NASA Battery Technology & My Career Path

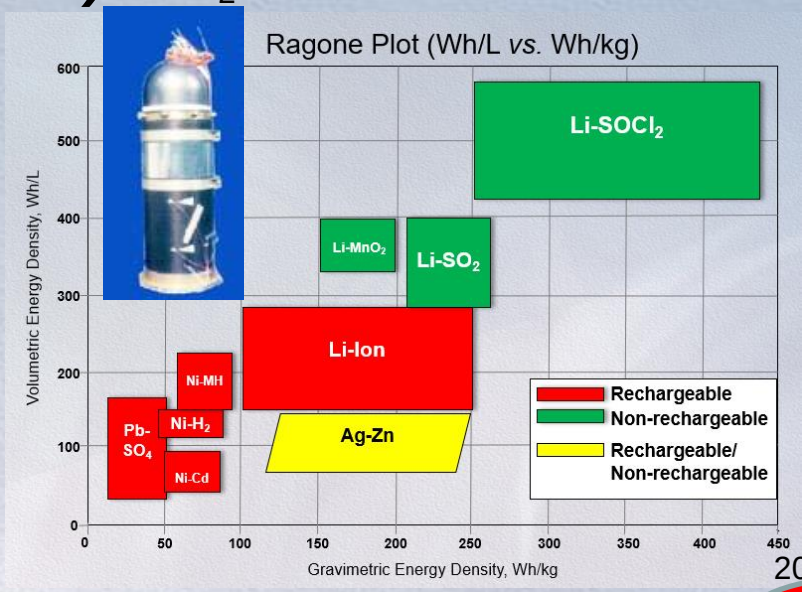
Eric Darcy/NASA-JSC
EA All Hands
26 Apr 2023

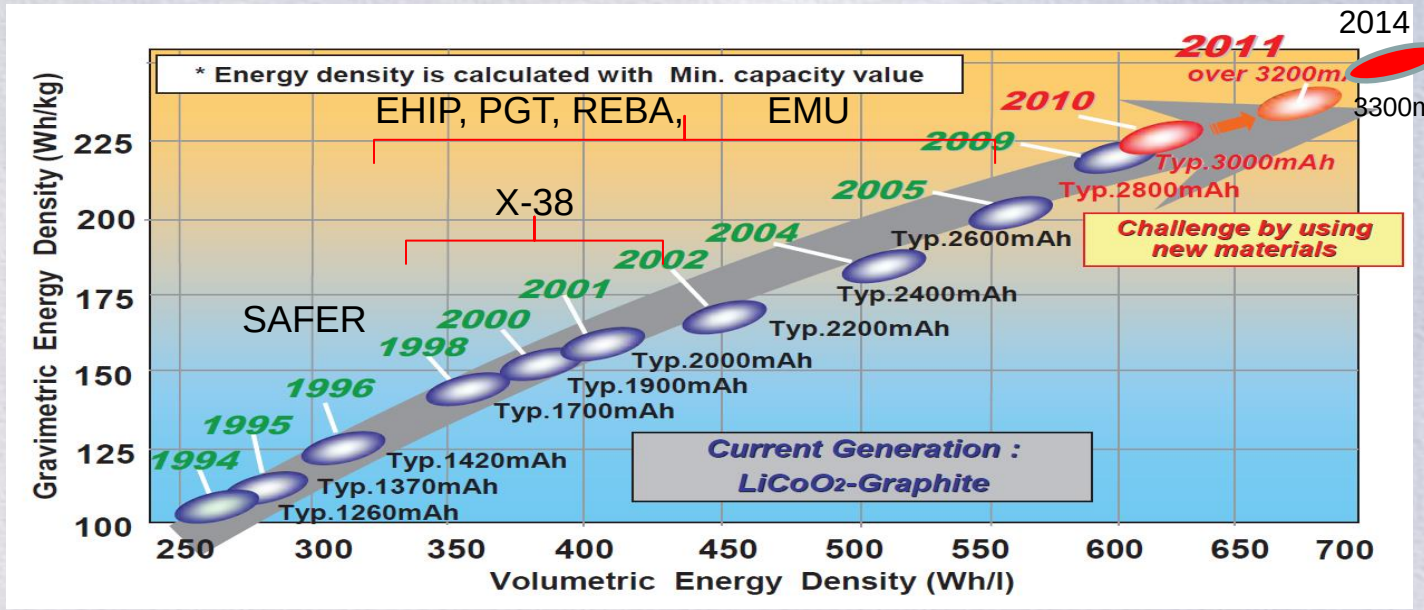
Background and Path To JSC

- Born in Paris, France, 1962, entire family is French
  - 4th grade in Bayonne, France
- Chemistry, BA, at Pomona College, Claremont, CA
  - Took engineering classes at Harvey Mudd College, Claremont, CA
- Chemical Engineering, MS, at TAMU, College Station, TX
  - Studied batteries under Dr. Ralph E. White
- Cecil Gibson (EP5 Branch Chief) hired me and I started in Mar 1987
  - No PCs, no faxes, and smoking offices

Early Career (1987-1997) $Ni-H_2$

- Shuttle in cabin and payloads
  - $Li-SOCl_2$, $Li-SO_2$, $Li-MnO_2$ one-shot (non-rechargeable)
  - Ag/Zn limited wet life
- NiCd vs NiH_2
- Lithium ion too immature
- Air Force $Li/SOCl_2$ replacing AgZn batteries on Centaur Orbital Stage
- In 1992, granted 1-yr sabbatical (#1) to complete course work for PhD at UH



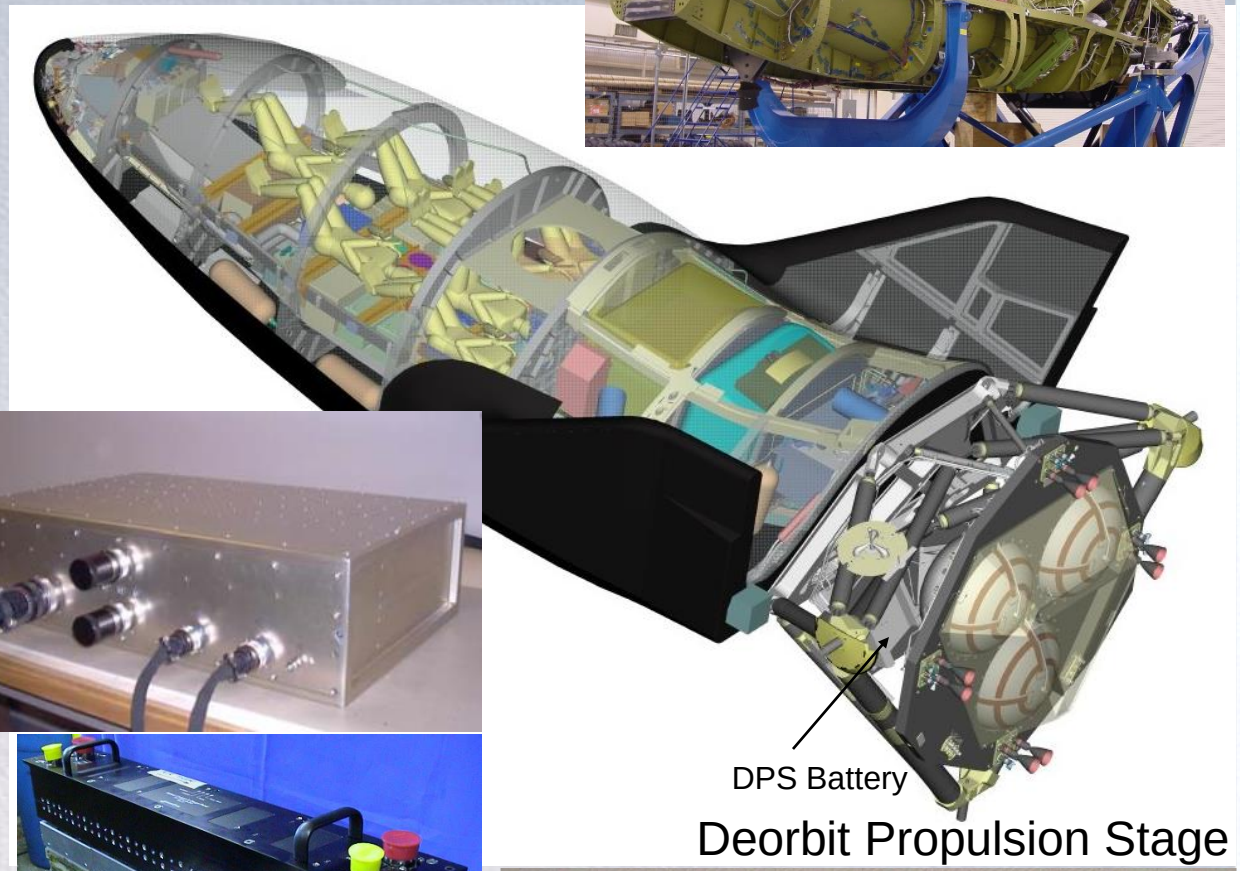


Lessons Learned During Early Career

- Flying in the KC135 was a blast
  - But getting the placebo drug limited the fun
- There are a lot of extremely knowledgeable and talents folks at NASA, seek their advice
- Seek continuing education
  - NASA helps pay for it
- Don’t stay too long away from school if you want your PhD

