KENEXIS

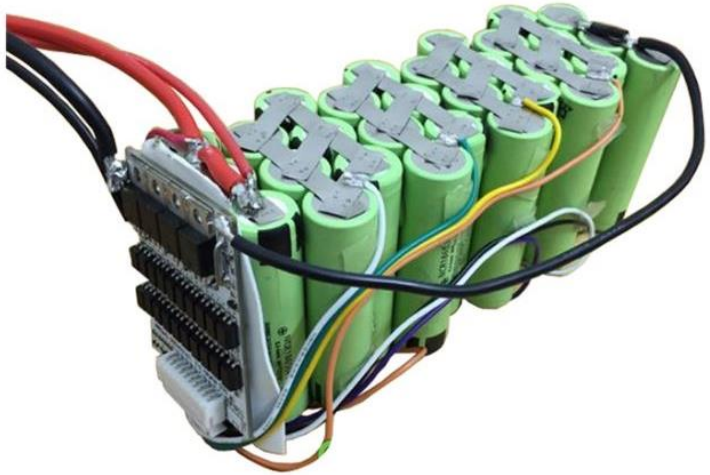
Designed for Safety, Security & Reliability

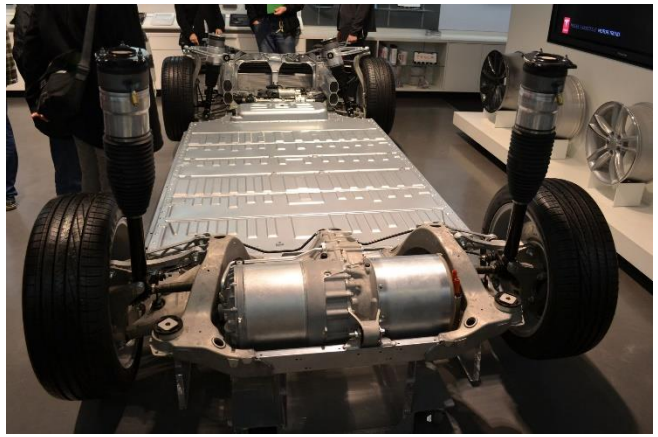
Lithium Ion Battery Thermal Runaway

SAFETY INSTRUMENTED SYSTEMS

Battery is a Chemical Plant

- Energy Stored as Chemical Reaction Potential
- Chemical Reaction to Charge
- Chemical Reaction to Discharge





Tesla Model S – 7,104 cells in 16 series wired modules – 1,200 lbs – 85kW/h

Power Storage Facility – 2mW/h – 28,235 lbs?
% Flammable Liquids?

