SFPE Denmark

CPD Event: A Scoping Review of Fixed Suppression Systems for Li-ion Battery

6 July 2023

Meeting Agenda

1. Welcome to Linfan Cai
2. Presentation
3. Q&A

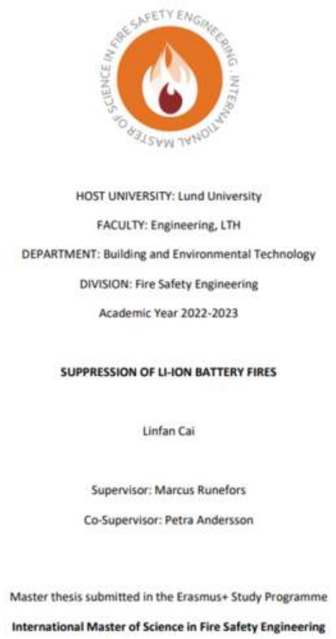
1. Welcome

The Society of Fire Protection Engineers (SFPE) Denmark Chapter is proud to present:

A Scoping Review of Fixed Fire Suppression System for Li-ion Battery

Synopsis A scoping review of fixed fire suppression systems and extinguishing agents for lithium-ion battery (LIB) fires will be presented. The review categorises different research experiments into cell-level, module-level, electric vehicle (EV) pack-level, battery energy storage system (BESS) rack-level and warehouse storage experiments, according to LIB configurations. More than twenty (20) different extinguishing agents (water-based, gas-based, powder-based and novel combinations of agents) and two (2) dispersion modes (total flooding and direct internal injection) are evaluated systematically. The advantages and drawbacks of each type of extinguishing agent are compared and discussed based on dispersion modes and LIB configurations. Suggestions on how to apply the findings from the small-scale experiments onto large-scale experiments and key findings of potential applications of extinguishing agents in EV and BESS will also be briefly discussed.

1. Welcome


HOST UNIVERSITY: Lund University

FACULTY: Engineering, LTH

DEPARTMENT: Building and Environmental Technology

DIVISION: Fire Safety Engineering

Academic Year 2022-2023

SUPPRESSION OF LI-ION BATTERY FIRES

Linfan Cai

Supervisor: Marcus Runefors

Co-Supervisor: Petra Andersson

Master thesis submitted in the Erasmus+ Study Programme

International Master of Science in Fire Safety Engineering

Linfan Cai graduated in 2023 from the International Master of Science in Fire Safety Engineering (IMFSE).

Linfan performed the master's thesis at Lund University.

Linfan is a registered Mechanical Engineer in Singapore.

https://lup.lub.lu.se/student-papers/search/publication/9117771

2. Presentation

- Objective
- Background
- Metholodology
- Results & Discussions
- Conclusions
- Future Works

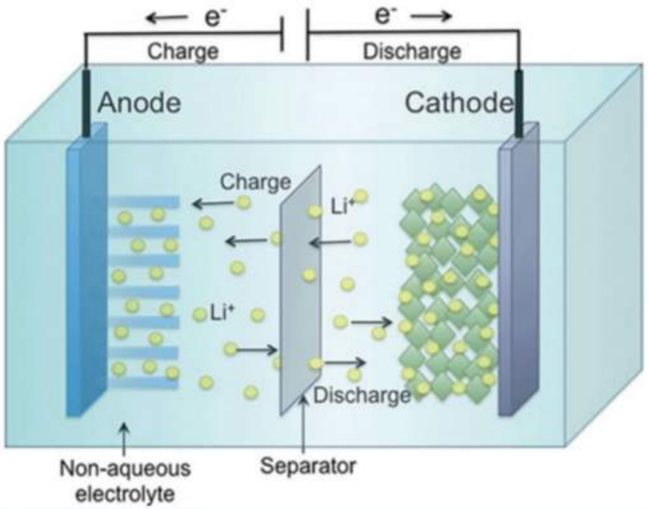
Objective

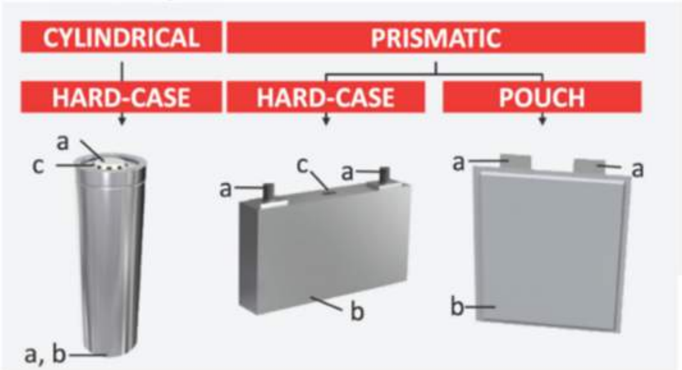
- Conduct a systematic **scoping review** of published data of research on fire suppression of lithium-ion batteries

- Analyse the gathered research results and discuss their **effectiveness and potential field applications**, i.e. electric bus and battery energy storage system

Background

What is Lithium-Ion Battery?





