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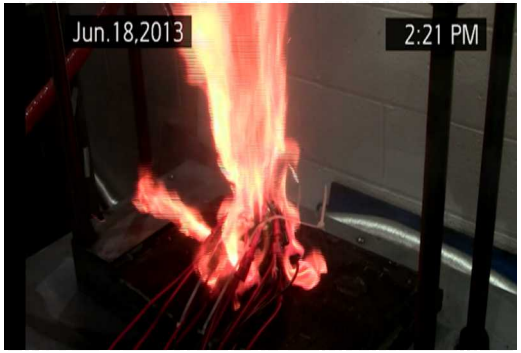

Advanced Methodology for the Development of Safe and Reliable Energy Storage Systems

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Introduction

As an increasing number of energy storage systems are deployed, the risk of safety incidents increases.

Damage to Facilities

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

- There were two fires in a year at the Kahuku Wind Farm
- There was significant damage to the facility
- Capacitors in the power electronics are reported to be associated with the failure.

Impact to First Responders

2013 Storage Battery Fire, The Landing Mall, Port Angeles WA

- First responders were not aware of the best way to extinguish the fire,
- It reignited a week after it was thought to be extinguished.

Systems Thinking (Safety)

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"Safety is an emergent property that arises when system components interact with each other within a larger environment."

(Leveson 2012) [1]

Battery Cell Properties

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- ✓ Capacity
- ✓ Energetics
- ✓ Temperature Range
- ✗ Safety

"Safety" is not a property of a component

Battery System Properties

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- ✓ Capacity
- ✓ Service Life
- ✓ Control Algorithm
- ✓ Safety

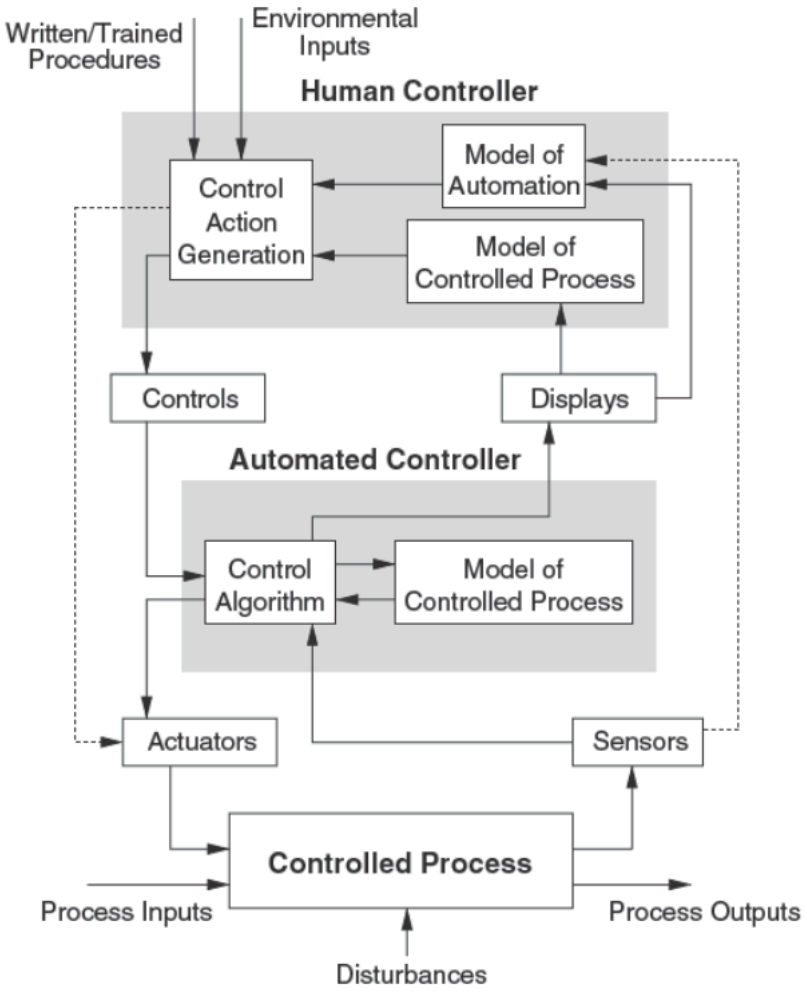
Safety is a system property

How do battery properties influence system safety?

