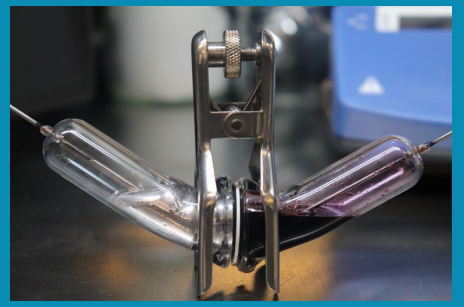
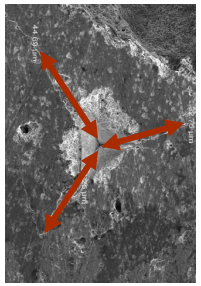
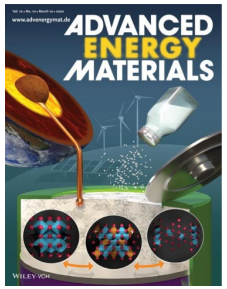
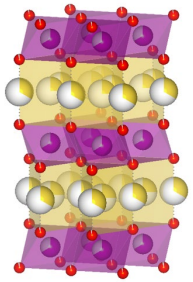
Sodium-Based Batteries









PRESENTED BY

Erik D. Spoerke, Ph.D.

Presentation ID: 400

DOE Office of Electricity Virtual Peer Review 2022
October 11-13, 2022

This work at Sandia National Laboratories is supported by Dr. Imre Gyuk through the U.S. Department of Energy Office of Electricity.

SAND No.: SAND2022-13665 C

Sodium Batteries: Diverse Technologies

Sodium batteries…

- Take advantage of globally abundant sodium…10^3 more Na than Li!
  - 6th most abundant element in Earth's crust and 4th most abundant in the oceans.
  - 5X the annual production of aluminum
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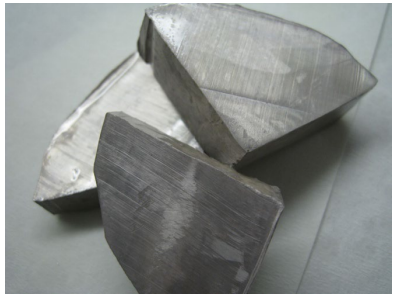

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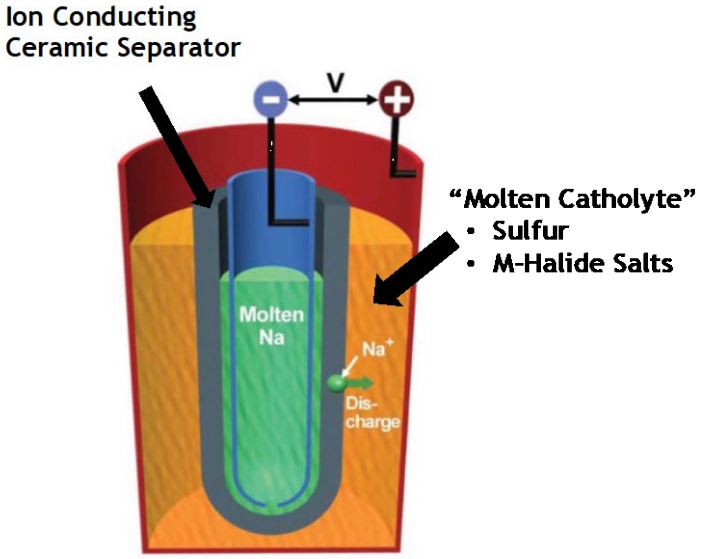

- Sodium Image from Dnn87 at English Wikipedia. - Transferred from en.wikipedia to Commons., CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3831512

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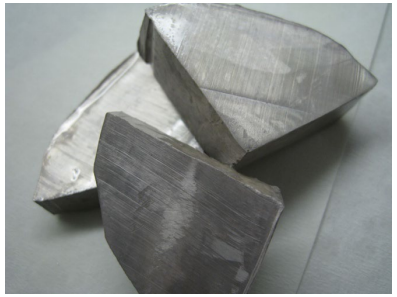

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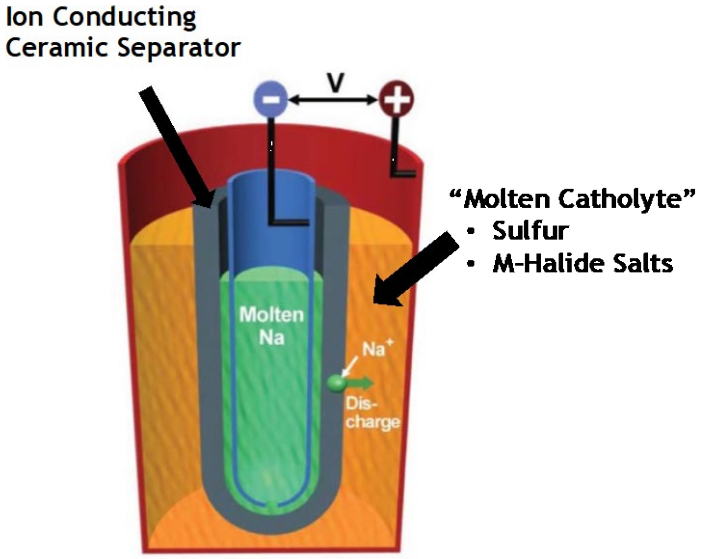

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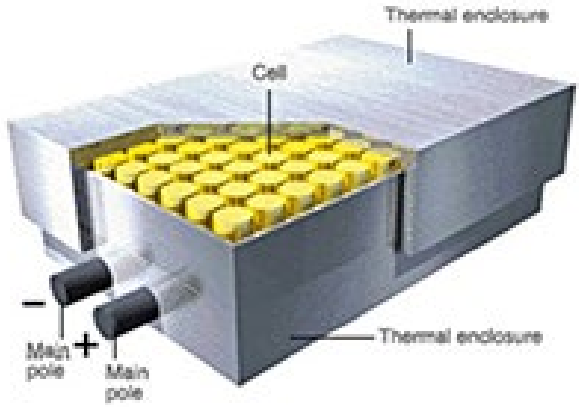
Molten Sodium Batteries: Where Does the Industry Stand?

