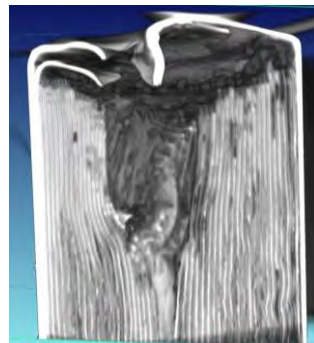


Exceptional service in the national interest



Electrochemical Abuse Testing

Joshua Lamb, Leigh Anna M. Steele, Chris Grosso, Jerry Quintana, Loraine Torres-Castro, June Stanley, Summer Ferreira and John Hewson

Sandia National Laboratories

Energy Storage Peer Review

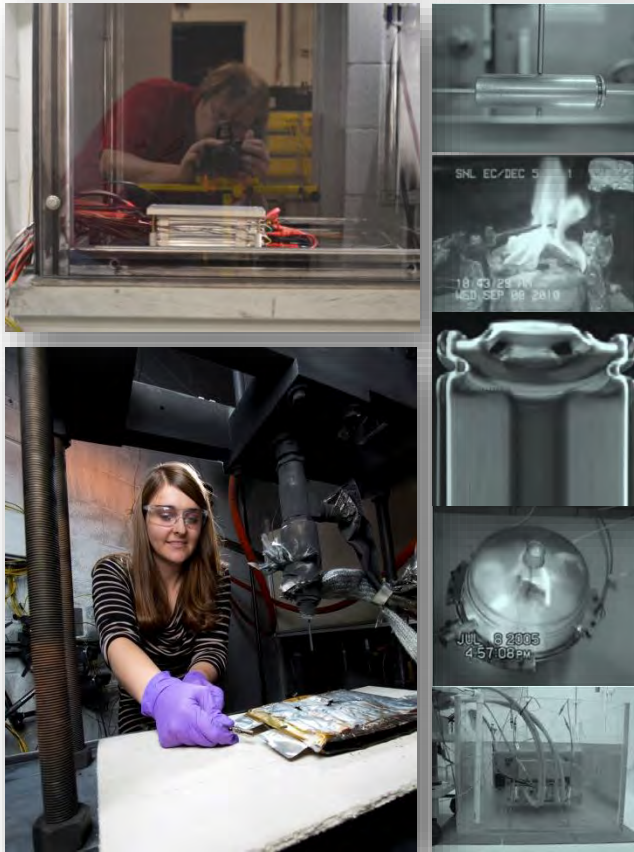
San Diego, CA, October 11-12, 2017



Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Approach and Capabilities

Cell and Module Testing Battery Abuse Testing Laboratory (BATLab)



Battery Pack/System Testing Thermal Test Complex (TTC) and Burnsite



Battery Calorimetry



Understanding Battery Safety



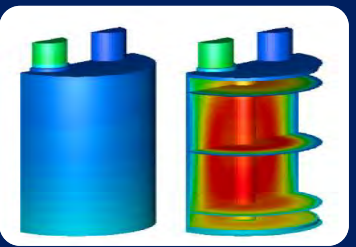
Materials R&D

- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials



Testing

- Electrical, thermal, mechanical abuse testing
- Large scale thermal and fire testing (TTC)
- Failure propagation testing on batteries/systems
- Diagnostic techniques for battery state of stability
- Development for DOE Vehicle Technologies and USABC



