 tons

$$F = \pi d \times t \times \sigma$$

d = 3.0" t = 0.25" σ = 150,000 (psi)

Armor plate material now assumed to be super-strength steel specifically developed for military applications

$F = 3.1416 \times \boxed{3.0} \times \boxed{0.25} \times \boxed{150{,}000}$

$F = \boxed{176.8}$

(Note: Enter number as decimals. Round final answer to one decimal point.)

Assumption: Tesla' s "armor plate" is instead composed of super- strength ATI Defense ATI-500-MIL

Will theorized 25 ton impact force pierce battery's armor?

Results and conclusions

Unless composed of soft metal, 25 ton force will not pierce real armor plate

- ✓ To date, Tesla has not provided a detailed explanation as to exactly how they estimated the piercing force on battery pack's "armor plate" to be ~25 tons
- ✓ Except in case of soft aluminum (12.4 tons) and based on our assumptions, calculated force required to pierce Tesla's "armor plate" ranged from 37.7 up to 176.8 tons for assortment of stronger Aluminum alloys and various steels
- ✓ While unspecified by Tesla, it is possible that their so-called "armor plate" protecting Model S battery pack from impacts arising from below car is really composed of some sort of light metallic/plastic composite material that has a tensile strength of ~21,000 psi (calculated by solving formula backwards). If this speculation happened to be correct, it would seem to be somewhat of a misnomer for Tesla to publicly characterize such a material as being an "armor plate" in the rigorous metallurgical sense of the term
- ✓ If in fact a "large metallic object" pierced battery pack's "armor plate" with great force, would likely have shot 3" 'bullet' of metal deep into first module

Is Tesla's theory consistent with runaway event timeline?

Lattice Energy LLC

Is Tesla's theory consistent with runaway event timeline?

How much time passed from very first hint of trouble to a blazing fire?

Our analysis suggests probable elapsed time of at least 2 - 3 minutes

- ✓ When firefighters first arrived at the scene, driver had already exited the disabled vehicle and the front hood area of the Tesla Model S was completely engulfed in blazing flames that were swirling to a height of ~6 feet (determined by examining the amateur video clip of incident that was posted on Jalopnik)
- ✓ Kent, WA fire department stated to AP reporters that they arrived at the location of the burning car within 3 minutes of receiving the very first 911 call about the incident; firefighters remained present at the scene for at least 2.5 hours (ref.: Baker & Krisher, Associated Press, Oct. 3, 2013)
- ✓ Distance from previous exit on Southbound #167 to exit where Model S driver actually left the 4-lane highway is ~1.6 miles; the exit ramp distance to the spot where the car finally stopped and began burning is ~0.2 miles for a total likely maximum distance traveled of ~1.8 miles (assuming object was hit and first sign of trouble occurred just past prior exit)
- ✓ According to WA DOT report "SR 167 - HOT Lanes Pilot Project" (Sept. 2011), average rush-hour vehicle speeds in HOT lanes (= HOV in Kent fire dept. report) in which Tesla car was traveling when incident began are ~59 mph (0.983 miles/minute); assuming car traveled at that speed to final stopping point suggests a minimum elapsed time of > 1.8 min
- ✓ All considered, it appears at least ~2 - 3 minutes passed from first hint of trouble to time when large flames became readily visible to other motorists (several of whom called 911)

Lattice Energy LLC

Is Tesla's theory consistent with runaway event timeline?

Posits substantial ~instantaneous mechanical damage to battery module

Impalement would have instantly destroyed at least four 18650 battery cells

- ✓ Tesla Model A 85 kWh battery pack contains ~7,000 Panasonic 18650 cells distributed across 16 isolatable modules; assuming distribution is uniform, this implies ~438 cells per module
- ✓ If a hypothetical large, presumably conductive metallic object 3” in diameter had struck perfectly perpendicular to Tesla Model A’s “armor plate” and then punched a hole into the first module located at the front edge of the battery pack, it would have instantly physically destroyed and shorted-out roughly four 18650 battery cells, just from simple geometric considerations. If the object and piece of the armor ‘bullet’ traveled further into module on a pathway that ran at an oblique angle, many more cells could potentially have been destroyed along with their current-carrying wiring connections to rest of the vehicle’s battery pack
- ✓ Tesla’s battery management system’s (BMS) fine-grained sensor and communication networks would have become aware of this situation almost instantly when large voltage, current, and excess temperature anomalies would have suddenly begun appearing in data from multiple 18650 cells associated with the first module in the Model A’s battery pack
- ✓ At that point, BMS would most likely have been programmed by Tesla to --- at the very least --- send some sort of a ‘battery malfunction’ warning notice to car’s driver, which is apparently what happened according the car's owner. In addition, it is entirely possible if not highly probable that car’s system was programmed to immediately send pertinent telemetry data to Tesla’s vehicle operations center. It is also conceivable that Tesla routinely collects data from all of its cars in ~real-time, just as Boeing does on its customers’ fleets of 787 Dreamliners

Is Tesla's theory consistent with runaway event timeline?

Posits substantial ~instantaneous mechanical damage to battery module

Impalement would have instantly destroyed at least four 18650 battery cells

Close-up image: module in 60 kWh Model S pack shows dense battery packing

- ✓ **Panasonic batteries are packed in dense vertical arrays within each Tesla Model A battery pack module**
- ✓ **Three-inch diameter metallic object piercing into such a module perpendicularly would damage it heavily; very likely, at least four 18650 cells would be totally destroyed along with wiring**
- ✓ **If 'bullet' piece of "armor plate" were shot obliquely deeper into array, damage level could be far worse**

Panasonic NCR18650A 3100mAh $LiNiCoAlO_2$ 18650 battery cells

Standard size: dia. 18.6 mm; length 65.2 mm

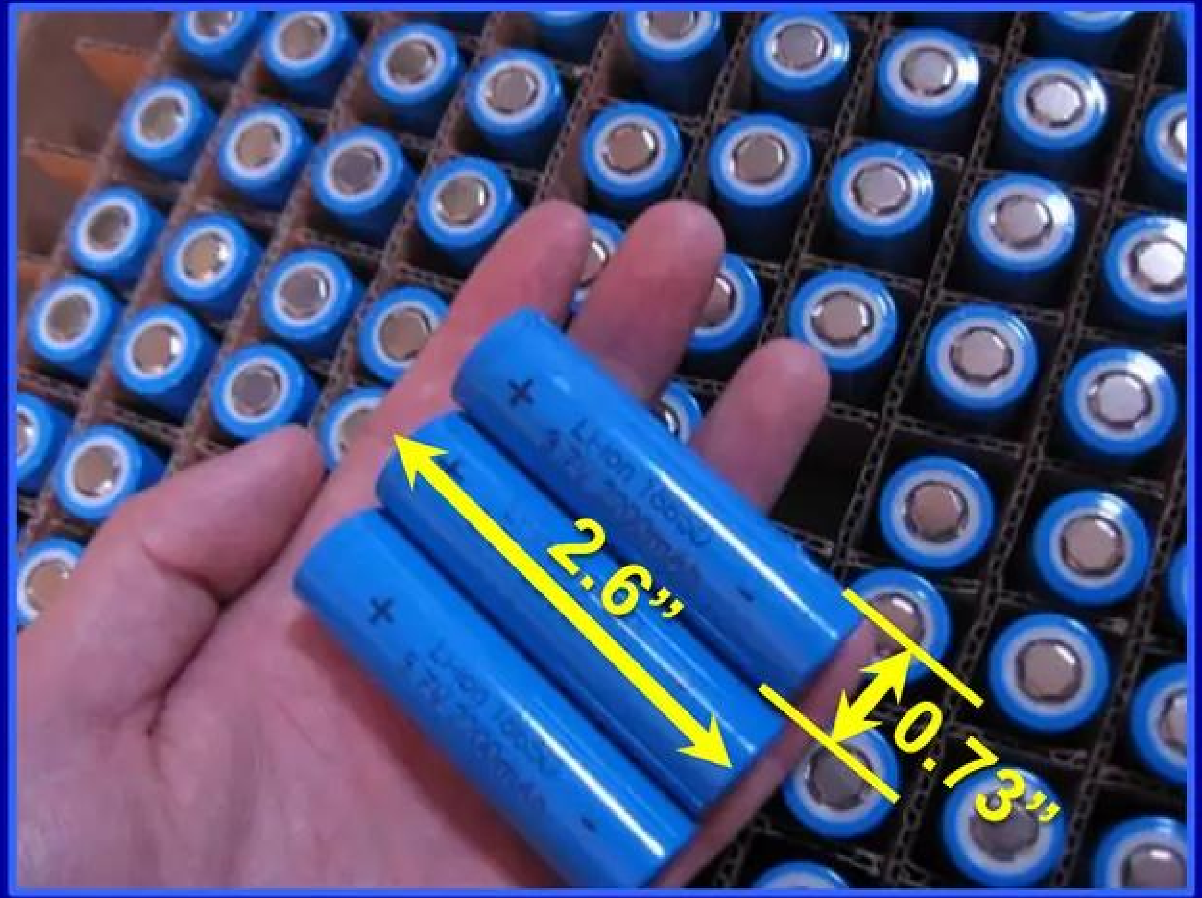


Image source: Panasonic

Batteries oriented vertically in Tesla module

Image source: NHTSA

Is Tesla's theory consistent with runaway event timeline?

