Li-ion Technology Overview

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Current Market for Rechargeable Li-ion Batteries

- First commercialized in 1991
- Now "preferred" rechargeable battery chemistry for portable consumer electronics
- Estimate over **2 billion*** Li-ion cells will be manufactured in 2006 for portable applications

Major Applications for Small Li-ion Batteries	Approx. share of total Li-ion production*
Mobile phones	**~ 55%**
Notebook PC's	**~ 25%**
Cameras, Camcorders, MP3, PDA's, Games, etc.	**~ 20%**

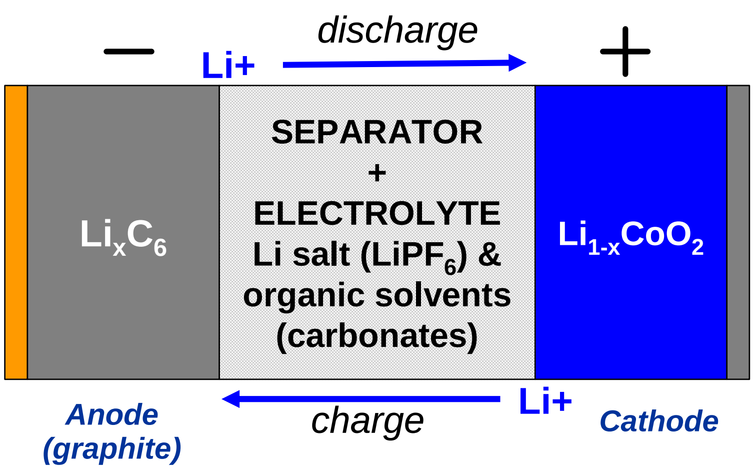
*Reference: H. Takeshita, Institute of Information Technology

- Supply Chain:
  - Cell manufacturers: Predominantly in Asia (Japan, Korea, China)
  - Pack manufacturers: Worldwide, but majority in Asia
  - Final packing with Host Device: Worldwide

Advantages of Li-ion

- Volumetric and gravimetric **Energy Density** exceeds other rechargeable chemistries (NiMH, NiCd, Lead Acid)
- Good power density
- Reasonable cost, very low “dollar per watt-hour”
- Cell voltage well matched to portable applications (3.7 V nominal)
- Good cycle life
- Low self-discharge
- No “memory effect”

Basic Chemistry



discharged ⇄ **charged**

Anode

$$Li^+ + C_6 + e^- \rightleftarrows Li_xC_6$$

$x < 1$

$1.0\ V < E^o < \sim 0.05\ V$ vs. Li

Cathode

$$LiCoO_2 \rightleftarrows x\,Li^+ + Li_xCoO_2 + e^-$$

$x < 0.5$

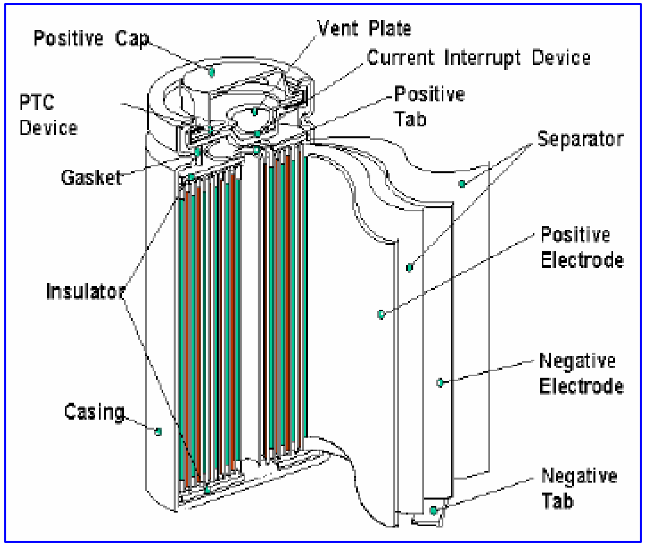
$3.5\ V < E^o < \sim 4.25\ V$ vs. Li

- Lithiated metal oxide cathode (usually cobalt based)
- Graphite anode
- Organic solvent electrolyte with lithium salt.
- ***No lithium metal***