Simulations and Modeling

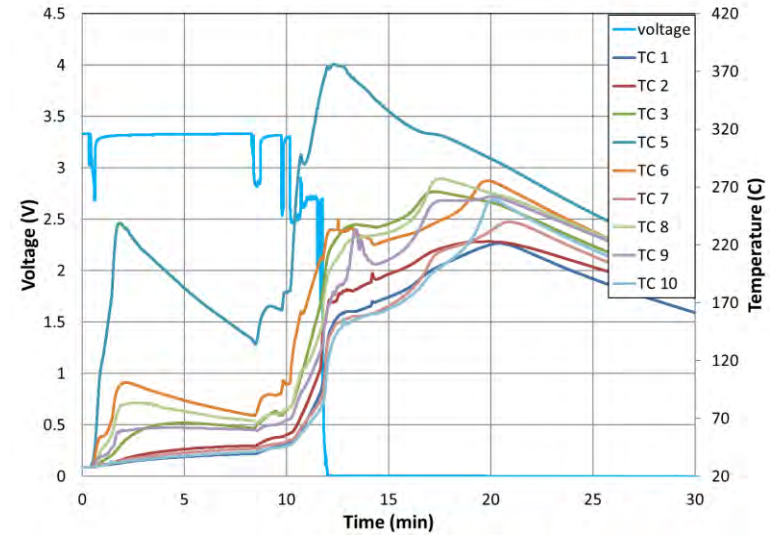
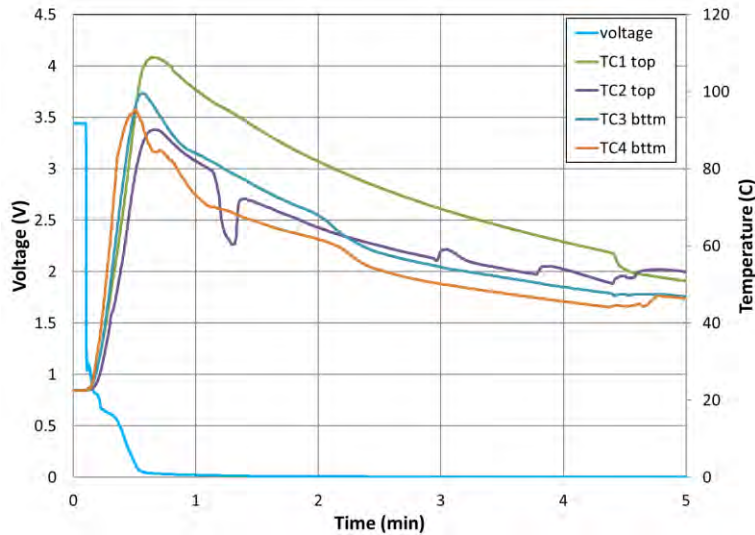
- Multi-scale models for understanding thermal runaway
- Validating vehicle crash and failure propagation models
- Fire Simulations to predict the size, scope, and consequences of battery fires



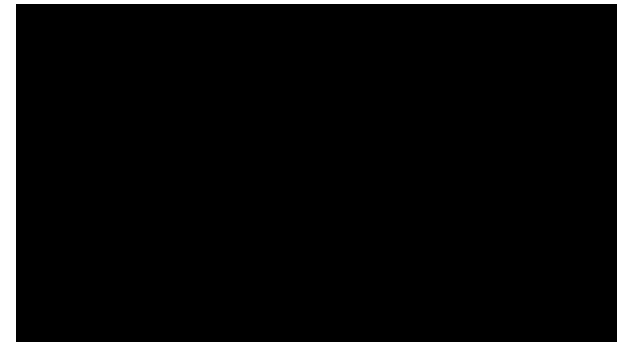
Procedures, Policy, and Regulation

- USABC Abuse Testing Manual (SAND 2005-3123)
- SAE J2464/UL 1642 procedures and standards
- R&D programs with NHTSA/DOT to inform best practices, policies, and requirements

Motivation for propagation testing

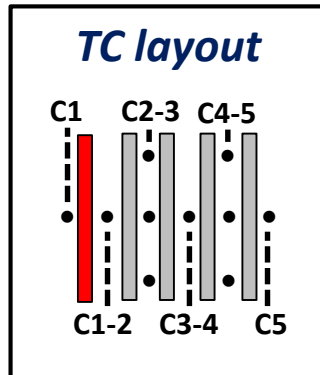
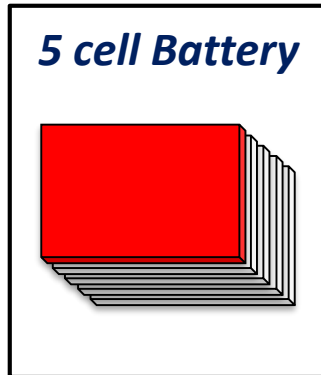