Molten Sodium Battery Basics



*NaS battery schematic from NGK Insulators.

Na-S

NGK INSULATORS

$xS + 2Na \leftrightarrow Na_2Sx$ $(3 \leq x \leq 5)$ E_{cell} ~2.08 V at 350°C

✓ 700 MW/4.9 GWh of deployed storage in over 200 cites globally

Na-$NiCl_2$

FZSoNick

$NiCl_2$ (s) + 2Na (l) ↔ 2NaCl + Ni (s) E_{cell} ~2.58 V at 300°C

✓ Approximately 130MWh deployed storage globally

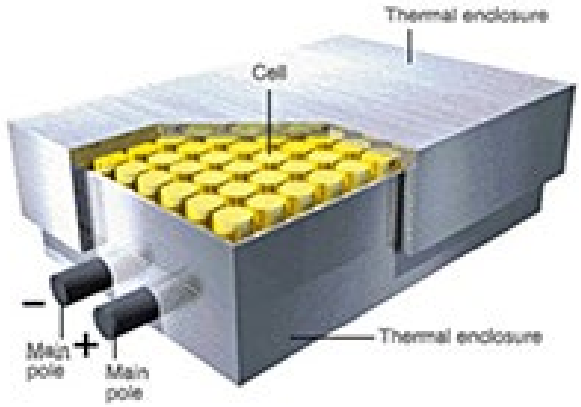
NaS and Na-$NiCl_2$ batteries are used today for Renewables Integration, Grid Services, Consumer Applications, and Microgrids

	Practical Energy Density (Wh/L)	Expected Cycle Life (cycles at 80% DOD)	Expected Lifetime (years)	Operating Temperature (°C)	Suitable Ambient Temperature (°C)	Discharge Duration (at rated power)	Round Trip Efficiency
NaS	300-400	4,000-4,500	15	300-350	-20 to + 40	6-7 hours	80%
Na-$NiCl_2$	150-190	3,500-4,500	20	270-300	-20 to +60	2-4 hours	80-85%

- Na-S takes advantage of low cost materials, but introduces some safety concerns.
- Na-$NiCl_2$ is a safer, greener chemistry, but high cost of Ni is a challenge.

High Temperature Operation Raises Costs

Molten Sodium Battery Basics



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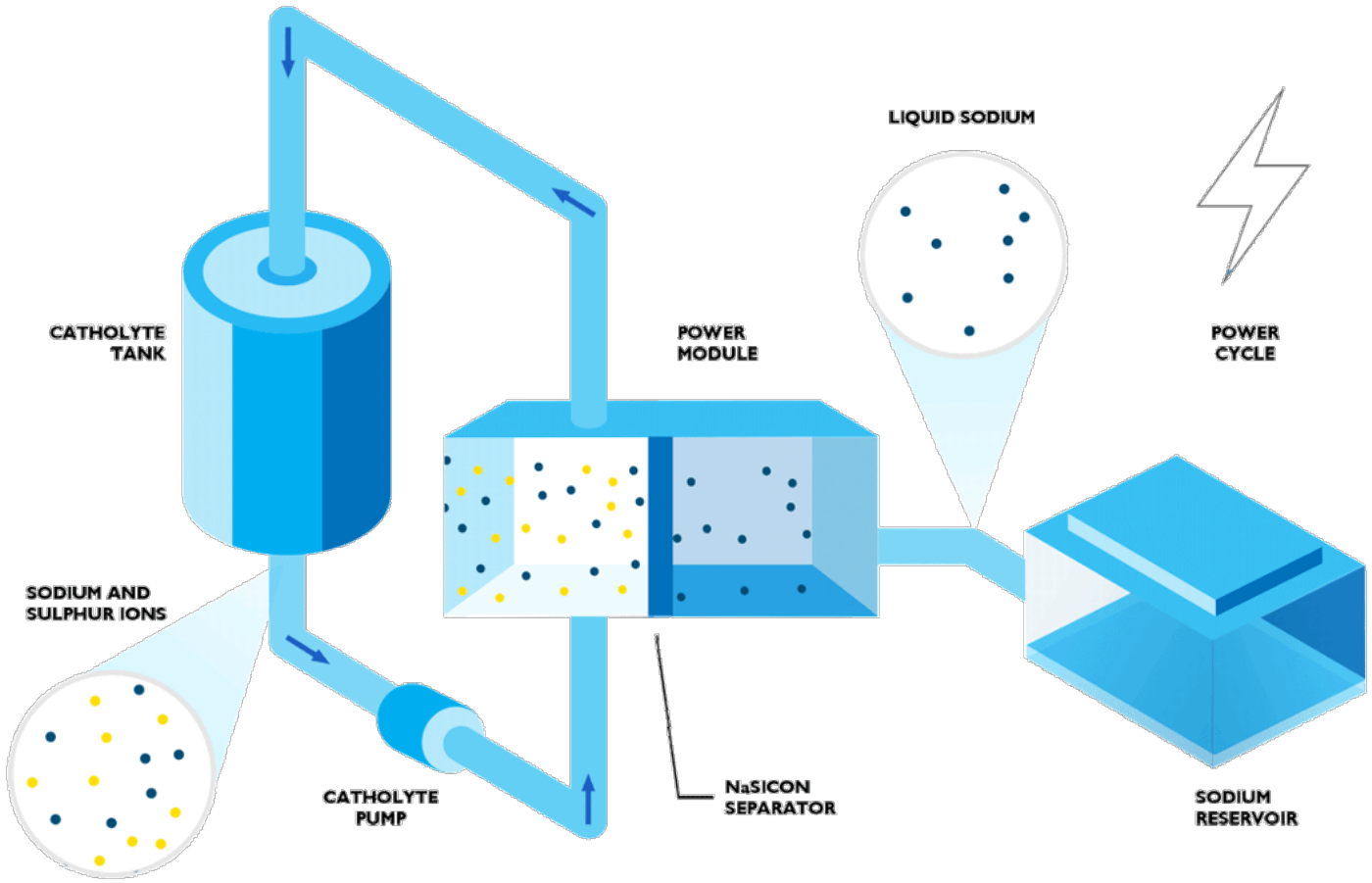
An Na-S Flow Battery in Development