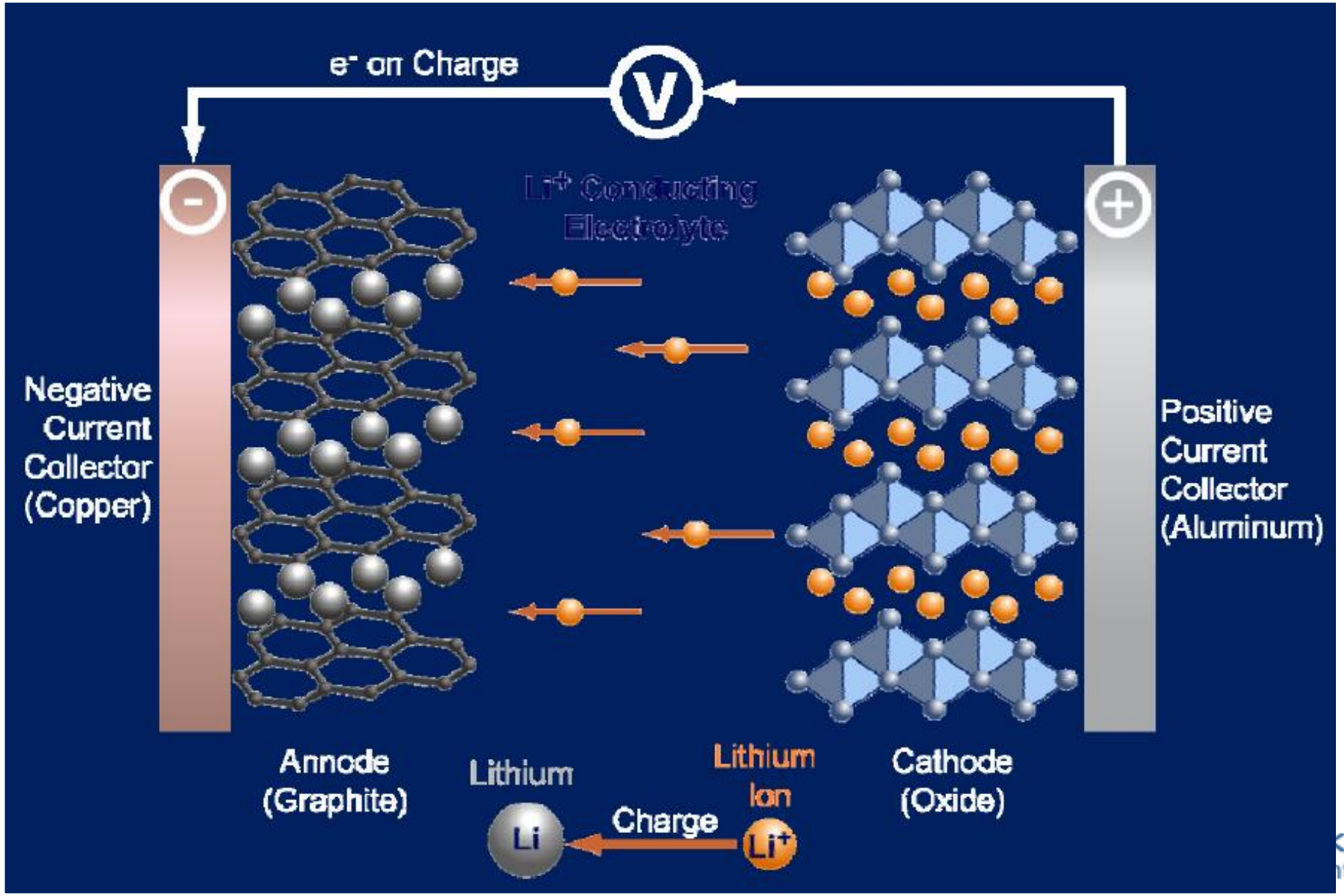
Patented 1976 – Exxon Researcher Stanley Whittingham – 2019 Nobel Laureate

Lithium Ion Battery Facility Explosion

- Arizona Public Service (APS)
- Surprise, AZ, outside Phoenix, April 19th, 2019
- Store Solar Power Generated During Day for Discharge at Night
- Firefighters called in to fight fire in facility
- Upon entering facility, explosion which sent four first responders to hospital
- Third similar event within company since 2012
- Fire Marshals now requiring use of gas detection

- 2 Megawatt-Hour

General Battery Operation

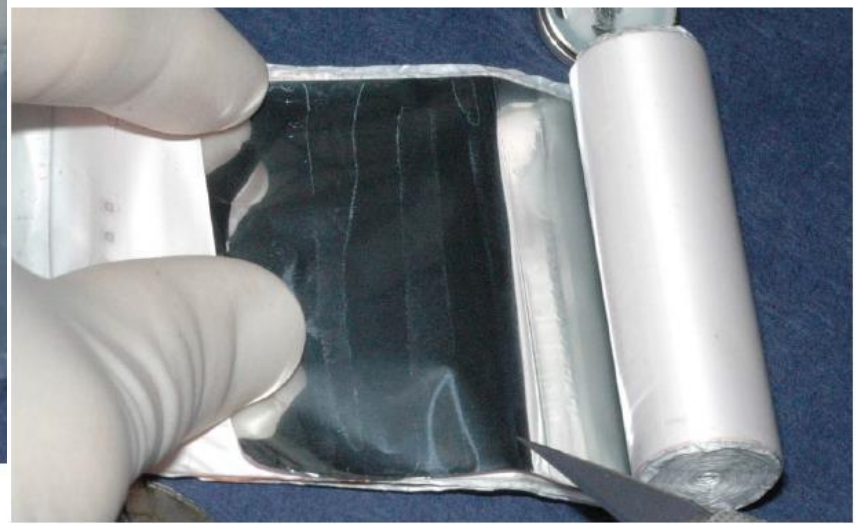


Components

- Anode (Graphite and Binder)
- Cathode - $LiCoO_2$
- Electrolyte
  - Organic Solvent
  - LiPF6
- Separator – PP, PP/PE Blend
- Current Collectors
  - Copper (Anode)
  - Aluminum (Cathode)