Posits substantial ~instantaneous mechanical damage to battery cells

Is there a well-known battery safety test analogous to Tesla's impalement?

Yes – it is called the "nail penetration test" in the battery business

- ✓ **In test, metallic nail is driven into a battery casing at some angle to the long axis of a cylindrical battery case ("can") enclosing the anode/separator/cathode "jellyroll"**
- ✓ **Parameters that can be varied include: composition of nail; diameter of nail; rate of penetration into case; rate of withdrawal from case (in some experiments, nail is not withdrawn); depth of penetration into case; angle of penetration; tip shape and taper thereon; etc. Bottom line is that anodes and cathodes inside 18650 jellyroll short-out**
- ✓ **Certain battery chemistries are more prone to react violently during a nail test; even in problematic chemistries, behavior can be very erratic: sometimes little happens**
- ✓ **While battery cell always 'killed' by this test, subsequent effects of nail penetration can be quite variable. Outcomes can range from simple cessation of operation all the way up to electric arc discharge shorts and thermal runaway events; sometimes accompanied by explosions (TIAX says not uncommon within 200 ms of penetration)**
- ✓ **Will explore this analogy by reviewing what happens in 18650 nail and crush tests**

Lattice Energy LLC

Is Tesla's theory consistent with runaway event timeline?

Nail penetration tests on 18650 Lithium-based batteries

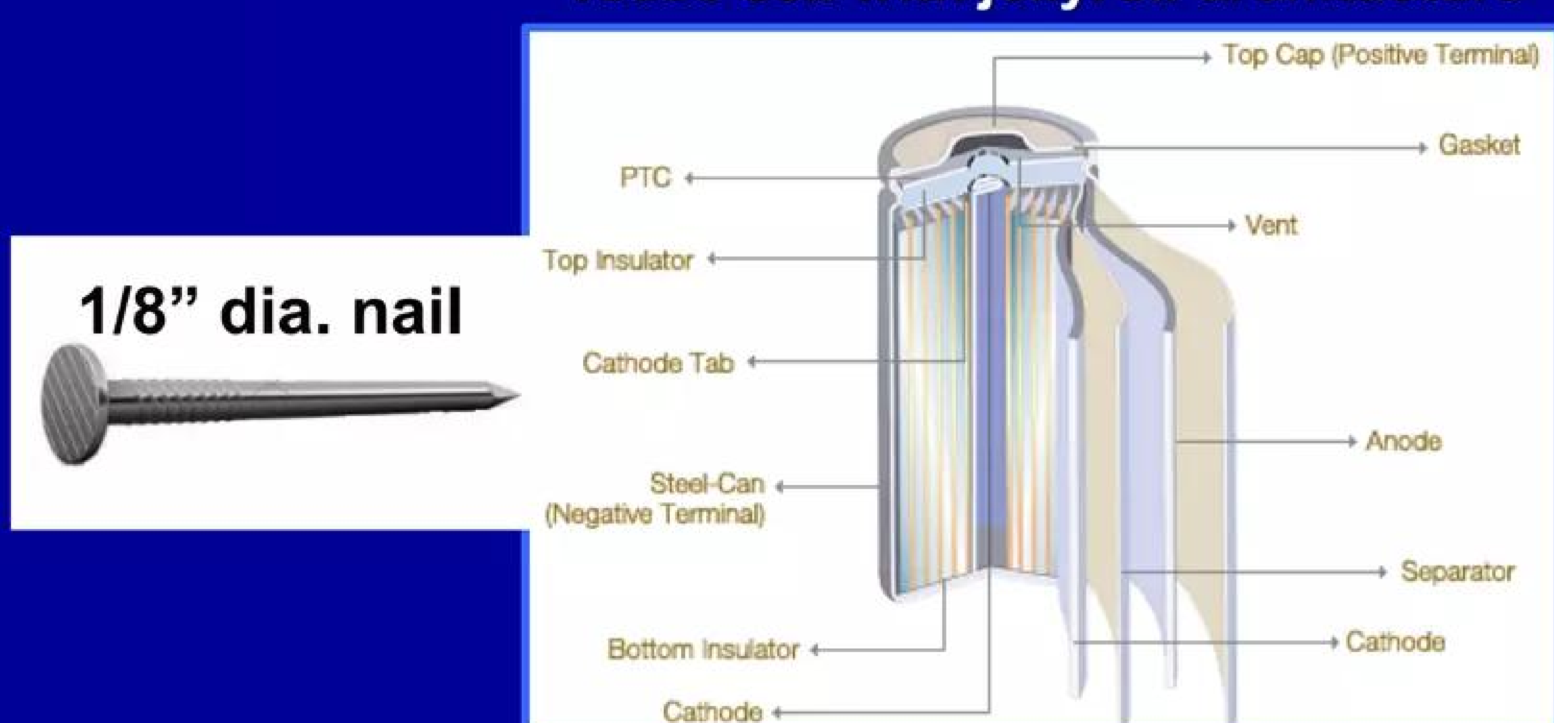
Tesla’s impalement theory is akin to single-cell nail penetration test on steroids

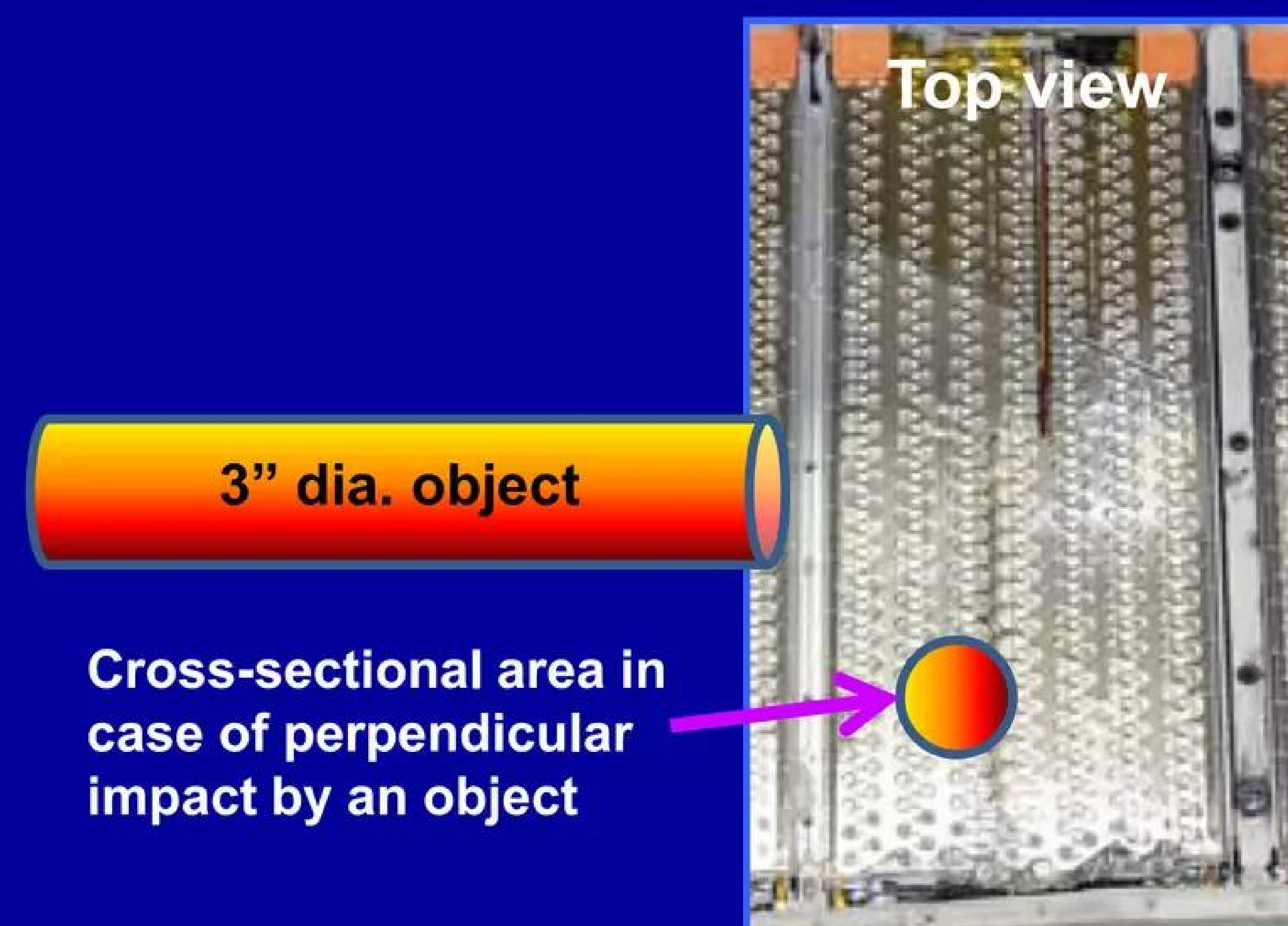
Situation physically analogous but on a much larger length-scale and more complex

