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NTSB reports indicate very high temperatures

Data suggests that extremely high temperatures likely occurred at local hotspots which were created by electric arcs that erupted inside certain GS Yuasa battery cells during Boeing 787 Dreamliner thermal runaway incident at Logan airport

Implications of "witches' brew cauldrons" in superheated regions of cells

NTSB Report No. 13-013
Scanning electron microscope (SEM) image

Presence of perfect stainless steel microspheres in battery debris suggests that local temperatures were > 3,000° C

Technical Discussion

Lewis Larsen

President and CEO
Lattice Energy LLC
May 7, 2013

"Facts do not cease to exist because they are ignored."

Aldous Huxley in "Proper Studies" 1927

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NTSB Report No. 13-013
Scanning electron microscope (SEM) image

Perfect stainless steel microspheres are created by condensation of droplets from a vapor phase; similarities to laser ablation

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Summary

Creation of stainless steel microspheres implies local hotspots > 3,000^{o} C

- ✓ **When NTSB scientists investigated charred debris found inside the ruined Logan GS Yuasa battery cells with a scanning electron microscope (SEM), near locations where electric arcs (internal short circuits) had obviously occurred they discovered notable numbers of *perfect (microscopic) stainless steel microspheres* lying amongst the disorganized rubble of various battery materials**

- ✓ **What most technical people following the NTSB's investigation may not have fully appreciated was that these beautiful little metallic microspheres are 'smoking gun' evidence for vaporization and condensation of stainless steel comprising the battery cell casing in local hotspots created by high-current, low voltage electric arcs, i.e., one or more internal shorts likely occurred inside GS Yuasa battery cell #5**

- ✓ **This experimental data implies that the local temperature of the battery casing's Type 304 stainless steel hotspots directly exposed to the internal short's arc plasma didn't just get to the melting point of such steel (~1,482 degrees C) --- instead these local areas *got all the way up to the boiling point of stainless* (> 3,000 degrees Centigrade), were turned into a gaseous vapor (expanding in volume by >50,000 x in the process of vaporizing); solid steel then recondensed from hot metallic vapor in the form of perfect nanoscale steel spheres as portions of the super-hot metallic Fe-alloy vapor quench-cooled. We will now discuss the NTSB's important factual data.**

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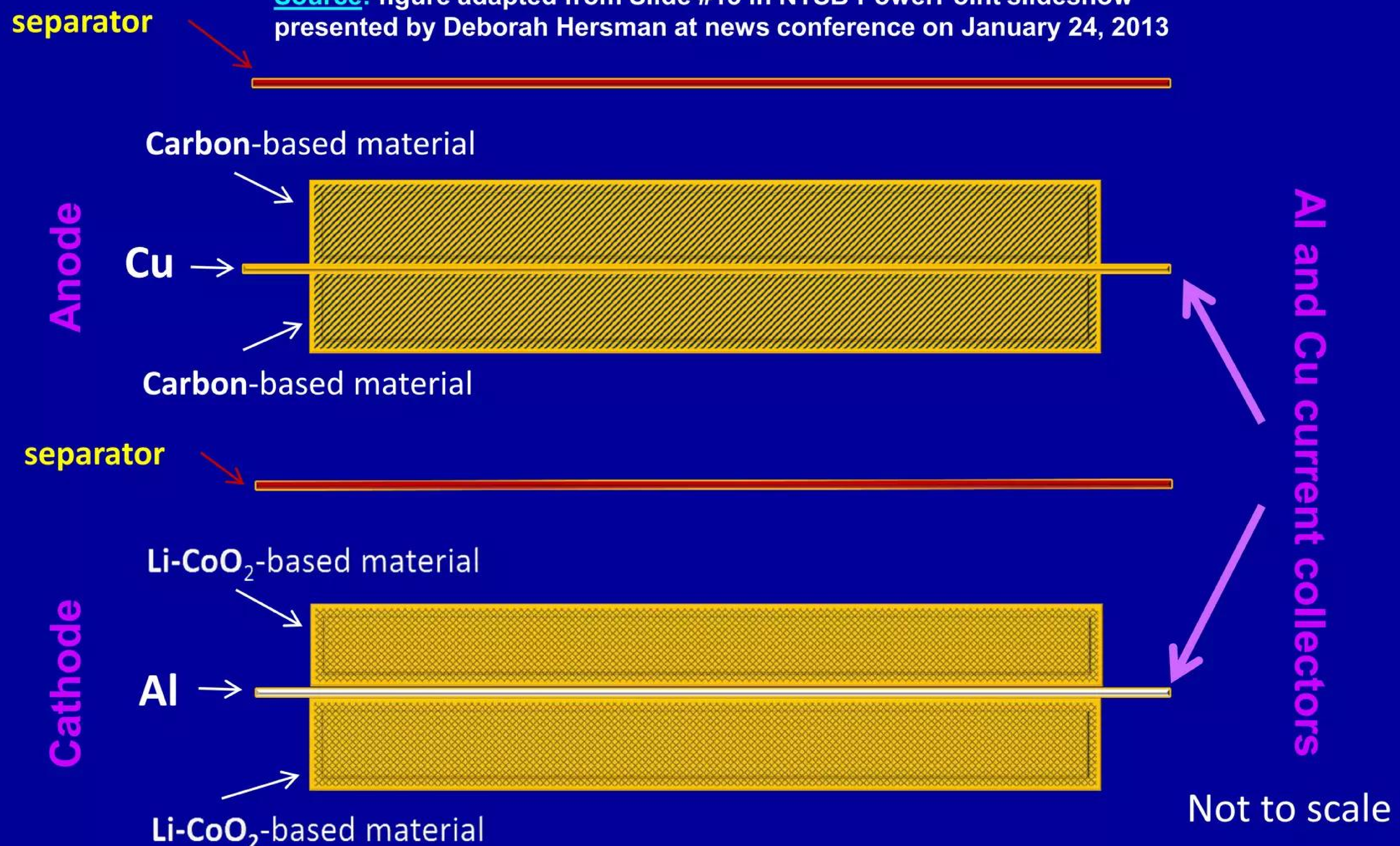
Dreamliner GS Yuasa battery: electrode construction

Source: figure adapted from Slide #13 in NTSB PowerPoint slideshow presented by Deborah Hersman at news conference on January 24, 2013



Copy of source document: http://www.ntsb.gov/investigations/2013/boeing_787/JAL_B-787_1-24-13.pdfs

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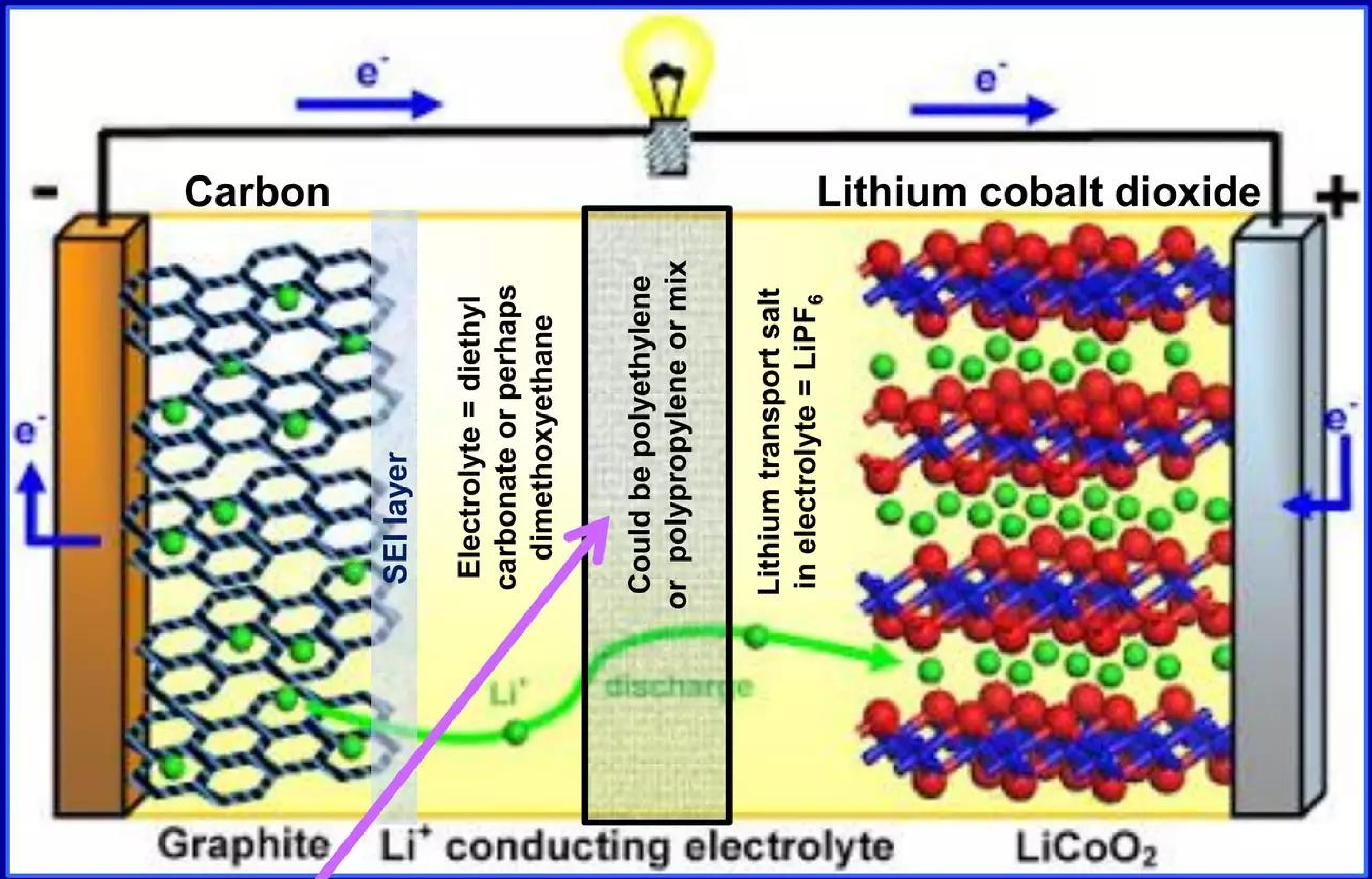
Dreamliner GS Yuasa battery: conceptual schematic

Separators: polyethylene (M.P. ~125^o C) or polypropylene (M.P. ~155^o C)

Anode



Cathode

Separator: microporous insulating plastic film that allows Li+ ions to freely migrate through it, but still prevents anode and cathode from coming into direct physical contact with each other and shorting-out via *hot* electric arcs; plastic film is only 25 μm thick

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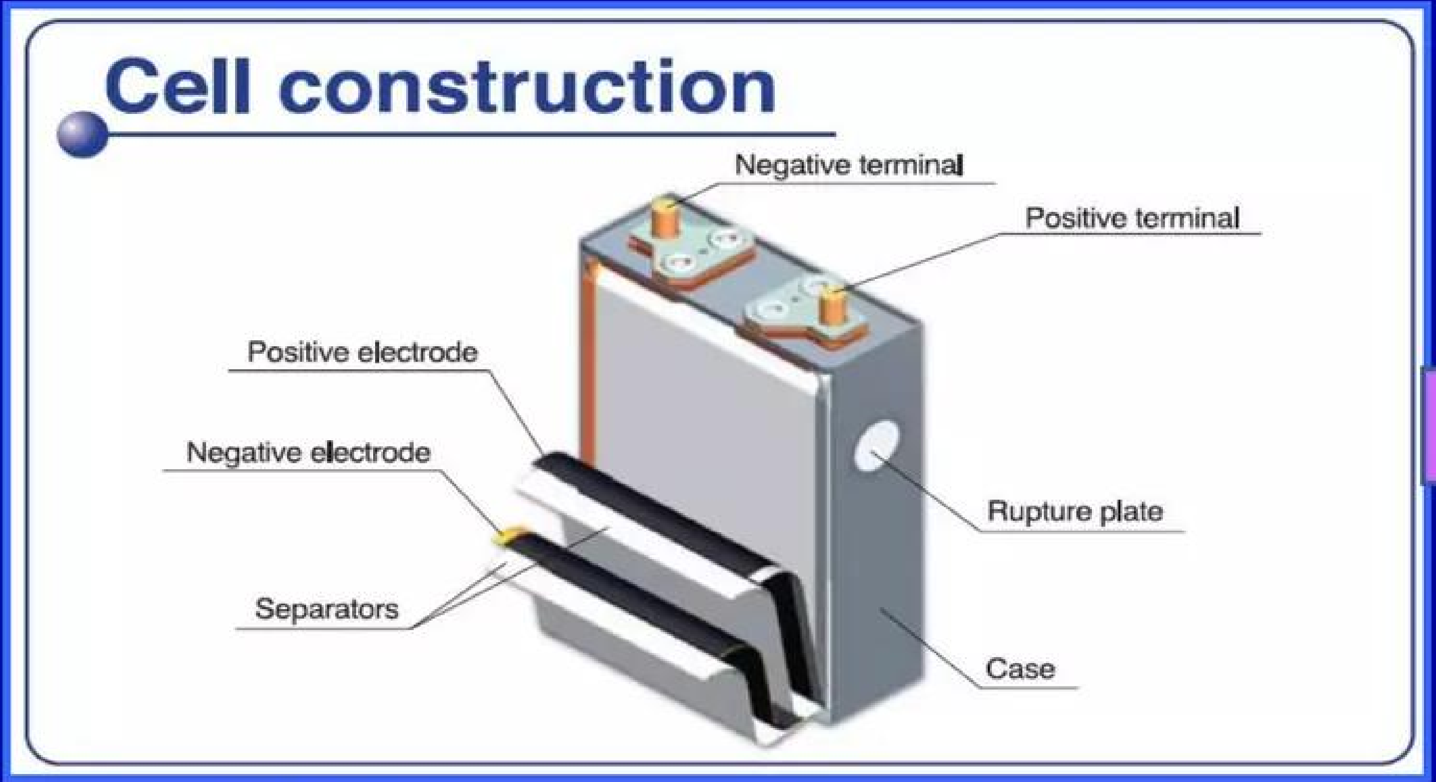
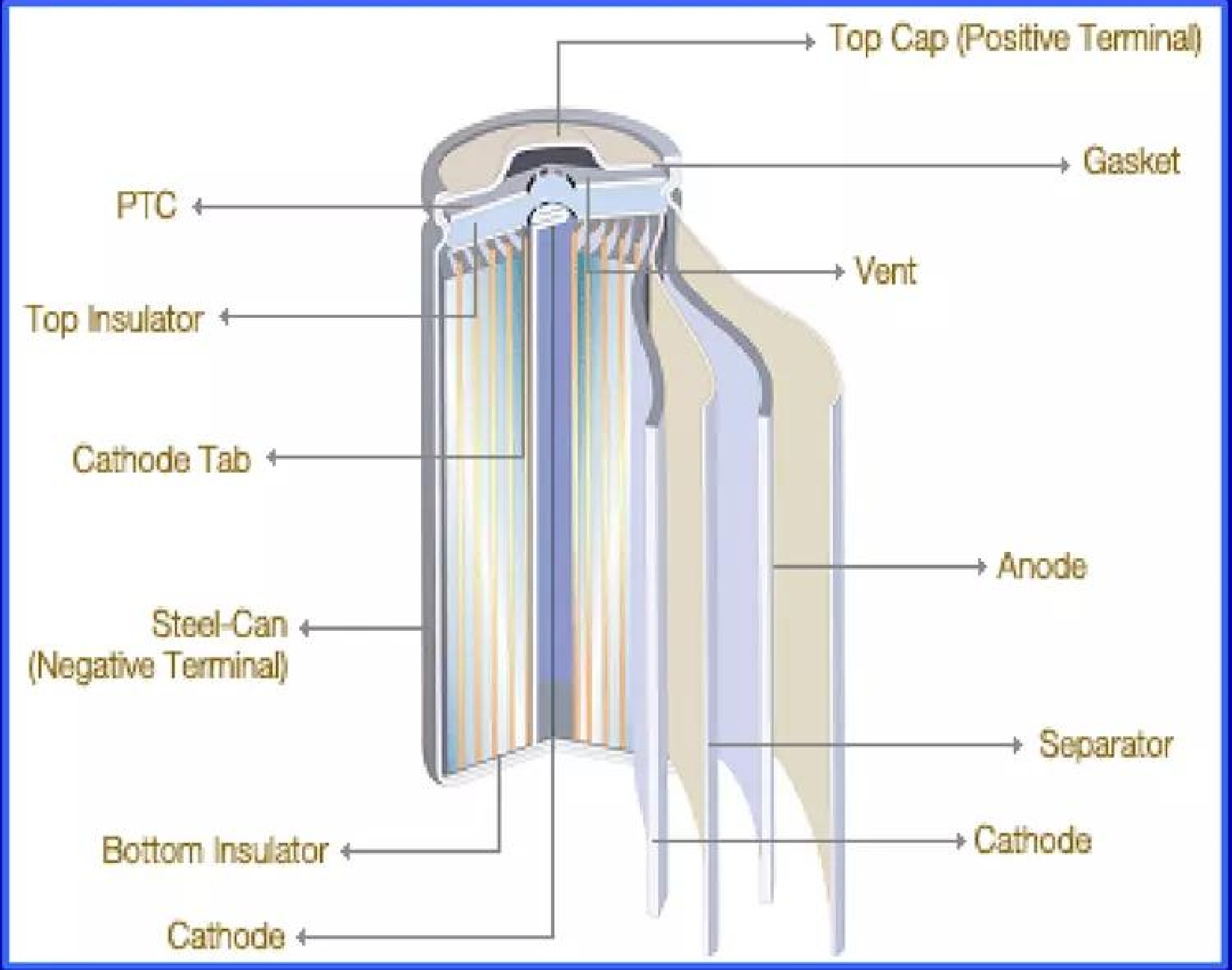
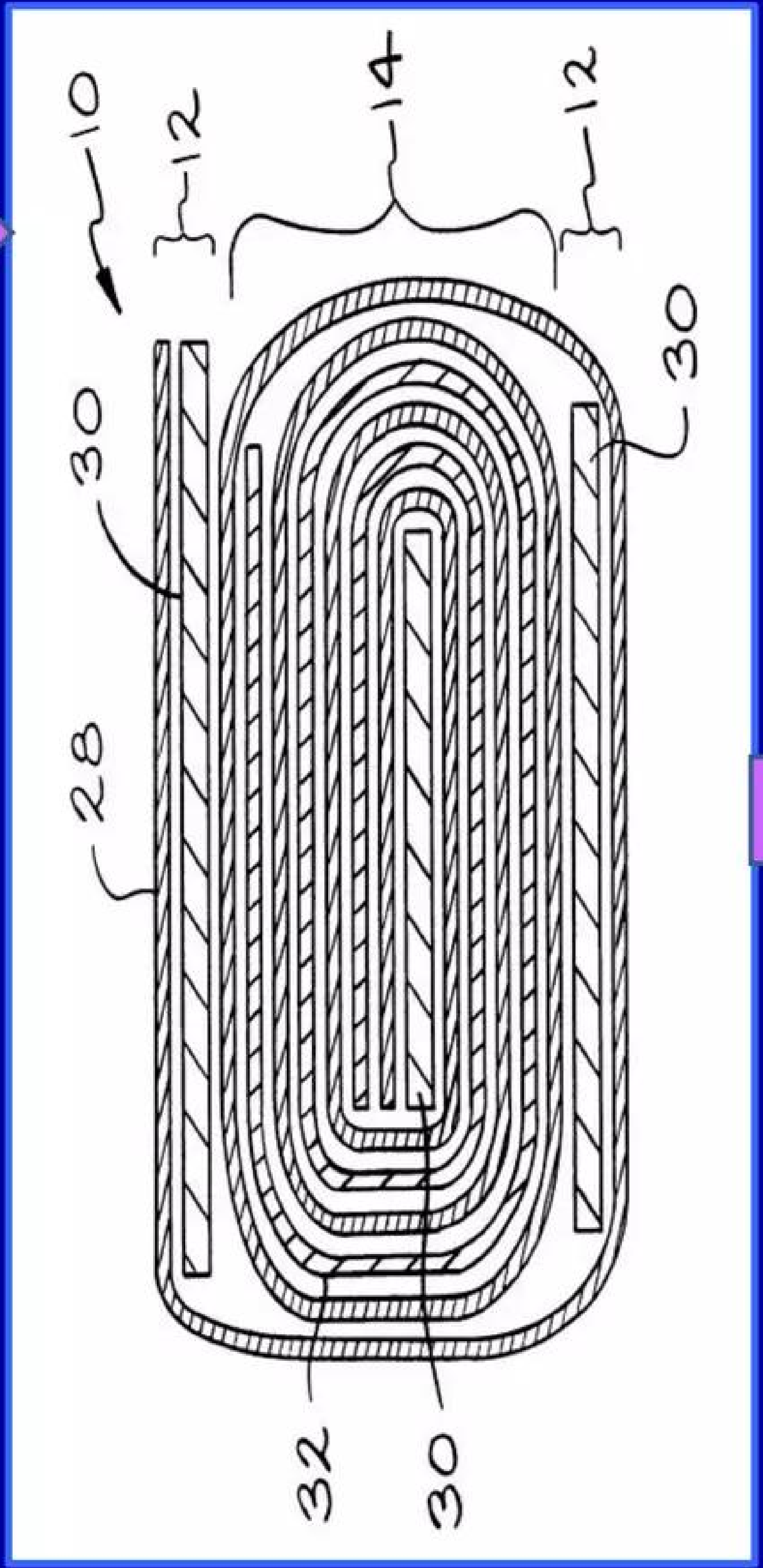
Internal physical organization of GS Yuasa battery cell



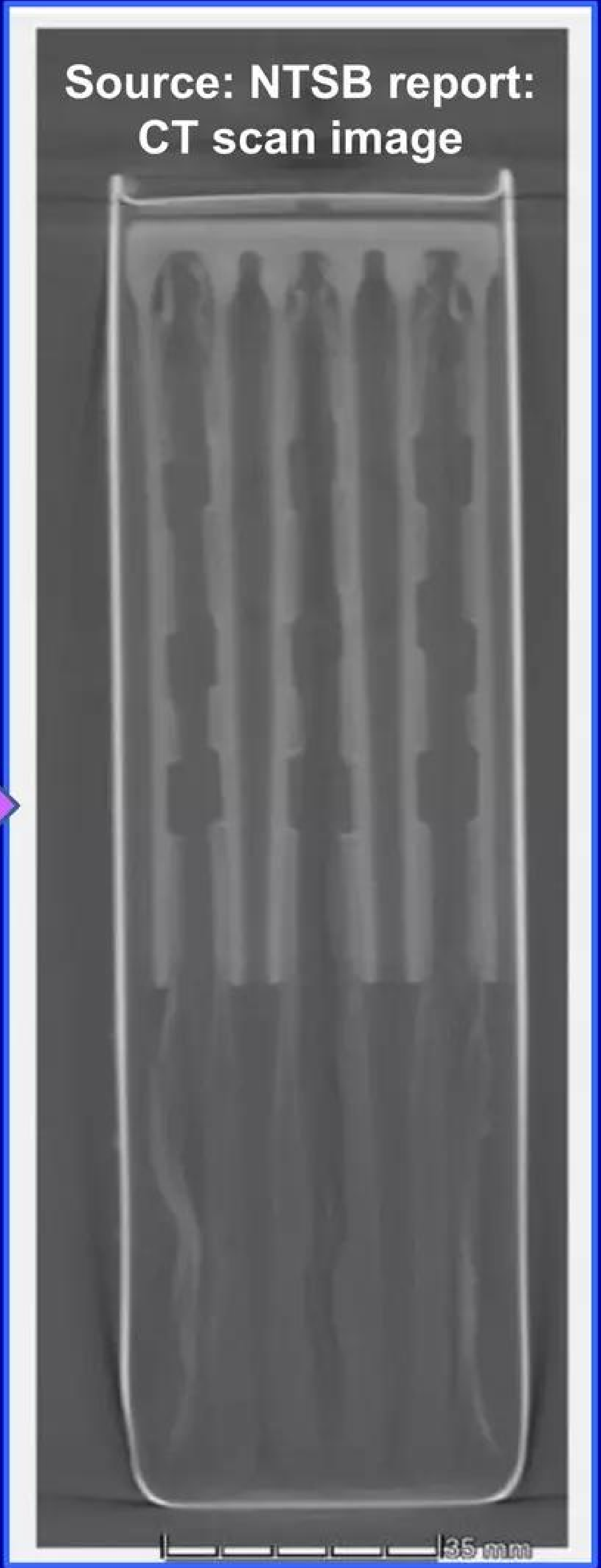
Source: GS Yuasa - prismatic cell *a la* 787 Dreamliner battery



Source: SONY "jelly roll" cell - commodity Lithium-ion battery



Source: USPTO – sample patent drawing for prismatic battery cell



Source: NTSB #13-013 February 19, 2013

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Hole punched through internal electrode by electric arc

Hole

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Excerpt from NTSB report

Source: page #18 in NTSB – Materials laboratory factual report No. 13-013 dated February 19, 2013

during cooling. There were a variety of spherical particles found embedded in the combustion compounds in hole 1 (see Figure 66). The composition of the spheres was consistent with the cell case material (stainless steel). Spherical particles on or near resolidified areas is consistent with the melting, separation, and solidification processes typical of electric arc damage. For reference, the temperatures that would be required to melt aluminum alloys are in excess of 1250° F, while those required to completely melt this stainless steel alloy are typically in excess of 2700° F.

Examination of the three other holes on the C5 cell case revealed similar results. Figure 67 and Figure 68 display holes 2 and 3, respectively, from the interior of the case. Of note was the spherical globule located near hole 3 on the exterior of the case. The globule was consistent with type 304 stainless steel, and it exhibited a reticulated surface pattern. The case material was wrinkled near hole 3. There were also indications of metallization "splats" of aluminum alloy near the hole (Figure 69). The flattened shape of this metallization is consistent with the case material being near the molten aluminum temperature during deposition. Near hole 4, a depressed lamellar structure was observed in the case material (Figure 70). This surface morphology is consistent with incipient melting of the material, which occurs at temperatures high enough to cause some of the alloy constituents to liquefy.[8]

Copy of source document: http://www.ntsb.gov/investigations/2013/boeing_787/docket_documents/787_docket_doc2.pdf

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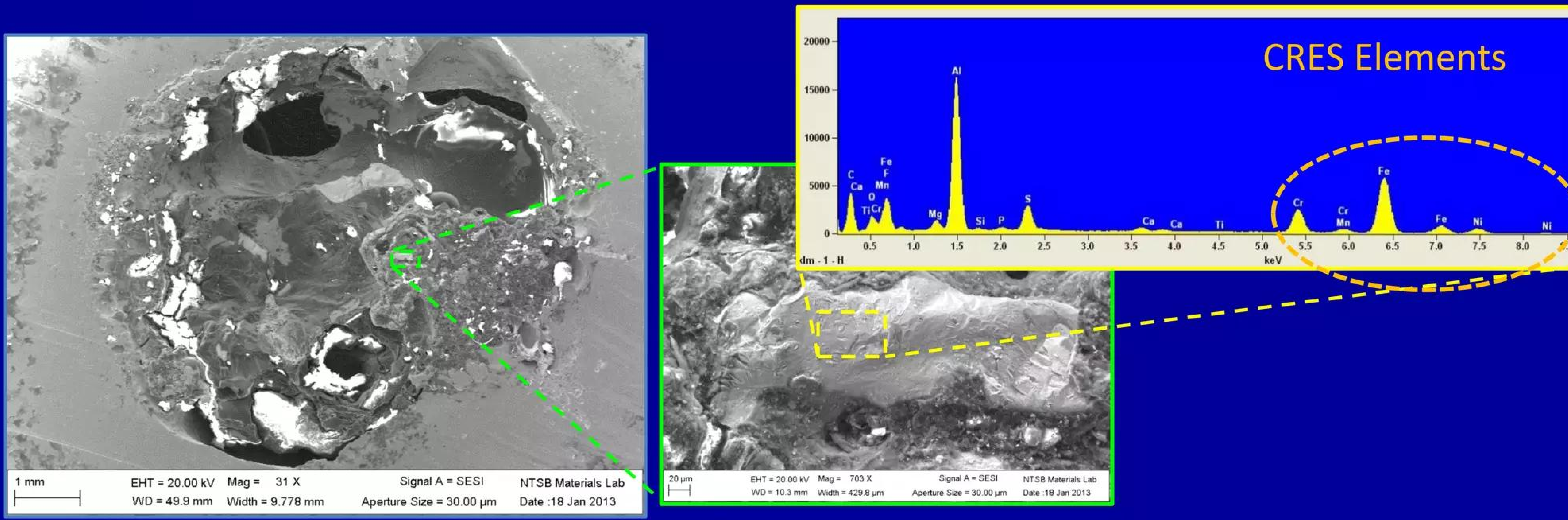
Excerpt directly from NTSB presentation

Source: Slide #28 in NTSB PowerPoint slideshow presented by Deborah Hersman - January 24, 2013



- Finding: electrical arc between battery cell and inside of battery case
- Not believed to be initiating event