ENLIGHTEN®

Enlighten Innovations (Canada, U.S.) has developed a long duration energy storage (LDES) *flow* system:

- Utilizes NaSICON solid-state separator
- Low-cost Na-S chemistry
- Decouples power and energy.
- Claim cost-competitive with Li-ion at 7+ hours of storage.

NaSICON: Nominally $Na_3Zr_2PSi_2O_{12}$

Further ZEBRA Battery Deployment?

Zhejiang Lvming Energy (Subsidiary of the Chilwee Group (China)) acquired GE's Durathon technology and has announced plans to begin manufacturing these batteries as part of a more comprehensive battery manufacturing effort.

The Fraunhofer Institute for Ceramic Technologies and Systems (IKTS) in Germany has also developed their own Na-$NiCl_2$ battery platform (Cerenergy®) for grid-based energy storage. They advertise an effort to adapt the cell design and improve materials chemistry in these systems to reduce cost, but at present, these systems are not widely deployed.

- 100 Ah cells have now been realized for the first time, (versus 38 Ah cells typically available on the market).

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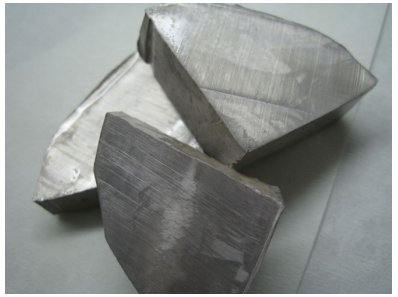

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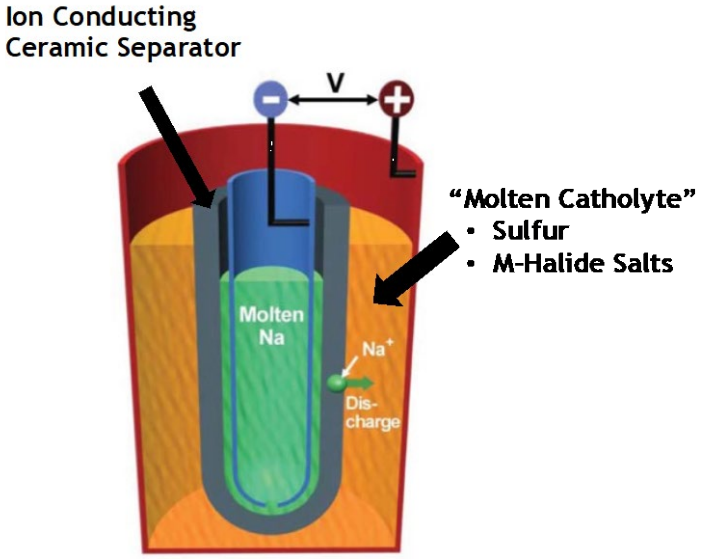
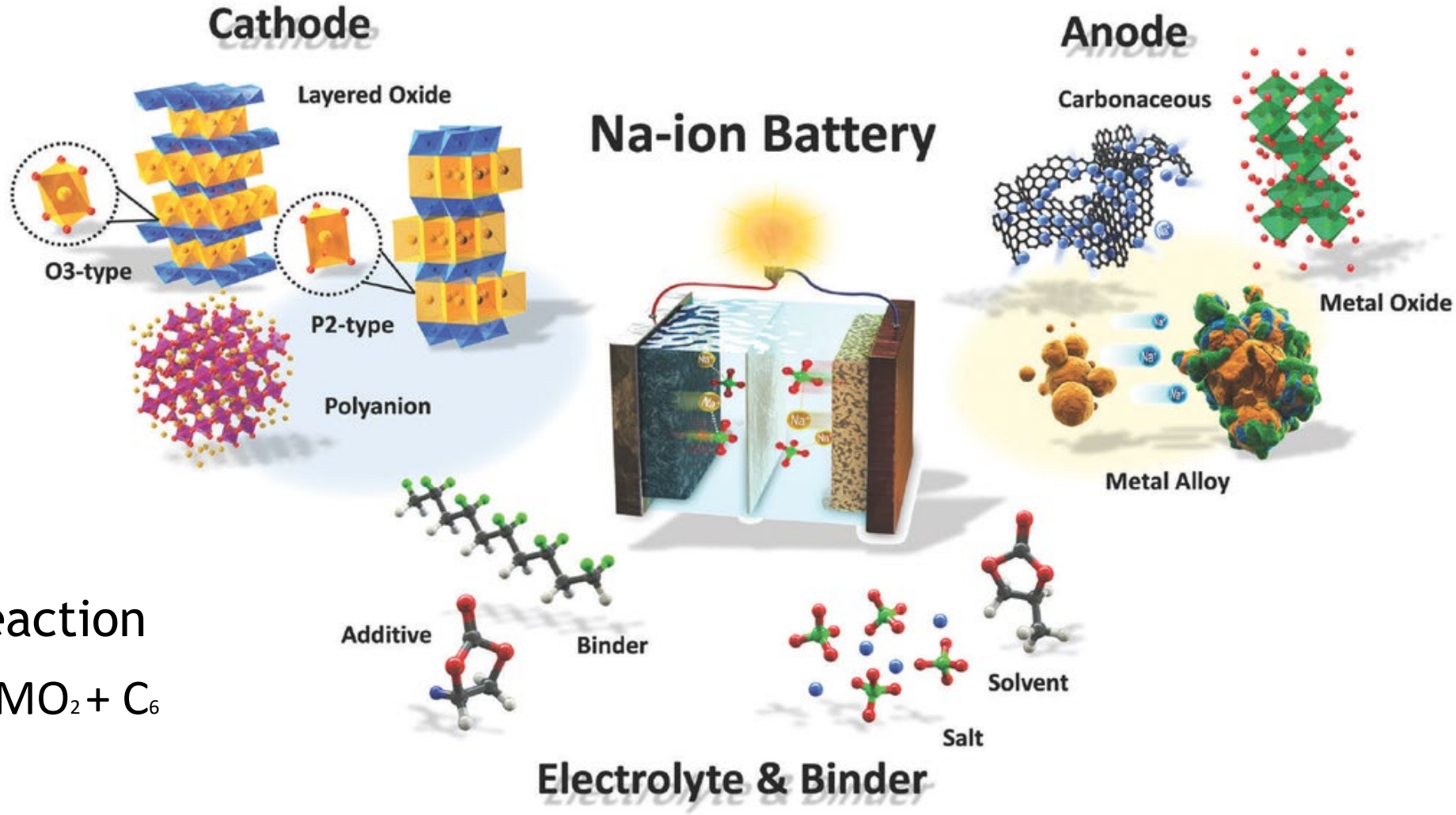