Single 18650 cell impaled by metal nail

Single Tesla module (great many cells) impaled by “large metallic object”

18650 cell with jellyroll architecture





Crucial differences: in impalement of Model S module by “large metallic object” at least four 18650 cells would be shorted-out and mechanically destroyed along with their current-carrying wiring; in addition, active coolant channels used by other battery cells could be disrupted; also, effectiveness of passive intumescent materials could be reduced by mechanical displacement

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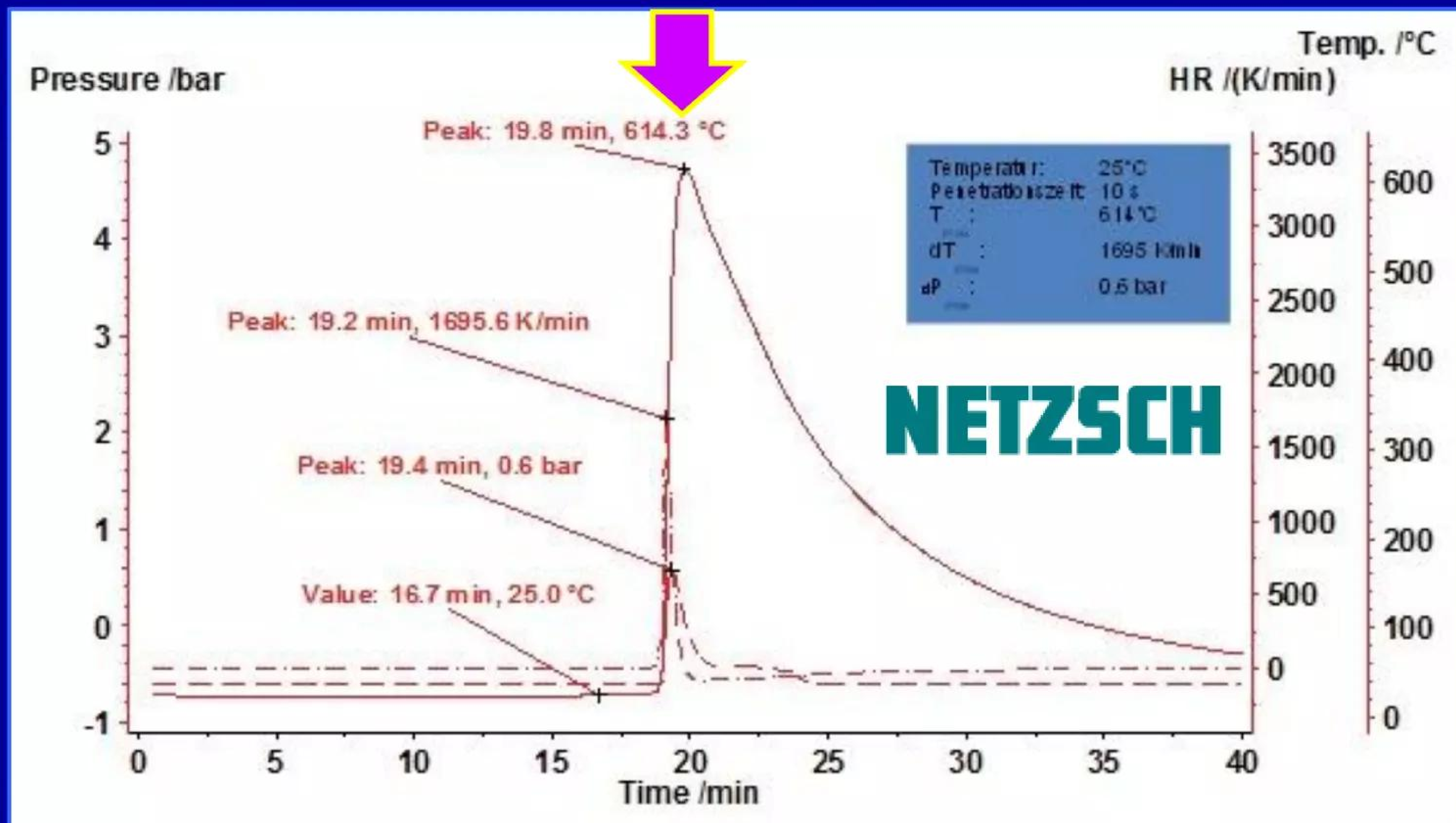
Is Tesla's theory consistent with runaway event timeline?

Nail penetration test on 18650 Lithium-based batteries

Battery cell temperature jumps upward by ~600° C after being pierced by nail

Nail penetration test on commercial 18650 Lithium-based battery cell in NETZSCH ARC 254

Quoting: **“Figure 3 shows the set of measurement results for a charged 18650 cell at room temperature. The cell was kept at a constant temperature within the calorimeter over a period of 18 minutes. The metal perforator penetrated the battery cell for a period of ten seconds and was then re-withdrawn from the battery. The electrical short circuit caused the temperature during the reaction to reach a maximum value of 614°C at a heating rate of roughly 1,700 K/min.”**



Source (downloads 3-page pdf Netzch “Application Note” - see Fig.3 on page 3): http://tinyurl.com/qzeq8w8