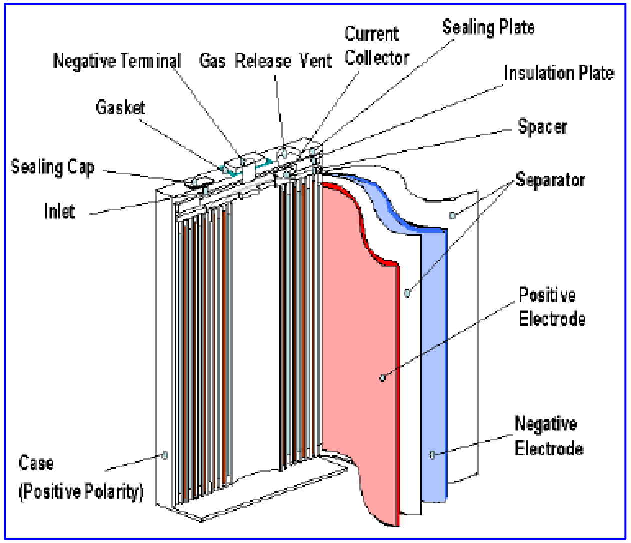
Basic Construction

Figures Reference: *IEEE 1725 Standard*

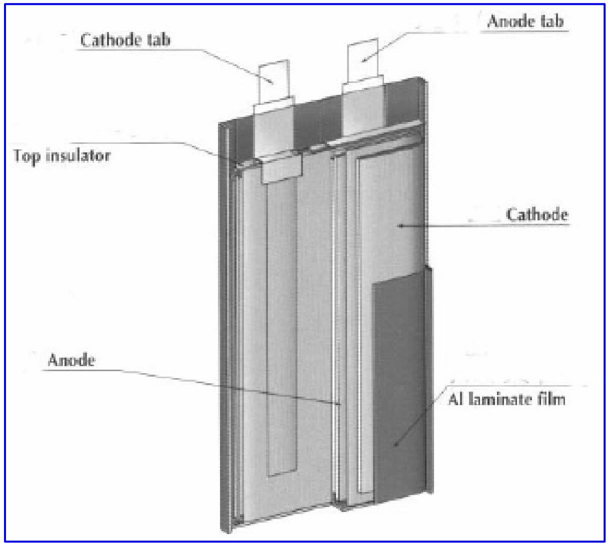
Cylindrical



Prismatic



Polymer



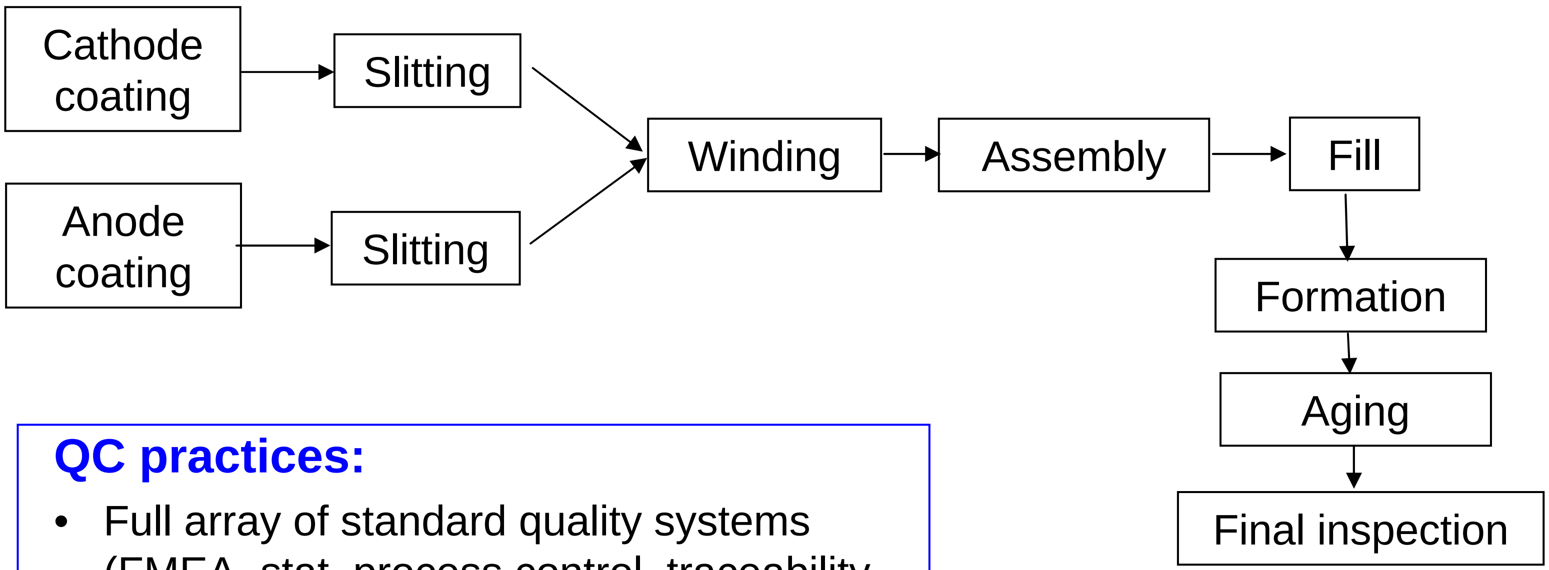
General:

- Coated foil electrodes
- Porous separator with absorbed electrolyte
- Spiral wound "jelly roll" or "cut and stack"
- Safeguard examples:
  - •Cell design
  - •Vent mechanism
  - •"Shutdown" separator
  - •PTC, fuses, etc. on larger cells

"Li-ion Polymer":

- Same basic chemistry and structure
- Polymer laminate casing replaces metal can
- Allows for some sizes not possible in cans
- Generally rigid, prismatic form factor
- Various electrolyte technologies
  - - Conventional liquid
  - - Gelled polymer

Cell Manufacturing Overview

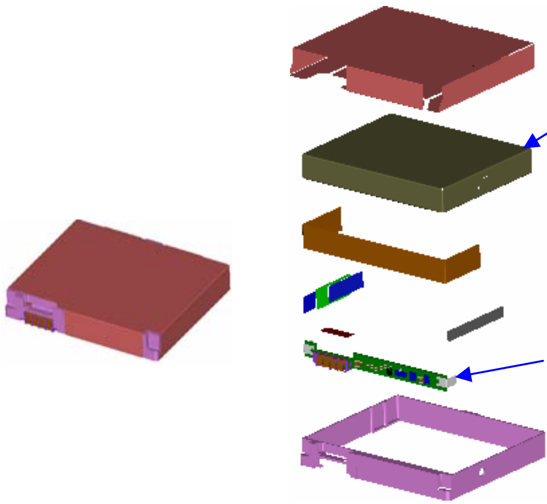


QC practices:

- Full array of standard quality systems (FMEA, stat. process control, traceability, etc.)
- 100% X-ray inspection following assembly
- 100% Mechanical at numerous points
- 100% Electrical (internal shorts, impedance, capacity) at numerous points
- 100% Formation/Aging process (capacity, internal shorts)

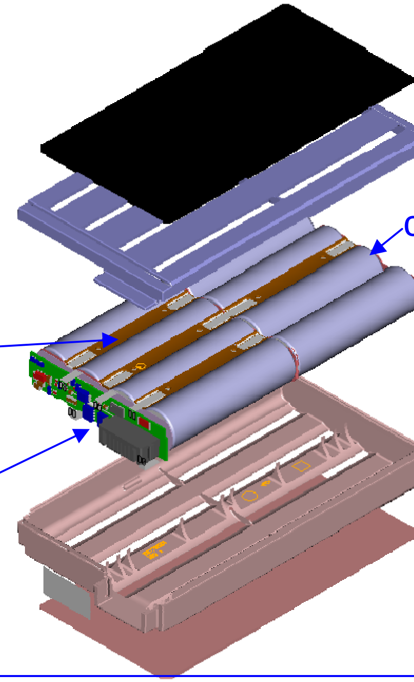
Battery Pack Construction and Manufacturing

Single Cell Pack



Multicell Pack

- Cells arranged in series (increase voltage) and/or parallel (increase capacity)
- Tabs typically welded to cells to form interconnects



Pack Level Safeguards

- Mechanical integrity
- Electrical controls
- Thermal controls

Design Considerations

- Prevent short-circuits & loss of functionality
- Insulators, component layout & isolation
- Mechanical integrity of connectors & packaging

Manufacturing QC

- **Full array of standard quality systems (FMEA, stat. process control, etc.)**
- **Protection circuit test (preassembly and End-of-Line)**
- **General mechanical and electrical tests**

Potential Failure Mechanisms

- ***Thermal runaway*** **=** sudden, rapid increase in cell temperature and pressure
  1. Cell heating
  2. Activation of exothermic reactions within the cell
  3. Activation of additional reactions
  4. Exponential increase in heat generation
  5. *Heat generation > Heat dissipation*
  6. *Thermal runaway: cell venting, internal temperatures > 200º C*

- **Potential causes**
  - Overcharge
  - Excessive environmental temperature
  - Internal short circuit
  - External short circuit