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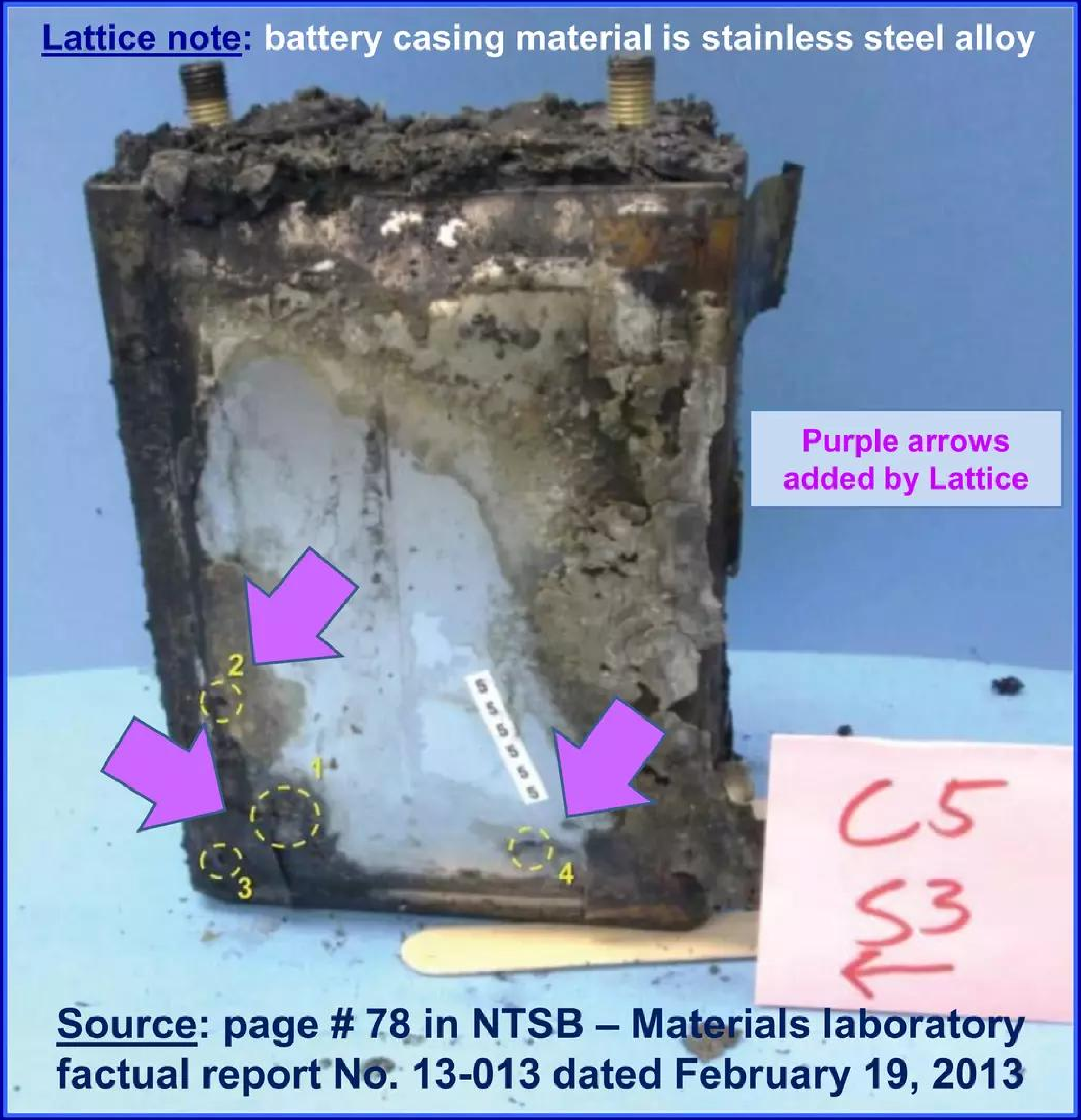
Electric arcs punched 4 holes thru battery cell #5 casing



Lattice comment: electric arcs from battery case definitely crossed 0.2” air gap and discharged into (blue painted) aluminum battery system enclosure (which is highly conductive compared to stainless steel). If this were just air, would require ~15 kilovolt potential for arc to cross gap. Since it was hot inside case during Logan fire, intervening gas was very likely more conductive with ionization present. Nonetheless, arcs could have been somewhere in kV range

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SEM images: stainless steel microspheres - NTSB report

DCA13IA037 Report No. 13-013 Page No. 82

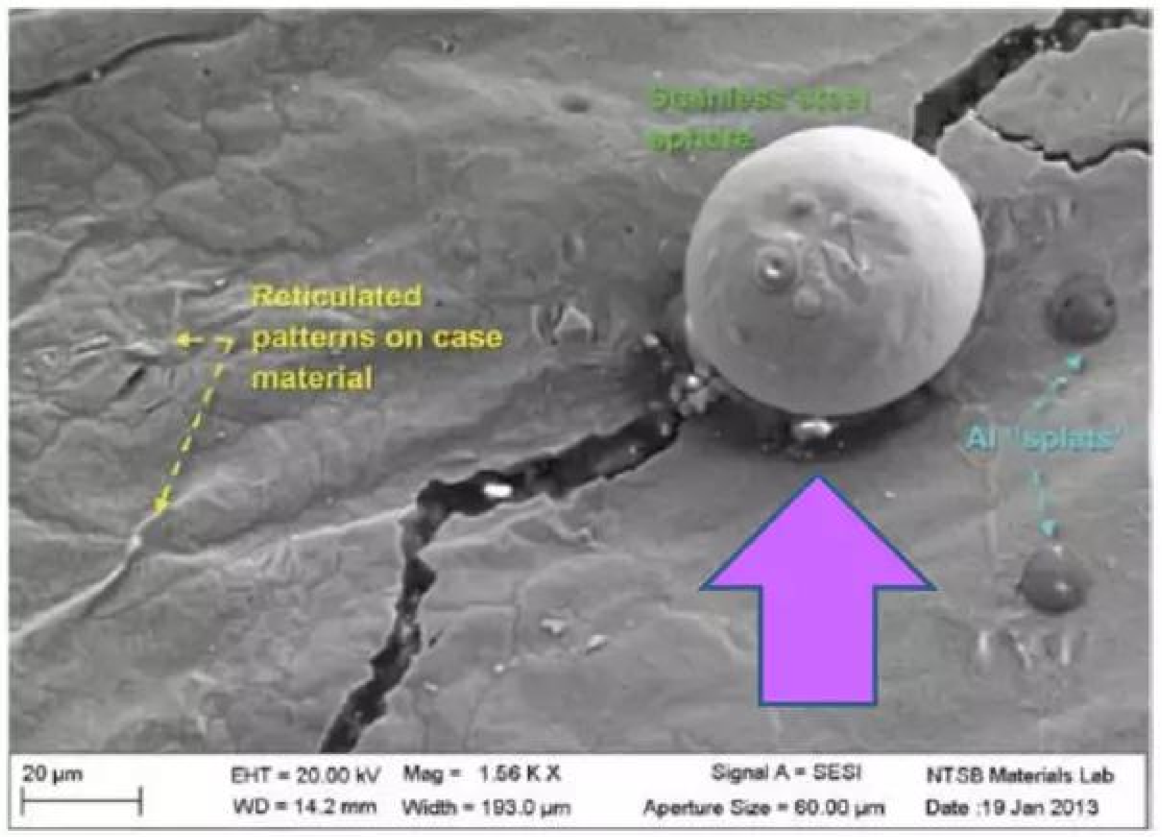

Figure 69. SEM micrograph of a spherical particle of stainless steel found near the exterior side of hole 3.

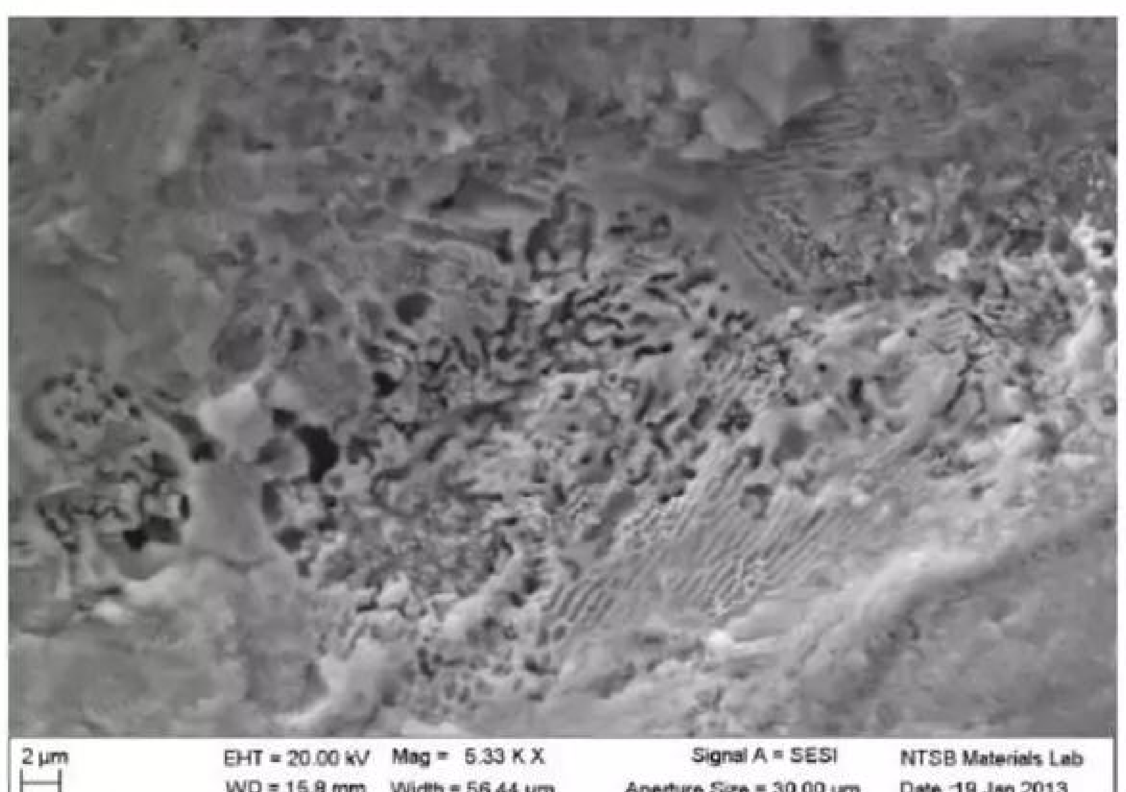

Figure 70. SEM micrograph of lamellar structure consistent with incipient melting near the exterior of hole 4.

Purple arrows added by Lattice

DCA13IA037 Report No. 13-013 Page No. 80

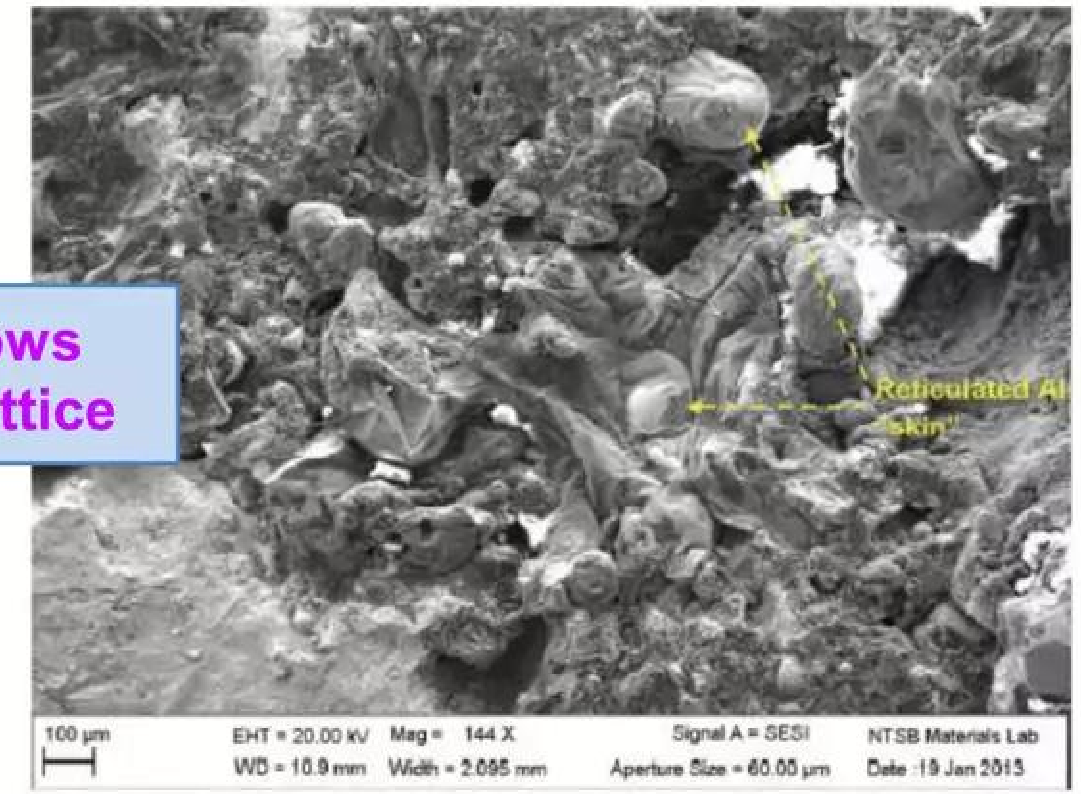

Figure 65. SEM micrograph of hole 1 from the exterior of the C5 cell case. This region exhibited rounded protrusions consistent with resolidified steel encompassed by an external layer of aluminum alloy.

Figure 66. SEM micrograph of steel sphere embedded in combustion products in the interior of hole 1 on the C5 cell case.

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Low-voltage electric arcs reach enormous temperatures

Source: PhD Thesis -"*Modeling and Simulation of Low Voltage Arcs*" by Luca Ghezzi, Technical University of Delft - Netherlands (2010)

Excerpted directly from Ghezzi's thesis:

The arc core reaches temperatures in the order of $10\,000 - 20\,000\,K$, but its surrounding zone, being in contact with the polymer, is considerably colder, with temperatures around $3\,000 - 5\,000\,K$. This temperature range is of the order of, or sometimes exceeds, some typical dissociation temperatures of polymer components, such as that of C_2H_4 ($1\,400\,K$), CH ($3\,700\,K$), C_2H ($4\,500\,K$) and CO ($7\,000\,K$) [139]. More than conduction or convection, heat is transferred from the arc to the polymer by means of radiation. Therefore, the thermal coupling is better if the spectral band of emission from the arc plasma and from the metal contacts and the spectral band of absorption of the polymer coincide or overlap [153].

To obtain a copy:

http://www.google.com/url?sa=t&rct=j&q=%E2%80%9Cmodeling%20and%20simulation%20of%20low%20voltage%20arcs%E2%80%9D%20luca%20ghezzi%20pdf&source=web&cd=1&cad=rja&ved=0CC4QFjAA&url=http%3A%2F%2Frepository.tudelft.nl%2Fassets%2Fuuid%3Addf219d8-5572-45c5-9249-aacbb68683cd%2FModeling_and_Simulation_of_Low_Voltage_Arcs.pdf&ei=vQeAUe3XCovO9ATNjYCoCQ&usg=AFQjCNGnoKc_QU7EMxau7xNIlz-tL8dceg&bvm=bv.45645796,d.eWU

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Similar results can occur during laser ablation of surfaces

Spherically-shaped droplets can be created in such processes

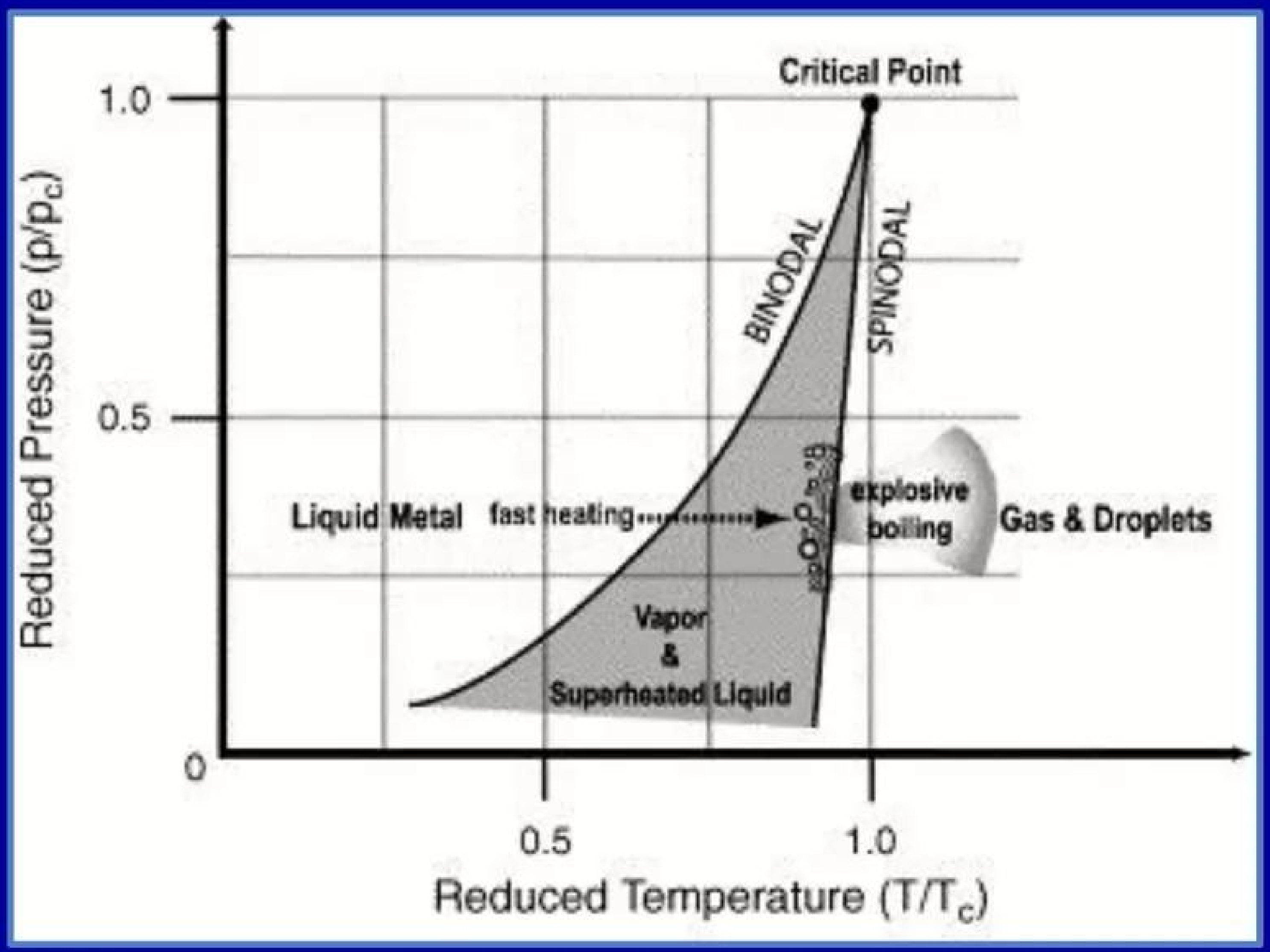

Fig. 1. Phase stability diagram of a liquid metal near the critical point. For fast heating, as obtained during *ns* laser ablation, the melt can be pushed close to critical conditions (superheating), which favors the realization of explosive boiling

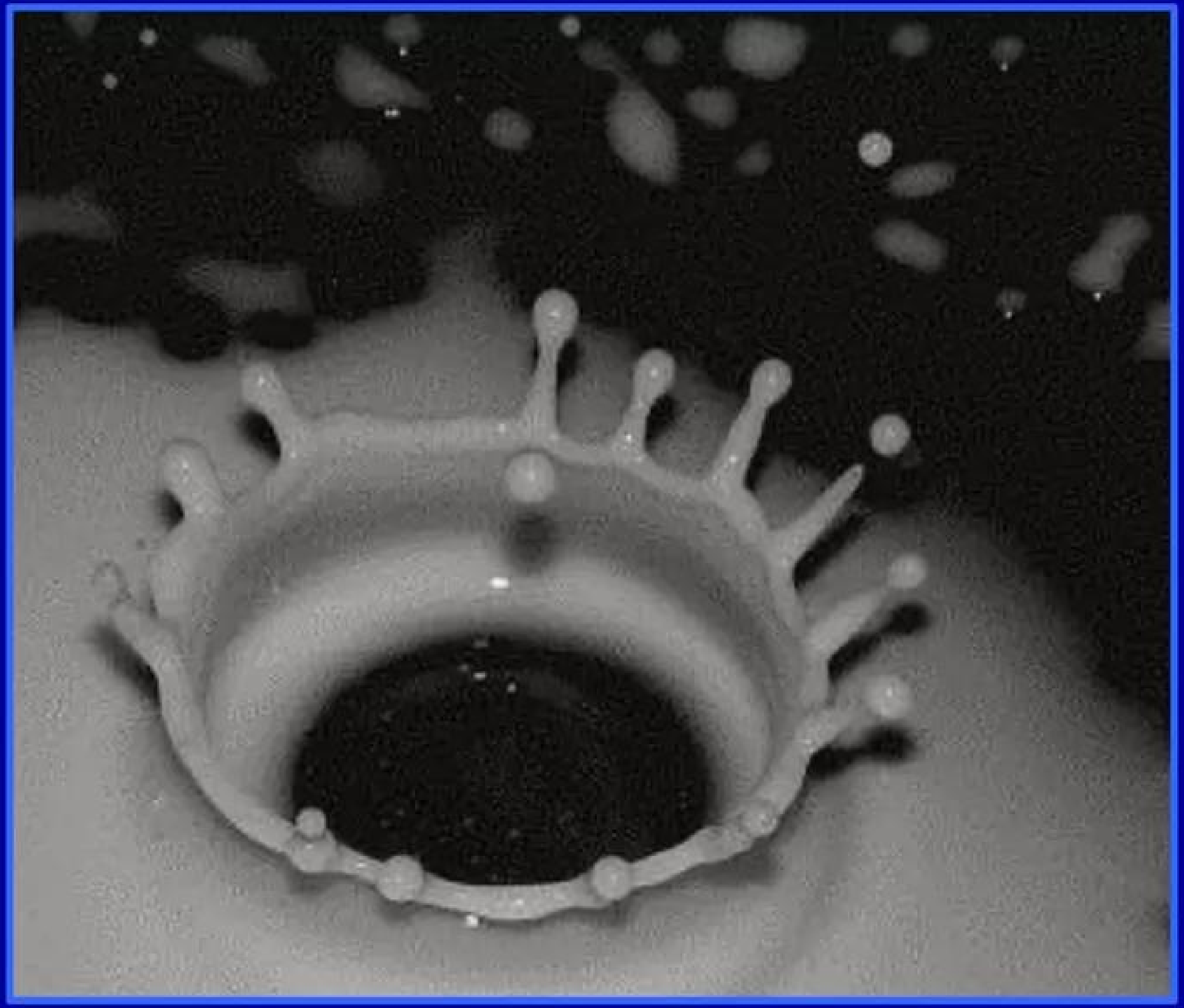

Fig. 2. Schematic visualization of the hydrodynamic evolution of a fluid system under and impulse stress (here milk). Note the non-deterministic formation of jets at the sides and their break-up into droplets. From Ref. [58].

Excerpted and quoted directly from:

"*Multiplicity and contiguity of ablation mechanisms in laser-assisted analytical micro-sampling*"
D. Bleiner and A. Bogaerts
***Spectrochimica Acta Part B: Atomic Spectroscopy* 61 pp. 421 - 432 (2006)**
http://www.sciencedirect.com/science/article/pii/S0584854706000437

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Similar results can occur during laser ablation of surfaces

Spherically-shaped droplets can be created in such processes

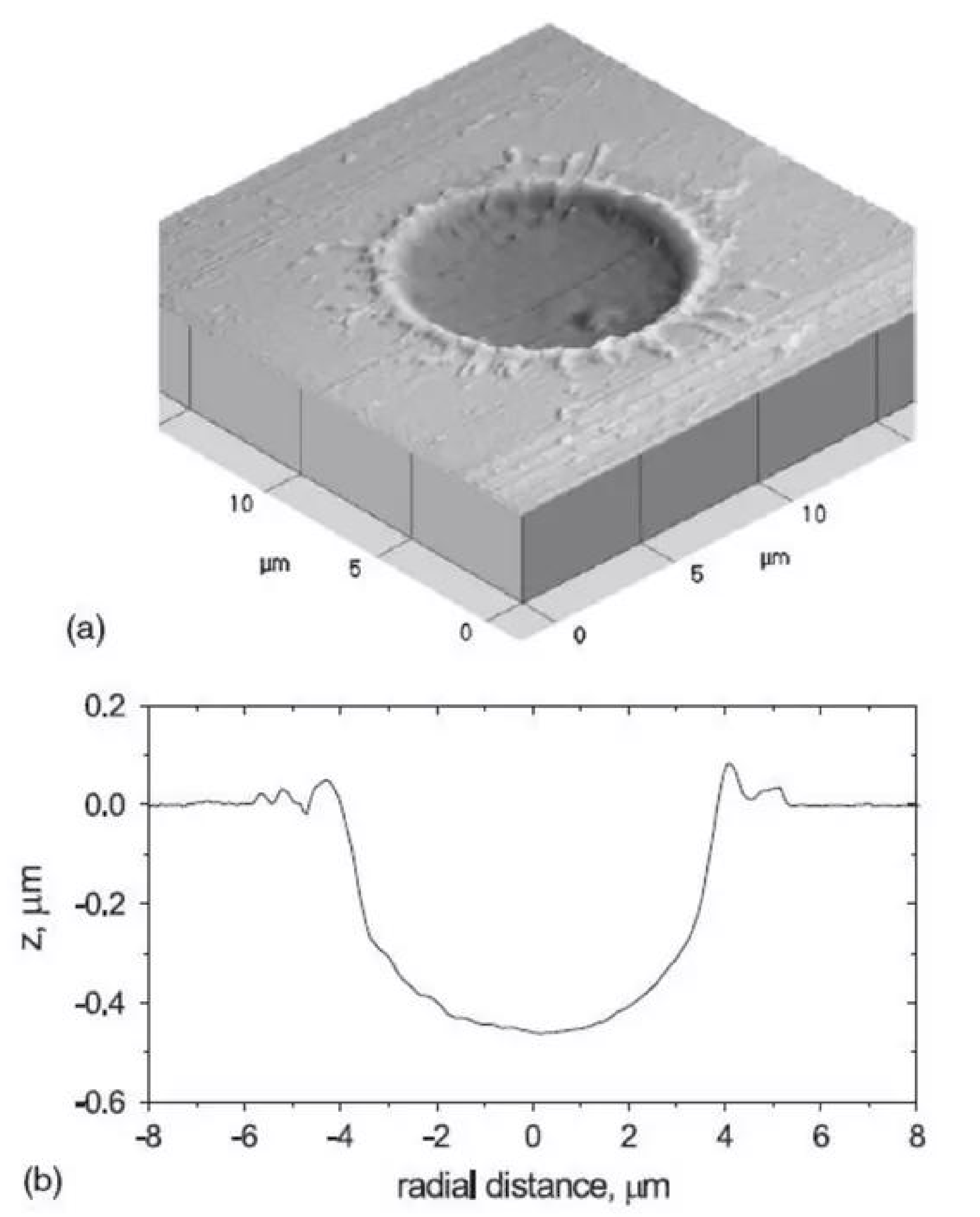

Figure 3. An AFM study of a single crater ablated with a 200 fs and 780 nm laser pulse of $F_0^{av} = 12.6\,\mathrm{J\,cm^{-2}}$. (*a*) The AFM image. (*b*) The ablation profile at the centre-line of the crater. The radius of the beam spot size is $w_0 = 5.9\,\mu\mathrm{m}$.