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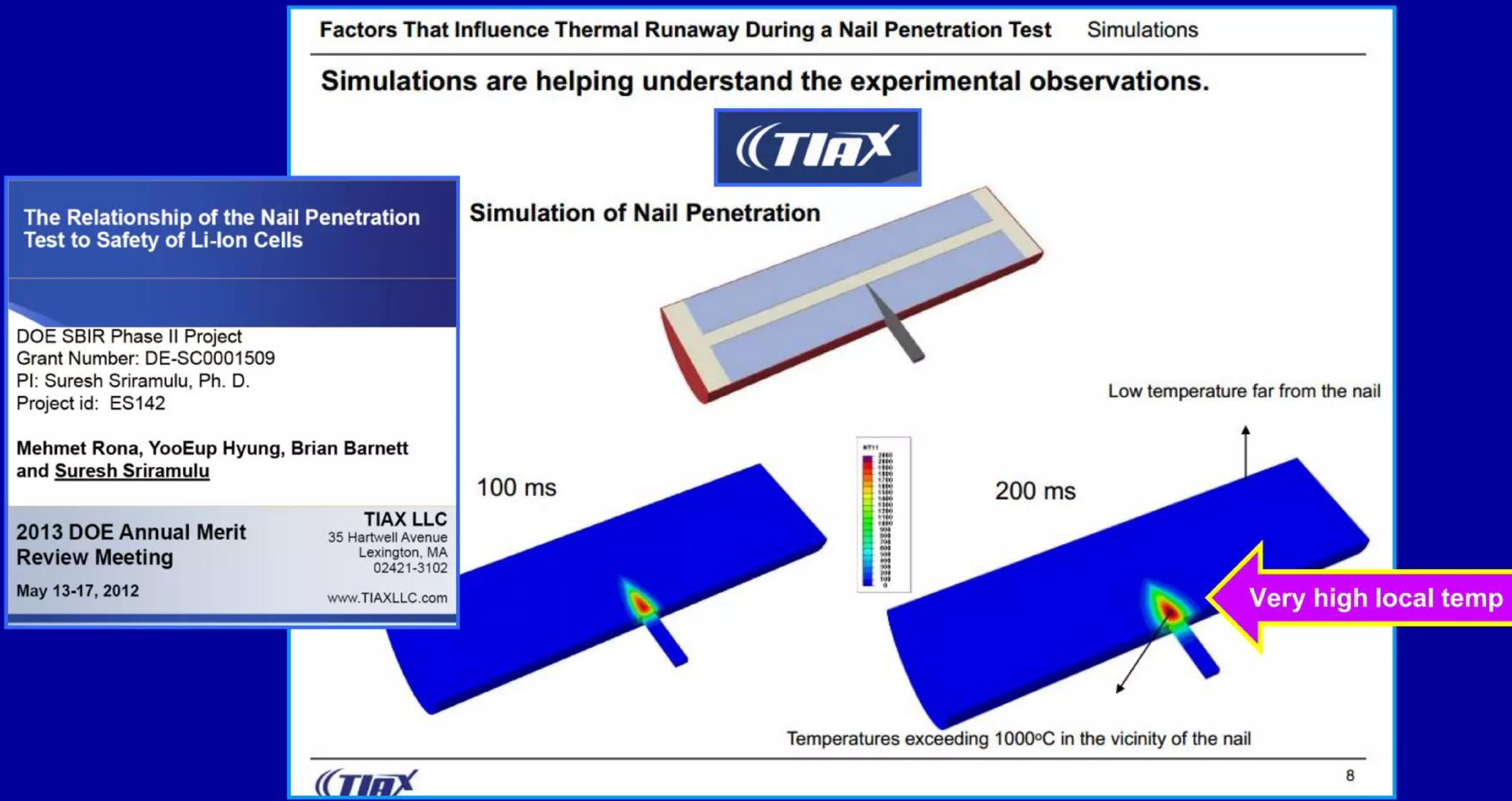
Is Tesla's theory consistent with runaway event timeline?

Nail penetration process on 18650 Lithium-based batteries

TIAX LLC simulations: temperatures >1,000° C near nail in ~200 milliseconds



Source: http://www4.eere.energy.gov/vehiclesandfuels/resources/merit-review/sites/default/files/es142_sriramulu_2013_p.pdf

Is Tesla's theory consistent with runaway event timeline?

Nail penetration tests on 18650 Lithium-based batteries

TIAX LLC conclusion: if runaway occurs, happens within 200 - 500 milliseconds

- Thermal runaway associated with nail penetration takes place within about 200-500 ms. The process by which a cell progresses to thermal runaway due to an internal short, as occurs in the field, involves very different physical processes.
- The nail penetration test is not a useful test for the type of internal shorts that develop over time in the field.
- Nail penetration tests produce variable results, are easily gamed and do not reflect the failure method by which internal shorts result in thermal runaway.
- Nail penetration tests best represent what happens when a nail penetrates a cell under narrowly defined conditions, (but nothing about propensity for thermal runaway events in the field via grown-in internal shorts).

Source: http://www4.eere.energy.gov/vehiclesandfuels/resources/merit-review/sites/default/files/es142_sriramulu_2013_p.pdf

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Is Tesla's theory consistent with runaway event timeline?

