SAND2019-6586PE

ESS Fire Hazard Elimination and Suppression

Analysis – Design – and Documentation of Safety

PRESENTED BY

David Rosewater - 6 – 14 – 2019

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Outline

- Introduction
- Hazard Analysis in Complex Systems
- Thermal Runaway as a Controllable Process
- Parting Knowledge

Introduction

Safety is critical to the widescale deployment of energy storage technologies.

Bloomberg


Bloomberg

Hyperdrive

Explosions Threatening Lithium-Ion's Edge in a Battery Race

By Brian Eckhouse and Mark Chediak
April 23, 2019, 4:58 PM MDT *Updated on April 24, 2019, 8:24 AM MDT*

- Battery exploded at plant in Arizona; two others were shut
- Arizona utility regulator calls for 'thorough investigation'

Another lithium-ion battery has exploded, this time at an energy-storage complex in the U.S.

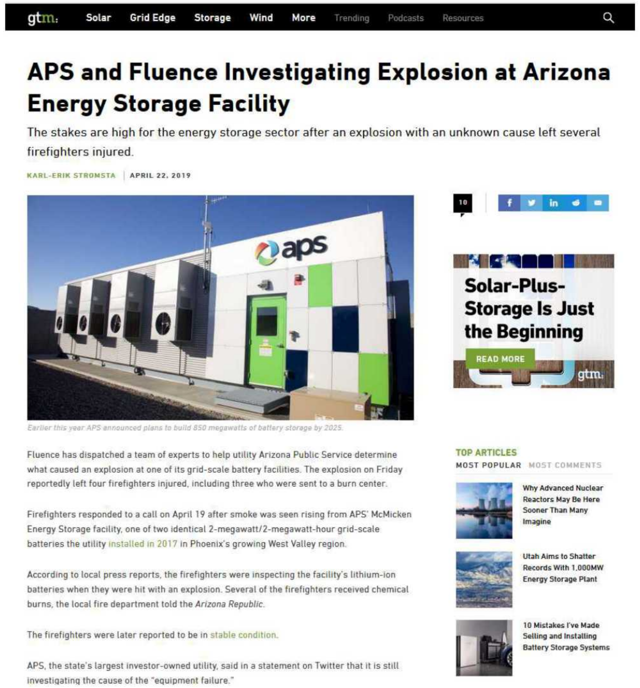
At least 21 fires had already occurred at battery projects in South Korea, according to BloombergNEF. But this latest one, erupting on Friday at a facility owned by a Pinnacle West Capital Corp. utility in Surprise, Arizona, marked the first time it has happened in America since batteries took off globally.

https://www.bloomberg.com/news/articles/2019-04-23/explosions-are-threatening-lithium-ion-s-edge-in-a-battery-race

There is a tendency to use the availability heuristic when considering risk.

To avoid this, consider how many batteries continue to operate without problems every day.

Greentech Media


APS and Fluence Investigating Explosion at Arizona Energy Storage Facility

The stakes are high for the energy storage sector after an explosion with an unknown cause left several firefighters injured.

KARL-ERIK STROMSTA | APRIL 22, 2019

Earlier this year APS announced plans to build 850 megawatts of battery storage by 2025.

Fluence has dispatched a team of experts to help utility Arizona Public Service determine what caused an explosion at one of its grid-scale battery facilities. The explosion on Friday reportedly left four firefighters injured, including three who were sent to a burn center.

Firefighters responded to a call on April 19 after smoke was seen rising from APS' McMicken Energy Storage facility, one of two identical 2-megawatt/2-megawatt-hour grid-scale batteries the utility installed in 2017 in Phoenix's growing West Valley region.

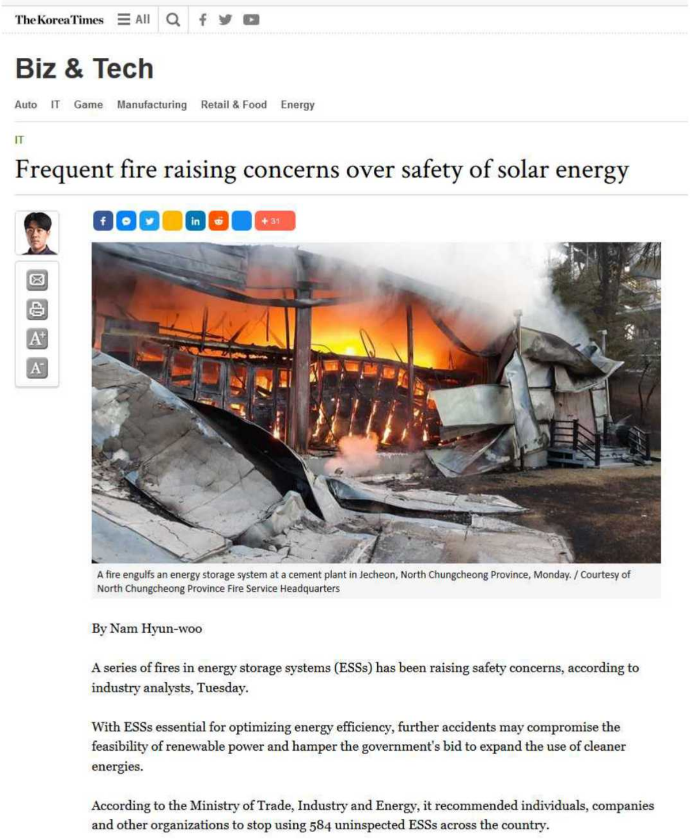
According to local press reports, the firefighters were inspecting the facility's lithium-ion batteries when they were hit with an explosion. Several of the firefighters received chemical burns, the local fire department told the *Arizona Republic*.

The firefighters were later reported to be in stable condition.

APS, the state's largest investor-owned utility, said in a statement on Twitter that it is still investigating the cause of the "equipment failure."

https://www.greentechmedia.com/articles/read/aps-and-fluence-investigating-explosion-at-arizona-energy-storage-facility#gs.gpky5k

The Korea Times


Biz & Tech

IT

Frequent fire raising concerns over safety of solar energy

A fire engulfs an energy storage system at a cement plant in Jecheon, North Chungcheong Province, Monday. / Courtesy of North Chungcheong Province Fire Service Headquarters

By Nam Hyun-woo

A series of fires in energy storage systems (ESSs) has been raising safety concerns, according to industry analysts, Tuesday.

With ESSs essential for optimizing energy efficiency, further accidents may compromise the feasibility of renewable power and hamper the government's bid to expand the use of cleaner energies.