- *Results of single cell nail penetration and 1S10P propagation test*
- *26650 LFP cell*
- *Single cell has relatively minor failure*
- *Significant increase in intensity with a 10 cell pack*

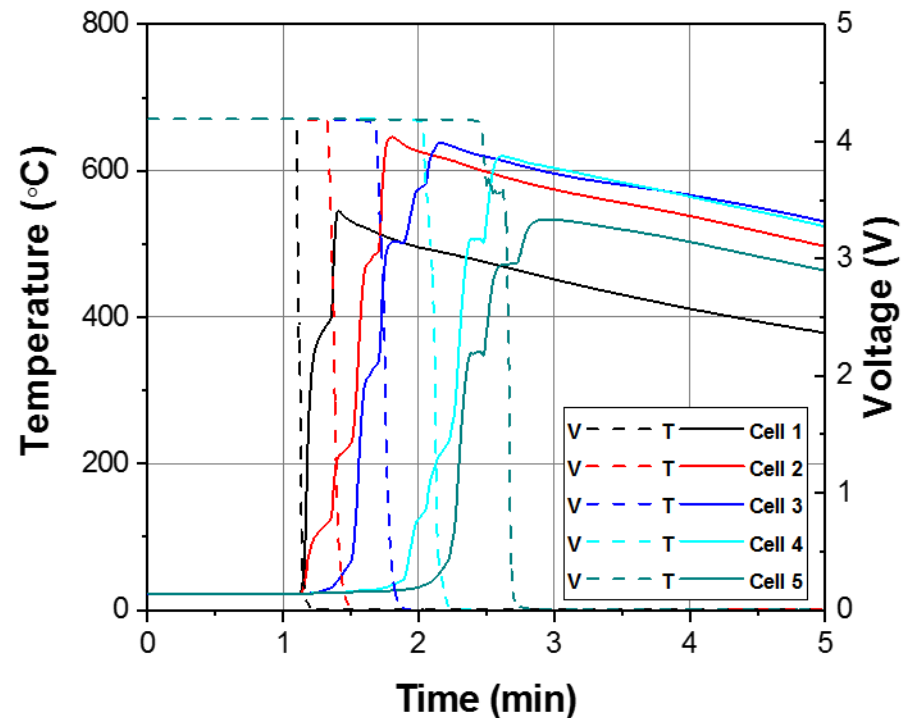


Failure Propagation: No Thermal Management

Failures initiated by mechanical insult to edge cell of COTS LiCoO₂ packs (3Ah cells)