Crush tests: Lithium-based 18650 batteries with different chemistries

"Large metallic object" would also cause crushing of cells in Tesla module

Crushing triggered thermal runaway in Oxide 18650 cell; Phosphate reacted little

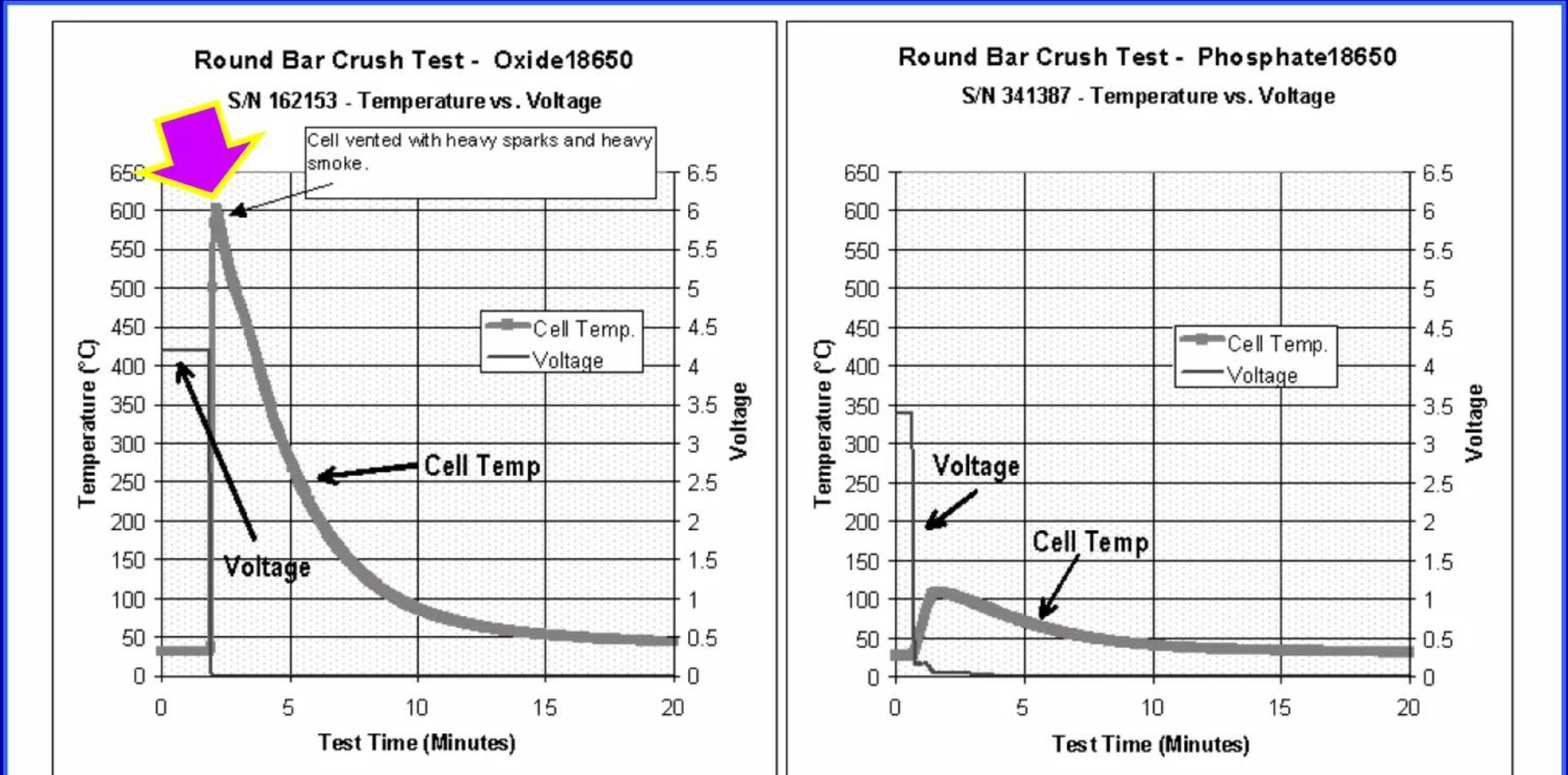

Figure 2. Round Bar Crush Test Results

Source: http://www.battcon.com/PapersFinal2004/NguyenPaper2004.pdf

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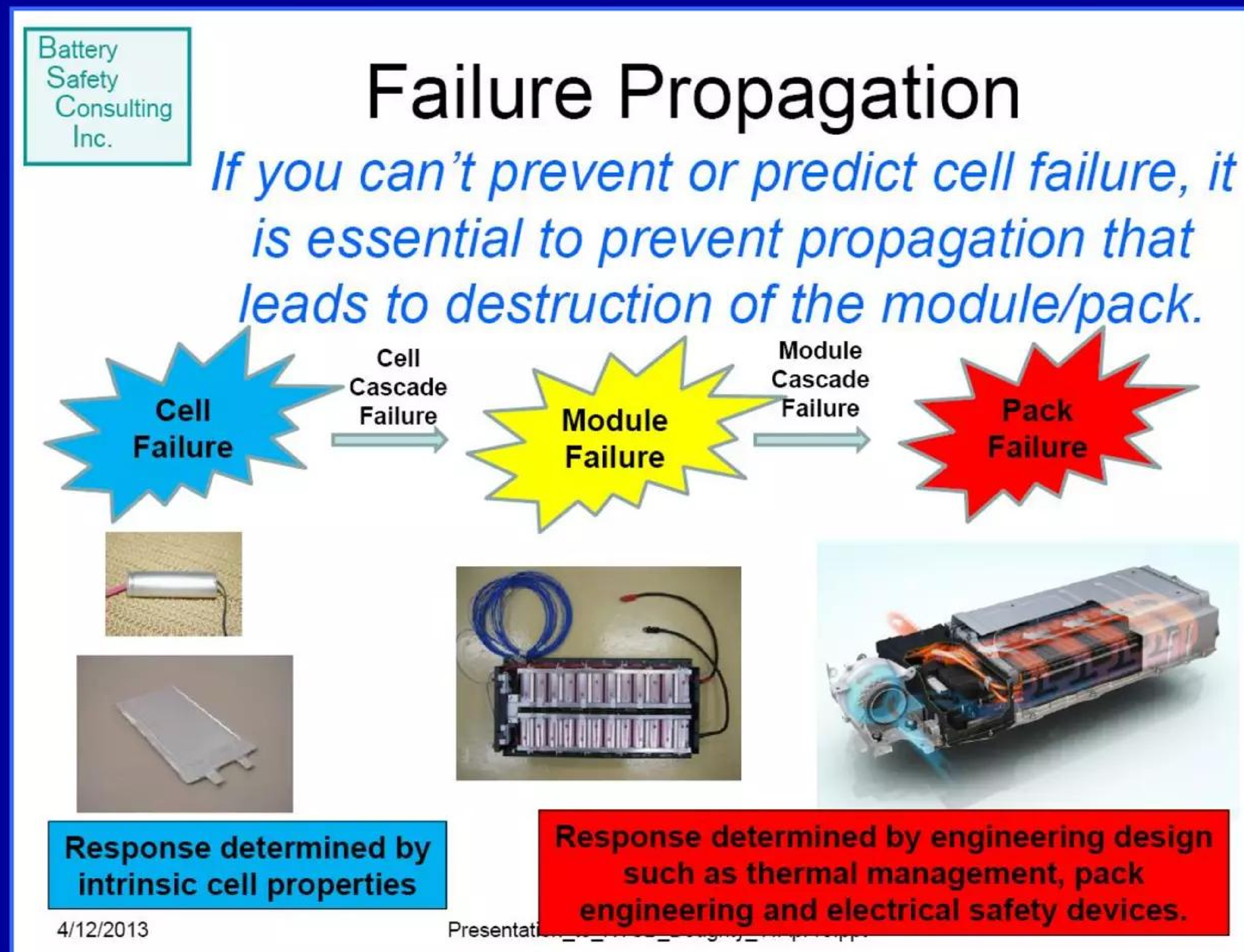
Is Tesla's theory consistent with runaway event timeline?

In October 1, 2013 runaway event Tesla experienced a module failure

At 2013 NTSB battery forum, D. Doughty of Battery Safety Consulting, Inc. said:

"Failure mechanisms of Li-ion batteries"

Dr. Daniel Doughty
Battery Safety Consulting, Inc.
April 11, 2013
NTSB Battery Forum
12 MS-PowerPoint slides



Source: http://www.ntsb.gov/news/events/2013/batteryforum/presentations/Doughty%20Sandia%20Presentation%20-%20Battery%20Forum.pdf

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Is Tesla's theory consistent with runaway event timeline?

Applicable insights from penetration/crush tests on 18650 battery cells

When a thermal runaway occurs it is often within few seconds of impalement

3” dia. metal ‘nail’ piercing a Tesla module would likely trigger an instant runaway

- ✓ According to Tesla’s theory, in hypothesized freak-accident scenario a “large metal object” impaled first, front-edge module of a Model S’ battery pack; to do so, it pierced 0.25” “armor plate” protecting the battery pack with a force of 25 tons, causing massive internal damage inside the impaled module (note: as explained earlier herein, its force was likely >>25 tons if protective plate was really armor)

- ✓ Under this scenario, Tesla posits massive, near-instantaneous catastrophic mechanical damage to the front-edge module in the battery pack; they implicitly assume this damage caused a “perfect storm” of factors that in the end overwhelmed four key elements of Tesla’s very sophisticated thermal runaway defense system (1. tight BMS control over voltage and temperature of individual battery cells within a safe operating range; 2. active cooling of individual cells; 3. passive intumescent materials that create additional ‘pop-up’ thermal isolation barriers between cells if overheating occurs; 4. ability to quickly electrically isolate either individual troublesome or failing cells/modules, or even entire battery pack)

- ✓ Key point: experimental data on 18650 nail penetration and crush tests shows that if violent thermal runaways occur in such situations, they frequently start within less than a second or two. That clearly was not the case in October 1 incident: driver first “thought he hit something,” received battery trouble warning from vehicle, smelled burning smell/smoke, and still had enough time to drive to next highway exit, go down a 0.2 mile exit ramp, pull to side of road and then safely exit the vehicle before 6’ flames engulfed the front-end --- all of this took > 2 - 3 minutes. This surprisingly long event timeline is not very consistent with 18650 piercing data or with massive instant damage implied in Tesla’s theory

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Is Tesla's theory consistent with runaway event timeline?

Applicable insights from penetration/crush tests on 18650 battery cells

If Tesla's theory is inconsistent with timeline then what scenario may fit better?

Timeline is consistent with field-failure of one cell: Tesla systems slowed propagation

- ✓ Lattice's alternative theory for the October 1 model S runaway posits that: field-failure internal electrical short (whatever its proximate cause might truly be) occurred in a single 18650 cell that was located somewhere in first front module of vehicle's battery pack
- ✓ Field-failure-triggered event caused catastrophic overheating of the affected cell, creating huge local temperature increase within a few seconds. Note: field-failures are known to burn vastly hotter than "garden variety" thermal runaways and can generate their own Oxygen supply from battery materials - see Appendix 1 for more details about field-failures
- ✓ Small explosion could have occurred inside front battery module without breaching the armored pack; unsuspecting, very surprised driver (Mr. Robert Carlson) could have easily misinterpreted a 'whomph' he could have felt with his body as an indication that his vehicle had run over some sort of object lying on the road (while admittedly speculative, this idea is plausible in view of fact that existence of "large metallic object" has not been demonstrated)
- ✓ Propagation of field-failure-induced runaway condition into adjacent cells ("thermal fratricide") within the same battery pack module was slowed rather significantly by previously-noted 4 key features of Tesla's battery safety system ("controlled burn"). This lengthened runaway event timeline to observed longer total duration of > 2 - 3 minutes

