Brief: Digital Twin Testbed for Advanced Battery Management and Utilization in Naval System

Introduce proposed Center for Battery Safety and Durability (CBSD) at UofSC

Austin R.J. Downey

Assistant Professor, Department of Mechanical Engineering

UNIVERSITY OF South Carolina

SCEPTER - SOUTH CAROLINA ENERGY AND POWER TESTBED FOR ENGINEERING RESEARCH

Two DC zone cabinets, 10 bus system, (AC cabinets not yet complete)

Operator Displays for Digital Twins and system measurements

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DON OPERATIONAL ENERGY GOALS

Department of the Navy Operational Energy Goals

1. Extend operational reach of current and future weapons systems through more effective use of energy.
2. Reduce external energy logistics requirements to forward deployed strike groups and expeditionary units.
3. Increase energy resilience of forward bases, supply depots, and cooperative security locations – Get more energy to the warfighter.
4. Increase the effective use, conversion, distribution, and control of energy to enable the integration of future weapons and sensors into single platforms.
5. Foster and guide an energy culture through policy, training and education in our Marines and Sailors.

Unclassified//Distribution A

- Tactical Energy Management (TEM)
- Reduce fuel consumption
- Increase energy resilience at the warfighter
- Enable higher power weapons and sensors through TEM
- Though not directly to Marines and Sailors, we are training and educating students to be future engineers and technicians on this problem set

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PROJECT BIG PICTURE PURPOSE

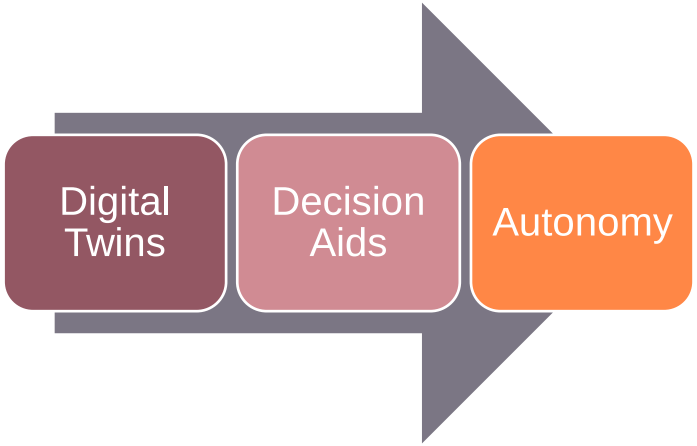
Better with Less

Better than the enemy, but with fewer casualties and lower costs

Better

- Offense – Weapons
- Defense – Sensors
- Speed
- Mission length
- Mission effectiveness
- Reliability
- Maintainability
- Resiliency

How?



Less

- Casualties in theater
- Sailors at risk
- Human decisions to make
- Barrels of fuel
- Logistics
- Equipment downtime
- Susceptibility to enemies
- Cost

PROJECT OBJECTIVE AND MAJOR TASKS

Objective

- Enable deployment of digital twin technology to improve the performance and resiliency of Navy Power and Energy Systems to achieve military superiority on the seas with fewer casualties and lower cost.

Major Tasks

1. Design Digital Twins for Power and Energy Systems
2. Complete the Ship Electrical Grid Testbed
3. Integrate Digital Twins into the Testbed
4. Test and Evaluate Performance of Digital Twin Integrated Systems

Resiliency:

The capability of the NPES to **adapt to and recover from unplanned events and disruptions** ranging from minor faults or degradation that might arise in individual components, to damage sustained to large portions of a ship during combat operations, to large sudden changes in either supply or demand for electrical power.

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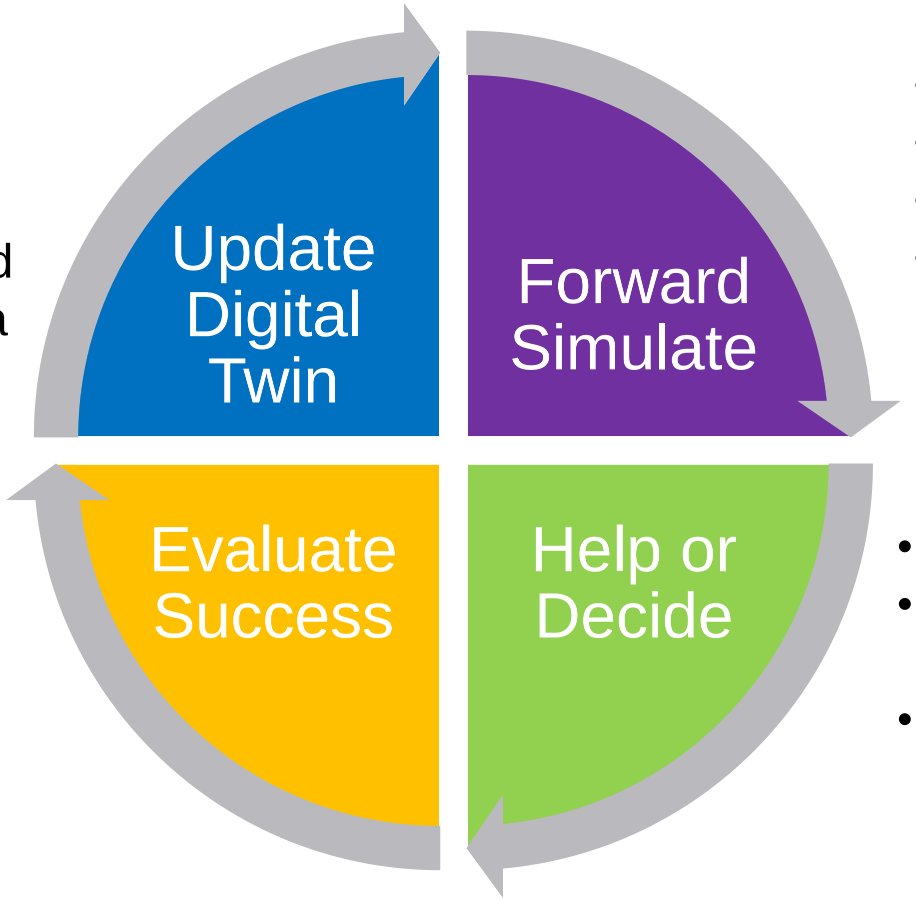
DIGITAL TWIN BASED APPROACH

- Digital model of NPES physical asset
- High or low fidelity
- Continuously updated based on physical twin sensor data
- Maintains accuracy as conditions change

- Machine learning and AI
- Quantify success
- Learn and adjust to be better next time



- Future TEM scenarios
- Various fidelities
- Various prediction horizons
- Up-to-date twins provide accuracy

- Intelligent TEM decision aids
- Survey many future outcomes
- Recommend or pick the best one

Ship PES performs better than it would have in the past, better than the enemy's ship, and with fewer lives at risk and lower cost.

