U.S.–China Clean Energy Research Center
中美清洁能源研究中心

U.S.-China Clean Energy Research Center

Clean Vehicle Consortium (CVC)

Ouyang Minggao (China Director, Tsinghua University)

Huei Peng (CVC1 U.S. Director, University of Michigan)

Don Hillebrand (CVC2 U.S. Director, Argonne National Laboratory)

2016.7.1 Beijing China

U.S.–China Clean Energy Research Center
中美清洁能源研究中心

Outline

CVC1.0 Achievements

CVC2.0 Research Plan

CVC2.0 Initial Results

U.S.–China Clean Energy Research Center
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CVC1.0 Academic Partners

U.S.

University of Michigan

The Ohio State University

Massachusetts Institute of Technology

Sandia National Laboratories

Oak Ridge National Laboratory

Argonne National Laboratory

jbei Joint BioEnergy Institute

China

Tsinghua University

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CVC1.0 Industrial Partners

U.S.

Ford DELPHI DENSO EATON

TOYOTA HONDA pjm TE connectivity Aramco Services Company

China

SAIC GEELY JAC CAERI CATARC 上汽通用五菱 SGMW

LISHEN Potevio JJE ECTEK KeyPower 科易动力

U.S.–China Clean Energy Research Center
中美清洁能源研究中心

Organization of CVC 1.0

Director:
Huei Peng

Deputy Director:
Jun Ni

Director:
OUYANG Minggao

Deputy Director:
Wang Hewu

Deputy Director:
Qiu Xinping

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CVC1.0 Annual Meetings

Kick-off meeting, Michigan, Jan 2011

1st annual meeting, Beijing, Oct 2011

2nd annual meeting, Michigan, Aug 2012

3rd annual meeting, Beijing, Aug

4th annual meeting, Michigan, Aug 2014

5th annual meeting, Beijing, Aug.,2015

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U.S.-China Electric Vehicle and Battery Workshop

- 1st:Sept. 2009 in Beijing, China
- 2nd:Sept. 2010 in Chicago, USA
- 3rd:March 2011 in Beijing, China
- 4th:Aug. 2011 in Chicago, USA
- 5th:April 2012 in Hangzhou, China
- 6th:Aug. 2012 in Boston, USA
- 7th:April 2013 in Berkeley, USA
- 8th:Sept. 2013 in Chengdu, China
- 9th: Aug. 2014 in Seattle, USA
- 10th: March 2015 in Beijing, China
- 11th : May 2016 in Denver, USA

CVC1.0

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Personnel Exchange

Name	Status	TA	Date
Caihao Wang	Ph.D. (UM)	TA2	05/11-06/11
Xiankun Huang	Ph.D. (THU)	TA1	07/11-08/12
Xiaowu Zhang	Ph.D. (UM)	TA2	06/12-06/12
Xuerei Ma	Ph.D. (SJTU)	TA2	12/12-12/13
Mingxuan Zhang	Ph.D. (THU)	TA2	01/13-02/13
Cong Hou	Ph.D. (THU)	TA2	06/13-08/13
Yugong Luo	Prof. (THU)	TA5	08/13-08/14
Xuning Feng	Ph.D. (THU)	TA3	12/13-12/14
Tze-You Song	Ph.D. (THU)	TA1	12/13-12/14
Tanjin He	Ph.D. (THU)	TA2	01/14-06/14
Lin-Jun Song	Prof. (BHU)	TA6	06/13-06/14
Yong Xia	Prof. (THU)	TA4	06/14-12/14
Han Hao	Prof. (THU)	TA6	06/14-06/15
Xiaobin Zhang	Ph.D. (THU)	TA6	03/15-03/16

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CERC-CVC 1.0 Thrust Areas

1. Advanced Batteries System

2. Clean Combustion and Thermal Recovery

3. Vehicle Electrification

4. Lightweight Structures

5. Vehicle-Grid Integration

6. Energy Systems Analysis, Technology Roadmaps

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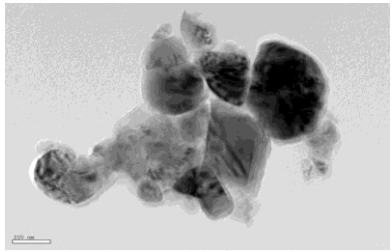
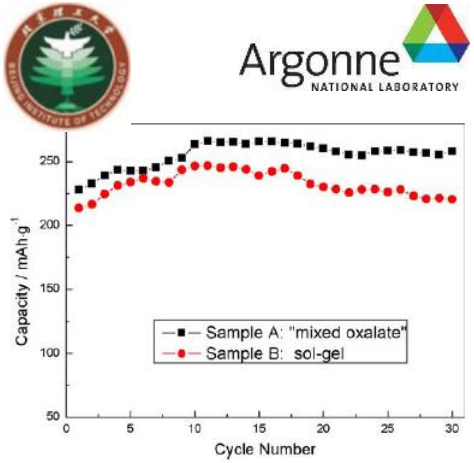
High Energy Density Chemistries

University of Michigan

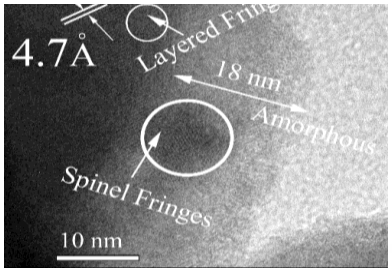
Argonne National Laboratory



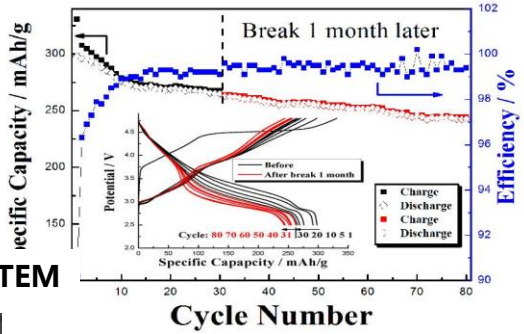
富锂锰基正极材料SEM照片

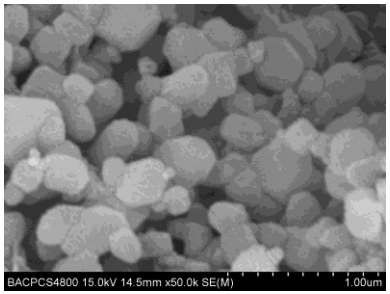


Research produced computational tools and models to identify and characterize the mechanisms limiting performance in some promising, high-energy-density chemistries—primarily lithium-air, lithium-sulfur, and sodium-air。

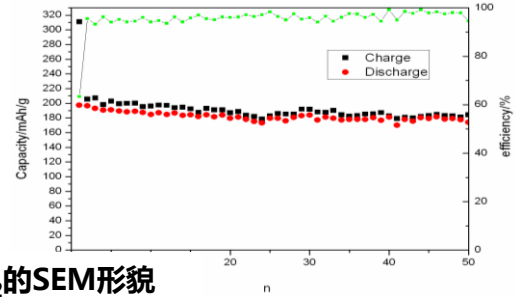


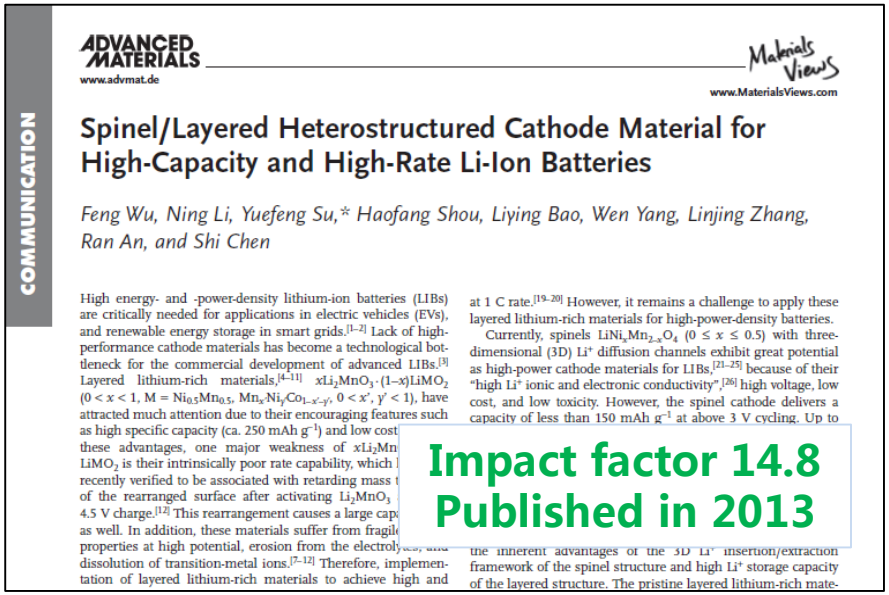
包覆氧化锰富锂锰基正极材料TEM





合成$Li[Li_{0.1}Mn_{0.495}Ni_{0.405}]O_2$的SEM形貌





COMMUNICATION

ADVANCED MATERIALS
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Materials Views
www.MaterialsViews.com

Spinel/Layered Heterostructured Cathode Material for High-Capacity and High-Rate Li-Ion Batteries

Feng Wu, Ning Li, Yuefeng Su, Haofang Shou, Liying Bao, Wen Yang, Linjing Zhang, Ran An, and Shi Chen*

High energy- and -power-density lithium-ion batteries (LIBs) are critically needed for applications in electric vehicles (EVs), and renewable energy storage in smart grids.[1–2] Lack of high-performance cathode materials has become a technological bottleneck for the commercial development of advanced LIBs.[3] Layered lithium-rich materials,[4–11] $xLi_2MnO_3 \cdot (1-x)LiMO_2$ ($0 < x < 1$, M = $Ni_{0.5}Mn_{0.5}$, $Mn_xNi_yCo_{1-x'-y'}$, $0 < x', y' < 1$), have attracted much attention due to their encouraging features such as high specific capacity (ca. 250 mAh g^{-1}) and low cost

these advantages, one major weakness of xLi_2Mn

$LiMO_2$ is their intrinsically poor rate capability, which

recently verified to be associated with retarding mass

of the rearranged surface after activating Li_2MnO_3

4.5 V charge.[12] This rearrangement causes a large cap

as well. In addition, these materials suffer from fragil

properties at high potential, erosion from the electrolyte, and dissolution of transition-metal ions.[7–12] Therefore, implementation of layered lithium-rich materials to achieve high and

at 1 C rate.[19–20] However, it remains a challenge to apply these layered lithium-rich materials for high-power-density batteries.