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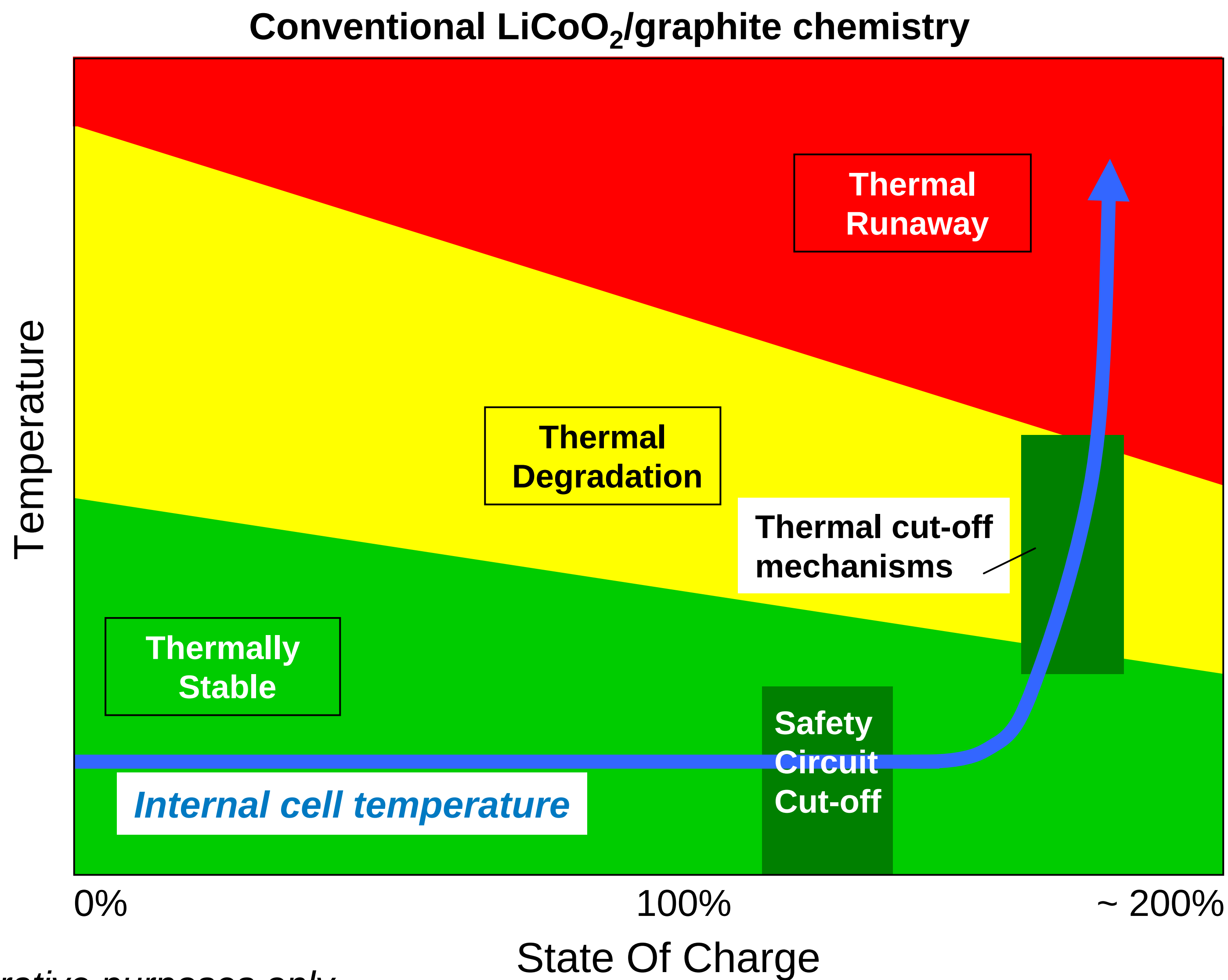
