MARCH 6TH, 2019

SAND2019-2116C

DESIGN OF DEFLAGRATION VENTING FOR LI-BESS EXPLOSION MITIGATION

2019 ESS Safety & Reliability Forum

SPEAKER: AUSTIN R. BAIRD

CSMP Student
Sandia National Laboratories
Building & Fire Safety Department

Technical Contributors:

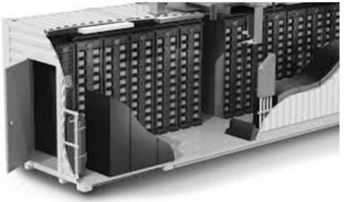
UT Fire Research Group-
Erik Archibald
Robert Kennedy
Dr. Kevin Marr
Dr. O.A. (DK) Ezekoye

UL-
Dr. Judy Jeevarajan

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND No. 2019-####

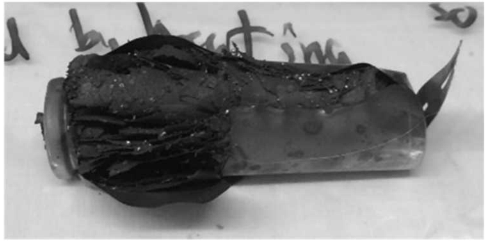
Battery Energy Storage System

- Used in numerous industries:
  - Military
  - Aircraft
  - Spacecraft
  - Densely populated environments
    - Commercial & Residential
- Failure can lead to higher consequence



Safety:

- Catastrophic failure:
  - manufacturing defects
  - thermal abuse
  - electrical abuse
  - mechanical damage
- Exothermic reaction within the sealed battery
  - Thermal Runaway
  - Venting of Flammable Gases



Recent Incidents

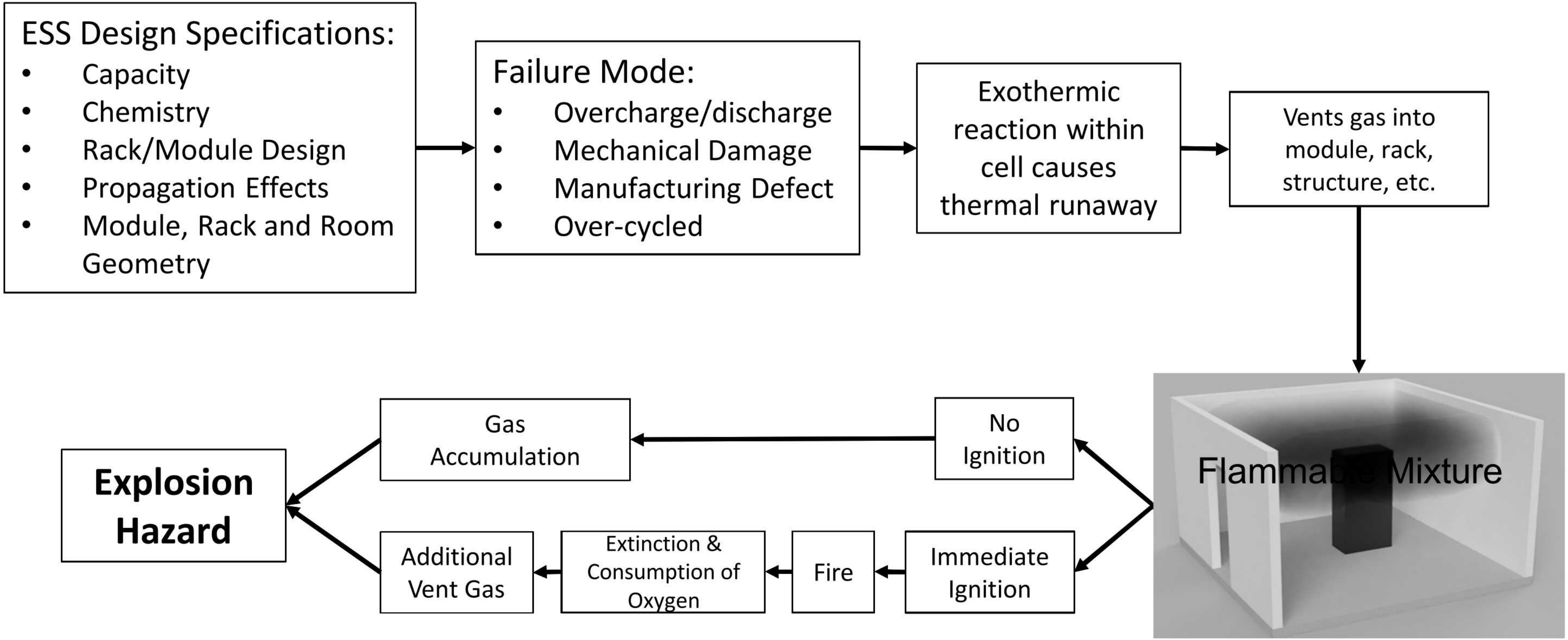
- April 2017 – Houston Train Car Explosion, Union Pacific 53' double stacked rail car
  - Rail car was transporting used consumer based Li-Ion batteries to recycling facility
  - Explosion broke windows about 500 ft away

- 2018 a cement plant in Jecheon, North Chungcheong Province, South Korea experienced over $3 million in damage
  - 15th reported ESS fire in Korea in the past year

- November 2017 – Belgian Battery Fire, containerized lithium-ion ESS burned at a utility plant
  - Was equipped with fire detection and suppression which failed to extinguish the flames

- FAA FRC Experiment – 5000 18650 Cylindrical Cells & ~40 kWh of energy storage
  - Fire Resistant Container designed to limit oxygen to contain Class A fires
  - Aerosol fire suppressant extinguished fire at about 20 minutes & Explosion occurs after 45 minutes