Currently, spinels $LiNi_xMn_{2-x}O_4$ ($0 \le x \le 0.5$) with three-dimensional (3D) Li^+ diffusion channels exhibit great potential as high-power cathode materials for LIBs,[21–25] because of their "high Li^+ ionic and electronic conductivity",[26] high voltage, low cost, and low toxicity. However, the spinel cathode delivers a capacity of less than 150 mAh g^{-1} at above 3 V cycling. Up to

the inherent advantages of the 3D Li^+ insertion/extraction framework of the spinel structure and high Li^+ storage capacity of the layered structure. The pristine layered lithium-rich mate-

Impact factor 14.8
Published in 2013

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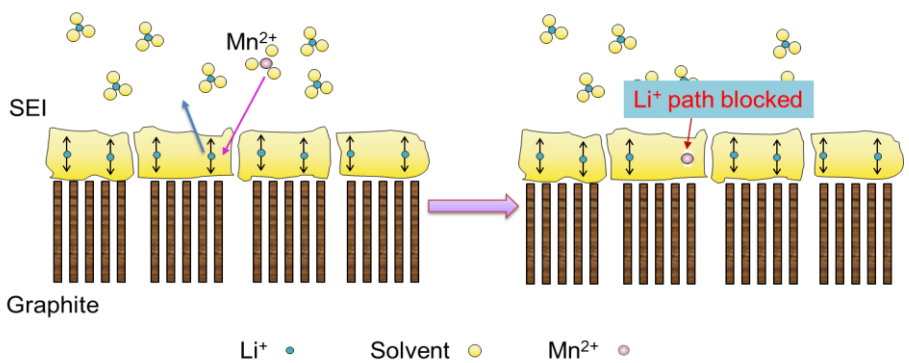
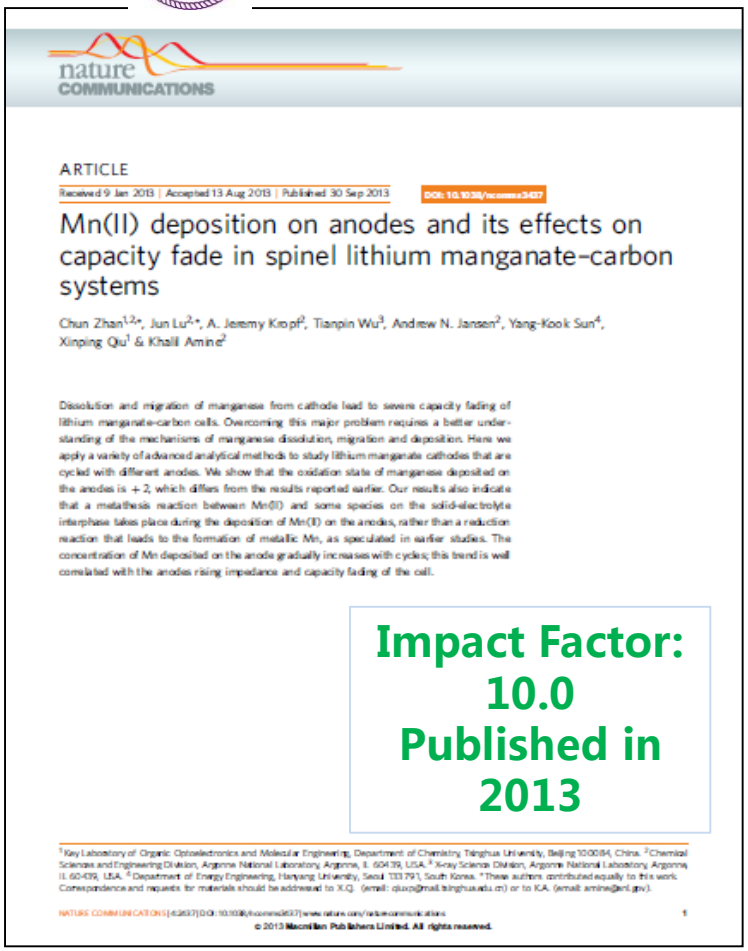
Battery Capacity Fade Mechanism

Important breakthrough in the fundamental science of Lithium battery performance degradation. Joint publication in "Nature Communications" in 2013.

- Denying electrochemical reduction mechanism
  $Mn^{2+} + 2e \rightarrow Mn$
- Raise other possibility: Ion exchange model





nature COMMUNICATIONS

ARTICLE

Received 9 Jan 2013 | Accepted 13 Aug 2013 | Published 30 Sep 2013

Mn(II) deposition on anodes and its effects on capacity fade in spinel lithium manganate–carbon systems

Chun Zhan[1,2*], Jun Lu[2*], A. Jeremy Kropf[2], Tianpin Wu[3], Andrew N. Jansen[2], Yang-Kook Sun[4], Xinping Qiu[1] & Khalil Amine[2]

Dissolution and migration of manganese from cathode lead to severe capacity fading of lithium manganate–carbon cells. Overcoming this major problem requires a better understanding of the mechanisms of manganese dissolution, migration and deposition. Here we apply a variety of advanced analytical methods to study lithium manganate cathodes that are cycled with different anodes. We show that the oxidation state of manganese deposited on the anodes is +2, which differs from the results reported earlier. Our results also indicate that a metathesis reaction between Mn(II) and some species on the solid-electrolyte interphase takes place during the deposition of Mn(II) on the anodes, rather than a reduction reaction that leads to the formation of metallic Mn, as speculated in earlier studies. The concentration of Mn deposited on the anode gradually increases with cycles; this trend is well correlated with the anodes rising impedance and capacity fading of the cell.

Impact Factor: 10.0
Published in 2013

[1] Key Laboratory of Organic Optoelectronics and Molecular Engineering, Department of Chemistry, Tsinghua University, Beijing 100084, China. [2] Chemical Sciences and Engineering Division, Argonne National Laboratory, Argonne, IL 60439, USA. [3] X-ray Science Division, Argonne National Laboratory, Argonne, IL 60439, USA. [4] Department of Energy Engineering, Hanyang University, Seoul 133-791, South Korea. * These authors contributed equally to this work. Correspondence and requests for materials should be addressed to X.Q. (email: qiuxp@mail.tsinghua.edu.cn) or to K.A. (email: amine@anl.gov).

NATURE COMMUNICATIONS | 4:2837 | DOI: 10.1038/ncomms3837 | www.nature.com/naturecommunications 1

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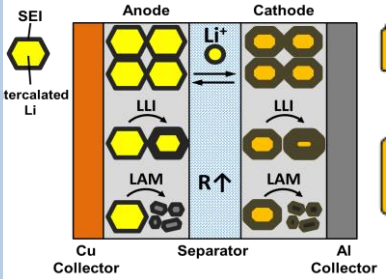
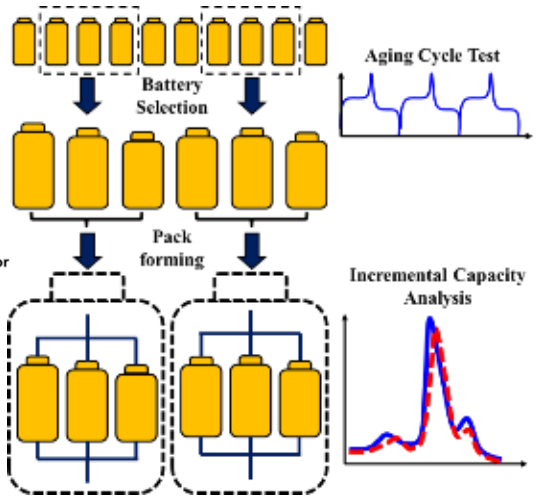
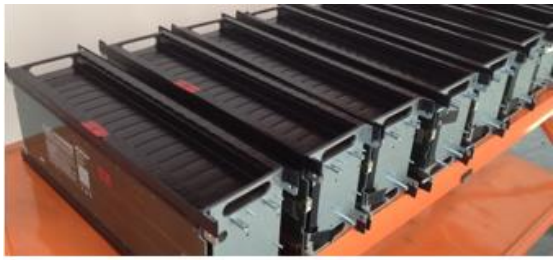
Battery System Performance Research and Application

Researchers in both countries performed different kinds of SOH diagnosis. The applications of the SOH diagnosis have been performed on a real BMS manufactured by Key-Power for a battery electric logistic vehicle.







SOH application in Key-Power's battery module for EVs

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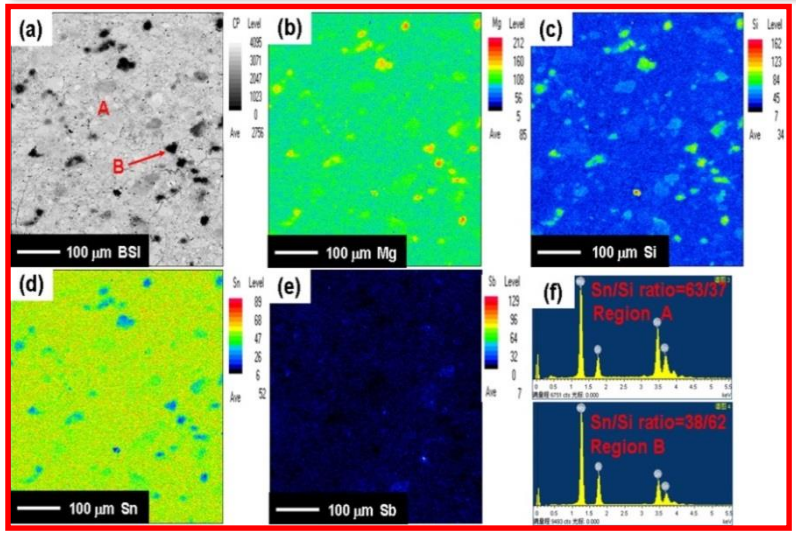
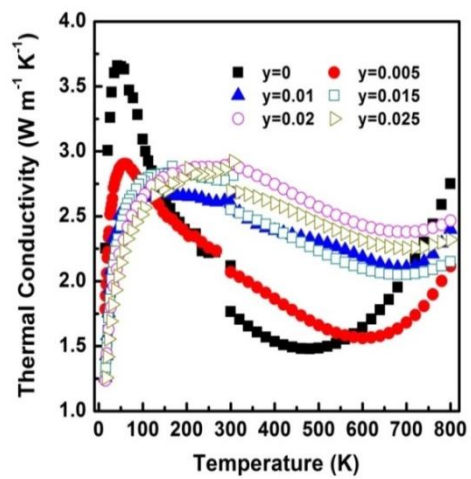
Fuel Combustion and Thermal Recovery

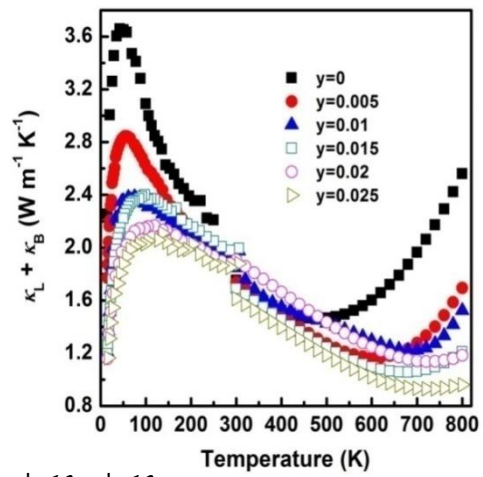
Study uniformity of SHS-synthesized materials using Scanning Thermoelectric Microscopy



Darker regions are rich in Si

Elemental mapping of $Mg_{2.16}(Si_{0.4}Sn_{0.6})_{1-y}Sb_y$





$$\kappa = \kappa_e + \kappa_L + \kappa_B$$

Joint publications

[1] W. Liu, X. F. Tang, C. Uher, et al., Journal of Materials Chemistry 22, 13653 (2012).
[2] W. Liu, X. J. Tan, X. F. Tang, C. Uher, et al., Physical Review Letters 108, 166601 (2012)
[3] X. J. Tan, W. Liu, H. J. Liu, X. F. Tang, C. Uher, et al., Physical Review B 85, 205212 (2012).
[4] W. Liu, X. F. Tang, C. Uher, et al., Journal of Solid State Chemistry 203, 333 (2013).

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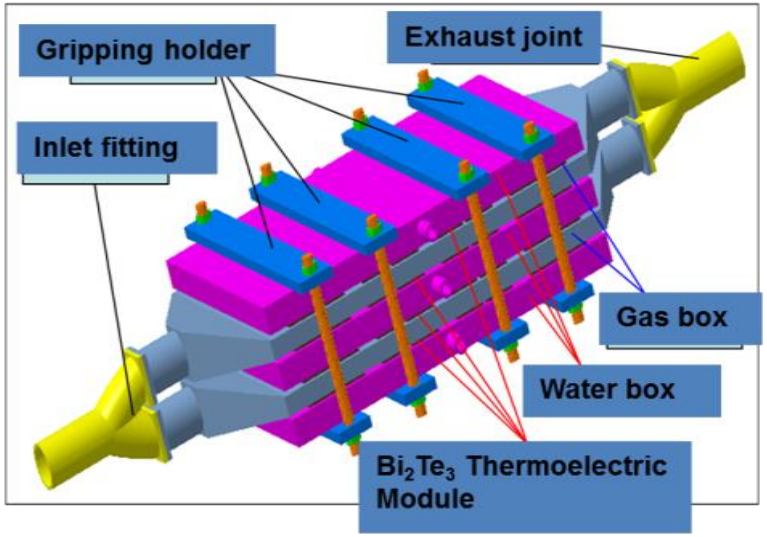
New Synthesis Process for Thermal Electric Materials

Construct and test a prototype thermoelectric module, the highest energy efficiency is 25%

University of Michigan · Wuhan University of Technology · Sandia National Laboratories · Oak Ridge National Laboratory

Structure of the stack gas box



- Compact structure. Improve the space utilization and cooling efficiency.
- Increase the temperature gradient. Improve the homogeneity of temperature distribution.