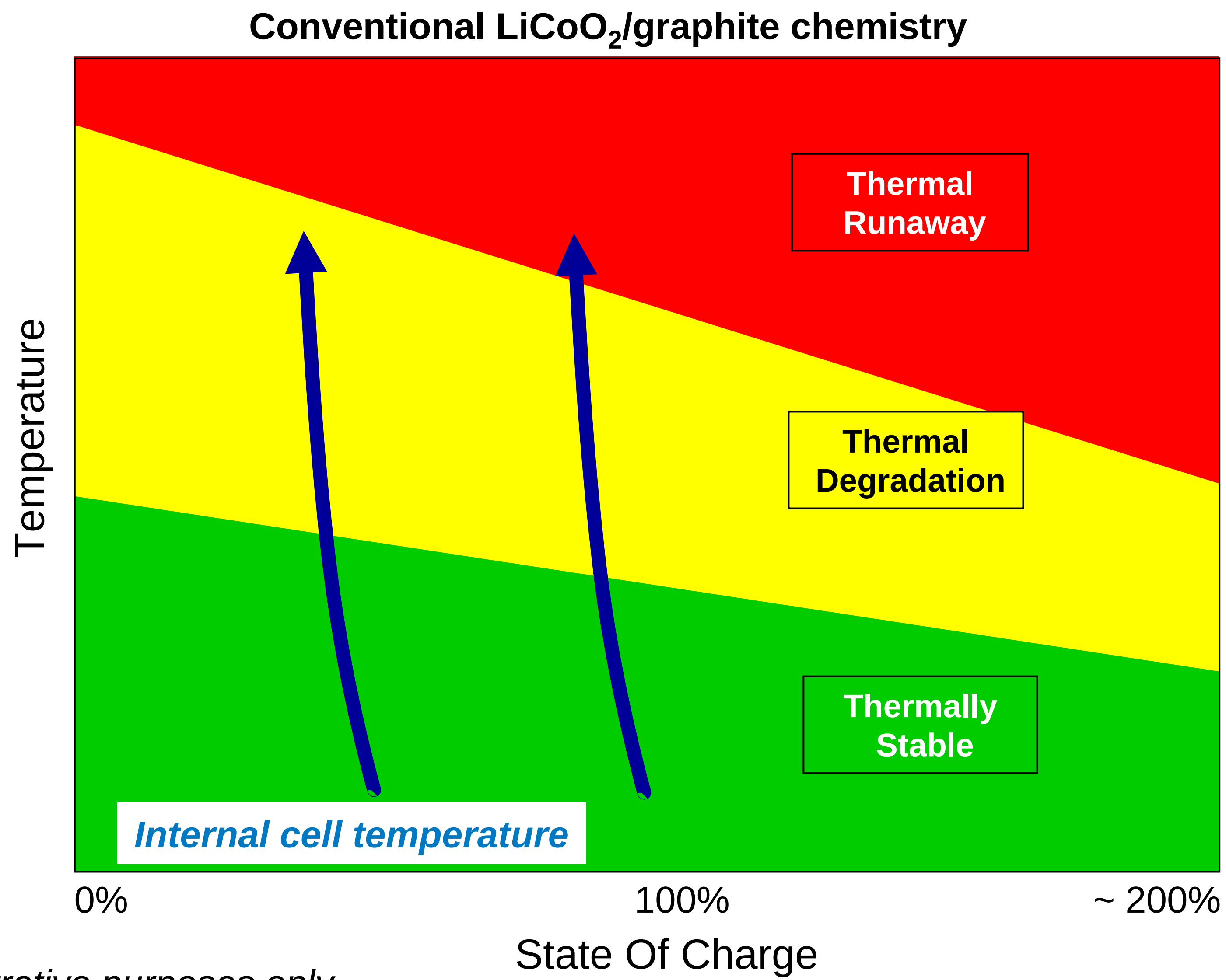
Overcharge and Thermal Runaway