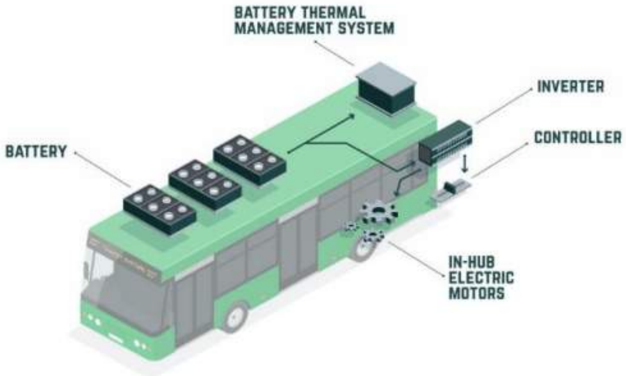
a – tab; b – housing; c – pressure valve

- Lithium Nickel Manganese Cobalt Oxide (NMC)
- Lithium Iron Phosphate (LFP)
- Lithium Cobalt Oxide (LCO)
- Lithium Titanate Oxide (LTO)
- Lithium Manganese Oxide (LMO)
- Lithium Nickel Cobalt Aluminium Oxide (NCA)

Background

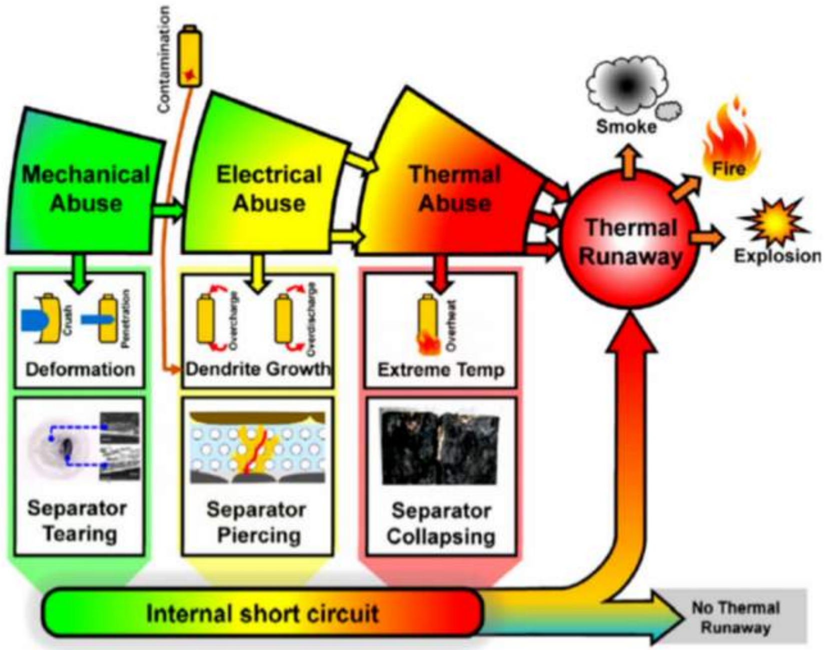
Why Lithium-Ion Battery?

- Green energy carrier
- Lightweight
- High energy density
- Long battery life
- Fast charging
- High efficiency



Background

What are problems? → THERMAL RUNAWAY



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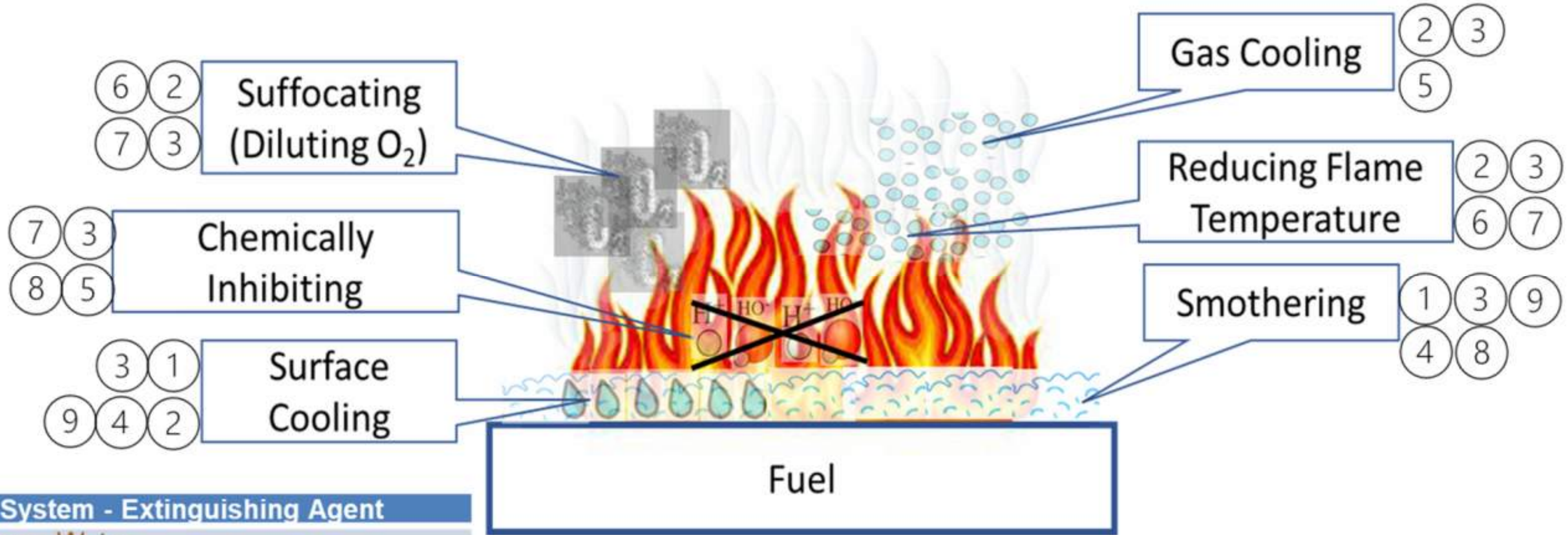
Background

