Defining the State of Safety (SOS) for Lithium-Ion Batteries in EVs – A Discussion

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Introduction

- The use of lithium-ion batteries (LIB) are expanding rapidly for many applications including electric mobility and grid energy storage
- LIBs pose a potential risk of thermal runaway (TR) and fires.
  - Fires in EVs, E-bikes, stationary energy storage have been documented
  - Although EV fires are rare, they are very difficult to extinguish, and they pose challenges for first responders
  - The risk of fire could increase containment costs and insurance premiums.
- Despite ongoing efforts and R&D to enhance safety, fire incidents in EVs and energy storage systems persist and could increase with more growth EVs
- State of Health (SOH) has been extensively studies and agreed upon; tools are available that could give a measure of LIB longevity and cycle/calendar life
- From conversations with various stakeholders, it appears there is a need to develop an equivalent measure for the **State of Safety** (SOS) or **hazard severity level** (HSL) to establish a common terminology & scale within the industry.

Current Challenges with Defining/Scaling SOS

- LIB hazard severity levels to various abuse conditions have been defined and describes by EUCAR (see slide # 14)
  - **Scale 0** means no effect; **Scale 7** means explosion, fire, toxic gas release (worst case)
  - SAE & USABC have adopted EUCAR hazard levels (SAE Standard J-2464-2021-8)
- Some have suggested to use scales of 1-4 with 1 being worst; 4 being safe
- Some have proposed **0 as unsafe** with **1 as completely safety** with various 0.1 incremental safety/hazard levels between
- Some first responders would like to see Red as unsafe, Green as safe, with Yellow as caution.
- So, it seems that there is no common definition or scale that all stakeholder can speak to the same universal meaning.
- The aim of this presentation is to open a dialogue between various stakeholders in battery and EV (and may be grid storage) communities to see if a common definition for SOS (or HSL) would be valuable.

Who are Some of Stakeholders Interested in SOS

- Battery manufacturers
- Vehicle manufacturers
- Regulation agencies
- Driver/customer
- First responders
- Towing companies
- Public
- Standard setting organizations
- Charging station owners
- Testing organizations
- Dealerships
- Repair shops
- Vehicle recyclers
- Vehicle auction houses
- Shipping companies
- Second use companies
- Battery recyclers
- R&D organizations
- Safety component makers
- Sensor makers
- Others ?????

State of Health versus State of Safety

- State of Health (SOH) between 0% and 100%
  - There is a general agreement on its definition (capacity and power over lifespan).
  - It is easy to measure using voltage (V), temperature (T), current (C), and perhaps electrochemical impedance spectroscopy (EIS), with many tools/software available.
  - It provides a measure of aging and remaining life, enabling stakeholders to make informed decisions regarding warranty, repairs, replacements, reuse, recycling, etc.
- State of Safety (SOS)
  - Challenging to define, as it depends on the application and specific situation.
  - It could refer to the condition or status of a battery's ability to **operate** without posing risks such as thermal runaway or fire.
  - It may also describe the hazard status of a LIB system **after incidents**, such as EV crashes, EV submersion during hurricanes, or BESS damage after a severe storm (particularly relevant for first responders).
  - Additionally, it could refer to the hazard status of a battery system at the **end of its life** in EVs and grid storage, including risks associated with second-life applications or recycling.
  - Correlating various measurements to hazard levels is challenging, as a lack of correlation could lead to false negatives.)

Background

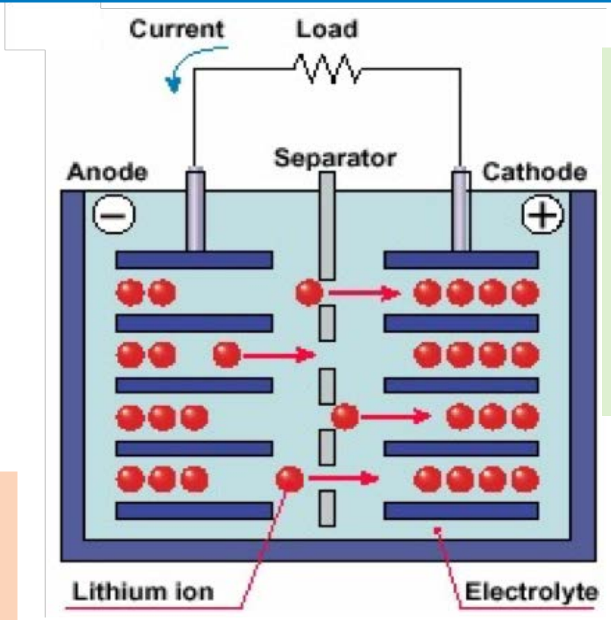
To define the **State of Safety** (or Hazard Severity Level), it is essential to understand:

- How lithium-ion batteries undergo thermal runaway and cause fires.
- The impact of various factors on a battery’s abuse response.
- Observable indicators that can be measured both before and after the onset of thermal runaway.

Lithium-Ion Batteries Basics and Chemistries

Many anodes are possible
Carbon/Graphite
Titanate ($Li_4Ti_5O_{12}$)
Silicon & Silicon/Carbon
Lithium Metal

Many electrolytes are possible
Carbonates with $LiPF_6$ or other Salts
Ionic liquids
Polymer electrolytes
Various solid electrolytes



Li: lightest metal
High voltage (~ 4.5V)
Cycle life ~1000-5000+
Calendar life ~ 8-12+
Wh/kg ~150-350+
Wh/l ~ 400-800+

Many cathodes are possible
Cobalt oxide
Iron phosphate
Nickel cobalt aluminum
Nickel manganese cobalt (xyz)
Nickel rich – no cobalt

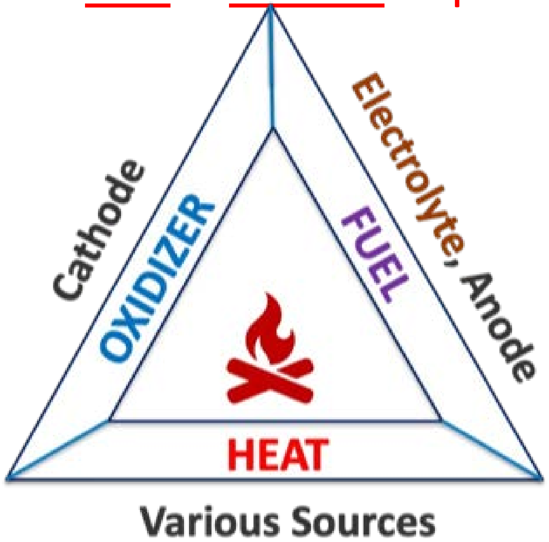
Many separators are possible
Polypropylene
Ceramic coated
Polymer
Aramid
Garnet
Ceramic

From: A. A. Pesaran, "Lithium-Ion Battery Technologies for Electric Vehicles: Progress and challenges," in *IEEE Electrification Magazine*, vol. 11, no. 2, pp. 35-43, June 2023, doi: 10.1109/MELE.2023.3264919

Mechanisms of Thermal Runaway/Fire and Instigators

Fire is initiated when fuel is heated in presence of an oxidant.

Most cathodes (except for Iron Phosphate) release oxygen when unstable



Commonly used electrolytes in today's LIB are flammable and act as fuel; anodes too

Combustible gases and ejectiles heating cells

In a cell **heat** could come from External Short Circuits, Over Charging, External Heating, Object Penetration, Crush, Internal Short Circuits (manufacturing defects), or Out of Spec Operation.