Advanced Methodology

- Systems Theoretic Process Analysis
  - Accidents occur when interactions violate **safety constraints**,
  - The system enforces these constraints using **feedback control**.

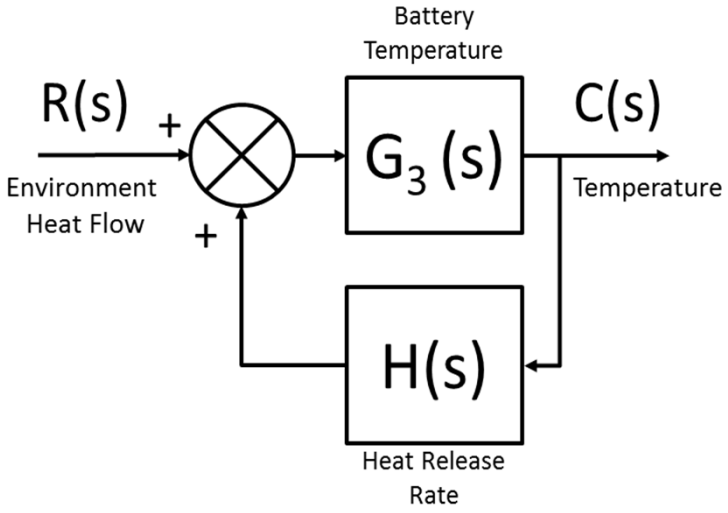
More information on using STPA for Lithium-Ion Battery System Safety is in [2]



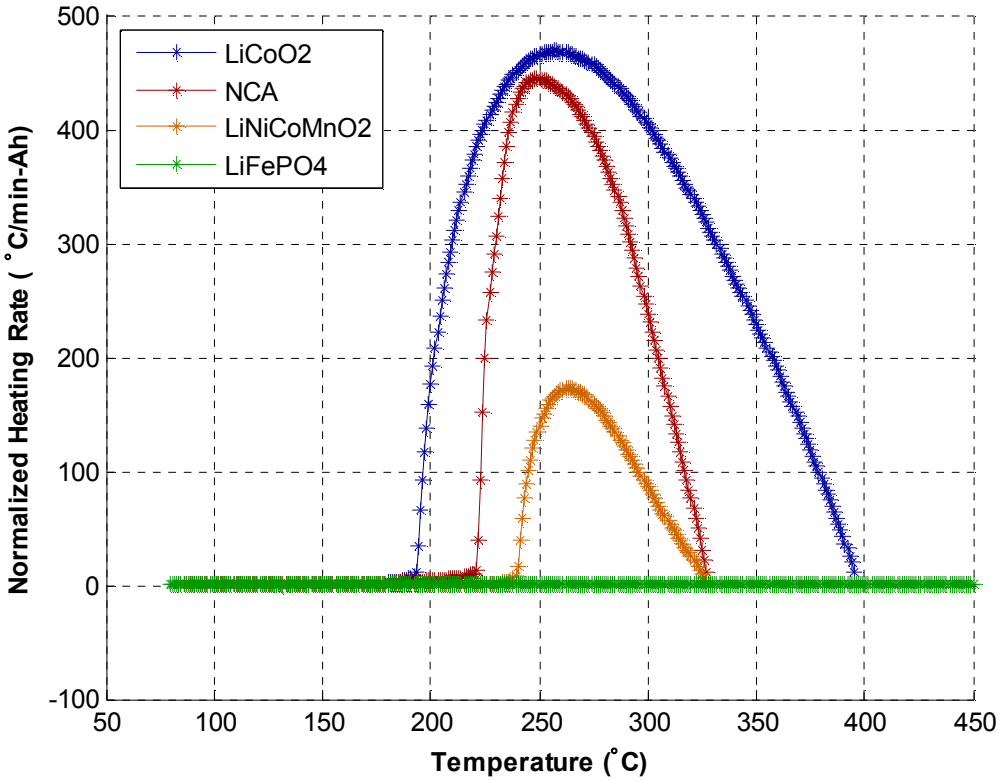
Generalized Hierarchical Control Structure From [1]