Li-BESS Explosion Hazard



Common Explosion Hazards

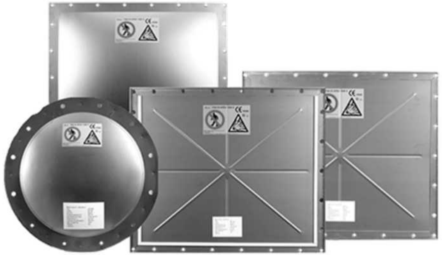
Flammable Gases

- Solvents evaporating in processes/ovens
- Large-scale natural gas fired combustion plant
- Hydrogen as an alternative fuel and process gas
- Transportation of gases through pipe systems

Combustible Dusts

- Spraying and chemical processing
- Food and grain processing
- Pharmaceuticals
- Woodworking
- Metal grinding and cutting
- Handling, collecting and confining dusts such as metal, grains, sugar and woods

Explosion Mitigation



- Several ways to mitigate explosion:
    1. Deflagration Venting- *Passive System*
    2. Explosion Suppression and Inerting- *Active System*
- How do we design deflagration vents?
    - Based on NFPA 68 Chapters 5 thru 9
- Passive system ensures hazard is mitigated in event active systems such as BMS, Suppression, etc. fail

Flammable Gas Hazard

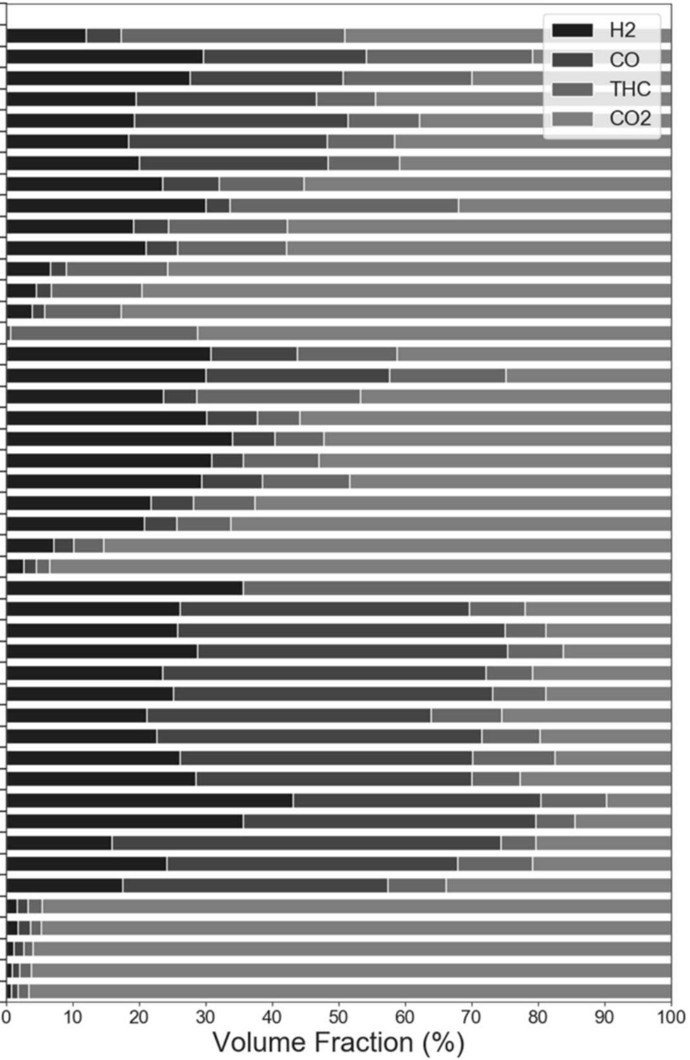
- Handling gas in space, what do I need to know?
  - S_U: Laminar flame speed
  - C_d: Vent discharge coefficient
  - ρ_u: Unburned gas-air density which also required fuel-to-air ratio
  - P_{max}: Maximum pressure developed in a contained deflagration
  - P_{red}: Maximum pressure developed in a vented deflagration
  - Enclosure Surface Area
  - L/D: Enclosure Length to Hydraulic Diameter Ratio
  - Area for vents

Gas	Flame Speed (m/s)	Lower Flammability Limit (Volume Fraction)
Methane	0.38	5.0%
Propane	0.40	2.1%
Hydrogen	2.80	4.0%

Gas Species

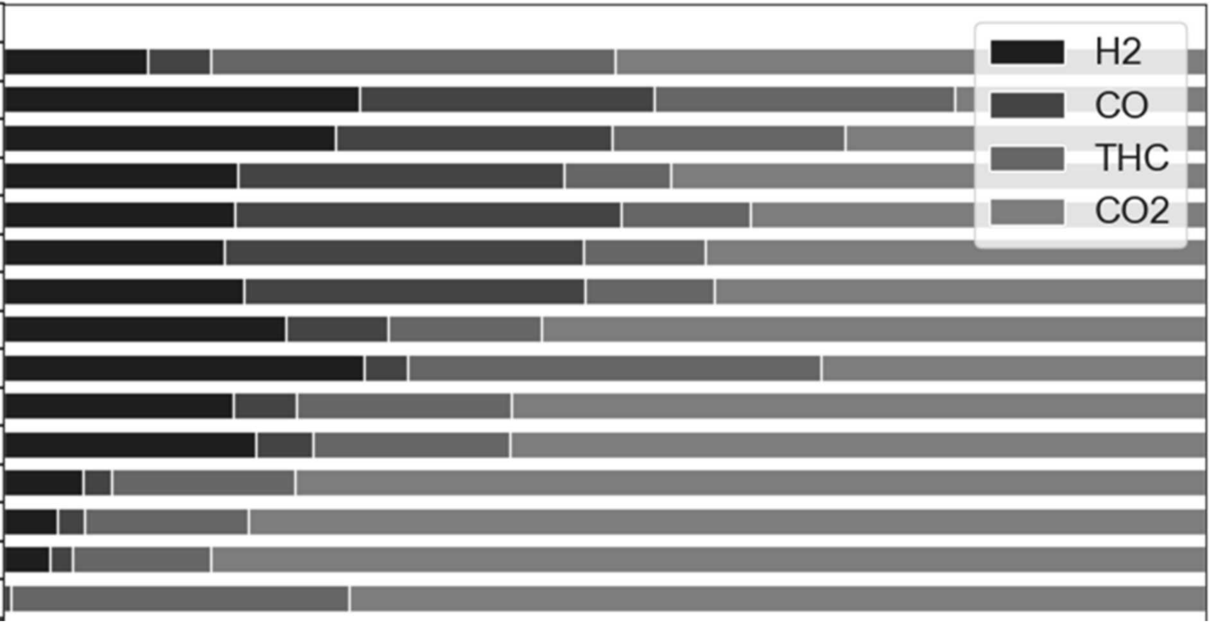
- Literature Review:
  - State of charge
  - Cathode Chemistry
  - Failure Tests
- This shows the gas composition, but the hazard also depends on total gas volume vented