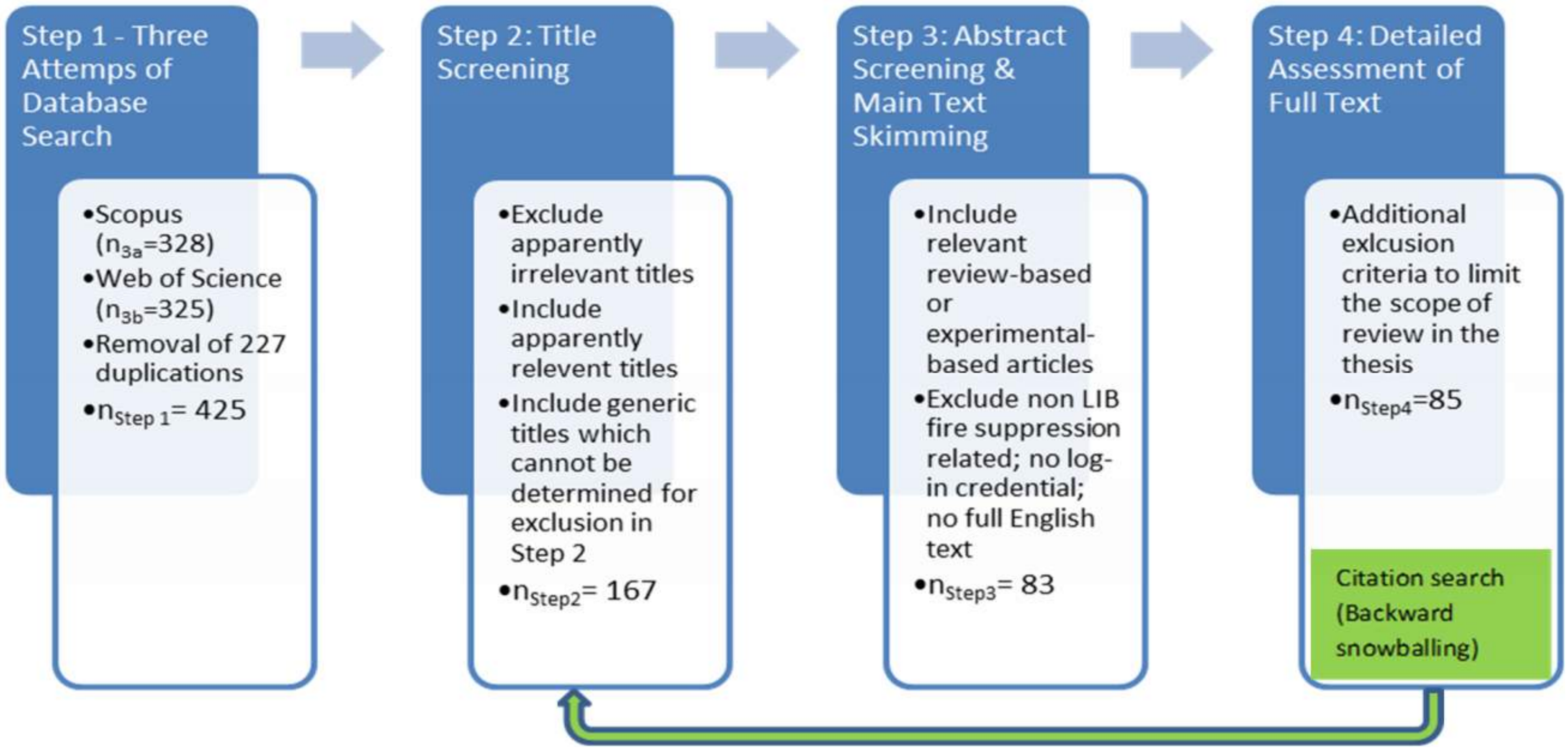
Available Fire Suppression Systems and Working Mechanism



	Suppression System - Extinguishing Agent
1	Sprinkler System - Water
2	Water Mist System - Water Fog
3	Water Mist System with Additives
4	Foam System - Water + Foams
5	Novec 1230 System - $C_6F_{12}O$
6	Inert Gas System - N_2, Ar, CO_2
7	Aerosol System - Fine Alkaline Salts + Gas Matters
8	Dry Power System - ABC Dry Powder
9	Aqueous Vermiculite Dispersion System