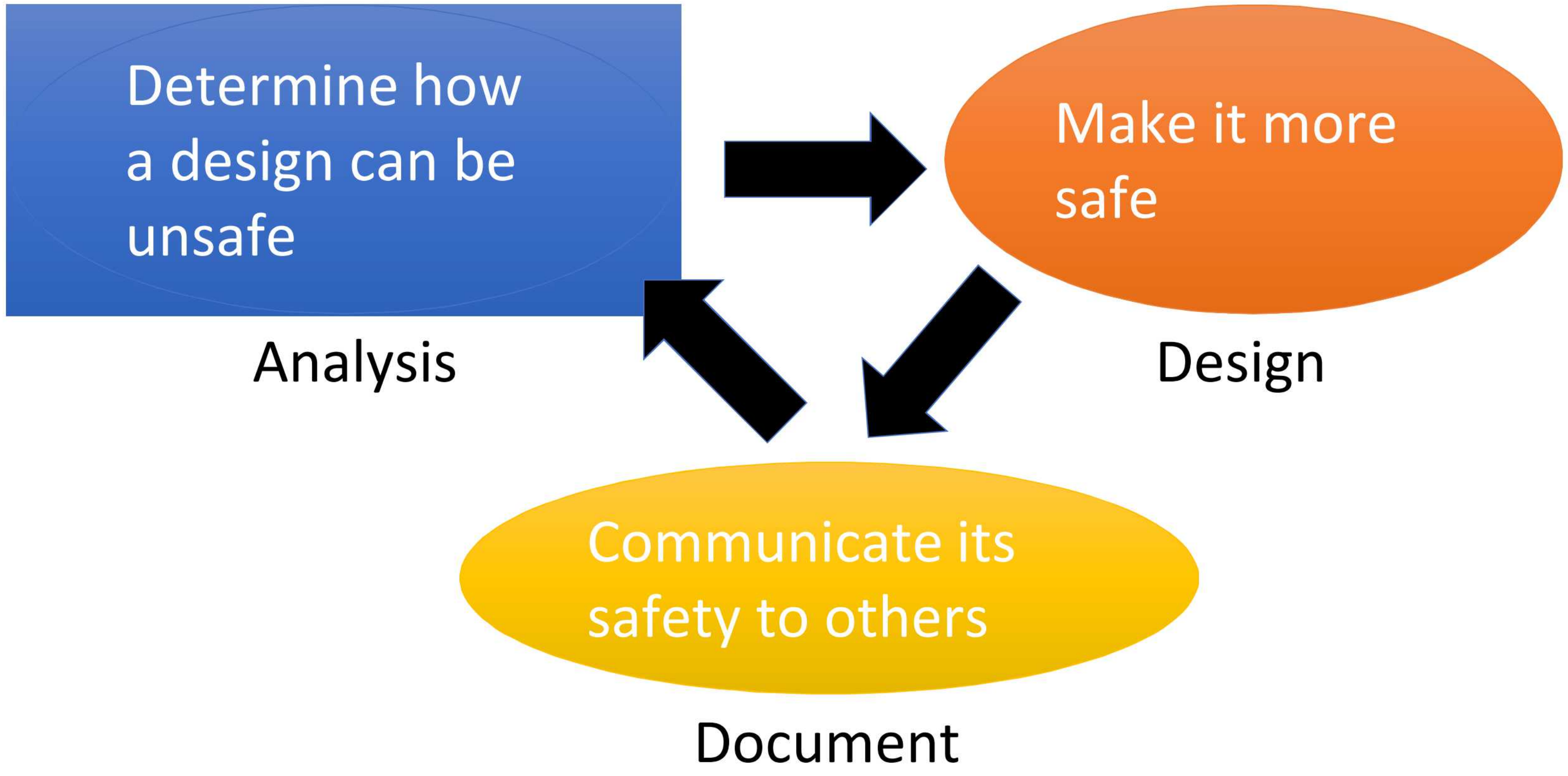
According to the Ministry of Trade, Industry and Energy, it recommended individuals, companies and other organizations to stop using 584 uninspected ESSs across the country.

https://www.koreatimes.co.kr/www/tech/2018/12/133_260560.html

Hazard Analysis in Complex Control Systems

Hazard Analysis

- Safety: Freedom from accidents
- Hazard: System state that could lead to an accident
- Hazard Analysis: Process of identifying hazards along with their causes and conditions



Systems Thinking

Many components, interacting in simple ways, can develop complex emergent patterns of behavior .

Carbon Analogy: Structure

Traffic Analogy: Emergence

Sand Analogy: Hierarchy

“With systemic thinking, we recognize that "the cause" frequently lies in the very structure and organization of the system.” (Senge 1990)

Systems Thinking (Safety)

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

(Leveson 2013)

Battery Cell Properties

- ✔ Capacity
- ✔ Volatility
- ✔ Temperature Range
- ✘ Safety

"Safety" is not a property of a component

Battery System Properties

- ✔ Capacity
- ✔ Service Life
- ✔ Control Algorithm
- ✔ **Safety**

Safety is a system property

If safety is an emergent property, why/how do accidents happen?

Systems Theoretic Process Analysis (STPA)

Hazard Analysis Based on Systems-Theoretic Accident Model and Processes (STAMP) [Leveson, 2012]

- Accidents occur when interactions violate **safety constraints**,
- The system enforces these constraints using **control**.

Example:

(a) External (b) Internal

Transpower GridSaver Battery Energy Storage System

STPA Setup

Defining System Losses and Hazardous States

Example Accidents (Losses)

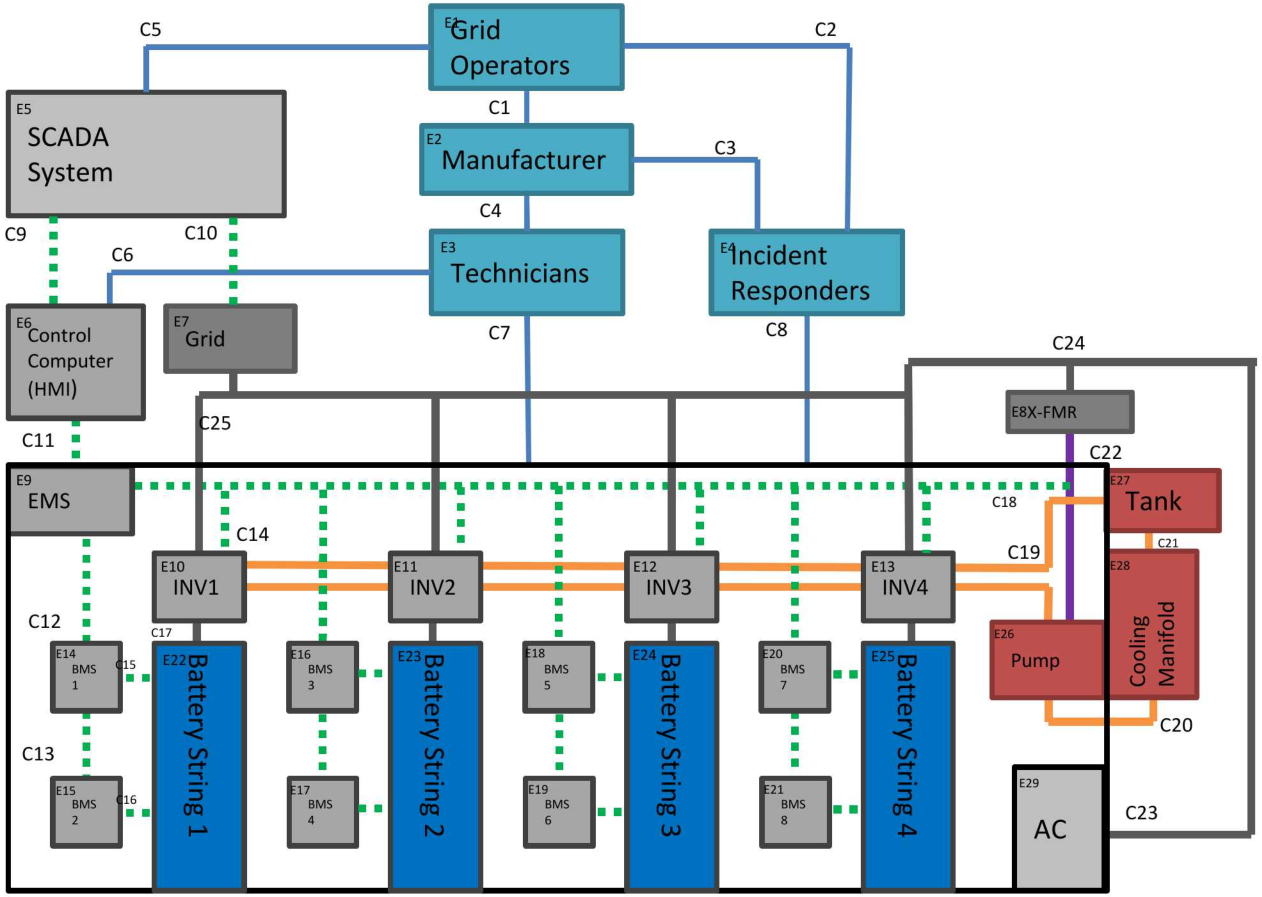
1. Loss of life/injury
2. Loss of investment (damage to equipment)
3. Loss of reputation (cost overrun, frequent service interruptions)