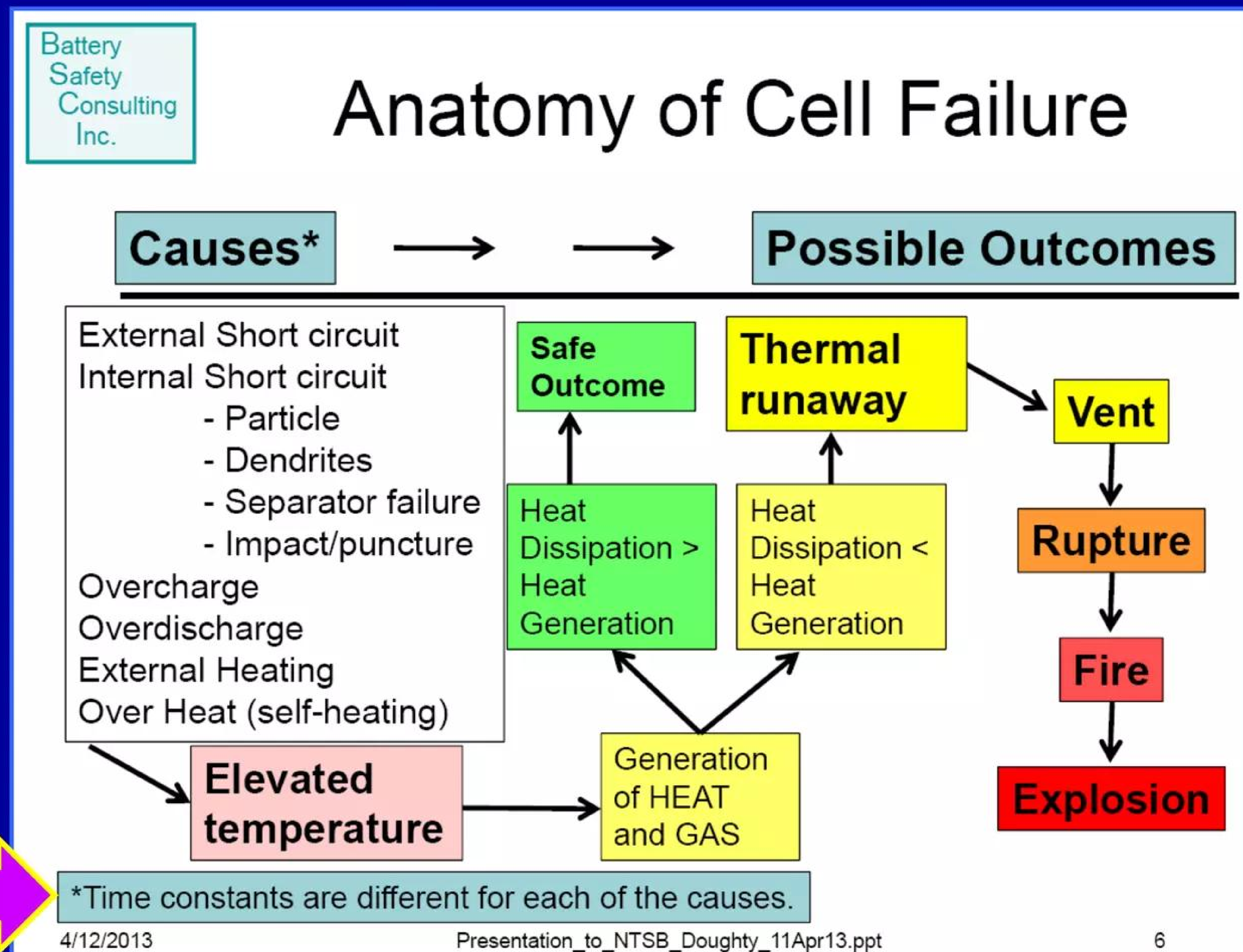
Is Tesla's theory consistent with runaway event timeline?

Field-failure in a single battery cell could have caused October 1 event

At a 2013 NTSB forum, Doughty presented an excellent conceptual summary:

"Failure mechanisms of Li-ion batteries"

Dr. Daniel Doughty
Battery Safety Consulting, Inc.
April 11, 2013
NTSB Battery Forum
12 MS-PowerPoint slides



Source: http://www.ntsb.gov/news/events/2013/batteryforum/presentations/Doughty%20Sandia%20Presentation%20-%20Battery%20Forum.pdf

Is Tesla's theory consistent with runaway event timeline?

Are runaway timelines faster in systems without Tesla's safety features?

Battery thermal runaway incident with a Boeing Dreamliner at Logan Airport

GS-Yuasa didn't have sophisticated safety features - thus a faster event timeline

- ✓ For details and additional information about Boeing 787 Dreamliner's GS-Yuasa battery runaway incident at Logan airport earlier in 2013 that Lattice believes was most likely triggered by a field-failure event in a single battery cell, see following Lattice PowerPoint as follows:

  "NTSB reports indicate very high temperatures"
  Lewis Larsen, Lattice Energy LLC, May 7, 2013 [51 slides]
  http://www.slideshare.net/lewisglarsen/lattice-energy-llc-technical-discussionntsb-logan-dreamliner-runaway-data-suggest-high-local-tempsmay-7-2013

- ✓ Willard *et al*. just published a paper on battery reliability in view of GS-Yuasa battery runaway:

  "Lessons learned from the 787 Dreamliner issue on Lithium-ion battery reliability"
  N. Willard *et al*., *Energies* 6 pp. 4682 - 4695 (2013) free open access journal
  http://www.mdpi.com/1996-1073/6/9/4682

- ✓ See Logan Airport Dreamliner runaway event timeline on pp. 4688 in Willard *et al.*; from 10:21:04 - 08 A.M. (4-second period; anomalous events recorded in aft GS-Yuasa battery pack, e.g., spike occurred in APU battery current while voltage dropped from 31V to 30V); at 10:21:50 (46 seconds after first anomalous battery data) aircraft's cleaning crew smelled smoke in the aft cabin; at 10:23:10 (2 min. 6 sec. elapsed) the 787's APU automatically shut-down, indicating major problems with battery system; thus, within ~2 minutes 787's battery runaway was raging

Wrap-up

discussion

Wrap-up discussion

Numerous questions about runaway incident remain unanswered

- ✓ NHTSA was unable to conduct a timely, independent third-party investigation of incident because of U.S. government shutdown; will one finally occur soon after the government reopens?
- ✓ Owner and driver of runaway car, Robert Carlson, has yet to be directly interviewed by reporters; he has only released statements through Tesla. While Carlson disclosed that he is an investor in Tesla and understandably could be reluctant to make public statements that might harm the company's stock price, some clarification of certain points by Mr. Carlson would be helpful
- ✓ To date, there is still no evidence that WA DOT road crew was truly working in the area at time of the incident and that it recovered a hypothesized "large metallic object"; if Tesla does have this object in its possession, why hasn't more info about it been released?
- ✓ Did Tesla receive GPS and remote telemetry data about the battery system from vehicle during the incident? On Oct. 6, *Inside EVs* reported that Tesla had Carlson's Model S in its possession; was BMS data recovered from nonvolatile memory that survived fire?
- ✓ Exactly how many battery modules burned during fiery runaway? If flames shown in image were fueled by combusting electrolyte, many more than just a handful of battery cells were immolated

October 1, 2013 - Kent, WA USA
Scene just as firefighters arrived

Lattice comment:

If this mini-inferno is truly "controlled" then we are astounded.

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Wrap-up discussion

Final comments and Lattice's conclusion

Battery impaled by "large metallic object" less likely than field-failure in one cell

Tesla's safety features did not prevent runaway: bought extra time for driver to exit safely

- ✓ **One additional issue to note with Tesla's impalement theory --- quoting from Kent fire dept. incident report: "E71 then used a high lift jack to expose the undercarriage of the vehicle, in an attempt to completely extinguish the battery pack. E71 discovered that there was no access to the battery from the undercarriage. E71 then used a circular saw to cut an access hole into front structural member to apply water to the battery pack." Now please examine photo of Tesla Model S' remarkably smooth, low drag, hole-free undercarriage shown on Slide #15 herein**

- ✓ **Open question: If a highly visible, jagged 3" hole had truly been present somewhere in area of the front module of burned car's battery pack as Tesla's impalement theory posits, wouldn't Kent firefighters surely have noticed it in the undercarriage the moment they jacked-up the car? Firemen would have immediately used it as alternative access route to inject more water to further cool car's battery pack and totally extinguish a smoldering, episodically reigniting fire**

- ✓ **To date, there is no conclusive evidence beyond vague, unsupported assertions by various parties that the claimed "large metallic object" even exists, let alone was recovered by anyone for study and microscopic forensic SEM/EDX/SIMS analysis by independent third-party experts**

- ✓ **In absence of such unequivocal proof, Lattice concludes that Model S thermal runaway fire on October 1 was more likely caused by a field-failure event in single Panasonic 18650 battery cell**

Additional information for the more technically inclined

Additional information for the more technically inclined

Convergence of advanced batteries, energetic materials and LENRs :

"Large increases in battery energy densities drive convergence between energetic materials, LENRs and batteries"

L. Larsen, Lattice Energy LLC, September 6, 2013 [110 slides with detailed table of contents]

http://www.slideshare.net/lewisglarsen/lattice-energy-llc-increased-energy-densities-drive-convergence-of-batteries-and-lenrssept-6-2013

Document concerns great difficulties in containing and extinguishing thermal runaways:

"Systems to contain Lithium-based battery thermal runaways and fires; is it a feasible engineering goal or just a fool's paradise?"
L. Larsen, Lattice Energy LLC, August 6, 2013 [93 slides – includes detailed table of contents]

http://www.slideshare.net/lewisglarsen/lattice-energy-llc-containment-of-lithiumbased-battery-firesa-fools-paradiseaug-6-2013

Index to large collection of documents re LENR theory, experimental data, and the technology:

"Index to key concepts and documents" v. #15
L. Larsen, Lattice Energy LLC, May 28, 2013 [108 slides] Updated and revised through December 4, 2013

http://www.slideshare.net/lewisglarsen/lattice-energy-llc-index-to-documents-re-widomlarsen-theory-of-lenrsmay-28-2013

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Appendix 1

Runaways and field-failures

--- batteries behaving really badly

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Appendix 1

Runaways and field-failures --- batteries behaving really badly

At a 2013 NTSB forum, Doughty presented good summary of safety concerns:

"Failure mechanisms of Li-ion batteries"

Dr. Daniel Doughty
Battery Safety Consulting, Inc.
April 11, 2013
NTSB Battery Forum
12 MS-PowerPoint slides

Battery Safety Consulting Inc.