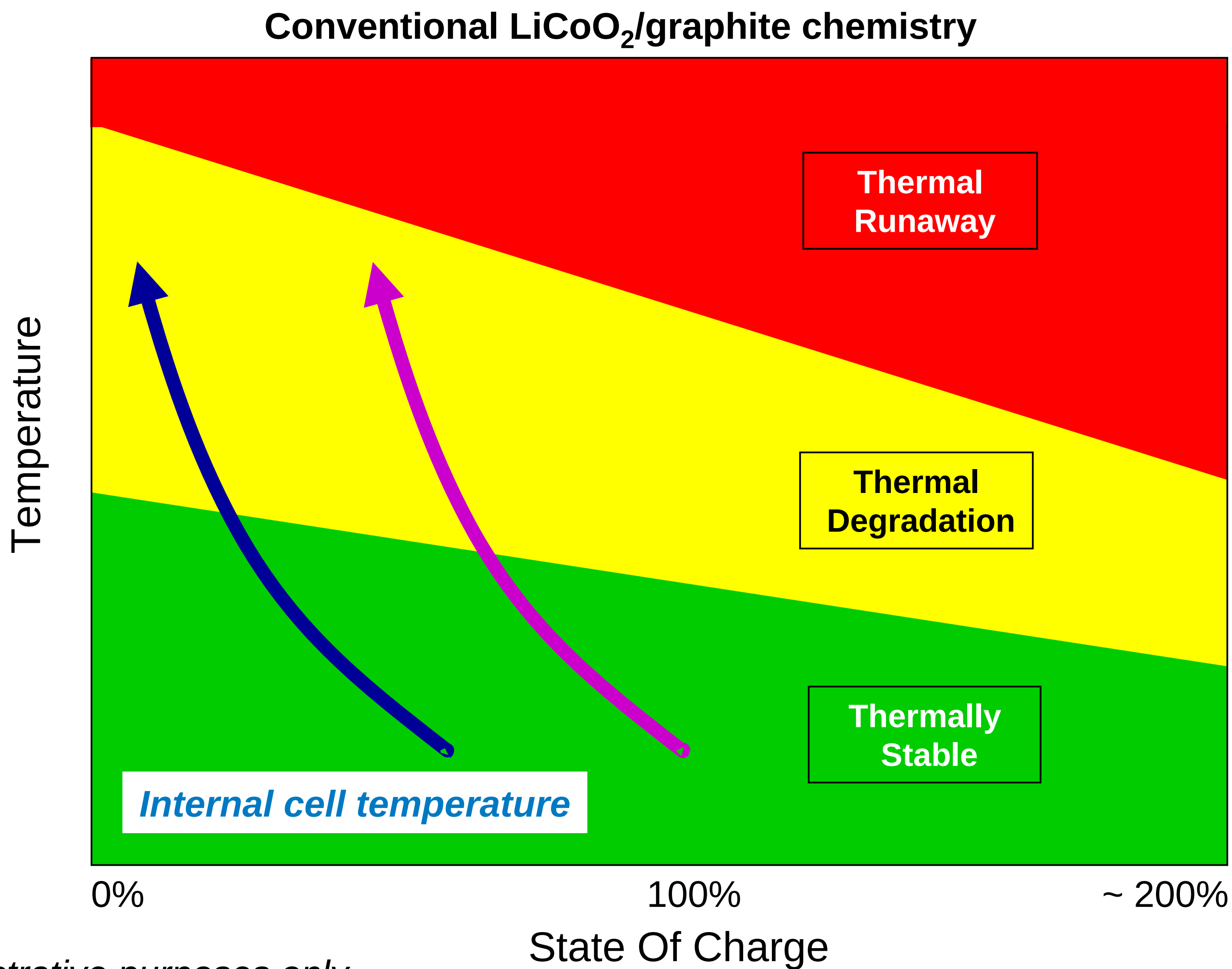
*for illustrative purposes only

External Heating and Thermal Runaway



for illustrative purposes only

Short Circuit and Thermal Runaway



**for illustrative purposes only*

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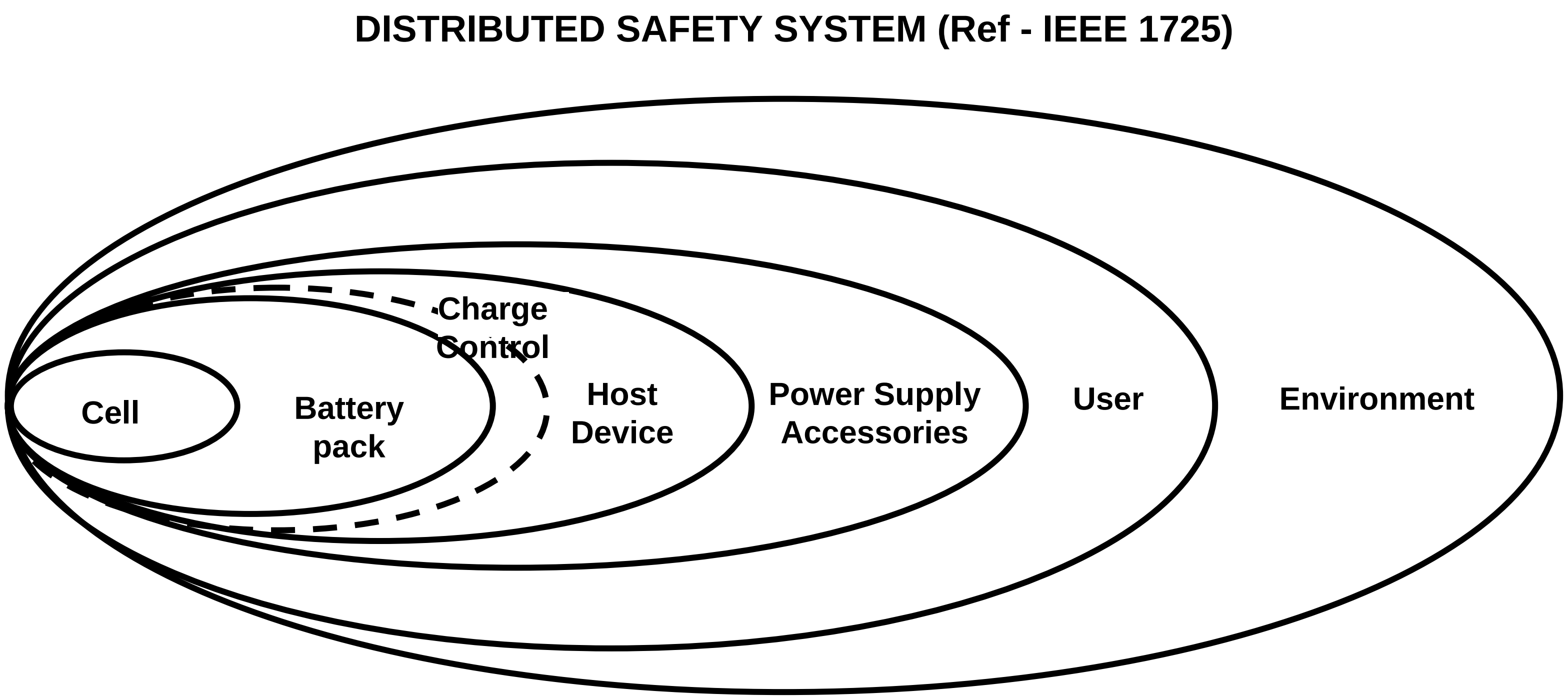
Ensuring Safety and Reliability