Example Hazards (System States)

1. Human exposed to high voltage
2. Human exposed to arc-flash/blast potential
3. Fire (thermal runaway)
4. Combustible vent gas buildup
5. Human exposed to toxic vent gases
6. Low reliability components or integration

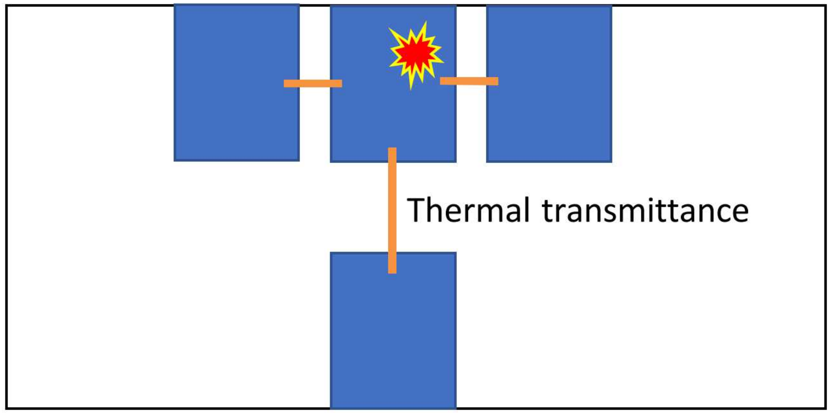
STPA Setup

- Safety Control Structure



Example Accident: Loss of investment (damage to equipment)
Example Hazard: Battery cell in thermal runaway

Battery racks in a container



Relevant Direct Control Actions
- Physical Separation Between Cells
- Physical Separation Between Racks
- Fire Suppression
- Emergency Response

Physical Separation Between Cells

Enforced by

Cell and module testing

Physical Separation Between Racks

Enforced by

Unit level mockup test [3]

Fire Suppression

Enforced by

Type testing and simulation analysis

Emergency Response

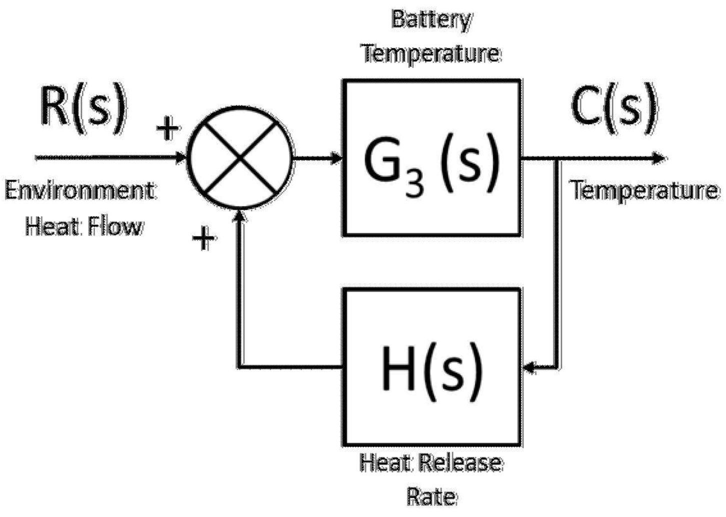
Enforced by

Training programs and hazard communication between owner and fire service

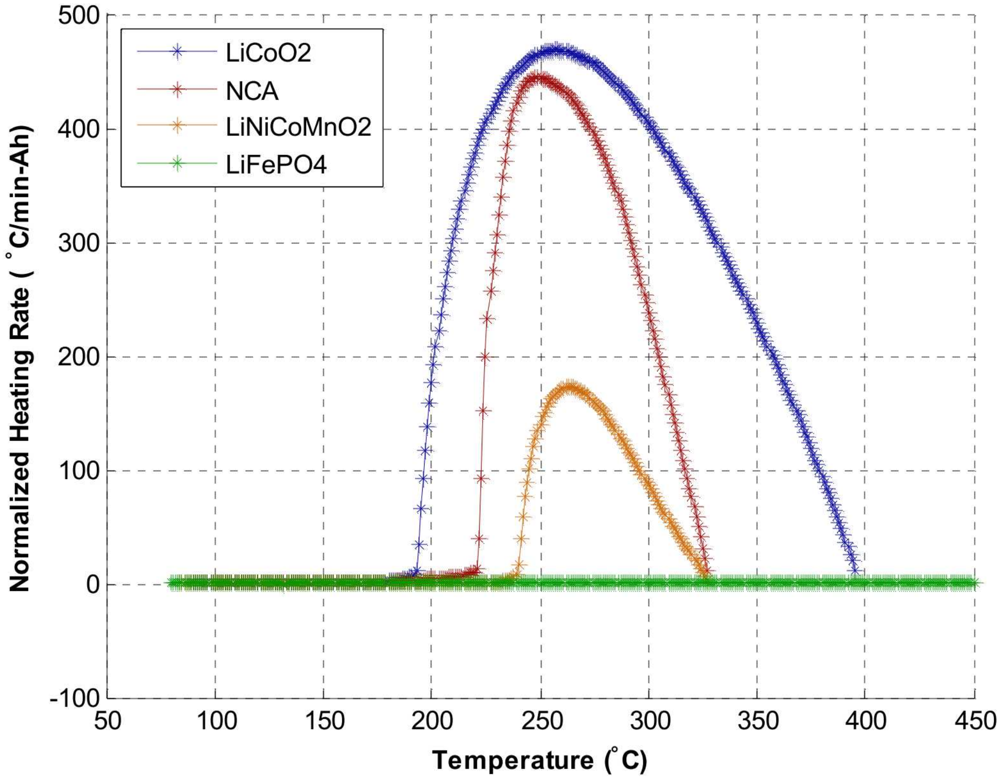
Thermal Runaway as a Controllable Process

Instability of Thermal Runaway

- Accelerating Rate Calorimetry (ARC)