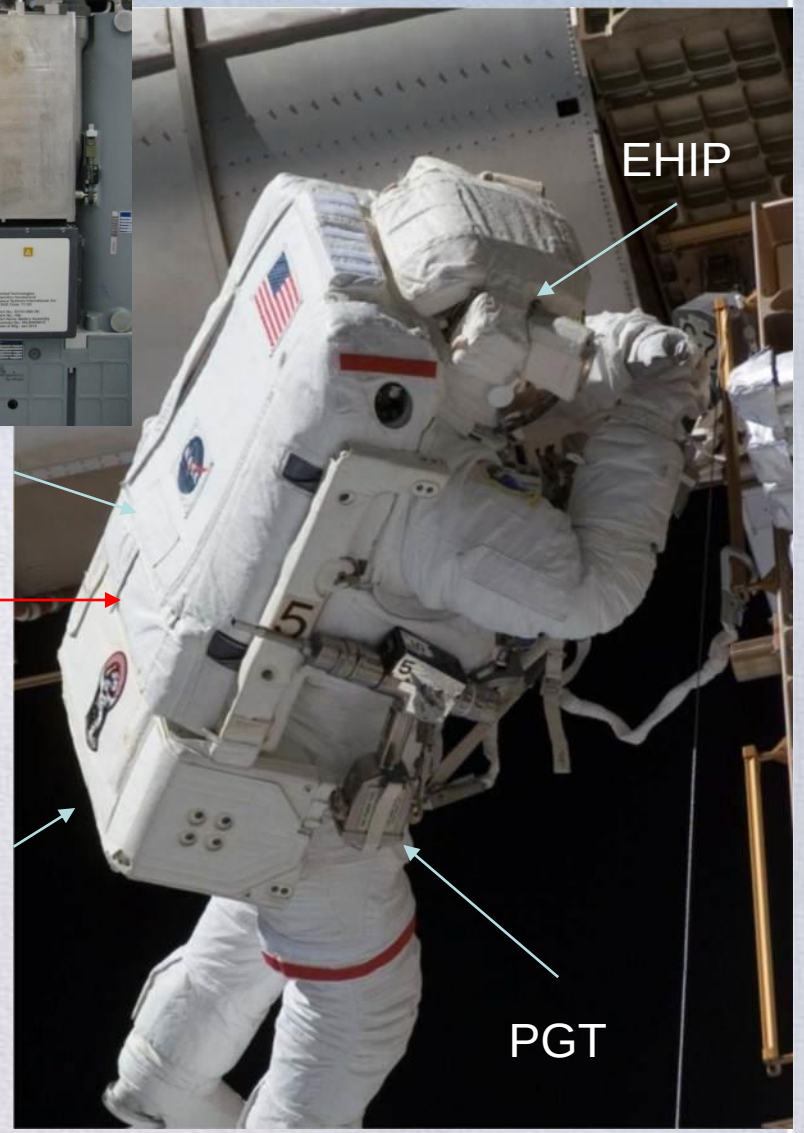
Mid Career (1997-2012)

- X-38 Crew Return Vehicle (GFE)
  - Largest Li primary battery for DPS
    - 36V, 350Ah battery using 36Ah F-cell Li/MnO_2 cell from Friwo
  - Rechargeable battery for vehicle once DPS was jettisoned
    - 28V, 50Ah batteries x 8 (400Ah system) using NiMH commercial 4/3A cells
  - First high voltage battery qualified for manned spaceflight
    - 270V, 8Ah batteries x 4 using NiCd commercial subC cells
    - Powered EMAs for flight control surfaces and parachute winches
  - Battery developments started in 1998 and flight hardware delivered by 2001
    - “Faster, better, cheaper”



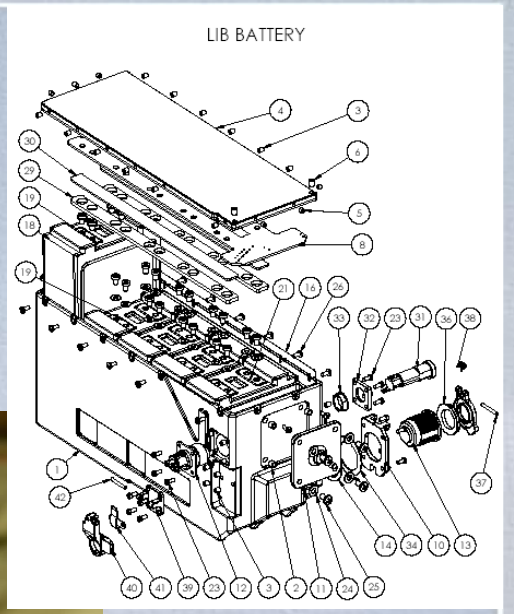
Mid Career (1997-2012)

- GFE Batteries for ISS EVAs
  - Li/MnO_2 for SAFER (1996-7)
  - NiMH for EHIP, PGT, REBA (1997-8)
  - Li-ion for EMU-PLSS (2004-2010)
    - Designed (LLB) with commercial cylindrical (18650) cells
    - LLB first EVA in 2011 and serves flawlessly through 2018 until replaced by PPR redesign (LLB2) still used today
  - Developed an expertise in spinning in commercial cells into high performing batteries

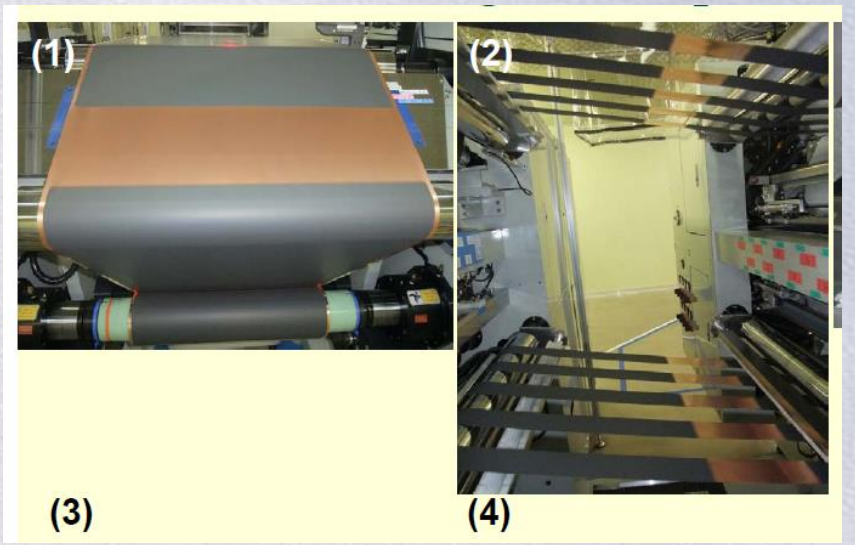


Mid Career (1997-2012)

- Cell Quality is Paramount
  - In 2004-2006, LIB EMU battery with abuse tolerant, custom pouch cell design from Electrovaya was too unreliable due to poor manufacturing quality control
    - Latent defect rate too high
    - Internal short circuit during storage on a screened flight battery

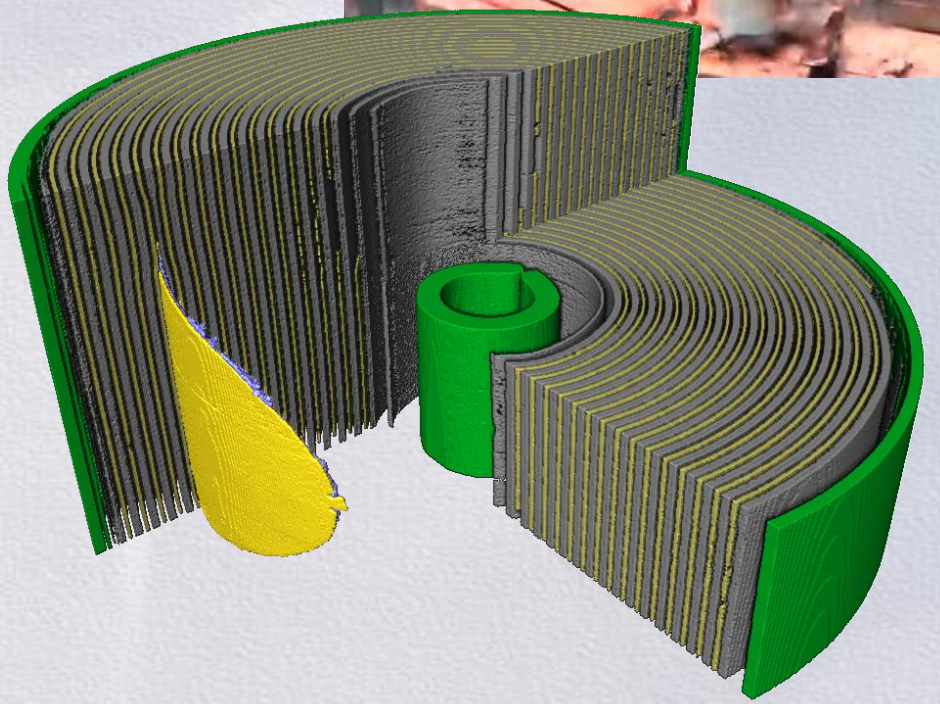


- Organized the audits of the production lines of 5 Li-ion cell manufacturers for ISS main power battery upgrade (2009-2011)
  - Focused on how defects are controlled