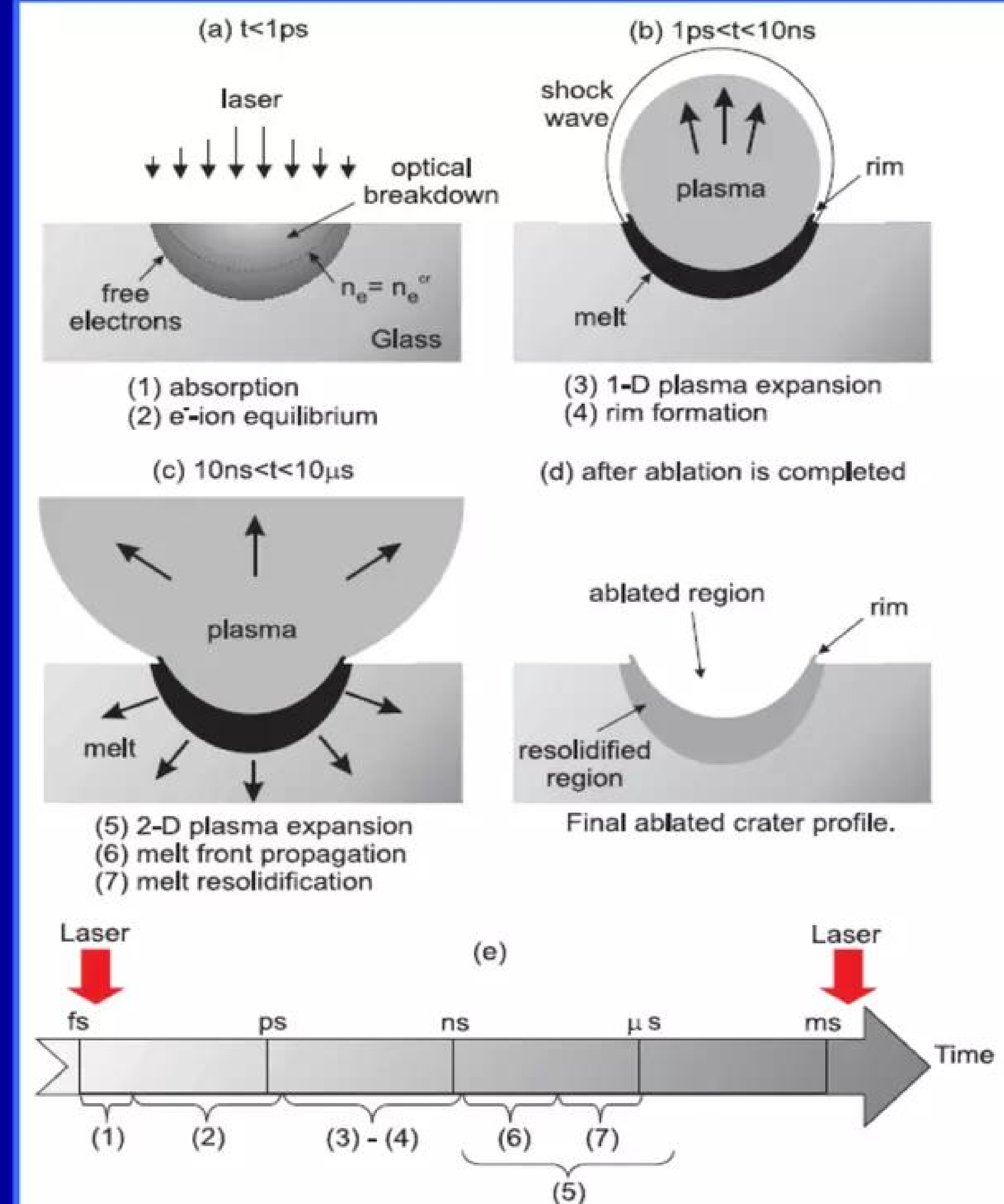

Figure 4. A schematic description of ablation process of glass with a femtosecond laser pulse (*a*)–(*d*) and time scales associated with various processes (*e*).
(This figure is in colour only in the electronic version)

<u>**Excerpted and quoted directly from**</u>**:**

"*Thermal and fluid processes of a thin melt zone during femtosecond laser ablation of glass: the formation of rims by single laser pulses*", A. Ben-Yakar *et al.*, *Journal of Physics D: Applied Physics* 40 pp. 1447 - 1459 (2007)
http://www.stanford.edu/~rlbyer/PDF_AllPubs/2007/423.pdf

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Cathodic arc discharges and LENRs are very energetic

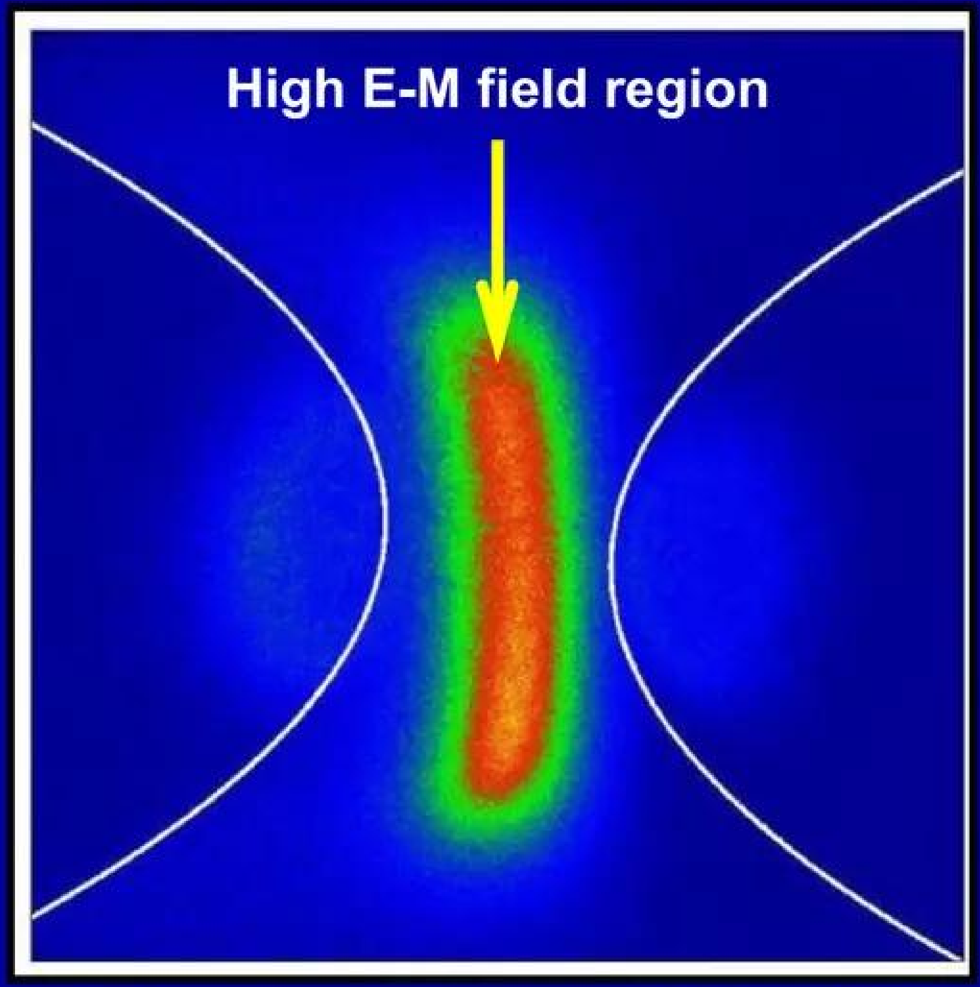
Amazingly, details of electric arcs are still imperfectly understood

Electrical breakdown and arc discharges (i.e., sparks, shorts):

Although they have been studied for 200 years, in many ways electric discharges are still not all that well understood. Recent measurements (2007) of spark discharge in low-pressure Xenon gas using rapidly pulsed lasers has helped better understand the still enigmatic process:

"A spark flying between a metal doorknob and your hand is an intricate chain of electrical events … researchers report the first direct measurements of the sharply changing electric fields that pave the way for a visible flash in a precisely controlled laboratory arc. Their results provided concrete detail in an area where theoretical modeling remains scanty, and may offer a way to study electrical discharges in settings ranging from plasma televisions to lightning strikes ... Whether it's a lightning bolt or the spark inside a bad switch, the process is the same: The voltage across a region of air becomes large enough to drive an electric current by creating a plasma. The process starts when a few stray electrons--accelerated by the electric field--knock into atoms and liberate more electrons, which continue the process. In carefully designed lab experiments the region between a pair of electrodes fills with plasma smoothly, starting at the positive end, with a wave front that sweeps quickly across to the negative end. At the leading edge of this so-called ionization front is a narrow band of enhanced electric field, according to theory and indirect experiments, but theorists only vaguely understand what determines the field's profile. Nor have experimenters been able to map the field profile directly, because inserting metal probes distorts the discharge. Researchers have tried to infer field strengths from the glow following the breakdown, but that light is feeble and only appears once the ionization is well under way.

Source: D. Monroe, *Physical Review Focus*, "Xenon on the verge of an electric breakdown," Feb. 9, 2007 URL = http://focus.aps.org/story/v19/st4



E. Wagenaars/Eindhoven Univ. of Tech

Reference: E. Wagenaars, M. Bowden, and G. Kroesen, "*Measurements of electric field strengths in ionization fronts during breakdown,*" *Physical Review Letters* 98 pp. 075002 (2007)

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Cathodic arc discharges and LENRs are very energetic

Field emission is precursor to surface breakdown and electric arcs

Field electron emission (associated with very high, often rapidly changing local E-M fields):

"Field emission (FE) (also known as electron field emission) is an emission of electrons induced by external electromagnetic fields. Field emission can happen from solid and liquid surfaces, or individual atoms into vacuum or open air, or result in promotion of electrons from the valence to conduction band of semiconductors. The terminology is historical because related phenomena of surface photoeffect, thermionic emission or Richardson-Dushman effect and 'cold electronic emission', i.e. the emission of electrons in strong static (or quasi-static) electric fields, were discovered and studied independently from 1880s to 1930s. When field emission is used without qualifiers it typically means the 'cold emission'."

"Field emission in pure metals occurs in high electric fields: the gradients are typically higher than 1000 volts per micron and strongly dependent upon the work function. Electron sources based on field emission have a number of applications, but it is most commonly an undesirable primary source of vacuum breakdown and electrical discharge phenomena, which engineers work to prevent."

"Field emission was explained by quantum tunneling of electrons in the late 1920s. This was one of the triumphs of the nascent quantum mechanics. The theory of field emission from bulk metals was proposed by Fowler and Nordheim. A family of approximate equations, 'Fowler- Nordheim equations', is named after them."

"In some respects, field electron emission is a paradigm example of what physicists mean by tunneling. Unfortunately, it is also a paradigm example of the intense mathematical difficulties that can arise. Simple solvable models of the tunneling barrier lead to equations (including the original 1928 Fowler-Nordheim-type equation) that get predictions of emission current density too low by a factor of 100 or more. If one inserts a more realistic barrier model into the simplest form of the Schrödinger equation, then an awkward mathematical problem arises over the resulting differential equation: it is known to be mathematically impossible in principle to solve this equation exactly in terms of the usual functions of mathematical physics, or in any simple way. To get even an approximate solution, it is necessary to use special approximate methods known in physics as "semi-classical" or "quasi-classical" methods. Worse, a mathematical error was made in the original application of these methods to field emission, and even the corrected theory that was put in place in the 1950s has been formally incomplete until very recently."

Source: Wikipedia article titled "Field electron emission" as of July 10, 2010 http://en.wikipedia.org/wiki/Field_electron_emission

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Cathodic arc discharges and LENRs are very energetic

Seidman: "… highest power density commonly found in Nature"

D. Seidman's candid comments on field emission and breakdown in a grant proposal written back in 2005:

Dave Seidman is the Walter P. Murphy Professor of Materials Science and Engineering at Northwestern University in Evanston, IL, and leads the Seidman Research Group at NWU's Center for Atom-Probe Tomography (NUCAPT) - http://arc.nucapt.northwestern.edu/Seidman_Group

Prof. Seidman has a unique knowledge of high surface electric fields, field emission, and arc discharges as a result of his many years of work with atom-probe tomography (APT) which uses nanoscale local electric fields of 10^{10} V/m *and higher* to image the structure and analyze the chemical composition of surfaces on near atomic-scales (see image to right courtesy of Imago, Inc., a manufacturer of APTs)

Quoting (*ca.* 2005), "NUCAPT is among the world leaders in the field of three-dimensional atom-probe microscopy, particularly as result of the recent installation of a LEAP microscope, manufactured by Imago Scientific Instruments. Currently only three other LEAP microscopes, with a comparable performance, exist throughout the world."

Readers will find a boldness and blunt candor in Seidman's insightful remarks to follow that tend to be absent in published refereed papers

Seidman's quoted remarks were made in the context of a publicly posted 2005 grant proposal: Seidman, D., and Norem, J., "Experimental study of high field limits of RF cavities"

Please see source URL:

http://www.hep.uiuc.edu/LCRD/LCRD_UCLC_proposal_FY05/2_49_Seidman_Norem.pdf

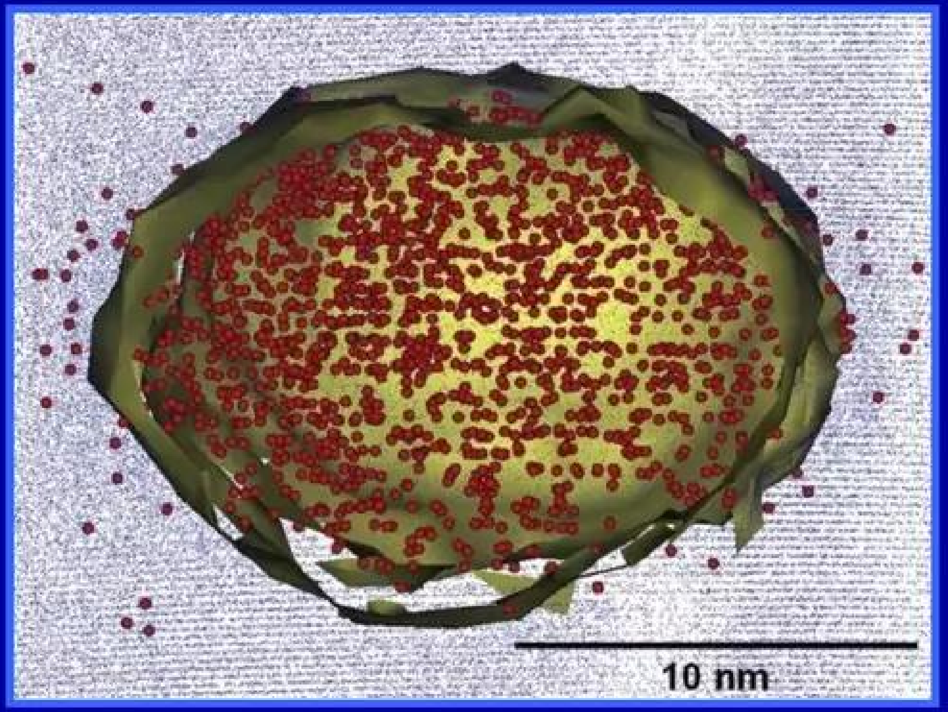

Image: Larson & Kelly, Imago, Inc., local-electrode atom probe image of ordered $L1_2$ Al_3Sc precipitate in aluminum matrix (Al – blue, Sc – red). The <200> planar spacing of the crystalline Al lattice (spacing ~0.2nm) is evident and contrasts with the <100> planar spacing (~0.4 nm) of the Al_3Sc precipitate. Alloy provided by van Dalen, Dun, and Seidman

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Cathodic arc discharges and LENRs are very energetic

Seidman: "… highest power density commonly found in Nature"

Seidman's comments *circa* 2005:

"[Electric arc] breakdown at surfaces was discovered by Earhart and Michelson, at [the University of] Chicago, in 1900 … While checking the new 'electron' theory of gas breakdown at small distances, they discovered that there were two mechanisms present, at large distances gas breakdown dominated, and at small distances [i.e., on small length-scales] breakdown of the surface was correctly identified as the mechanism. The break point where the two mechanisms met, at atmospheric pressure, occurs at about 300 V … This was confirmed 5 years later by Hobbs and Millikan, and is consistent with modern data on vacuum breakdown."

"Although high electric fields have been used in DC and RF applications for many years, up to now there has been no fundamental agreement on the cause of breakdown in these systems … Until our work, no theoretical understanding of this process developed over the last 100 years, although many papers have been written."

"Another interesting feature of this [electrical breakdown] mechanism is that the power densities involved are enormous. The numbers can be obtained from the values we measured for field emitted currents, electric field, the emitter dimensions, and volume for transferring electromagnetic field energy into electron kinetic energy. Combining these gives, $(10\ \mathrm{GV/m})(10^{-7}\ \mathrm{m})(1\ \mathrm{mA})/(10^{-7}\mathrm{m})^3 = 10^{21}\ \mathrm{W/m}^3$, a value that seems to be greater than all other natural effects, except perhaps Gamma Ray Bursters (GRB's). The power density is comparable to nuclear weapons. Michelson and Millikan noticed the 'hot sparks' in 1905, bought a vacuum pump, (which they didn't have), and invented vacuum ultraviolet spectroscopy. Both moved on, and did not look in detail at the mechanisms involved."

Seidman, D., and Norem, J., "Experimental study of high field limits of RF cavities"

Again, please refer to source URL:

http://www.hep.uiuc.edu/LCRD/LCRD_UCLC_proposal_FY05/2_49_Seidman_Norem.pdf

In the following Slide, we modify a chart shown in Seidman & Norem's above-noted proposal to illustrate the very approximate regions of physical parameter space in which LENRs may occur if ALL the necessary preconditions that we have previously outlined are obtained. Please note carefully that just the presence of very high local E-M fields by itself does not guarantee that LENRs will take place at a given location in time and space

Also please note that once the nuclear processes begin, power densities in LENR-active 'patches' can go even higher for brief periods of time until nearby nanostructures are destroyed by violent 'flash' heating and LENRs temporarily cease in a given 'patch' (all of this occurs on the order of <1 to 300 nanoseconds)

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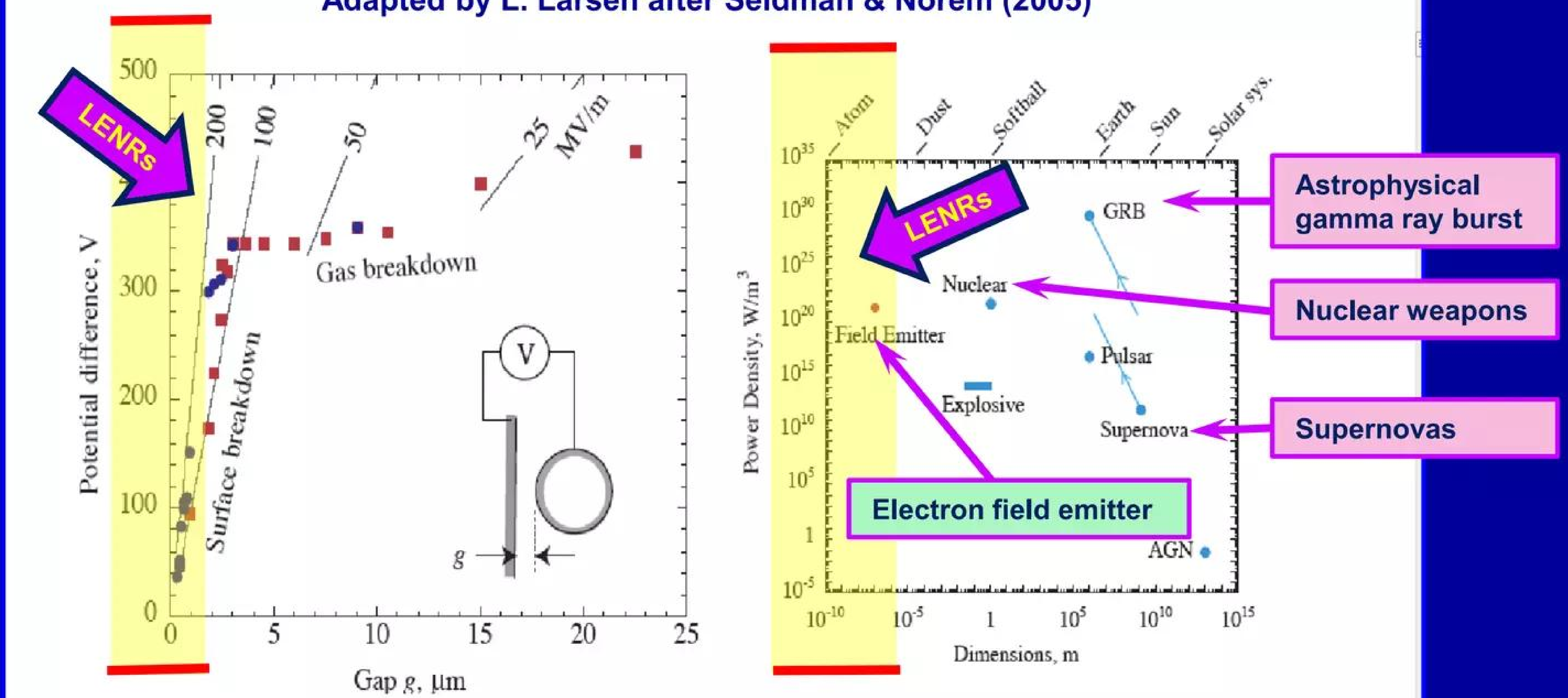
Cathodic arc discharges and LENRs are very energetic

Seidman: "… highest power density commonly found in Nature"

Local micron-scale power densities can be enormous during brief 'lifetime' of an LENR-active 'patch'

They can *exceed* huge power densities reached during electrical breakdown *a la* Seidman & Norem



Lattice modification of original chart: yellow-shaded regions 'capped' by red-colored bars are approx. regions of parameter space where LENRs may occur in condensed matter systems IF all of the necessary conditions met (please refer back to earlier Slides)

Source: Fig. 2, pp. #3, Seidman & Norem 2005 proposal, *"Experimental study of high field limits of RF cavities"*

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Cathodic arc discharges and LENRs are very energetic

Seidman: "… highest power density commonly found in Nature"

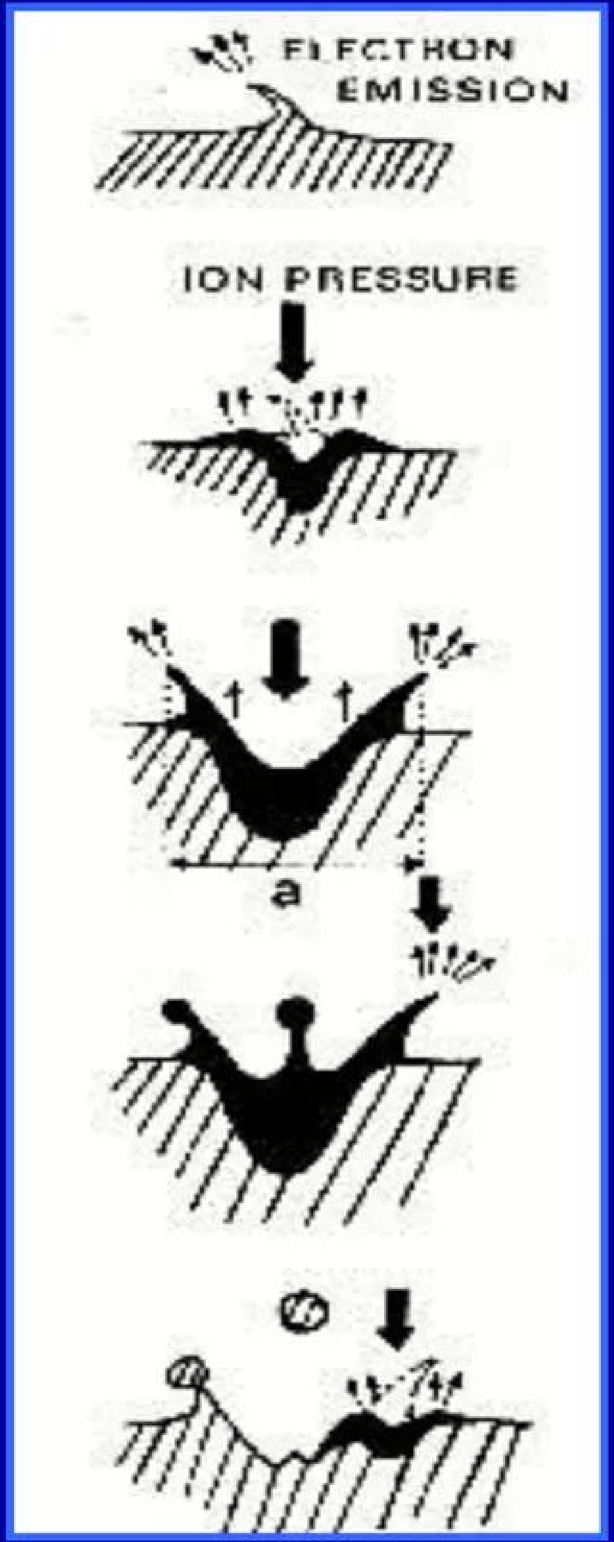
D. Seidman's comments *circa* 2005 (continued):

"We think we have developed a model of breakdown that explains the phenomenon in almost all environments ….The model strongly argues that breakdown events are the result of fragments or clusters breaking off of the surface and rapidly being ionized in the electron beams from the field emitter. Within the active volume, the power involved in these beams is comparable to nuclear weapons. This model is also generally in agreement with the experience with APFIM samples at the high fields used. Tiny APFIM samples operate at fields about 5 times higher than the local E field limit we postulate, but they also frequently fail, however there has been no systematic study of these failure modes."

"Combining these two ideas, however, one can conclude that: 1) this mechanism produces perhaps the highest power density commonly found in nature, and, 2) it is accessible to anyone with a wall switch or an electric light, and is used many times a day by everyone."

"While there has been extensive study of the time development of breakdown events from the first small local ionization to complete breakdown of a cavity, the trigger for breakdown, and how it was related to the metallurgy of surfaces has received very little attention until now. Our model predicts that the production of clusters and fragments is an essential component of breakdown. This is consistent with experience in Atom Probe Tomography, however there is almost no systematic data on sample failures under the high field environment used in data taking. Our previous work has been published in three refereed papers and many conference papers."

Note creation of ~spherical droplets



**Breakdown of surface
Figure courtesy of B. Jüttner, Berlin**

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Cathodic arc discharges and LENRs are very energetic

Anders has developed model for "arc spot ignition" runaways

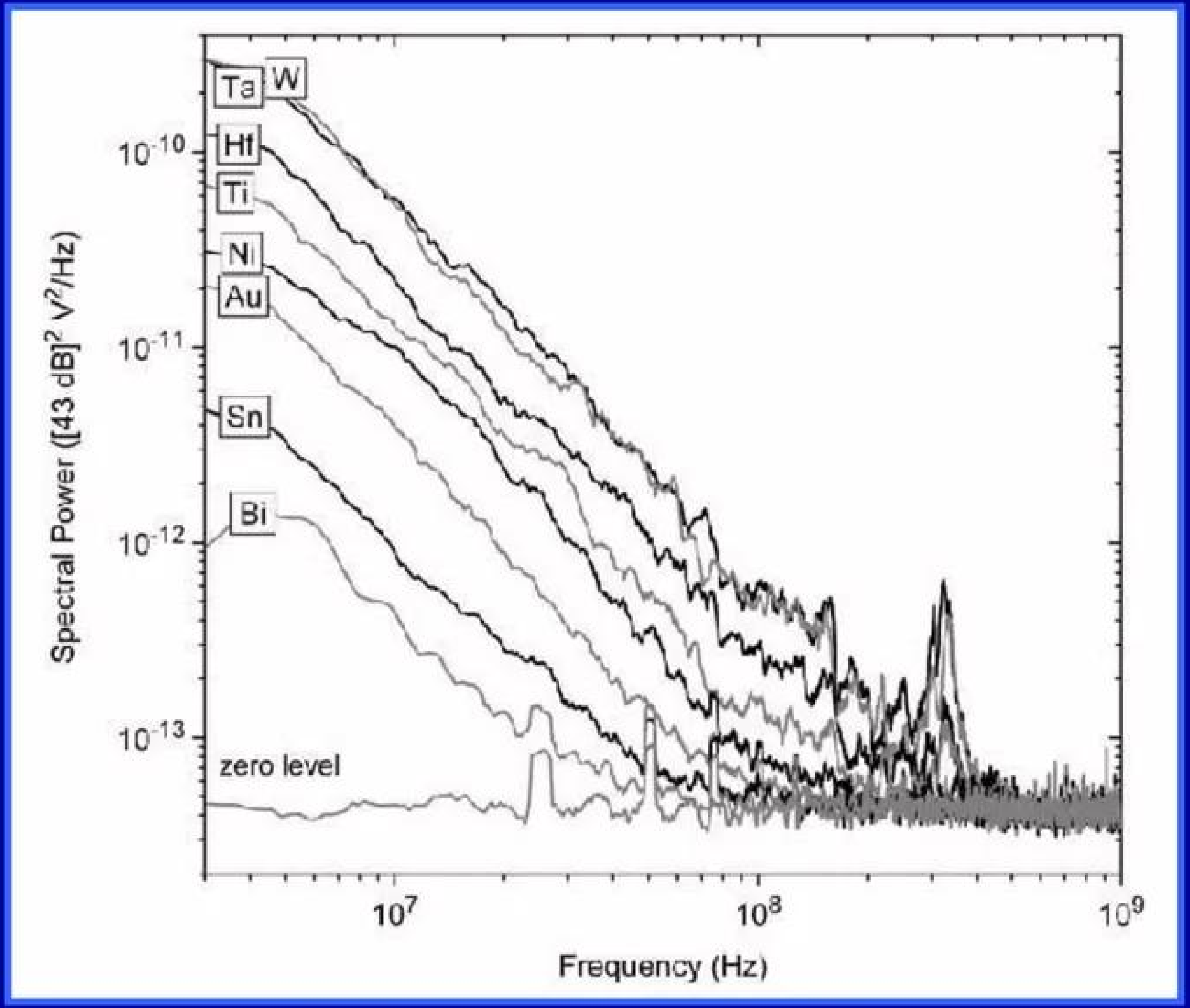
In 2010, Dr. Andre Anders of Lawrence Berkeley National Laboratory (LBNL) publicly posted a very interesting 32-slide PowerPoint presentation titled "*Cathodic Arcs, and related phenomena*":

- ✓ **Among other things, he believes that 'hot cathode spots' are fractal, as shown in the Figure to the right, and that the electron current is higher than the arc current (his Slide #6)**

- ✓ **On his Slide #7, he makes an important distinction between *collective* electron emissions that occur in arc discharge regimes (namely, thermionic, field, thermo-field, and explosive emissions) versus "*individual*" electron emission mechanisms (such as secondary electron emission by primary ion, electron, or excited atom impact, and photo-emission) that tend to occur in glow discharge regimes**

- ✓ **On Slide #11, he describes an "*arc spot ignition*" involving a, "*Local thermal run-away process [that] leads to micro-explosion and formation of extremely dense plasma*"**

Evidence that "cathode spots" are fractal:



Original source: A. Anders, "*Cathodic Arcs*," Springer, NY (2008)

In 2010, this Figure appears in a workshop presentation:

A. Anders (Lawrence Berkeley National Laboratory - LBNL), "Cathodic Arcs, and related phenomena," work supported by the U.S. Department of Energy under Contract DE-AC02-05CH11231

URL =

https://twindico.hep.anl.gov/indico/getFile.py/access?sessionId=3&resId=0&materialId=1&confId=69

Lattice Energy LLC

Cathodic arc discharges and LENRs are very energetic

Anders' model for "arc spot ignition" runaways can lead to LENRs

Dr. Andre Anders - LBNL (continued):

On Slide #11, he then elaborates his model as follows:

High [local] electric field, enhanced by:

- **Protrusion (e.g. roughness, previous arcing) [e.g., dendrites]**
- **Charged dielectrics (e.g. dust particles, flakes) [nanoparticles]**