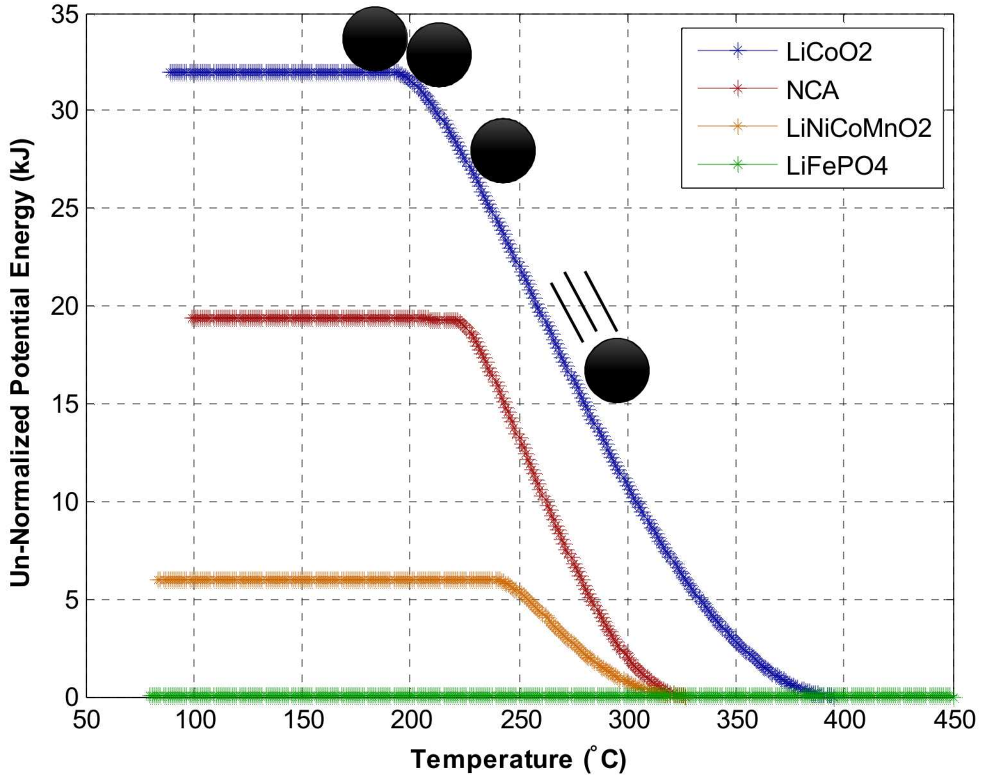
Positive Feedback Process



ARC Data collected by the Sandia BATLab

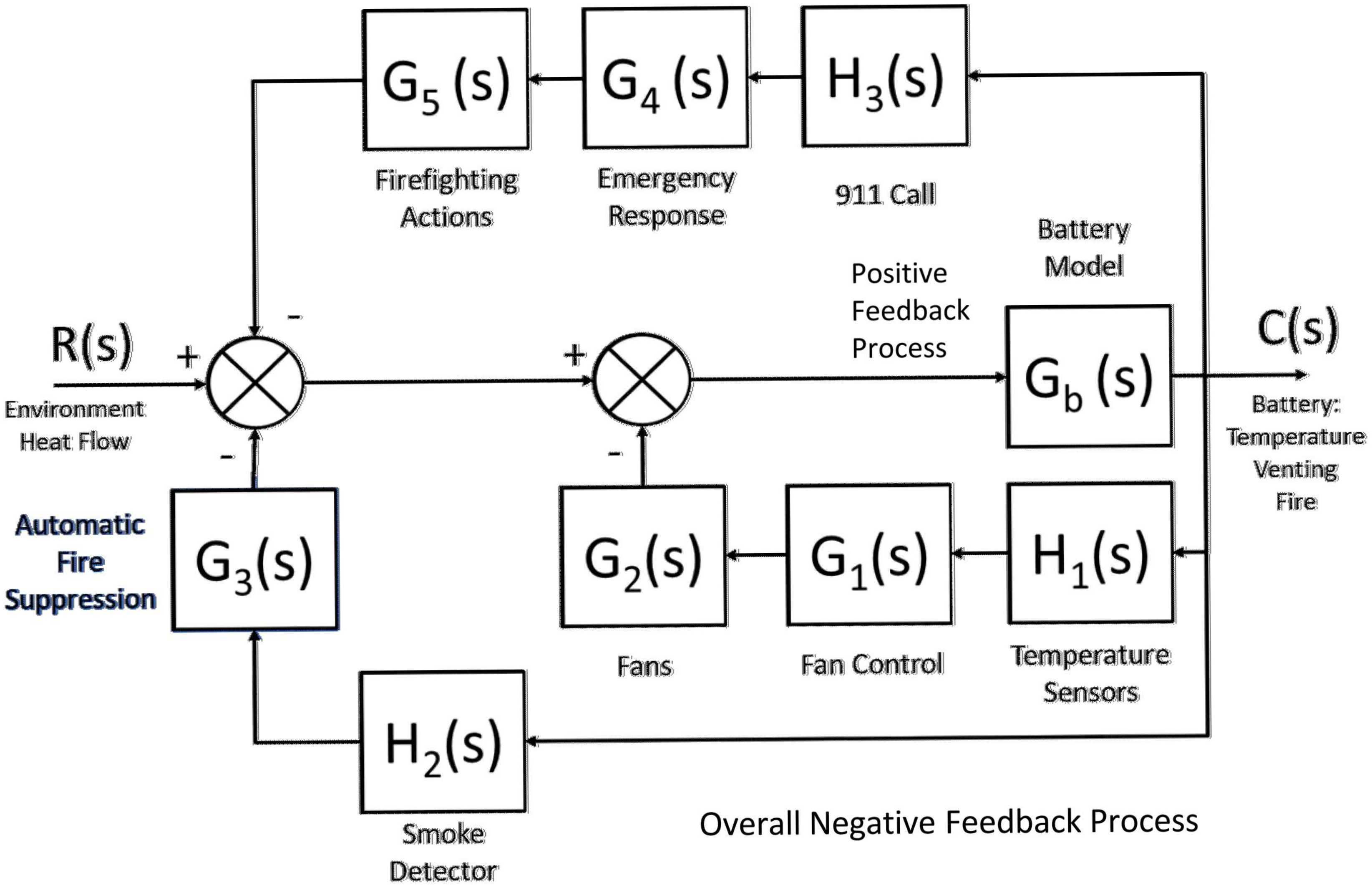
Heating Rate Analysis

- 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



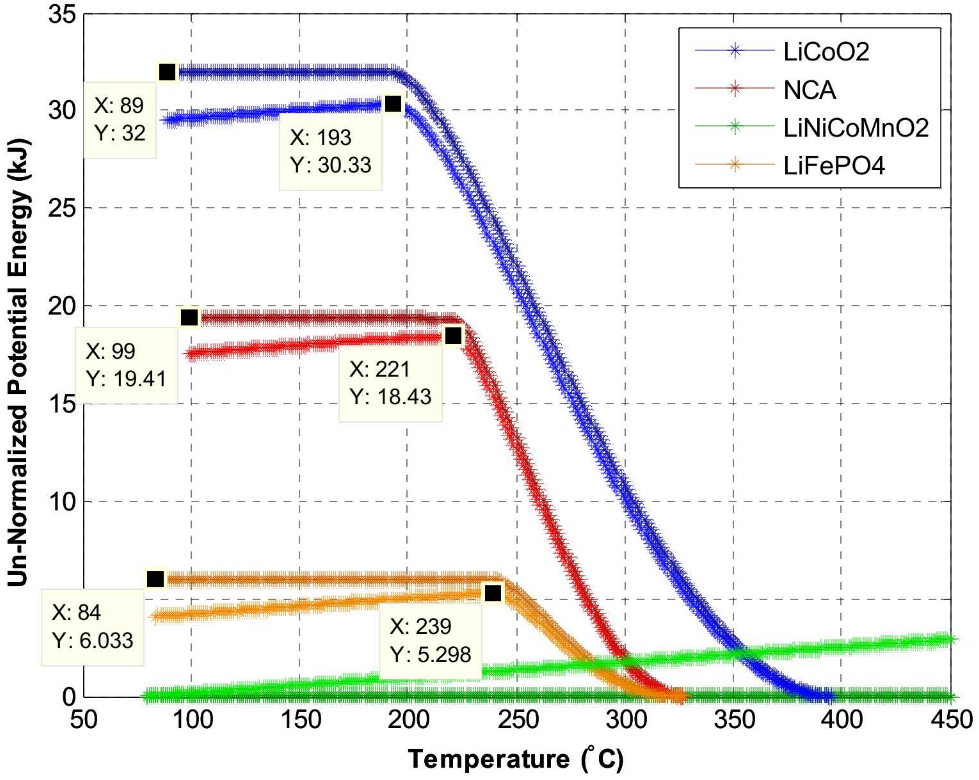
Integral of ARC Data collected by the Sandia BATLab

Feedback Control to Prevent Propagation



Heating Rate Analysis (w/ Fire Suppression)