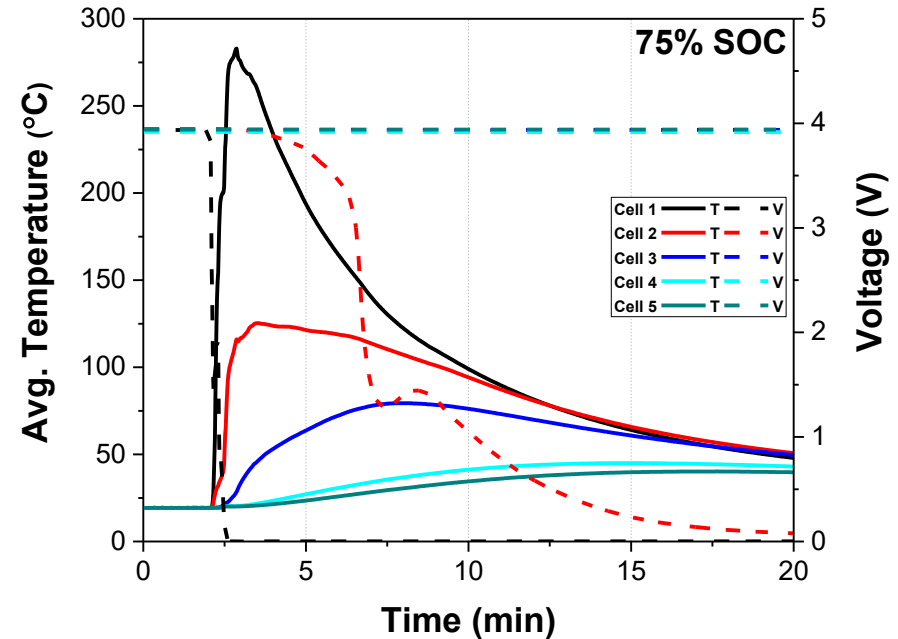
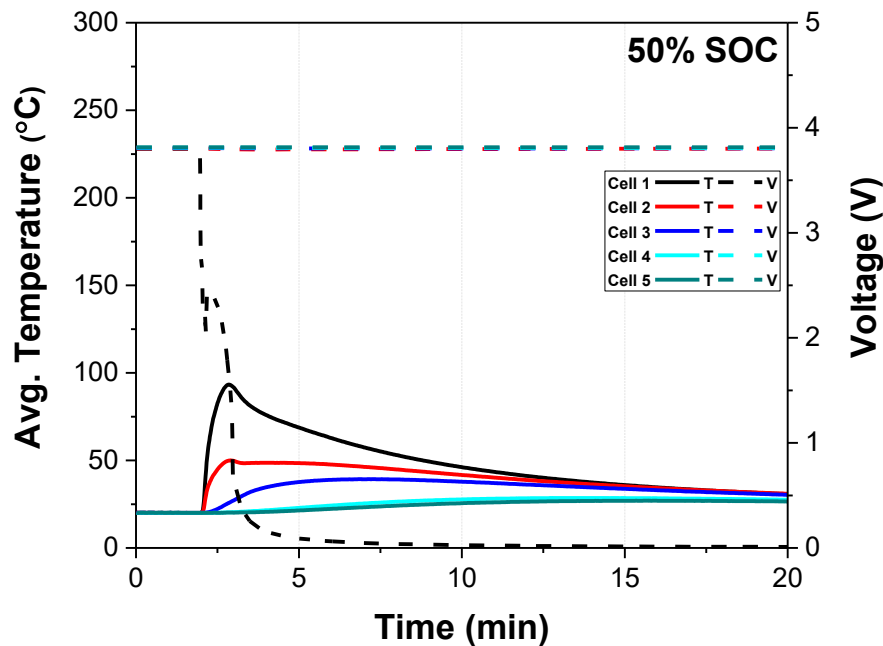


- Successful initiation at Cell #1
- Propagation to adjacent cells
- Cascading failure to entire battery over 60 s