Literature	Chemistry	SOC (%)
Ohsaki (2005)	LCO	OCH
Somandepalli (2014)	LCO	150
Somandepalli (2014)	LCO	100
FAA Study (2016)	LCO	100
FAA Study (2016)	LCO	90
FAA Study (2016)	LCO	80
FAA Study (2016)	LCO	70
FAA Study (2016)	LCO	60
Somandepalli (2014)	LCO	50
FAA Study (2016)	LCO	50
FAA Study (2016)	LCO	40
FAA Study (2016)	LCO	30
FAA Study (2016)	LCO	20
FAA Study (2016)	LCO	10
Kumai (1999)	LCO	0
Golubkov (2014)	NMC	100
Golubkov (2014)	LCO/NMC	100
Fernandes (2018)	LFP	190
Golubkov (2015)	LFP	130
Golubkov (2015)	LFP	115
Golubkov (2015)	LFP	100
Golubkov (2014)	LFP	100
Golubkov (2015)	LFP	75
Golubkov (2015)	LFP	50
Golubkov (2015)	LFP	25
Golubkov (2015)	LFP	0
Zheng (2016)	LFP	0
Golubkov (2015)	NCA	143
Golubkov (2015)	NCA	132
Golubkov (2015)	NCA	127
Golubkov (2015)	NCA	120
Golubkov (2015)	NCA	112
Golubkov (2015)	NCA	104.6
Golubkov (2015)	NCA	100
Golubkov (2015)	NCA	100
Golubkov (2015)	NCA	100
Lammer (2017)	NCA-32A	100
Lammer (2017)	NCA-35E	100
Lammer (2017)	NCA-MJ1	100
Golubkov (2015)	NCA	75
Golubkov (2015)	NCA	50
Golubkov (2015)	NCA	0
Golubkov (2015)	NCA	0
Golubkov (2015)	NCA	0
Golubkov (2015)	NCA	0
Golubkov (2015)	NCA	0



Gas Species- LCO Chemistry

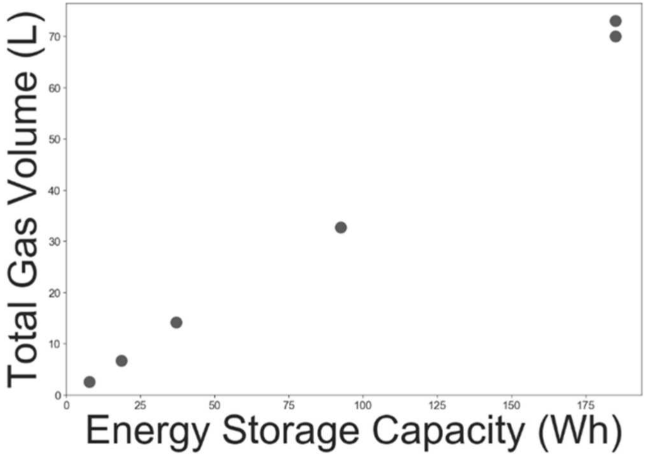
Literature	Chemistry	SOC (%)
Ohsaki (2005)	LCO	OCH
Somandepalli (2014)	LCO	150
Somandepalli (2014)	LCO	100
FAA Study (2016)	LCO	100
FAA Study (2016)	LCO	90
FAA Study (2016)	LCO	80
FAA Study (2016)	LCO	70
FAA Study (2016)	LCO	60
Somandepalli (2014)	LCO	50
FAA Study (2016)	LCO	50
FAA Study (2016)	LCO	40
FAA Study (2016)	LCO	30
FAA Study (2016)	LCO	20
FAA Study (2016)	LCO	10
Kumai (1999)	LCO	0

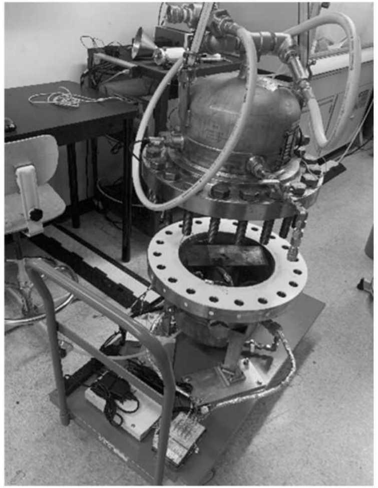


- Increase in SOC, Increase in flammable gas fraction
- Total Volume Production needs to be considered

Gas Production

- Total volume production must be understood as with the species
- Linear relationship shown with initial testing
  - 0.38 L/Wh





Vent Gas Characterization

- Cantera: open-source chemical kinetics software
  - Lower Flammability Limit
  - Laminar Flame Speed
  - Maximum Over-Pressure
- Direct inputs into NFPA 68 Vent Size Calculations
- Compared and Validated models with Literature

Lower Flammability Limit Estimates

Different Methods to Estimate:

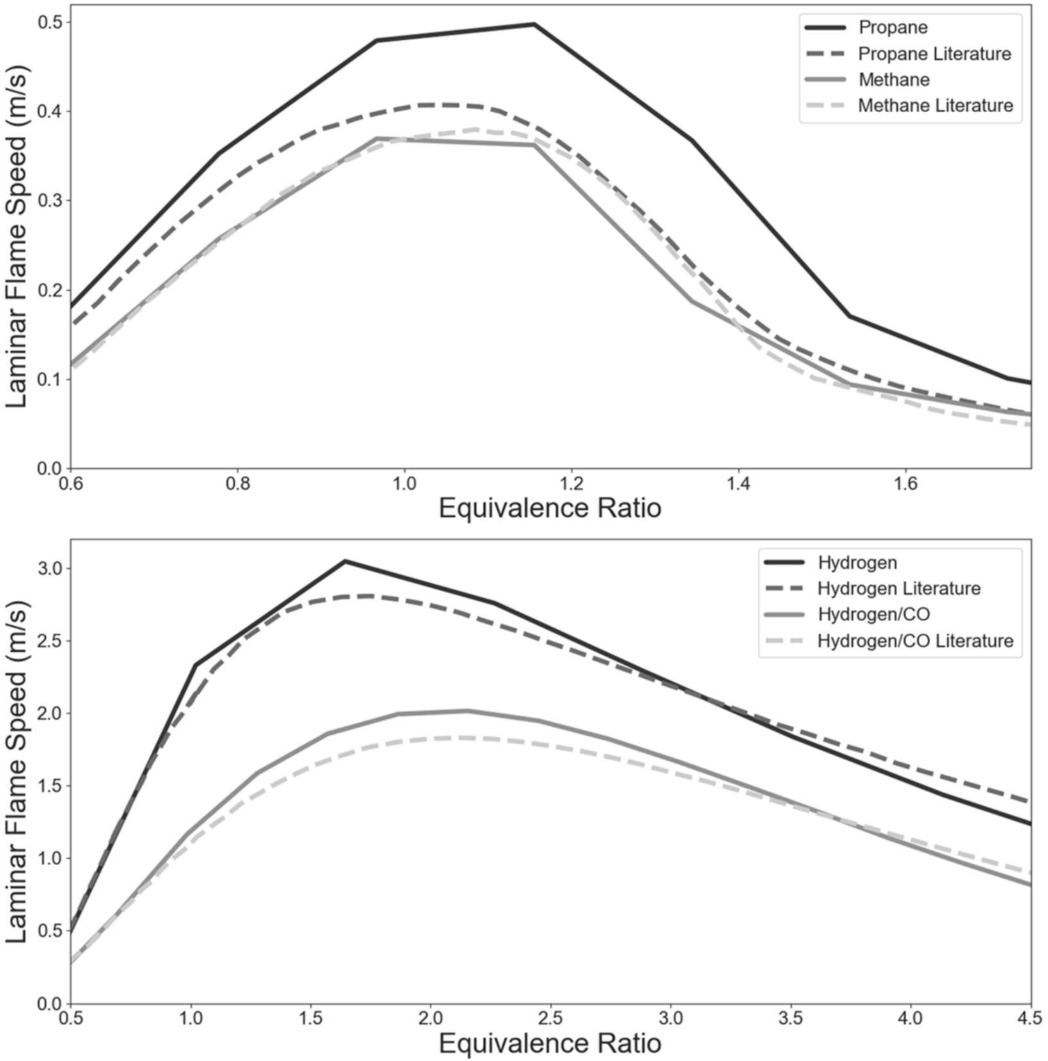
1. Experimental Measurements
2. Le Chatelier's law: $$\frac{1}{X_{\mathrm{L}}} = \sum_{i=1}^{fuels} \frac{X_{\mathrm{i}}}{X_{\mathrm{L_i}}}$$
3. Equilibrium Method Using Cantera
   - Taking inert diluents into account (CO2)

$$X_{\mathrm{L}}(T_{\mathrm{u}}) = \frac{\tilde{c}_{\mathrm{p,u}}(1573K - T_{\mathrm{u}})}{\Delta h_{\mathrm{c}}}$$

Cell Chemistry	**Lower Flammability Limit (Volume Fraction)**
Somandepalli et. al LCO- 150% SOC	6.3%
FAA 2016 Report LCO- 100% SOC	8.5%
LCO- 100% SOC	10% to 16%
LFP- 100% SOC	18% to 21%
NCA- 100% SOC	14% to 17%