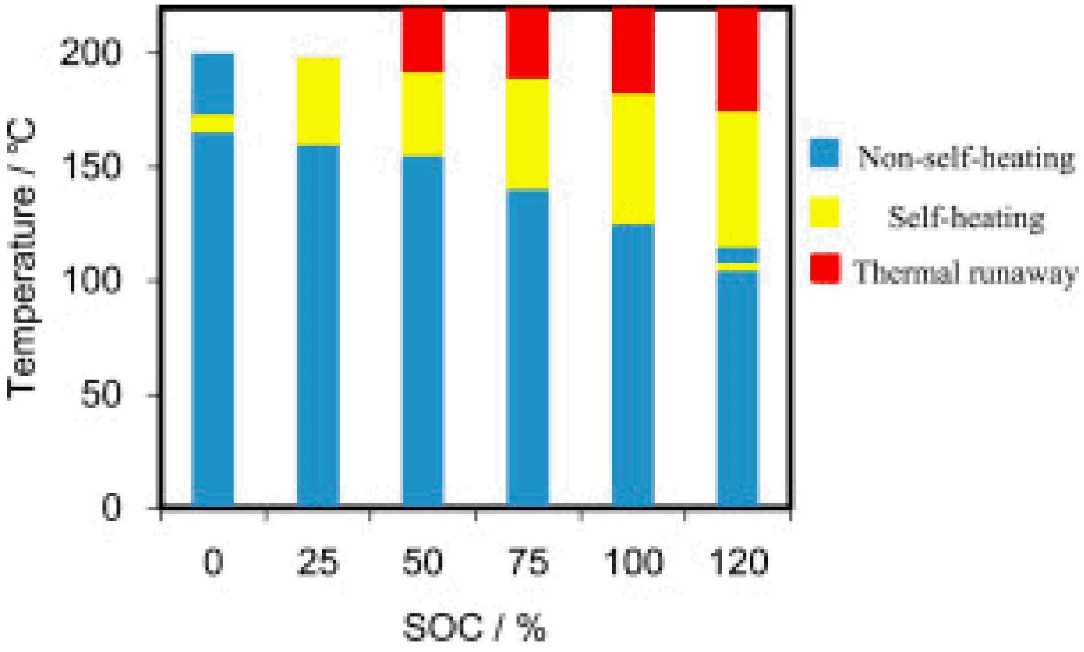
- Direct cooling raises the thermal runaway critical temperature
- Early action could (potentially) dissipate potential thermal energy before a fire
- Runaway reactions can temporarily exceed the ability of water to cool them



Effects of Fire Suppression on Thermal Stability

Thermal Runaway and SOC

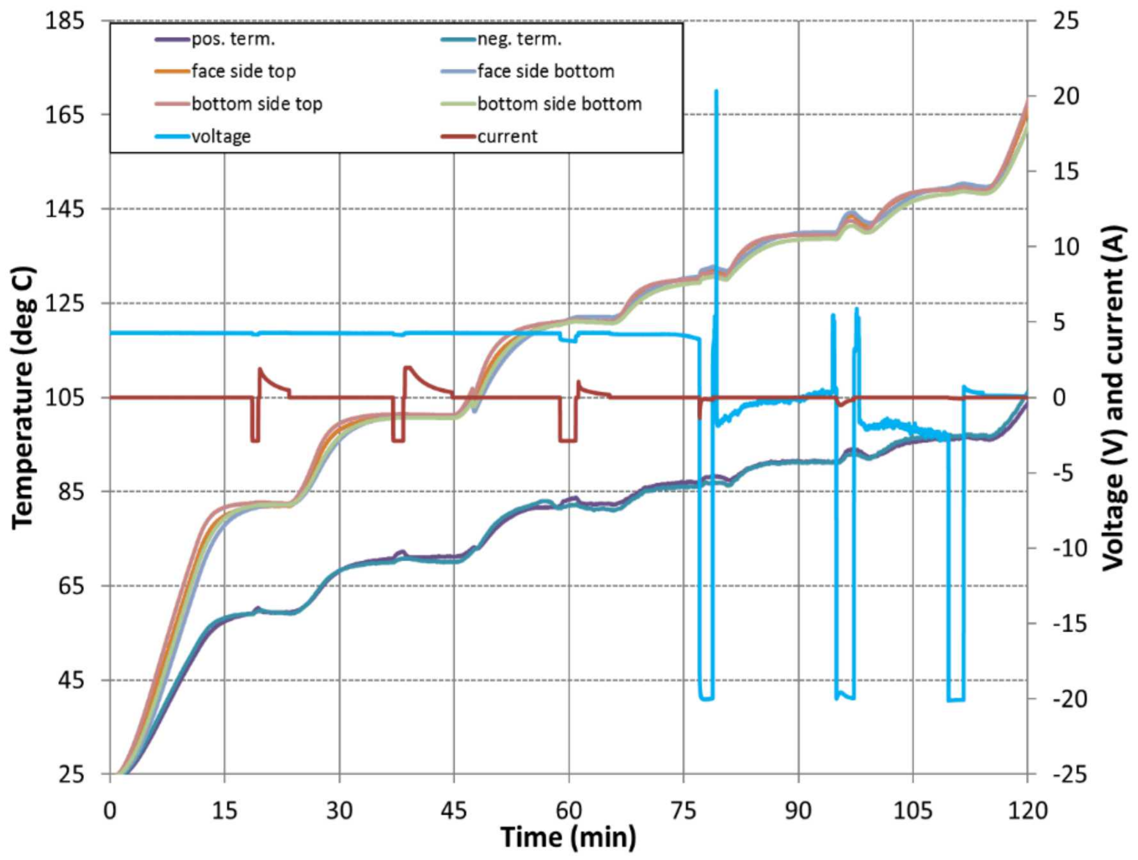
If SOC can be reduced, thermal runaway, may be avoided or abated.



Thermal mapping of LCO-Graphite cell as a function of SOC. Non-self-heating (blue), self-heating (yellow) and thermal runaway (red) regions are identified.

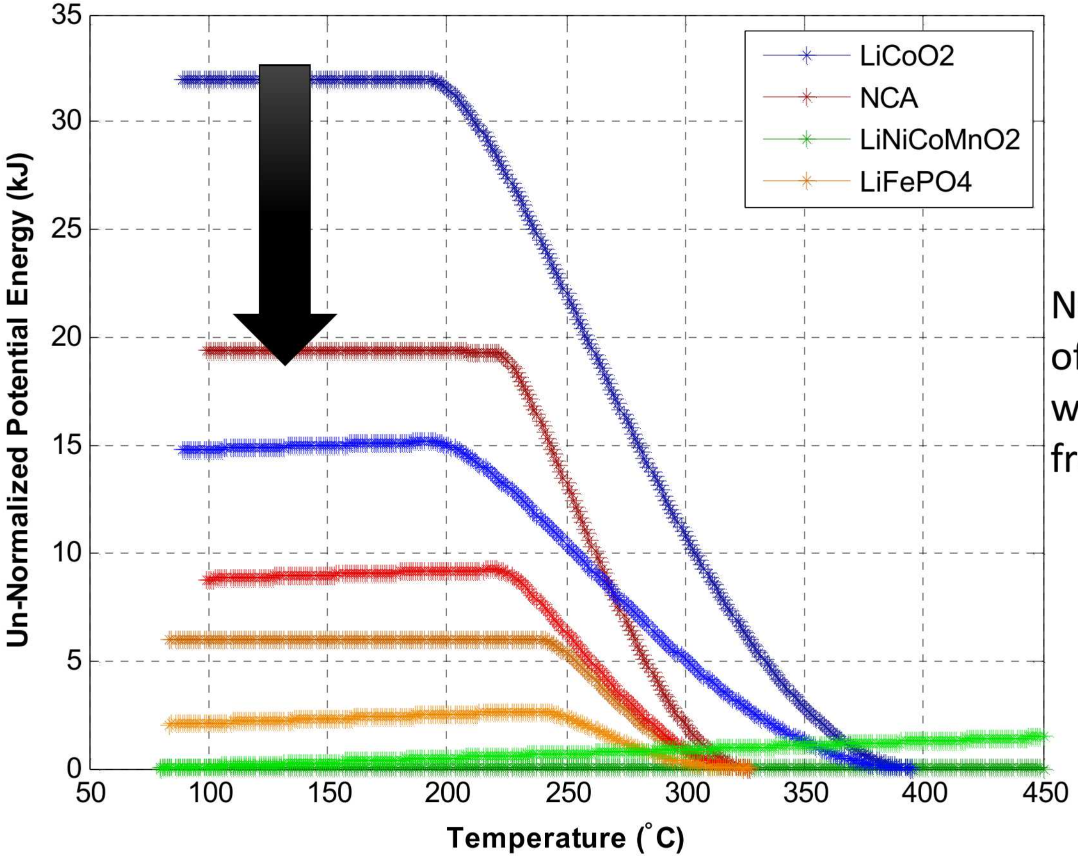
Graphic Source: Omar Samuel Mendoza-Hernandez, Hiroaki Ishikawa, Yuuki Nishikawa, Yuki Maruyama, Minoru Umeda, Cathode material comparison of thermal runaway behavior of Li-ion cells at different state of charges including over charge, Journal of Power Sources, Volume 280, 15 April 2015, Pages 499-504