Feedback loop

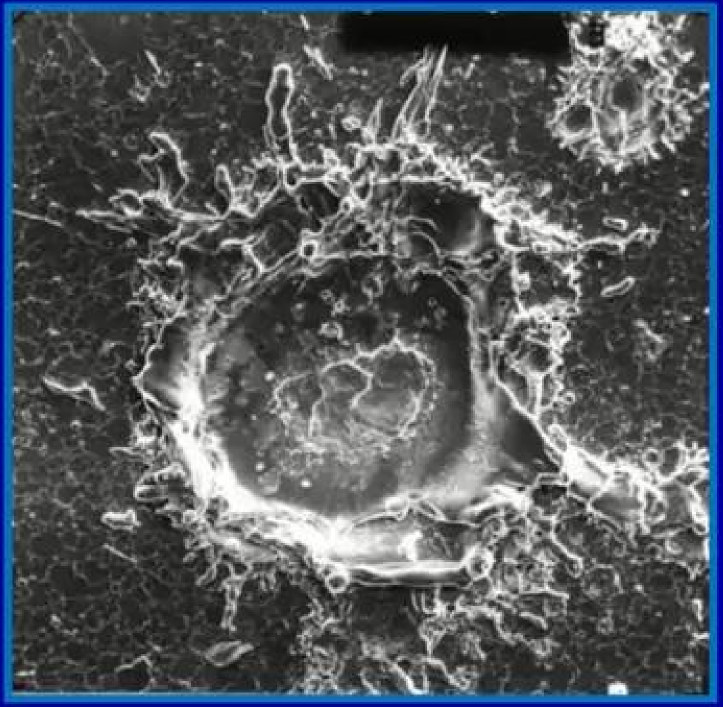
1. **Higher field leads to locally greater e-emission**
2. **Joule heat enhances temperature of emission site**
3. **Higher temperature amplifies e-emission non-linearly**
4. **Runaway!**

To which we would add, based on the Widom-Larsen theory:

5. **LENRs --- if other necessary preconditions are also fulfilled, as we have outlined elsewhere**

Anders then goes on to show an array of fascinating SEM images of surfaces on which 'explosive' cathode arcs have occurred that bear a certain resemblance to post-experiment SEM images of LENR cathodes (with a difference in their aspect-ratios that we will explain)

"Crater" in cathodic arc experiment:



A. Anders: "*Cathodic Arcs, and related phenomena,*" Slide #12 of 32 (2010)

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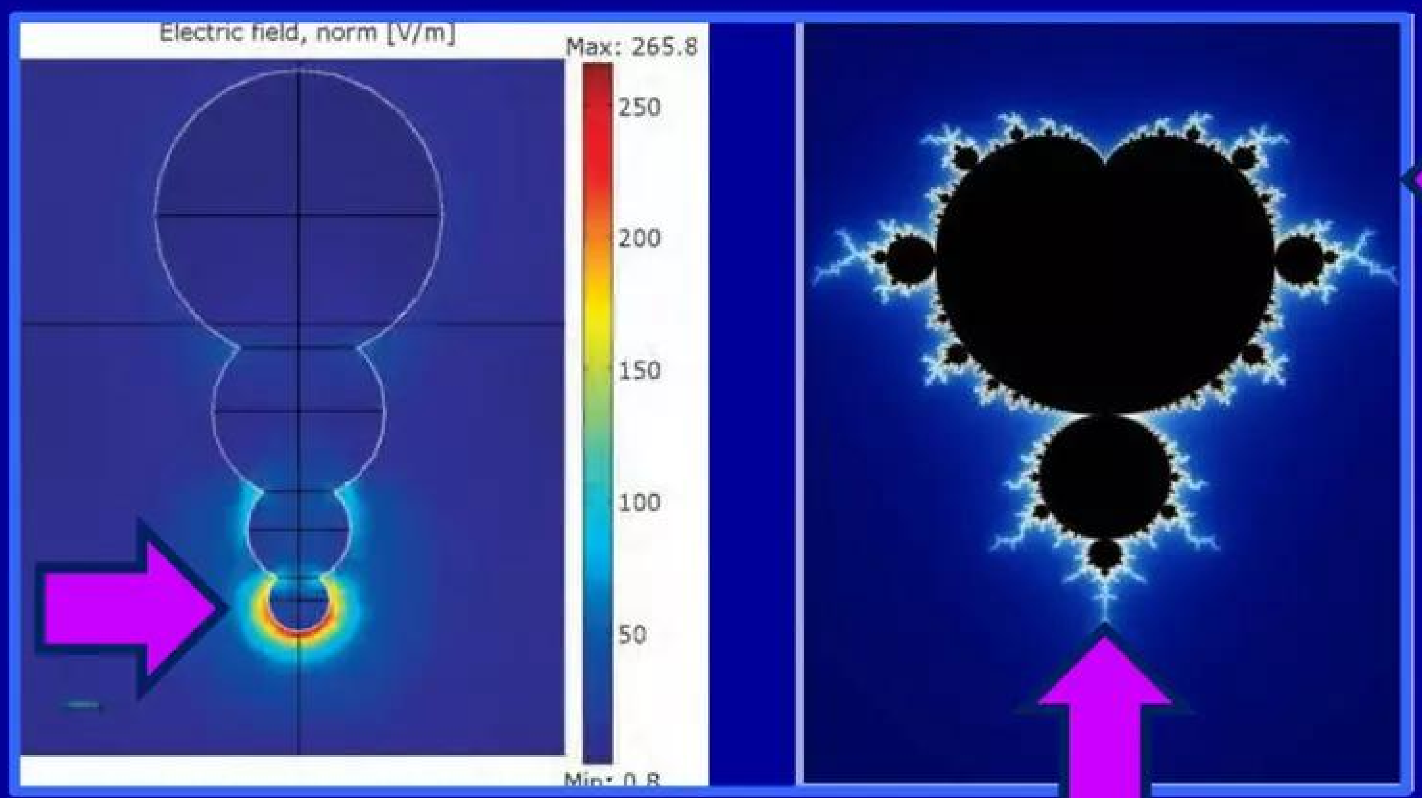
Arcs and LENRS both involve very high local E-M fields

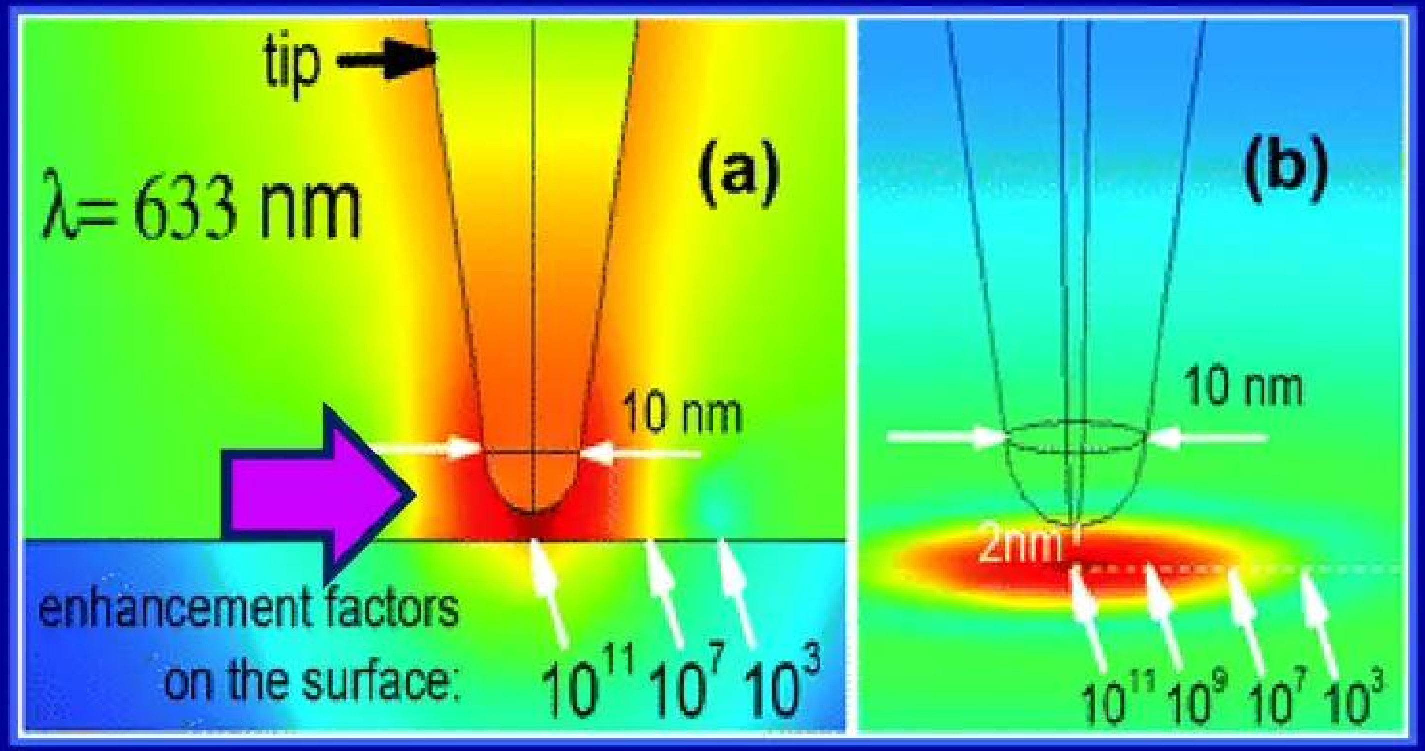
E-fields can increase greatly between nanoparticles and at sharp tips



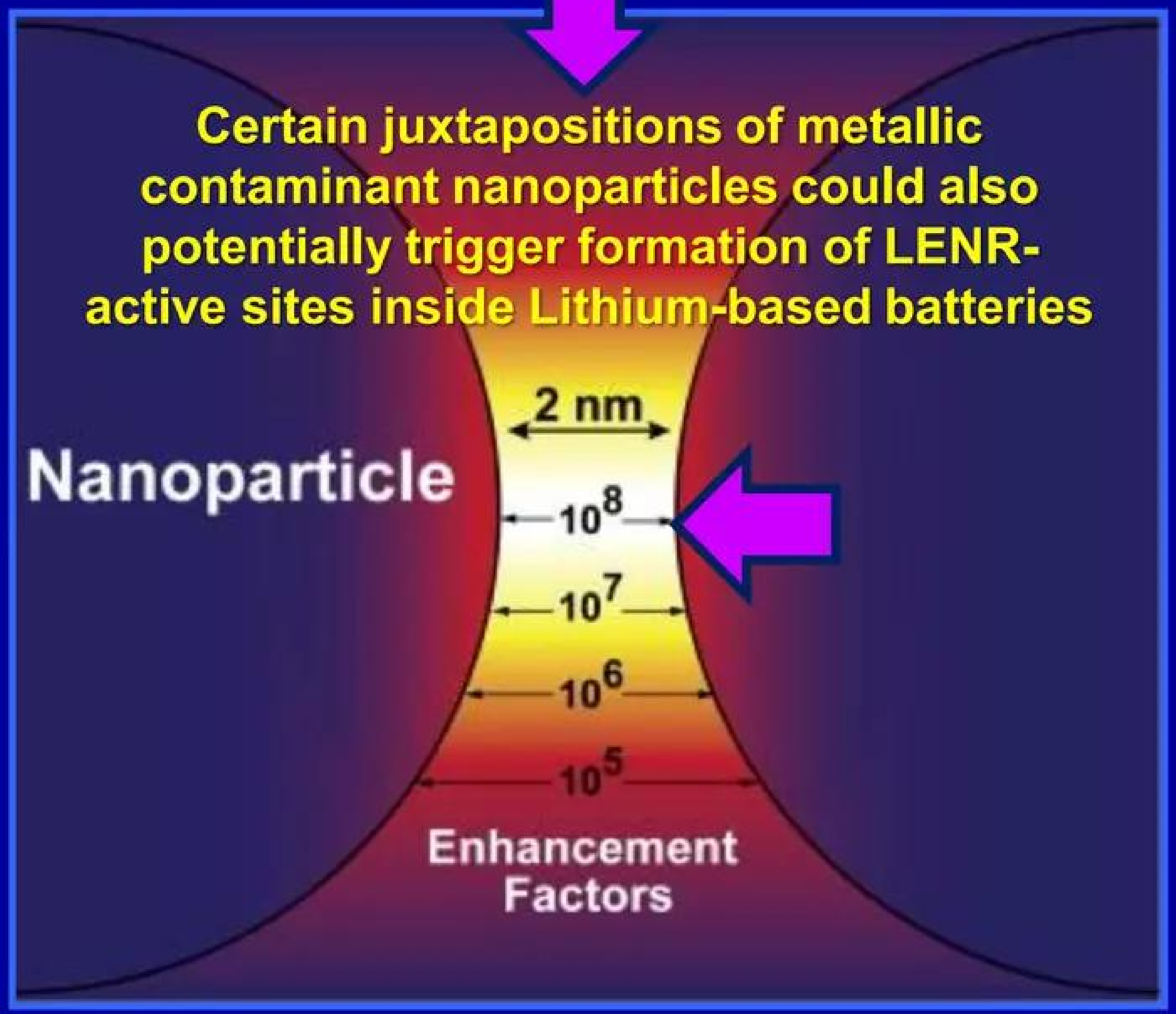
Electric field enhancement
at nano-antenna tip:
R. Kappeler *et al.* (2007)

Above: classic
Mandelbrot fractal form

Sharp tips can exhibit the so-called "lightning rod effect" in terms of local enhancement of electric field strengths; dendrites are but one type of such a structure – *there are others*



E-M field strength enhancement as a function of interparticle spacing



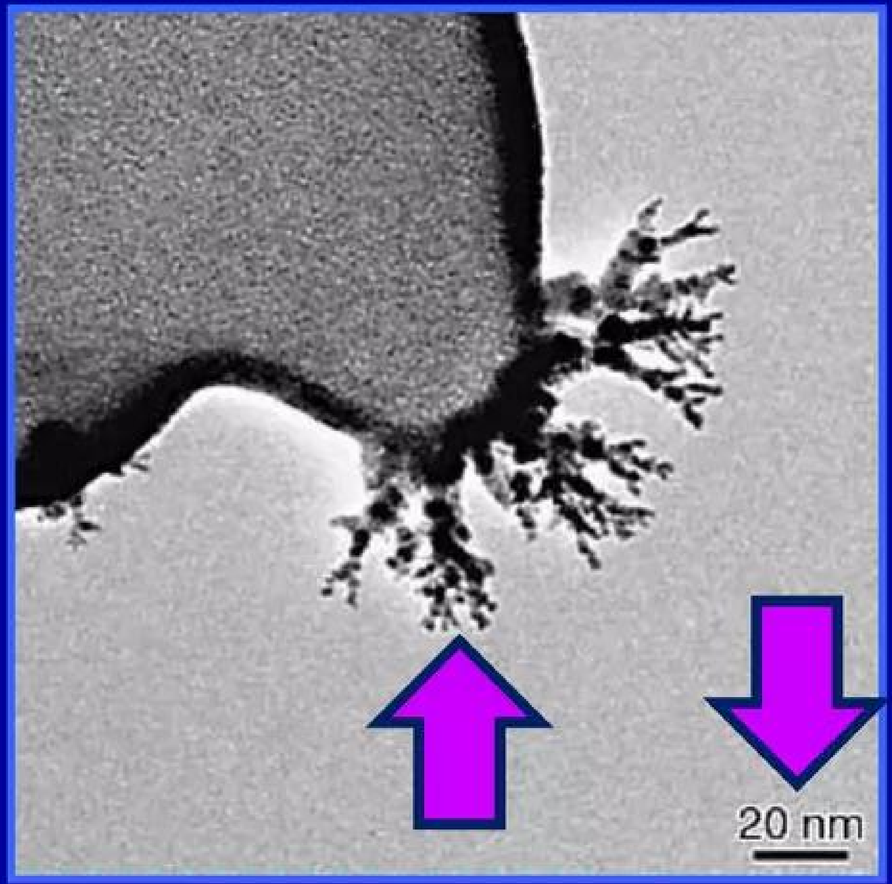
Lattice Energy LLC

Arcs and LENRS both involve very high local E-M fields

E-fields can increase greatly between nanoparticles and at sharp tips

Many fractal or dendrite structures have sharp, tapered tips:

Fractals are intrinsically self-similar on all length-scales, from meters down to nanometers. As illustrated in these Figures, many types of natural fractal forms narrow-down to very sharp tips on smaller length-scales. Structures with such geometries can be prone to exhibit the lightning rod effect if they happen to be comprised of materials such as metallic conductors



TEM image: *nm*-scale Tungsten dendrite
Credit: Furuya & Hasegawa, CNMT - Korea

Image: macroscopic *cm* length-scale Copper dendrite growing in aqueous Copper Sulfate solution

Image: terrestrial lightning very large length scale

Image: *mm* length-scale Lichtenberg Figures from electrical discharge through plastic

Lattice Energy LLC

Arcs and LENRS both involve very high local E-M fields

E-fields can increase greatly between nanoparticles and at dendrite tips

Examples of fractal dendritic structures that can grow inside Li-ion batteries over time and many charge/discharge cycles:

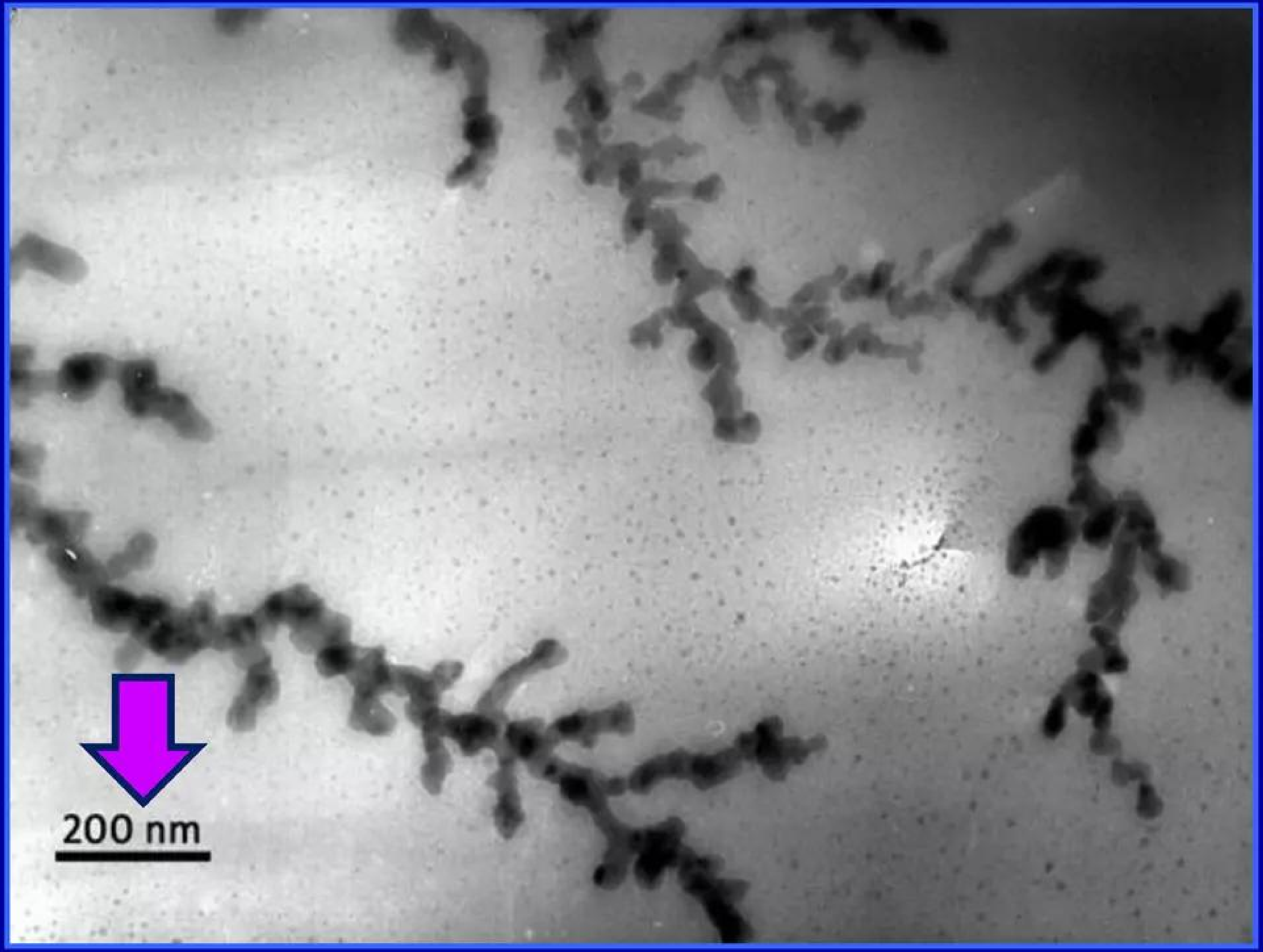
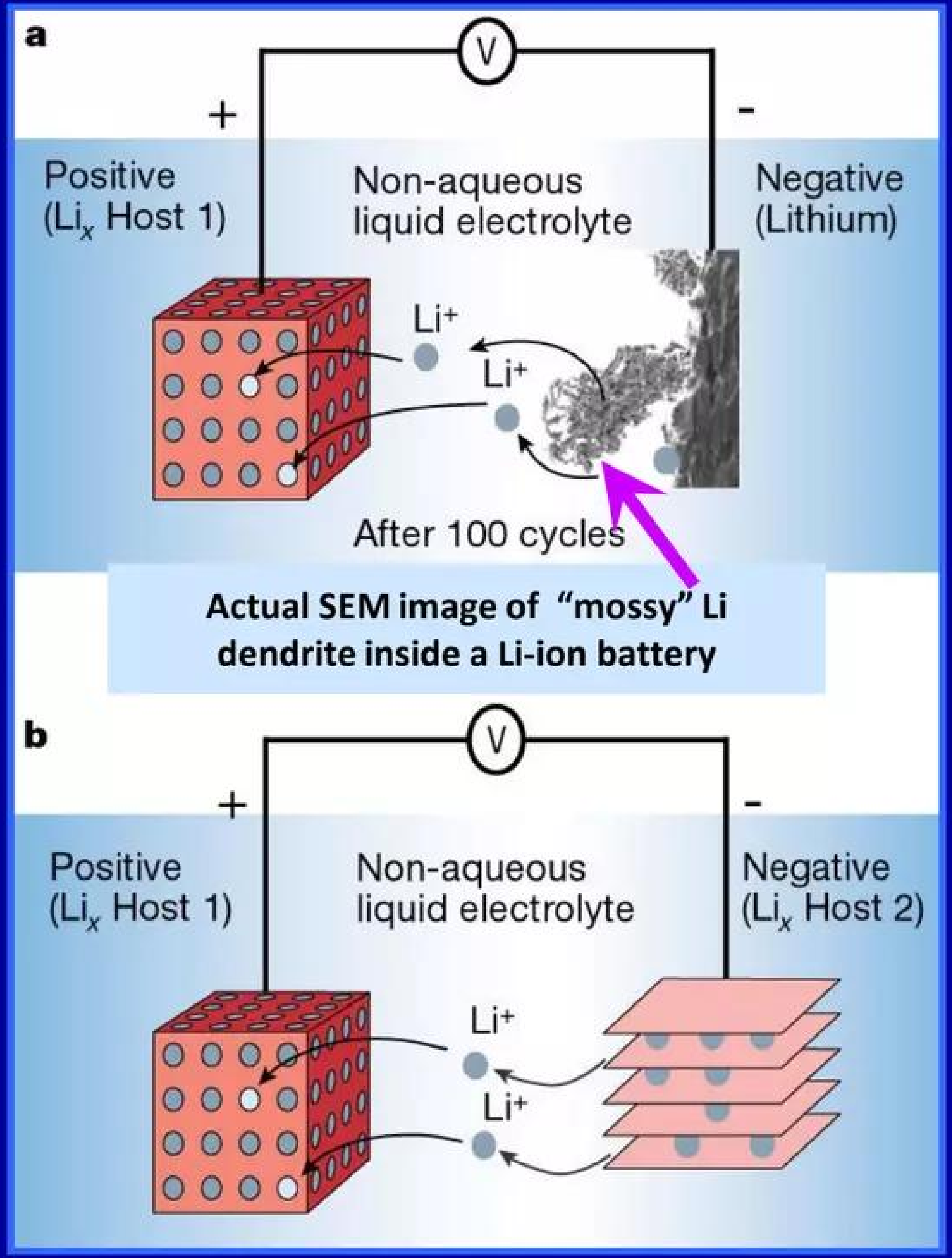


Image: Lithium metal dendrites growing within solid polymer electrolyte - G. Stone et al., Lawrence Berkeley National Laboratory, APS March 17, 2010

Abstract: Q16.00005 - "*Retarding Dendrite Formation in Rechargeable Lithium Metal Batteries with Block Copolymer Electrolytes*"



Source: Fig. 2 in J. Tarascon and M. Armand, "*Issues and challenges facing rechargeable lithium batteries*" *Nature* 414, pp. 359 - 367 (2001)

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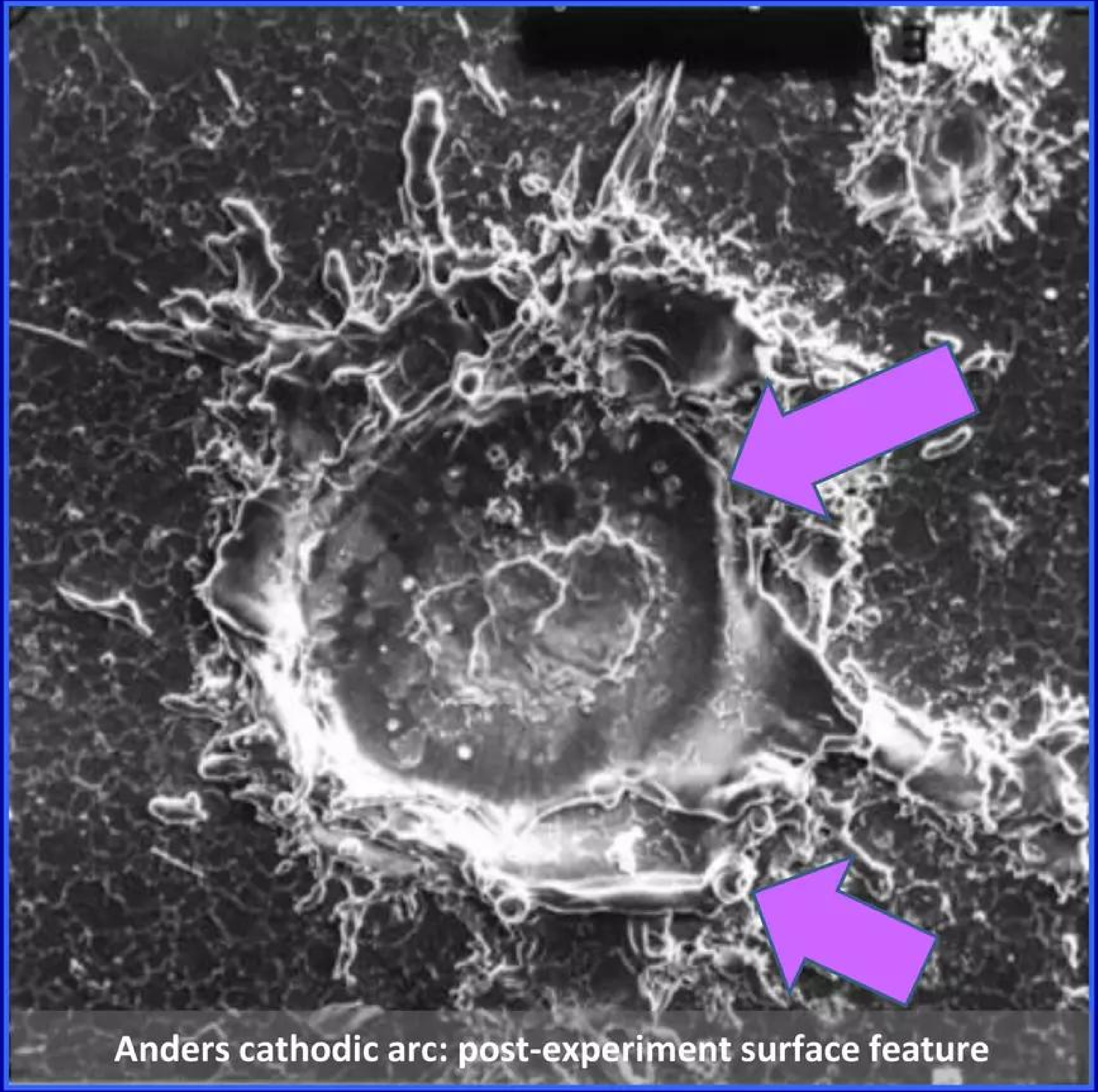
Morphological similarities between arc 'craters' and LENRS