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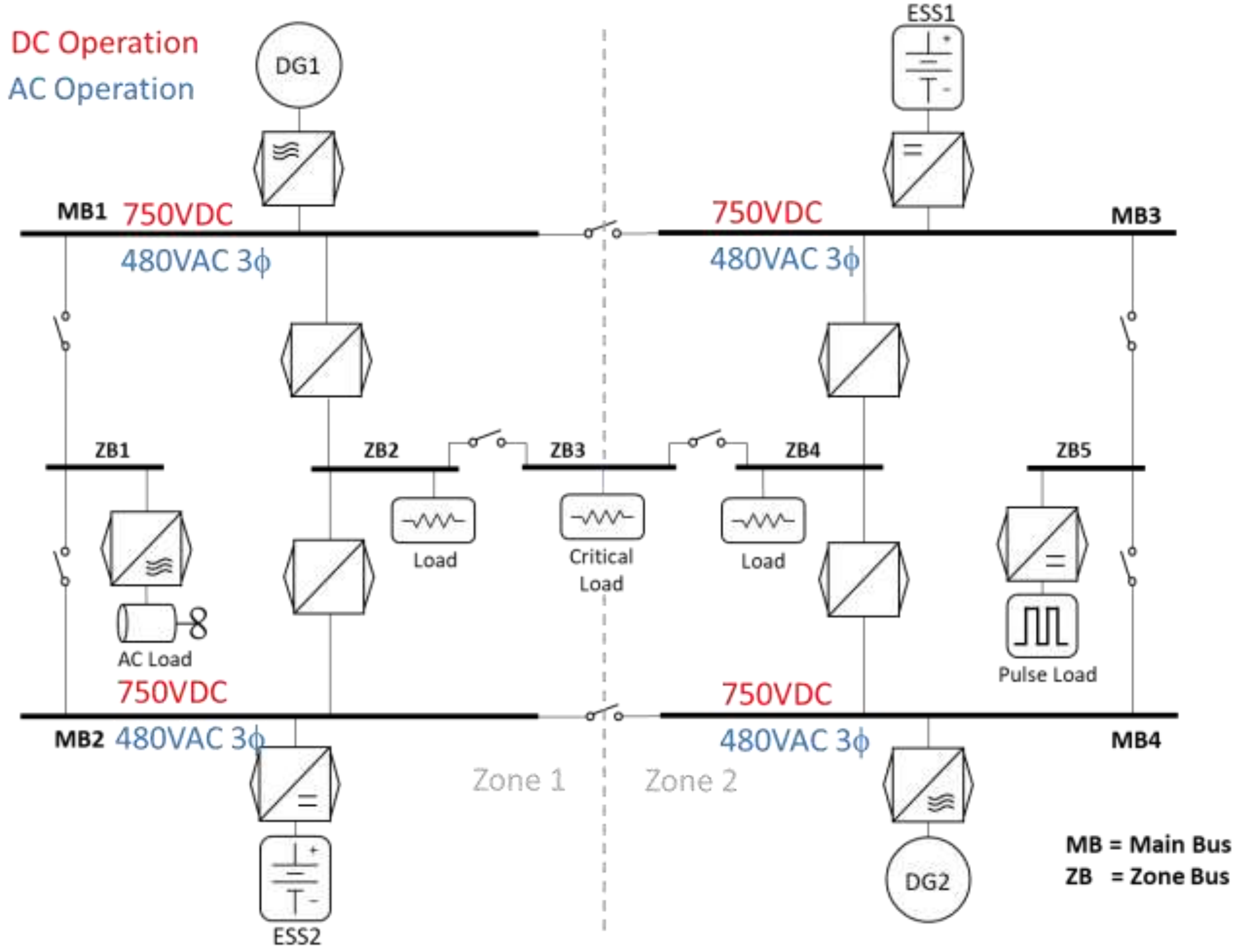
TESTBED ARCHITECTURE

TESTBED ARCHITECTURE



- Representative of many possible shipboard power and energy systems, including electrical, mechanical, and thermal/fluid aspects.
- DC/AC flexible bus arrangement, can represent wide variety of ship types. Initially implement as dc only.
- Real time simulator with power interface enables wide range of studies.
- Hierarchical arrangements of digital twins reflect coarse and fine system performance.
- Heavily sensorized and with pervasive edge computing capabilities.

TESTBED AND CONTROL STATION

Two DC zone cabinets, 10 bus system, (AC cabinets not yet complete)

Operator Displays for Digital Twins and system measurements

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TESTBED LAYOUT

Testbed room for future expansion, including AC bus, pulse loads, propulsion loads, supercapacitors, energy storage

Two 350V, 12.3 kWh liquid cooled battery packs Lithos Energy (to be installed)

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STAGE 1 TESTBED IMPLEMENTATION

Operator Station
- 7 Displays for User monitoring and control

DC1 Cabinet
- Fieldbus I/O
- Breaker Control
- Voltage and Current Measurements
- Network Switch

MCS Cabinet
- PLC
- OAS Server
- UPS
- Network Switch

DC2 Cabinet
- Fieldbus I/O
- Breaker Control
- Voltage and Current Measurements
- Network Switch

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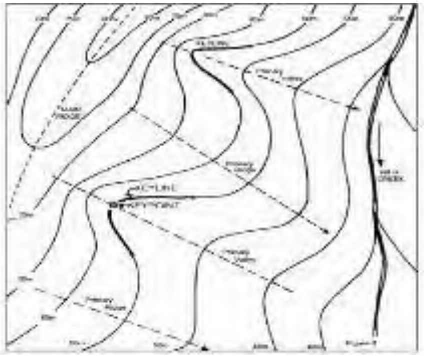
AUTOMATIC SIMULATION MANAGEMENT

Key factors of the automatic simulation

- **Efficiency** of the AI pipeline
- **Reusability** of the collected metadata
- **Explanation** of the decisions made

Operator View

Remaining Time: -
Fuel Rate: 2.6 gal/hr



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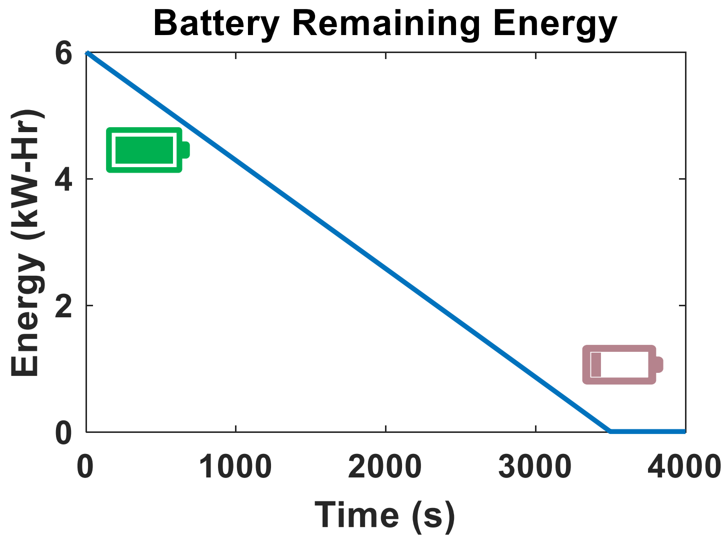
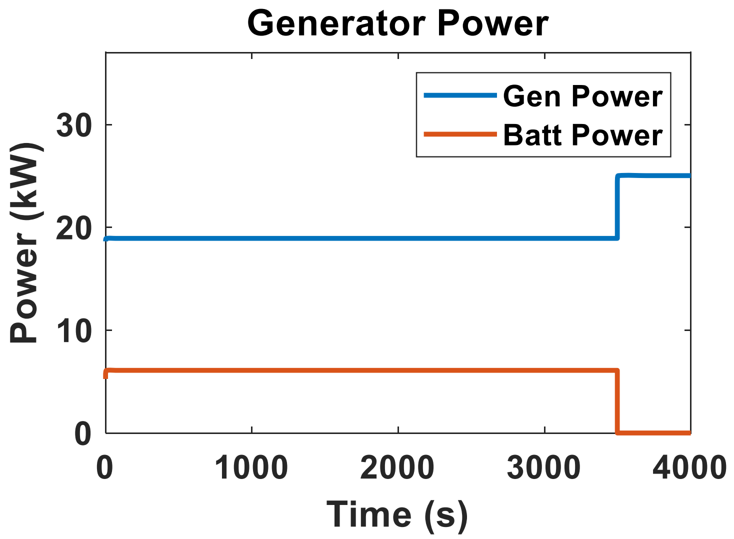
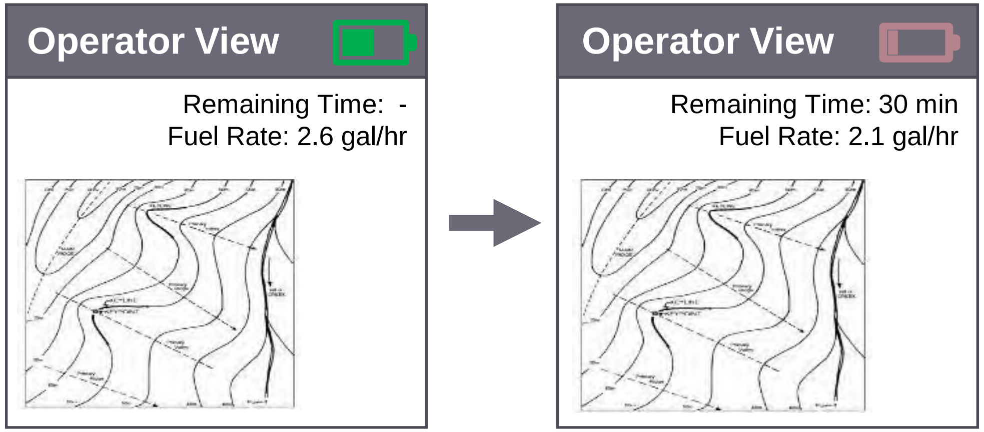
LOAD SHARING EXAMPLE