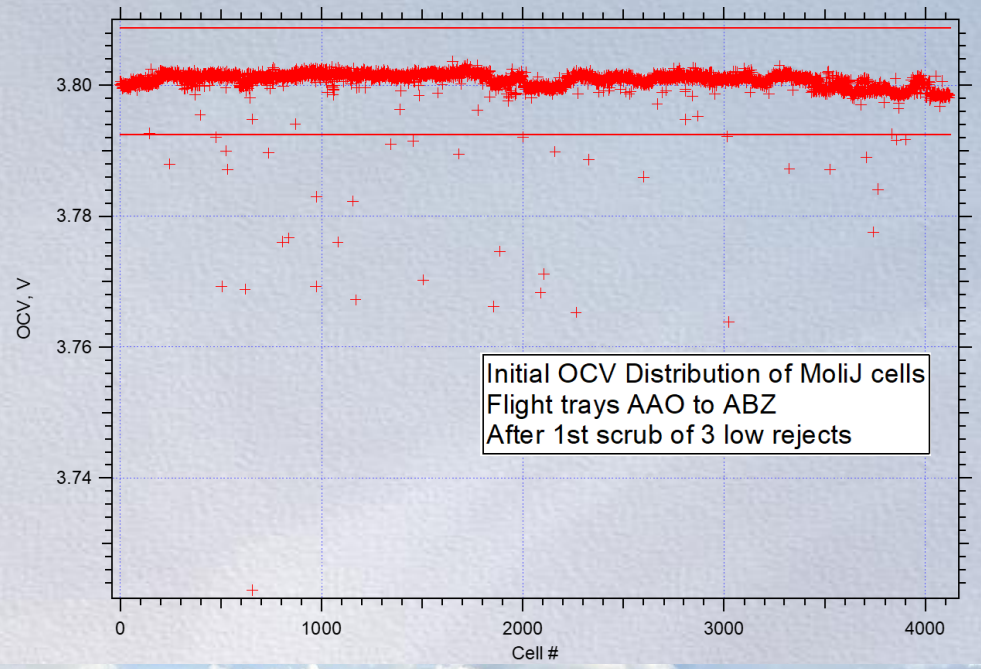
Mid Career (1997-2012) Continued

- Sabbatical #2 – Selected for NASA Innovative Ambassador Rotation (2010) by HQ
  - Joined Battery Group at National Renewal Energy Laboratory (NREL) in Golden, CO
  - Co-invented the on-demand, implantable Internal Short Circuit Device (ISCD)
    - Invented in 2010, retrofitted in a pouch cell
    - 2011: Implanted in pouch cell design
    - 2012-2014: trials with Moli in 2.4Ah 18650
    - 2015-2017: Used as trigger cell in battery PPR tests
    - 2018: Exclusive Licensee: KULR Technology



Lessons Learned During Mid Career

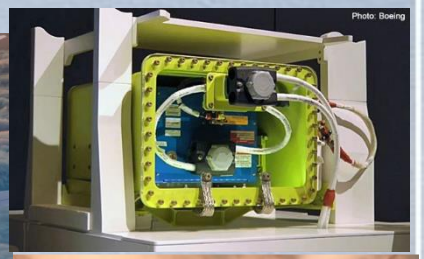
- GFE experience was incredibly valuable and formative
  - *Responsible for flight hardware performance and quality*
- Quality control commitment can't be taught to commercial contractors, commitment must come from within
- Assumed that all cell thermal runaway could only be controlled by rigorous prevention measures
  - Mature designs, no recalls, rigorous testing and screening
- Persistence with ISC Device development pays off
  - Exclusive licensee 8 years after invention
- In Oct 2010, came back to JSC after NREL sabbatical with family staying put in Ridgway CO
  - Telework agreement (2 weeks in TX, 2 weeks in CO per month) – Many doubted it would work

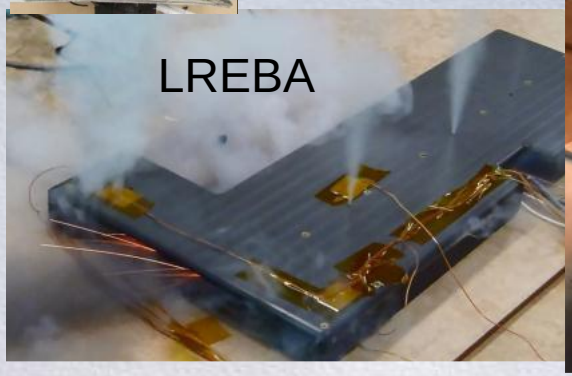


Late Career (2013-Present)

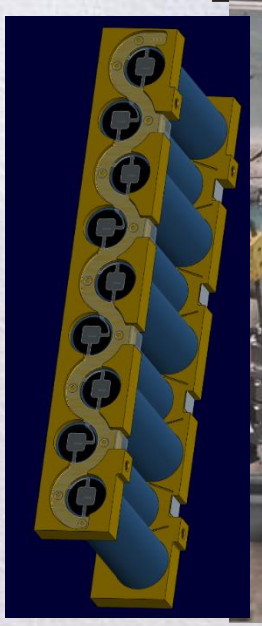
- SpaceX demonstrates first passively propagation resistant (PPR) battery designs using 18650 cells for Dragon in 2012
  - Tesla did it first with active cooling using the same Li-ion cells
- 787 battery TR failures with large 75Ah cells in 2013
  - made in same production line in Kyoto, Japan, as 134Ah ISS cell
- NESC leads effort (2014-2017) to examine vulnerability to NASA batteries
  - ISS main – Vacuum PPR test
  - EVA batteries – PPR redesign demos for LREBA, LPGT, and LLB with my technical leadership
  - Not acceptable to **not** know the risk, JSC20793C
  - Developed 5 design guidelines for getting to pass PPR test campaigns