- System Level Design
- Manufacturing Quality
- Testing and Validation

Industry Standards and Transport Regulations

UN Recommendations for Transportation of Lithium and Li-ion Batteries

- **Testing, packaging, labeling**

Traditional Cell and Battery Standards

- **UL 1642, UL 2054, IEC 62133**
- **Includes Electrical, Mechanical, Thermal abuse tests**

IEEE System-Level Standards

- **1625 (notebooks) & 1725 (cell phones)**
  - system level approach
  - design analysis
  - manufacturing practices
  - incorporate “best practices” and “lessons learned”

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Li-Ion State of Charge for Transportation

- **Minimum state of charge**
  - Must maintain capability to activate control circuit following prolonged storage
  - Batteries will self-discharge following prolonged storage
  - Prolonged storage in overdischarged state can permanently damage Li-ion cell due to dissolution of copper current collector
- **Maximum state of charge**
  - Parasitic reactions in Li-ion cells can slowly degrade rechargeable capacity ("irreversible capacity loss")
  - Driven by time, temperature, and state of charge
  - Temperature/time effects in fully charged cells can lead to unacceptable irreversible capacity losses. (Permanent damage).

- *Optimum state of charge for shipment is about 30 - 50%.*

Sample Reference Studies on Li-ion Cells

(provided by the Portable Rechargeable Battery Association)

1. ***Flammability Assessment of Bulk-Packed, Rechargeable Lithium ion Batteries in Transport Category Aircraft*** **(Draft), U.S. Federal Aviation Administration (2006).**

2. ***U.S. FAA-Style Flammability Assessment of Lithium ion Cells and Battery Packs in Aircraft Cargo Holds*****, Exponent Failure Analysis (2005).**

3. ***Flammability Assessment of Bulk-Packed, Nonrechargeable Lithium Primary Batteries in Transport Category Aircraft*****, U.S. Federal Aviation Administration (2004).**

4. ***Effect of Cell State of Charge on Outcome of Internal Cell Faults*****, Exponent Failure Analysis (2004).**

5. ***Dealing With In-Flight Lithium Battery Fires In Portable Electronic Devices*****, UK Civil Aviation Authority (2003).**

6. ***A Study of Passenger Aircraft Cargo Hold Environments*****, Exponent Failure Analysis (2001).**

7. ***Safety Testing of Li-ion Cells*****, U.S. Department of Transportation (2001).**

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Highlights from Reference Studies

- Reduced state of charge mitigates risk in Li-ion batteries from crush, internal shorts, and excessive heating.
- Halon is effective on fires involving Li-ion batteries.
- Conventional fire extinguishers may be used on fires involving Li-ion batteries.
- Cargo liner resists fires involving Li-ion batteries.
- Significant differences between primary lithium and Li-ion batteries.