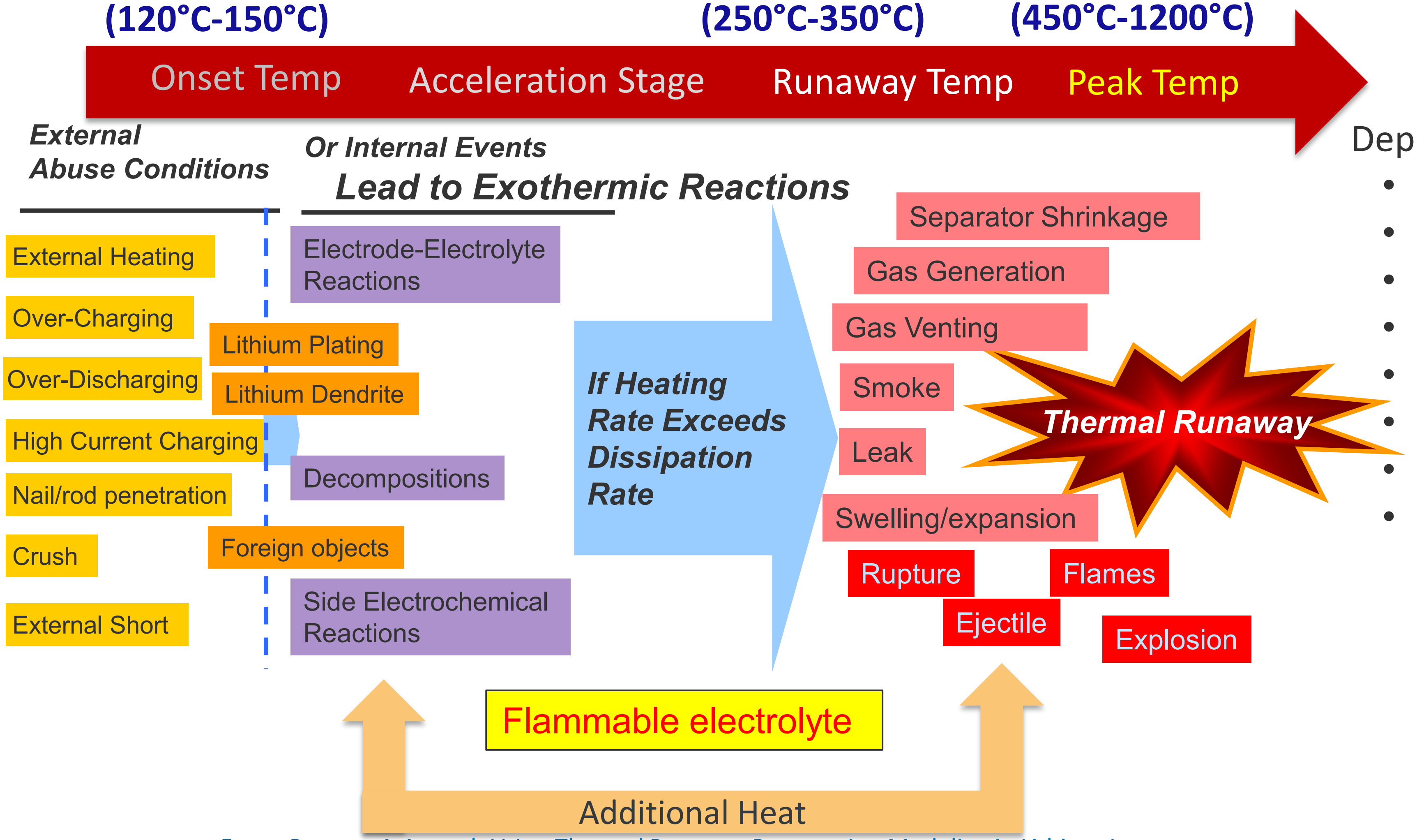
In a pack/system **heat** comes from: TR in one cell could propagate to other cells, malfunctioning BMS/Controls, poor pack designs, or incidents from 12V auxiliary battery.

Field data and lab testing have shown ejection material and/or vented gases such as hydrogen could be ignited outside a cell and release significant **heat** to battery leading to TR.

Incidents such as crashes, seawater submersion, may cause corrosion, short circuit, and arcing.

Cascading Reactions after Abusing a Lithium-ion Battery

Various Factors Could Lead to Thermal Runaway (TR) of a Cell



(120°C-150°C) Onset Temp

Acceleration Stage

(250°C-350°C) Runaway Temp

(450°C-1200°C) Peak Temp

External Abuse Conditions

- External Heating
- Over-Charging
- Over-Discharging
- High Current Charging
- Nail/rod penetration
- Crush
- External Short

Or Internal Events

- Lithium Plating
- Lithium Dendrite
- Foreign objects

Lead to Exothermic Reactions

- Electrode-Electrolyte Reactions
- Decompositions
- Side Electrochemical Reactions

If Heating Rate Exceeds Dissipation Rate

- Separator Shrinkage
- Gas Generation
- Gas Venting
- Smoke
- Leak
- Swelling/expansion
- Rupture
- Ejectile
- Flames
- Explosion

Thermal Runaway

Flammable electrolyte

Additional Heat

Depends on:

- Chemistry
- Electrolyte
- Additives
- Separator
- Cell design
- Safety features
- Environment
- State of charge

From: Pesaran A.A. et.al, LI-Ion Thermal Runaway Propagation Modeling in Lithium-Ion Modules with and without PCM, International Battery Seminar, March 2017

What Could be Observed Before and After Onset of Thermal Runway; How Can they be Measured?