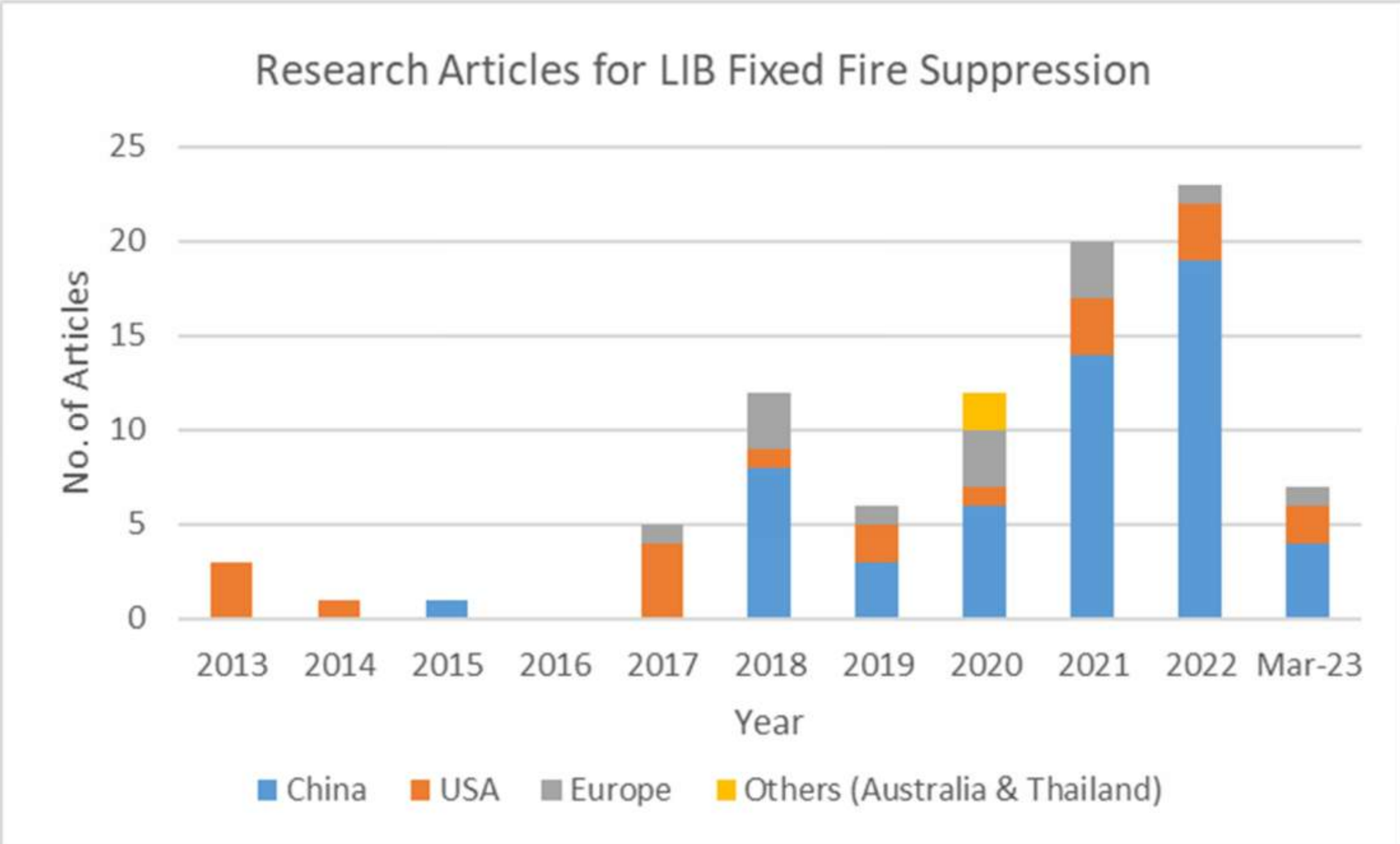
Methodology

Preferred Reporting Items for Systematic Reviews and Meta-Analysis Extension for Scoping Reviews (**PRISMA-ScR**) Framework



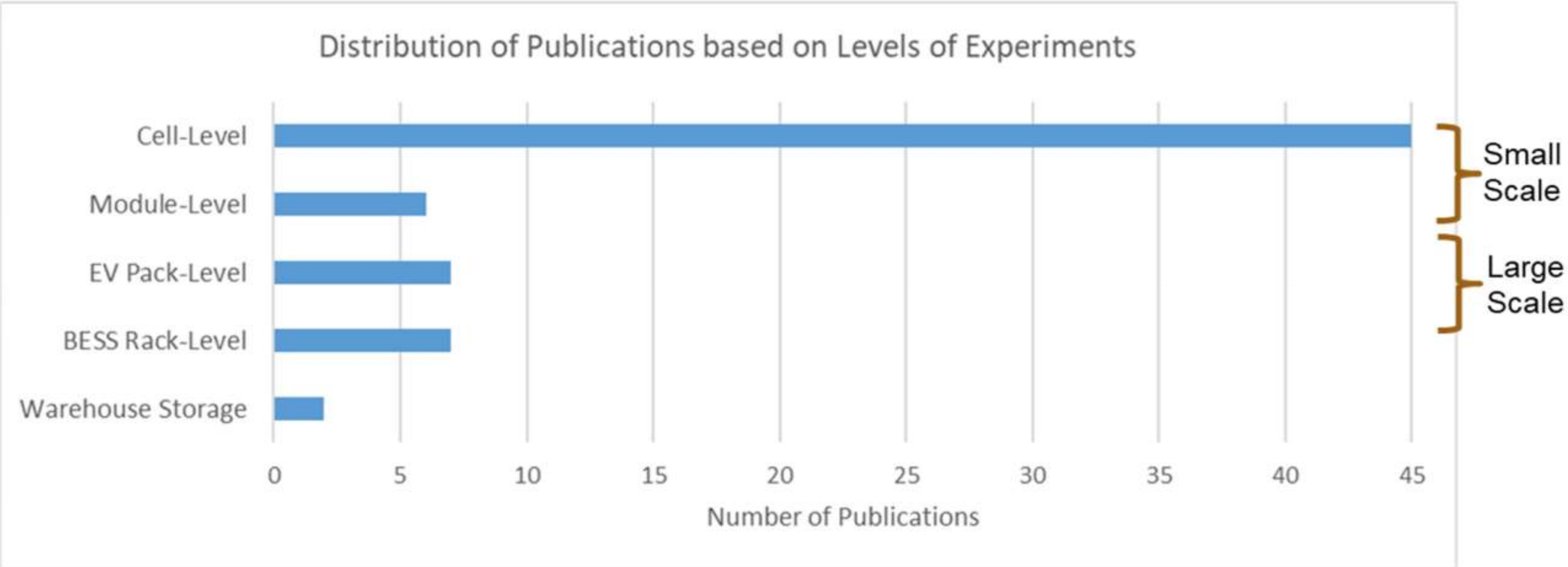
Results and Discussions

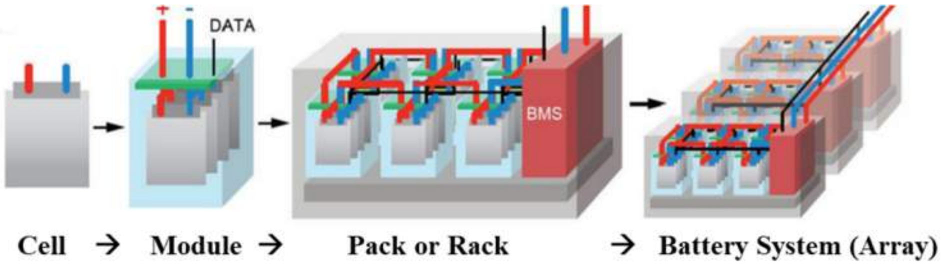
Bibliometric Analysis (65 Experimental-Based Publications)