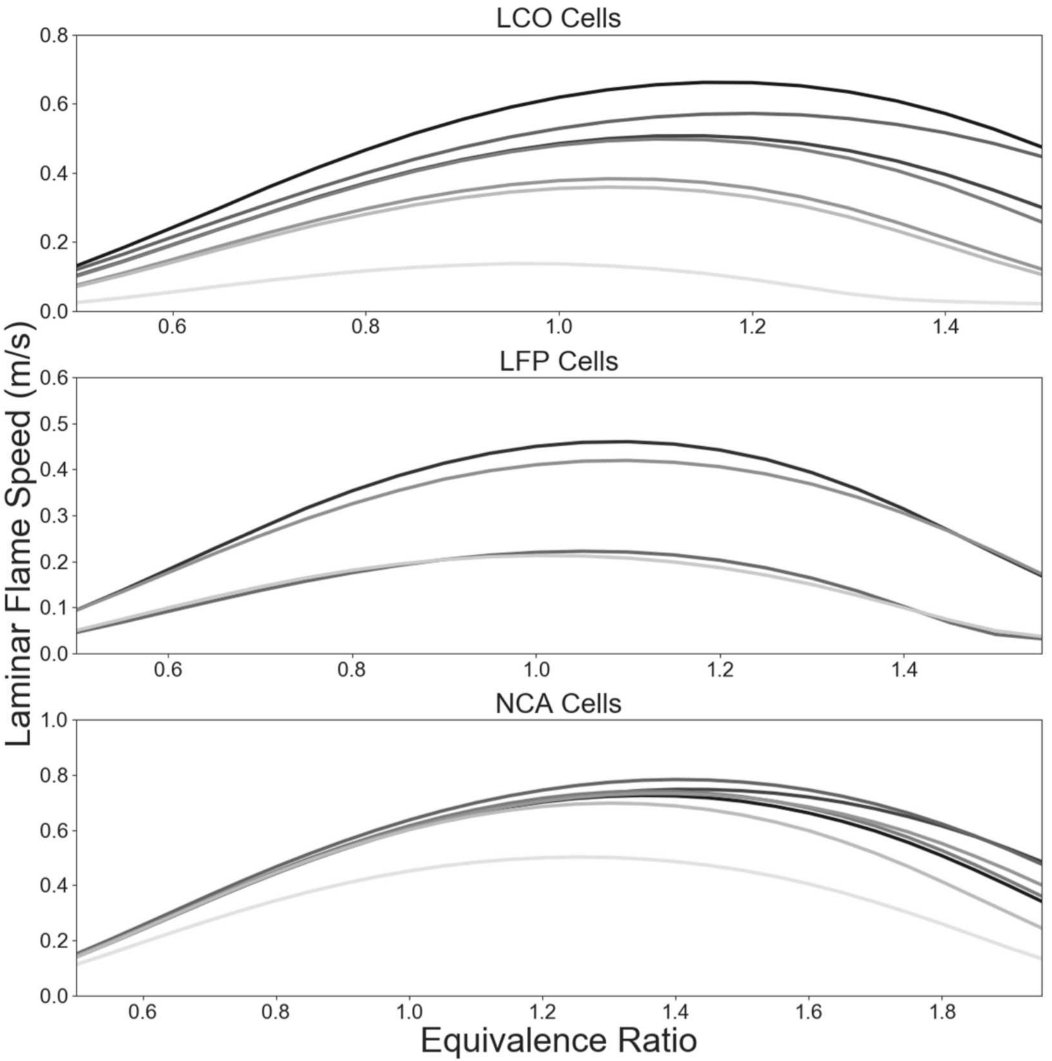
Verification of Flame Speed Model

- Compared models to literature of well known gases
- Only propane was slightly higher than literature



Estimated Flame Speeds

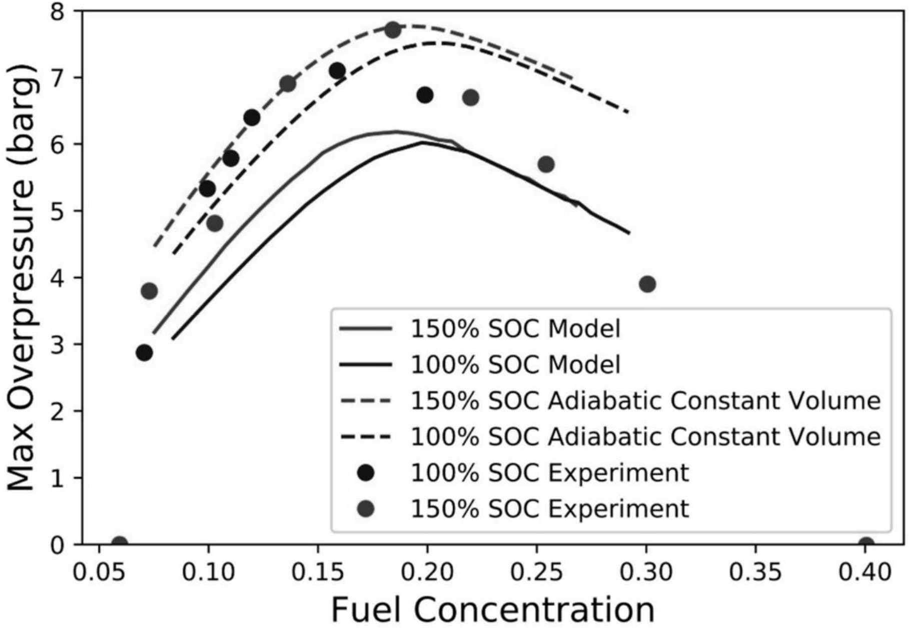
- Flame speed increases as SOC goes up
- Includes various capacities, failure tests, constructions, etc.

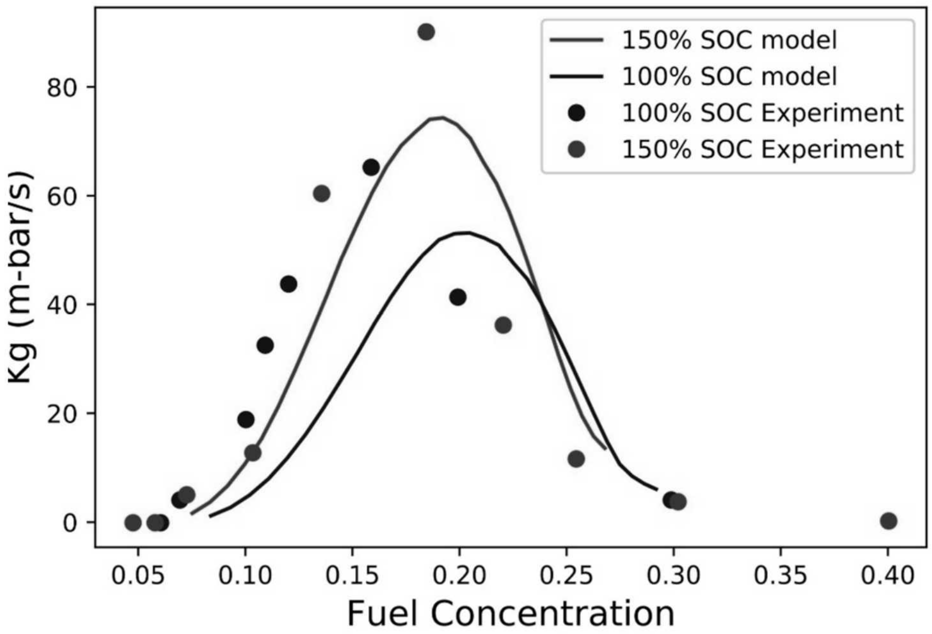


Max Over-Pressure & Deflagration Index

- Calculated based on gas mixture properties in Cantera
- Calculate thermodynamic, equilibrium pressure for constant volume, adiabatic process
- Compared against experiment by Somandepalli, Marr and Horn in 2014