Na-Ion Batteries (NaIBs, NIBs, NiBs)

A possible alternative to Li-Ion?

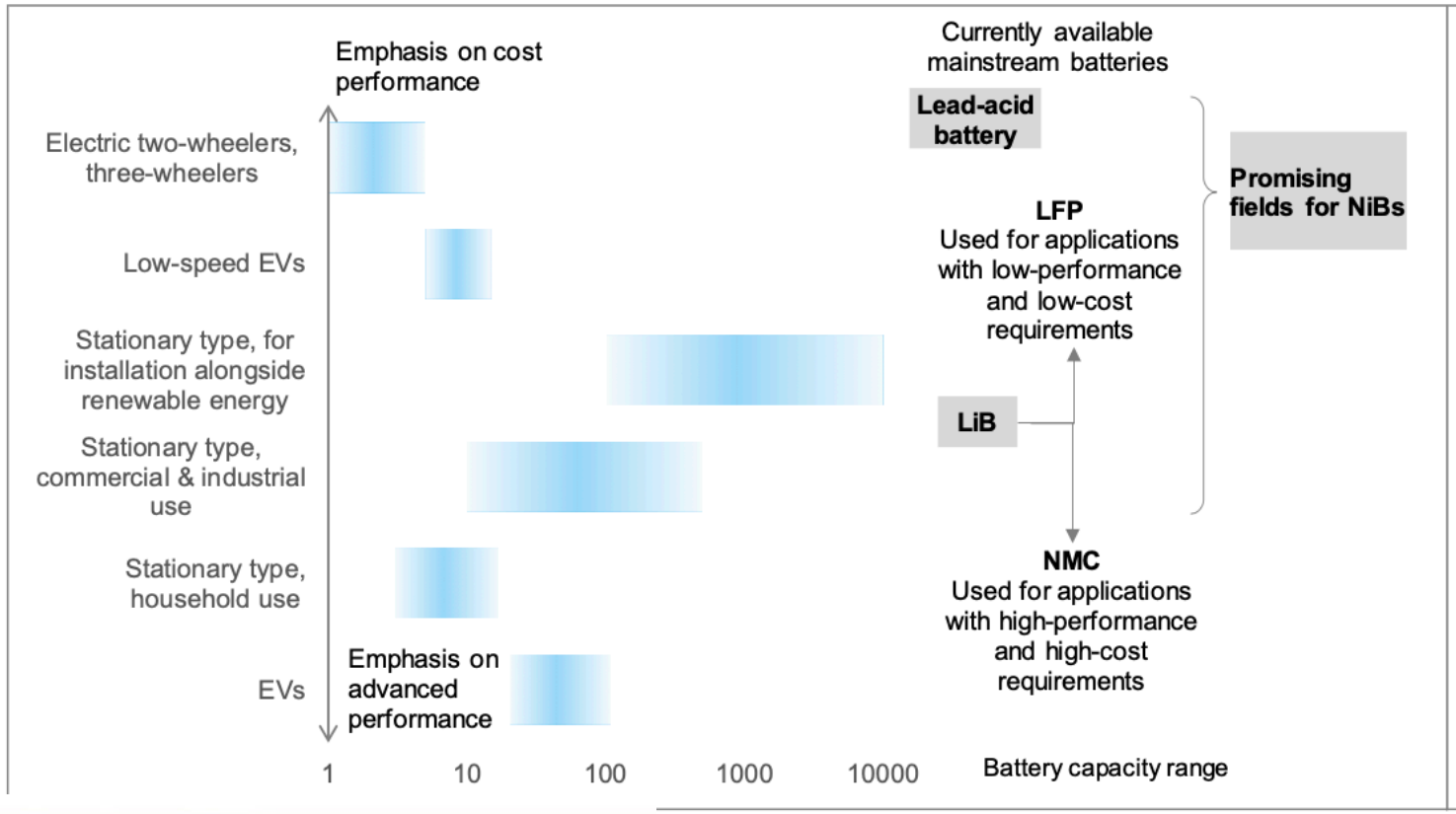


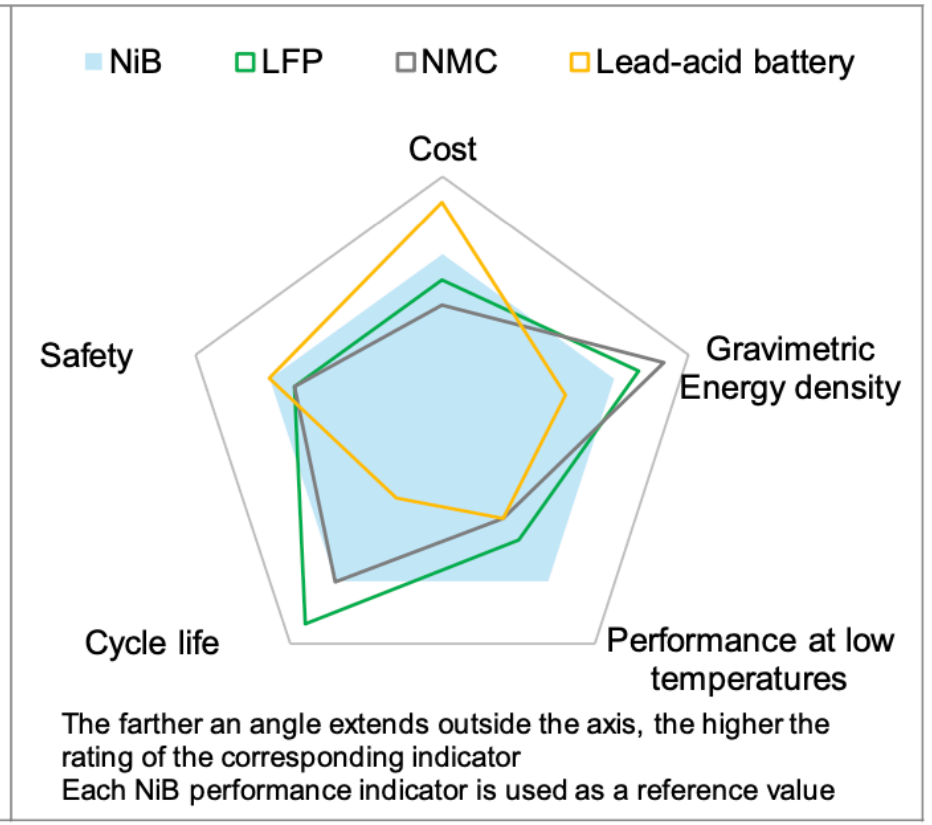
Overall Discharge Reaction

$Na_xC_6 + Na_{1-x}MO_2 \rightarrow NaMO_2 + C_6$

ACS Energy Lett. 2020, 5, 3544−3547

Na-Ion Battery (NaIB, NIB, NiB) Opportunity Space





Mitsui & Co., June 2022

Application of NIBs

- Projected lower cost, simplified cell architectures, and improved safety are benefits of NaIBs.
- While NaIBs are unlikely to replace LiBs for high power (e.g., EV) applications, low-speed vehicles and stationary storage is likely to be a growing market.
  - Market in 2021 was estimated near $650M
  - CAGR is estimated at 11.2%
  - 2028 market is expected to reach $2.8B

https://www.fnfresearch.com/sodium-ion-battery-market

Emerging/Evolving Sodium Ion Batteries

Several manufacturers of NaIBs are in development or early production/deployment of Li-Ion “Analogs”:

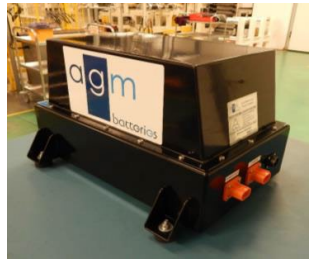
- Contemporary Amperex Technology Co. (CATL, China) –debuted initial Na-ion line in 2021, planning “basic industrial chain” in 2023.
  - Developing hybrid Li-ion, Na-ion system.
- Faradion (UK) – produced over 50kWh of prototypes with sodium-nickel layer oxide cathodes since 2011).
  - Acquired by Reliance Industries (India) with aims at Gigafabs in India in 2024.
- AGM Batteries Ltd. (AMTE Power) – Multiple battery chemistries manufactured/assembled. Targeting GW-scale production.
- HiNa Battery Technology Co. (China) – Over 10,000 prototypes, currently demonstrating 100kWh prototype with anthracite anode and Co,Ni-Free layered metal oxide cathode.
- Tiamat Energy (France - Spin-Off of CEA/CNRS) Focus on mobile and stationary products with fast charging, high cycle-life 18650 cells.