Accessible Free Energy



Ability to sustain a discharge of a $LiCoO_2$ cell at abusive temperatures. The cell shows a reasonable ability to sustain discharge up to 120 °C but above that temperature the cell becomes increasingly resistive.

Heating Rate Analysis (w/ Discharge)



Notional Example of how discharge would effect the free energy

Discharging the cells can increase the margin to safely dissipate the free energy from surrounding cells and hence suppress thermal runaway propagation

Parting Knowledge

1. Safety is a property of complex social/technical systems (not of individual components)
2. Accidents occur when interactions violate safety constraints, and the system enforces these constraints using control.
3. Thermal runaway is an unstable (but foreseeable) hazard
4. The safety constraints involved in preventing fire propagation are easier to enforce with:
    1. Reduced state-of-charge
    2. Early, active cooling

Thank You to the DOE OE and especially Dr. Gyuk for his support for work to promote 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

[3] Omar Samuel Mendoza-Hernandez, Hiroaki Ishikawa, Yuuki Nishikawa, Yuki Maruyama, Minoru Umeda, Cathode material comparison of thermal runaway behavior of Li-ion cells at different state of charges including over charge, Journal of Power Sources, Volume 280, 15 April 2015, Pages 499-504

[4] Adam Barowy, "UL 9540A Large Scale Testing of Energy Storage Systems: Fire Protection and Response Considerations" Energy Storage Safety Forum, March 6, 2019 Avalible [Online]: https://share-ng.sandia.gov/ess/wp-content/uploads/2019/03/3c_Barowy_UL9540A_Sandia_Mar2019.pdf

Backup Slides
Hazard Identification

Properties in Battery Systems that Can Develop Hazards

Voltage

Arc-Flash/Blast

Fire

Combustion

Toxicity

Voltage

The number of battery cells per string in grid energy storage can be higher than in mobile applications, resulting in higher DC voltage and a need for additional precautions. In the voltage range 100-1000V DC, the National Fire Protection Agency's (NFPA) standard 70E on electrical safety in the workplace establishes a limited approach boundary for unqualified workers at 1.0m. This boundary is to prevent those who are unable to avoid hazards from coming within arms reach of the exposed electrical conductors.

Source: NFPA70E

Properties in Battery Systems that Can Develop Hazards

Voltage

Arc-Flash/Blast

Fire

Combustion

Toxicity

Arc-Flash/Blast

High string voltage affects both the potential for shock and the potential for arc-flash/blast. The equations below show the maximum power point method for calculating the incident energy in DC arc-flash. Indecent energies calculated by this equation are described as "conservatively high" and other methods are being explored for calculating and classifying the potential harmful energy in a DC arc-flash. Arc-blast results from explosive components of an electric arc (e.g. vaporized copper) and depends greatly on the equipment and environment involved in the arc. Common controls to prevent injury from arc flash include increasing separation between positive and negative conductors, regular maintenance to prevent equipment failure, and arc-rated PPE for electrical workers.

$$I_{arc} = 0.5 I_{bf}$$

$$IE = 0.01 V_{sys} I_{arc} T_{arc} / (D^2)$$

Source: NFPA70E

Where:
Iarc = Arcing current (amps)
Ibf = System bolted fault current (amps)
IE = incident energy at a given working distance (cal cm 2)
Vsys = System voltage (volts)
Tarc = Arcing Time (sec)
D = working distance (cm)

Properties in Battery Systems that Can Develop Hazards

Voltage

Arc-Flash/Blast

Fire

Combustion

Toxicity

Fire

As a Fuel Source

Plastic burns, some electrolytes are flammable.

Thermal Runaway

Thermal runaway is chemical process where self-heating in a battery exceeds the rate of cooling causing high internal temperatures, melting, off-gassing/venting, and in some cases, fire or explosion. Thermal, mechanical, and electrical abuse can lead to thermal runaway; internal short circuit from manufacturing defects; or the development of metallic dendrites that form an internal short over time.

Source: David Rosewater, Adam Williams, Analyzing system safety in lithium-ion grid energy storage, Journal of Power Sources, Volume 300, 30 December 2015, Pages 460-471, ISSN 0378-7753

Properties in Battery Systems that Can Develop Hazards

Voltage

Arc-Flash/Blast

Fire

Combustion

Toxicity

Combustion

Hydrogen buildup from charging

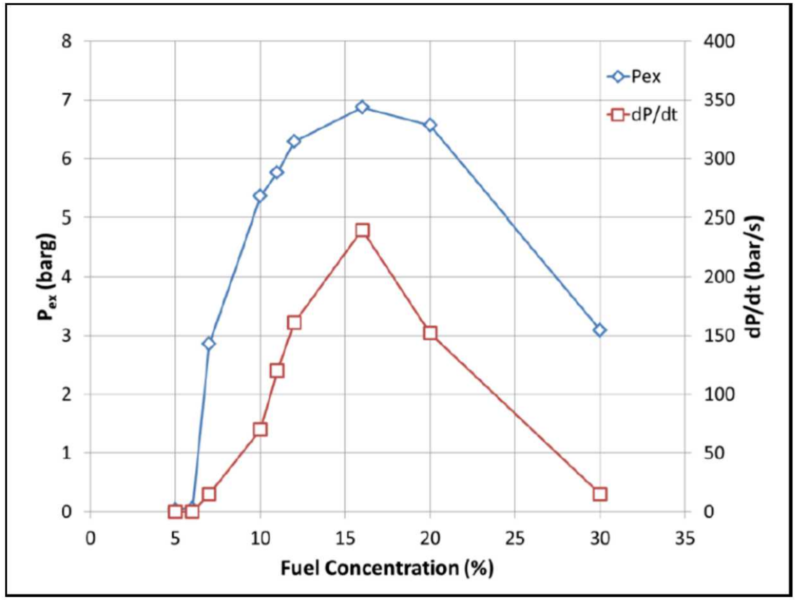
Charging aqueous batteries can crack water into hydrogen and oxygen. Without proper ventilation this hydrogen can build up in an enclosed space. The Lower Explosive Limit (LEL) for hydrogen is 4% concentration in air. Battery system with this hazard are equipped with alarm systems.