Distribution of TE module on the Gas Box

- Low temperature Bi_2Te_3 module: Conversion efficiency ~5%
- 32 chips per layer. 4 layers. Total: 128 chips.

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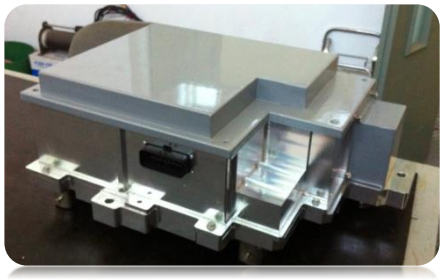
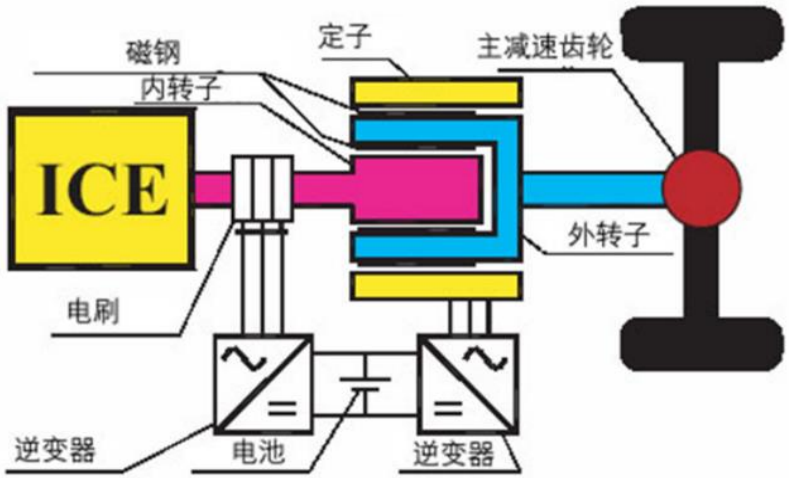
Simulation/Design/Control of Driving Motor

- **Development of EVTT system for SUV and passenger car**
- **10 patents and 14 publications**

The Ohio State University

Parameters	Prototype	Optimization
Rated power	20kw	20kW
Power density	1kw/kg	1.2kW/kg
Volume	1	0.68
Efficiency @rated power	93%	95%





15kW/20kW DMPM for small sedan

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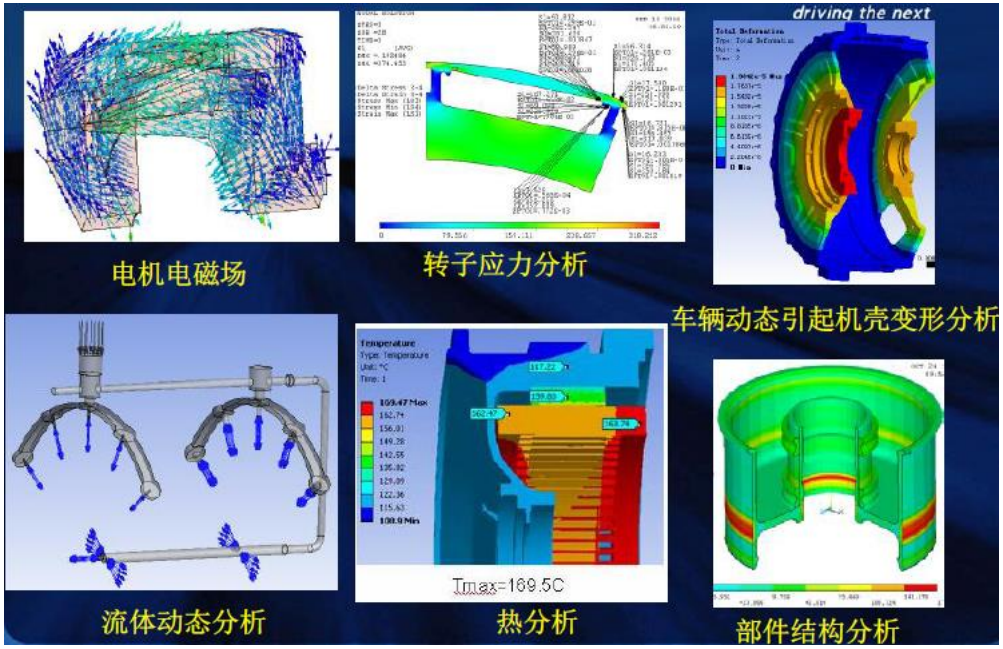
Simulation/Design/Control of Driving Motor

CVC industrial partner (Jingjin Electric) developed a advanced motor system, with 100K units produced so far



150 –300kW
High Power EV/PHEV
Traction Motor

2000-3500Nm
High Torque eMotor
For Bus & Truck

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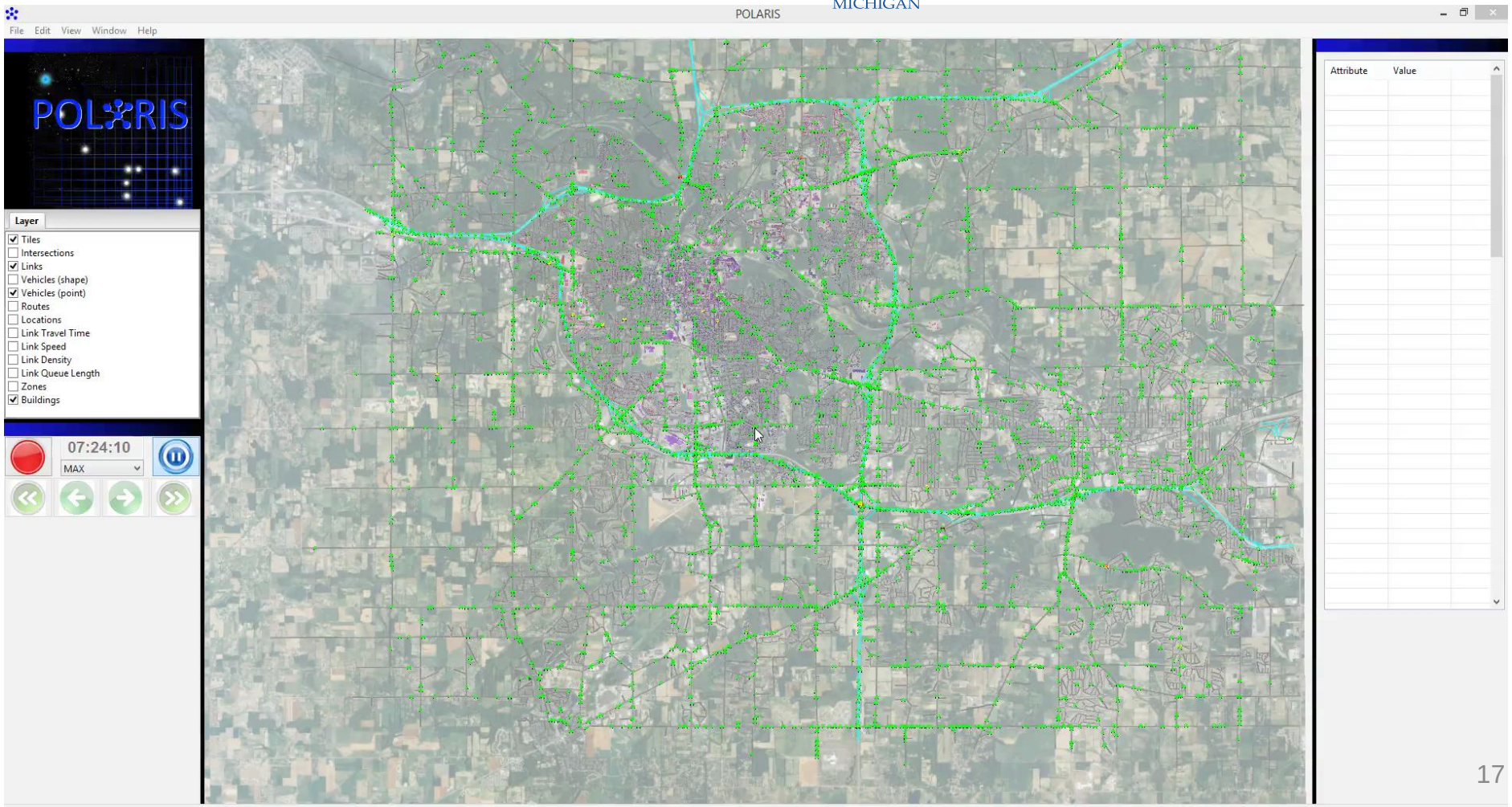
Connected and Automated Vehicle Modeling

Simulation results for Ann Arbor

University of Michigan

Argonne National Laboratory



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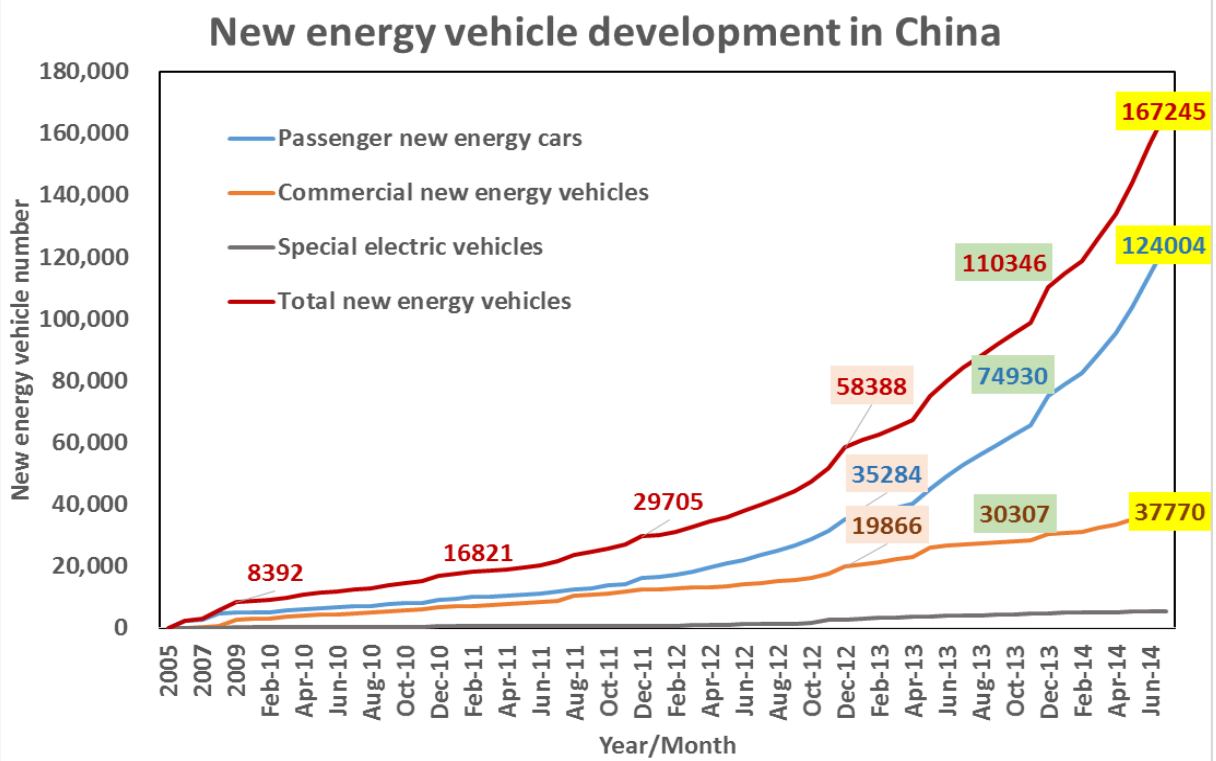
NEV Data Sharing

NEV Market Database Development and Data Sharing

A "Chinese NEVs market data base" was built based ANL's E-drive car data base platform



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Hewu wang (王贺武) wanghw@tsinghua.edu.cn