Instability of Thermal Runaway

- Accelerating Rate Calorimetry (ARC)



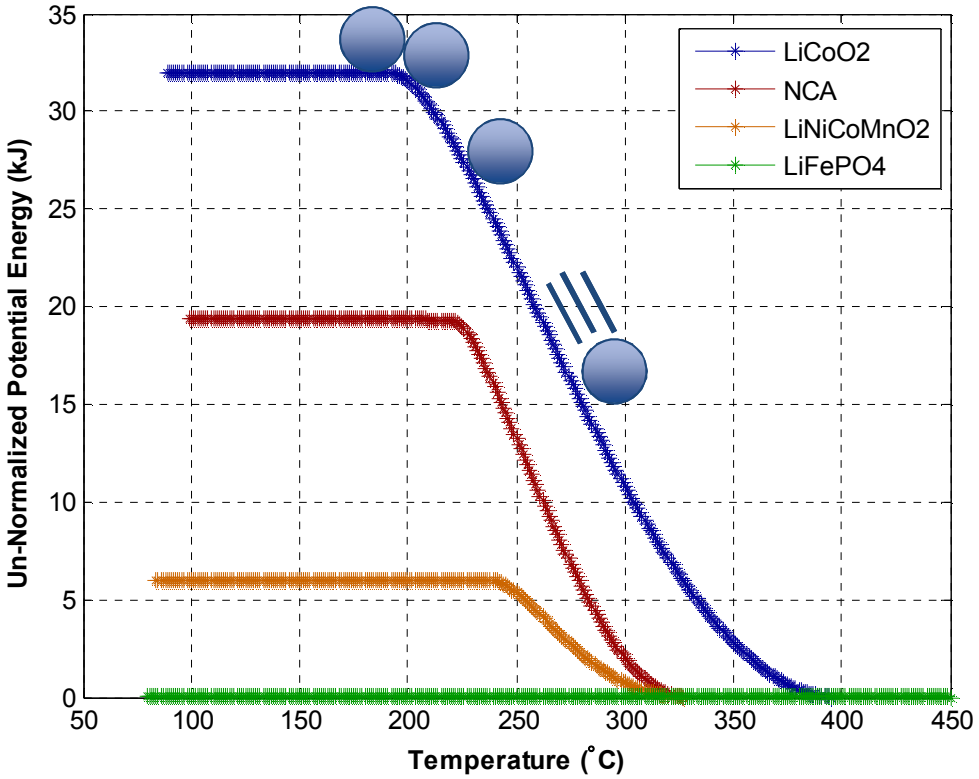
Positive Feedback Process



ARC Data collected by the Sandia BATLab

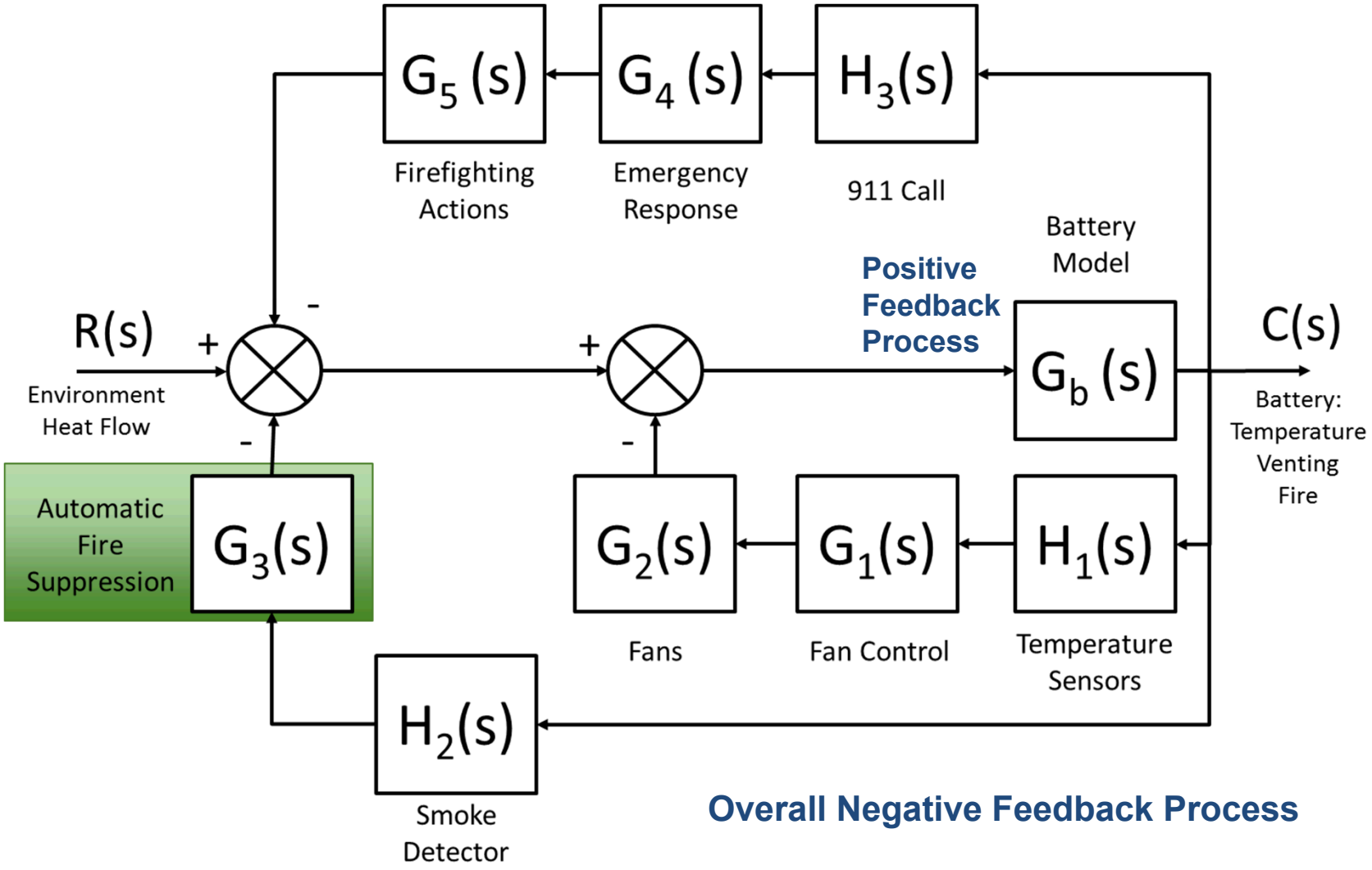
Heating Rate Analysis

- Below the critical temperature the reaction is non-spontaneous
- Above the critical temperature the reaction is spontaneous
- “Gibbs Free Energy” diagrams provide a useful visualization of thermal runaway phenomena