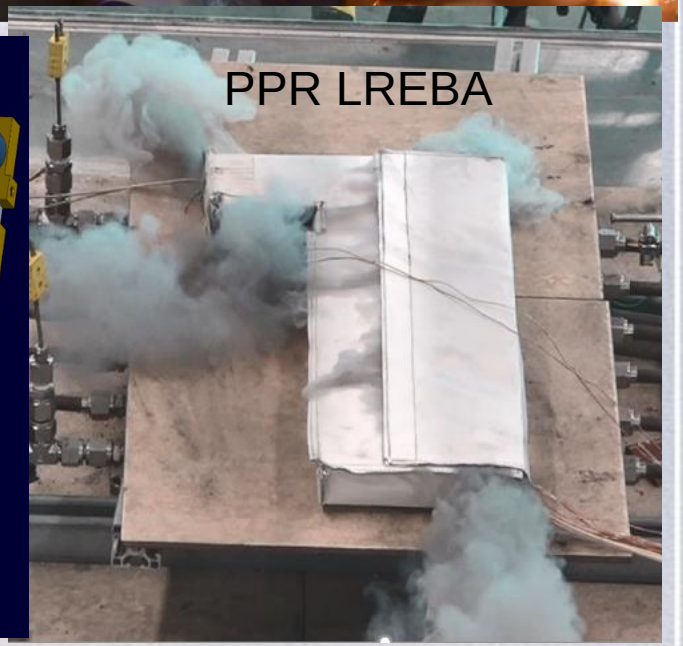
Steel box for battery





LREBA

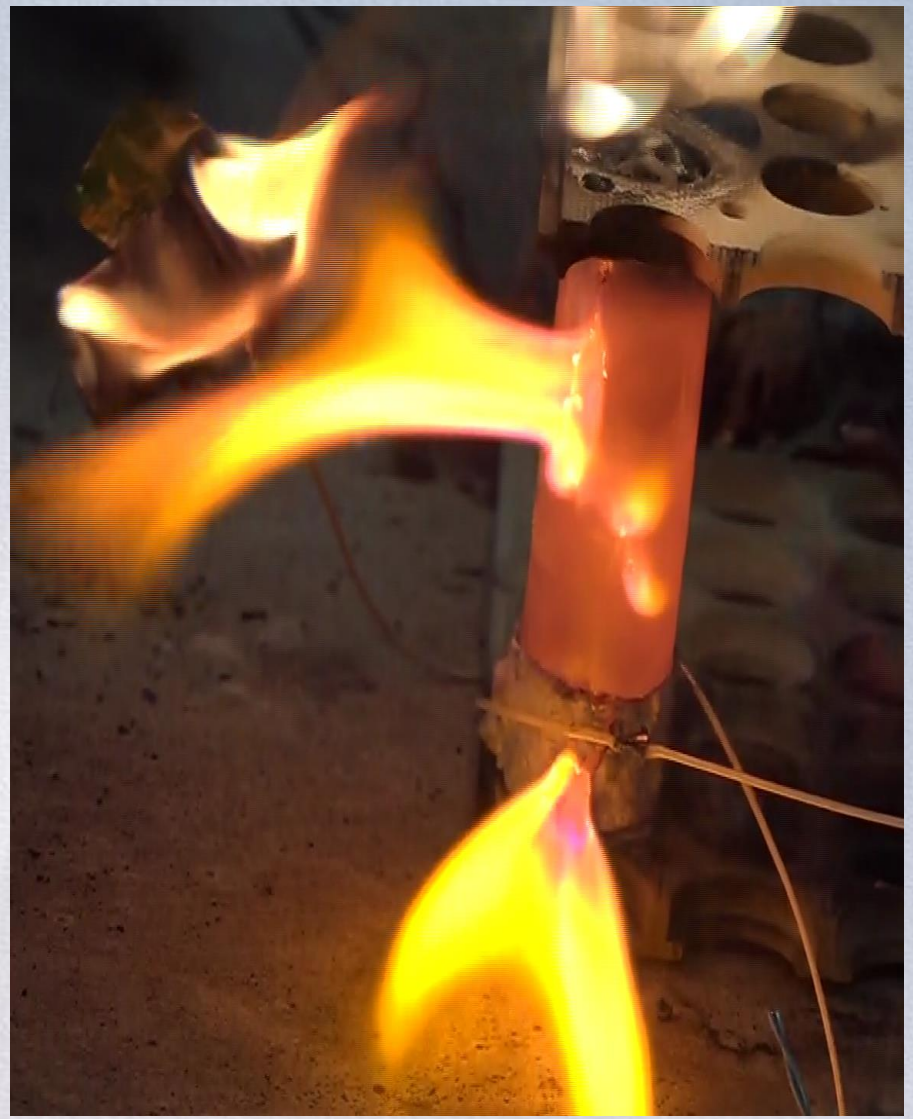




PPR LREBA

Battery Design Guidelines for Reducing Hazard Severity from a Single Cell TR

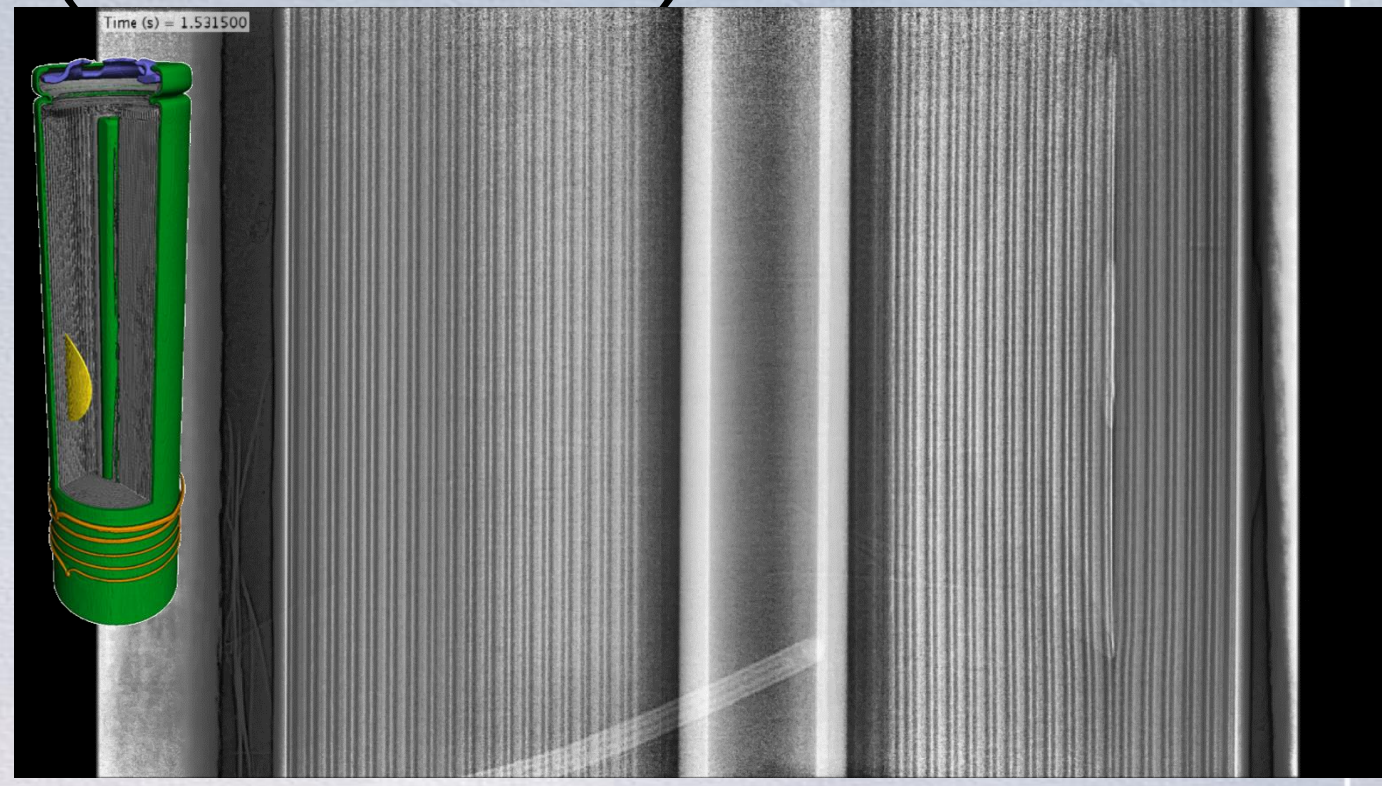
1. Reduce risk of cell can side wall breaches
   - Without structural support most high energy density (>660 Wh/L) designs are very likely to experience side wall breaching during TR
   - Battery should minimize constrictions on cell TR pressure relief
2. Provide adequate cell spacing and heat rejection
   - Direct contact between cells nearly assures propagation
   - Spacing required is inversely proportional to effectiveness of heat dissipation path
3. Individually fuse parallel cells
   - TR cell becomes an external short to adjacent parallel cells and heats them up
4. Protect the adjacent cells from the hot TR cell ejecta (solids, liquids, and gases)
   - TR ejecta is electrically conductive and can cause circulating currents
5. Prevent flames and sparks from exiting the battery enclosure
   - Provide tortuous path for the TR ejecta before hitting battery vent ports equipped flame arresting screens

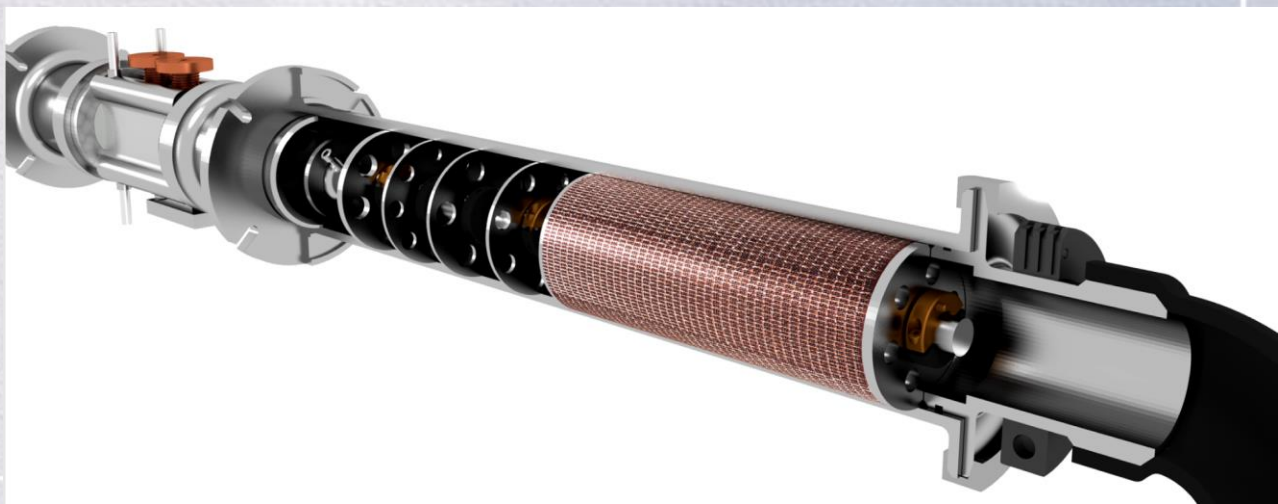


Source: NASA NESC Task Report TI-14-00942 “Assessment of ISS/EVA Lithium-ion Battery TR Severity Reduction Measures” May 2017

Late Career (2013-Present)

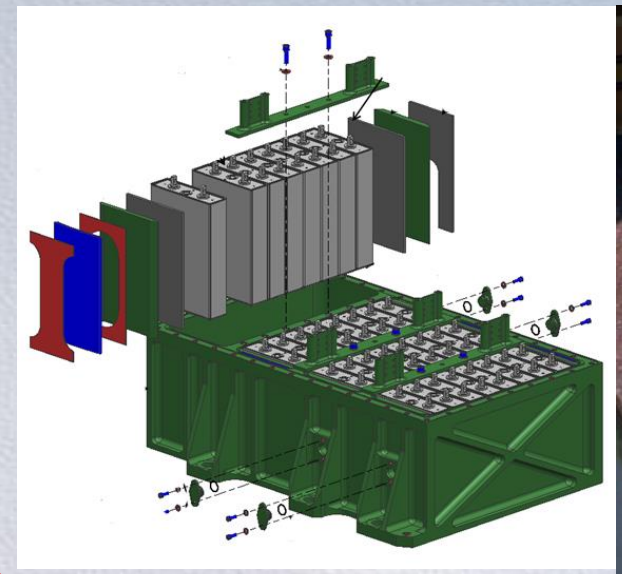
- ISC Device becomes reliable trigger cell in 2015 in 2.4Ah Moli J cells
  - PhD student at UCL wants to synchrotron viewing or our trigger cells
  - Invited to Battery Conference in Korea
    - LG implants device in their 3.5Ah MJ1
  - NASA-UCL SAA for synchrotron experiments
- Our team invented the Fractional Thermal Runaway Calorimeter (2016)
  - Discerns conducted from ejected heat during cell TR
  - Enables safe, high throughput synchrotron experiments
  - Will Walker, Jacob Darst & David Petrushenko