New DT Instance Predictions:

- Battery Supplies 25% power
- 1 Hour of Battery Energy Remaining



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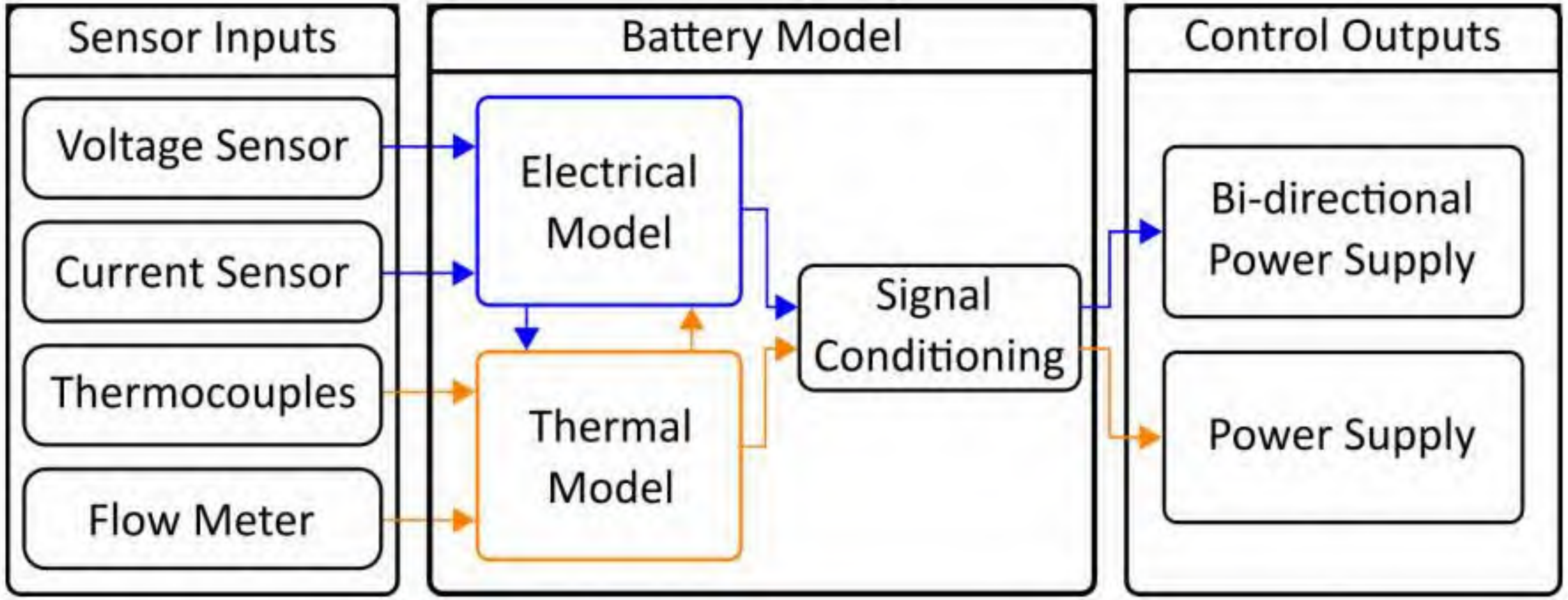
BATTERY RESEARCH AT THE SCEPTER TESTBED

ELECTRO-THERMAL BATTERY EMULATION

Developing an electro-thermo hardware-in-the-loop battery emulator,

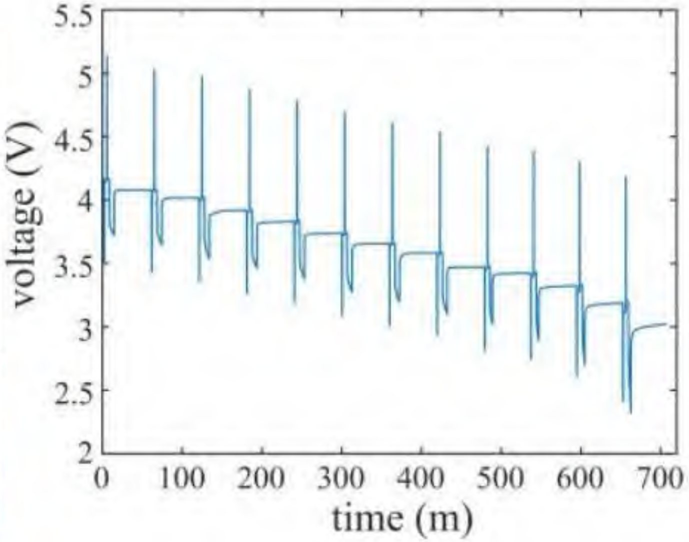
- Will be used for testing and validating electrical power systems with shared cooling between power electronics and energy storage.
- Enables the simulation of extreme loads on batteries in full-scale power systems without safety concerns of full-scale batteries.

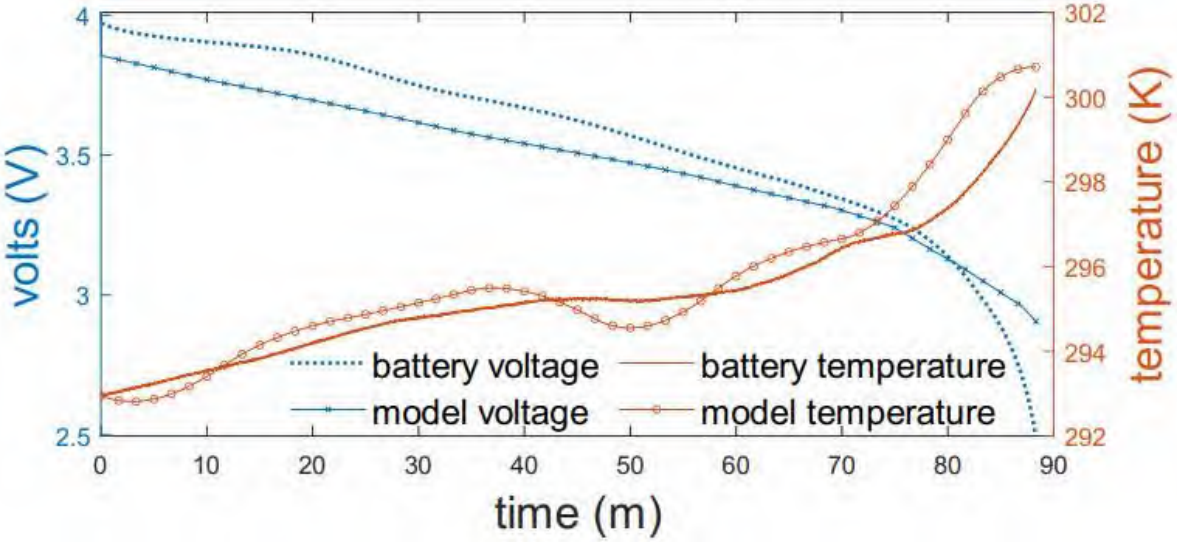


BATTERY TESTING CAPABILITIES

The real-time coupled electro-thermal model,

- Is coupled through the shared electrical and thermal parameters of the two sub-models.
- Is an isothermal reduced order model that include the heat loss from convection.
- Modeled using in-house battery cell data obtained through a hybrid pulsed power setup to characterize the batteries over a wider range of power draws (up to failure) and temperature.