Argonne NATIONAL LABORATORY

中国节能与新能源汽车产业数据库

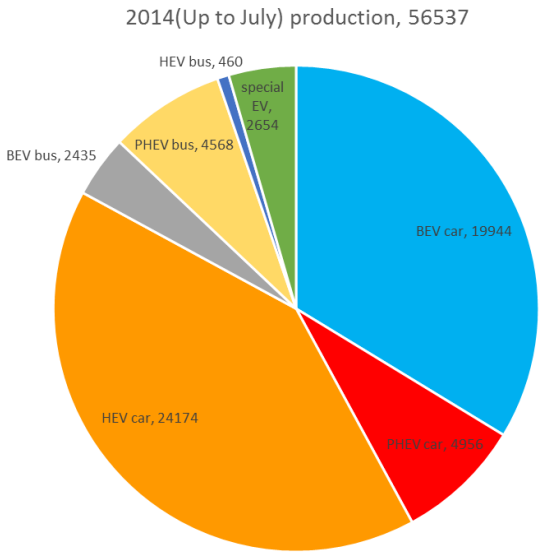
Data Base of Electric Vehicle Production in China

数据库开发：王贺武；wanghw@tsinghua.edu.cn

项目支持：科技部高新司(863、科技支撑)、国际合作司（中美清洁汽车联盟专项）

版权：清华大学汽车系/汽车安全与节能国家重点实验室

引用请注明：王贺武. 中国节能与新能源汽车产业数据库，清华大学汽车安全与节能国家重点
Citing as: Hewu WANG. Data Base of Electric Vehicle Production in China, State Key



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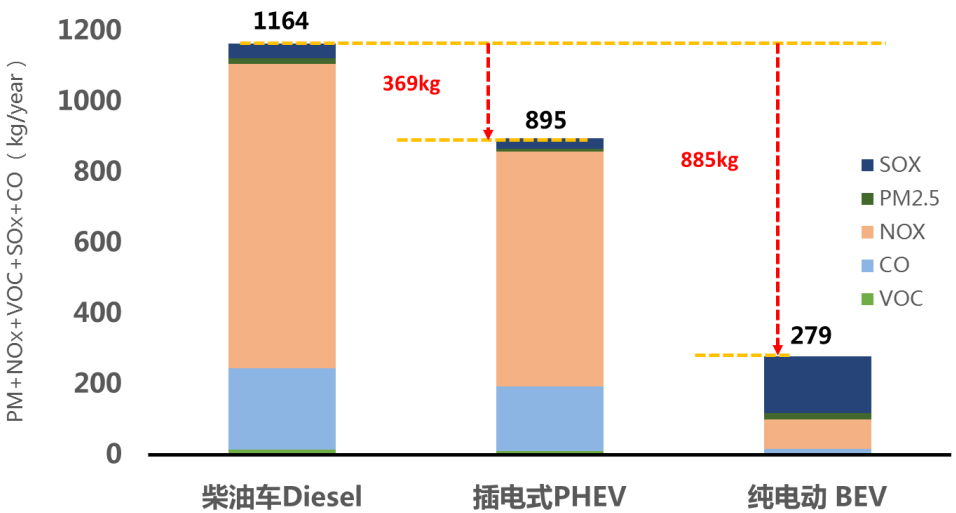
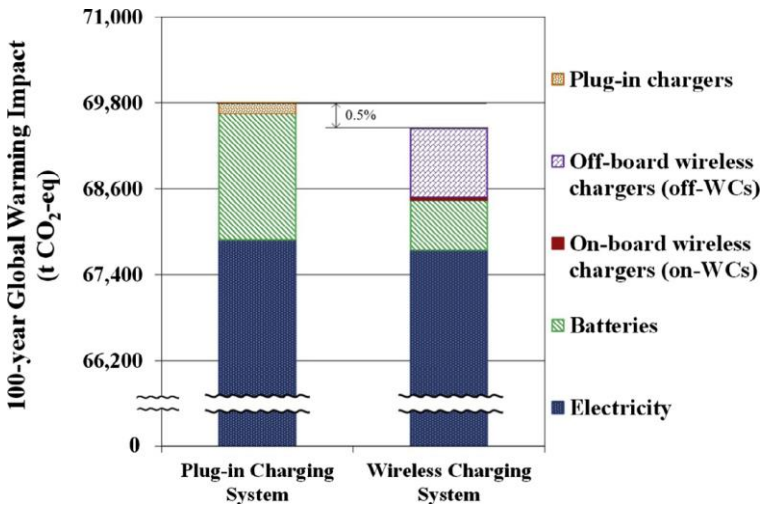
EV Pathways for City Bus

Electric bus lifecycle analysis comparison (Shenzhen-China, Ann Arbor-USA)

GHG、 PM、 NOx emitted from the EV bus are lower than diesel bus in both countries.

Fast charging and wireless charging have economic advantages in BEV bus over the PHEV Bus.





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Performance Metrics

- Joint conferences, workshops and symposia organized
  - 6 CERC-CVC-wide meetings, 11 EVI workshops
  - ~100 meetings per year (mostly by individual TA)
  - ~ 100 short-term visits, 30 long-term (> 30 days) visits planned or executed
- Journal and conference papers published
  - >400 papers published or accepted, joint 30 papers
- IP disclosures filed; US, China, and international patents issued
  - 71 in China, 28 in US (20 from Chinese side)
- Highlights of achievements
  - Significant collaboration results in all six thrust areas

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Summary of Key Outcomes

1. Advanced Batteries system

3. Vehicle Electrification

4. Lightweight Structures and crash safety

5. Vehicle-Grid Integration

6. Energy Systems Analysis, Technology Roadmaps

(1) Material development for safety improvement

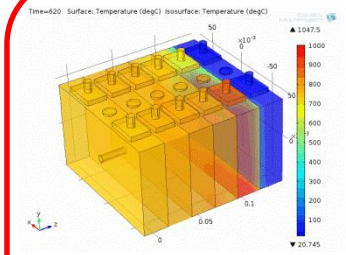
(2) Thermal runaway mechanism of traction battery

EV battery management system

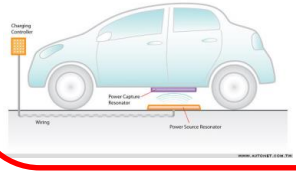
Battery safety issue during vehicle crash

Advanced charging technologies: wireless charging

Battery testing standards



Address safety issues associated with power batteries



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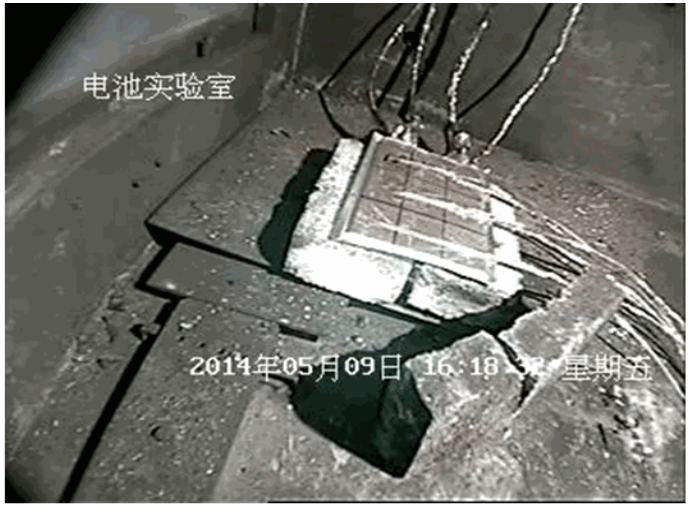
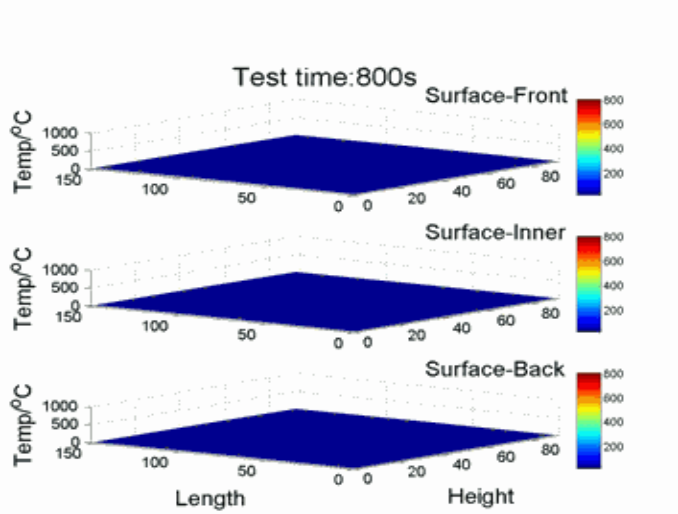
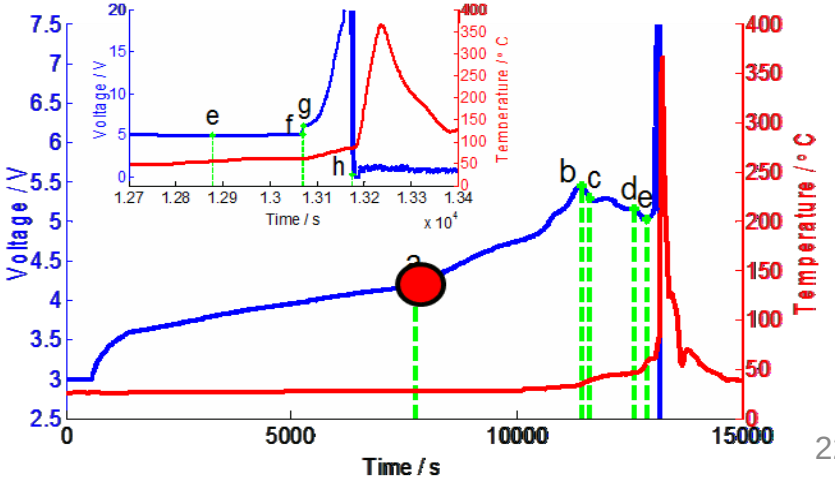
Thrust 1 Thermal Runaway Mechanism of Batteries