Cell Enclosures

- Single Cell
- Hard Case
- Pouches
- Collections
  - Cell
  - Module
  - Pack



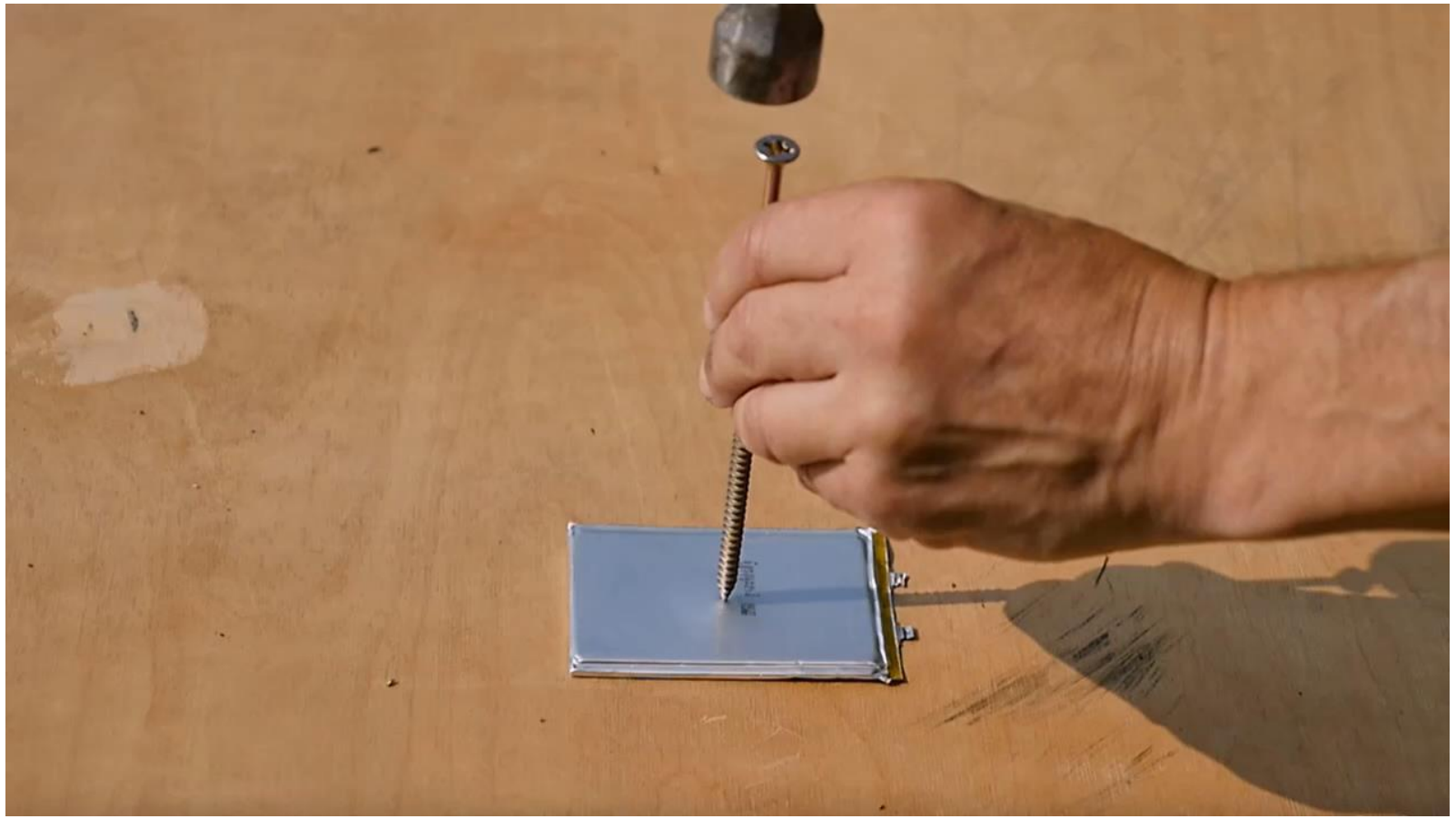
Failure Modes

- Thermal Runaway
  - Self Accelerating Decomposition Temperature (SADT) – 66.5 C
  - No Return Temperature (TNR) – 75 C
- External Fire
- Short Circuit
  - Through separator
  - Internal due to component failure
  - External
- Puncture