Observations

- Temperature increase to above 100°C
- Voltage wide variation or drop
- Current increase
- Electrolyte venting
- Gas releases
- Smoke release
- Sparks and arching
- Heat release rate increase
- Pressure build up
- Applied force
- Cell casing expansion (swelling)
- Cell casing rupture
- Sounds from disintegration, projectile
- Fire

Measurements (Example Sensors)

- Temperature (NTC thermistors, RTDs, IR)
- Voltage (resistive voltage sensors)
- Current (shunt resistors, hall effects)
- Electrolyte venting (Hydrocarbon sensors)
- Gas releases (H_2, CO, CO_2 sensors)
- Smoke release (photoelectric sensors)
- Sparks/Arcs (optical and sound sensors)
- Heat release (heat flux sensors)
- Pressure (piezoelectric sensors)
- Force (force gauges)
- Cell expansion (strain gauge sensors)
- Sounds (acoustic sensors, microphones)
- Fire (optical sensors)

The rate of change of some these parameters could be more of an indication of thermal runway

Other Signal/Measurements

- AC Impedance changes – measured with Electrochemical Impedance Spectroscopy (EIS)
- DC Residence changes – measured by battery internal resistance meters
- Lithium inventory – measured by EIS or Differential Voltage Analysis (DVA)
- Lithium plating/dendrite – measured by EIS or by DVA
- Signs of corrosion and rusts – optical sensors
- Signs of water intrusion – optical or resistance sensors
- Ultrasound – in mid-stage R&D phase
- Electromagnetic field change – in early-stage R&D phase
- ???

The rate of change of these parameters could be as important for detection of fault