Key difference: LENR 'craters' can have much higher aspect-ratios

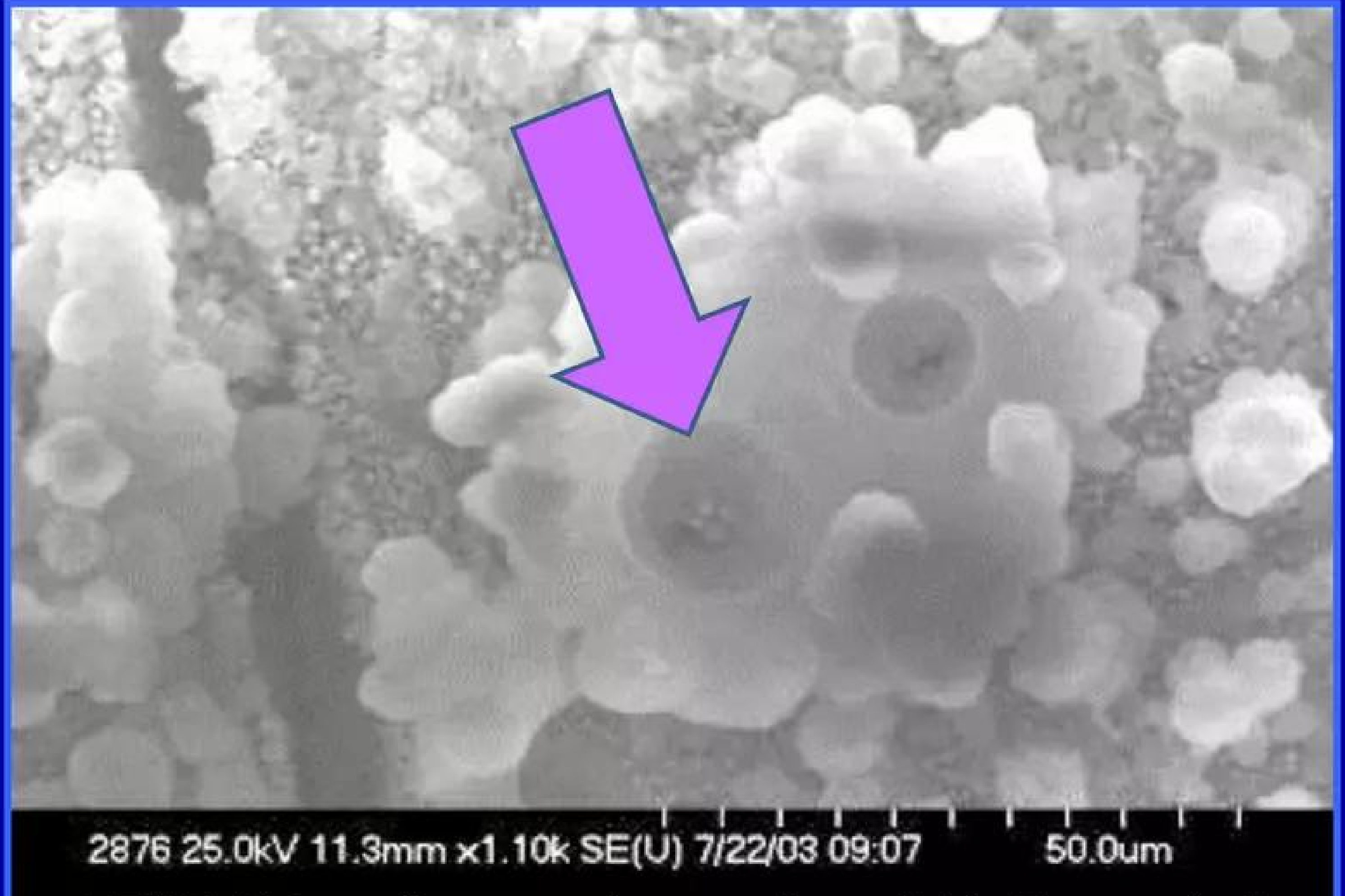
Anders' SEM photos vs. selected images of post-experiment surfaces in LENR experiments:

Cathodic arcs



Anders cathodic arc: post-experiment surface feature

LENRs



LENR Pd surface post-experiment: P. Boss *et al.*

Please note what appears to be a somewhat common morphological difference between LENR 'craters' and those produced by prosaic cathodic arcs as discussed by Anders. Many central 'craters' in LENR SEM images often appear to have more sharply defined, 'crisper' interior walls and greater depths (relative to the surface area) compared to arc discharges without LENRs (i.e., a higher aspect-ratio); this may be indicative of much more rapid, higher levels of heating than those envisioned by Anders

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This example of laser ablation 'crater' has high aspect-ratio

'Craters' at many LENR-active sites often have high aspect-ratios

Fig. 6 from Karnakis *et al.* (2009)

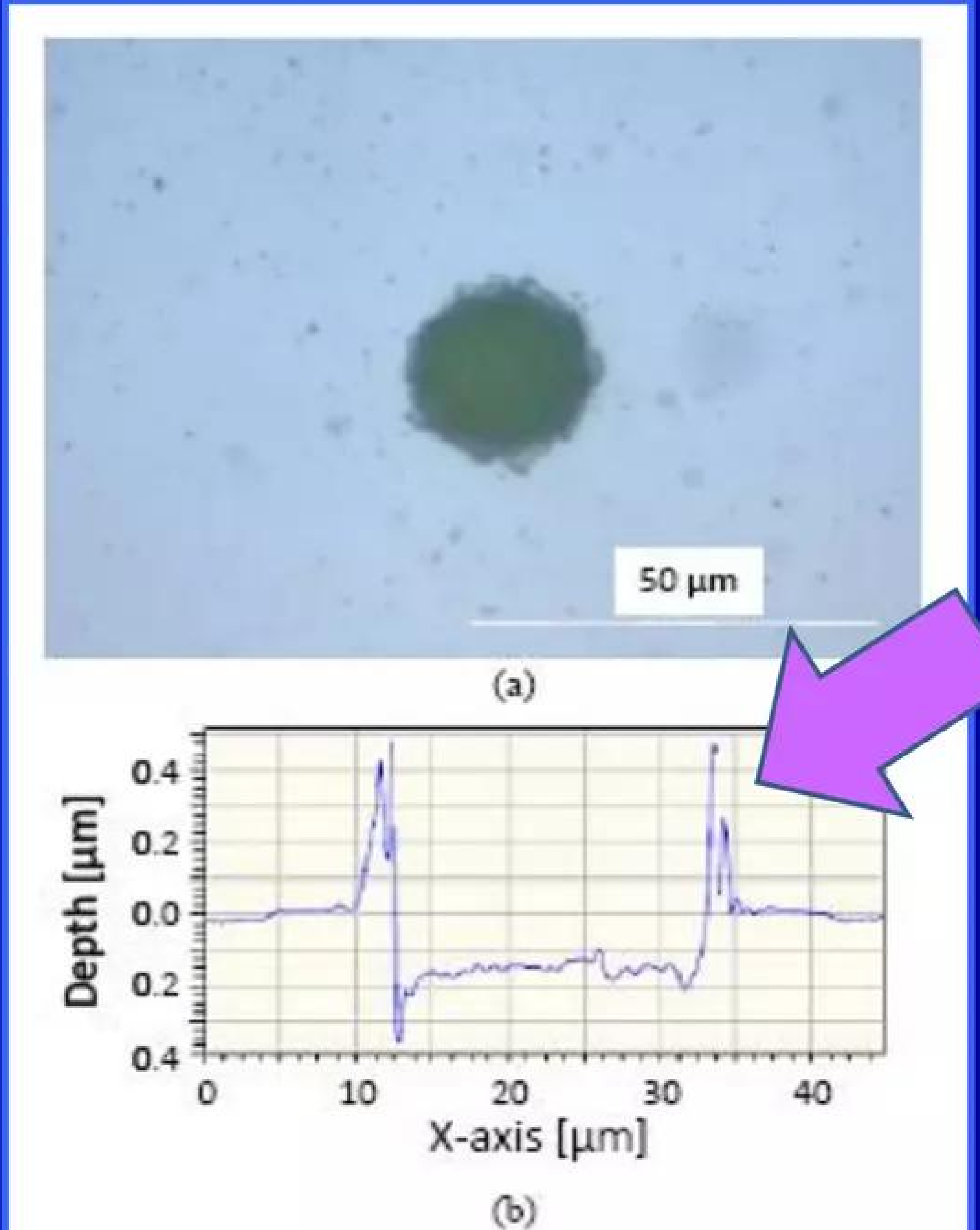


Fig. 6 (a) Optical microscope image of ps laser ablated cathode crater on LEP. Single pulse ablation, 532nm, 10ps, 2.5µJ; Bar 50µm, (b) Depth profile of the ablated crater, depth~140nm. Scale (X):2.5µm/div, (Y):25nm/div.

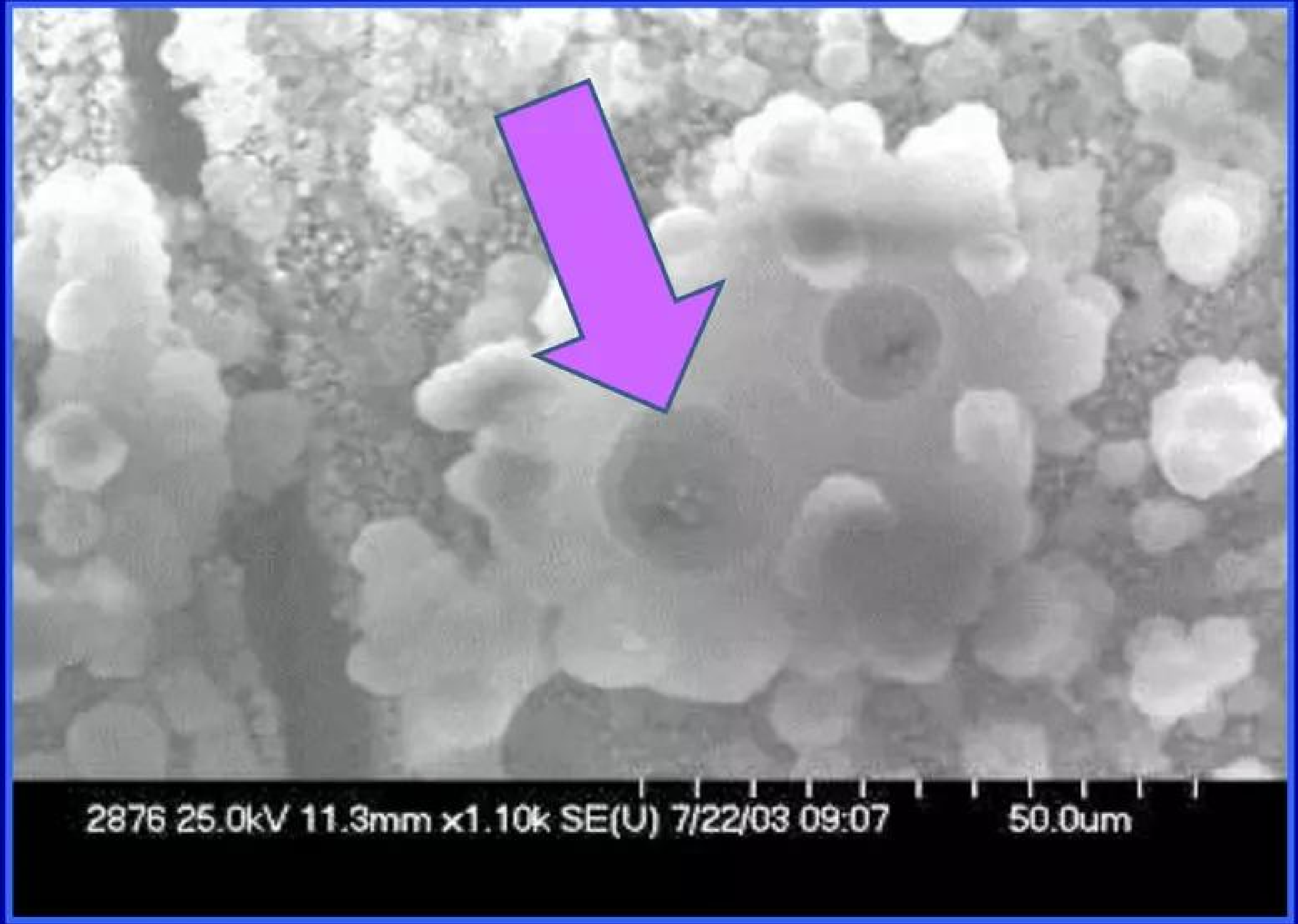
Quoting from Karnakis *et al.*:

"Laser irradiation at fluences between 137-360 *m*J/cm^2 removed the cathode layer only, resulting in a uniform flat floor and an intact LEP surface, allowing a relatively wide process window for cathode removal.

A typical example of such laser patterned Ba/Al cathode layer on the OLED stack is shown in Figure 6.

The average fluence was 230 mJ/cm^2 irradiated with an estimated spot diameter at 1/*e*^{2} of 35 *µm*.

This resulted in a crater diameter of 21.5 *µm*."



LENR Pd surface post-experiment: P. Boss *et al.* US Navy - SPAWAR

Excerpted and quoted directly from:

"*Ultrafast laser patterning of OLEDs on flexible substrate for solid-state lighting*"
D. Karnakis, A. Kearsley, and M. Knowles
***Journal of Laser Micro/Nanoengineering* 4 pp. 218 - 223 (2009)**
http://www.jlps.gr.jp/jlmn/upload/25e2c628adb23db70b26356271d20180.pdf

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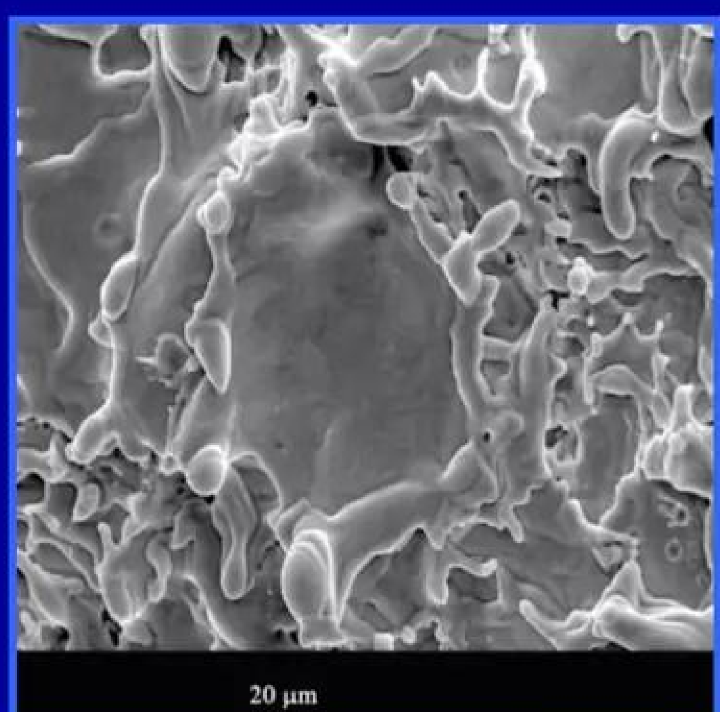
Morphological similarities between arc ‘craters’ and LENRS

Note quenched droplets ‘frozen’ in mid-formation on ‘crater’ rims

Anders’ SEM photos vs. selected images of post-experiment surfaces in LENR experiments:

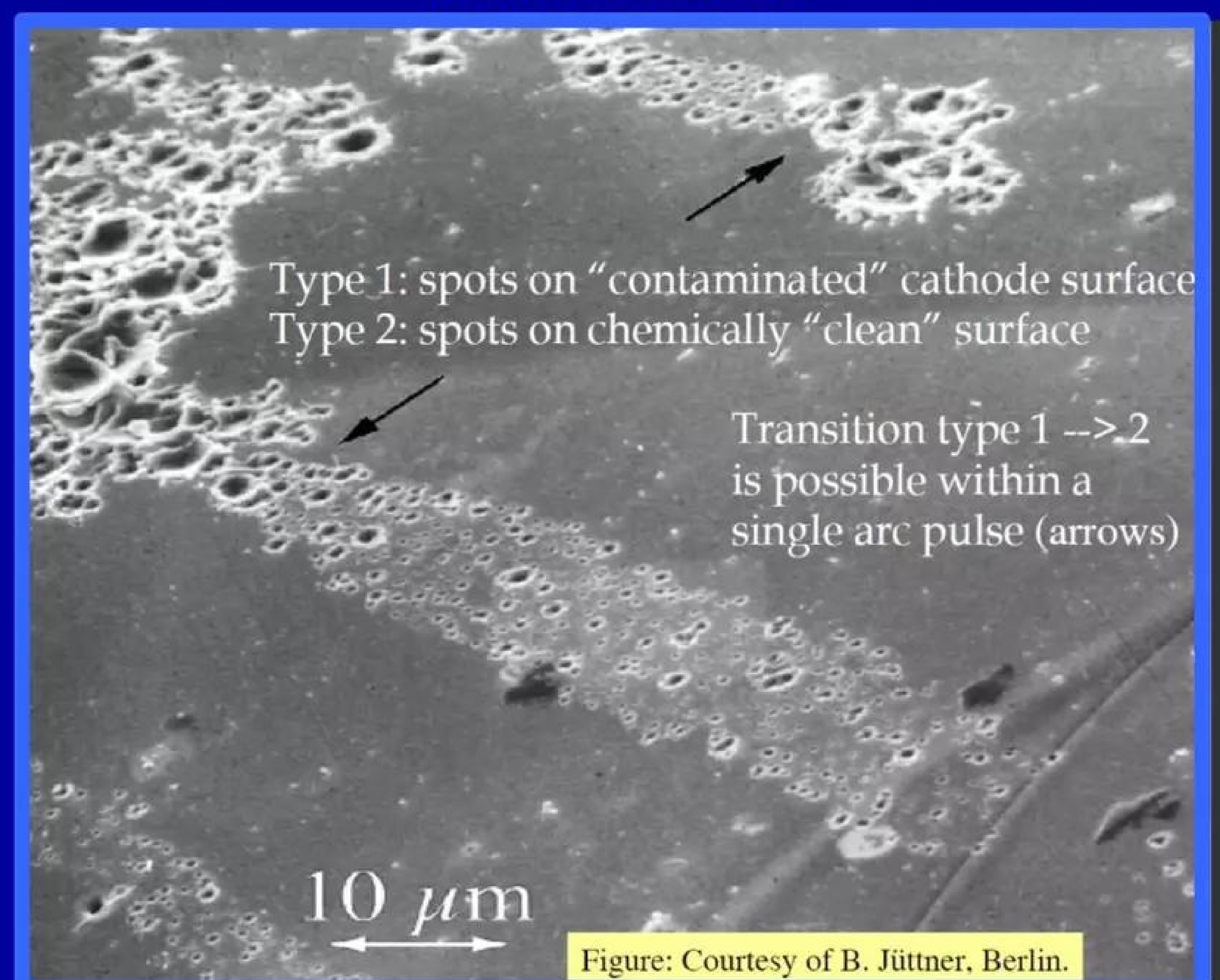
Cathodic Arcs



A. Anders “*Cathodic Arcs, and related phenomena*” (2010)

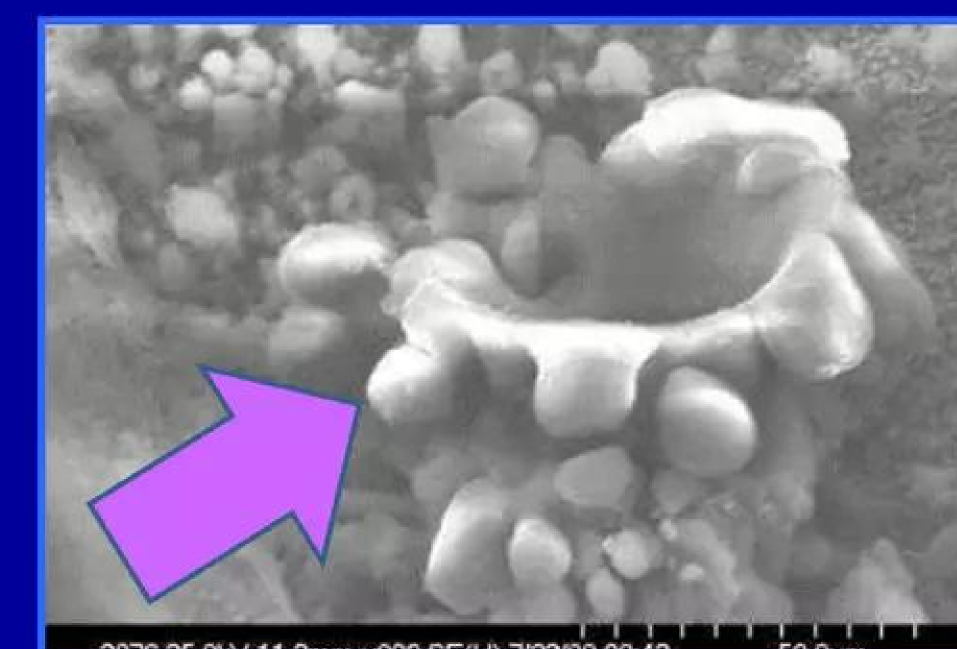
Cathodic Arcs

Anders: Slide #27

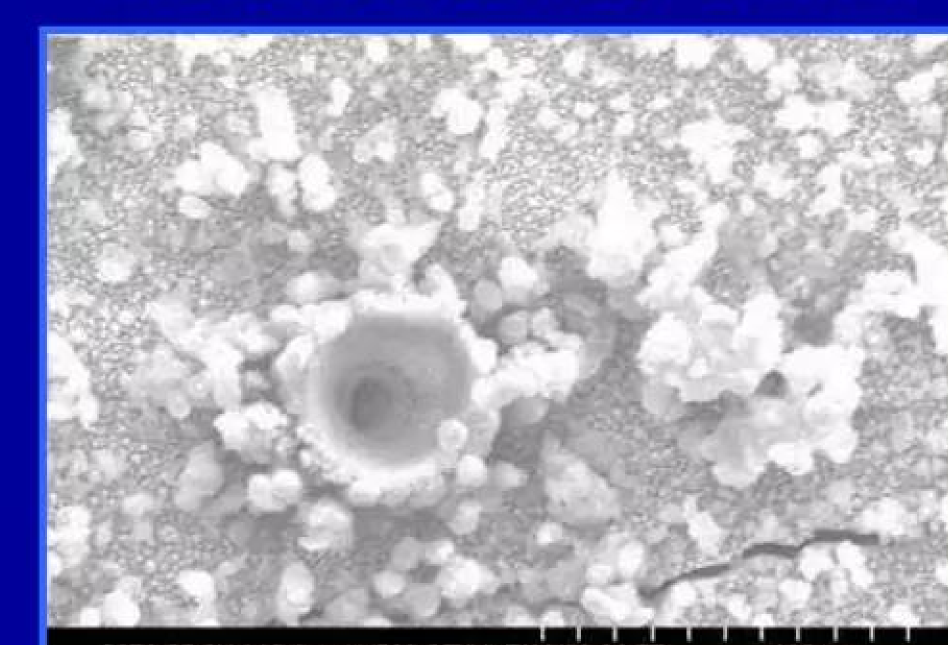


A. Anders “*Cathodic Arcs, and related phenomena*” (2010)

LENRs



Pd surface post-experiment SEM
P. Boss *et al.* , US Navy - SPAWAR



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Morphological similarities between arc 'craters' and LENRS

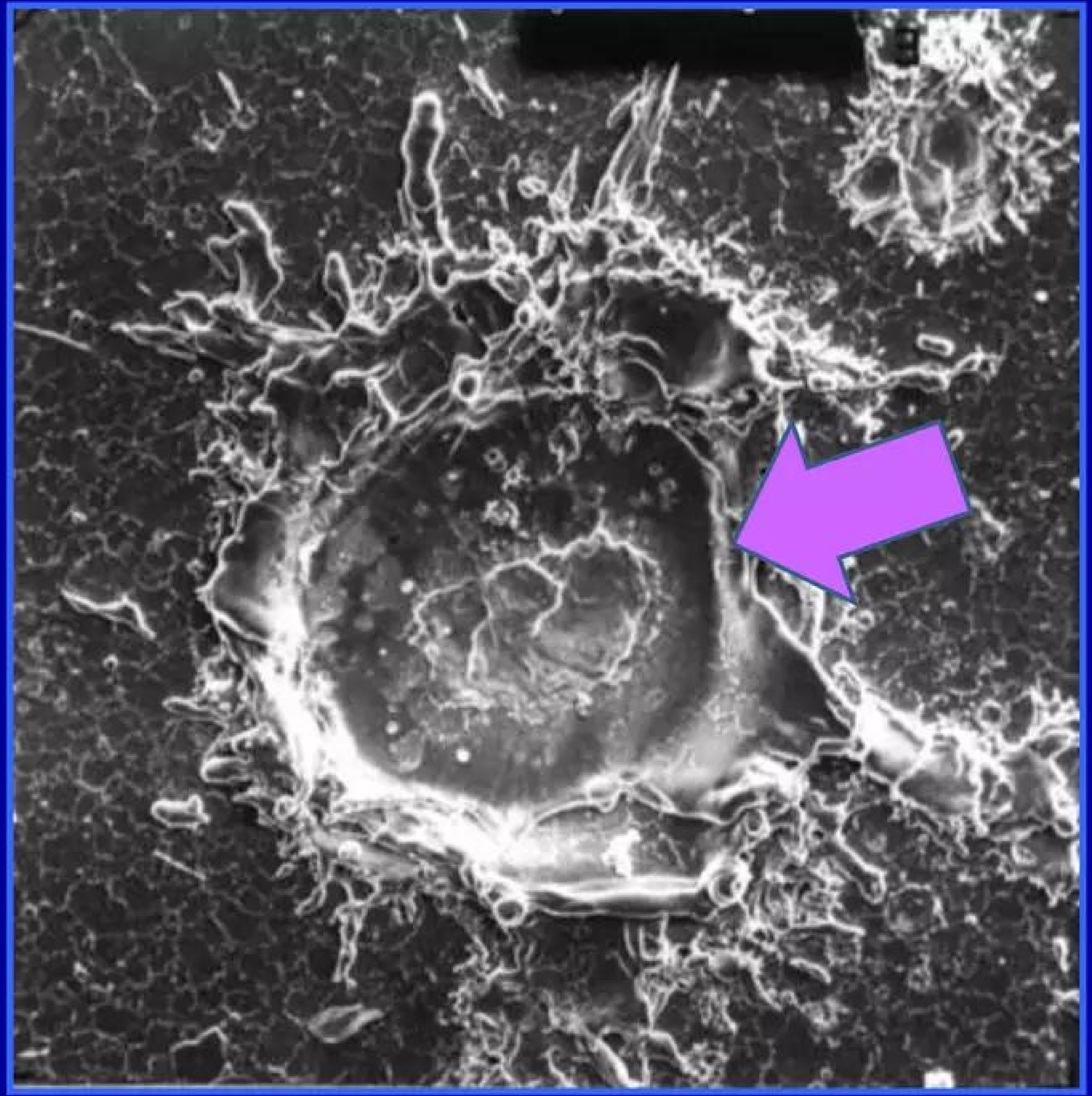
Note much higher aspect-ratios of some LENR crater-like structures

<u>Anders' SEM photos vs. selected images of post-experiment surfaces in LENR experiments</u>:

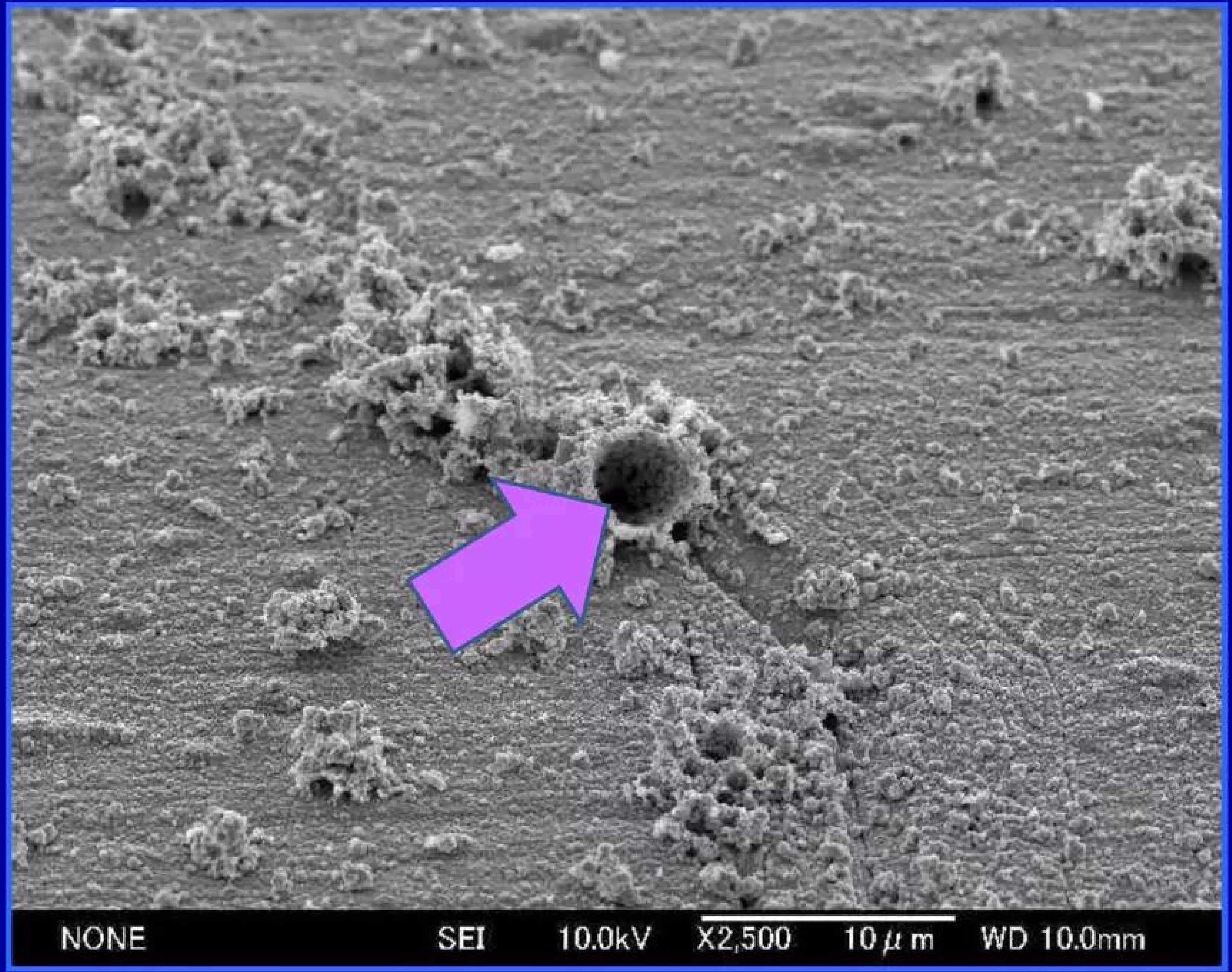
Cathodic Arcs

LENRs

<u>Free copy of paper</u>: http://www.lenr-canr.org/acrobat/ToriyabeYelementala.pdf



<u>A. Anders</u>: "*Cathodic Arcs, and related phenomena*," Slide #12 of 32 (2010)



"*Elemental analysis of palladium electrodes after Pd/Pd light water critical electrolysis*" Y. Toriabe *et al*., Fig. 9