Pinhole failure of separator

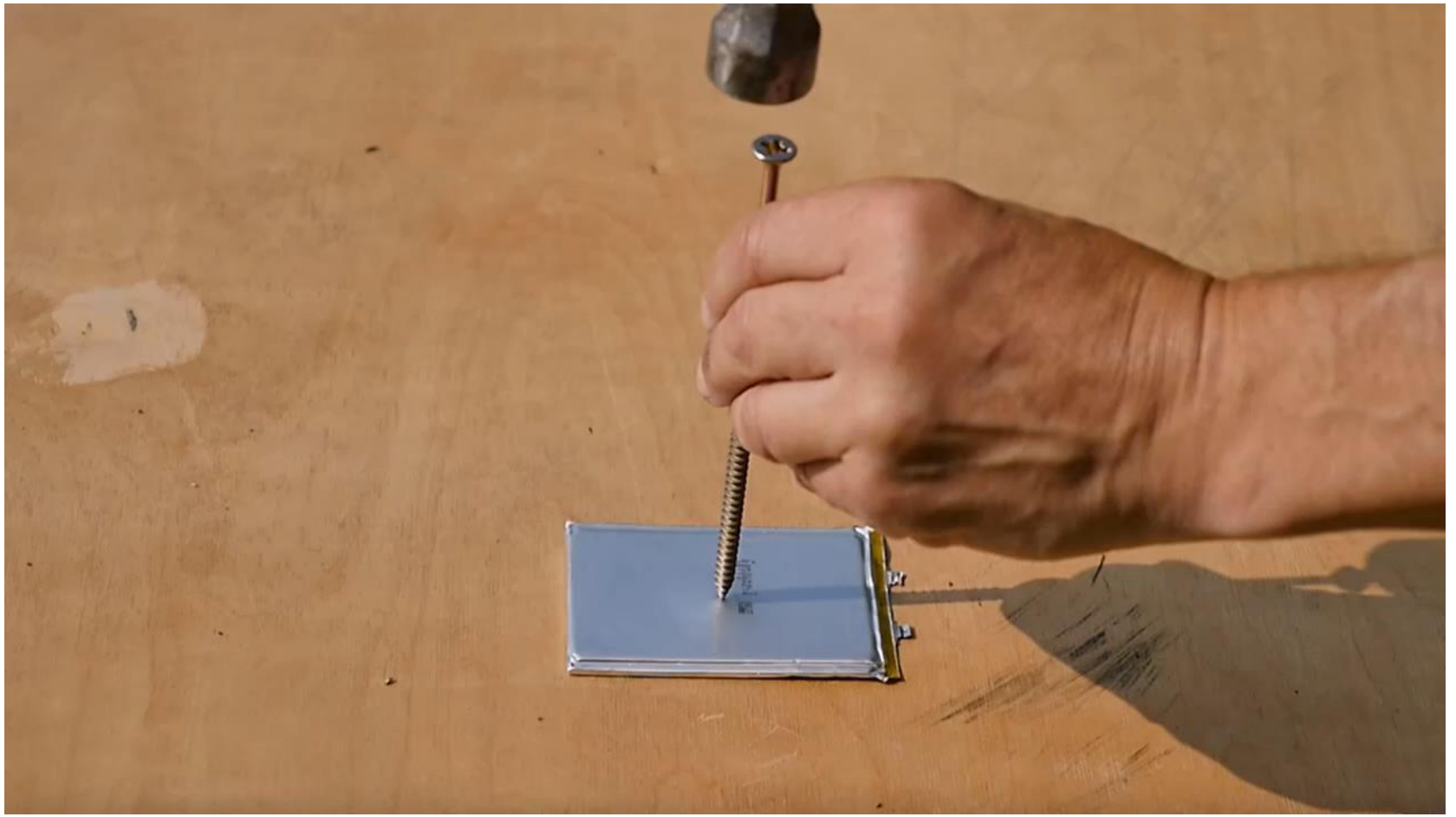
Thermal Runaway

- Stages and Effect of Thermal Runaway
  - Energy discharge – heating
  - Electrolyte cracking – First gassing phase
  - Separator and Anode decomposition – second gassing phase
  - Ignition – flash fire or vapor cloud explosion