Literature Review
SOS Definition, Hazard Classification, Scale

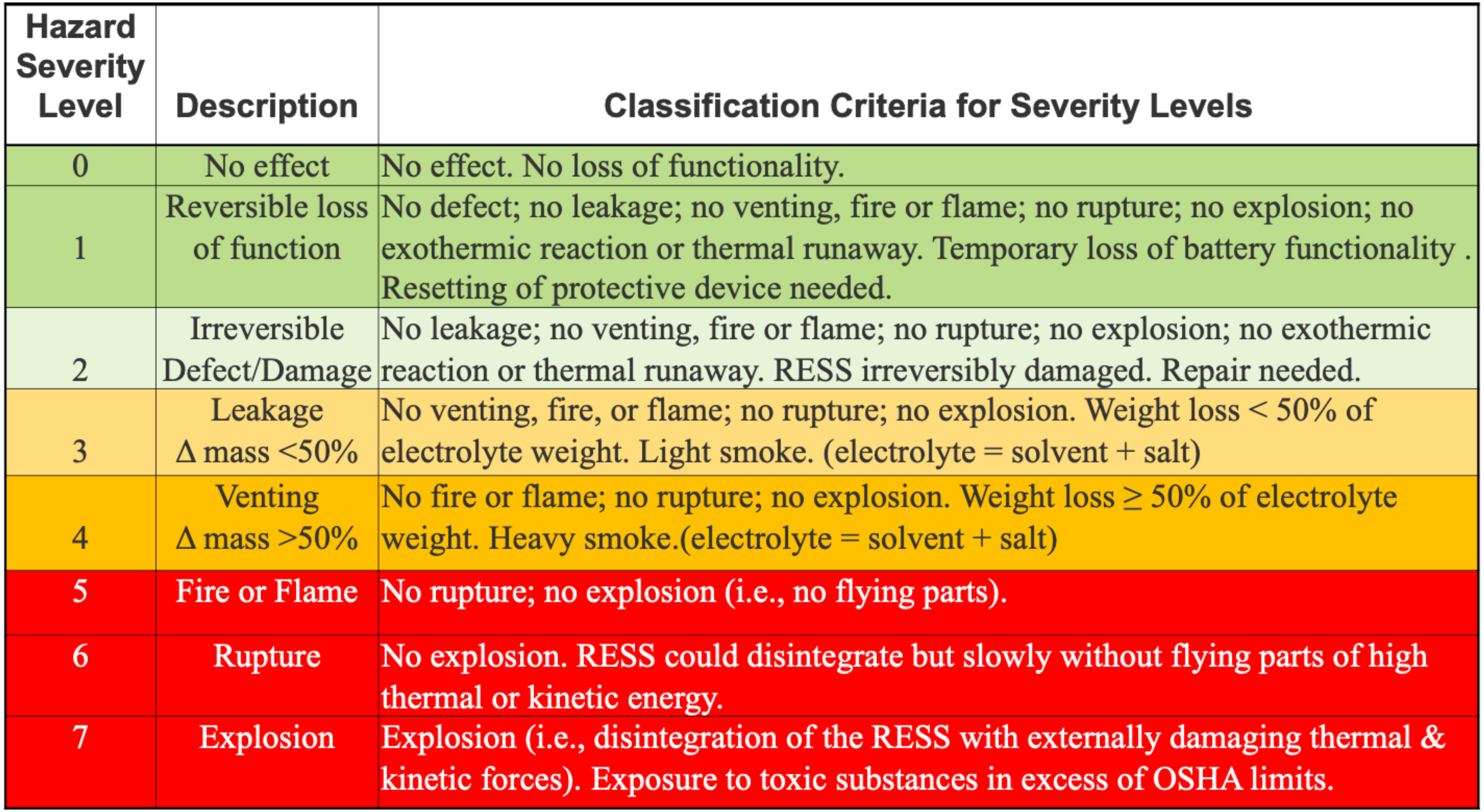
- EUCAR[1] has classified hazard severity levels post abuse (0 – 7 scale)
  - EUCAR hazard level was adopted by SAE (J2464)[2]and USABC/DOE/SNL[3]
- DOD Standard Practice for System Safety Risk Matrix[4] (1-4 scale)
- Ashtiani[5] utilized a methodology called hazard modes and risk mitigation analysis and used EUCAR <u>hazard severity</u> multiplied by the <u>probability of occurrence</u> to define the hazard risk number
- Technical University of Munich[6] produced a formulation of SOS as the reciprocal of a probability function of abuse; and developed an approach to produce SOS based on individual variable (Scale 0-1)

[1] EUCAR: European Council for Automotive R&D (https://www.eucar.be)
[2] Society of Automotive Engineers Recommended Practice J2464-202108 (https://www.sae.org/standards/content/j2464_202108)
[3] USABC Battery Abuse Testing Manual for Electric and Hybrid Vehicle Applications - Sandia Repot 2022-0089R (https://www.osti.gov/servlets/purl/183858)
[4] DOD Standard Practice System Safety (https://acqnotes.com/wp-content/uploads/2014/09/MIL-STD-882E-change-1-1.pdf)
[5] C.N. Ashtiani, Analysis of battery safety and hazards' risk mitigation, ECS Trans. 11 (2008) 1e11, http://dx.doi.org/10.1149/1.2897967.
[6] Calculation of the State of Safety (SOS) for Lithium-Ion Batteries (https://www.sciencedirect.com/science/article/pii/S0378775316306140?via%3Dihub)