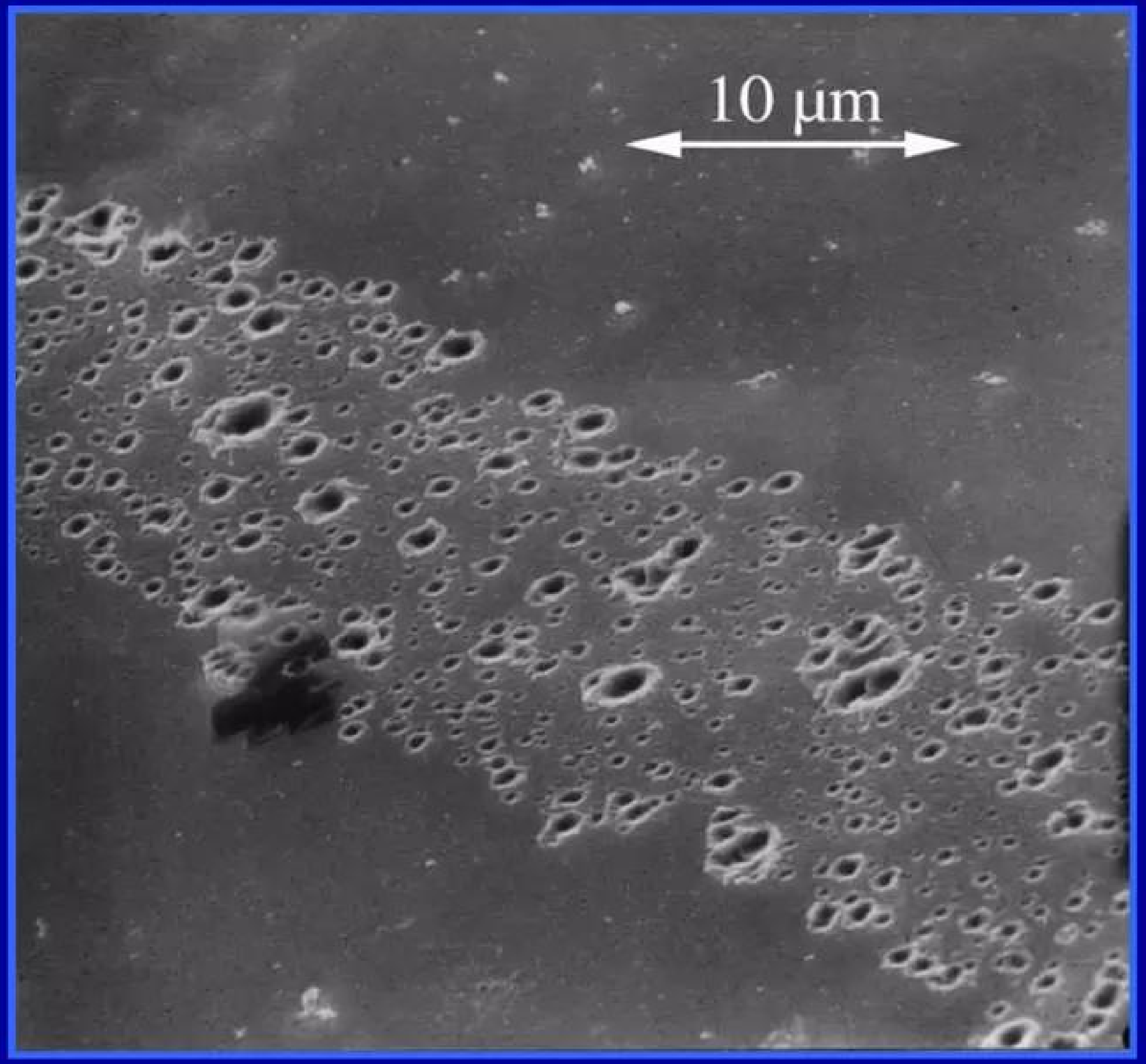
Morphological similarities between arc 'craters' and LENRS

Anomalous non-contaminant elements seen near LENR-active sites

Anders' SEM photos vs. selected images of post-experiment surfaces in LENR experiments:

Cathodic Arcs

A. Anders "Cathodic Arcs, and related phenomena" (2010)



A. Anders: Spot Type 1 - "*contaminated*" surface

LENR surface shown to right, which started-out smooth at the beginning of the experiment, appears to be much rougher in texture than the cathodic arc

Free copy of Zhang and Dash paper at:

http://www.lenr-canr.org/acrobat/ZhangWSexcessheat.pdf

Quoting from discussion of Fig. 10: "Ni was listed as "not detected" in the chemical analysis provided by the vendor of the Pd foil. It is very unlikely to have resulted from the cold rolling process or from electrodeposition because it is highly localized near one corner of the cathode. If it is the result of either contamination from the rolling mill or from electroplating it should not be highly localized on only one corner of the cathode. It could not have resulted from SEM systems because the stainless steel components of the SEM chamber also contain Fe and Cr. Fe and/or Cr are not present in any of the spectra. The SEM does not have components made of pure Ni. Therefore, the origin of the Ni is not known.".

LENRs

Zhang and Dash (2007) --- Fig. 10. SEM picture of region #2 in Fig. 4(b). SEM No.WS060424Pd-H-CC-i2-150X

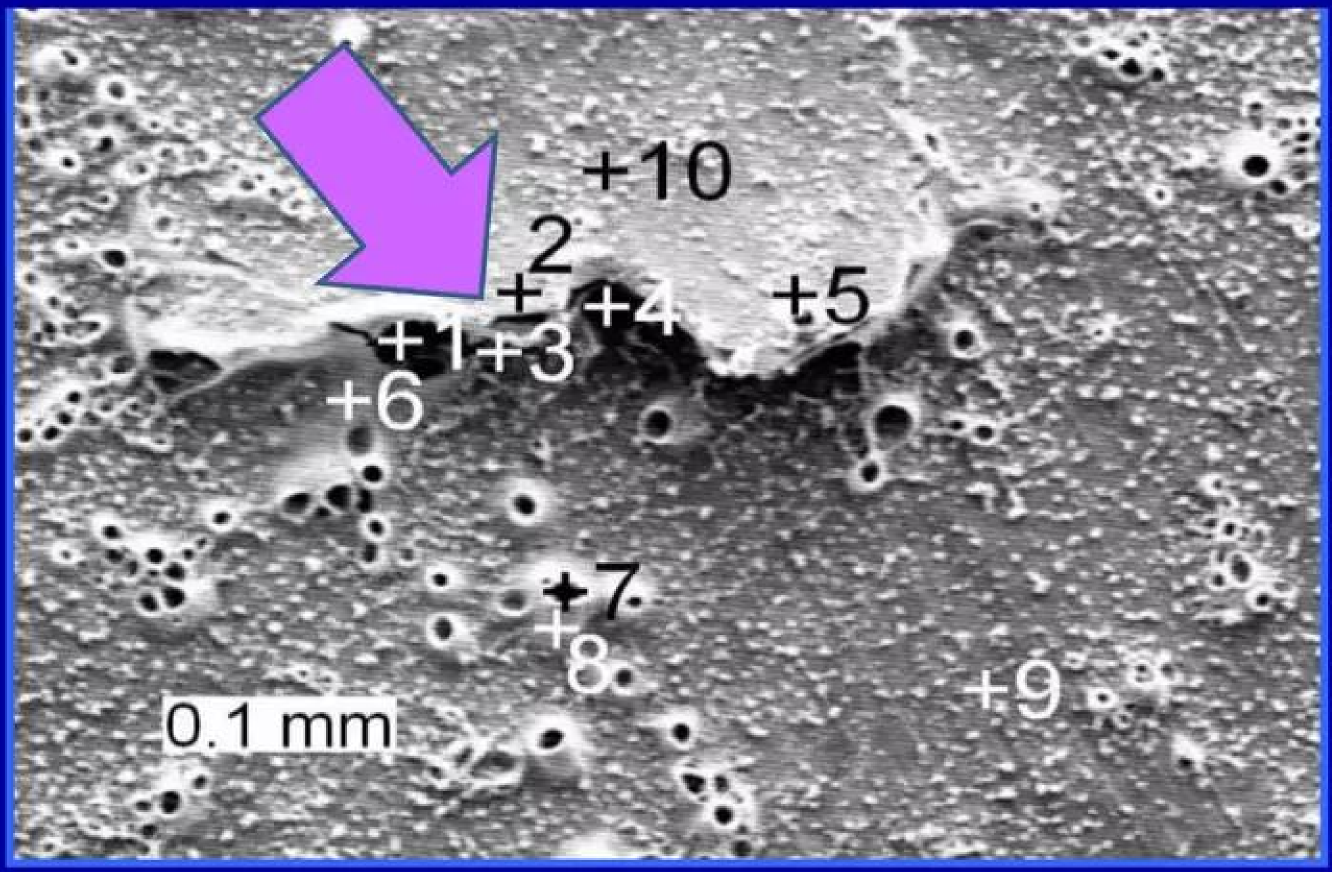
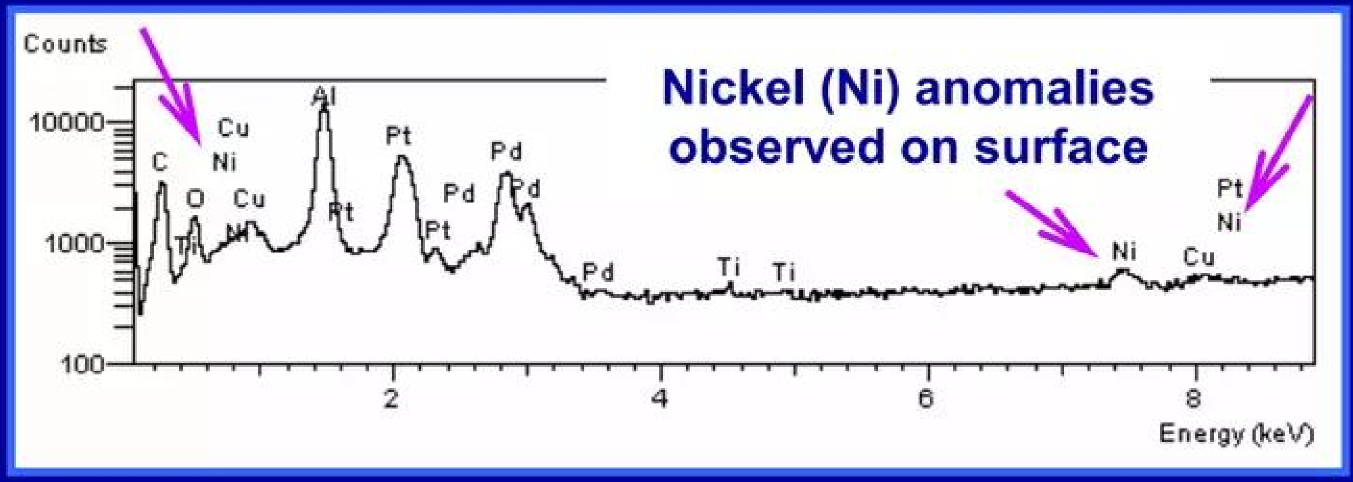


Fig. 11. Characteristic X-ray spectrum of spot #1 in Fig. 10.



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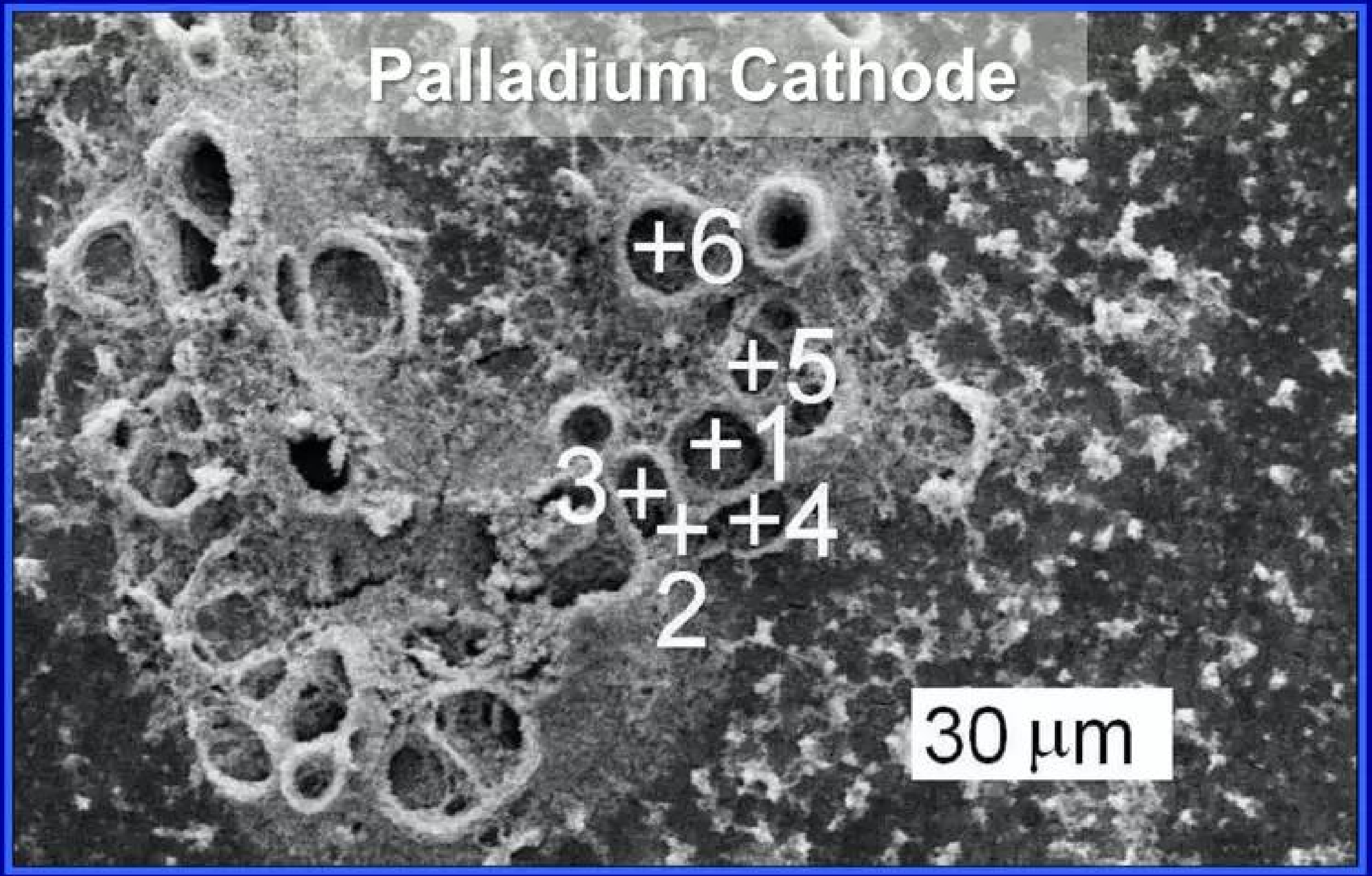
LENR transmutation products can be found near 'craters'

Number of other researchers have also observed this with SIMS

Selected images of post-experiment surfaces in LENR experiments by Zhang and Dash:

LENRs: Zhang and Dash (2007) - Fig. 8



Note: Pd surface b.p. = 2,970° C

Free copy of Zhang and Dash paper at:

http://www.lenr-canr.org/acrobat/ZhangWSexcessheat.pdf

LENRs: Zhang and Dash (2007) - Fig. 9

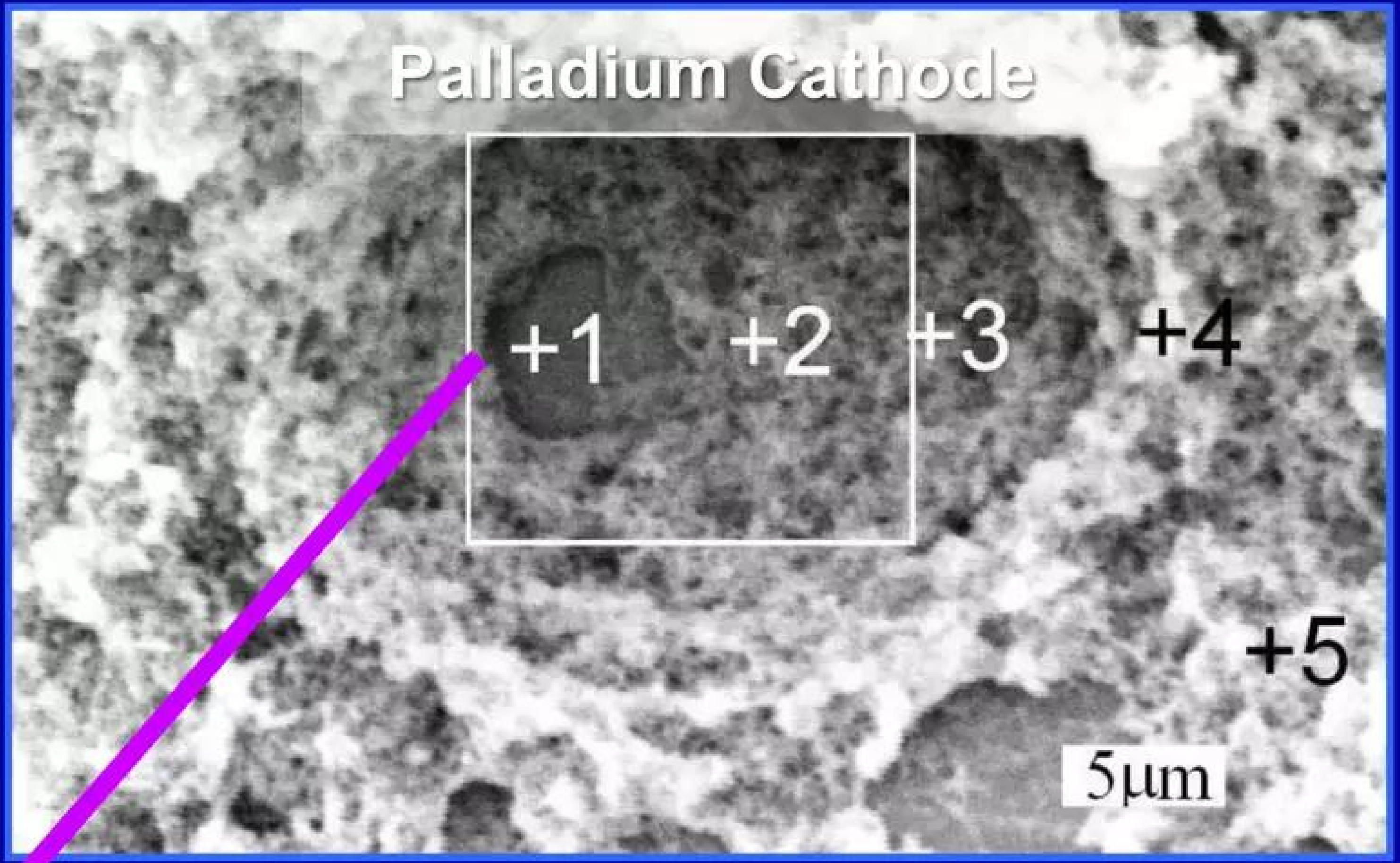


Fig. 9. SEM picture of crater at another time. SEM No.WS060607Pd-H-CC-i2-2kX

Quoting: "The most common finding is that silver occurs in craters, such as those shown in Fig. 8. These craters with rims almost certainly formed during electrolysis. Pt deposition was concentrated on these protruding rims."

Zhang and Dash: Table IX. Relative atomic percent concentrations of silver (Ag) in area and spots shown in Fig. 9

Spot #	wa*	area**	+1	+2	+3	+4	+5
Ag/(Pd+Ag)	1.2 +/- 0.5	5.6 +/- 0.4	6.8 +/- 0.4	5.6 +/- 0.3	6.3 +/- 0.4	3.6 +/- 0.6	1.2 +/- 0.5

*wa = whole entire area comprising image in Fig. 9

** area = delimited by the white square outlined in Fig. 9

Following likely took place in these experiments:

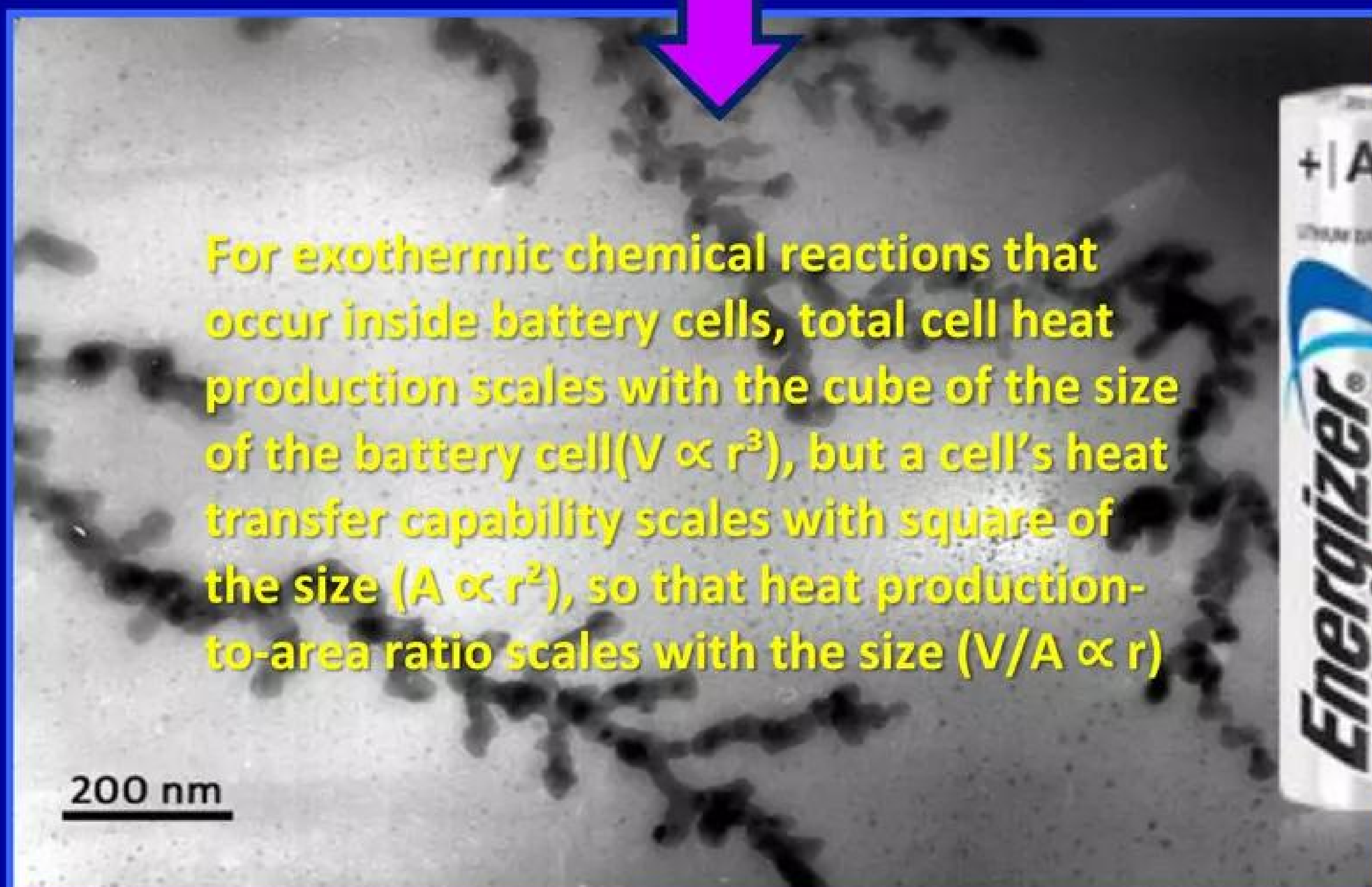
Pd + *n* → (neutron capture) unstable *n*-rich Pd isotope → (beta decay) Ag isotopes

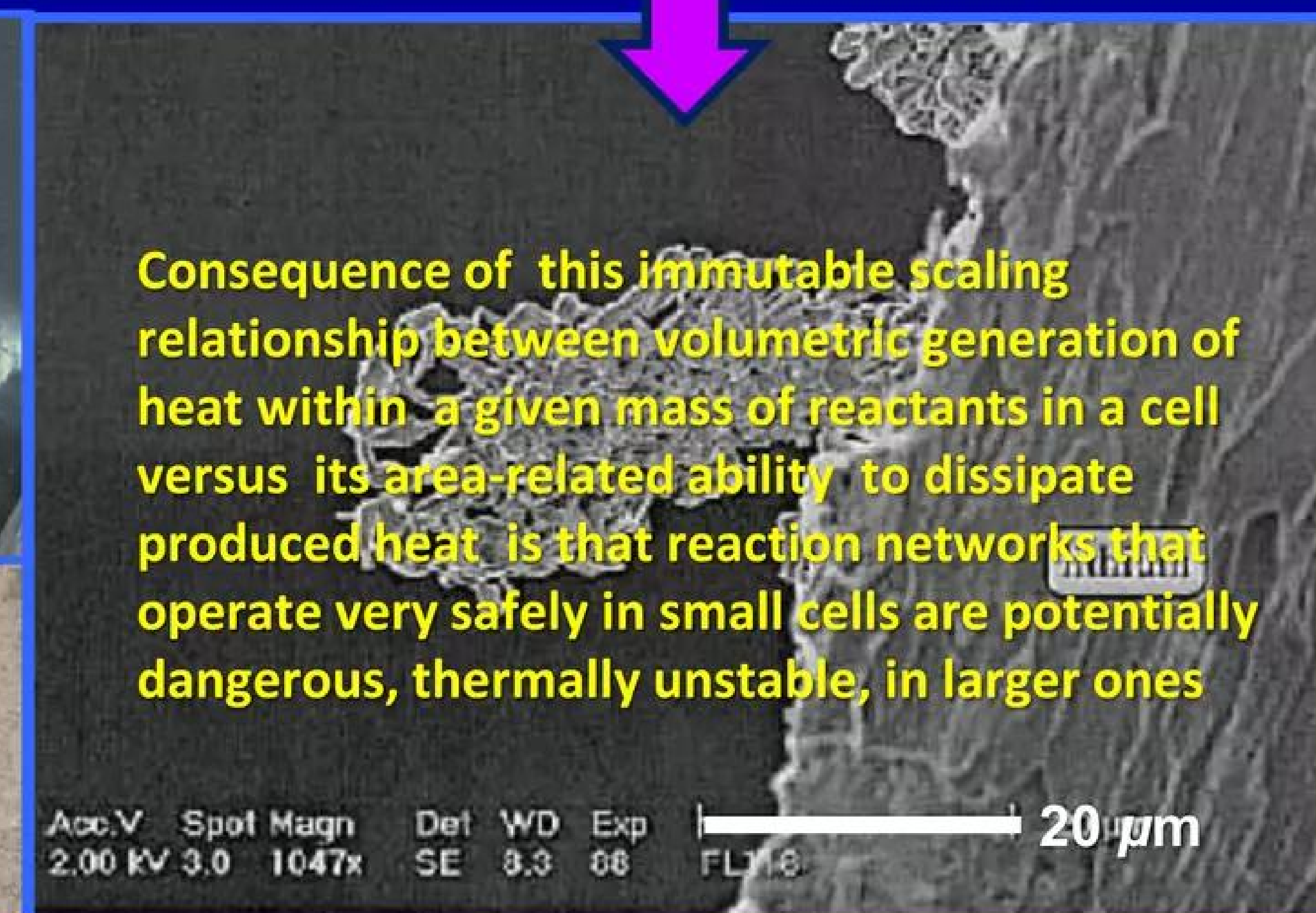
Arcs and LENRS are both extremely energetic processes

Uncontrolled heating can lead to thermal runaways of varying severity

Lithium metal ‘classic’ dendrites growing in solid polymer electrolyte

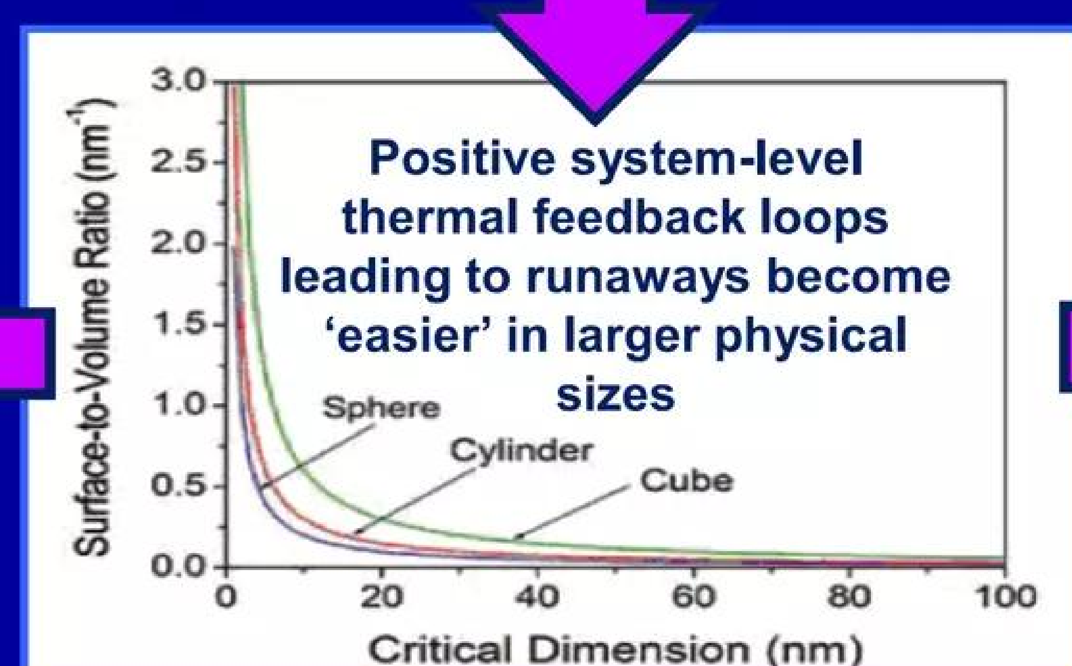
‘Mossy’-type Lithium dendrite growing in solid polymer electrolyte





Scale-up of the internal energy densities, electrical capacity, and sheer physical size of battery systems can lead to much larger thermal runaway events

Zotye M300 EV taxi - Hangzhou, China (2011)