Short Circuit/Penetration

Overcharge







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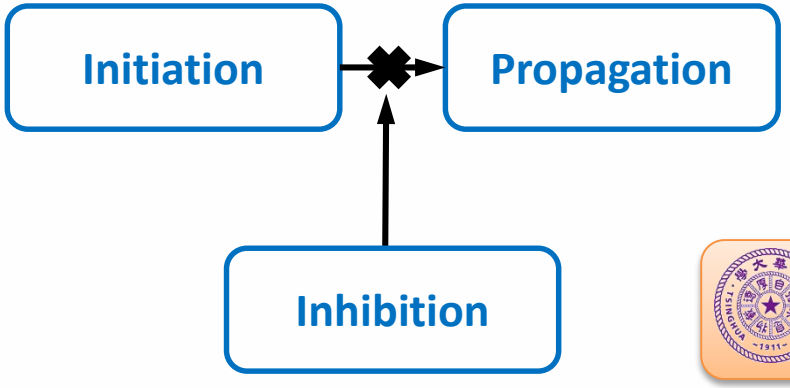
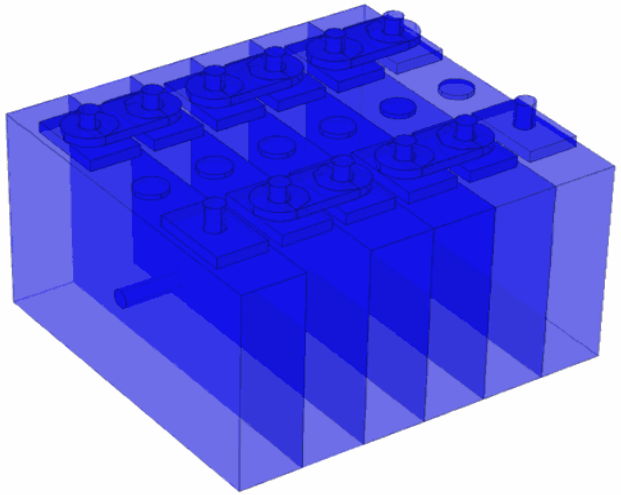
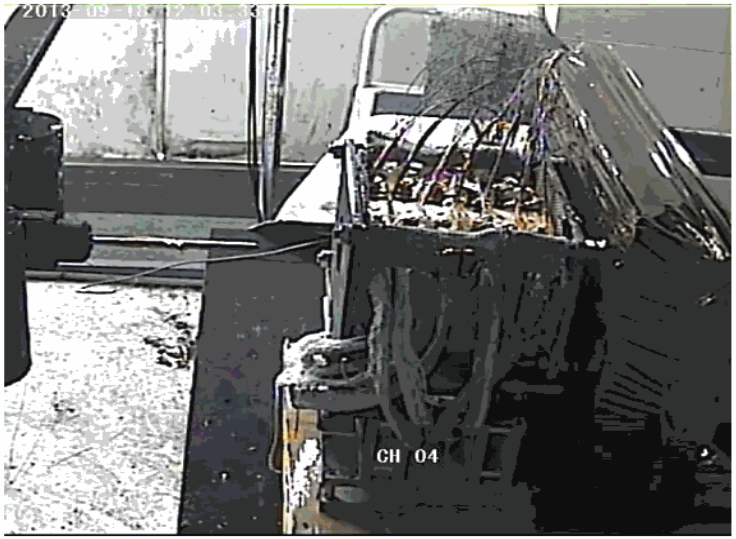
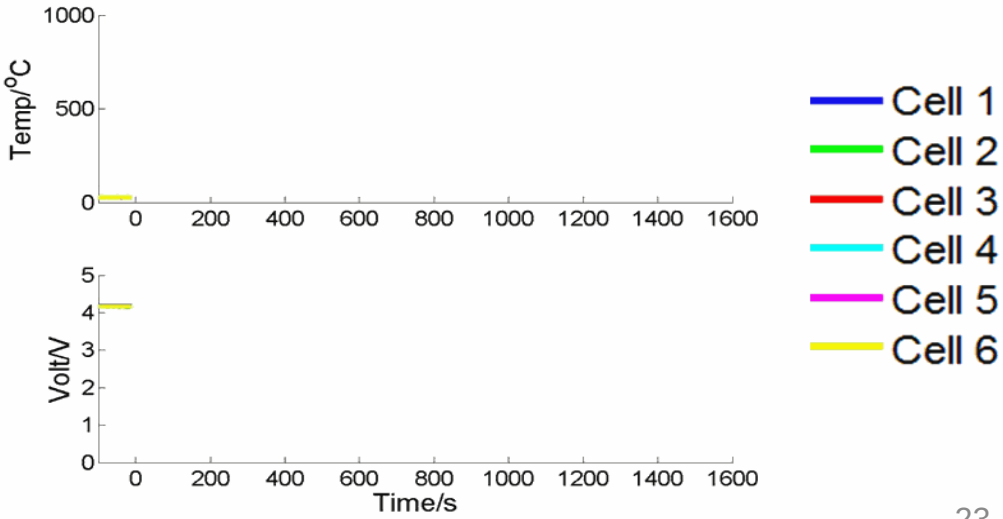
Thrust 1 Thermal Runaway Mechanism of Batteries

Thermal runaway propagation









Thrust 1 Advanced Material Safety Development

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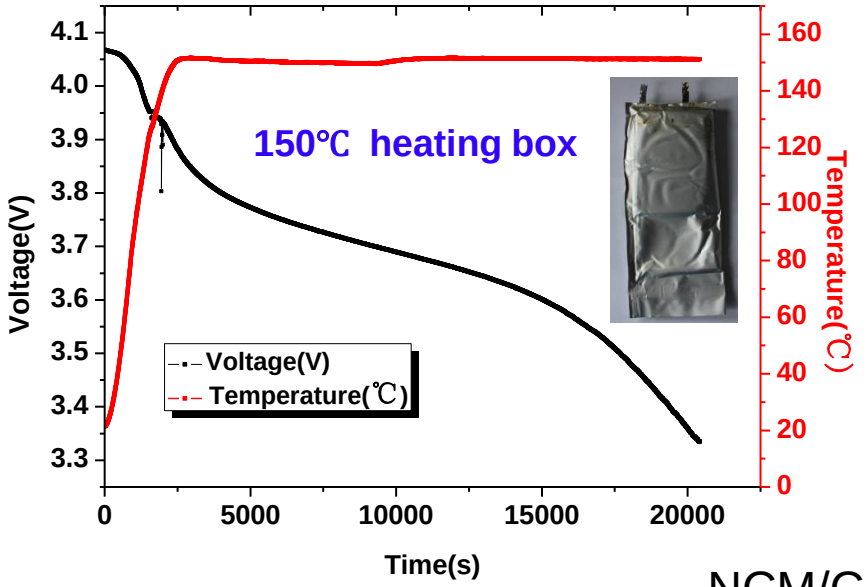
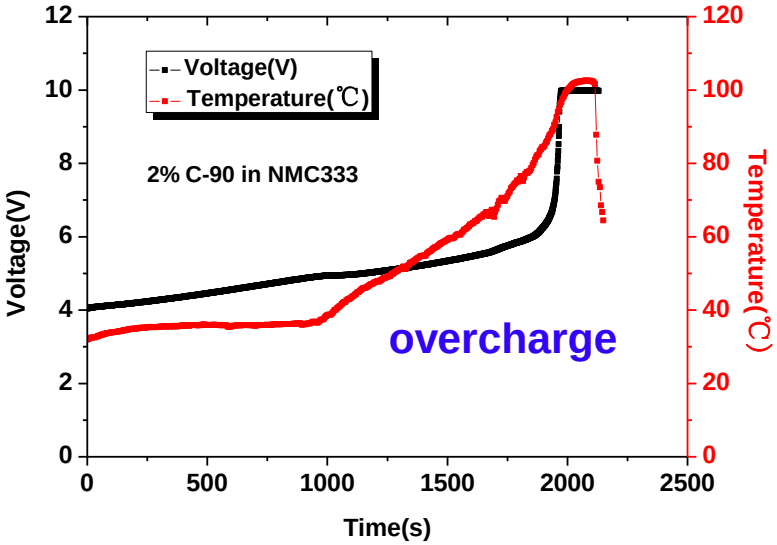
Polymer additive of safety： stabilizing electrolyte

1. Design of polymer structure for safety additive, optimized synthesis, scale-up of preparation
2. Patented technology
3. Stabilizing interface, improving safety and life of cell

Scale up





NCM/C cell safety tests

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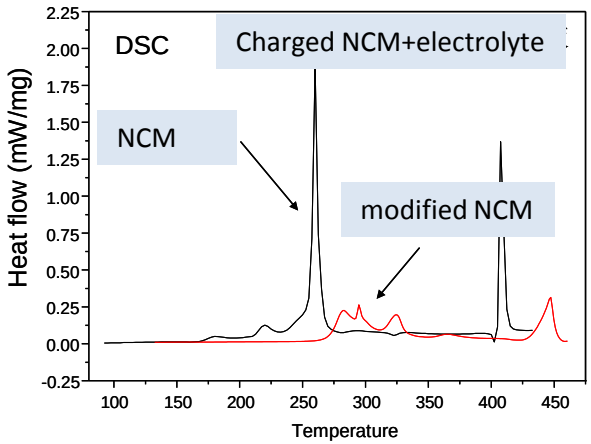
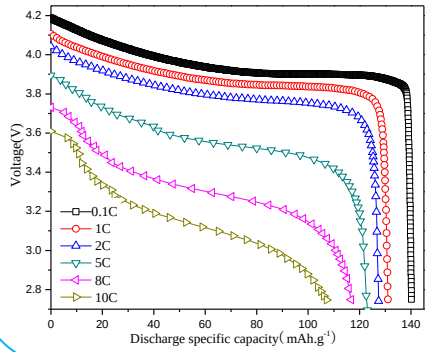
Thrust 1 Advanced Material Safety Development

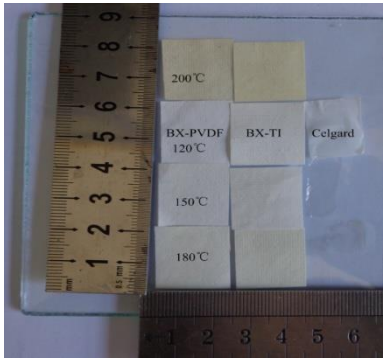
Modified NCM： highly stable against thermal runaway



1. Low heat generation
2. High onset temperature

Low shrinkage separator at high temperature





1. High electrochemical performance
2. No shrinkage up to 150℃

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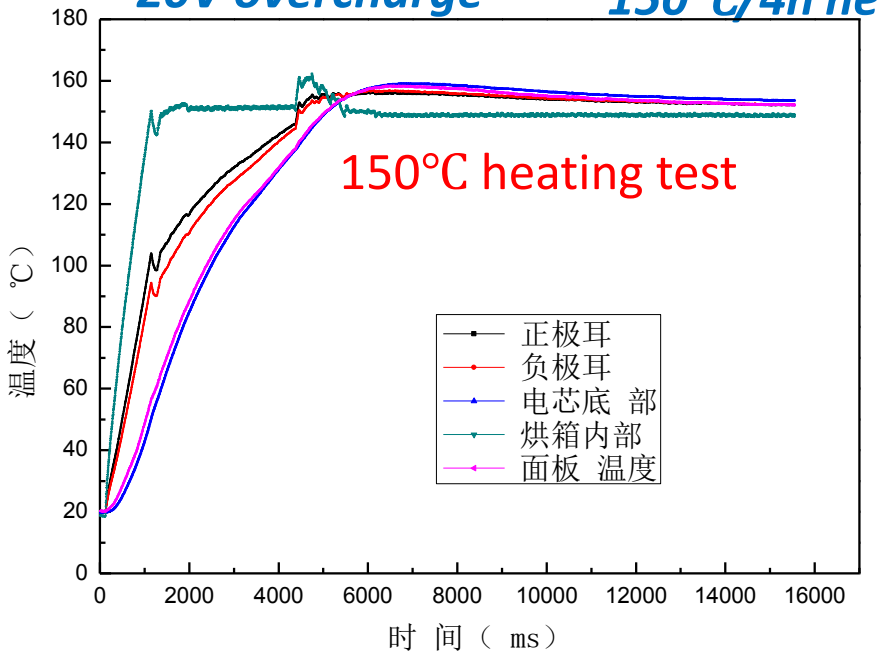
Thrust 1 Advanced Material Safety Development

System specific energy density: 156Wh/kg

Specific energy density of cell made of new material:180-200Wh/kg

20V overcharge *150℃/4h heating* *Short circuit*



Safety testing at extreme conditions

Testing conditions： 100%SOC, 150℃
Constant temperature （>4hr）

No fire, no leakage and no explosion under abuse tests

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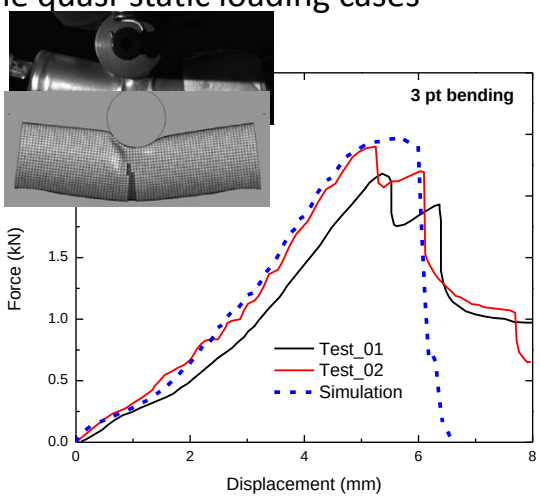
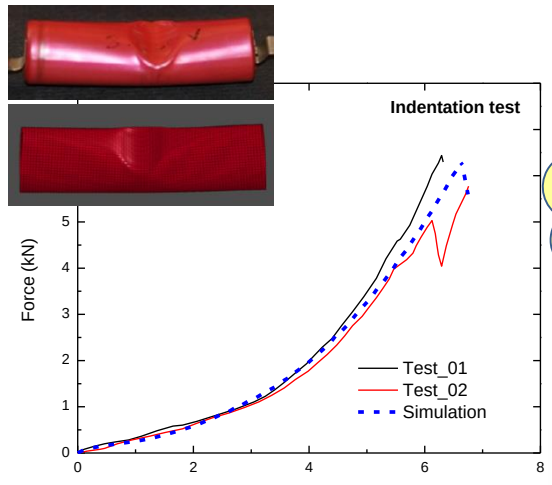
Thrust 4 Battery Safety During Crash