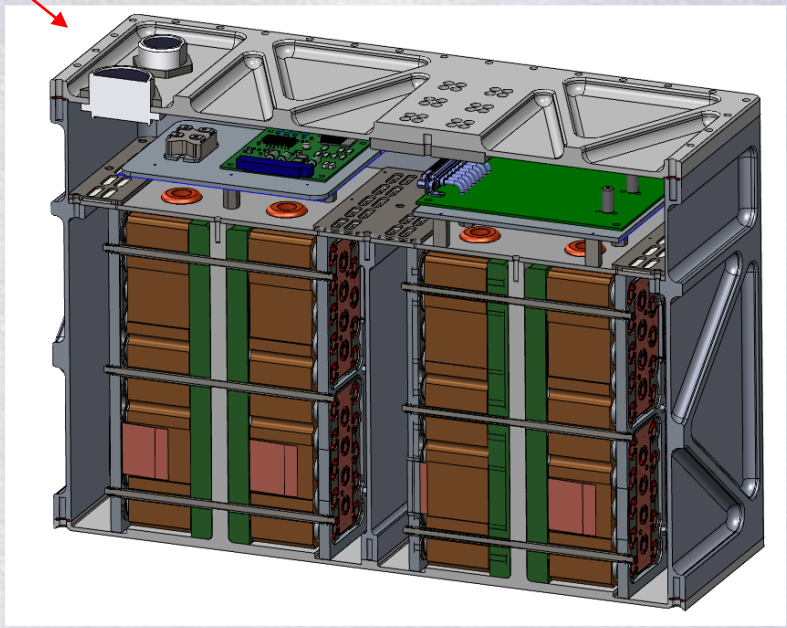


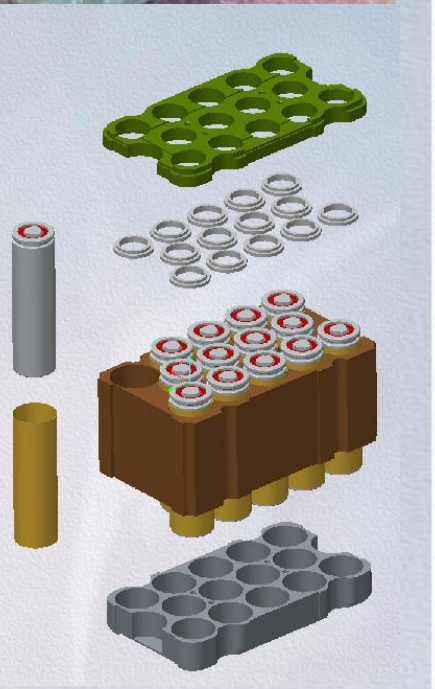


Late Career (2013-Present)

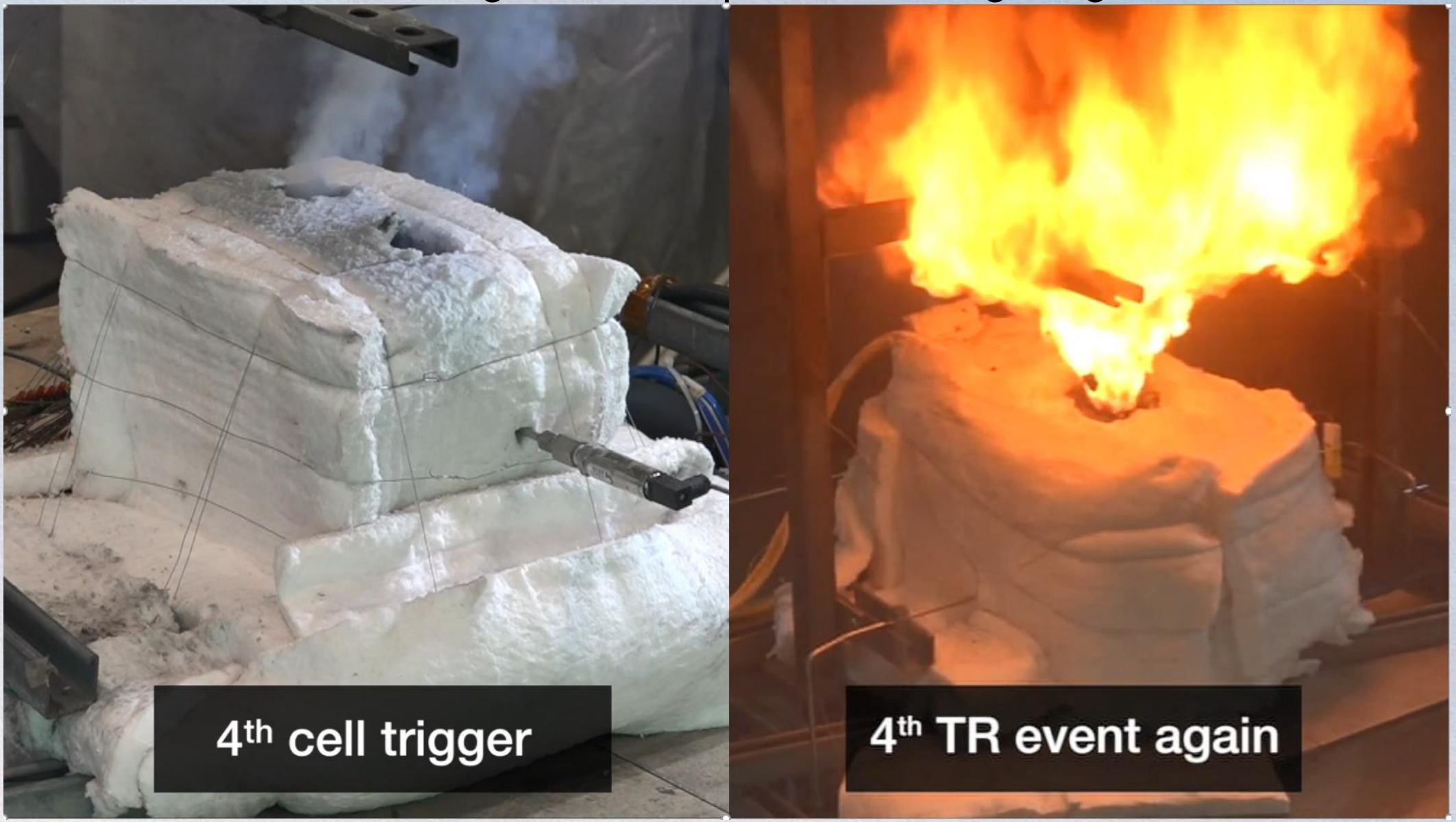
- Orion CM large cell battery from LM/Yardney
  - Convinced program to PPR test at ESTA (Sep 2014)
  - Worked GFE small cell battery alternative prototype PPR (Feb 2015)
  - Comparison video convinces Orion to fund small cell alternative (next page)
  - By Jan 2017: LM & EPT directed to use our in-house design for first manned flight (AR2) and beyond







Small Cell vs Large Cell Comparison During Single Cell TR



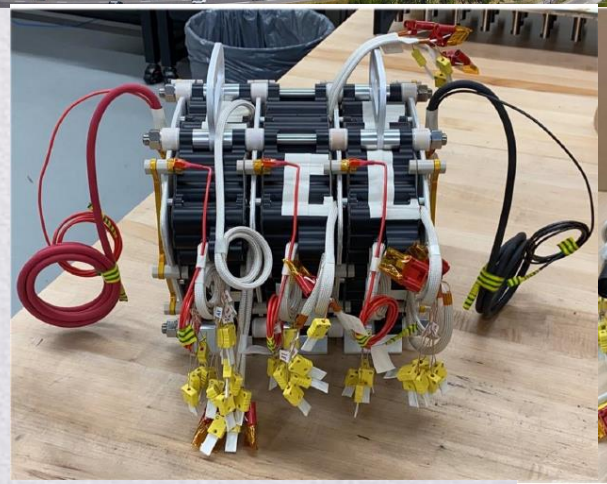
Above Video Feb 24 2015 Test Orion Small Cell Battery shows Five independently heater triggered cells in Proto-case housing (left frame) compared side by side with Sept 2014 CMB Large Cell TR propagation with single cell overcharge trigger,

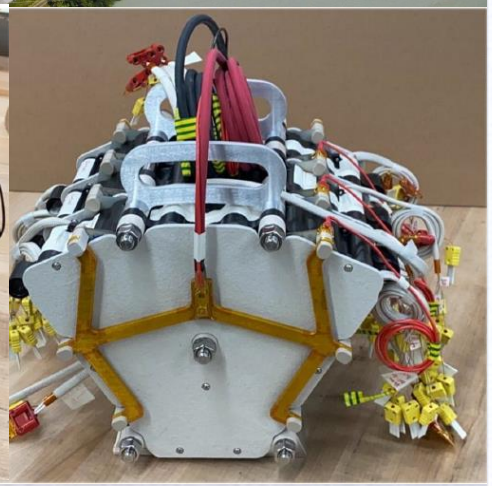
Late Career (cont.)