Results and Discussions

Bibliometric Analysis

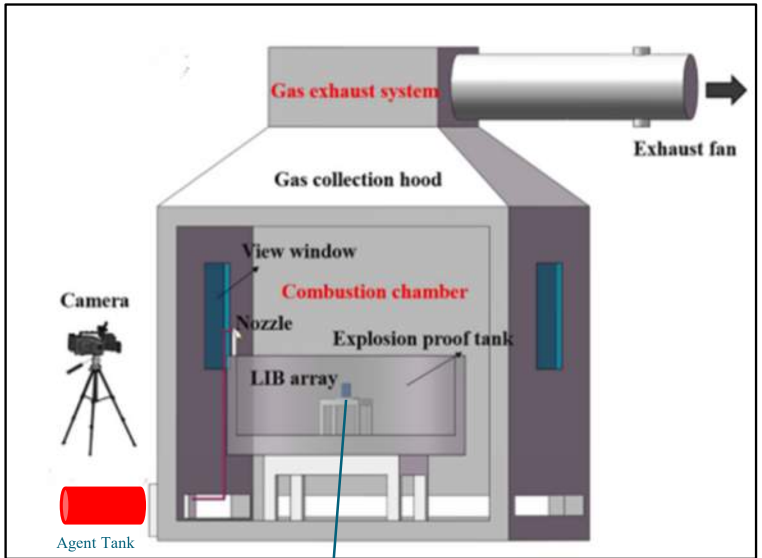


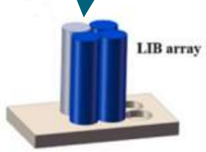


Results and Discussions

Cell-Level Experiment – Typical Experimental Setup

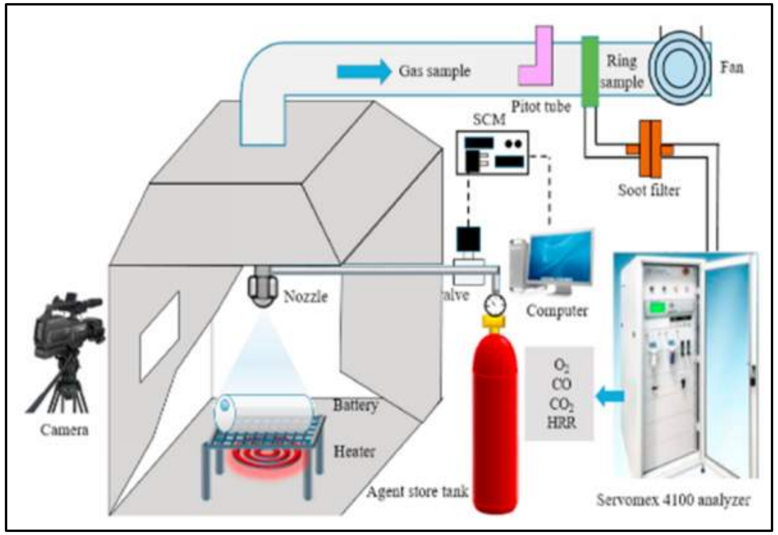
With Explosion Proof Tank





OR

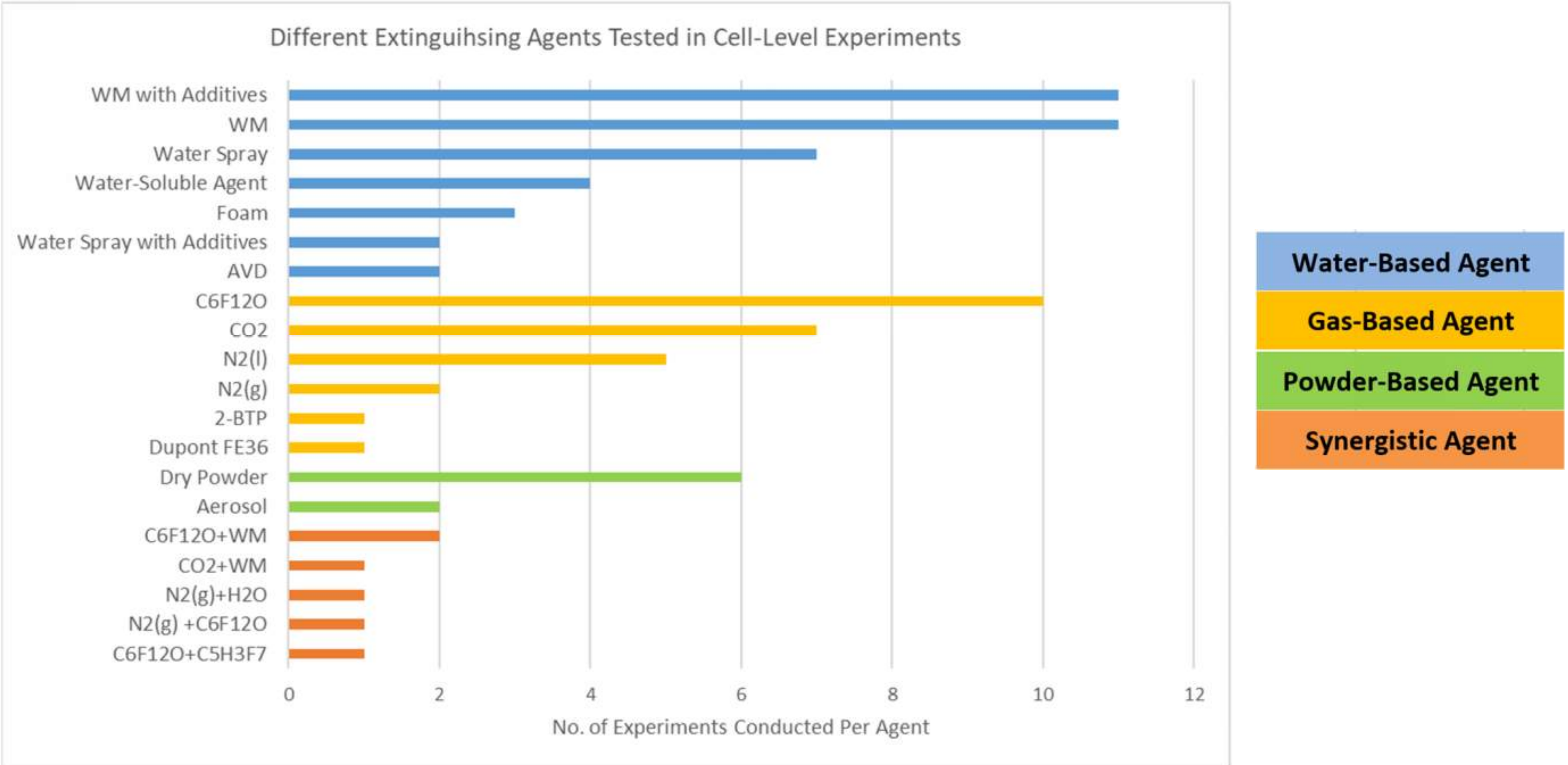
Without Explosion Proof Tank



Cells are directly exposed to Extinguishing Agents

Results and Discussions

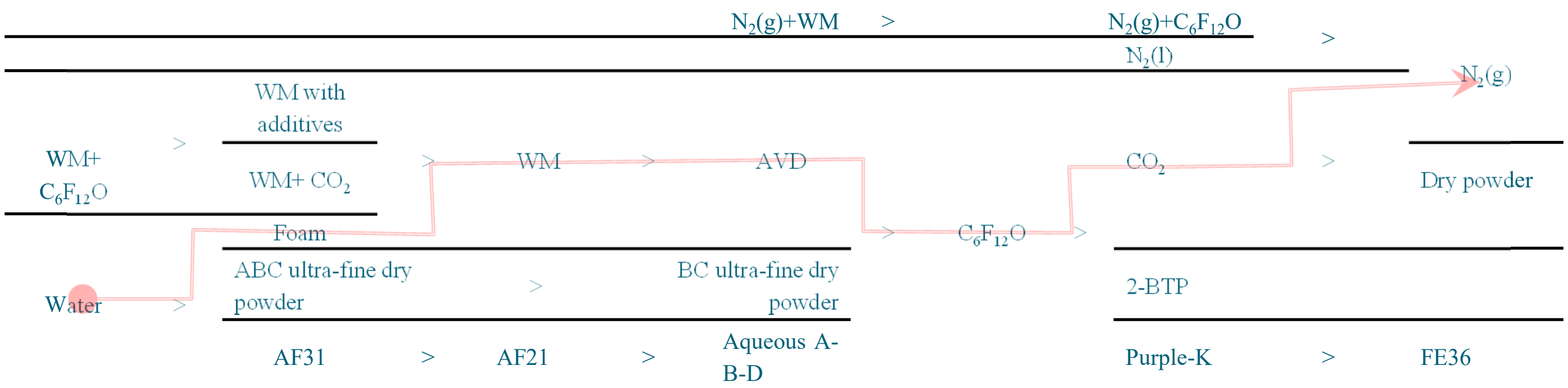
Cell-Level Experiment – Tested Agents



Results and Discussions