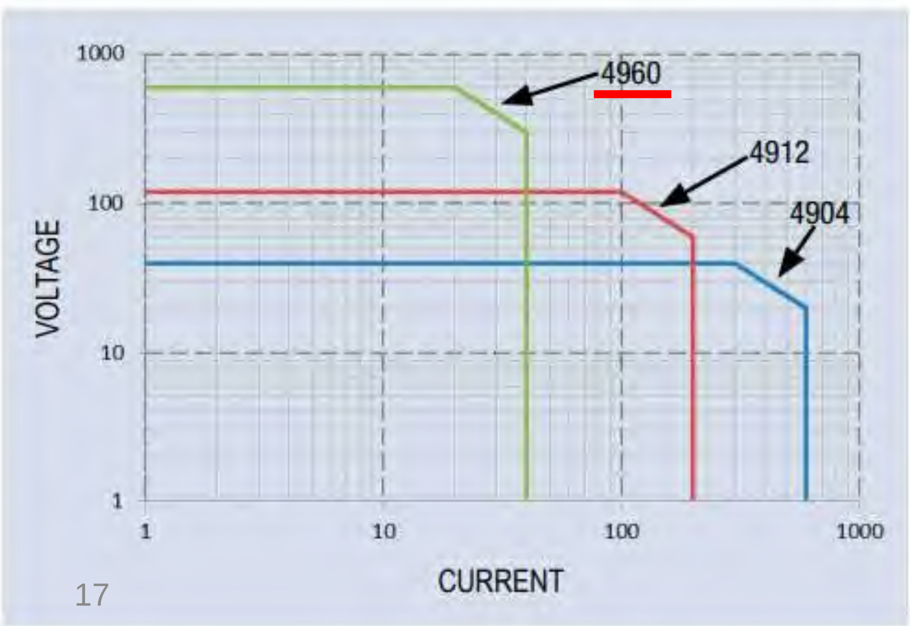




FULL-SCALE BATTERY PACK TESTING

Recently acquired battery pack test system,

- 108 kW Maximum test power (All three cabinets required).
- 9 channels at 12 kW per channel.
- Power module maximums of 600 V and 360 A.
- Can be coupled with shock and vibration testing.



EXPERTISE IN ENERGY AT THE UNIVERSITY OF SOUTH CAROLINA

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> 40% OF THE FACULTY IN CEC WORK IN ENERGY

$10 million research program aims to digitally replicate U.S. naval power and energy systems

Posted on March 10, 2022; Updated on March 10, 2022
By Chris Woodley, cwoodley@mailbox.sc.edu

The doomed Apollo 13 space mission was one of the first instances where the public understood that performing experiments in a simulation model could save a system. The three astronauts on board would never have survived if not for engineers who ran simulations and predicted a course of action that rescued the mission.

CEC's General Atomics Center seeks innovations in nuclear fuels and waste to meet future needs

Mustain shows there's hope for anion exchange membrane fuel cells after all

Andreas Heyden receives $1M grant to develop methane conversion method

University of South Carolina, Navatek win contract to research Navy power and energy systems

Producing ethylene through a more environmentally safe process

Two CEC professors awarded significant funding from the Office of Naval Research

By Chris Woodley

College of Engineering and Computing faculty Roger Dougal and Yi Wang have been awarded a combined $14.75 million in funding from the U.S. Office of Naval Research (ONR) for their respective research. Both awards are for three years, and Columbia-based Integer Technologies will serve as subcontractor for both research projects.

"Receiving funding from ONR is indeed quite competitive and a mark of

CEC professor Lucy Yu leads effort to enhance safety of nuclear fuel storage

Proposed solution will prevent leak of radioactive materials at storage sites

Lucy Yu, an associate professor of mechanical engineering in the College of Engineering and Computing, is developing a technology that will repair and mitigate stress corrosion cracks in nuclear spent fuel storage containers. Her research will potentially reduce the safety hazards associated with nuclear spent fuel storage by preventing leaks of radioactive materials.

UofSC power electronics team reimagines America's energy grid

Research could change how power is moved to homes and businesses

By Leigh Thomas | September 28, 2020

The University of South Carolina College of Engineering and Computing's power electronics team has spent the past two years conducting a study with Emera Technologies that has the potential to transform the endpoints of the United States' electrical grid. The research aims to incorporate direct current (DC) power into America's dated and aging alternating current (AC) energy system. Through the team's work, the way in

RELATED NEWS

A 20-year seat at energy distribution's most important table

Areas of Expertise and Research Infrastructure

Energy Efficiency, Conversion and Storage

Electrochemical Energy Conversion and Storage
Advanced Batteries
High and Low T Fuel Cells
Water Electrolysis
Cell and Stack-Level Simulation
Corrosion

Advanced Energy Carriers and Fuels
Emerging Fuels: H_2, NH_3, Biomass
Nanostructured Catalysts
Advanced Hydrocarbons
Combustion
Pollution Prevention

Thermal Processes and Nuclear
Reactor Design
Storage and Safety
Systems Modeling and Prediction
Behavior in Extreme Environments
Structured Materials

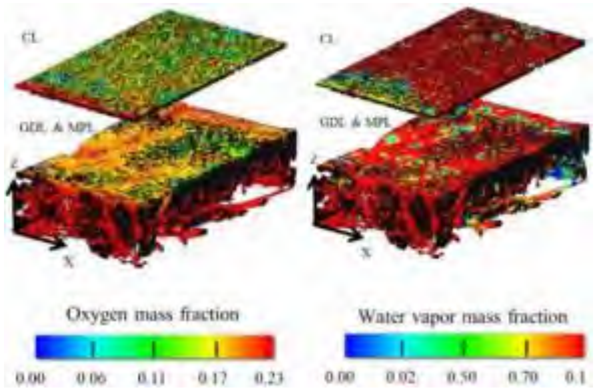
Energy Systems Optimization
Power Management Topology
Energy Systems Optimization
Machine Learning/AI
Multi-Source Integration
Vulnerability, Failure and Recovery

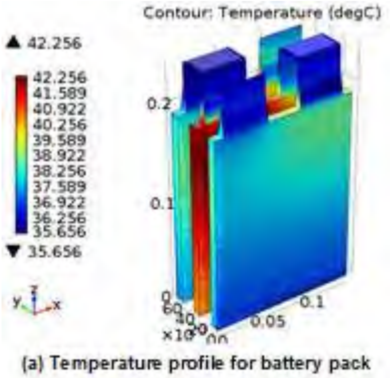
Electrical Energy Conversion and Controls
Wide Band Gap Devices
Digital Twins
Power Electronic Converters
Advanced Controls
Data Enabled Power Management

- Center for Electrochemical Engineering
- Solid Oxide Fuel Cell SmartState Center
- Hydrogen and Fuel Cell Center
- Center for Rational Catalyst Synthesis (CeRCAS)
- Catalysis for Renewable Fuels (CREF)
- Strat. Approaches to the Generation of Electricity (SAGE)
- McNair Center
- Center for Transformational Nuclear Technologies
- Nuclear Science and Energy Center
- AI Institute
- Center for Infrastructure Resiliency (TBD)
- Photonics-Microelectronics Laboratory
- Center for Grid-connected Adv. Power Electronic Systems (GRAPES)

Electrochemical Energy Conversion and Storage

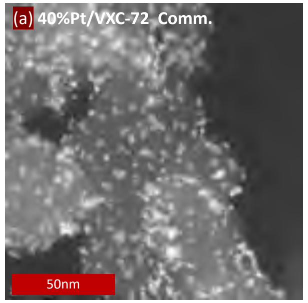
Cell and Stack-Level Simulations

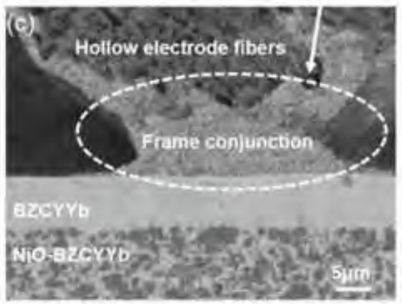


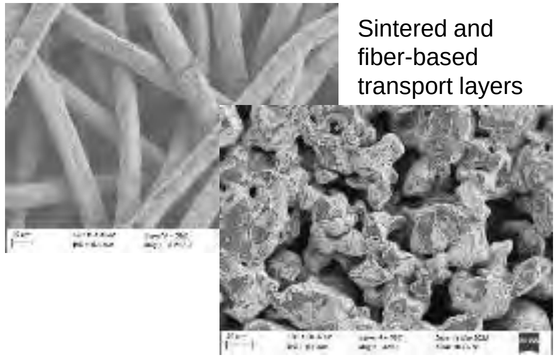


Macro-scale understanding of reactant and thermal distribution in batteries, fuel cells, etc.