Partnerships

- University College of London
  - Access to Synchrotrons in Grenoble, France and near Oxford, UK
  - Microfocus CT imaging of failed cells
- NREL
  - Synchrotron videography imagery

- Navy
  - Strategic cell reserve partner
  - PPR battery design for smart undersea unmanned vehicles
    - Benefitting our redesign of the Starliner battery

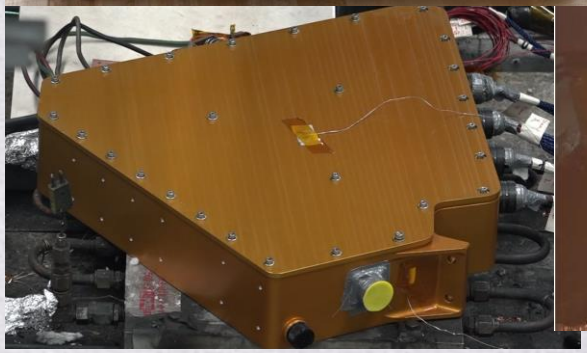




Late Career (2013-Present)

- 2015-2018: Boeing CST100 battery didn't adequately demonstrate PPR
  - Brought dissenting opinion to JSC & KSC directors (2019)
    - Cell design selected most prone to side wall rupture (SWR) during TR
    - Marginal on 3 other design guidelines
    - No full scale high fidelity verification
  - Program funds our remediation steps
    - SWR cell characterization (2021)
    - Battery PPR test with best SWR cell (2022)
      - Failure identifies other design flaws
      - *David Petrushenko meticulously designed and assembled high fidelity PPR battery*
  - Battery redesign underway (Nov 2022)

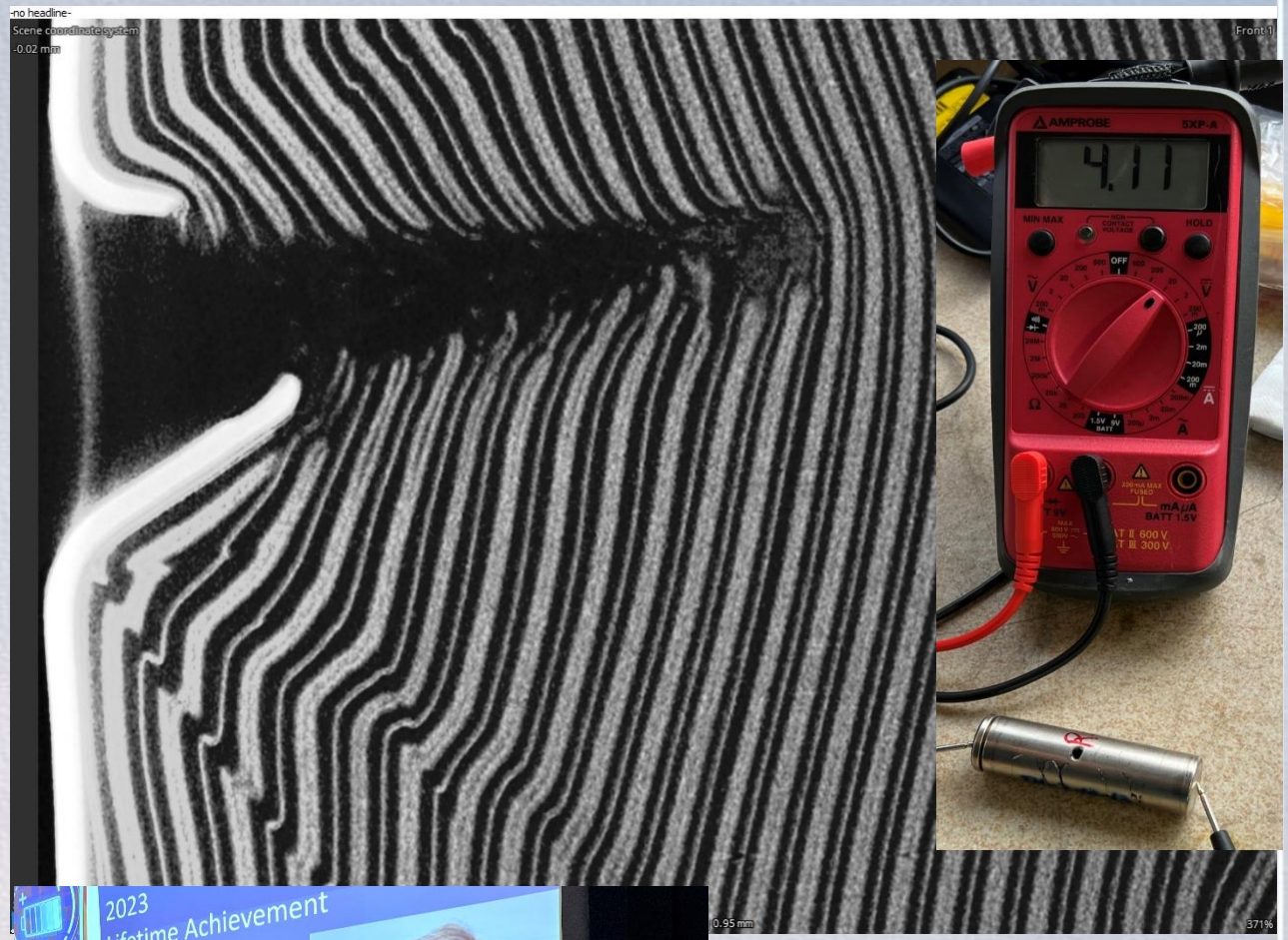
2015 Testing



Sep 2022

Late Career (2013-Present)

- Plastic Current Collectors show greatest near term promise for eliminating battery fires
  - Invented by Soteria in SC
  - Our high speed X-ray videography and microfocus CT scan show how they isolate internal shorts
    - Tolerates nail penetration
  - Synchrotron tests provide unique and invaluable insights in cell safety
- Recognized in Feb 2023 by NAATBatt
  - 600+ peers at mtg

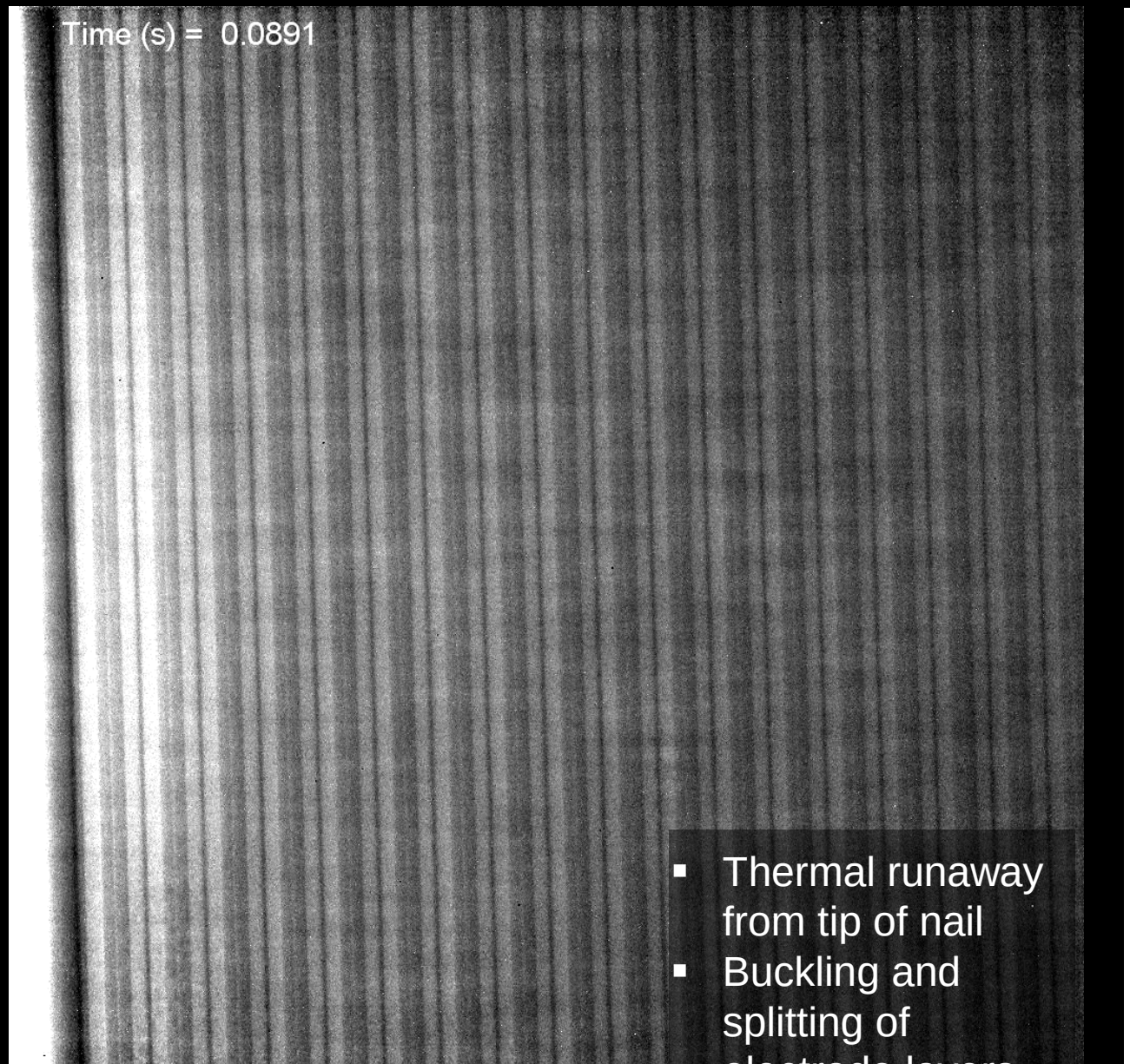


Radiography at 3000 fps of 21700 cells

Dense material is dark (nail, can, NMC)