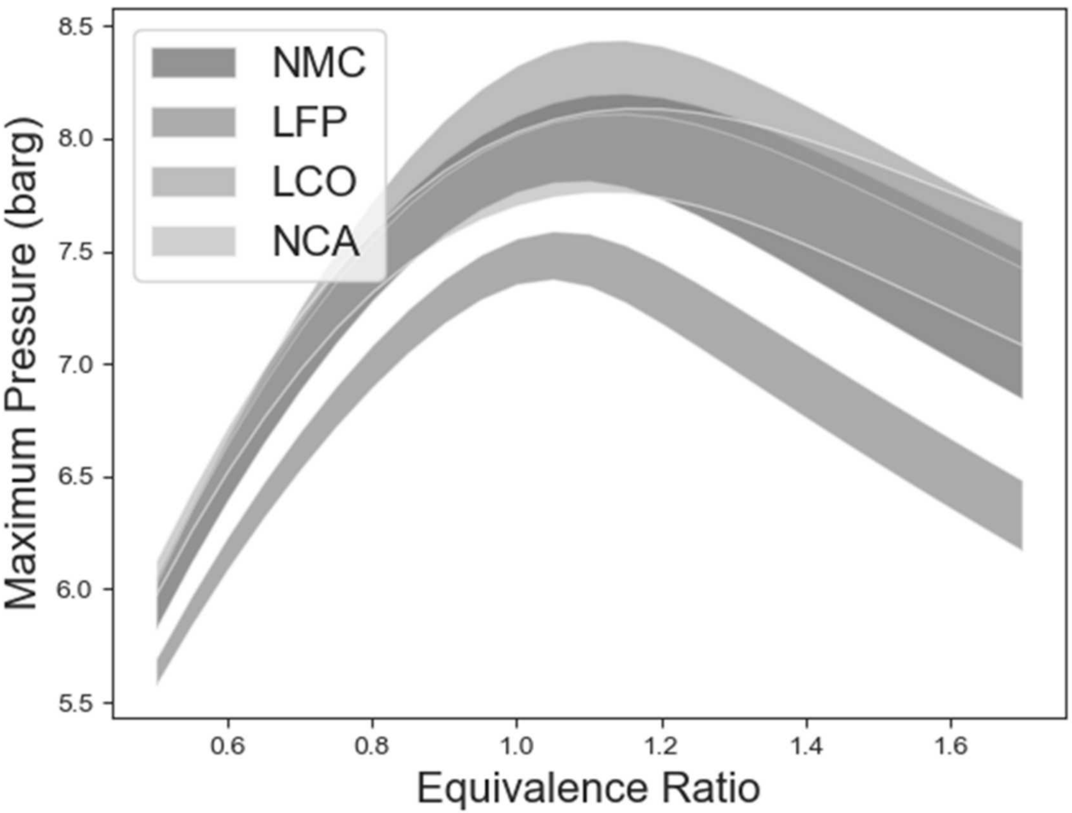
$$\frac{dp}{dt} = \text{Max rate of pressure rise} \qquad K_g = \frac{dp}{dt} V^{\frac{1}{3}}$$





Estimated Maximum Over-Pressure

- All at 100% SOC
- As with flame speeds, the LFP chemistry has a lower maximum pressure compared with NCA & LCO



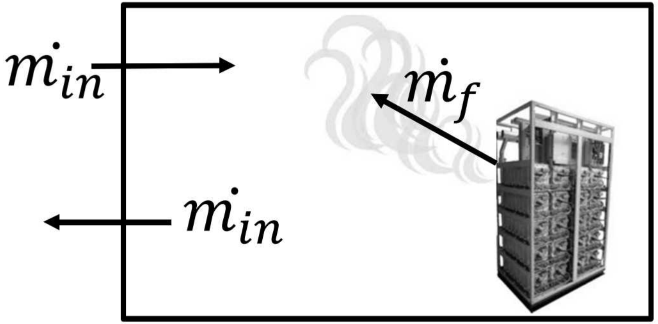
Example of Application

- Basic example to compare hazards combustible dusts, flammable gases and energy storage systems
- Consider a BESS in Utility Room or
  Purpose Driven BESS Storage Container:
  - 20’ x 8’ x 8’
  - 608 ft^2 (56.5 m^2) of Surface Area for Vents
  - Rack in Corner of Room
  - Initially assume no obstructions
  - Gases vent outside of rack
  - P_{red} = 0.06 bar-g
  - 10 Total Vents
  - Full Volume Cloud