EUCAR Hazard Severity Levels Has Been Used Routinely

Abuse response in usually ranked using the EUCAR scale and used in SAE J2464

From: https://www.osti.gov/servlets/purl/183858



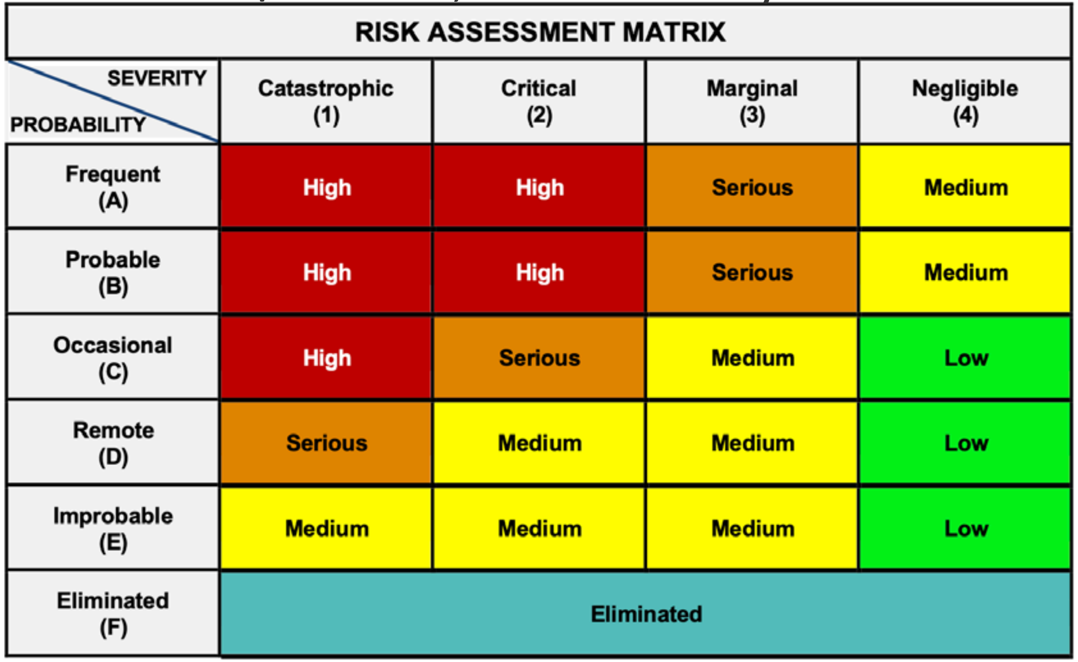
Hazard Severity Level	Description	Classification Criteria for Severity Levels
0	No effect	No effect. No loss of functionality.
1	Reversible loss of function	No defect; no leakage; no venting, fire or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Temporary loss of battery functionality . Resetting of protective device needed.
2	Irreversible Defect/Damage	No leakage; no venting, fire or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. RESS irreversibly damaged. Repair needed.
3	Leakage Δ mass <50%	No venting, fire, or flame; no rupture; no explosion. Weight loss < 50% of electrolyte weight. Light smoke. (electrolyte = solvent + salt)
4	Venting Δ mass >50%	No fire or flame; no rupture; no explosion. Weight loss ≥ 50% of electrolyte weight. Heavy smoke.(electrolyte = solvent + salt)
5	Fire or Flame	No rupture; no explosion (i.e., no flying parts).
6	Rupture	No explosion. RESS could disintegrate but slowly without flying parts of high thermal or kinetic energy.
7	Explosion	Explosion (i.e., disintegration of the RESS with externally damaging thermal & kinetic forces). Exposure to toxic substances in excess of OSHA limits.

Color-coded here to show safe zones (green) and unsafe zones (red) and others in warning zones.

Although these are good descriptions and may be extended to state of safety, they may not correlate easily to field scenarios and their hazard levels

Hazard Levels and Safety/Abuse Scales

1: Explosion; 2: Fire;
3: Leak/Caution; 4: Potentially Safe



RISK ASSESSMENT MATRIX

SEVERITY / PROBABILITY	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequent (A)	High	High	Serious	Medium
Probable (B)	High	High	Serious	Medium
Occasional (C)	High	Serious	Medium	Low
Remote (D)	Serious	Medium	Medium	Low
Improbable (E)	Medium	Medium	Medium	Low
Eliminated (F)	Eliminated			

Department of Defense General Standard Practice for System Safety Table III (From: https://acqnotes.com/wp-content/uploads/2014/09/MIL-STD-882E-change-1-1.pdf)

- Ashtiani's approach needs to make some major assumptions such estimating rate of occurrence for each risk
  - No Risk Zone (safe)
  - Low Risk Zone (warning)
  - High Risk Zone (unsafe)
- Technical University of Munich
  - Uses formulation to define SOS
  - Considers both the EUCAR hazard level and Ashtiani's method of three scales
  - Scale of 0 – 1 with 0.1 intervals.
    - 0: completely unsafe
    - 0.5: somewhere between
    - 1: completely safe

No consistent Definition of SOS. What would be a reasonable common scale for a robust definition of SOS and how to measure it

What is a Good way to Define an SOS Scale for EVs?