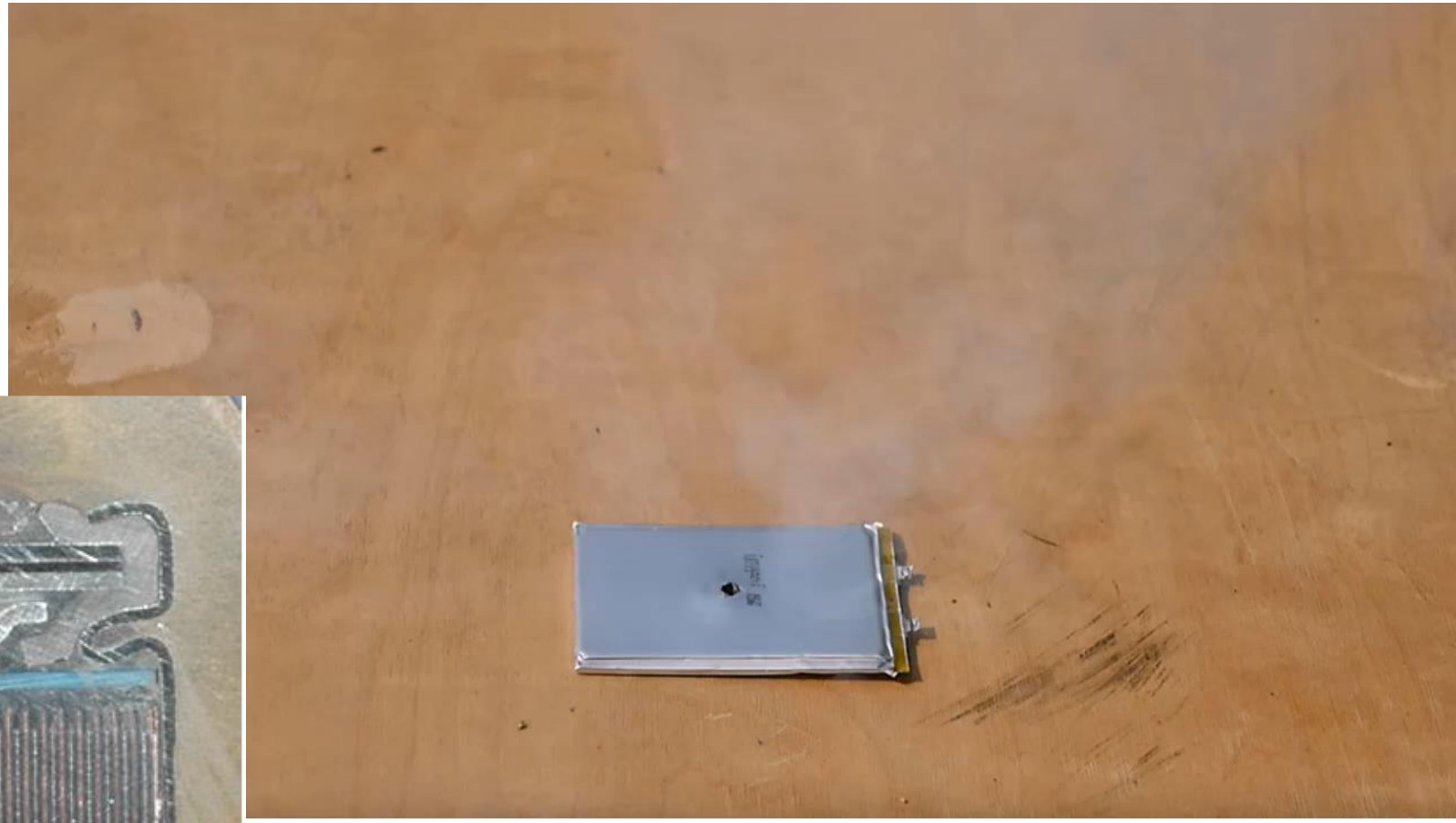
Stage 1 – Energy Discharge - Heating

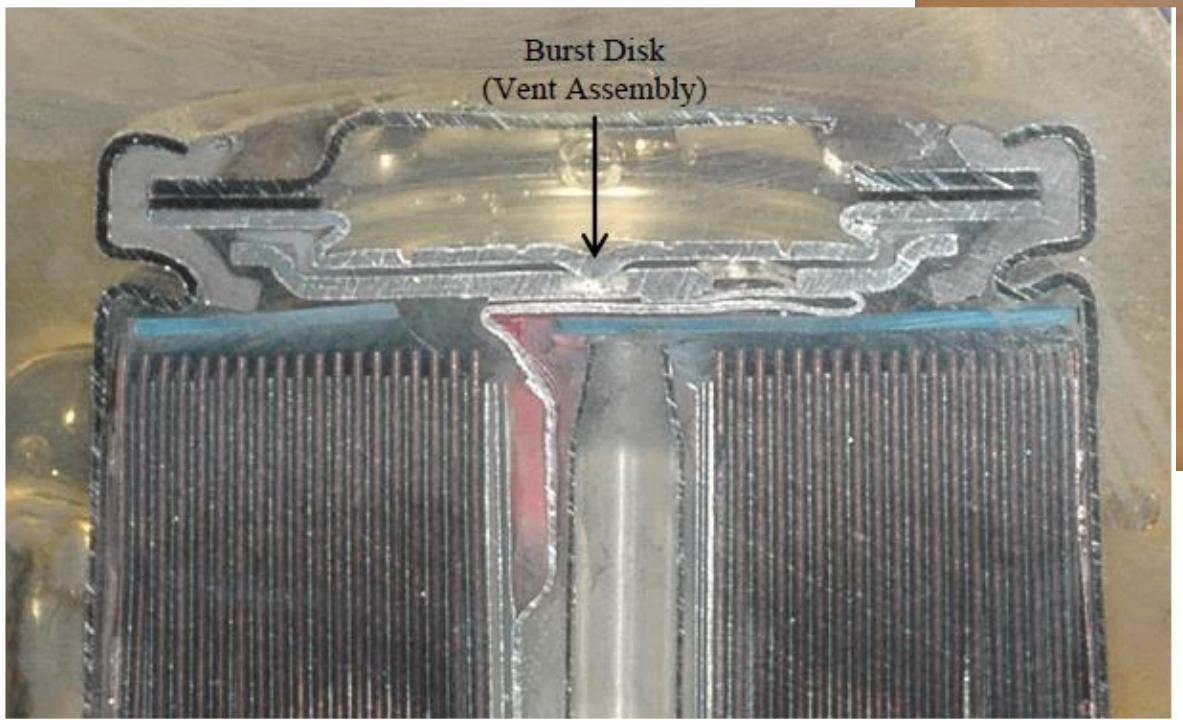
- Energy in Battery is Suddenly Discharged
  - Generally the result of a short circuit
  - Stored energy mostly converted to intense heat
  - No gas expansion typical of hydrocarbon combustion at this stage



Stage 2 – Electrolyte Cracking / Gassing

- High temperature causes flashing/cracking of electrolyte
  - LiPF6 and Organic Solvent (Ethylene Carbonate)





Stage 3 – Separator and Anode Cracking / Gassing

- High temperature causes flashing/cracking of anode and separator
  - Graphite, Binder, PE/PP Film
  - Incomplete cracking decomposition, gas discharge becomes smoky

Stage 4 – Ignition and Combustion

- Loss of momentum and air entrainment result in ignition
  - Generally above auto-ignition
  - If insufficient air is present, flammables will accumulate – potential for explosion
  - Entire battery (capable of combusting

Recommendations for Safeguarding

- PHA
  - Study types
    - HAZOP
    - FMEA
  - Guide Words / Failure Modes
- Implement Safeguards
  - Pressure Relief
  - SIS
  - FGS
    - External Fire
    - Knock-On
    - Gas Detection

Conclusions

- Li Ion batteries in large quantities inside fixed facilities pose significant facility risk
- Hazards of Li Ion battery usage should be formally assessed
- Appropriate safeguards should be included in the facility design