High and Low T Fuel Cells



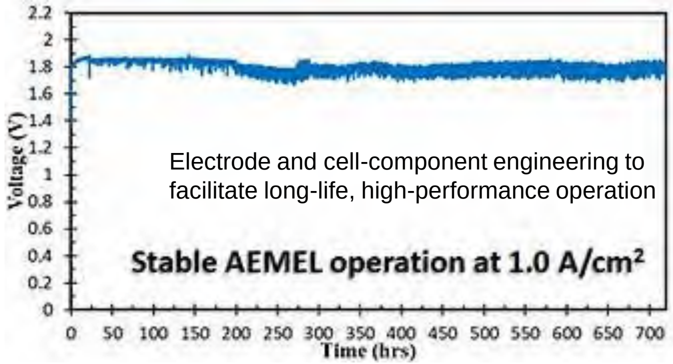




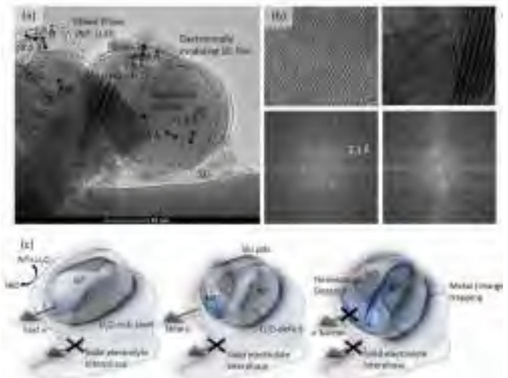
Sintered and fiber-based transport layers

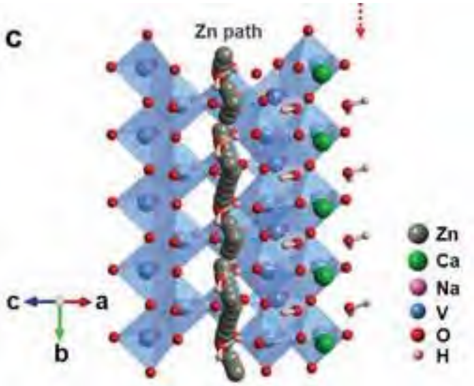
New catalysts, interfaces of materials, integration into stacks and systems

Water Electrolysis



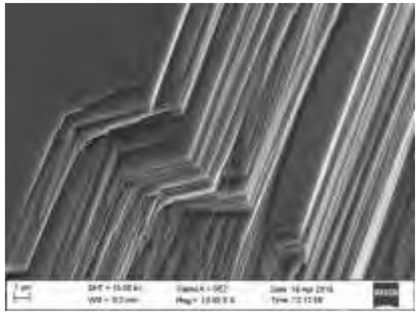
Advanced Batteries

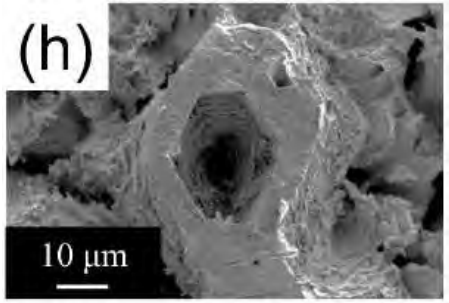




Materials conception and properties, degradation mechanisms, full-cell assembly and long-term testing

Corrosion





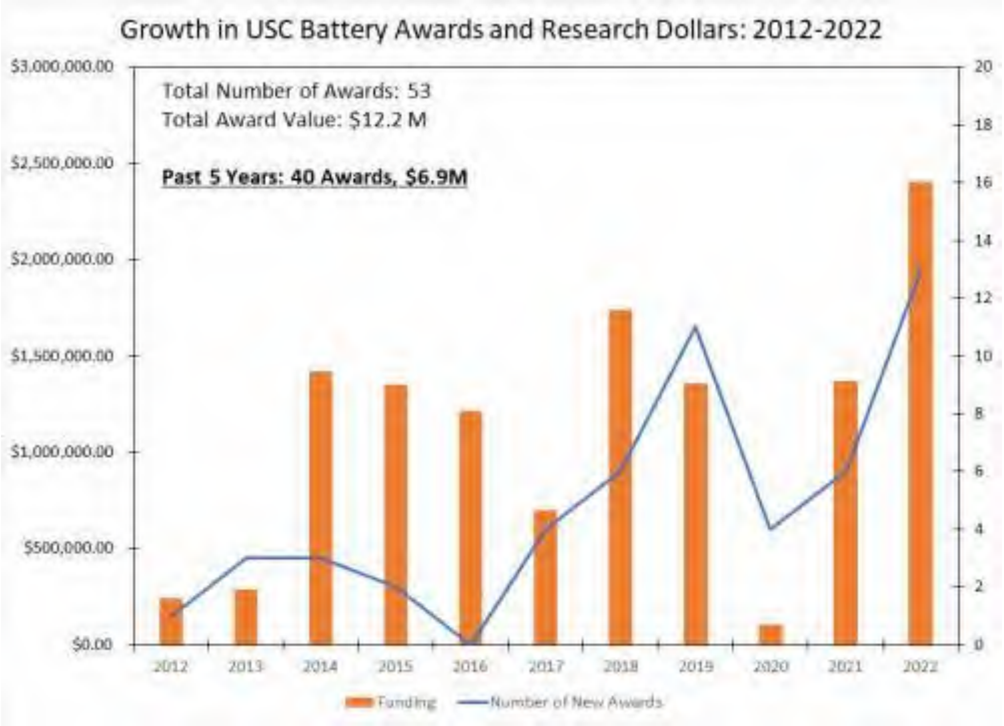
Long-term behavior of materials in extreme environments (T, pH, potential)

Battery Research Collaborators and Funders

Office of Naval Research
ONR
Science & Technology
TESLA
amazon
NASA
NSF
Fraunhofer
GM
Argonne NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY
saft
DURACELL
BOEING
NantEnergy
SRNL
ENERVENUE
Soteria™
Ford
LORDSTOWN
arpa·e CHANGING WHAT'S POSSIBLE
NREL NATIONAL RENEWABLE ENERGY LABORATORY
CATL
EAGLEPICHER TECHNOLOGIES

Areas of Strength and Growth

- New materials, chemistries and integration into realistic formats
- Electrolyte design – both liquid and solid-state electrolytes
- Simulation from the material → microstructure → stack levels
- Battery safety in abuse and mechanical impact scenarios
- Alternative geometries – e.g. structural and flexible batteries
- Commercially relevant battery recycling systems for consumer batteries
- Developing highly modular, compact power electronics for integration into the next generation of power grid