- Defining any safety metric would be complicated as should include many parameters.
- SOS definition could depend on the situation
- Normal Operation – for example for the driver/car owner
  - The LIB is in Safe Zone – Driver is not notified
  - The LIB is in Warning Zone - Driver is notified to take the EV to dealership for investigation and potential repair
  - The LIB is in Unsafe Zone – Driver is notified to take immediate action - that park the car in a safe area and contact first responders
- After an Incident (EV Crash, submerged in seawater during hurricane) SOS provides a hazard level assessment to help first responders make informed decisions in accordance with **SAE J2990 Recommended Practices** and **Emergency Response Guides**.
  - The vehicle can be operated safely
  - The vehicle can be towed away safety
  - There is danger of safety incident with towing the vehicle
  - Special precautions and hazmat control for damaged battery
- At the end-of-life
  - What is the state of health and safety of battery to be send for second life application

How to Measure and Assign a Scale to SOS?

- Slide 11 provided details of what observations and associated signals we might have (a few or may)

Measurements (Example Sensors)

- Temperature (NTC thermistors, RTDs, IR)
- Voltage (resistive voltage sensor)
- Current (shunt resistors, hall effects)
- Impedance (electrochemical impedance spectroscopy)
- Electrolyte venting (Hydrocarbon sensors)
- Gas releases (H_2, CO, CO_2 sensors)
- Smoke release (photoelectric sensors)
- Sparks/Arcs (optical and sound sensors)
- Heat release (heat flux sensors)
- Pressure (piezoelectric sensors)
- Force (force gauges)
- Cell expansion (strain gauge sensors)
- Rupture (acoustic emission sensors)
- Sounds (acoustic sensors, microphones)
- Fire (optical sensors)
- Lithium inventory (EIS, DVA)
- Lithium Plating (EIS, DVA)

Some of Variables/Parameters along with their rate of change to include (Independent of the battery design and chemistry)

Parameter	Signal	Rate of Change With time
T	Temperatures	$\partial T/\partial t$
V	Voltage	$\partial V/\partial t$
C	Current	$\partial C/\partial t$
I	Impedance	$\partial I/\partial t$
R	Resistance	$\partial R/\partial t$
E	Electrolyte vented	$\partial E/\partial t$
G	Gases released	$\partial G/\partial t$
H	Heat rate	$\partial G/\partial t$
P	Pressure	$\partial G/\partial t$
F	Forced	$\partial F/\partial t$
S	Strain	$\partial S/\partial t$
A	Acoustic/Sound	$\partial A/\partial t$
O	Optical	$\partial O/\partial t$

Considerations for SOS Measurements and Scale?