Summary: What are the Critical Safety Concerns?

- ***Energetic thermal runaway of active materials***
  - Exothermic materials decomposition, gas evolution, electrolyte combustion.
- ***Electrolyte degradation, gas generation & flammability***
  - Overpressure and cell venting is accompanied by an electrolyte spray which is highly flammable.
- ***Internal short circuit***
  - Internal short circuit may cause very rapid release of heat and gas.
    - Very low probability, but consequence can be high.
  - No screening tests or effective mitigation is available.
- ***Propagation***
  - Observed in field failures.
    - Laptop failures in 2006 included several explosions from a single laptop, separated by several minutes, until the entire battery pack was consumed.
  - Experimentally observed in test labs.
  - Propagation as been modeled* using Accelerating Rate Calorimetry (ARC) data as well as convective, conductive and radiative heat transfer.

4/12/2013 *Spotnitz, Doughty et al., Journal of Power Sources 163 (2007) 1080–1086. 12

Source: http://www.ntsb.gov/news/events/2013/batteryforum/presentations/Doughty%20Sandia%20Presentation%20-%20Battery%20Forum.pdf

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Appendix 1

Runaways and field-failures --- batteries behaving really badly

At a 2013 NTSB forum, Doughty summarized his thinking on runaway triggers:

"Failure mechanisms of Li-ion batteries"

Dr. Daniel Doughty
Battery Safety Consulting, Inc.
April 11, 2013
NTSB Battery Forum
12 MS-PowerPoint slides

Battery Safety Consulting Inc.

What Are The Triggers of Thermal Runaway and How Can They Be Managed?

Trigger	Why can this occur ?	Is this managed ?
External short circuit	Defective connections, foreign debris.	Yes, cell-level safety devices and pack safety fuses.
Overcharge	Defective connections, failure of charging circuit.	Yes, battery management system. Yes, cell-level safety devices.
Overheating from external sources	Battery pack placed too close to a heat source.	Yes, cell-level safety devices open the cell at suitable internal pressure.
Cell crushing creating massive internal shorts	Physical abuse of battery pack.	Yes, design enclosures are built more tolerant to abusive events.
Internal short-circuit	Internal-short caused by manufacturing defects.	No, new technologies needed.
Propagation of thermal runaway	Affected cell can raise the temperature of surrounding cells.	Yes, in a few cases, but new technologies needed.

4/12/2013 Presentation_to_NTSB_Doughty_11Apr13.ppt 9

Source: http://www.ntsb.gov/news/events/2013/batteryforum/presentations/Doughty%20Sandia%20Presentation%20-%20Battery%20Forum.pdf

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Appendix 1

Runaways and field-failures --- batteries behaving really badly

At a 2013 NTSB forum, Doughty presented an excellent conceptual summary:

"Failure mechanisms of Li-ion batteries"

Dr. Daniel Doughty
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Battery Safety Consulting Inc.

Comparison of Failure Modes

- There are important differences between safety abuse testing, versus field failures (*generally attributed to internal short circuit*).

Abuse Tolerance	Field Failures
Predictable	Not predictable
Common to all cells	One-in-ten-million (or less)
Can/should be evaluated at the cell level	Difficult to evaluate at the cell level, or through QC
Various chemistries can/should be evaluated for relative abuse tolerance	Materials must be evaluated for relative kinetics, pressures
Time constants relatively long	Much higher temperatures can occur *quickly*
Can be augmented by protection devices	PTC, CID, shutdown separators, electronic controls are not effective

2/4/2013 Battery_Safety_Doughty_2013.ppt 5

Source: http://www.ntsb.gov/news/events/2013/batteryforum/presentations/Doughty%20Sandia%20Presentation%20-%20Battery%20Forum.pdf

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Appendix 1

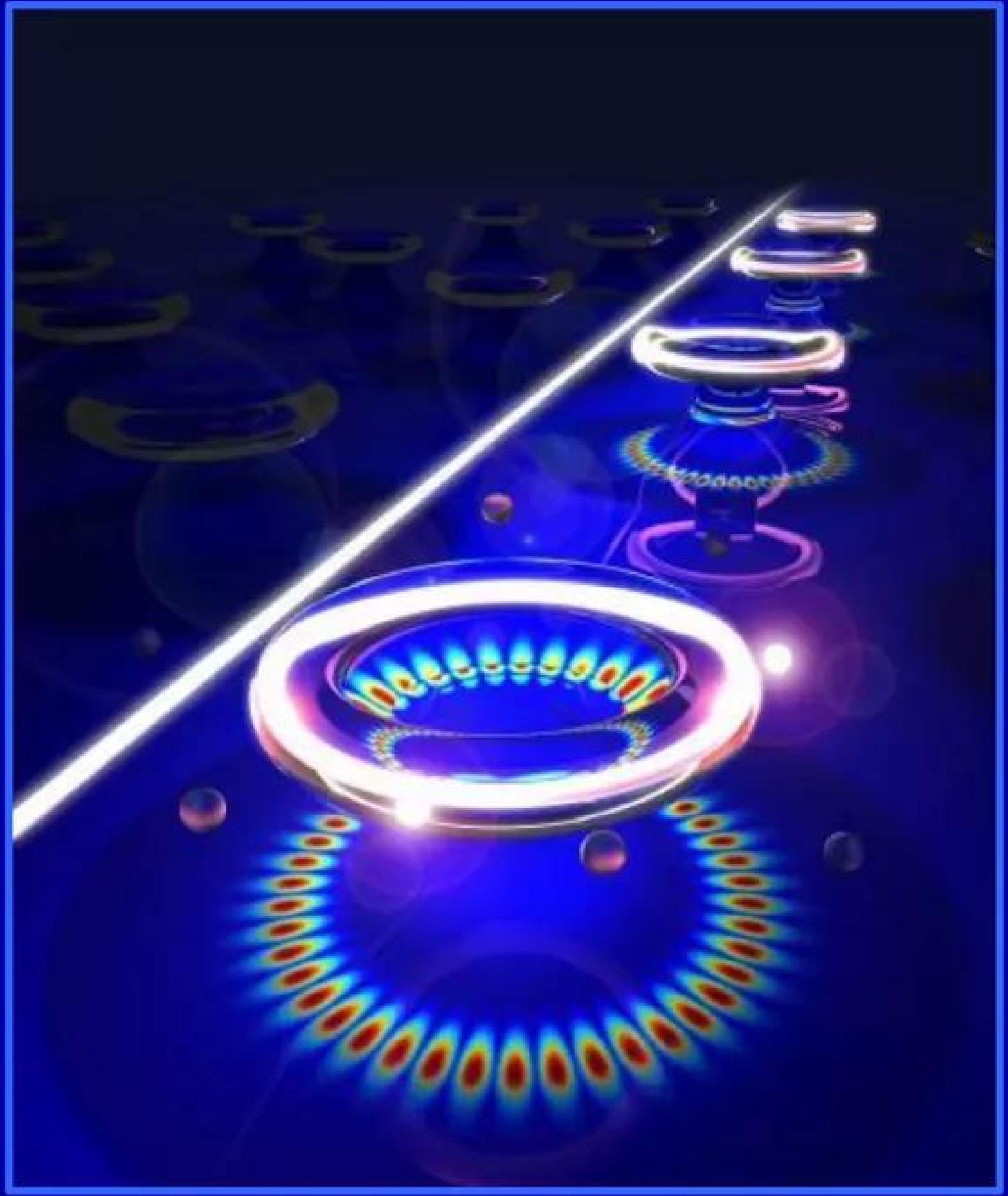
Runaways and field-failures --- batteries behaving really badly

No Lithium-based battery chemistry is 100% immune to runaway risks

- ✓ Market success of lithium-based batteries and large increases in cell energy densities have encouraged battery technologists familiar with relatively small-scale applications to scale-up into physically larger lithium-based cells and huge arrays of cells that can address vastly larger electrical energy storage requirements of stationary back-up power systems and mobile platforms, e.g., hybrid and all-electric plug-in vehicles, as well as new aircraft such as the Boeing Dreamliner. Unfortunately, this scale-up has led to unforeseen safety issues that were either simply not readily apparent to anyone or irrelevant risk factors in smaller-scale system applications