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BATTERY SAFETY RESEARCH THRUST AT THE UNIVERSITY OF SOUTH CAROLINA

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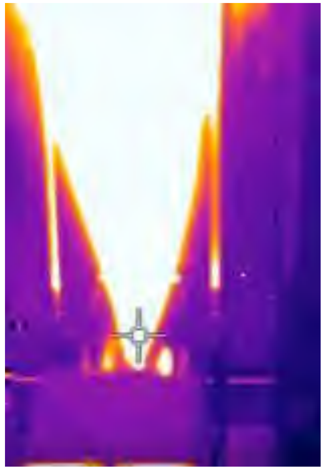
MECHANICAL ABUSE TOLERANCE STUDY OF LITHIUM-ION BATTERIES

- Cell and module level impact/crush testing capabilities
  - Can test small and large cells (100s of Ahs) at various state of charging, from 0~100% SoC
  - Can simulate various weather conditions (-80 C to 50 C)
  - Custom designed drop towers with custom impactors, can impact large cell from various directions, at a wide range of speed and energy levels (10s~1000s of Joules)
  - Precision measurement of intrusion distance, force, velocity, acceleration, and cell responses
  - Help establish cell damage/failure threshold

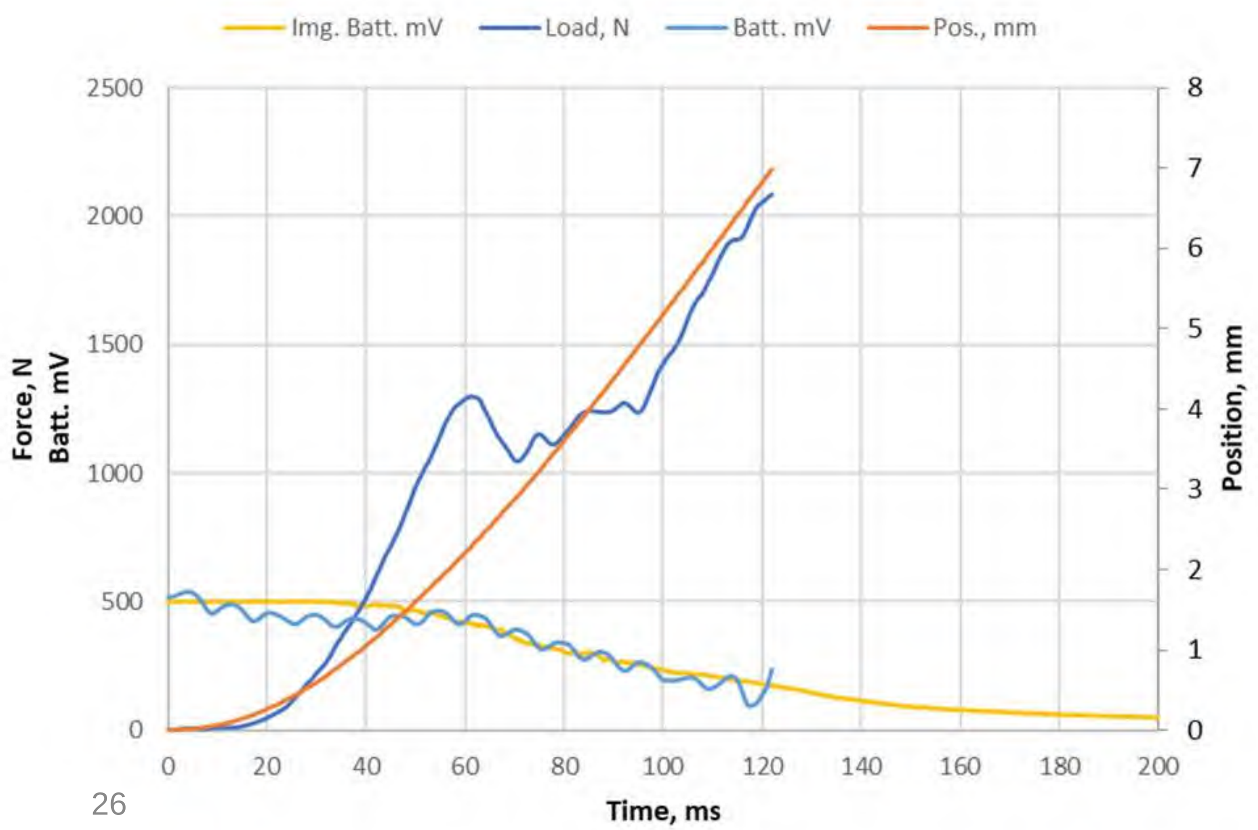
- *In situ* monitoring during impact
  - High speed video
  - Voltage, current, temperature (IR thermography)
- Post test monitoring
  - Voltage decay, temperature variation, Electrochemical impedance spectroscopy
- Post-mortem characterization to support root-cause analysis
  - Full cell tear-down
  - X-ray tomography
  - Physical chemical characterization

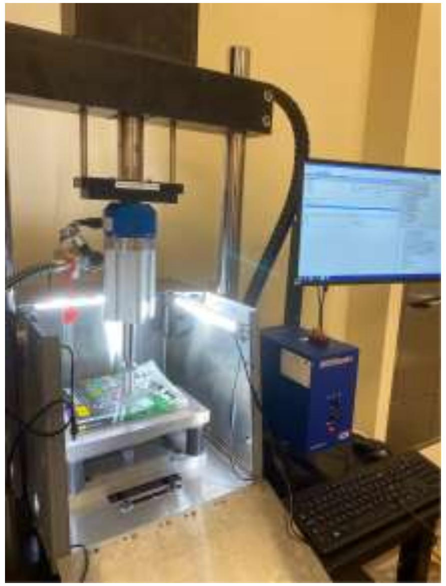


Large pouch cell thermal run-away triggered by mechanical impact

PENETRATION OF LARGE POUCH CELL

- Penetration resistance test of a large battery pouch test with a 6-mm dia. ball-end punch





Large pouch cell under testing

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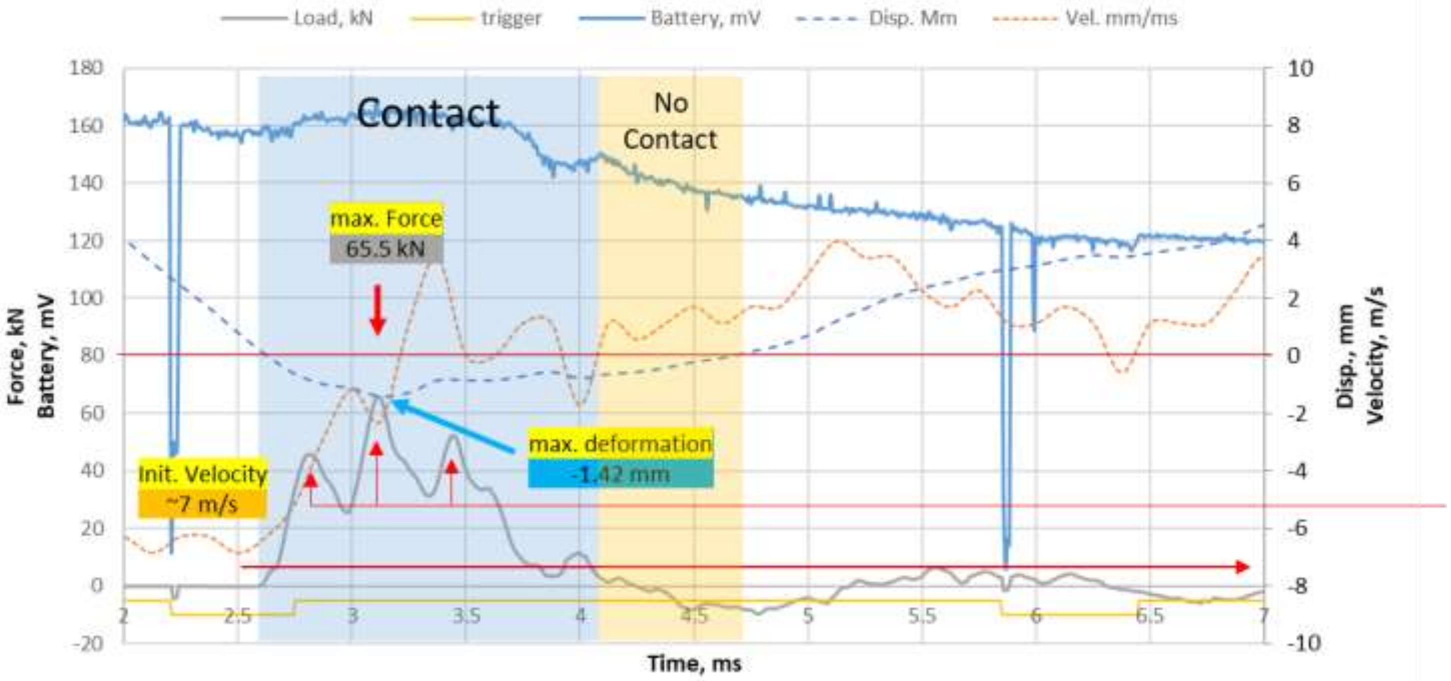
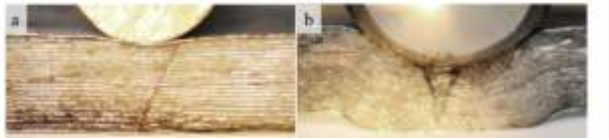
IMPACT TESTING ON POUCH CELLS