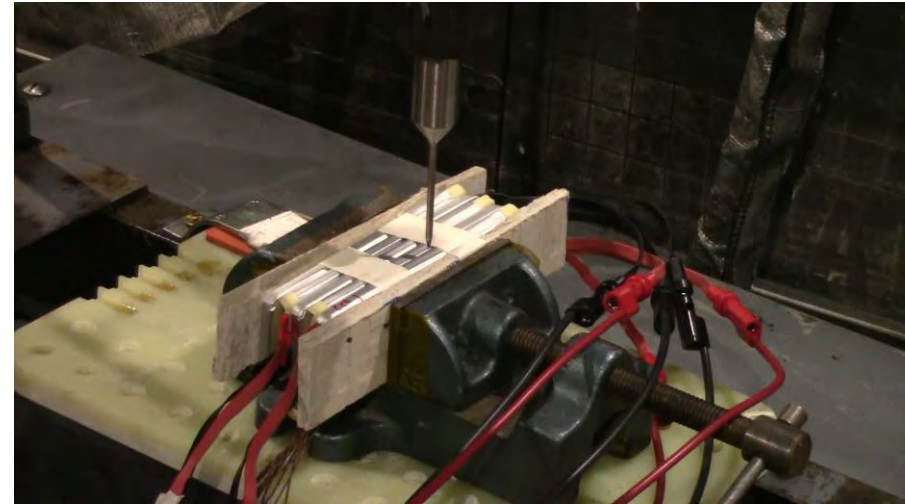
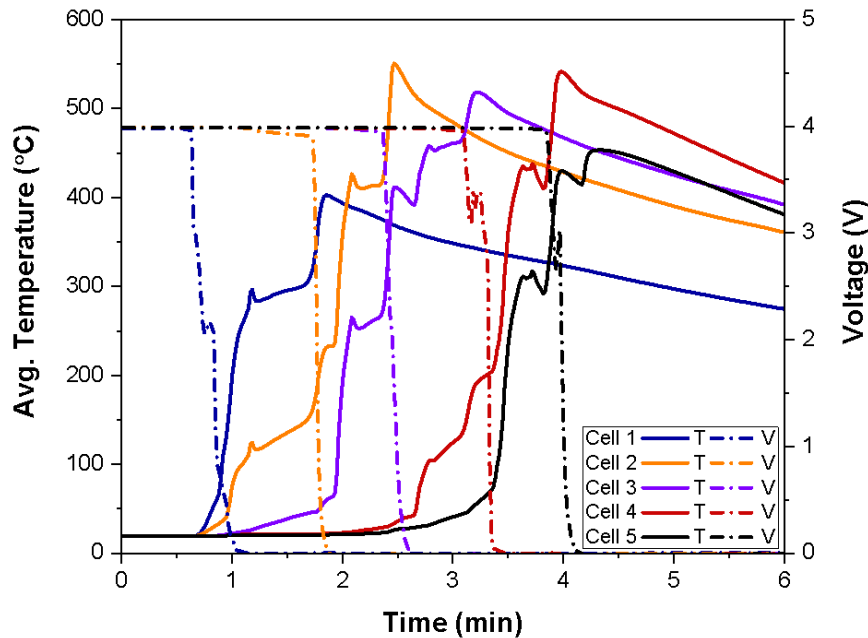
- ***Observed complete propagation when cell are close packed with no thermal management***

Mitigation through de-rating cells



- **50% SOC no cell to cell propagation observed**
 - *Thermal runaway of initial cell failure also fairly minimal*
- **Limited propagation at 75%**
 - *Cell 2 went into thermal runaway following the failure of cell 1*
 - *Some other cell damage was observed but no high rate thermal runaway events seen in cells 3-5*

Limits to cell de-rating



- **Full failure of pack observed starting at 80% SOC**
- **Compared to unmitigated baseline, peak temperatures observed were only marginally lower (550 °C vs 620 °C)**
- **Total pack propagation observed after ~4 minutes vs ~80 seconds at 100% SOC**

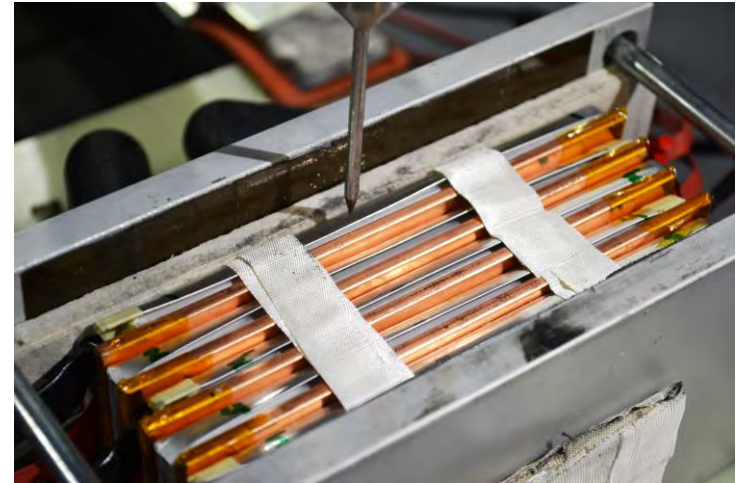
Failure Propagation Testing: Inclusion of Thermal Management

Methodology:

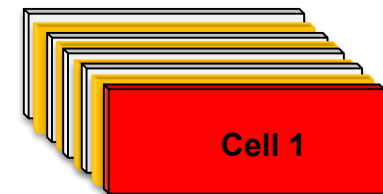
- Experimentally determine a reproducible thermal runaway initiator for each cell type
- Use this initiator to trigger a single cell thermal runaway failure in a battery
- Evaluate the propagation of that failure event