Surface area vs. volume decreases with increased size

Boeing 787 Dreamliner - Logan Airport, Boston (2013)

Lattice Energy LLC

Arcs/LENRs can trigger very exothermic chemical reactions

Their high temps can melt/decompose/vaporize/ignite anything in cell

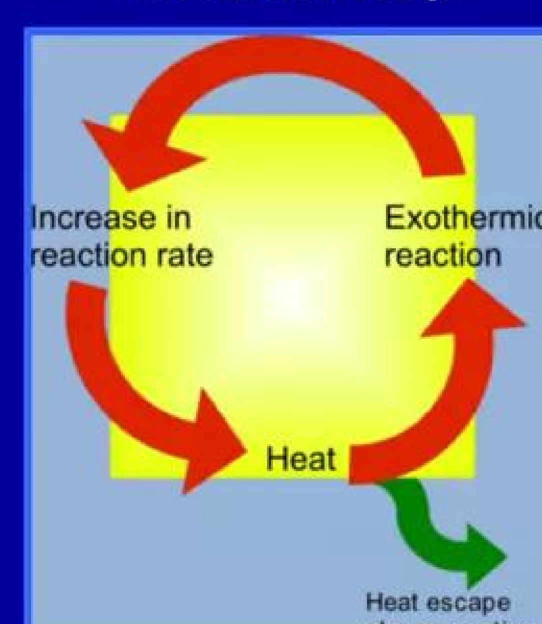
Causative agent that can trigger thermal runaways	Regime or requirements	Physical dimensions	Key details	Temperature range in ^{o} C	Comments
Electric discharges: that is, **arcs or sparks**; alternative names for internal electrical short circuits that can occur inside battery cells	Outer 'edges' of tubular arc plasma sheath	Arc lengths can range in length from 2 *nm* between metallic nanoparticles all the way up to as long as several centimeters (*cm*) between larger structures	Chemical and nuclear reactions can occur within; dep. on current	~2,727 up to ~4,727	Heat radiation is mainly created via Joule heating by electrons and ions found in arc discharge plasma; very damaging to materials; can even breach battery cell case
	Innermost core of arc plasma's tubular sheath-like structure			~9,726 up to ~19,726	
LENR-active 'hotspots': can occur on metallic surfaces or at oxide-metal interfaces anywhere inside battery where be: e^-, p^+ and metals	Require local presence of hydrogen (protons), metals, and surface plasmon or π electrons	2 nanometers (*nm*) to as large as ~100^+ microns (μ) in diameter; roughly circular in shape	MeV-energy nuclear reactions occur within	~3,700 up to ~5,700	Directly radiate infrared heat photon energy; ionizes nearby molecules, materials, destroys μ-scale nanostructures

Extremely high temperatures can drive very complex, rapidly evolving chemical reaction networks

Scale-up of the internal energy densities, electrical capacity, and sheer physical size of battery systems can lead to much larger thermal runaway events

Zotye M300 EV taxi - Hangzhou, China (2011)

Runaway thermal feedback loop



Renault F1 car: Li-ion battery in KERS system (2011)

Lattice Energy LLC

Arcs or LENRs trigger very exothermic chemical reactions

Heating accelerates chemical reactions and drives complex networks

- ✓ Within as little as milliseconds after the creation of an electric arc or LENR-active site, *nm*- to *cm*-scale local regions of a battery cell at or near such locations can become a super-hot, fiendishly complicated chemical "*witches' brew*"[1.] consisting of many different types of old and newly created compounds, expected thermal decomposition products, various ionized species, and many mutually competing chemical reaction pathways
- ✓ Positive thermal (heat) feedback loop: the hotter a given region gets, the faster local chemical reactions accelerate therein and the more widely the conflagration spreads into previously unaffected regions of a given battery cell (this is causative root of "*thermal runaway*" effect and "*thermal fratricide*" between cells)
- ✓ Evolution of such complex chemical systems is very rapid and incompletely understood - quite unpredictable with respect to final results: outcomes can range from minor thermal damage to single cell; to combustion of flammable electrolytes and charring of materials inside case and outside via venting; and at worst, to complete combustion of all materials located inside of and including cell casings --- even all contents of surrounding multi-cell enclosures; worst-case 'Armageddon' scenarios involve thermite-like, violent pyrotechnic processes

Causative agent that can trigger thermal runaways	Regime or requirements	Physical dimensions	Key details	Temperature range in º C	Comments
Electric discharges: that is, arcs or sparks; alternative names for internal electrical short circuits that can occur inside battery cells	Outer 'edges' of tubular arc plasma sheath	Arc lengths can range in length from 2 *nm* between metallic nanoparticles all the way up to as long as several centimeters (*cm*) between larger structures	Chemical and nuclear reactions can occur within; dep. on current	~2,727 up to ~4,727	Heat radiation is mainly created via Joule heating by electrons and ions found in arc discharge plasma; very damaging to materials; can even breach battery cell case
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LENR-active 'hotspots': can occur on metallic surfaces or at oxide-metal interfaces anywhere inside battery where be: e^-, p^+ and metals	Require local presence of hydrogen (protons), metals, and surface plasmon or π electrons	2 nanometers (*nm*) to as large as ~100⁺ microns (μ) in diameter; roughly circular in shape	MeV-energy nuclear reactions occur within	~3,700 up to ~5,700	Directly radiate infrared heat photon energy; ionizes nearby molecules, materials, destroys μ-scale nanostructures

1. As far as known, the term "witches' brew" was first used in this context by Prof. Michel Armand (Univ. Picardie, Paris, France)

Lattice Energy LLC

Arcs or LENRs trigger very exothermic chemical reactions

Heating accelerates chemical reactions and drives complex networks

- ✓ If electric arc plasmas and/or micron-scale LENR-active hotspots happen to occur on or near battery materials or structures containing Oxygen, e.g., such as a battery cathode (Li_xCoO_2); electrolytes such as Diethyl carbonate ($C_5H_{10}O_3$) or Dimethoxyethane ($C_4H_{10}O_2$); or whatever may contain Oxygen, these compounds can be thermally decomposed which can in turn rapidly release reactive gaseous Oxygen to support combustion. If local heat-pulse from a given arc or LENR-hotspot is large relative to rate at which thermal energy can be transported away from an affected area, can potentially create an aggressive self-propagating flame-front that creates own Oxygen supply as it consumes materials (would burn in a vacuum)
- ✓ Huge phase-change volume expansion of many metals when flash-vaporized: expansion factor for common transition metals on order of >50,000x; though volumes involved may be tiny, can damage nearby materials
- ✓ *Dangerous* nano-thermites (see Wikipedia at http://en.wikipedia.org/wiki/Nano-thermite) can potentially form in super-heated regions of failing battery, e.g., Aluminum-copper(II) oxide; Aluminum-iron(II,III) oxide, etc.

Causative agent that can trigger thermal runaways	Regime or requirements	Physical dimensions	Key details	Temperature range in ^{o} C	Comments
Electric discharges: that is, arcs or sparks; alternative names for internal electrical short circuits that can occur inside battery cells	Outer 'edges' of tubular arc plasma sheath	Arc lengths can range in length from 2 *nm* between metallic nanoparticles all the way up to as long as several centimeters (*cm*) between larger structures	Chemical and nuclear reactions can occur within; dep. on current	~2,727 up to ~4,727	Heat radiation is mainly created via Joule heating by electrons and ions found in arc discharge plasma; very damaging to materials; can even breach battery cell case
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Lattice Energy LLC

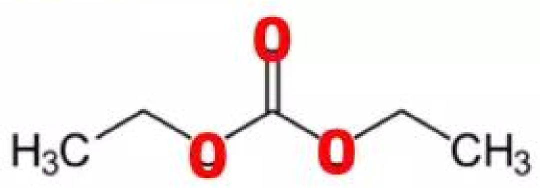
Arcs or LENRs trigger very exothermic chemical reactions

Electrolytes are readily ignited by these two types of energetic processes

GS Yuasa 878 Dreamliner battery: it is unspecified by either Yuasa or the NTSB; could possibly be either diethyl carbonate or perhaps dimethoxyethane

Diethyl carbonate $C_5H_{10}O_3$

Melting point: - 43° C
Boiling point: 126 - 128° C
Flash point: 25 - 33° C
Auto-ignition: 458° C



Comment: readily forms explosive mixtures at >25° C when exposed to air; combusted: forms carbon monoxide/dioxide

Dimethoxyethane $C_4H_{10}O_2$

Melting point: - 58° C
Boiling point: 85° C
Flash point: - 2° C
Auto-ignition: 202° C

Comment: ignitable under most ambient temperature conditions; can serve as alternative fuel for gas turbines

In either, LENR-active hotspots and/or electric discharge arcs can trigger *at least local* combustion of electrolyte

Causative agent that can trigger thermal runaways	Regime or requirements	Physical dimensions	Key details	Temperature range in ° C	Comments
Electric discharges: that is, arcs or sparks; alternative names for internal electrical short circuits that can occur inside battery cells	Outer 'edges' of tubular arc plasma sheath	Arc lengths can range in length from 2 *nm* between metallic nanoparticles all the way up to as long as several centimeters (*cm*) between larger structures	Chemical and nuclear reactions can occur within; dep. on current	~2,727 up to ~4,727	Heat radiation is mainly created via Joule heating by electrons and ions found in arc discharge plasma; very damaging to materials; can even breach battery cell case
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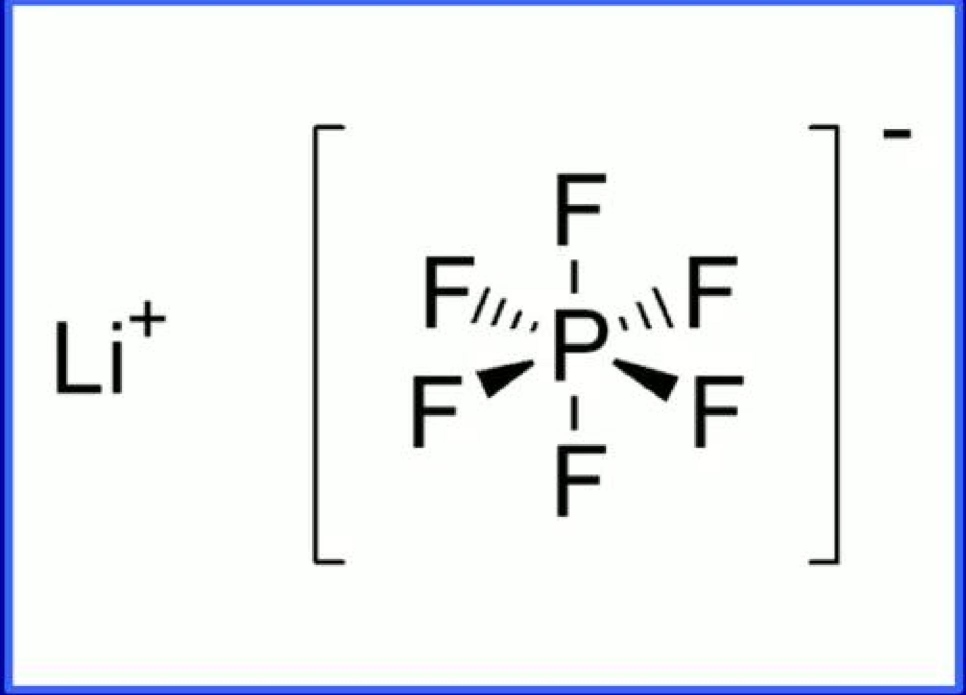
LENR-active 'hotspots': can occur on metallic surfaces or at oxide-metal interfaces anywhere inside battery where be: e^-, p^+ and metals	Require local presence of hydrogen (protons), metals, and surface plasmon or π electrons	2 nanometers (*nm*) to as large as ~100^+ microns (μ) in diameter; roughly circular in shape	MeV-energy nuclear reactions occur within	~3,700 up to ~5,700	Directly radiate infrared heat photon energy; ionizes nearby molecules, materials, destroys μ-scale nanostructures

Lattice Energy LLC

Arcs or LENRs trigger very exothermic chemical reactions

Lithium salt in electrolyte readily undergoes thermal decomposition

B787 GS Yuasa = $LiPF_6$ Lithium hexafluorophosphate:



- ✓ **Identified in NTSB report as being detected during post-Logan incident materials analysis; right: ionic molecular structure**
- ✓ **Chosen for ferrying Li^+ ions between anode and cathode because highly soluble in non-aqueous, nonpolar electrolyte solvents such as diethyl carbonate and dimethoxyethane**
- ✓ **Melts at ~194^o C; thermal decomposition begins 262- 284^o C; then decomposes into LiF and PF_5 - see comment to right**

Formation of LiF releases one of the highest known energy *per mass of reactants*, only second to that of BeO

Causative agent that can trigger thermal runaways	Regime or requirements	Physical dimensions	Key details	Temperature range in ^{o} C	Comments
Electric discharges: that is, arcs or sparks; alternative names for internal electrical short circuits that can occur inside battery cells	Outer 'edges' of tubular arc plasma sheath	Arc lengths can range in length from 2 *nm* between metallic nanoparticles all the way up to as long as several centimeters (*cm*) between larger structures	Chemical and nuclear reactions can occur within; dep. on current	~2,727 up to ~4,727	Heat radiation is mainly created via Joule heating by electrons and ions found in arc discharge plasma; very damaging to materials; can even breach battery cell case
	Innermost core of arc plasma's tubular sheath-like structure			~9,726 up to ~19,726	
LENR-active 'hotspots': can occur on metallic surfaces or at oxide-metal interfaces anywhere inside battery where be: e^-, p^+ and metals	Require local presence of hydrogen (protons), metals, and surface plasmon or π electrons	2 nanometers (*nm*) to as large as ~100^+ microns (μ) in diameter; roughly circular in shape	MeV-energy nuclear reactions occur within	~3,700 up to ~5,700	Directly radiate infrared heat photon energy; ionizes nearby molecules, materials, destroys μ-scale nanostructures

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Arcs or LENRs trigger very exothermic chemical reactions

Formation of LiF from thermal decomposition of $LiPF_6$ battery salt

This process produces lots of heat and a strongly reactive Lewis acid, PF_5

Formation of solid lithium fluoride from the gaseous Li^+ and F^- ions:

$$Li^+(g) + F^-(g) \longrightarrow LiF(s)$$

Formation of solid lithium fluoride from the gaseous Li^+ and F^- ions:

$$Li^+(g) + F^-(g) \longrightarrow LiF(s)$$

This corresponds to the lattice energy for LiF, which is −1047 kJ/mol.

Since the sum of these five processes yields the desired overall reaction the sum of the individual energy changes gives the overall energy change:

	Process	Energy Change (kJ)
	$Li(s) \rightarrow Li(g)$	161
	$Li(g) \rightarrow Li^+(g) + e^-$	520
	$\frac{1}{2}F_2(g) \rightarrow F(g)$	77
	$F(g) + e^- \rightarrow F^-(g)$	−328
	$Li^+(g) + F^-(g) \rightarrow LiF(s)$	−1047
Overall:	$Li(s) + \frac{1}{2}F_2(g) \rightarrow LiF(s)$	−617 kJ (per mole of LiF)

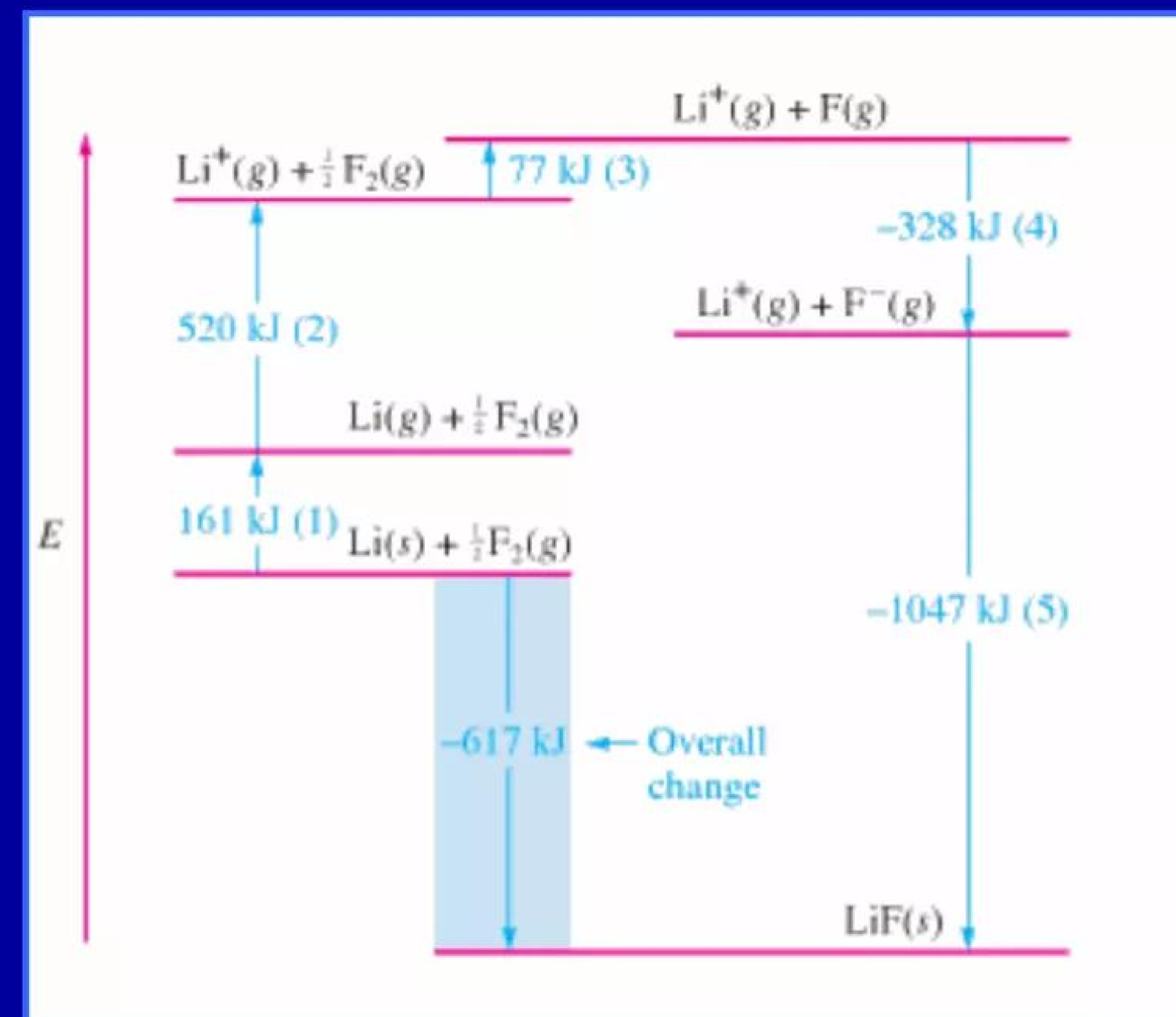

Figure 13.9 in Zumdahl

Source: "*Chemical Principles*" S. Zumdahl, pp. 608 in 6th edition, Houghton Mifflin (2009)

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Arcs or LENRs trigger very exothermic chemical reactions

PF_5 then attacks battery cell electrolytes, releasing copious CO_2 gas

Voluminous production of Carbon dioxide can force venting of electrolytes

- ✓ **"The main effect on safety is that the large and sudden generation of [CO_2] gas causes the cell to vent and release gas and flammable electrolyte solvent vapor, possibly generating an explosive fuel-air mixture [inside the enclosure for the battery cells]. Ignition of these vapors can then result in damage and rupture of other cells [depending on their proximity] as well as ignition of other materials in the battery. In the worst case outcome, this can result in a cascading failure of cells leading to a much larger release of energy."**

- ✓ **"Gas generation will result whenever the cell reaches the solvent decomposition temperature, whether from internal or external sources. Even the safest cathode chemistries will not prevent this release of flammable vapors. The volume of gas released from a cell in full thermal runaway is more than can be contained by any standard cell fixture, either pouch or laser-welded can. Many cell designs purposely allow gases to be released through a designed vent. Measurements … have shown that volumes of gas released at the end of the thermal runaway peak [they specifically state that it is, "*…typically 350^o C*"] were all nearly equal (normalizing for cell capacities) … volume of electrolyte used in cell construction is a main factor in predicting gas generation volume and vent response."**

- ✓ **"The energy released by electrolyte combustion is several times larger than the electrical energy stored in a battery. However, the amount of oxygen released by even some of the most reactive cathodes is not nearly sufficient to cause complete combustion of the cell electrolyte … [they state it is only 5 - 15% in case of Li-Ni-Mn-Co oxide] … largest source of oxidizable material is the vented solvents which, if burned in air, have an energy release several times that of the self-contained reaction enthalpies of the electrode materials."**

Source: "*How electrolytes influence battery safety*," E. Roth and C. Orendorff, The Electrochemical Society *Interface* pp. 45 - 49 (2012) http://www.electrochem.org/dl/interface/sum/sum12/sum12_p045_049.pdf

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Arcs or LENRs trigger very exothermic chemical reactions

If arcs/LENRs are trigger, can release much more Oxygen from materials

In local regions heated by arcs or LENRs, CO and even CO_2 can decompose

Lattice comments re Roth & Orendorff:

- ✓ Temperatures inside catastrophically failing Li-ion batteries rapidly become very heterogeneous: large regions may be at hundreds of ^{o}C while tiny localized volumes can be at *thousands* of degrees
- ✓ They seem to imply that ~450^{o} C is maximum "full thermal runaway" temperature peak; *au contraire*, in much rarer cases where arcs or LENRs happen to be causative triggers, worst-case Armageddon peak temps in large regions of battery cells or enclosures might reach *thousands of degrees C*
- ✓ As shown herein, stainless steel microspheres created during Logan runaway event prove that temperatures in at least some small regions of cell #5 reached values >3,000 degrees Centigrade

- At ~1,626^{O} C: large proportion of CO_2 will thermally decompose into CO and O_2: Y. Nigara and B. Cales, "*Production of carbon monoxide by direct thermal splitting of carbon dioxide at high temperature,*" *Bull. Chem. Soc. Jpn.* 59 pp. 1997 - 2002 (1986)
- At ~400 - 600^{O} C: in the presence of catalytic Iron oxide nanoparticles (likely present near superheated Fe alloy battery case) CO will thermally decompose into pure Carbon (forms nanotubes under certain conditions) and CO_2: O. Prilutskiy *et al.*, "*Synthesis of carbon nanomaterials by a catalytic disproportionation of Carbon monoxide,*" *Fullerenes, Nanotubes, and Carbon Nanostructures* 13 pp. 1 - 15 (2005)
- Note: might be very interesting to see whether carbon nanotubes of some sort can be detected in post-failure analysis of battery debris after thermal runaway events, presuming that they're not present anywhere in Carbon anode to begin with

Arcs or LENRs trigger very exothermic chemical reactions

Thermal decomposition and combustion of cathode material: $LiCoO_2$

"You don't believe, we're on the eve of destruction"[2.]

- ✓ Hot LENR-active 'patches' situated in close proximity to both cathode material and plastic separator can locally melt separator and thus trigger electrical short arc discharges at such locations (polyethylene M.P. ~125^o C; polypropylene ~155^o C)
- ✓ "Thermal decomposition of $Li_{0.5}CoO_2$ by accelerated rate calorimetry (ARC) and X-ray diffraction (XRD) has been reported which states that the oxygen loss from the cathode remains above 200° C. However, the reaction of $Li_{0.5}CoO_2$ with ethylene carbonate: diethyl carbonate (EC: DEC) solvents starts at a temperature as low as 130° C which is much lower than the decomposition temperature of $Li_{0.5}CoO_2$." [decomposes at ~170^o C]
- ✓ "From DSC measurements for reaction of $Li_{0.49}CoO_2$ with electrolyte the authors reported two peaks, one at 190° C, due mainly to the decomposition of the solvent with the active cathode surface and the other at 230° C caused by oxygen release from $Li_{0.49}CoO_2$."
- ✓ "In (Maleki *et al*., 1999), the thermal stability study of fully charged 550 mAh prismatic lithium ion cell and the components inside the cell showed that the self-heating exothermic reactions start at 123° C and thermal runaway at 167° C."

Source of quotes: Doh & Veluchamy (2010)

2. Lyric from popular Vietnam war protest song written by P. F. Sloan and recorded by Barry McGuire titled "*Eve of Destruction*", Dunhill Records (1965)

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Arcs or LENRs trigger very exothermic chemical reactions

Thermal decomposition and combustion of cathode material: $LiCoO_2$

"You don't believe, we're on the eve of destruction"

- ✓ **"Reports state that an internal short is more dangerous than an external short, because the former (soft-nail test) induces an enormous heat instantaneously and locally to cause thermal runaway of the electrolyte and electrode materials."**
- ✓ **"Decomposition temperature decreases for Li_xCoO_2 as the x value decreases. The decline in the thermal stability of the cell on overcharge is also due to both removal of lithium ions from the cathode and deposition over anode surface."**
- ✓ **Meltdown of the separator and combustion of the organic electrolyte with the released oxygen would have been instantaneous to cause volume expansion and violent explosion … maximum dc power … is ~39W … cell surface temperature reaches 300°C."**
- ✓ **"At the instant the experiment is started, the voltage falls to zero and the surface temperature of the cell shoots up to 420°C which could only be attributed to a high surge of discharge current resulting in a high joule heat followed by separator meltdown and contact of the anode and cathode."**
- ✓ **GS Yuasa's MSDS document dated 2009 simply states that M.P. of $LiCoO_2$ > 1,000° C**

Source of quotes: Doh & Veluchamy (2010)

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Arcs or LENRs trigger very exothermic chemical reactions

Thermal decomposition and combustion of anode material: Carbon

When heated-up hot enough with Oxygen present a battery anode can burn

- ✓ Persistent, compositionally complex solid-electrolyte-interphase (SEI) layer forms on Carbon anode during 1st recharging cycle (unstable at >90° - 120° C)
- ✓ Once formed, SEI layer (which does not conduct electrons) chemically stabilizes and protects anode by shielding it from direct contact and further reaction with electrolyte molecules; yet $Lithium^+$ ions can readily shuttle back-and-forth through it to intercalate with anode's carbon (graphite)
- ✓ "The battery becomes hazardous when there arises flow of surge current into or out of the charged cell to cause SEI film break down resulting in direct contact of the electrolyte with the electrode materials initiating exothermic chemical reactions ultimately leading to failure, bursting or bulging of the battery (Doh *et al*., 2008). The authors in (Richard & Dahn, 1999) point out that at elevated temperatures, the SEI film is not stable which is why a rechargeable lithium battery with a lithium metal anode is unsafe." (Source of quote: Doh & Veluchamy, 2010)
- ✓ Local thermal damage to SEI layer by hot arcs or LENRs can destabilize an anode and potentially trigger a thermal runaway event within a battery cell
- ✓ LENR 'patch' or arc occurring on surface of Carbon anode in the presence of adequate amounts of Oxygen can potentially trigger rapid, irreversible combustion of the anode at very high temperatures, thus superheating cell

Simple carbon arc lamp:

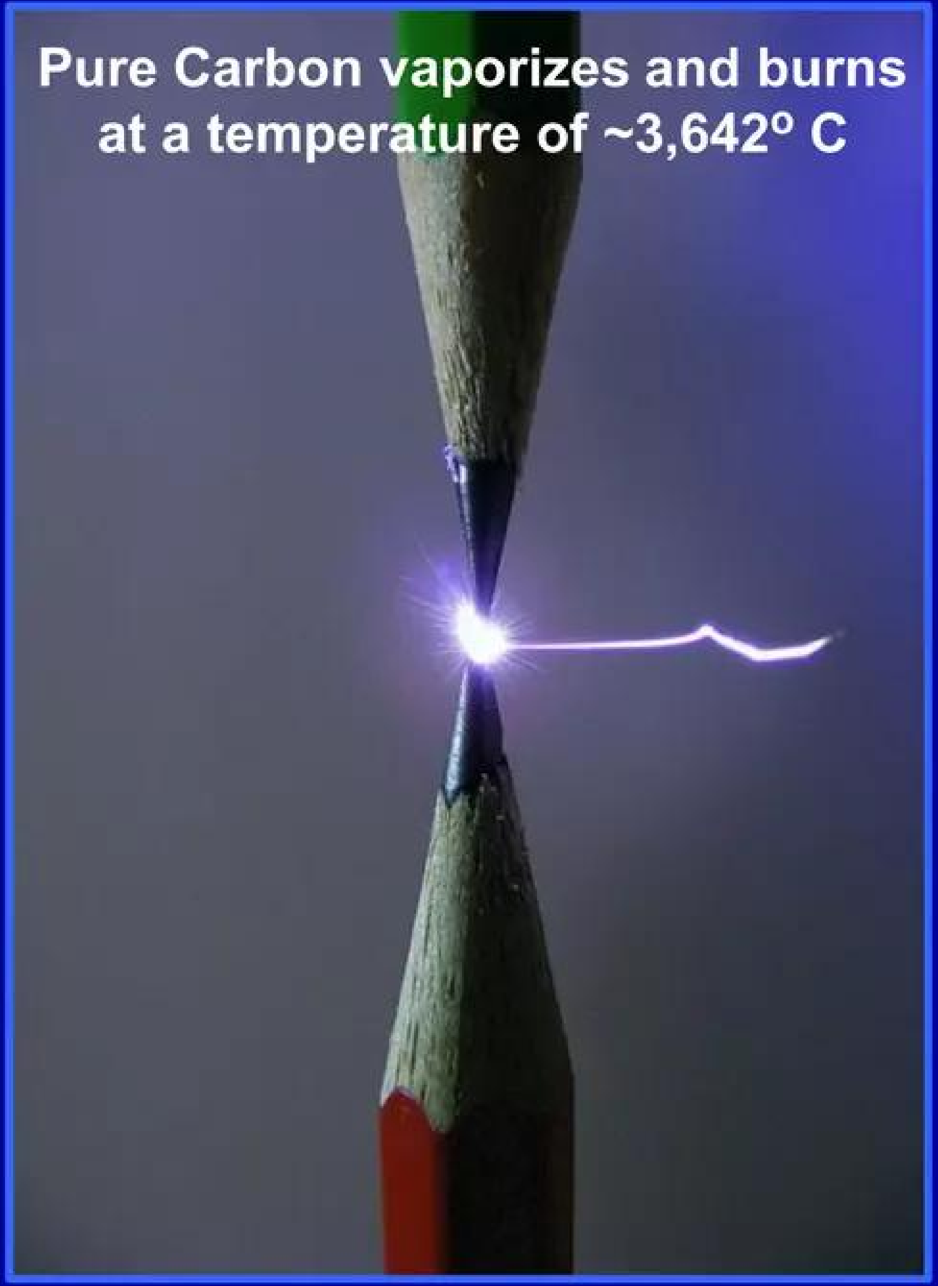

Photo credit: Conorod (UK - 2009) using a FujiFilm FinePix S5700 S700 digital camera; Exposure details: exposure time : 1/2 sec; F number : f 3.5; ISO speed rating : 100

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Arcs or LENRs trigger very exothermic chemical reactions

Bottom line: almost nothing stable at temps created by arcs and LENRs

Rise of autocatalytic "witches' brews" in locally superheated battery regions

"Burn 'em all --- let God sort 'em out."[3.]