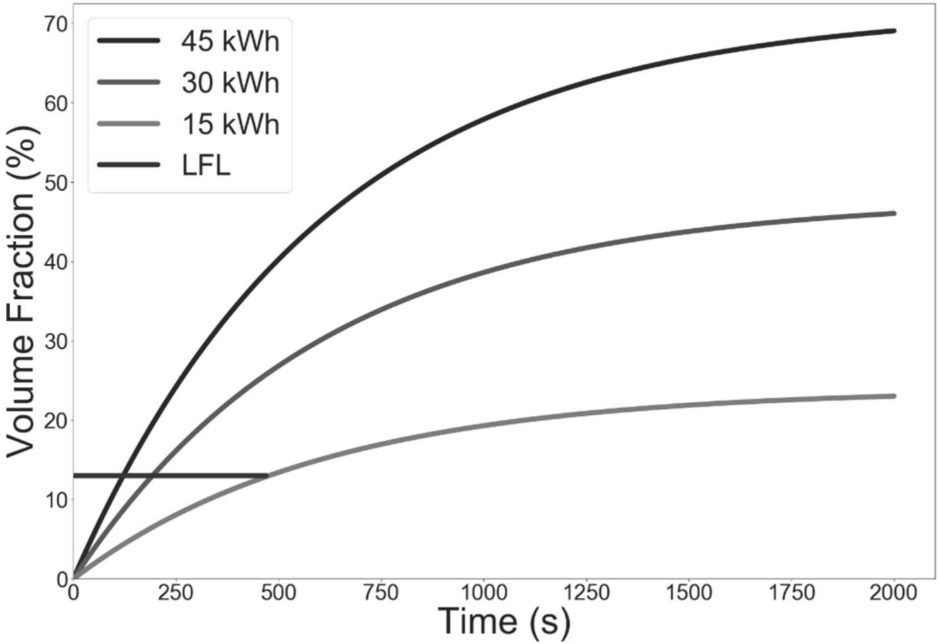
Explosion Scenario

1. Vent gas releases into room

$$X_{\mathrm{f}}(t) = \frac{mdot_{\mathrm{f}}}{mdot_{\mathrm{out}}} * \frac{M_{\mathrm{air}}}{M_{\mathrm{f}}} * \left(1 - \exp(-\frac{mdot_{\mathrm{out}}}{m_{\mathrm{T}}})\right)$$

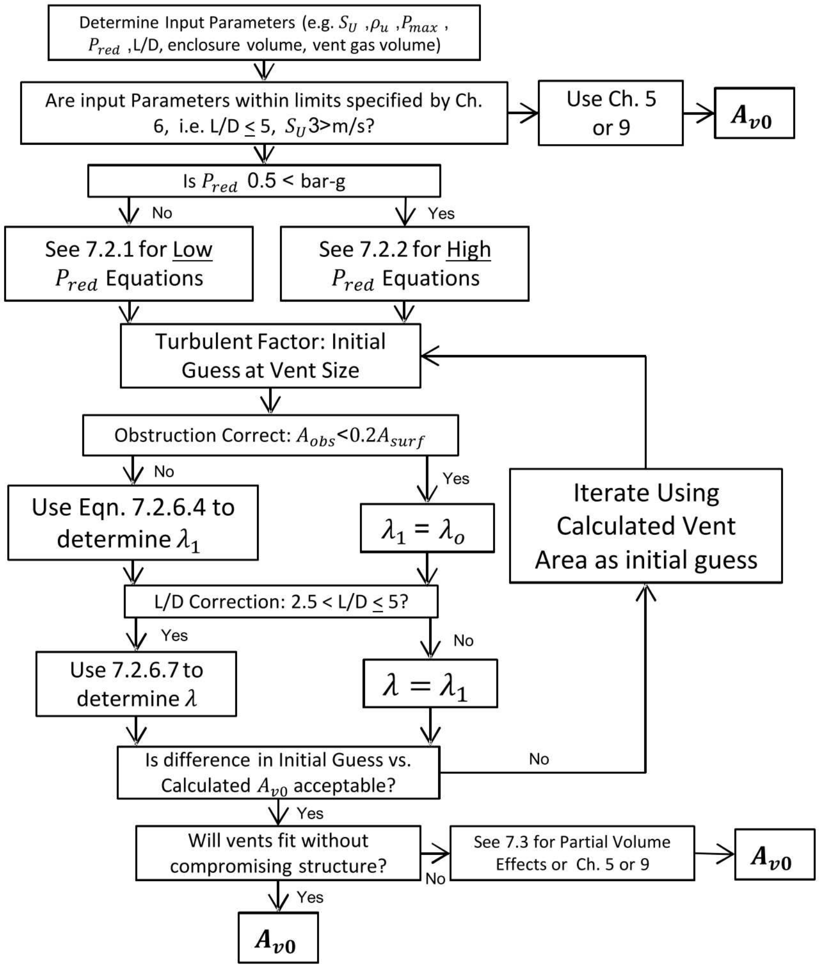


2. Once LFL is reached, explosion hazard exists
3. Time to LFL depends on numerous factors
   - Vent gas species & LFL
   - BESS Capacity
   - Room Ventilation vs. Gas release rate
   - Module Design
   - Propagation effects
   - Room size and gas accumulation



Vent Sizing Process

- Inputs depend on known constraints and parameters such as:
  - L/D
  - P_{red}
  - Total obstruction area
- Example of flow diagram for Flammable Gases



Vent Size Calculation

- Assume $P_{red} = P_{es}$ where $P_{es} = {}^{2}/_{3}$ enclosure ultimate strength
- Turbulence Factor: λ
  - Grows Exponentially with increasing Obstruction Area
  - Grows quadratically based on L/D increasing
- Discharge Coefficient: C_d
  - Based on Vent Design
- Ratio of Unburned Specific Heats: γ_b
- Unburned Sonic Flow Mass Flux: G_u
- Unburned gas-air density: ρ_u

$P_{red} \leq$ 0.5 bar-g

$$A_{v0} = \frac{AsC}{\sqrt{P_{red}}}$$

$$C = \frac{S_L \rho_u \lambda}{2 G_u C_d} \left[\left(\frac{P_{max} + 1}{P_0 + 1} \right)^{1/\gamma b} - 1 \right] (P_0 + 1)^{1/2}$$

$P_{red} >$ 0.5 bar-g

$$A_{v0} = A_s \frac{\left[1 - \left(\frac{P_{red} + 1}{P_{max} + 1} \right)^{1/\gamma b} \right]}{\left[\left(\frac{P_{red} + 1}{P_{max} + 1} \right)^{1/\gamma b} - \delta \right]} \frac{S_u \rho_u}{G_u} \frac{\lambda}{C_d}$$