Experiment

- COTS LiCoO₂ 3Ah pouch cells
- 5 cells closely packed
- Failure initiated by a mechanical nail penetration along longitudinal axis of edge cell (cell 1)
- **The current effort is focused on understanding extent of propagation with inclusion of passive thermal management in the form of heat sinks between pouch cells (aluminum and copper)**

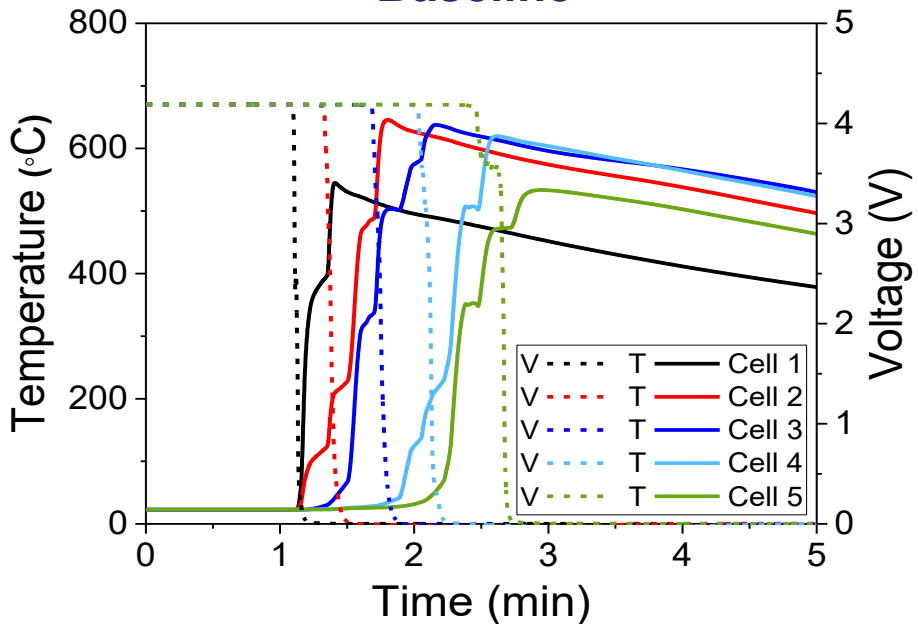


5 cell pack with aluminum or copper spacers between cells

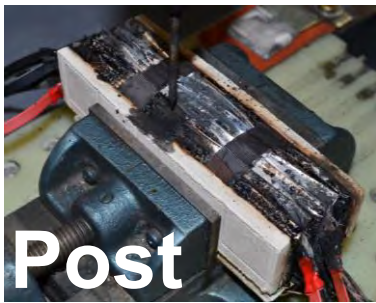
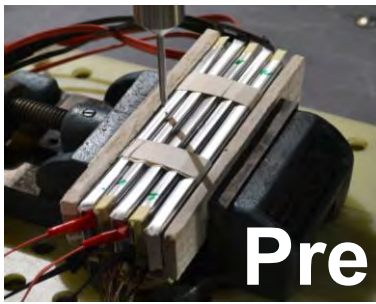
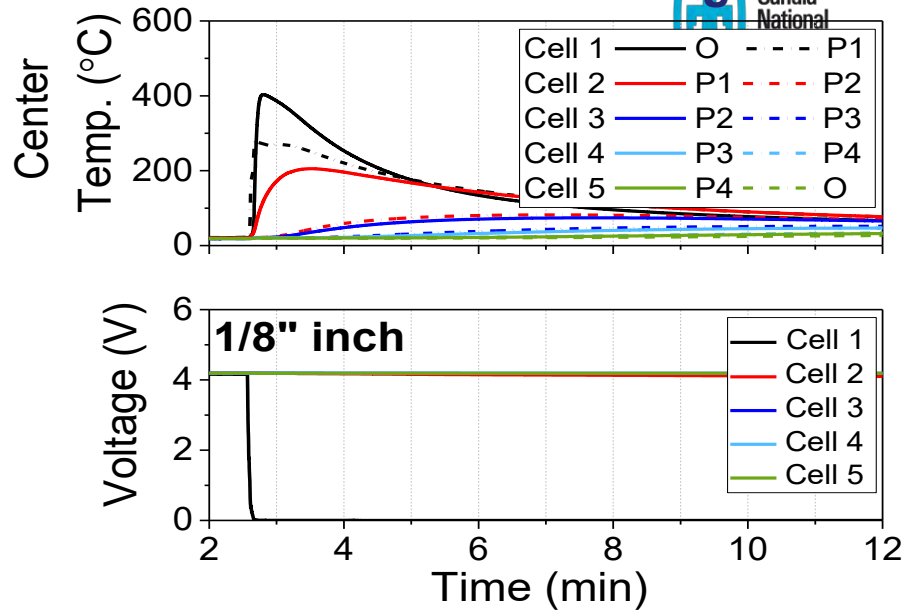