Traction Battery Crash Test

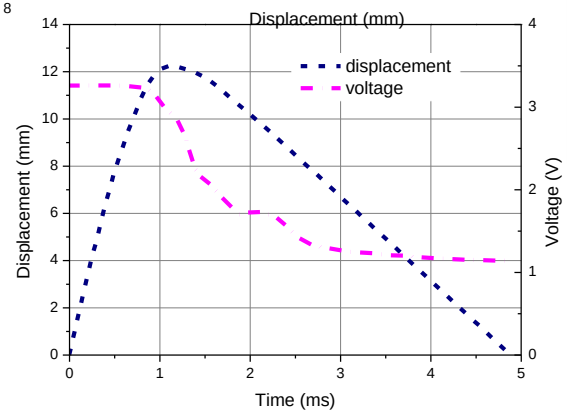
- Quasi-static tests of battery cells by monitoring real-time change of load, voltage and temperature
- Reveal correlation between mechanical failure and battery short circuit
- Homogenized model, currently capable of predicting battery short circuit under some quasi-static loading cases

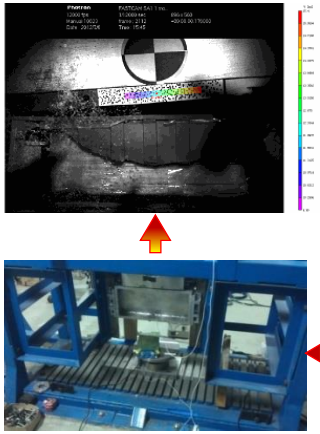




Key: Equivalent characterization of jellyroll in battery cell, including failure criterion

- Drop-tower impact tests of battery
- Large deformation and damage – voltage drop
- Provide info for developing crash model and tolerance of batteries





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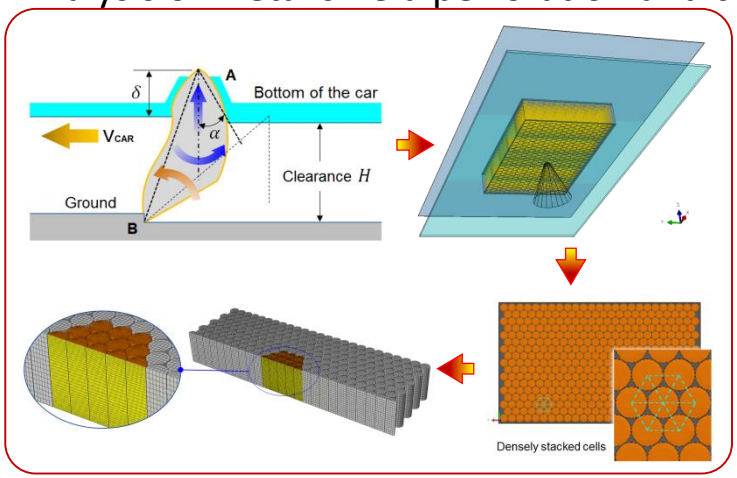
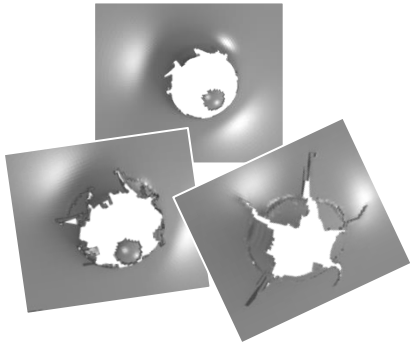
Thrust 4 Battery Safety During Crash

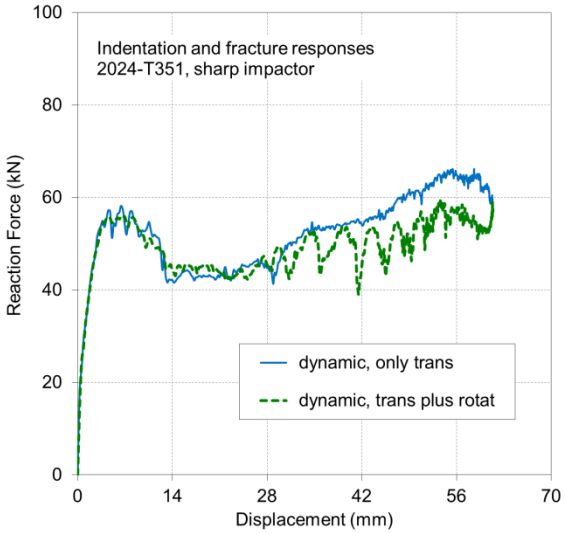
Model of ground impact of battery packs in EVs

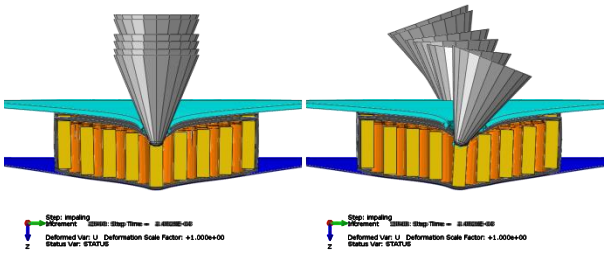
- Background: fire of Tesla Model S caused by debris impact on highway
- Definition of model for ground impact of plate-like battery pack, and parametric study
- Analysis of metal shield perforation and crack propagation pattern





Crack propagation patterns of shields made of different materials





Translational vs. rotational impact

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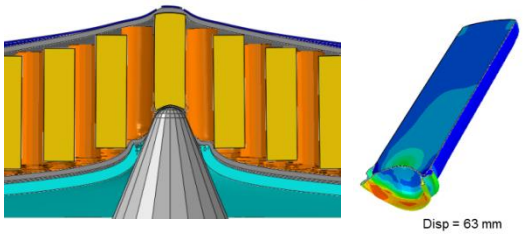
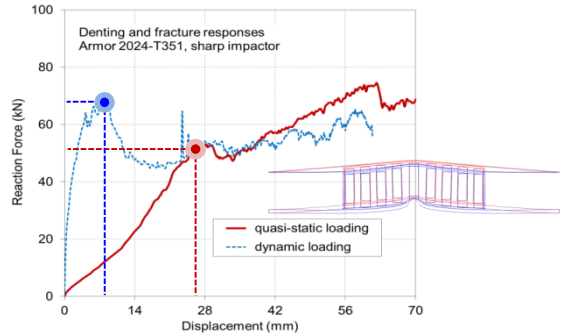
Thrust 4 Battery Safety During Crash

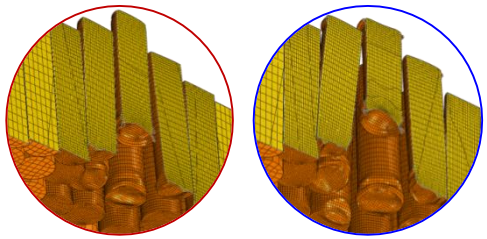
Model of ground impact of battery packs in EVs

- Analysis with multi-scale models
- Bottom structure deformation and perforation → localized deformation of individual battery cells → detailed analysis of battery cells

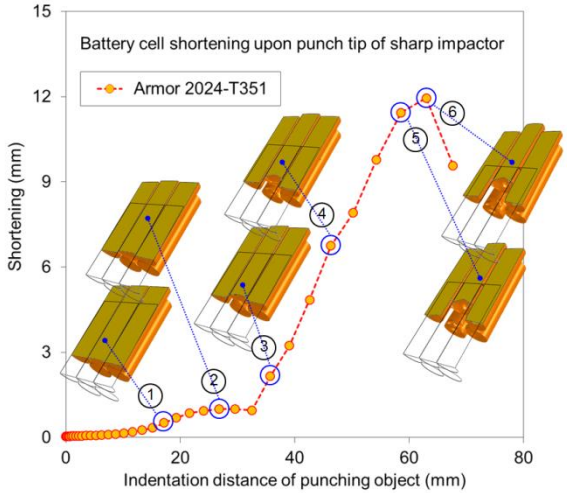


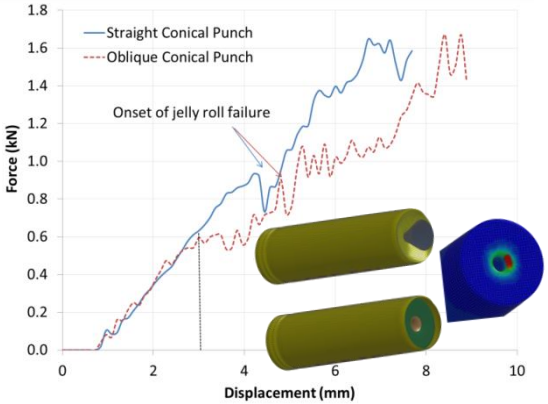


Difference of indentation response between quasi-static and dynamic cases

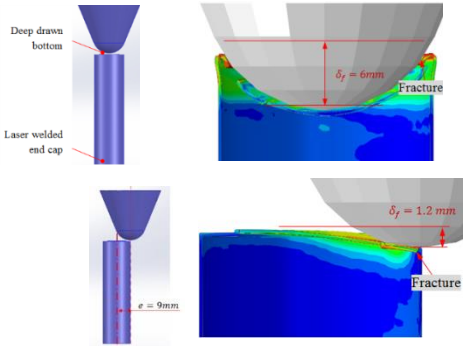


Localized deformation of battery cells beneath different floor panel structures





Deformation and failure of jellyroll in battery cells under different indentation modes



Deformation and failure of shell casing of battery cells under different indentation models

Thrust 4 Lightweight EV Crash Simulations

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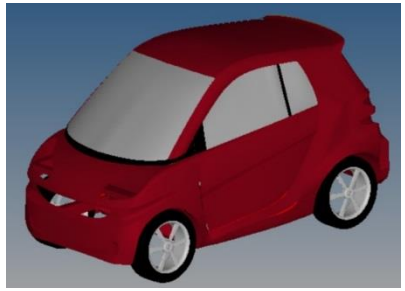
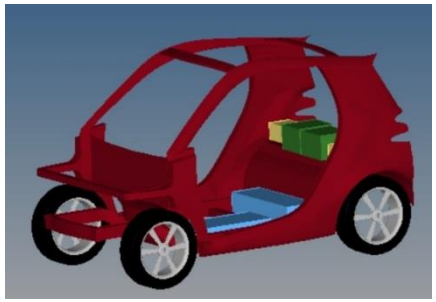
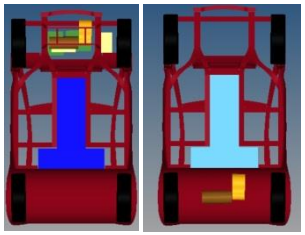
Design of lightweight Micro-EV bodies, full vehicle crash simulations

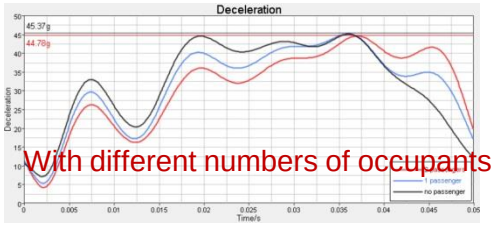
University of Michigan

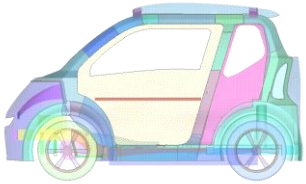


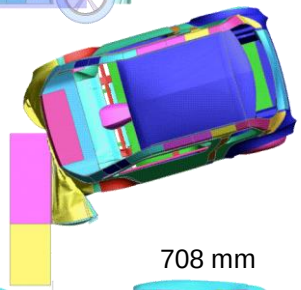


- Create 1000kg / 600kg Micro E-car models, for analysis related to
- Influence of mass distribution of batteries and occupants on crash performance
- Influence of lightweight materials on weight reduction and safety