Backup

Properties of LiC_6

Theoretical specific capacity = 372 mAh/g
(Li metal = 3860 mAh/g)

Li valence state in fully charged LiC_6 is between 0 and 1 *

Reaction kinetics limited by slow mass transfer of Li^+ through carbon matrix
- Limited rate capability for Li-ion batteries
- Limited reactivity with water
    - Slow generation of H_2 gas
    - Less than 14 liter/kg hr **
    - Meets PKG group III requirements

* M. Fujimoto et al., *Electrochemical Society Proceedings Series,* Vol. 93-23, 1993.
** CEA Associates, "Risk Assessment of Li-ion Batteries", September 30, 1997

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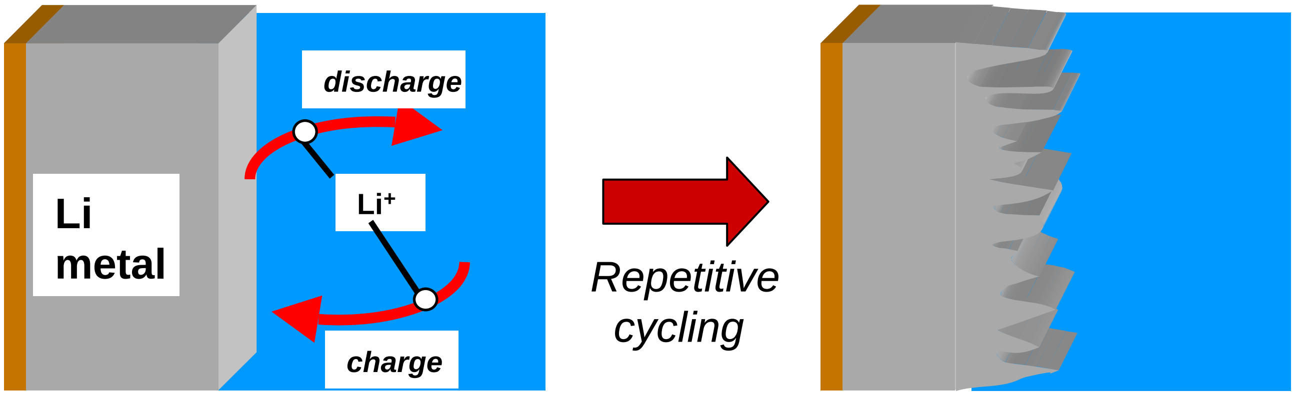
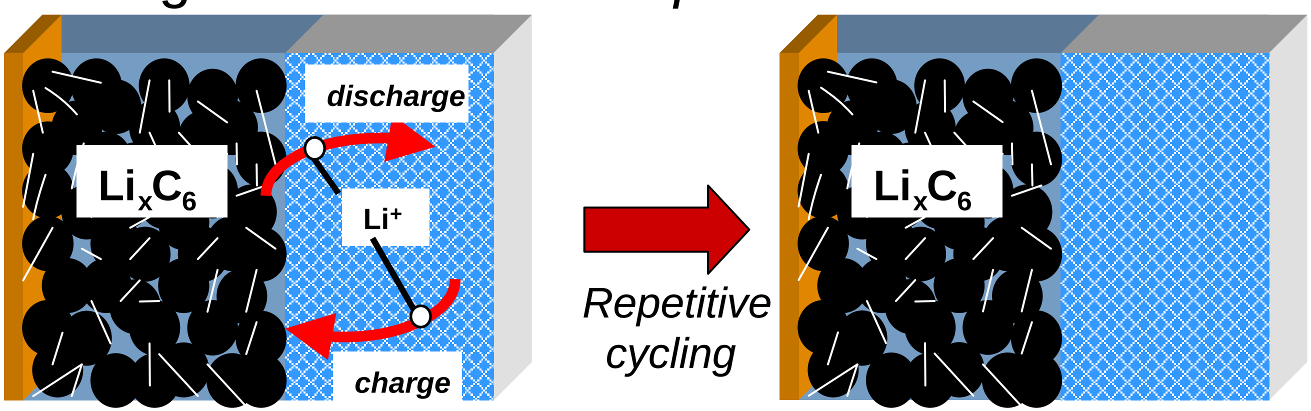
Rechargeable Li-ion vs. Li Metal

Rechargeable Li Metal / liquid electrolyte:



- Increased interfacial surface area
- Increased reactivity
- Potential for dendritic short-circuit
- ***Interface stability issues***

Rechargeable Li-ion: *Developed as solution to Li-metal instability*



- Constant interfacial morphology
- Unchanged reactivity
- ***Improved stability***

Overcharge vs. Internal Short

	Overcharge	**Internal Short**
Electrochemical Energy vs. Rated Capacity	Can be 200%	$\leq$ 100%
Heating Source	External, Continuous	Internal, Limited
Chemical Reactivity	Increasing ➡ Faster Energy Release	Decreasing or Unchanged
Mitigated by Protective Circuits?	Yes	No

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