Vent Sizing for Different Hazards

Hazard	Flame Speed (m/s)	Kst (bar-m/s) Flame speed	Pmax (bar-g)	Min Vent Size (m^2)	Max Vent Size (m^2)
Class 1 Dust: Sugar	N/A	138	8.5	N/A	5.2
Class 3 Dust: Aluminum	N/A	415	12.4	N/A	19
Propane	0.40	N/A	8.6	N/A	5.2
Hydrogen	2.80	N/A	7.4	N/A	**33.2**
LCO 100% SOC	0.49 - 0.65	N/A	7.81 - 8.44	6.7	10
LFP 100% SOC	0.37 - 0.42	N/A	7.38 - 7.60	4.0	4.9
NCA 100% SOC	0.69 - 1.07	N/A	7.74 - 8.13	**10**	**32**

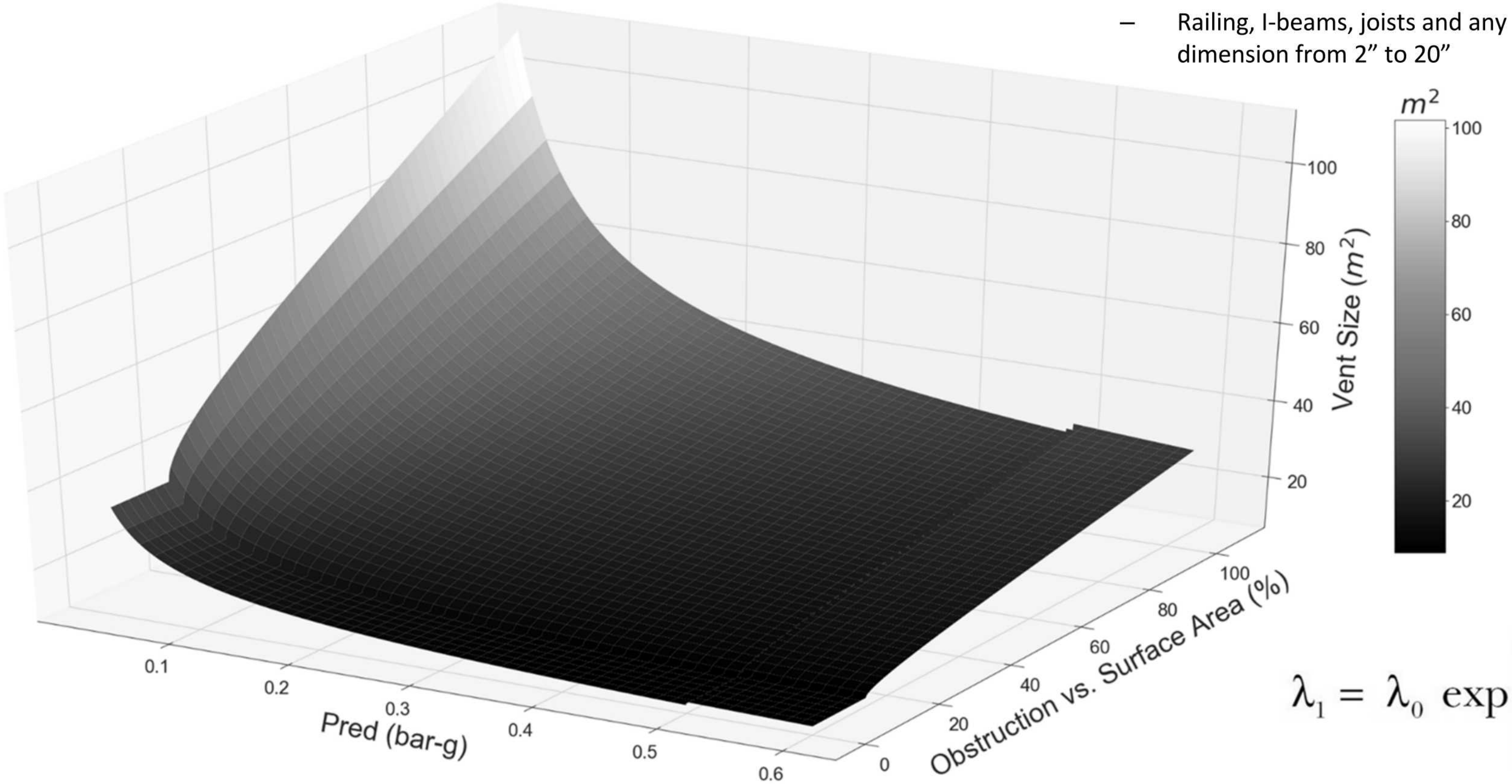
Deflagration Experiments

- Gexcon performed hydrogen tests with iso-containers
- Numerous experiments with varying obstructions, volume concentration and deflagration vent sizes
- From test #18:
  - 21% Concentration of H_2
  - Pipe-rack and perforated film
  - 8 Vents at 1 m^2 each
- NFPA 68 Vent Calculations:
  - Requires 25-26 m^2 of vent area based on $Pred$ of 0.1 bar-g and 10% Obstruction Area

- Deformation occurs even with deflagration vents

Effects of Obstructions & P_{red}

- Only 56.5 m^2 of Surface Area for Vents
- Obstructions include:
  - Conduit, pipe, tubes with diameter of ½” or greater
  - Railing, I-beams, joists and any feature that has a dimension from 2” to 20”



$$\lambda_1 = \lambda_0 \exp\left(\sqrt{\frac{A_{obs}}{A_s}} - 0.2\right)$$

Conclusions and Future Work

- Low order model to approximate hazard and compare with well known and documented industrial hazards
- Everybody can use these programs to analyze their own specific cases
- This analysis gives a starting point but leaves a lot more to consider:
  1. Additional modeling/studies to validate models, understand smaller scales such as rack ventilation
  2. Experiments- how does gas production scale up
  3. Effects from obstructions need further analysis
  4. Large variation in flame speed and maximum pressure show understanding of cell construction, capacity and chemistry are important parameters when designing safety system

Questions?

- Contacts:

Austin Baird- baird79@utexas.edu/arbaird@sandia.gov

Erik Archibald- archy@utexas.edu

Kevin Marr- kevin.c.marr@utexas.edu

The University of Texas at Austin
Mechanical Engineering
Cockrell School of Engineering