CATL

faradion

Reliance Industries Limited

agm batteries



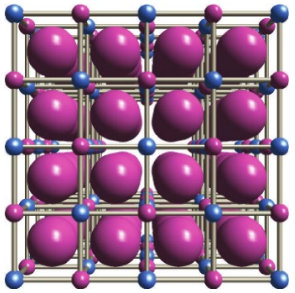
Na 中科海钠 HiNa BATTERY

TIAMAT

Alternative Sodium Ion Batteries on the Horizon

Prussian blue analogs (PBAs)

- Utilize ferric ferrocyanide salts as electroactive materials (mostly cathodes)
- Natron Energy is developing NaIBs with PBAs aimed at 8kW units for data server backup power.
  - With Clarios (Michigan, Li-ion facility) aiming for 600MW annually starting in 2023.
- As many as 50,000 cycles projected!
- Altris (Sweden) (Focus on sustainable materials) – Prussian White (Fully Reduced and sodiated PB) (Pilot Line underway)



Y. Moritomo, *Adv. Cond. Matt. Phys.* (2013) 539620.

"Salt-water batteries"

- Carbon-titanium phosphate composite Anode, sodium perchlorate aqueous electrolyte, manganese oxide cathode.
- BlueSky Energy (Austria) – "Greenrock" Saltwater Battery (Aquion technology through BenAn Energy))
  - 5kWh-30kWh systems for renewables, emergency power, off-grid solutions
  - 15 year lifespan, 5,000 cycles, -5^{o}Cto +50^{o}C operation, safe and environmentally friendly

https://www.bluesky-energy.eu/en/greenrock-home-2/

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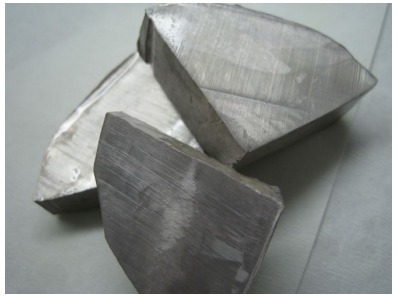

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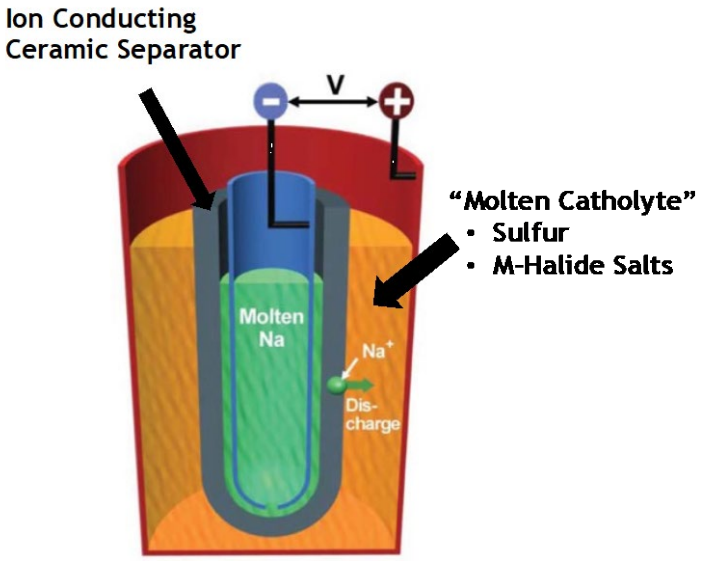
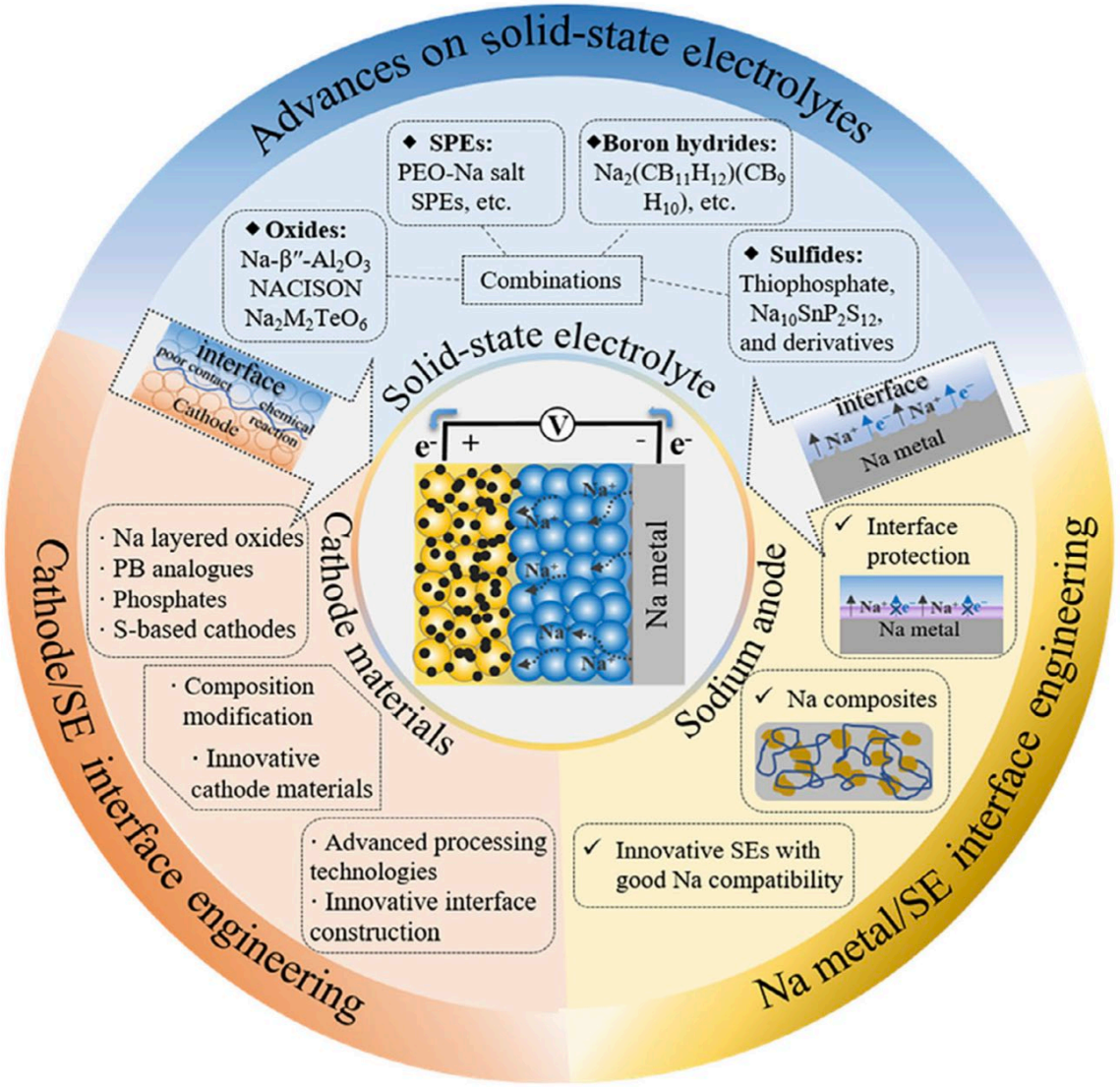