Control cell

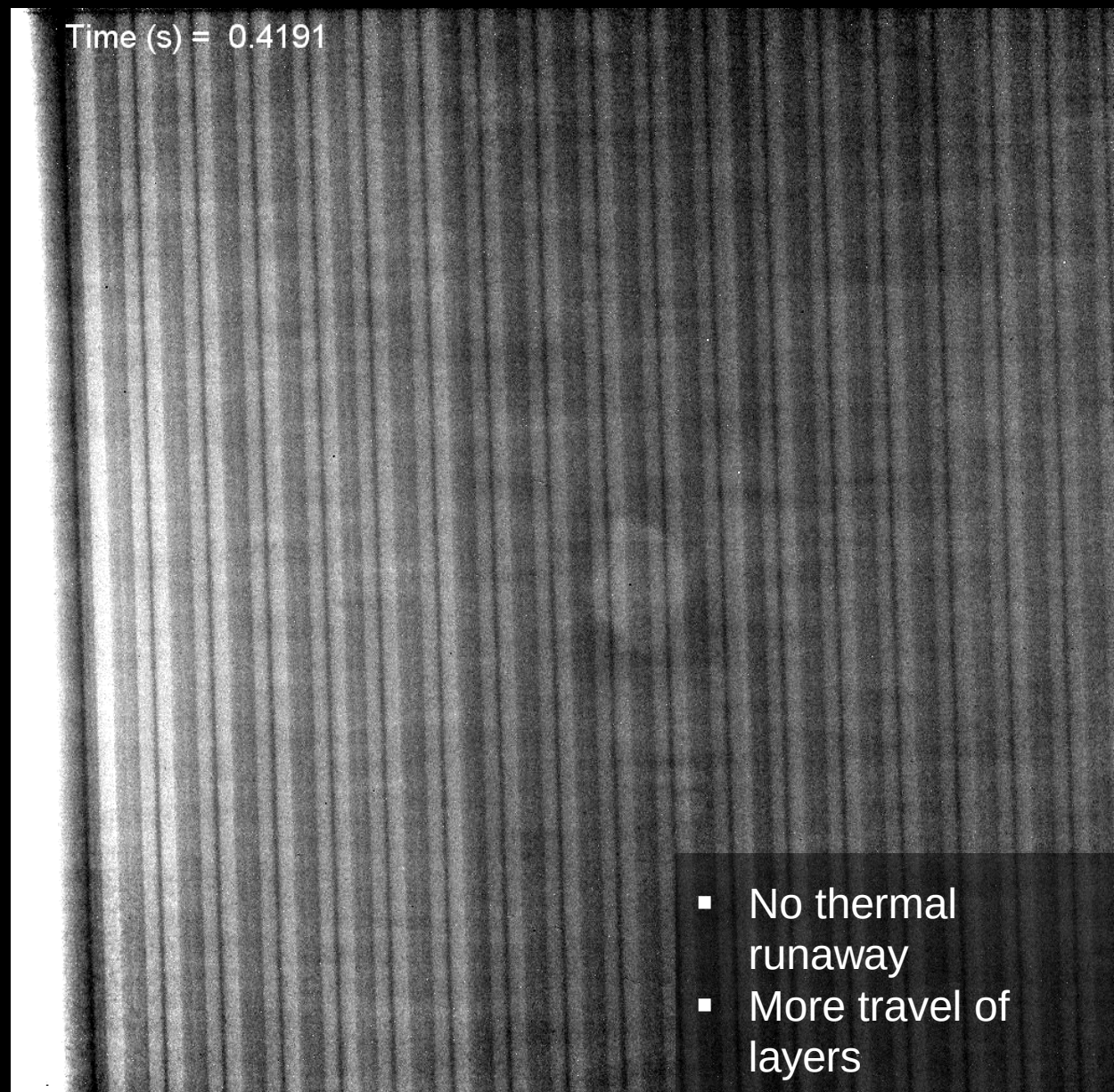
Run 025



- Thermal runaway from tip of nail
- Buckling and splitting of

Cell with PCC

Run 020



- No thermal runaway
- More travel of layers

Why I am still here at NASA-JSC?

- Why didn't I jump to NREL permanently in 2010?
- With the phenomenal growth in the battery industry in last 10 years, why I am still here?

Other Important Benefits

- Continued education opportunities
- Sabbatical year with pay
- Presenting at numerous technical conference even international ones
- Outside Partnerships
- Telework flexibility

- NASA is a unique
  - Many talented and driven folks
  - We are focal point for manned space
  - Have access to lessons learned from all programs/contractors
  - Job excellence is well rewarded
    - It is sought and respected
  - With excellence and persistence, standing your ground on technical issues can result in big impacts
  - ***Great new hires and interns, and outside partnerships are the key to our battery group success***
- Maturing plastic current collectors

Outstanding Battery Team

NASA

- Chris Iannello (NESC)
- Steve Rickman (NESC)
- Will Walker (now at KULR Technology)
- Jacob Darst
- David Petrushenko
- Zoran Bilc
- Chuck Haynes
- David Delafuente
- Sam Russell
- Jim Rogers
- Minh Tran
- Thuong Nguyen
- Jesus Trillo
- Brenda Esparza
- Casey Fortune (now at Archer)
- Algie Armstead
- Jason Graika
- Angad Mehrotra
- ESTA battery team
- And numerous interns

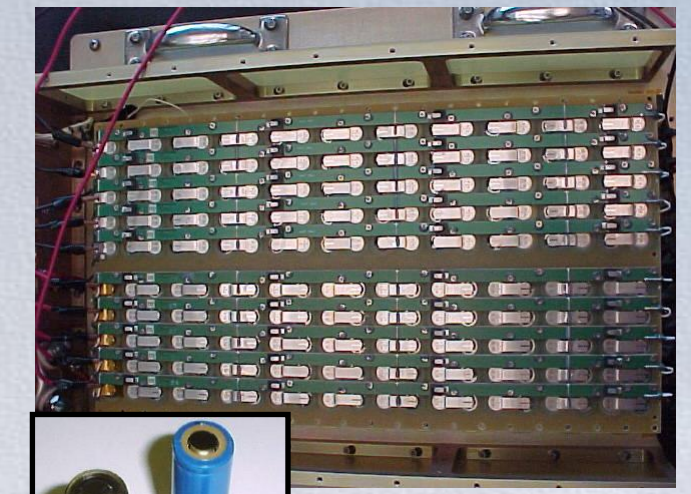
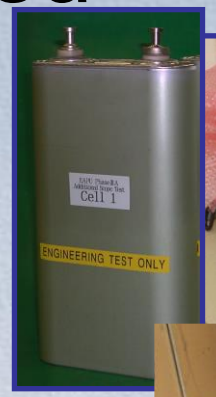
Partners

- Brad Strangways (SRI)
- Mark Shoesmith and Brian Way (e-One Moli Energy)
- Donal Finegan (NREL)
- Gary Bayles (SAIC)
- Paul Coman (White & Associates)
- Michael Mo (KULR Technology)
- Joe Turner & Ed Buiel (Coulometrics)
- Joe Fontaine (NAVSEA-NUWC)
- Tom Adams (NAVSEA-Crane)
- John Izzo (NAVSEA-NUWC)
- Clinton Winchester (NAVSEA-Carderock)
- Michael Brundage (Army-Aberdeen PG)
- Kurt Kelty (Tesla, now at Sila)
- Matt Soule and John Howard (SpaceX, now Parallel Systems)
- Celina Mikolajczak (Exponent, Tesla, now Lyten)
- Joe Troutman (ABSL, now Forgenano)
- Tom Barrera (Boeing, now LIBX consulting)
- Marshal Smart (JPL)
- Jeff Brewer (MSFC)
- Tom Miller (GRC)

Back Up

Mid Career (1997-2012) Continued

- Shuttle upgrade Electric APU with Li-ion battery (2000-2002)
  - Convinced program to drop Boeing's large cell approach for a safer, higher performing small commercial cell approach
    - GFE development of small cell battery
  - Columbia accident in 2003 ended this upgrade
- Selected for Independent Review Panel to advise Navy on how to safely develop Li-ion batteries
  - After manned electric submarine battery fails catastrophically in 2008