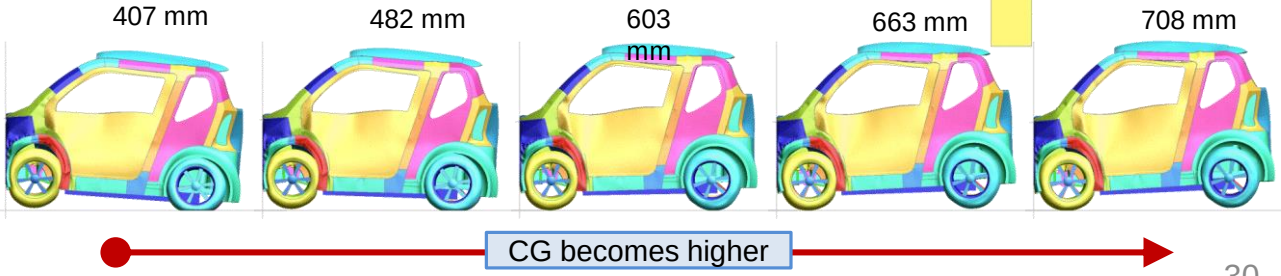








- Battery location → CG of full car
  - Pitching motion
  - Energy absorption in crash



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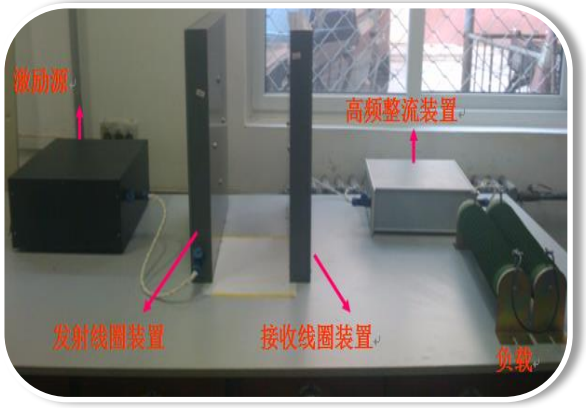
Thrust 5 Wireless Charging

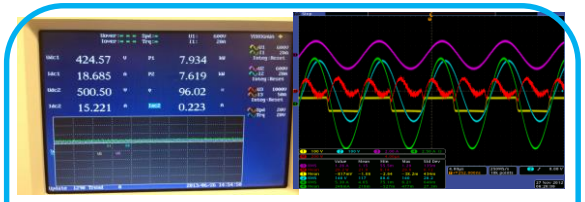
Electromagnetic Resonance Type

1st gen

1kW, 3.3kW wireless charging testing bed were setup



2nd gen



Simulation platform

3rd gen

Power:3.3kW
Transmission distance:20cm
System Efficiency: 90%

in-vehicle Testing

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Thrust 6 Battery Test Standards

A Comparison of US and Chinese EV Battery Testing Protocols

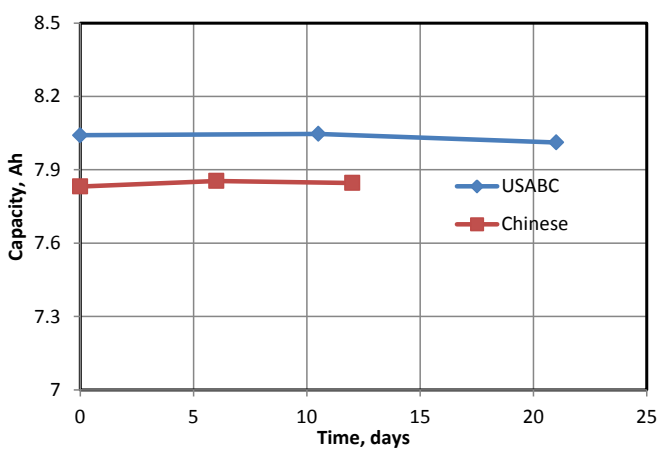
- **Similarities between China and US battery testing protocol:**

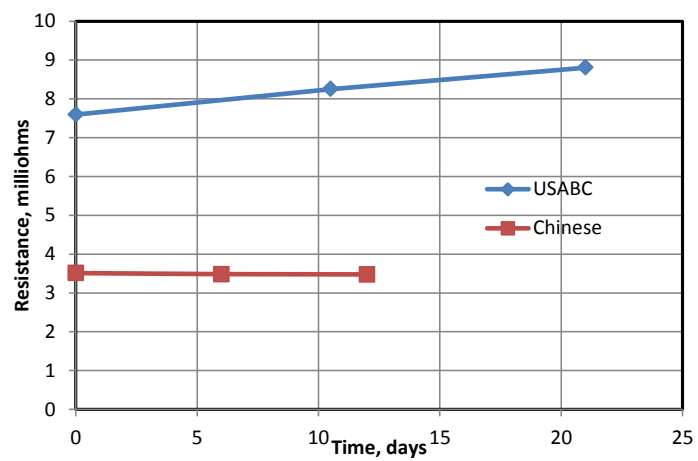
Voltage window, temperature and 80% capacity value is set as the end limit of cycle life.

- **Differences between China and US battery testing protocol:**

Battery performance testing method of constant current cycle, power density testing method, testing frequency of reference performance.

Testing Result Comparison





Outline

CVC1.0 Achievements

CVC2.0 Research Plan

CVC2.0 Initial Results

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CERC-CVC Phase 2 Thrust Areas

1. Advanced Batteries System

2. Advanced Biofuels, Clean Combustion and APU

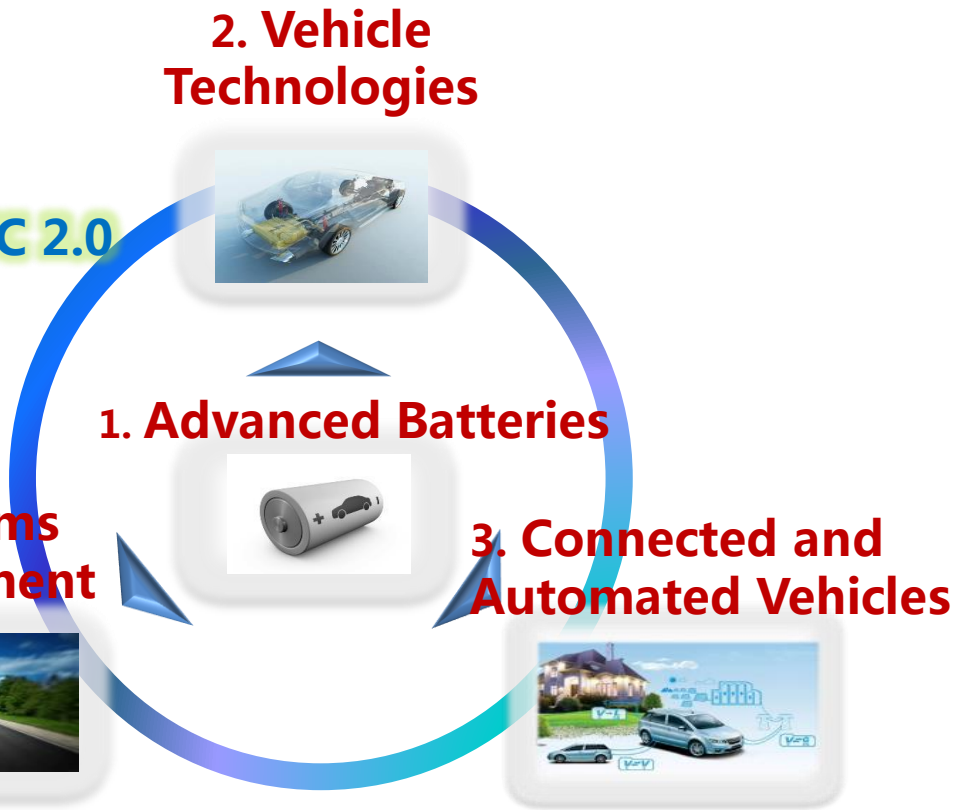
3. Vehicle Electrification

4. Lightweight Structures

5. Vehicle-Grid Integration

6. Energy Systems Analysis, Technology Roadmaps

CVC1.0 to CVC 2.0



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A Transition Year for CERC-CVC

- 2015 Steering Committee Meeting (Jan. 2015 Washington D.C.)
- 2015 CVC Annual Meeting (Aug. 2015 Beijing)
- CVC 2.0 Research Plan Planning (Dec. 2015 Beijing)
- CVC 2.0 JWP and TMP Signing (Jul. 2016 Beijing)

2015.01
Washington D.C.

2015.08 Beijing

2015.12 Beijing
CVC 2.0 research plan finalized

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Clean Vehicles Phase 2

CERC-CVC Phase 2 will be built on the success of CERC-CVC Phase 1

VISION: **Contribute to dramatic improvements in vehicle technologies with potential to reduce the dependence on oil and improve fuel efficiency in both countries.**

A website dedicated to CERC-CVC Phase 2: http://cerc-cvc.anl.gov/

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CERC-CVC Phase 2 Organization

Argonne NATIONAL LABORATORY

Director:
Don Hillebrand

Deputy Director:
Michael Wang

Deputy Director:
Khal Amine

Director:
OUYANG Minggao

Deputy Director:
Wang Hewu

Deputy Director:
Qiu Xinping

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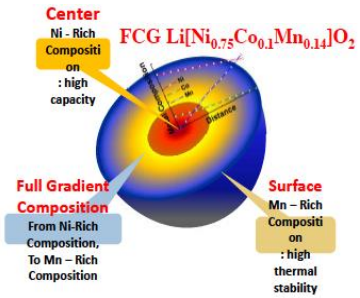
CERC-CVC Phase 2 Advanced Batteries

- Development of advanced in situ characterization toll to understand failure mechanism in different battery systems with focus on high voltage high energy cathode (230mAh/g) New Battery Chemistries
- Characterization of Silicon-Based Anode Materials and their Solid-Electrolyte Interphase (SEI)
- Characterization of Lithium Sulfur Batteries
- Investigation of the safety of batteries at the component and pack level
- Characterization and development of new catalysts to improve the efficiency of Li-O2 batteries and/or Zinc ion Battery



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CERC-CVC Phase 2 Vehicle Technologies

- Electrified Powertrain: Address input driving cycle, components optimization, powertrain optimization and evaluation
- Energy Conversion Devices: Identify combustion concepts that complement advanced PEV requirements using specific market constraints
- Vehicle Optimization: Evaluate PEV vehicle options and address design issues, influence of battery pack and battery protection

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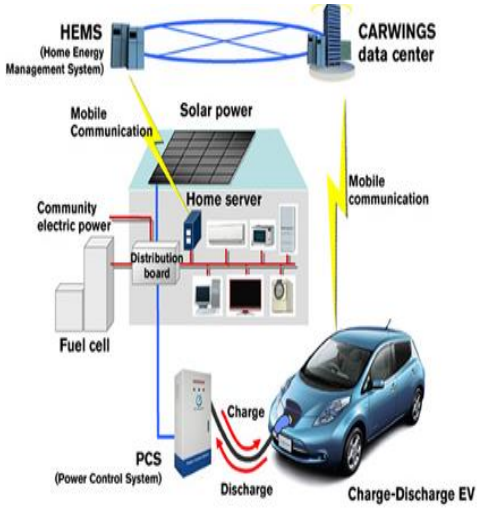
CERC-CVC Phase 2 Connected and Automated Vehicles

- Integrated Transportation Systems: Quantify the energy impact of connection and automation
- Charging Infrastructure and Technologies: Maximize electrified vehicle market penetration
- Shared Mobility: Evaluate the energy impact of connectivity and automation on shared mobility



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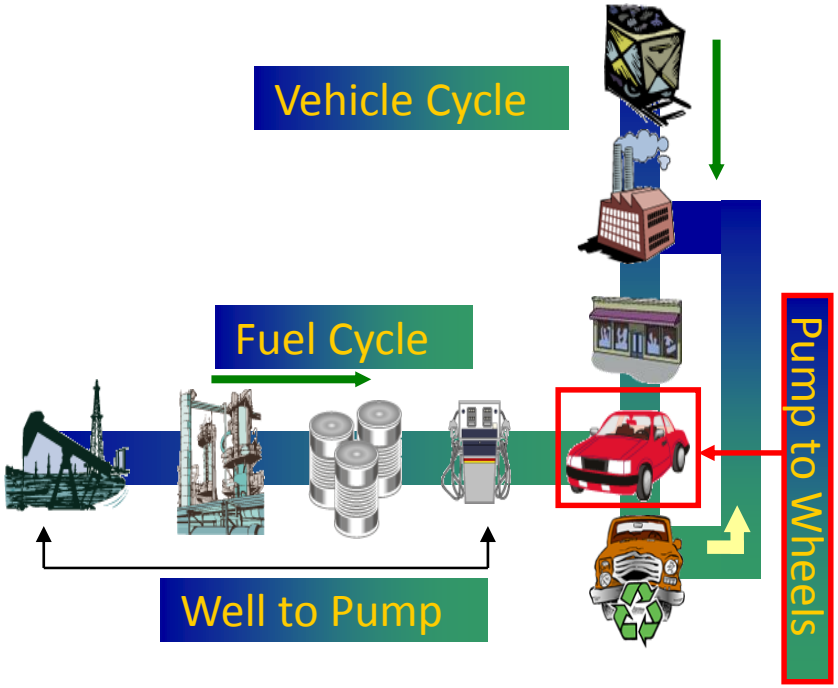
CERC-CVC Phase 2 Systems Assessment

- Characterize technologies and conduct LCA to evaluate energy and environmental impacts of CERC-CVC technologies
- Conduct consumer behavior research to understand consumer purchase behaviors, consumer driving behaviors, and PEV recharge patterns
- Examine the effectiveness of policies on consumer choice of PEVs and the influence of passenger vehicle fuel economy and GHG standards on energy efficiency technologies
- Assess PEV demonstration in both countries, Identify and develop novel strategies to bring clean technologies to market in U.S. and China



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CVC Phase 2 Academic and National Lab Partners

U.S.