- Sodium Image from Dnn87 at English Wikipedia. - Transferred from en.wikipedia to Commons., CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3831512

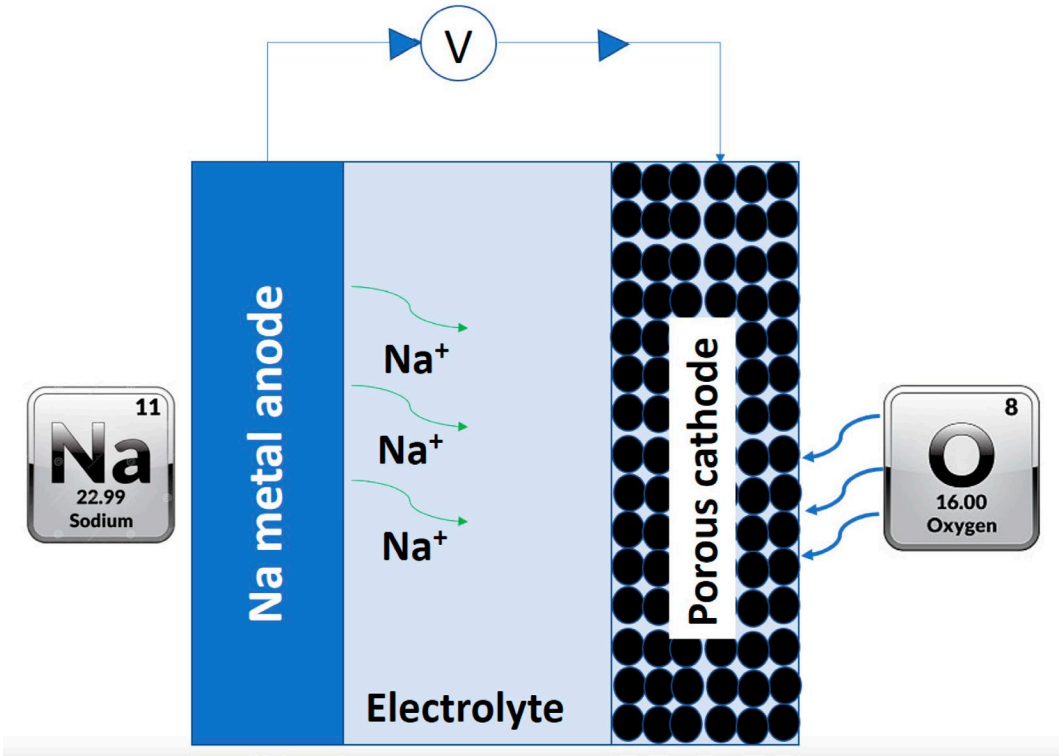
Solid State Sodium Batteries: In Development



- Promise exists
  - High energy density
  - Abundant materials
  - Low cost
- Challenges remain
  - Low rate capabilities
  - Sodium electrode stability
  - Interface control
  - Cathode performance

H-L Yang, *et al.* (2021) *Adv. Energy Sustainability Res.* **2**, 2000057

Sodium-Air Batteries: In Development



$4Na + O_2 + 2H_2O \leftrightarrow 4NaOH \qquad E_0 = 3.11\ V$

Or

$2Na + O_2 \leftrightarrow Na_2O_2 \qquad E_0 = 2.33V$

- Theoretical energy density: 3164 Wh/kg
- Specific capacity 1166 mAh/g
- Organic, Inorganic (aqueous) electrolytes
- Solid sodium, molten sodium

Challenges:

- Catalyst Development
- Anode protection
- Dendrite elimination

N. Chawla, et al. *Electronics* **2019**, *8*(10), 1201

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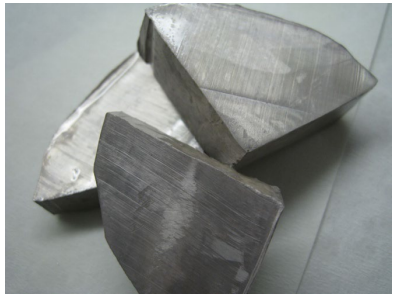