"You can run, but you can't hide."[4.]

- ✓ **Almost nothing can withstand enormous, star-surface-like local temperatures created by arcs or LENRS and remain unreactive**
- ✓ **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 'normal' electrochemistry**

Adapted from the US military motto:

Popularized by US special operations forces during the 1960s Vietnam war

3.. 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)

4. 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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Arcs or LENRs trigger very exothermic chemical reactions

Bottom line: worst-case Armageddon scenario very rare but happens

Speculation: extreme events involve thermite-like pyrotechnic metal reactions

"Curse of the pyrotechnics"

Examples of two 'classic' exothermic thermite reactions:

$$Fe_2O_3 + 2\,Al \rightarrow 2\,Fe + Al_2O_3$$

Al_2O_3 $\Delta f\, H^o$ (solid) = - 780 kJ/mol.

$$3\,CuO + 2\,Al \rightarrow 3\,Cu + Al_2O_3$$

- ✓ Please recall that LiF can be formed in battery cells; when it is heated enough beyond its B.P. (1,681° C) in witches' cauldrons it can decompose to form HF, which can then enable the following:

AlF_3 $\Delta f\, H^o$ (solid) = - 1510.4 kJ/mol.

$$2\,Al(s) + 6\,HF(g) \xrightarrow{400 - 600^oC} 2\,AlF_3(s) + 3\,H_2(g)$$

- ✓ Highest-temperature regions in and around localized witches' cauldrons (almost star-like in many ways) can be hot enough to liberate metal ions which can then react with Oxygen to effectively create burning metals, which is often a high-temperature process:

  Cobalt metal burns in air at ~2,760° C; Aluminum at ~3,827° C; Iron at ~870° C; etc. --- bottom line: burning metals spells big trouble

See Slide #3: Al, Fe, Cu, and O are all available somewhere inside the battery; potential to form incendiary compounds in or near "witches' brew cauldron" areas

material	energy density	
	by mass: MJ/KG	by volume: MJ/L
aluminothermic incendiaries		
Thermite ($Al + Fe_2O_3$)	4.13	18.40
Copper Thermite (Al + CuO)	4.00	20.90
nitro-aromatic explosives		
TNT (Trinitrotoluene)	4.61	6.92

Can potentially synthesize explosive nano pyrotechnic mixtures in localized regions

Note: many thanks to J. Bruce Popp of FedEx for sending Lattice down this fruitful line of inquiry

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Arcs or LENRs trigger very exothermic chemical reactions

Bottom line: worst-case Armageddon scenario very rare but happens

Speculation: extreme events involve thermite-like pyrotechnic metal reactions

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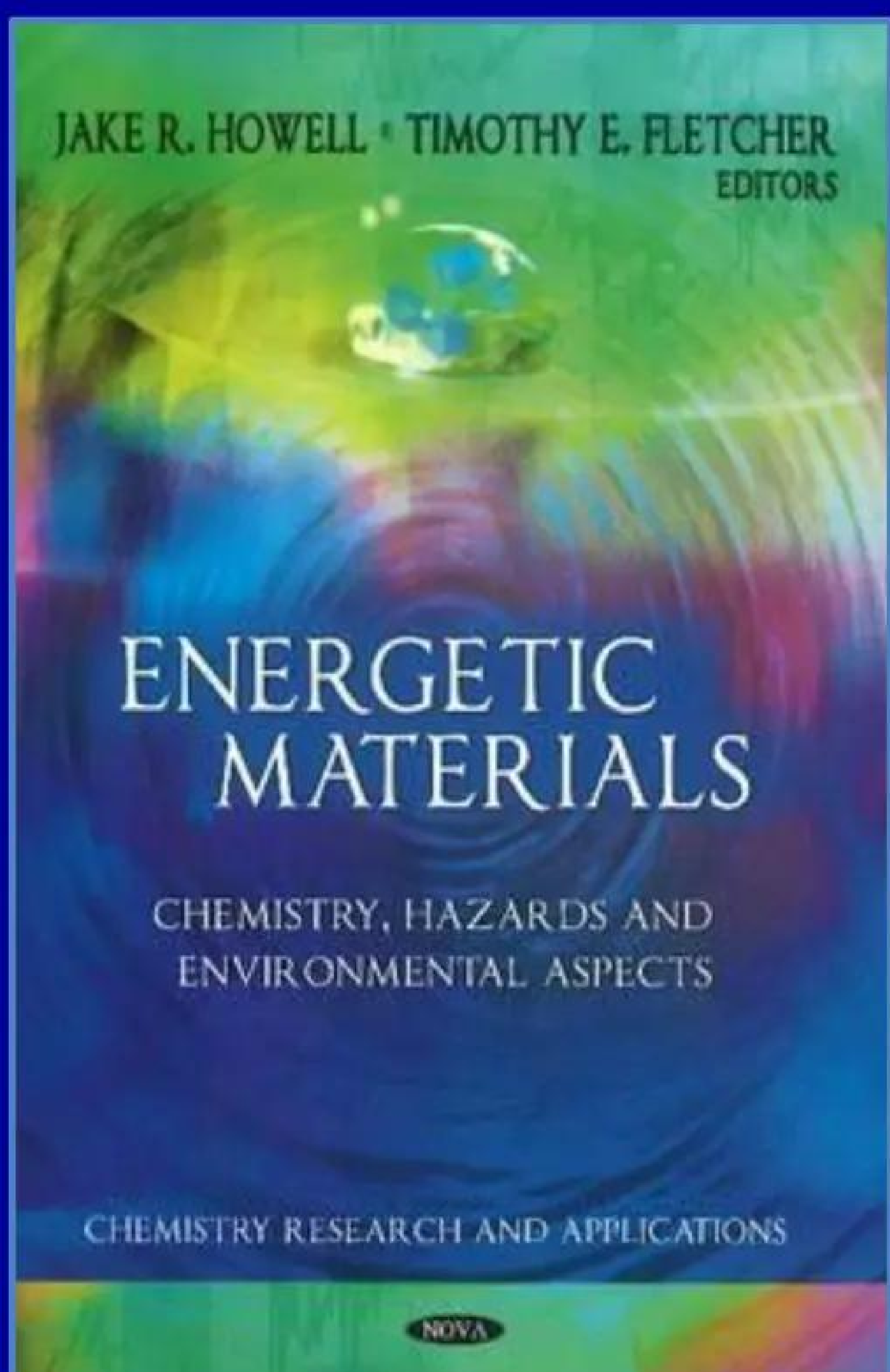
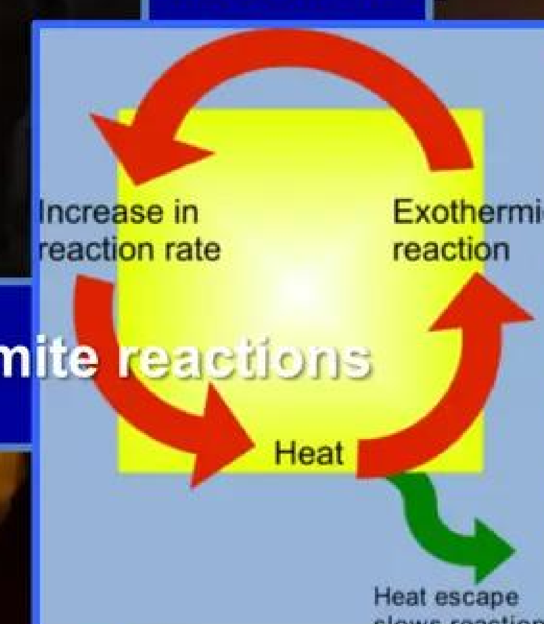


Runaway thermal feedback loop



Vivid examples of burning thermite reactions

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Arcs or LENRs trigger very exothermic chemical reactions

Bottom line: Armageddon scenario did not occur in Logan runaway

Conclusion: not worst case event - more extreme things might have happened

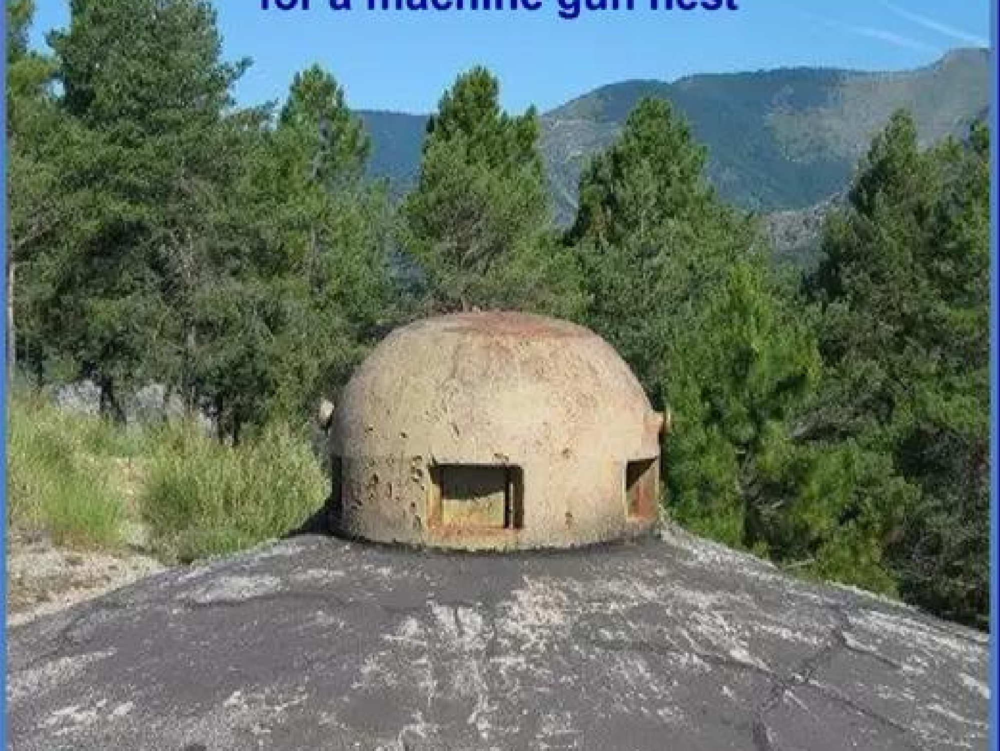
"Don't plan the future to win the last war"

- ✓ **First-responder at Logan incident reported seeing 3" blue flames coming from edges of two connectors at front of battery enclosure; according to Prof. Michel Armand[5.], this data indicates temperatures at that particular location at that time had to be > 800° C just inside blue box (but obviously below M.P. of Aluminum)**
- ✓ **Above observation is consistent with data from first-responder's thermal imaging camera which revealed a hot, irregularly-shaped 'blob' of material located inside at front of enclosure; noted 'blob' was unexpectedly *not* rectangular- shaped (likely composed of combustible or combusting gases or plasmas of some sort)**
- ✓ **Damage observed to materials located inside Logan battery enclosure were consistent with main destructive processes being venting and *partial* combustion of flammable electrolyte liquids; measured weight loss of ~6 lbs. vs. exemplar battery is consistent with this hypothesis; no large-scale evidence for occurrence of thermite-like pyrotechnic reactions; if so, would have had *vastly worse* damage**
- ✓ **While causing thermal damage, cell #5's short-circuit electric arc discharges may have been a blessing in disguise: arcs transported electrical energy that would have otherwise further heated-up battery materials, first to outer Al enclosure and then out through mounting bolts to dissipate in aircraft structures; if there had been <u>no</u> arcing, temperatures might have risen *much higher* during Logan event**
- ✓ **<u>Conclusion</u>: Logan battery runaway was not a worst-case Armageddon scenario**

<u>Maginot Line</u> (France pre-WWII):

Ineffectual defensive system of fixed fortifications France constructed along German and Italian borders based on combat experience gained in World War I

Recent photo of Maginot Line GFM cloche for a machine gun nest



http://en.wikipedia.org/wiki/Maginot_Line

***Cloche* is French term meaning *bell* due to its shape: all GFM cloches constructed of steel alloy and had non-retractable turrets; there were 1,118 GFMs in Maginot Line -- most common type of defensive fortification**

5. Private communication (2013)

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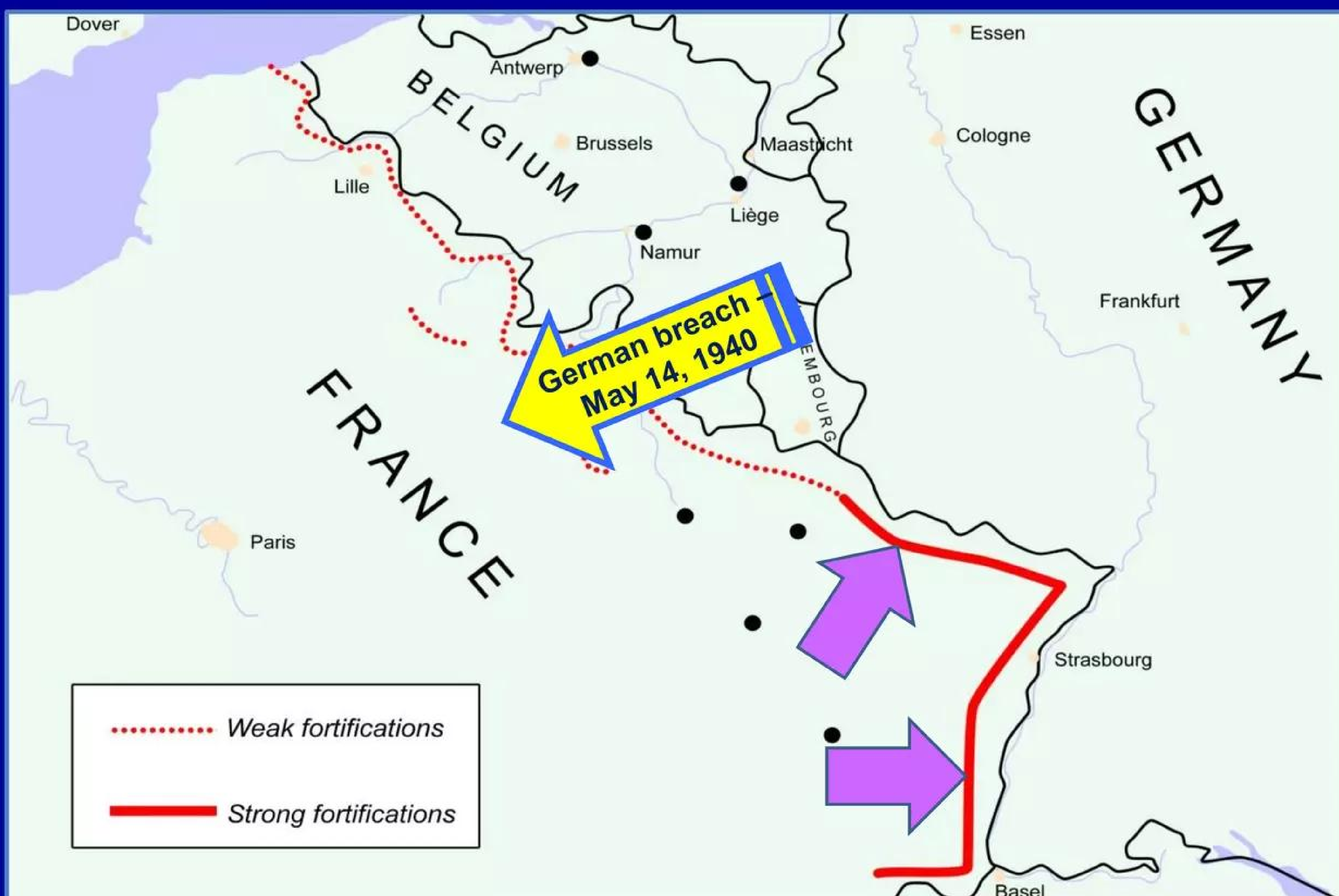
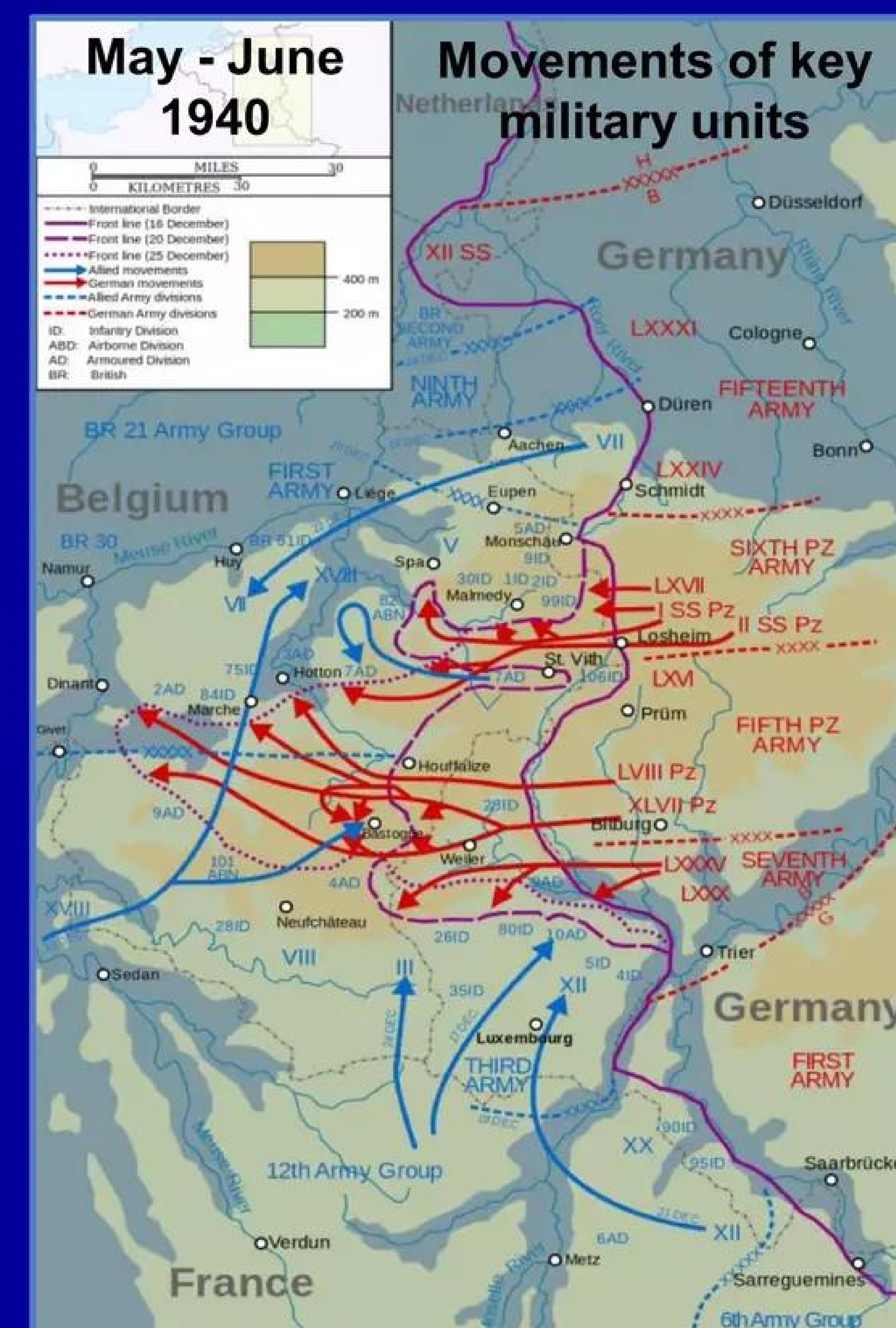
Managing battery risks: very exothermic chemical reactions

WWII: Germany outflanked Maginot Line - attacked to weaker North

Maginot Line safety thinking = assume Logan runaway is true worst-case

Mitigating real Armageddon scenarios → different engineering strategies





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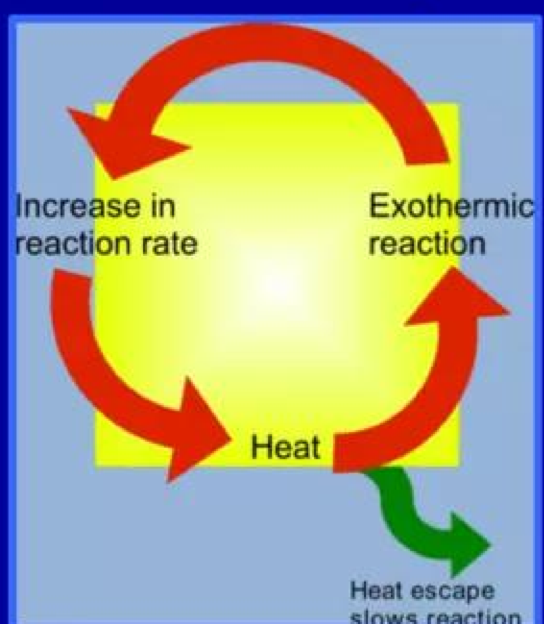
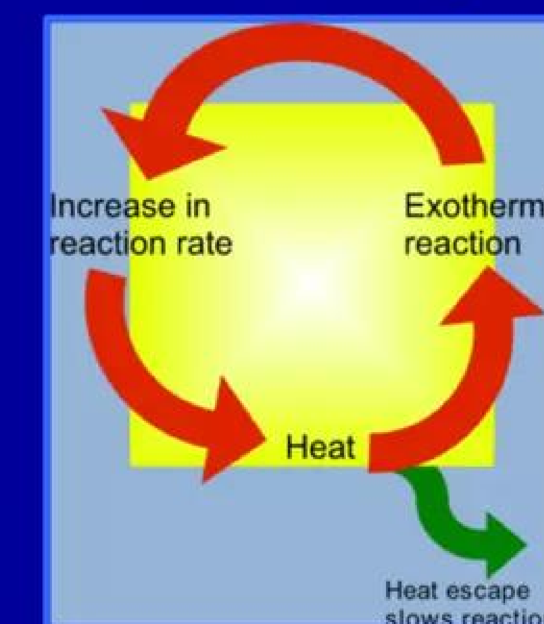
Highly recommended reference paper:

Runaway thermal feedback loop



"Thermo-chemical process associated with lithium cobalt oxide cathode in lithium ion batteries"
C. Doh and A. Veluchamy
Chapter 2 in book "*Lithium-ion Batteries*", Chong Rae Park, ed.
ISBN 978-953-307-058-2 open access content
Published by InTech (Shanghai, China) under CC BY-NC-SA 3.0 license
DOI: 10.5772/9116 (2010)
http://cdn.intechopen.com/pdfs/10407/InTech-Thermo_chemical_process_associated_with_lithium_cobalt_oxide_cathode_in_lithium_ion_batteries.pdf

Runaway thermal feedback loop



Summary of two additional causative mechanisms for thermal runaways in batteries:

Causative agent that can trigger thermal runaways	Regime or requirements	Physical dimensions	Key details	Temperature range in ° C	Comments
Electric discharges: that is, arcs or sparks; alternative names for internal electrical short circuits that can occur inside battery cells	Outer 'edges' of tubular arc plasma sheath	Arc lengths can range in length from 2 *nm* between metallic nanoparticles all the way up to as long as several centimeters (*cm*) between larger structures	Chemical and nuclear reactions can occur within; dep. on current	~2,727 up to ~4,727	Heat radiation is mainly created via Joule heating by electrons and ions found in arc discharge plasma; very damaging to materials; can even breach battery cell case
	Innermost core of arc plasma's tubular sheath-like structure			~9,726 up to ~19,726	
LENR-active 'hotspots': can occur on metallic surfaces or at oxide-metal interfaces anywhere inside battery where be: e^-, p^+ and metals	Require local presence of hydrogen (protons), metals, and surface plasmon or π electrons	2 nanometers (*nm*) to as large as ~100$^+$ microns (μ) in diameter; roughly circular in shape	MeV-energy nuclear reactions occur within	~3,700 up to ~5,700	Directly radiate infrared heat photon energy; ionizes nearby molecules, materials, destroys μ-scale nanostructures

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With or without LENRs, arcs can trigger thermal runaways

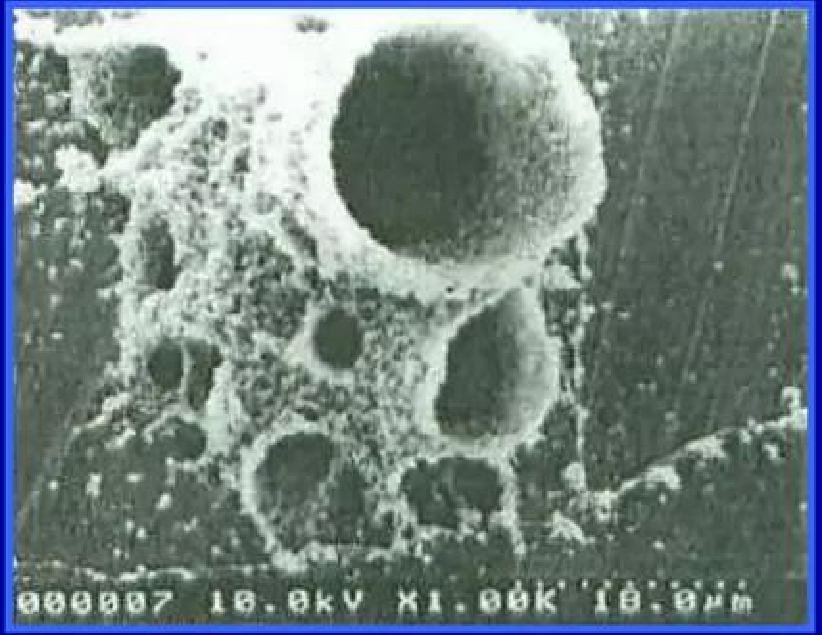
LENR-triggered runaways may be rarest but possibly deadliest type

Summary - roles of LENRs and electric arcs in runaway batteries:

- ✓ **Although there are differences, there is a degree of morphological similarity in SEM images of post-experiment cathodic arc surfaces (e.g., crater-like structures and related droplets) compared to those observed after LENR-related experiments**
- ✓ **To the extent that such morphologies are highly indicative of very rapid heating and quenching in small areas of cathode surfaces, it implies that temperatures reached in electric arc and LENR-active 'hot spots' or 'patches' are briefly high enough to melt and even *boil and vaporize* substrate metals, e.g., Palladium (Pd) boiling point = $2,970^{o}$ C or other transition metals, including refractory ones and even Tungsten**
- ✓ **Widom-Larsen theory predicts that if necessary preconditions are met, LENRs can be triggered in high-local-current arcs and high-EM-field electrical phenomena that include field emission and breakdown on surfaces, nanoparticles, and dendrite tips**
- ✓ **Variety of different nuclear transmutation products observed by a large number of LENR researchers in and around surface structures such as 'craters' suggests that LENRs probably occurred at non-negligible rates in and around such active regions**
- ✓ **Micron-scale LENR-active sites that happen to be located close to a plastic battery separator (with or without a ceramic layer) will vaporize and flash-ionize a local region of separator which can in turn trigger an internal electrical short right there; similarly, an LENR 'patch' occurring on surface of a Lithium cobalt oxide cathode or carbon anode can potentially trigger the irreversible combustion of an electrode**
- ✓ **With or without the help of LENRs, electric arcs (internal shorts) are capable of triggering catastrophic thermal runaways in batteries of many varied chemistries**

LENRs

Y. Toriabe *et al.*



Y. Toriabe *et al.*

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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 exactly the right conditions, just a single *microscopic* LENR site can trigger a chain of energetic electrical (Joule heating) and chemical (exothermic reactions) processes that together can 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 the total energy released is non-nuclear; LENRs are merely a very effective triggering mechanism. Also note that any internal electrical shorts --- whatever their cause --- can also trigger runaways.

That being the case, using SIMS it may be difficult to locate and detect tiny amounts of telltale anomalous elements and isotopic shifts arising from a single LENR 'trigger' site amidst all the vast mountains of debris found in a thermally ruined battery cell. However, 'difficult' does not mean impossible. A similar issue arose back in 1930 when Wolfgang Pauli predicted the existence of what is now called the neutrino particle. Hypothesizing correctly that neutrinos would barely interact with normal matter, Pauli lamented, "*I have done a terrible thing – I have postulated a particle that cannot be detected.*" Fortunately, it was: in 1934 Pauli's particle was incorporated in Enrico Fermi's theory of beta decay, and was finally detected experimentally by Reines & Cowan, who reported confirmation in 1956. Today, neutrinos are essential particles in the Standard Model.

"*Comparison of electron and muon neutrino events.*" This event occurred at 1998-04-04 08:35:22; false-color image was reconstructed as a muon with momentum of 603 MeV http://www.ps.uci.edu/~tomba/sk/tscan/compare_mu_e/

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"For the truth of the conclusions of physical science, observation is the supreme Court of Appeal."

Sir Arthur Eddington

"*The Philosophy of Physical Science*" pp. 9 (1939)