Cell-Level Experiment – Key Findings

- LIB cells are **directly exposed** to the extinguishing agents
- All tested agents could suppress battery fires except for CO_2 when handling high capacity NMC.
- Cooling is a key to mitigate thermal runaway.



Ranking of Cooling Effect from Left to Right
More Cooling → Less Cooling

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Results and Discussions

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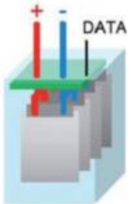
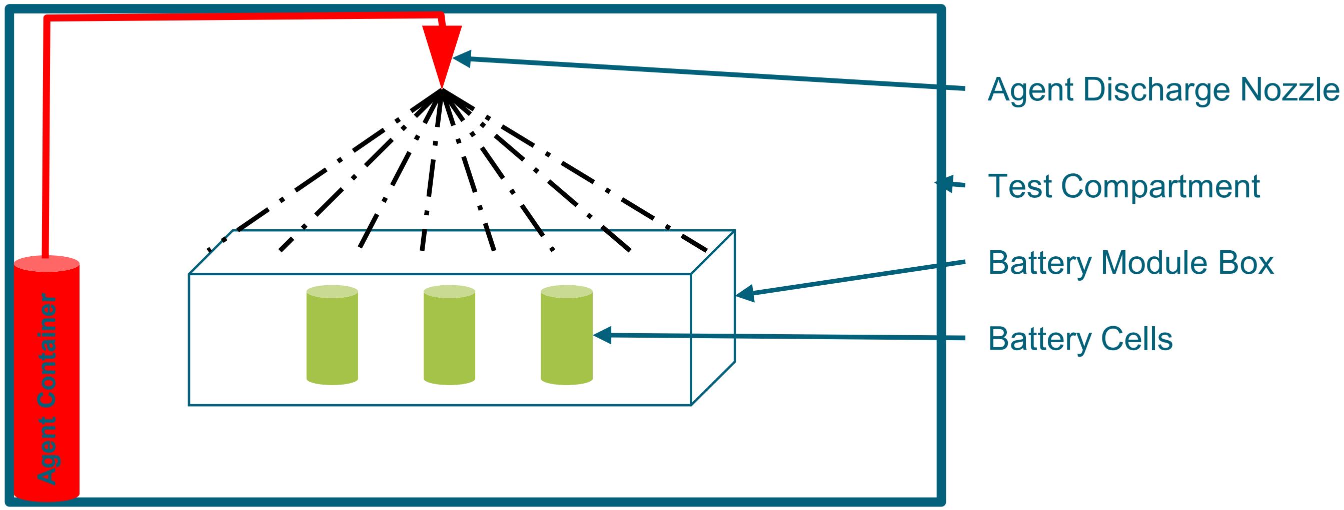
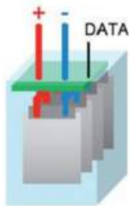


