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Tesla Motors Model S vs. the Nissan Leaf

Why has Leaf had fewer thermal runaways vs. Model S?

Answer potentially found in the frequency of battery field-failure events

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Tesla Model S

Price ~ US$ 62,000 up to 106,000

Nissan Leaf

Price ~ US$ 21,000 up to 27,000

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Tesla Motors Model S vs. the Nissan Leaf

Key take-aways

- ✓ Many have wondered why the Tesla Model S has experienced three catastrophic battery thermal runaway fires to date whereas the Nissan Leaf has apparently not experienced any such runaway incidents, at least so far
- ✓ Answer to this question can potentially be found with simple calculations that utilize manufacturers' estimated frequencies of battery field-failure events
- ✓ By employing a limited number of key simplifying basic assumptions and manufacturers' statistical data on estimated rates of field-failures, we can predict that the Nissan Leaf would be likely to experience a substantially lower frequency of major thermal runaway fire events compared to the Tesla Model S, which is exactly what has been observed so far to date
- ✓ Predicted number of observed macro-scale thermal runaway events appears to be accurate to within roughly one order of magnitude, i.e., a factor of ~10
- ✓ This level of accuracy suggests that thermal runaway events to date have likely been caused by internal field failures (whatever the trigger) rather than by mechanical damage via violent piercing of battery packs by metal objects

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Calculation predicts observed # of runaways within a factor of ~10

Predicted # of single-cell field-failures is an upper-bound estimate of runaways

Key simplifying basic assumptions:

1. Specific details of Lithium-based battery cell chemistry are irrelevant to single-cell field-failure frequency
2. Electrical capacity of battery pack is irrelevant to single-cell field-failure frequency
3. Likelihood per vehicle is directly and linearly proportional to total # of cells found in a given battery pack
4. Not all single-cell field-failures invariably result in catastrophic macroscopic thermal runaways (explained herein), so it represents an upper-bound estimate; observed module- or pack-level events will thus be lower #
5. Estimated frequency of single-cell field-failure ranges from 1 in every 10 million cells (Manufacturer #1 data = 0.0000001) up to as much as 1 in every 4.5 million cells (Manufacturer #2 = data 0.000000222)

Vehicle	Battery Chemistry	Battery pack electrical storage capacity (kWh)	Total number of discrete cells in each battery pack	Total number of vehicles sold to date	Predicted number of single-cell field-failure events to date	Observed total # of catastrophic macro-scale module/pack-level thermal runaways to date
Tesla Model S	$LiNiCoAlO_2$	60 or 85	~7,000	~21,000	32.6 - 14.7	3
Nissan Leaf	$LiMnO_2$	24	192	~90,000	3.8 - 1.7	0

Calculation for predicted number of cell field-failures to date =
(probability frequency) x (# of battery cells per vehicle) x (total # of vehicles sold to date)

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Understanding thermal runaway events

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

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

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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Understanding thermal runaway events

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

Triggering a thermal runaway is a relatively rare event but very troublesome

- ✓ 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 boundaries of design 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 not yet 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 triggered: only question is how bad they ultimately get before destroying enough of a battery to stop positive feedback-accelerated reactions

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

- ✓ By any reasonable standard, Lithium-based batteries are a relatively safe technology: garden variety thermal runaways only occur at frequencies of one such 'milder' event per several million battery cells
- ✓ Very worst, least understood type of thermal runaway, which goes under innocuous-sounding sobriquet of "field-failure" occurs at estimated rates that range from as little as one such event per 10 million Lithium-based battery cells up to as much as one event per every 4 to 5 million cells
- ✓ This estimated field-failure frequency rate applies to new, fresh batteries right off production lines and regardless of their chemistry or primary vs. secondary, according to long-term statistical data collected by two major Japanese manufacturers of Lithium-ion consumer batteries
- ✓ There's one more issue: although very difficult to specify quantitatively, probability of thermal runaways seems to increase significantly as batteries age and go thru a great many charge-discharge cycles

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"Garden variety" thermal runaways:

- Temps: ~300^o C up to 600^o C (Lattice's criteria)
- Reasonably well understood failure events
- Triggered by substantial over-charging or excessively deep discharges of Lithium-based 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^o C - can go up to thousands of ^{o} C with electric arcs
- Much rarer and comparatively poorly understood
- Many presently 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 (for details see other Lattice documents)

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Internal electric arc shorts and LENRs can mutually facilitate each other

- ✓ Please note that as little as a single blazing hot LENR-active site measuring only 30 microns in diameter --- if it happens to occur in vulnerable physical location deep inside a battery cell and adjacent to the surface of a plastic separator only 25 microns thick --- can effectively vaporize a tiny local region of the separator, almost instantly turning it into a dense, micron-sized ball of highly conductive plasma. This would in turn create an electrical short between anode and cathode at that location, triggering a large inrush of electrical arc current through the breach in the separator dam. Intense local Joule heating would ensue from the arc current, further enlarging the breach and spatially expanding the superheated region inside a given battery cell. Depending on many complex, event-specific details, such a conflagration may or may not grow to engulf an entire cell; thus rare LENR events do not inevitably cause catastrophic heat runaways

- ✓ Under just the right conditions, a single microscopic LENR site can trigger a chain of energetic electrical (Joule heating) and chemical (exothermic reactions) processes that together create spatially autocatalytic, very macroscopic thermal runaway events that destroy battery cells billions of times larger than volumes of LENR site(s). In course of such runaways, 99.9^{+}% of total energy released is non-nuclear; hot spark LENRs are just an effective triggering mechanism. Also note that internal electrical shorts - whatever their cause - can also trigger runaways

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

Other field-failure triggers include random vibrations and sharp impacts

- ✓ Random mechanical vibrations can readily influence and actually move various types of electrically conductive nanostructures found inside advanced batteries ---- if two charged nanostructures randomly vibrate a little too close to each other, dielectric breakdown and electric arcing (i.e., shorts) can potentially occur between them. Similarly for sharp, violent external impacts to battery cases or large multi-cell packs; penetration into the interior spaces of batteries by conductive objects is not required to trigger single-cell field-failures

- ✓ Above mechanical vibration triggering mechanism does appear to explain how and why the Toxco Lithium-ion battery recycling plant's storage facility in Vancouver, Canada, caught fire and blew-up in November 2009. This huge conflagration occurred even though large shrink-wrapped pallets of 'used' scrap Li-ion batteries were stored in buried underground bunkers at a temperature of 324 degrees below zero Fahrenheit (when all chemical activity should essentially be non-existent). Unfortunately, vibration-induced electromagnetic activity is much less affected by ambient temperature and consequently ... boom

- ✓ Lastly, from a thermal runaway fire risk standpoint, even non-rechargeable primary, one-time use Lithium-manganese batteries can still experience catastrophic thermal runaways just like their closely-related rechargeable versions. The only difference is that the probability of thermal runaway events per unit of time is significantly lower in primaries as compared rechargeable batteries with the same chemistry, all other things being equal; Honeywell transponder fire in a Boeing 787 parked at Heathrow Airport may be an example

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Thermal runaways can exhibit greatly varying degrees of physical damage

- ✓ **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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Field-failures can be truly catastrophic thermal events in chemical battery cells

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)

Understanding thermal runaway events

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

Absolute worst-case Armageddon runaways involve super hot 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^{o} C; this is nightmare scenario wherein even deadly explosions with shrapnel can potentially occur

Additional information for the more technically inclined

Technical analysis of Tesla Model S battery thermal runaway incident in Kent, WA:

"Tesla Motors Model S battery thermal runaway on Oct 1: maybe caused by field-failure instead of impalement by object"

L. Larsen, Lattice Energy LLC, October 16, 2013 [82 slides with detailed table of contents]

http://www.slideshare.net/lewisglarsen/lattice-energy-llc-technical-discussionoct-1-tesla-motors-model-s-battery-thermal-runawayoctober-16-2013

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. #14
L. Larsen, Lattice Energy LLC, May 28, 2013 [88 slides] Updated and revised through September 12, 2013

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