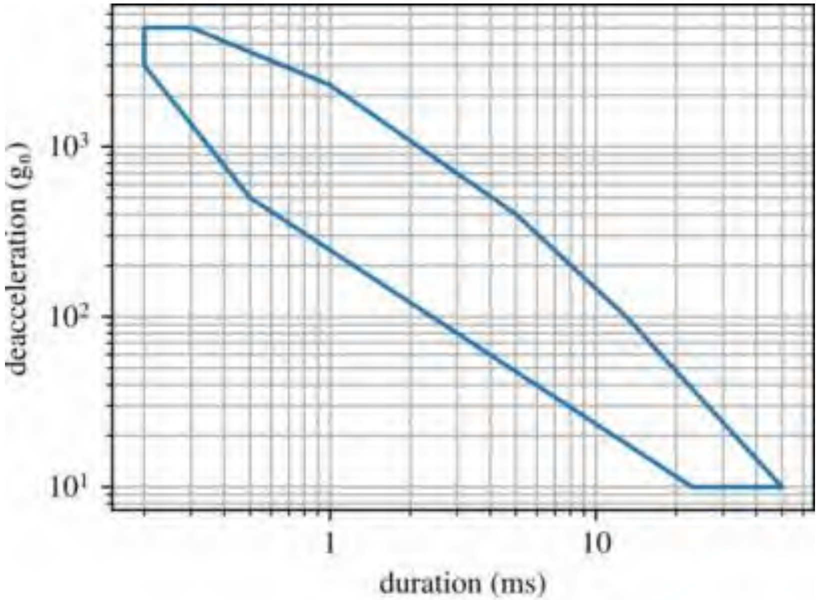


Help establish and verify cell internal material failure criteria

SHOCK AND VIBRATION TESTING CAPABILITIES

- Accelerated shock test system that can generate up to 5,000 g_n of de-acceleration and pulse times from 0.2 ms to 150 ms.
- Gravity shock test systems for testing full-scale battery components.
- 1-DOF vibration shake table for full-scale vibration testing of battery components.
- Substantial instrumentation for vibration and shock monitoring.

Accelerated Shock Test System



Gravity Shock Test System

Vibration Table

CENTER FOR BATTERY SAFETY AND DURABILITY (CBSD)

INDUSTRY–UNIVERSITY COOPERATIVE RESEARCH CENTERS (IUCRC)

Name: **C**enter for **B**attery **S**afety and **D**urability (CBSD)

Motivation: To understand the fundamental science and develop translational methodologies, protocols and tools for battery safety and durability.

Major themes:

1. New understanding of electrochemistry and interface instabilities
2. New modeling framework for battery safety behaviors (multiscale, from atomic to cell/pack level)
3. New testing protocols/experimental evaluations/characterizations for battery behaviors for lithium-ion batteries and beyond

Site 1: University of North Carolina at Charlotte (UNCC)

Site 2: South Carolina State University (SCSU)

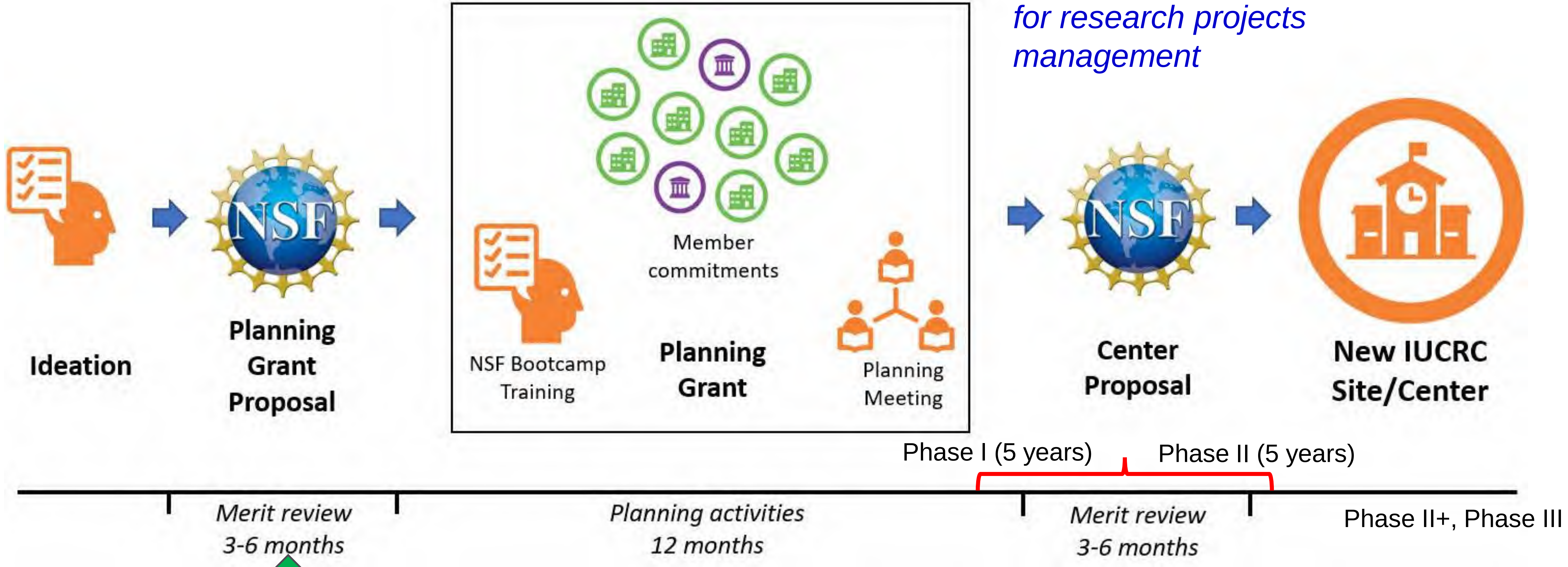
UNCC PIs: Dr. Jun Xu, Dr. Lin Ma, Dr. Youxing Chen …

UofSC PIs: Dr. Xinyu Huang, Dr. Bin Zhang, Dr. Austin Downey, Dr. Andrew Gross …

https://iucrc.nsf.gov/

IUCRC PROCESS

NSF sponsors 150K annually for research projects management



NSF sponsors 20K for a planning meeting

Requires "Letter of Commitment" from industry partners
Each site secures **3** letters.

We are here, preparing for conference

2023 BATTERY SAFETY WORKSHOP

- **Date:** June 8-9, 2023
- **Location:** UNC Charlotte Duke Centennial Hall Charlotte NC 28223
- **Organizers:** University of North Carolina at Charlotte, and University of South Carolina
- https://mees.charlotte.edu/research/research/2023-battery-safety-workshop
- Moving towards an NSF Industry-University Cooperative Research Centers (IUCRC)

THANK YOU!