Vent gas combustion from thermal runaway

Lithium-ion batteries undergoing thermal runaway can vent their internal contents in the form of gas. Without proper ventilation a combination of gasses can build up in an enclosed space. The Lower Explosive Limit (LEL) for this mixture can very. Oxygen starvation fire suppression in lithium-ion battery systems is not recommended.

Lithium-Ion Battery Thermal Runaway

For one cell type, thermal runaway vent gasses were found to be combustive above 6.3% concentration in air. Combustive strength for one sample was in-between methane and propane.



Source: K. Marr, V. Somadepalli, Q. Horn, Explosion hazards due to failure lithium-ion batteries, Global Congress on Process Safety (2013).

Table 2: Estimated battery energy to reach the IET and FLET values for the NO, CO, HCl, SO2 and HF toxic gases (exposure time of 60 minutes, fire occurring in a 50 m3 room) (adapted from [3])

(Wh)	HF	CO	NO	SO_2	HCl
IET	60	290	280	530	1320
FLET	110	1140	2080	4710	7880

Source: P. Ribiere, S. Grugeon, M. Morcrette, S. Boyanov, S. Laruel-lea, G. Marlair, Investigation on the re-induces hazards of li-ion battery cells by re calorimetry, Energy and Environmental Science 5 (2012) 5271{5280.

Voltage

Arc-Flash/Blast

Fire

Combustion

Toxicity

Properties in Battery Systems that Can Develop Hazards

- Voltage
- Arc-Flash/Blast
- Fire
- Combustion
- **Toxicity**

Toxicity

Smoke

Smoke can be toxic and smoke from batteries is no exception. Use of a positive pressure breathing apparatus is recommended whenever responding to battery system fires.

Liquid Electrolyte

Some flow-batteries contain electrolyte which can be toxic to the environment or to people. The MSDS should provide proper safety measures for handling and exposure. Liquid electrolyte can also be corrosive so avoid contact with the skin or eyes.

Backup Slides
Probability Risk Assessment

Probability Risk Assessment (PRA)

Accidents happen because the **stochastic** components of a system fail.

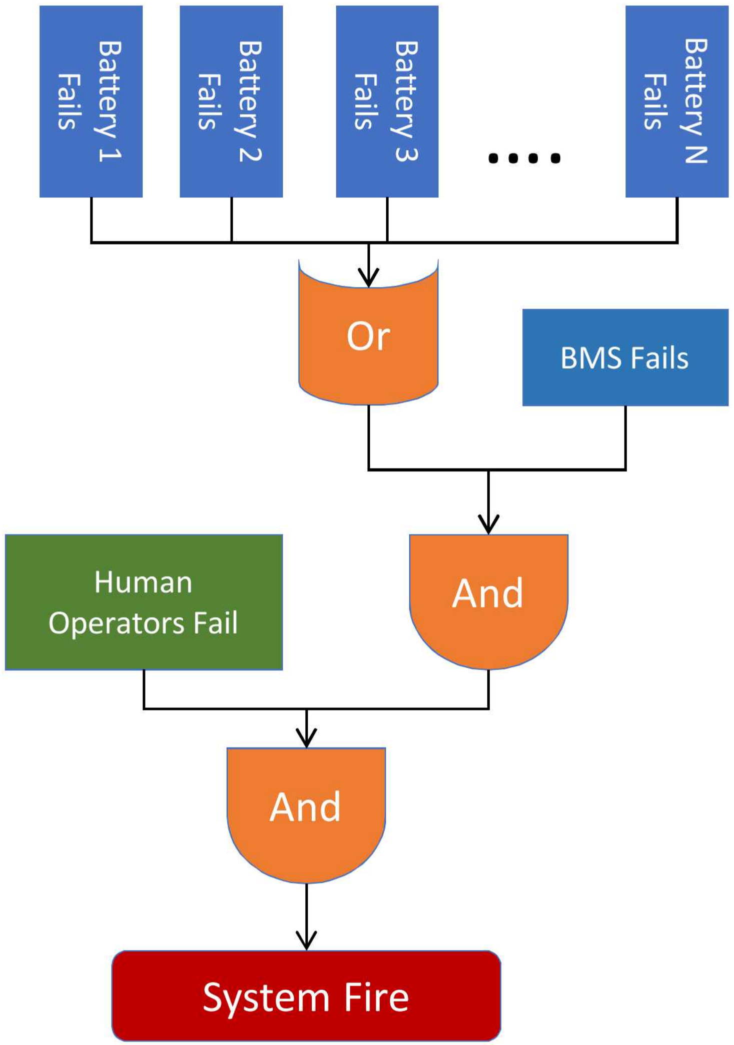
Analysis answers three questions:

1. **What** can go wrong?
2. How **likely** is that?
3. How **bad** would that be?

PRA Techniques

- *Event trees*
- *Fault trees*
- HAZOP
- FMEA and FMECA
- Monte Carlo Simulation

Example Fault Tree: If…



Probability Risk Assessment (PRA)

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)