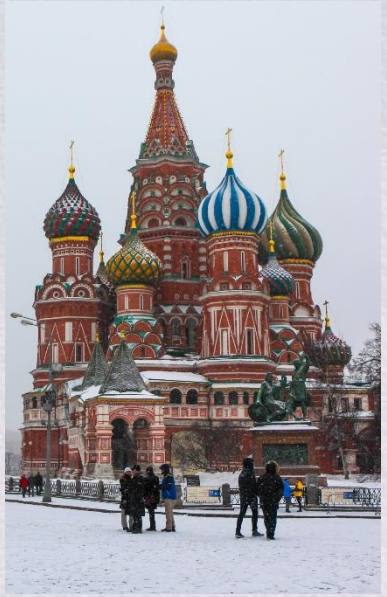

Denali (20,320 ft) in 2004

David Schuman/NASA

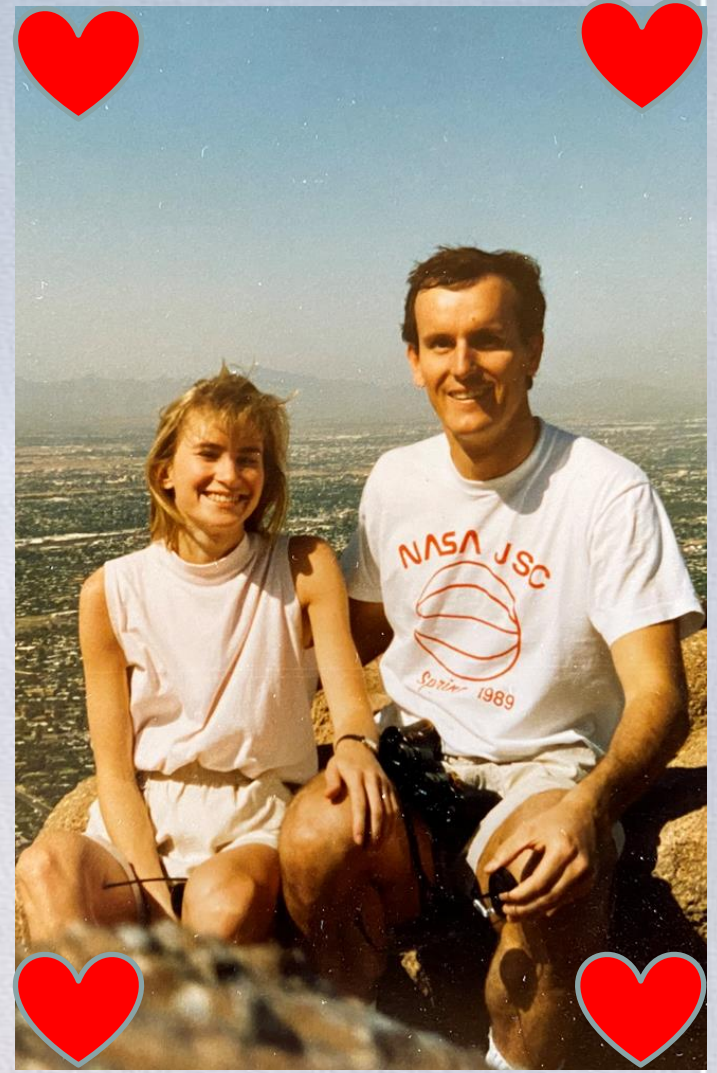
John Grunsfeld/NASA

Personal Info

- Married the love of my life, Cheryl, in 1990
  - She's a true ChE
- Blessed with 2 great kids, adopted from Moscow orphanage

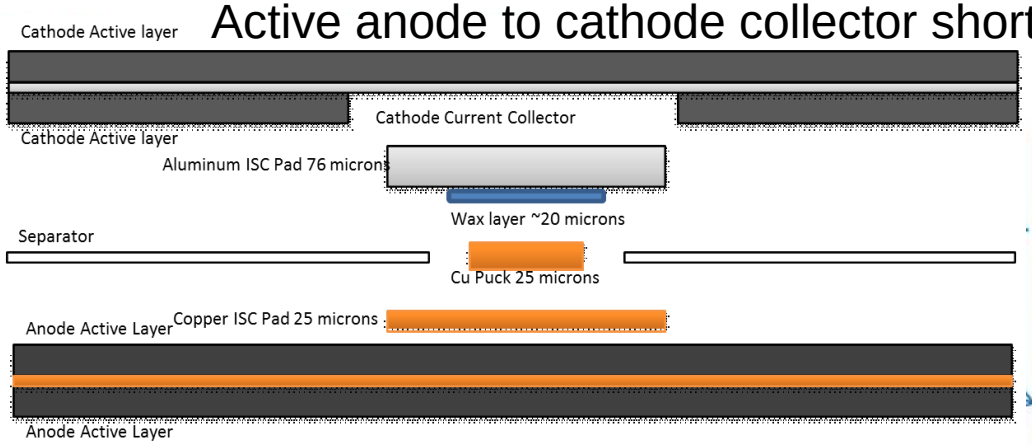


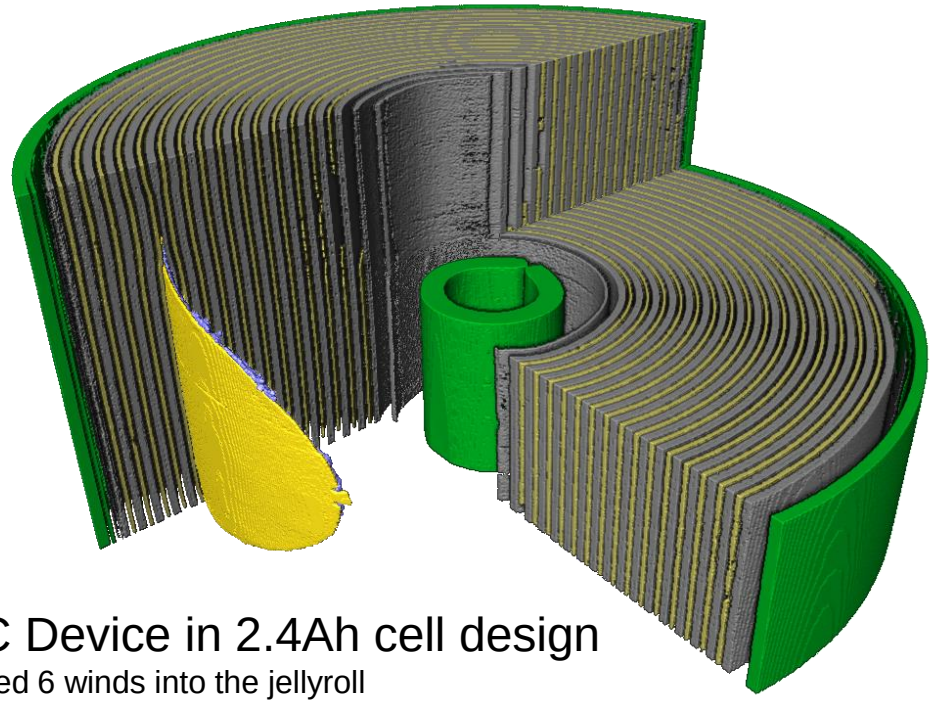
Oct 6, 1990, morning of our wedding on summit of Camelback Mtn



NREL/NASA Cell Internal Short Circuit Device

Active anode to cathode collector short





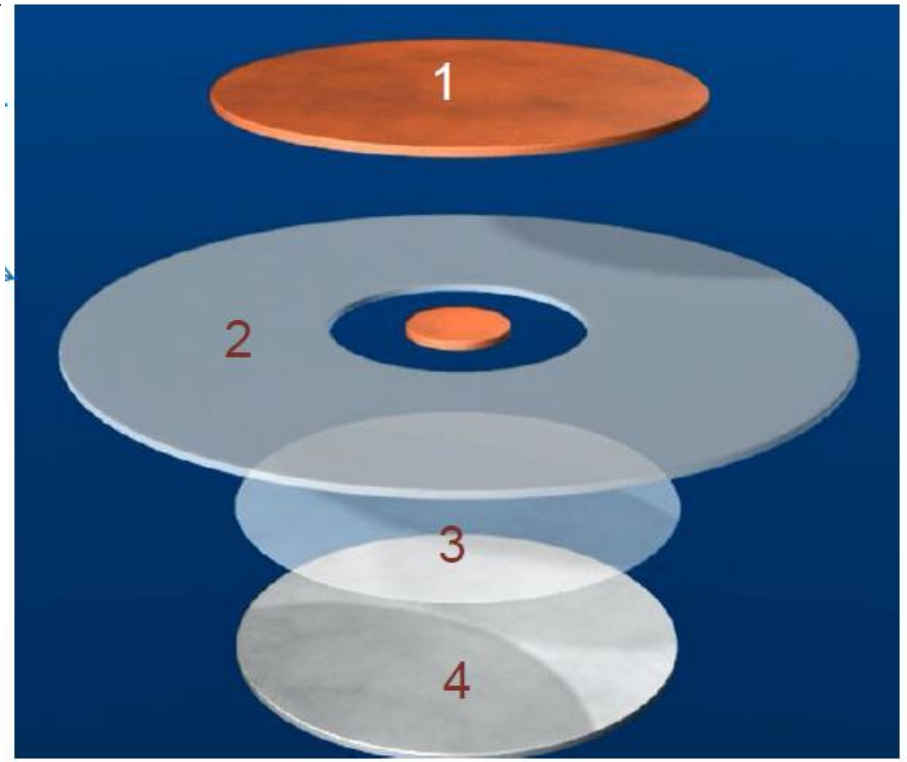
ISC Device in 2.4Ah cell design

Placed 6 winds into the jellyroll

5 mm

Tomography credits: University College of London

KULR Carbon Fiber Cooling™ Exclusive Licensee, March 2018



Graphic credits: NREL

Top to Bottom:

1. Copper Pad
2. Battery Separator with Copper Puck
3. Wax – Phase Change Material
4. Aluminum Pad

2010 Inventors:

- Matthew Keyser, Dirk Long, and Ahmad Pesaran at NREL
- Eric Darcy at NASA

US Patent # 9,142,829 issued in 2015

Thin (10-20 μm) wax layer is spin coated on Al foil pad

Wax formulation used melts ~57°C

Runner-up NASA Invention of 2017

R&D 100 WINNER

2016 Award Winner