Austin Downey

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UofSC South Carolina

Research Strengths: College of Engineering and Computing

Energy

Advanced Energy Carriers and Fuels
Thermal Processes and Nuclear
Power Generation + Management
Electrochemical Engineering
Energy Systems Optimization

Healthcare

Tissue Engineering
Therapeutic Development
Biomechanics
Biomarker Identification
Bioinformatics

Resiliency and Adaptation

Environmental Management
CO_2 Mitigation and Utilization
Soil and Water
Sustainability
Infrastructure

Artificial Intelligence and Control

Computer-Aided Design
Process Dynamics and Control
Systems Optimization
Mathematical Modeling
Machine Learning

Computing and Security

Cybersecurity and Privacy
Networking and Systems
High Performance Computing
Sustainable Computing
Internet-of-Things (IOT)

Materials and Manufacturing

Synthesis and Characterization
Aerospace
Automation and Diagnostics
Catalyst Design and Deployment
Advanced Semiconductors

Sensing and Communication

Sensor Design and Implementation
Target Identification
Defect Identification
Automation
Wireless Communication

ASN DIRECTIVES

Honorable Meredith Berger
Assistant Secretary of the Navy for Energy, Installations & Environment
2023 Feb 1 Briefing Takeaways

Energy

- Need more operations, less risk; More capability, less cost
- Operational energy = Warfighting capability

Fuel

- "Reduce demand, dependency, dollars."
- "For every 50 convoys of fuel, a marine was lost or wounded."
- Less fuel convoys, less mission risk

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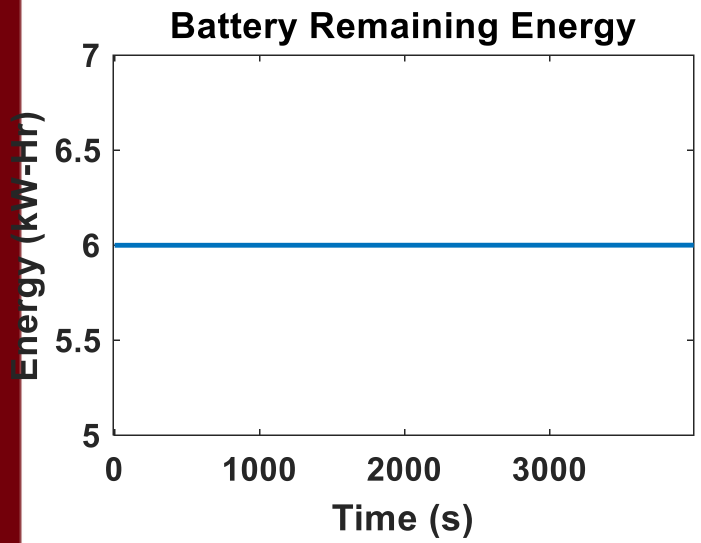
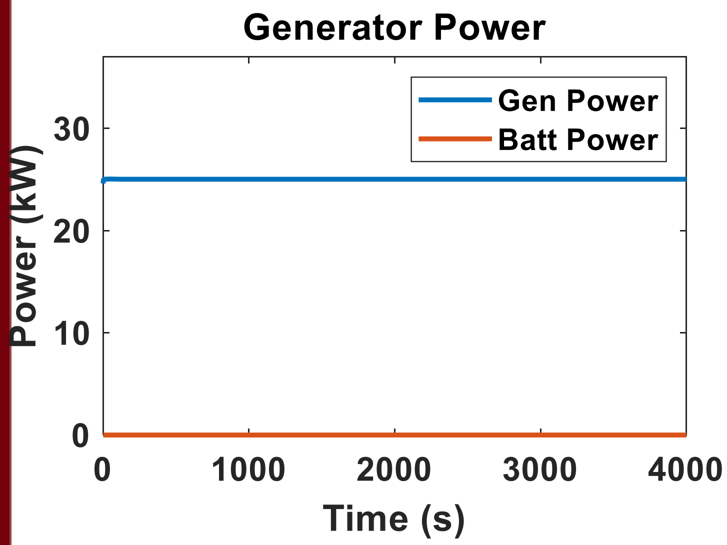
AUTOMATIC SIMULATION MANAGEMENT





Load Sharing

Increase →

New DT Instance Predictions:

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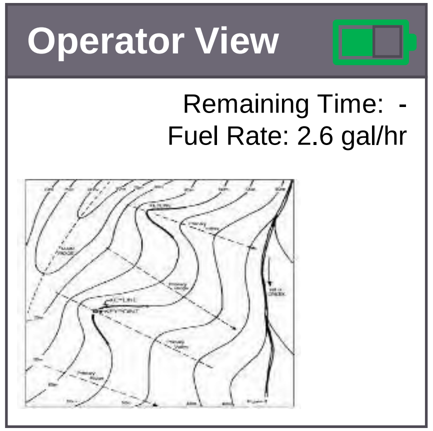

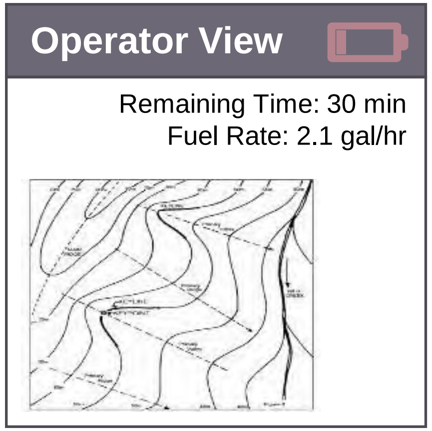

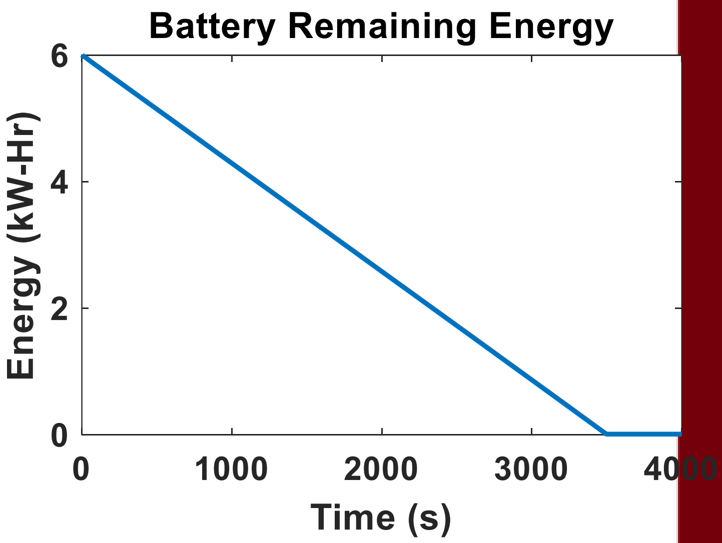

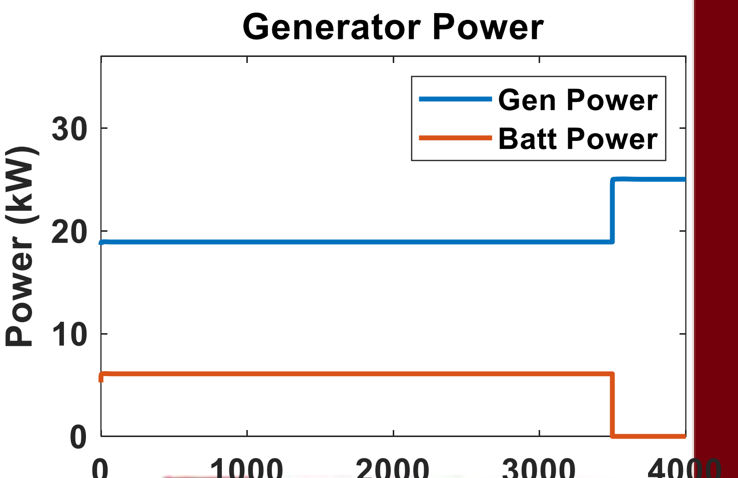

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