Module-Level Experiment – Typical Experimental Set-up



Reach of extinguishing agents to battery cells are
fully or partially hindered by battery module box

Results and Discussions



Module-Level Experiment – Tested Agents

- Water Mist (Low Pressure and High Pressure) – 3 Experiments
- Water Mist with Additives – 2 Experiments
- Water-Soluble Gel (FireIce) – 1 Experiment
- Foam (Pyrocool) – 1 Experiment
- Sprinkler – 1 Experiment
- Nitrogen Gas – 2 Experiments
- Aerosol - 1 Experiment

Results and Discussions

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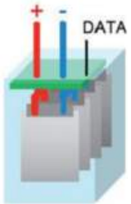


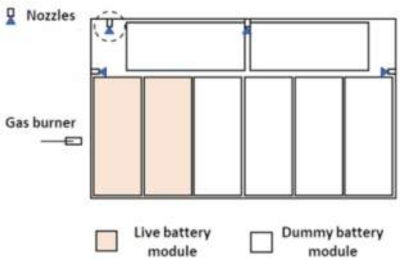
Module-Level Experiment – Key Findings

- External flame extinguishment ✓
- Internal flame extinguishment ✓✗
- Cooling to mitigate thermal runaway propagation for cells ✓✗
- Water-based agents generally exhibit better cooling effect than N_2 and aerosol
- One publication suggested if gas-based or aerosol suppression system is used, water-based suppression system can be adopted as a back-up.

Results and Discussions

EV Pack-Level Experiment – Typical Experimental Setup

Direct Internal Injection



Cells or Modules are directly exposed to Extinguishing Agents

OR

External Spray

Reach of extinguishing agents to cells or modules are hindered by battery pack cabinet

Results and Discussions

EV Pack-Level Experiment – Tested Agents

Direct Internal Injection:

- Most tested agent: $C_6F_{12}O$ (e.g. Novec1230) – 5 Experiments
- Water mist with foam additive – 1 Experiment
- Water spray – 2 Experiments
- Water spray with foam additive – 1 Experiment
- Foams (Class A Foam, Class F Foam, CAFS) – 3 Experiments
- Nitrogen gas – 1 Experiment
- AVD – 1 Experiment

External Spray:

- Water spray with foam additive – 1 Experiment

Results and Discussions

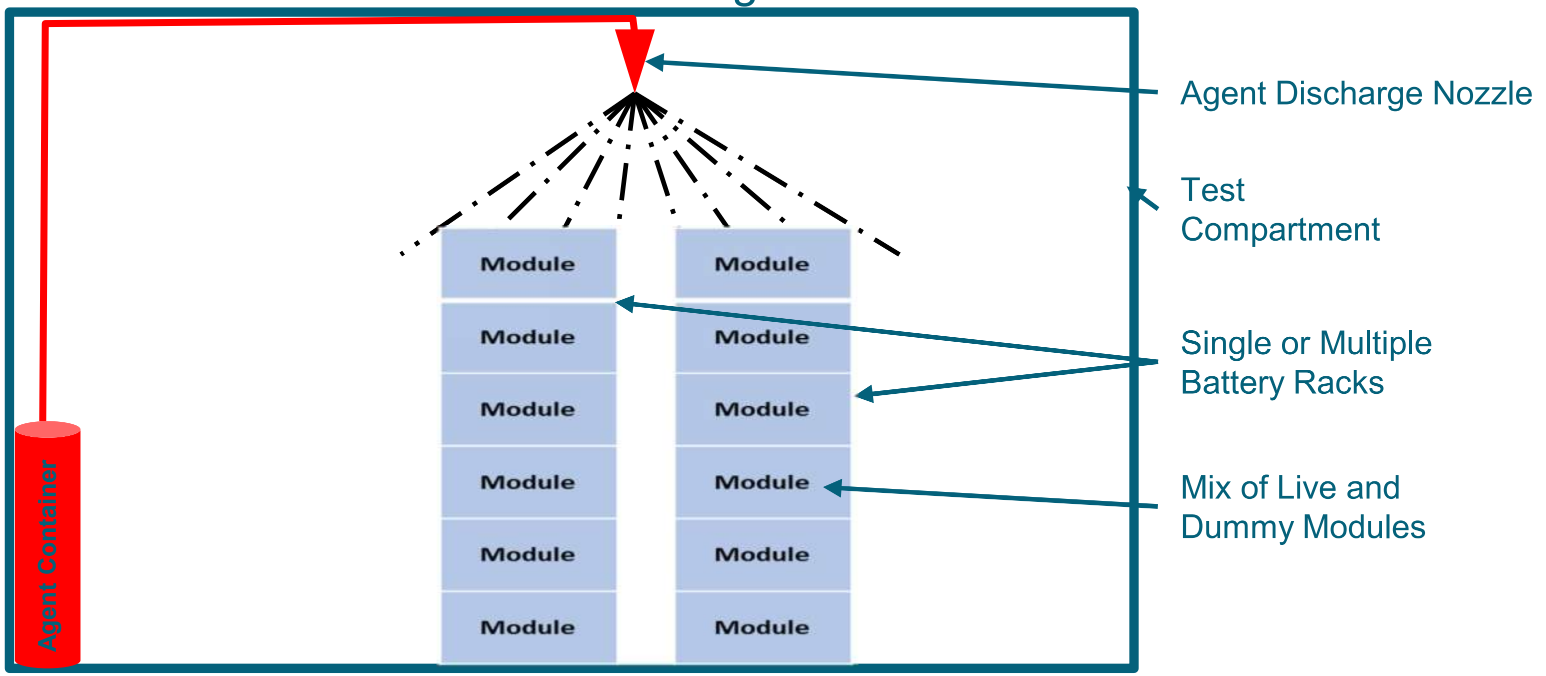
EV Pack-Level Experiment – Key Findings

- For Electric Bus, carry capacity of extinguishing agent is up to 13L
- <u>Direct Internal Injection</u>
  - All tested agents could **<u>extinguish the flame</u>**, except for the high-expansion foam
  - Water mist with foam additive has **<u>the best cooling effect</u>** to curb thermal runaway propagation.
  - Gas-based agents (N_2 and $C_6F_{12}O$) are **<u>less efficient</u>** in curbing thermal runaway propagation.
  - Similar to Cell-Level Experiment
- <u>External Spray</u>
  - Only extinguish external flame
  - No or a little contirbution to the internal cooling
  - Similar to Module-Level Experiment

Results and Discussions

BESS Rack-Level Experiment – Typical Experimental Setup

Total Flooding



Reach of extinguishing agents to battery cells are fully or partially hindered by battery module box and battery rack cabinet

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Results and Discussions

BESS Rack-Level Experiment – Tested Agents

Total Flooding

- Sprinkler with and without additive – 5 Experiments
- Low-pressure water mist with and without additive – 2 Experiments
- High-pressure water mist – 1 Experiment
- Novec1230 – 3 Experiments
- Inert gas (IG541 and N_2) – 2 Experiments
- Aerosol – 1 Experiment
- AVD – 1 Experiment

Direct Internal Injection

- Water spray – 1 Experiment
- CAFS – 1 Experiment

Results and Discussions

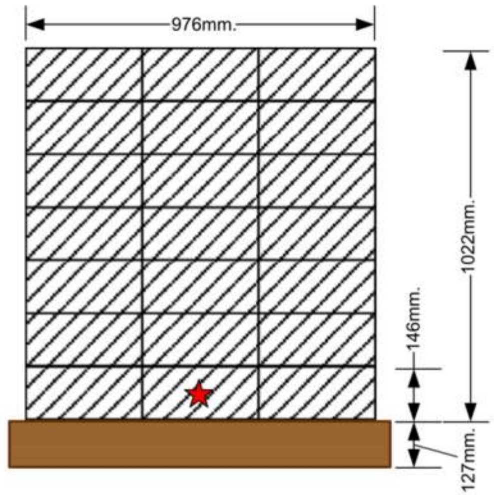
BESS Rack-Level Experiment – Key Findings

- Primary aim is to reduce module-to-module and rack-to-rack thermal runaway propagation.
- External flame extinguishment ✓✗
- Mitigation of cell-to-cell TR propagation ✗
- Early activation of extinguishing agents is preferred ✓
- Direct internal injection is more effective than total flooding, but rarely tested.
- Water-based agents have better cooling effect.

Results and Discussions

Warehouse Storage Experiment (Unique)

- Battery cells are stored in carton boxes and separated by plastic dividers.
- 80% of fire load belongs carton boxes and plastic dividers.
- Fire behaviour is similar to the cartoned unexpanded plastic.
- Only sprinkler was tested, wetting of the carton boxes is a key to minimize thermal runaway propagation.



Conclusions

How to Apply Small-Scale Experiment onto Large-Scale Experiment

Small-Scale Experiment
Cell (Agent on Cells)
Module (Direct Internal Injection – Agent on Cells)
Module (External – Agent on Module Boxes)

Large-Scale Experiment
EV Pack with Cells (Direct Internal Injection – Agent on Cells)
EV Pack with Modules (Direct Internal Injection – Agent on Module Boxes)
BESS Rack (Total Flooding – Agent on Module Boxes)
Warehouse Storage (Total Flooding – Agent on Carton Boxes)

Conclusions

- From EV Pack-Level Experiment, ranking of the cooling effect for internal thermal runaway propagation from high to low:

  WM with foam additive *> Water Spray with foam additive > [Water spray; Class A foam; Class F foam, low-expansion CAFS foam] >* $C_6F_{12}O$ *>* N_2(g)

- From BESS Rack-Level Experiment,

  HPWM with additives appears to be the best. *It can suppress the flame and provide surface and gas cooling. If gas-based or aerosol suppression systems are used, it is to be backed up by a water-based suppression system.*

- Regarding battery chemistries and capacities,

  LFP *is easier to be suppressed and cooled than NMC and LCO. LIB with* ***higher energy capacity*** *is more difficult to be suppressed and cooled, and requires more extinguishing agent.*

- Early activation of fire suppression system is always preferred.

  Hence, ***a sensitive smoke detection system and/or a good battery management system*** *are required to activate fire suppression system.*

Future Works

- Novel combination of agents {$WM+C_6F_{12}O$, $WM+CO_2$, $WM+N_2(g)$, $C_6F_{12}O+N_2(g)$, $C_6F_{12}O+C_5H_3F_7$, N_2(liquid) and AASD composited ABC dry powder} in cell-level experiments to be **further tested in pack- and rack-level experiments**.
- **More direct internal injection experiments** to be conducted for rack-level experiments.
- For EV application, **exterme ambient temperatures** to be considered for the extinguising agetns.

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3. Q&A

Thanks for your contribution to the success of SFPE Denmark

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