- ✓ There is really no such thing as a real-world Lithium battery chemistry that is 100% immune to danger of thermal runaways and/or catastrophic field-failures. From risk management perspective, various lithium chemistries only differ in their relative probabilities; some are more or less problem-prone than others

High-Q microresonators on a silicon wafer - class of devices called whispering-gallery-mode resonators



Credit: Image by Jiangang Zhu and Jingyang Gan/WUSTL

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Appendix 1

Runaways and field-failures --- batteries behaving really badly

Birth of a thermal runaway event

- ✓ Typically well-controlled electrochemical reactions in batteries ordinarily generate a certain amount of unavoidable process heat which is then dissipated harmlessly simply by emitting invisible infra-red radiation from the battery case out into the local environment; during normal operation, contents of battery cells still remain well-within proscribed boundaries of designed range of optimal thermochemical operating temperatures

- ✓ On rare occasions, for a variety of different reasons, a battery cell's electrochemical reactions can suddenly start running at greatly elevated rates that create more process heat than a battery's normal thermal dissipative mechanisms can easily handle, which then starts raising the temperature of battery cell contents out beyond their ideal safe operating range; threshold for out-of-control danger has not yet been crossed

At key point --- call it the Rubicon River for a failing battery cell --- a very dangerous positive (+) feedback loop is created: whereby, increasing cell temperatures further accelerate electrochemical reactions in cells which produces even more heat, boosting local cell temperatures even higher, etc.

Thermal runaways are thus born: only question is how bad they get before destroying enough of a battery to stop + feedback-accelerated reactions

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Appendix 1

Runaways and field-failures --- batteries behaving really badly

Field-failures are statistically rare but very fast and damaging when they occur

By any reasonable standard, lithium-based batteries are a pretty safe technology: garden variety thermal runaways only occur at frequencies of one such event per several millions of battery cells

The very worst, least understood type of thermal runaway, which goes under innocuous-sounding sobriquet of "field-failure," occurs at a rate of one such event per ~ 4 - 5 million lithium-based battery cells right off the production line and regardless of their chemistry or primary vs. secondary, according to statistics collected by a major Japanese manufacturer of lithium-ion consumer batteries

There's one more issue: although it's hard to quantitatively specify, probability of thermal runaways seems to increase significantly as batteries age and go thru a great many charge-discharge cycles

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Runaways and field-failures --- batteries behaving really badly

"Garden variety" thermal runaways:

- Temps: ~300° C up to 600° C (Lattice's criteria)
- Reasonably well understood failure events
- Triggered by substantial over-charging or excessively deep discharges of Li batteries
- Triggered by external mechanical damage to battery cells, e.g., crushing, punctures; growth of internal Li dendrites can mechanically pierce plastic separators

Field-failure thermal runaways also typically include electric arc shorting:

- Temps: > 600° C - can go up to thousands of ° C with electric arcs
- Much rarer and comparatively poorly understood
- Many believe triggered and/or accompanied by electrical arc discharges (internal shorts); what causes initial micro-arcs?
- Much higher peak temperatures vs. garden variety events
- Lattice suggests: super-hot low energy nuclear reactions (LENRs) could well be initial triggers for some % of them

Appendix 1

Runaways and field-failures --- batteries behaving really badly

Thermal runaways can have greatly varying degrees of severity

Garden variety single-cell thermal runaways can be as little as a battery that just heats-up a bit and simply stops functioning … or a battery's case can bulge significantly from internally generated heat without designed venting and releasing of contents from the inside before it stops functioning and then starts cooling down on its own

A slightly worse variant of a garden variety thermal runaway results in just a single cell venting or rupturing, but (in cases of flammable electrolytes) there are no hot, flaming battery contents spewed-out that could potentially ignite local combustibles and adjacent cells

In worst-case garden variety runaway, hot flaming electrolyte erupts from a ruptured battery cell, which may ignite nearby materials and cells; in this event variant (that is still not the worst-of-the-worst), internal peak temperatures usually not yet hot-enough to melt metals

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Appendix 1

Runaways and field-failures --- batteries behaving really badly

Field-failures are truly catastrophic events in chemical batteries

Battery industry definition of a field-failure thermal runaway event:

Safety concerns have been heightened by highly publicized safety incidents and ensuing widespread recalls of lithium-ion batteries used in laptop computers and cell phones [14, 15]. When these rare safety incidents occur, lithium-ion batteries operating under otherwise normal conditions undergo what appear to be spontaneous thermal runaway events, often with violent flaming and extremely high temperatures. Moreover, these failures usually involve cells and cell designs that have passed extensive abuse testing, including the standardized abuse safety tests. *Most such Li-ion safety incidents in the field are not preceded by any obvious external abuse*. We refer to these spontaneous safety incidents as "field-failures".

Source: "Batteries for Sustainability – Selected Entries from the Encyclopedia of Sustainability in Science and Technology," Ralph J. Brodd, Ed., Chapter 9 by B. Barnett et al., "Lithium-ion Batteries, Safety" Springer ISBN 978-1-4614-5791-6 (2012)

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Appendix 1

Runaways and field-failures --- batteries behaving really badly

Absolute worst-case Armageddon runaways involve burning metals

Field-failure category of thermal runaways can reach extremely high peak temperatures of thousands of degrees Centigrade along with big electric arcs

Such temperatures are hot-enough to melt metallic structures inside batteries and combust almost anything and everything located within a battery case

If initiating spark is hot-enough, battery materials containing chemically bound oxygen will release it as O_2; by creating its own oxygen supply, combustion process becomes self-sustaining, self-propagating flame front that consumes all burnable battery materials. Progressive thermal fratricide between cells can reduce batteries to unrecognizable debris; such fires could burn in a vacuum

In absolutely worst-case events, even METALS can start burning in very fast, thermite-like reactions that can boost temps up to ~ 4,000° C; this is nightmare scenario wherein even deadly explosions with shrapnel can potentially occur

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Appendix 1

Runaways and field-failures --- batteries behaving really badly

Leave domain of stable electrochemistry when batteries heat-up enough

“Burn ‘em all --- let God sort ‘em out.” [1.]

“You can run, but you can’t hide.” [2.]

LENRs are themselves energetic materials; can create many other energetic materials

- ✓ **Batteries cannot withstand star-like local temperatures created by electric arc discharges or LENRS and remain stable; LENR-based power systems can be designed to handle this, e.g. dusty plasmas**
- ✓ **Creation of nightmarish local “witches’ brew” cauldrons of inter-reacting compounds and ions in some regions of failing batteries; very fast, hyper-accelerated reaction rates in superheated zones**
- ✓ **Witches’ cauldrons can generate their own supplies of Oxygen to support combustion processes that propagate spatially within and between battery cells via fast-moving, autocatalytic flame-fronts coupled with intense emission of thermal infrared and UV radiation**
- ✓ **Arc- and/or LENR-heated regions’ behavior is almost more akin to chemistry of stellar atmospheres than everyday electrochemistry**

Adapted from a U.S. military motto:

Popularized by U.S. special operations forces during the 1960s Vietnam war

1.. Underlying motto unofficially adopted by various military groups; originally, was modernized from Latin, "Caedite eos. Novit enim Dominus qui sunt eius" which literally translated means “Kill them all. God will recognize His own." Quote attributed to Arnaud, Abbot of Citeaux, in reply to question asking how one might tell Cathar heretics from orthodox Catholics during siege of Beziers in Albigensian Crusade (July, 1209)

2. Threat made to Mad Max by a murderous character named “Wez” in Mel Gibson‘s cult-classic film, “The Road Warrior” (1981)

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Final quotation

"I cannot help fearing that men may reach a point where they look on every new theory as a danger, every innovation as a toilsome trouble, every social advance as a first step toward revolution, and that they may absolutely refuse to move at all."[1.]

"In a revolution, as in a novel, the most difficult part to invent is the end."[2.]

Alexis de Tocqueville (1840)

1. *Democracy in America* Volume II Book Three, Chapter XXI – "While great revolutions will become more rare" (1840)
http://www.gutenberg.org/files/816/816-h/816-h.htm
http://www.gutenberg.org/files/816/816-h/816-h.htm#link2HCH0062

2. "The Recollections of Alexis de Tocqueville", Alexis de Tocqueville, pp. 71 Macmillan (1896)