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   - B. **Sodium Metal Halide (Traditional ZEBRA Batteries)**
     - ✓ ***New ZEBRA Batteries (Ni-free, operate below 200°C) - PNNL, RIST***
     - ✓ ***Low Temperature (~100°C) Na-NaI Batteries - SNL***
2. Sodium Ion Batteries (NaIBs)
   - ***A. "Li-Ion Analogs" PNNL, ORNL***
   - B. Prussian Blue Analogs
   - ***C. Salt-Water Batteries - ORNL***
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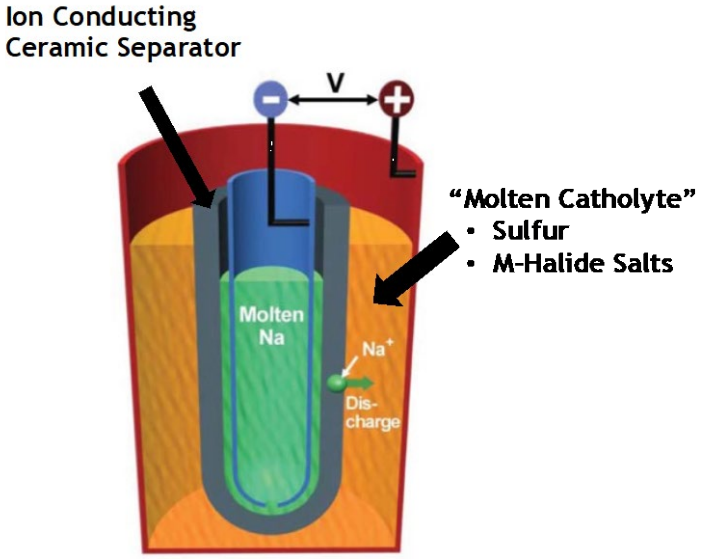

Please Don't Miss the Posters!

Institution	Title	Presenting Author
Sandia National Laboratories	*Experimental and Modeling Studies of Metal Halide Catholyte and Cathode Materials to Enable Low-Temperature Molten Sodium Batteries*	Adam Maraschky (Erik Spoerke)
University of Kentucky/Sandia National Laboratories	*Sodium Penetration through Solid State NaSICON Electrolytes under High Current*	Ryan Hill and Y-T Cheng
Sandia National Laboratories	*Al-Fe Based Molten Salts for Long Duration Energy Storage*	Stephen Percival
RIST/PNNL	Interfacial Resistance Reduction via Enhanced Na(l) Wetting in Na β"-Al2O3 Batteries at Lower Temperatures	Choongmo Yang
RIST/PNNL	Nickel-Ferronickel Composite as a Cathode Material for Low Cost Sodium-Metal Chloride (Na-MCl2) Batteries	Keeyoung Jung
Penn State University	Stable All-Solid-State Sodium-Sulfur Batteries for Low-Temperature Operation Enabled by Sodium Alloy Anode and Confined Sulfur Cathode	Li-Ji Jhang

On to the Main Show: Presentations

Session 4: Sodium Batteries

Time	Presentation	Presenter	Organization	Presentation #
8:50 – 8:57am	Sodium-Based Batteries	Erik Spoerke (Session Lead)	Sandia National Laboratories	400
8:57 – 9:12am	Low Temperature Molten Sodium Batteries	Leo Small (presented by Erik Spoerke)	Sandia National Laboratories	401
9:12 – 9:25am	Intermediate Temperature Sodium Battery Technologies	Guosheng Li	Pacific Northwest National Laboratory	402
9:25 – 9:35am	Polymer-Sealed Planar Na-$NiCl_2$ Batteries at 180^{0}C	Keeyoung Jung	Research Institute of Industrial Science and Technology (RIST)	403
9:35 – 9:50am	Sodium based Solid Electrolytes and Na-Metal	David Mitlin	University of Texas at Austin	404
9:50 – 10:05am	Sodium Battery Research at ORNL	Mengya Li	Oak Ridge National Laboratory	405
10:05 – 10:20am	Sodium Ion Battery Development	Xiaolin Li	Pacific Northwest National Laboratory	406
10:20 – 10:35am	Q&A			

Backup Slide: Commercial Molten Sodium Battery Deployments

NGK Insulators Sodium-Sulfur (NAS) batteries:

- Deployed 700 MW/4.9 GWh of storage in over 250 sites around the world.
- World's first commercialized battery system capable of megawatt-level electric power storage.
  - Up to 210 MW/1.5GWh in TEPCO Area, Japan
- Strong record of safety and reliability
  - Systems demonstrated operation for >10 years!
- Renewables Integration and Power Plants
  - Peaker Plant Replacement
- Grid Solutions (Ancillary Services, Investment Deferral)
- Long-Duration Storage Applications
- Consumers (Industrial, Commercial & Residential)
- Microgrids (Including Islands, Remote Grids)

https://www.ngk-insulators.com/en/product/nas/solutions/index.html

FZSoNick ZEBRA ($Na-NiCl_2$) batteries:

- Energy Backup (48-110V)
- Sustainable Mobility (300-700V)
- Energy Storage (48V and 620V)
- Approximately 130MWh deployed storage
- Energy Storage Systems
  - Renewables Integration
  - Microgrids
  - Grid Services (e.g., grid balancing, voltage regulation)
- Backup storage capacity (e.g., telecommunications)
- Environmentally friendly and *recyclable*
- “No maintenance”
- Passed UL9540A: "Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems"

https://www.fzsonick.com