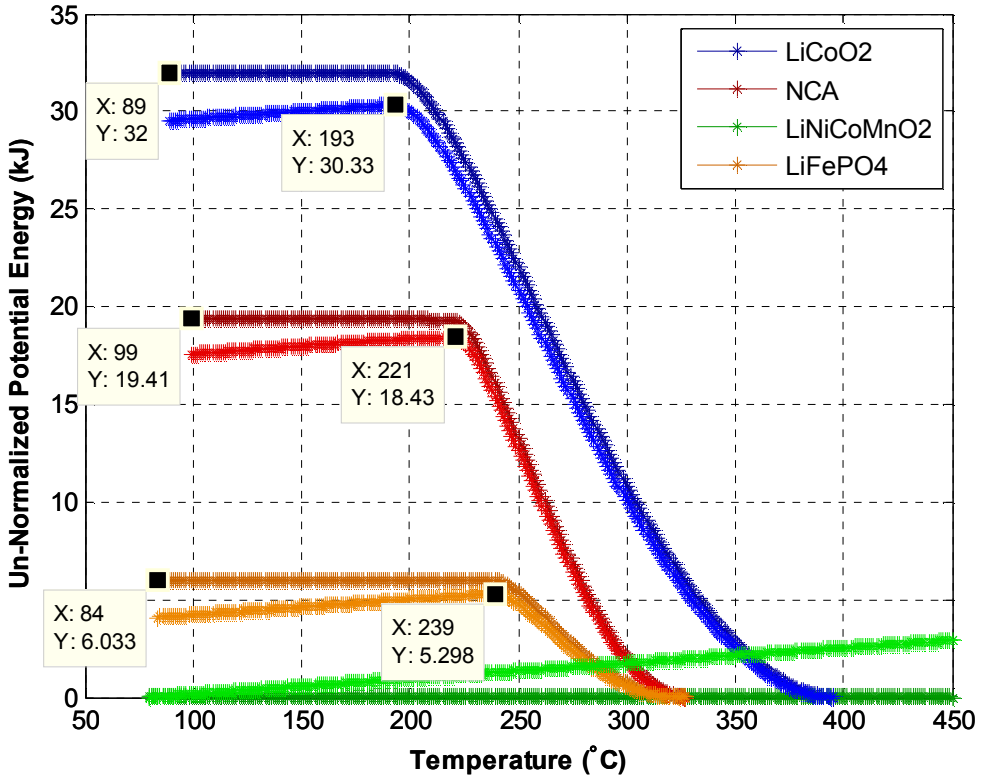
Integral of ARC Data collected by the Sandia BATLab

Feedback Control to Enforce Safety Constraints



Heating Rate Analysis (w/ Fire Suppression)

- Direct cooling raises the thermal runaway critical temperature
- Early action could (potentially) dissipate potential thermal energy before a fire
- Runaway reactions can temporarily exceed the ability of water to cool them



Effects of Fire Suppression on Thermal Stability

Initial Conclusions

- How do battery properties influence system safety?
  - Chemistry and design can determine emergency cooling, fire suppression, and emergency response requirements
  - Analysis to determine these requirements can be could be co-optimized if considered together
  - Further research will improve and expand analysis methodology

Thank You to the DOE OE and especially Dr. Gyuk for his dedication and support of work to ensure the safe integration of energy storage to the electric grid

Questions?

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References

[1] Nancy Leveson, 2012, Engineering a Safer World: System's Theory Applied to Safety, MIT Press, Cambridge, MA

[2] David Rosewater, Adam Williams "Analyzing system safety in lithium-ion grid energy storage" Power Sources, 300, p460-461, December, 2015

Established Methodology

It is challenging for engineers to incorporate thermal runaway energetics into a holistic design for system safety

Quantitative Risk Assessment

Where it works well

- Where there is a wealth of historical knowledge on all possible failure modes
- Where the interface boundaries are static and clearly defined (finished products)

Problems with QRA

- **Hard to apply on serial number 001 in the design phase (lack of data)**
- Blame for accidents is often assigned to convenient scapegoats: Hardware failures, Human error, Software "failures"
- Based on the assumption that Safety = Reliability