Parameter	Signal	Rate of Change With time
T	Temperatures	$\partial T/\partial t$
V	Voltage	$\partial V/\partial t$
C	Current	$\partial C/\partial t$
I	Impedance	$\partial I/\partial t$
R	Resistance	$\partial R/\partial t$
E	Electrolyte vented	$\partial E/\partial t$
G	Gases released	$\partial G/\partial t$
H	Heat rate	$\partial G/\partial t$
P	Pressure	$\partial G/\partial t$
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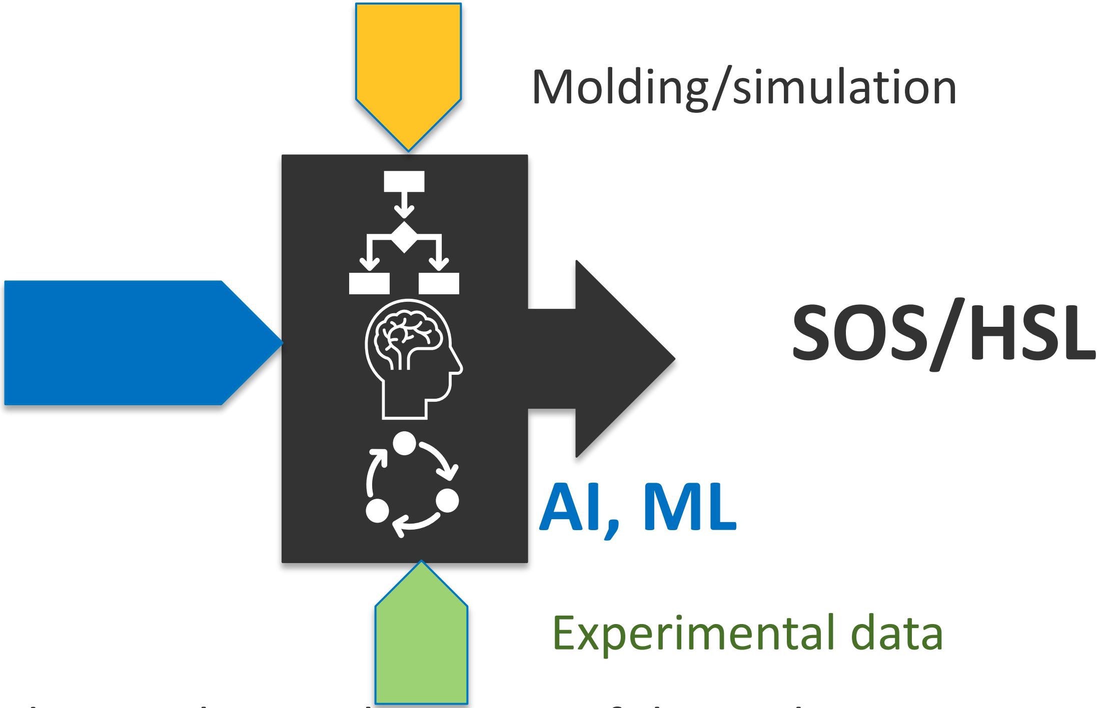
S	Strain	$\partial S/\partial t$
A	Acoustic/Sound	$\partial A/\partial t$
O	Optical	$\partial O/\partial t$



Molding/simulation

SOS/HSL

AI, ML

Experimental data

- The degree each sensor provides insights on the stages of thermal runaway or SOS level is different.
- How many sensors and what types needed?
- Combining signals provides a much better measure of SOS
- Is there a need for a lot of testing to develop correlation to SOS?
- Molding and simulation should be used to provide further insights & reduce testing
- AI and ML can speed of the developments and estimation of SOS
- R&D needed to evaluate and verify

Example of How a Battery SOS Could be Used?

- Assume Scale 1 to 10 (1: Unsafe, 10: Safe for now)
- During operation of an EV (stakeholders: driver, dealer, repair shop, OEM)
  - SOS > 8 Green: Battery is in safe zone; no indication going to TR
  - SOS > 5 - <7) Yellow: Battery is between safe and unsafe zones; needs diagnostics and potentially repair
  - SOS > 3 - < 5 Orange: Battery in unsafe zone – need urgent attention
  - SOS < 2 Red: Imminent TR - 5-minute warning to drive to park and call emergency
- After an incident (stakeholders: first responders, driver)
  - SOS > 6: Safe; SOS 4 – 5 Use caution; SOS <3 Unsafe
  - Follow SAE J-2990 and vehicle Emergency Response Guide
- End-of-Life EV and battery (stakeholders: 2nd use, recyclers, shippers)
  - SOS > 6 Safe for second use; SOS < 6 & > 2Recycle; SOS <2 Damaged category

These scales and suggested action are just for illustration.

Concluding Remarks

- Electric Vehicles with lithium-ion batteries have the potential to pose hazard of thermal runway and fire.
- An acceptable definition of State of Health is commonly used by the EV/battery community to express the remaining capacity for various situations.
- For State of Safety or Hazard Severity Level, there is no commonly acceptable definition; It is a complex topic and include many factors and depends on the situations (operation, incidents, end-of-life)
- But an acceptable definition of SOS is needed for communication between stakeholders.
- We reviewed the available definitions and proposed ideas to define and measure the SOS.
- We hope that this talk has initiated a dialogue for vested stakeholders to collaborate to further define SOS and produce methods to measure it.

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Thank You

Looking Forward to Feedback

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