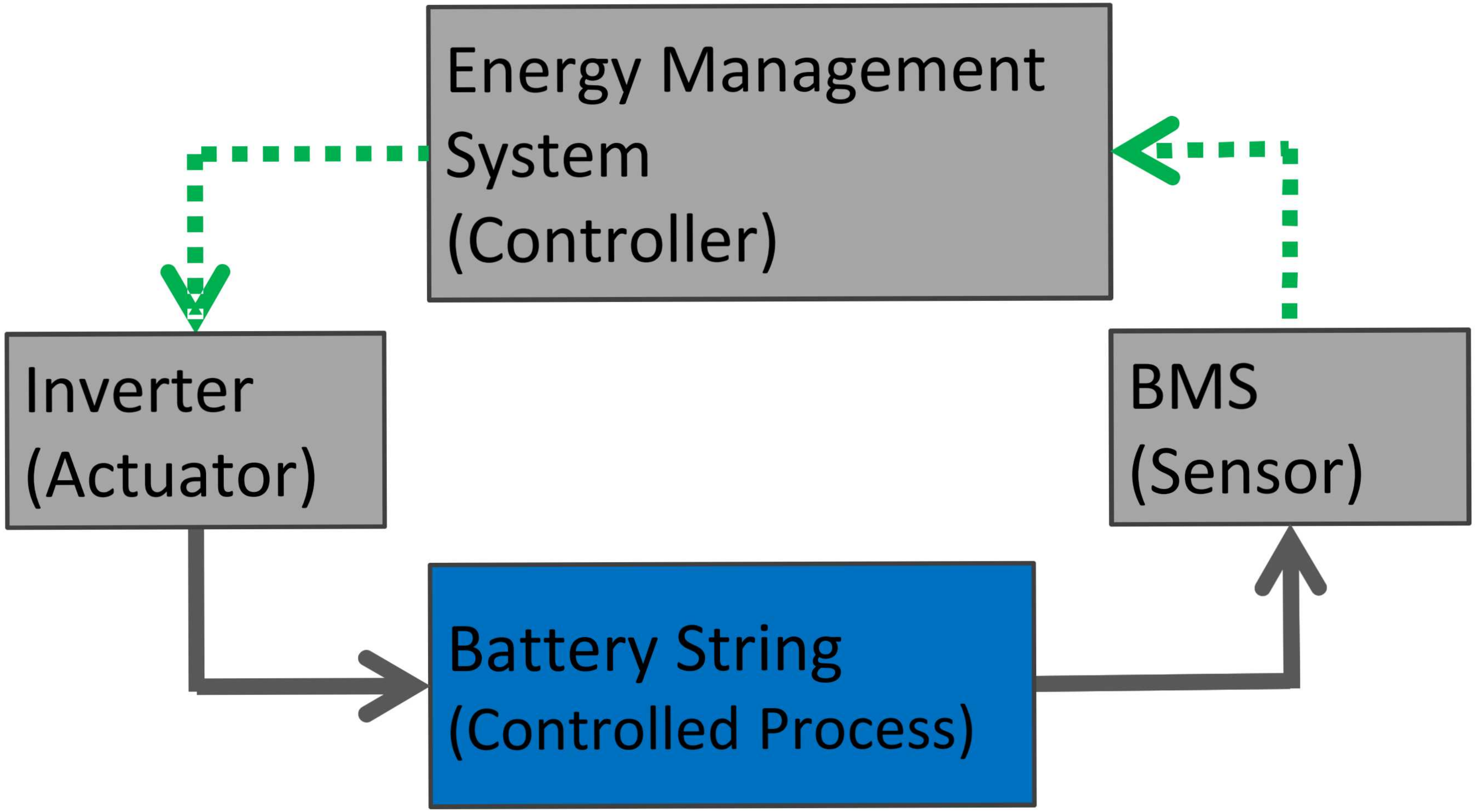
Problems with PRA

- Hard to apply on serial number 001 in the design phase
- Outcomes of analyses are often subjective rather than objective
- Blame for accidents is often assigned to convenient scapegoats: Hardware failures, Human error, Software "failures"
- Based on the assumption that Safety = Reliability

Backup Slides
STPA Detail

STPA Setup

- Example Control Loop



STPA Setup

- Safety Responsibilities, Constraints, and Control Actions

Name	Safety Responsibilities (Constraints / Control Actions)
EMS	Provide Inverter power commands within dynamically calculated system limits
Inverter	Actuate power commands within dynamic limits
Battery String	Allow BMS uninterrupted access to string current and each cell voltage and temperature for accurate data collection
BMS	Provide accurate and timely voltage, temperature, current, and fault data to the EMS

STPA Step 1 Unsafe control Actions

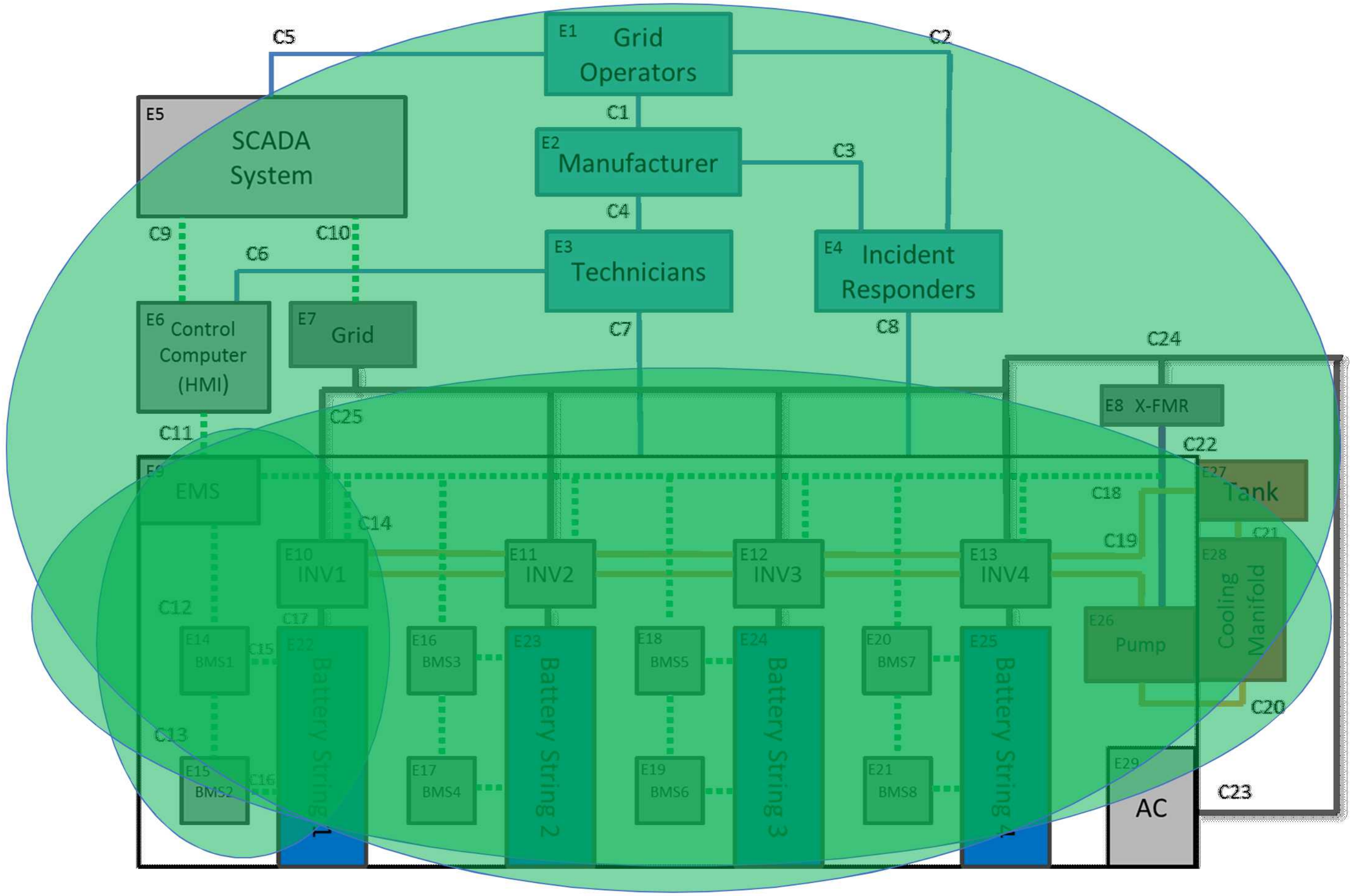
Control Action	Needed and Not Provided	Provided Incorrectly	Provided too early or too late (sequence)	Provided too long or too short (duration)
Provide Inverter power commands within dynamically calculated system limits	Power command not provided	Power command outside of dynamic limits	Power command too early or too late	Power command provided for too long or not long enough
Actuate power commands within dynamic limits	Power not actuated	Power actuated out of limits	Power actuated to early or late	Power actuated too long / short
Allow BMS uninterrupted access to string current and each cell voltage and temperature for accurate data collection	BMS access interrupted	Error introduced into BMS data collection	Delay introduced into BMS data collection	Latch sticks measurement and does not allow it to change
Provide accurate and timely voltage, temperature, current, and fault data to the EMS	Data not provided to EMS	Incorrect data provided to EMS	Data provided too quickly or with too long a delay	Data provided stuck

STPA Step 2 Causal Factors

Provided Incorrectly	Casual Scenario 1 … N (context matters)
Power command outside of dynamic limits	If a technician provides a software update to the EMS that changes how the battery's dynamic limits are calculated. The dynamic limit calculation algorithm may be adjusted over time. Doing so could be unsafe if it expands the limits beyond tested abuse conditions.
Power actuated out of limits	If the inverter requires excessive pre-charge circuit inrush current on startup. This could happen if the resistor is too small and/or the capacitance is too large in the pre-charge circuit, or if the batteries are very low SOC, or if the pre charge circuit is repeatedly activated.
Error introduced into BMS data collection	If there is high error between measurement and internal temperature. If a large temperature gradient exists between the inside of the cell and the negative terminal where temperature is measured then in inside of the cell may be several degrees hotter then the EMS process model expects. This could occur if the battery thermal model has not been validated or if it becomes invalid over time.
Incorrect data provided to EMS	If the calibration period is insufficient to correct for measurement drift. Measurement wires and isolation/amplification circuits can drift in accuracy over time and thermal cycles and should be recalibrated regularly in order to avoid process model inaccuracy.

STPA Step 2 Causal Factors

The search for causal factors spans all system components, control actions, and environmental conditions



Once all causes and concisions have been assessed, the analysis is complete.