Argonne National Laboratory

The Ohio State University

Massachusetts Institute of Technology

University of Michigan

UC Davis ITS Institute of Transportation Studies

icct The International Council on Clean Transportation

CALSTART

Oak Ridge National Laboratory

Pacific Northwest National Laboratory

Brookhaven National Laboratory

University of Washington

Carnegie Mellon University

China

Tsinghua University 1911

shevdc

CNTARC

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CERC-CVC Industrial Partners

U.S.

DELPHI
Aramco Services Company
State of California Energy Commission
GM
microvast Power Systems
ClimateWorks Foundation
萬向集團 WANXIANGGROUP
Farasis
A123 Systems
Excellatron

China

CATL
萬向集團 WANXIANGGROUP
SAIC
JAC
CAERI
CNTARC
上汽通用五菱 SGMW
LISHEN
LiBs
JJE
ECTEK
KeyPower 科易动力

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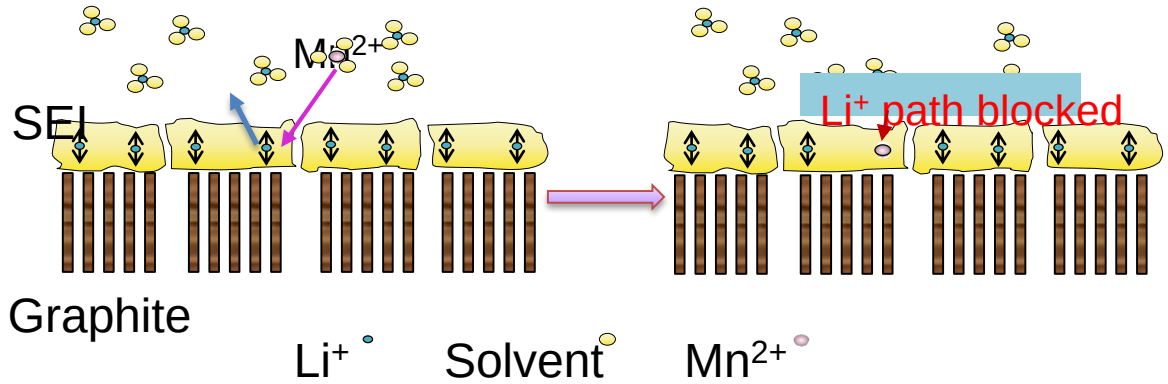
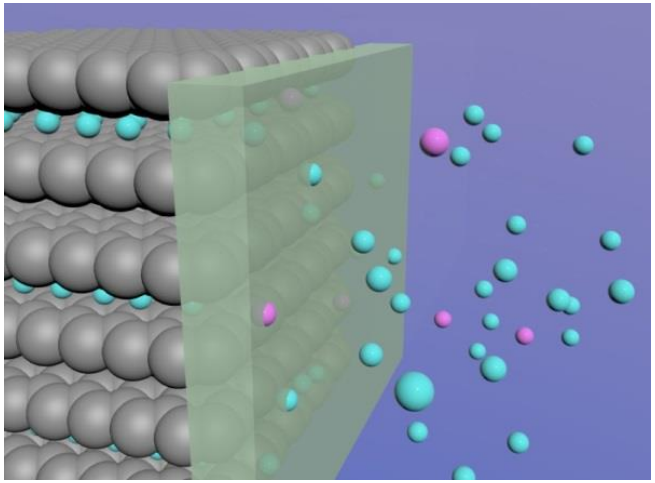
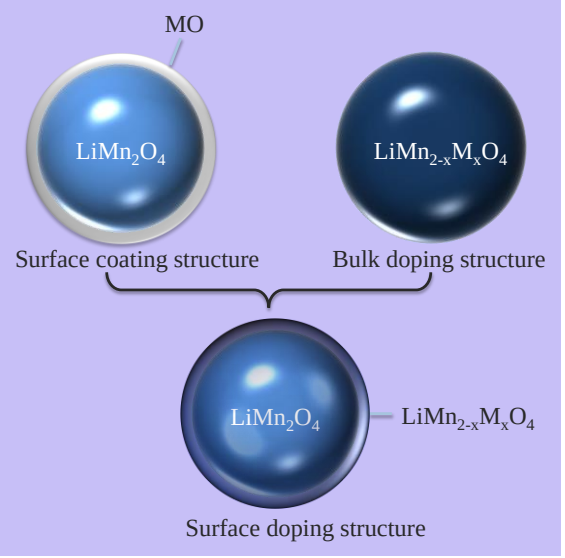
Mn Dissolution in Spinel Lithium Manganate–Carbon Systems





Nat. Commun. 4, 2437, **2013**



Nat. Commun. 5, 5693, **2014**

- **The oxidation state of manganese deposited on the anodes is +2**
- **A metathesis reaction between Mn^{2+} and some species on the SEI during the deposition of Mn on the anodes, rather than a reduction reaction that leads to the formation of metallic Mn otherwise**
- **The capacity fading is caused by changing of the SEI on the graphite anode**
- **Surface modification by ALD or sol-gel treatment has been shown to significantly improve the capacity and cycleability of LiMn2O4**

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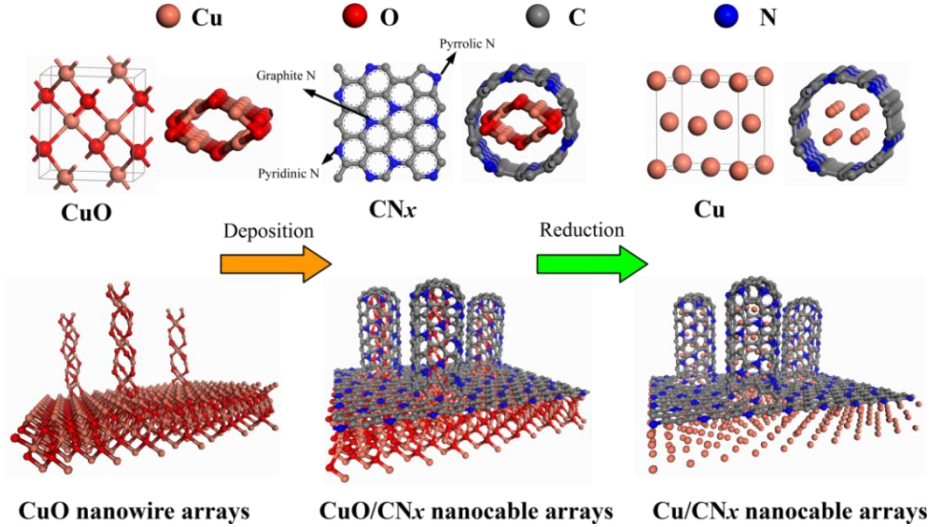
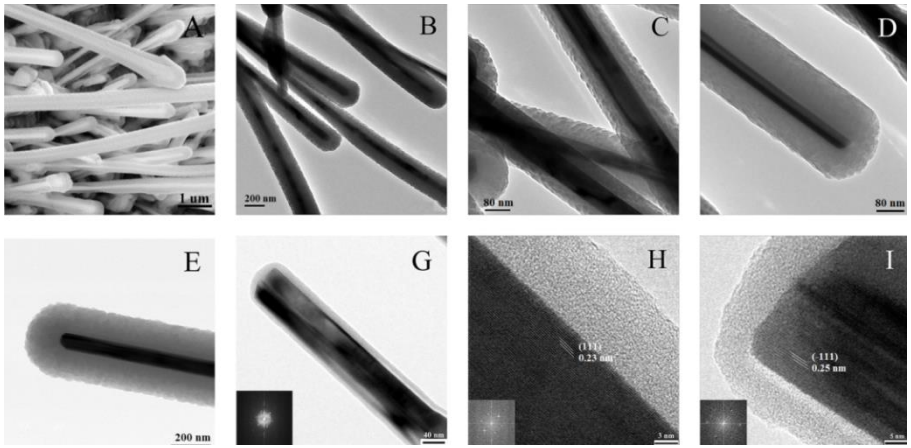
Free-Standing Nano-Arrays

Synthetic Mechanism



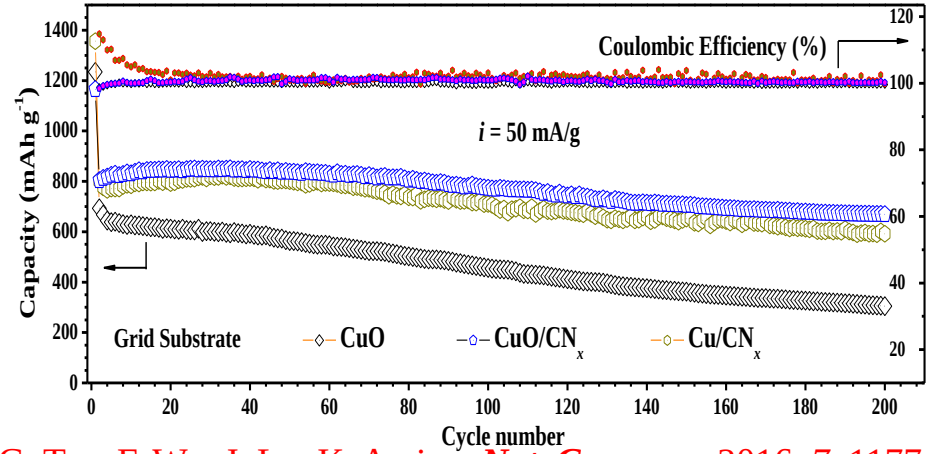
Core-Shell Nano-Arrays



Two-step electrode design consisting of oxide growth of CuO nanowires onto a Cu substrate followed by RF sputtering of CN*x* films, thus forming 3D core-shell nano arrays.

CuO/CNx core–shell structures accommodate volume change during (de)-lithiation processes, 3D nano-arrays provide abundant electroactive zones and electron/ion transport paths, and monolithic structural configuration improves energy/power densities of the whole electrode.

Cycling Performance



G. Tan, F. Wu, J. Lu, K. Amine, ***Nat. Commun***. 2016. *7*, 11774

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Outline

- Research thrust areas and projects have been defined for CVC phase 2. Over 100 researchers and students will be involved over the next five years
- 2016 CVC Annual Meeting will take place in the U.S. August 3-6, 2016
- Preliminary estimates of the cost share from partners will go over the target
- Existing IP plan is accepted by our partners, MOST, DOE Vehicle Technologies Office and Office of Energy Efficiency & Renewable Energy

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Thank You

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China: http://www.cerc.org.cn/