For more detail on these results please see poster titled “Mitigation techniques for failure propagation” presented by Dr. Loraine Torres-Castro

Baseline



Passive thermal management



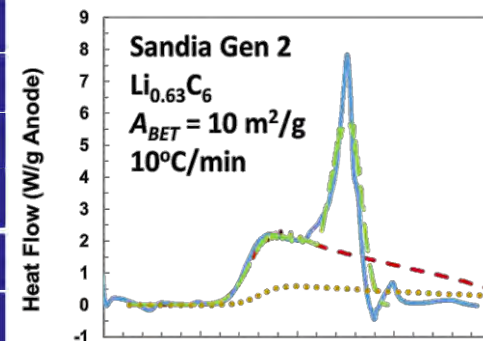
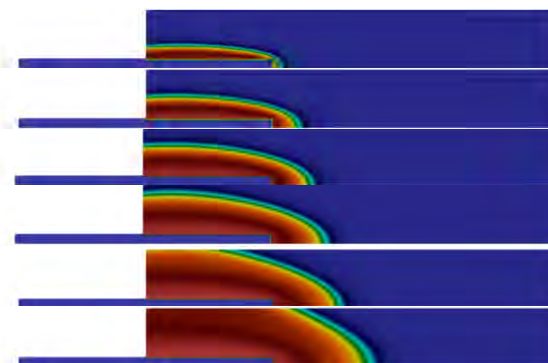
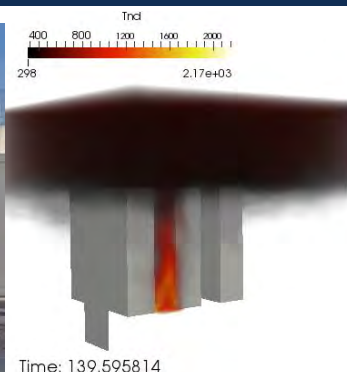
Discussion

- A cell may exhibit dramatically different failure response when in a string, module or pack than during single cell abuse testing
- Limiting the SOC can have a meaningful impact in propagating failure, however this comes at a significant cost to total energy storage
- Propagation can be mitigated through system engineering, however the results can be unpredictable. Further, electrical design will play a role in susceptibility to failure testing.
- Failure testing of large, complex systems is fairly resource intensive. Model based design presents a potential remedy to this, allowing us to infer a large amount of information from a relatively small number of tests.

Acknowledgements

- **Imre Gyuk – US Department of Energy
Office of Electricity**
- **Christopher Orendorff**
- **Babu Chalamala**
- **Randy Shurtz**
- **Heather Barkholtz**
- **Kyle Fenton**
- **Eric Allcorn**
- **Lorie Davis**
- **Mani Nagasubramanian**
- **Jill Langendorf**

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Predictive modeling for energy-storage safety in abnormal thermal scenarios

John Hewson, Randy Shurtz

Babu Chalamala, Summer Ferreira, Josh Lamb, Heather Barkholtz, Lorraine Torres-Castro

Sandia National Laboratories

Office of Electricity Peer Review

October 10, 2017

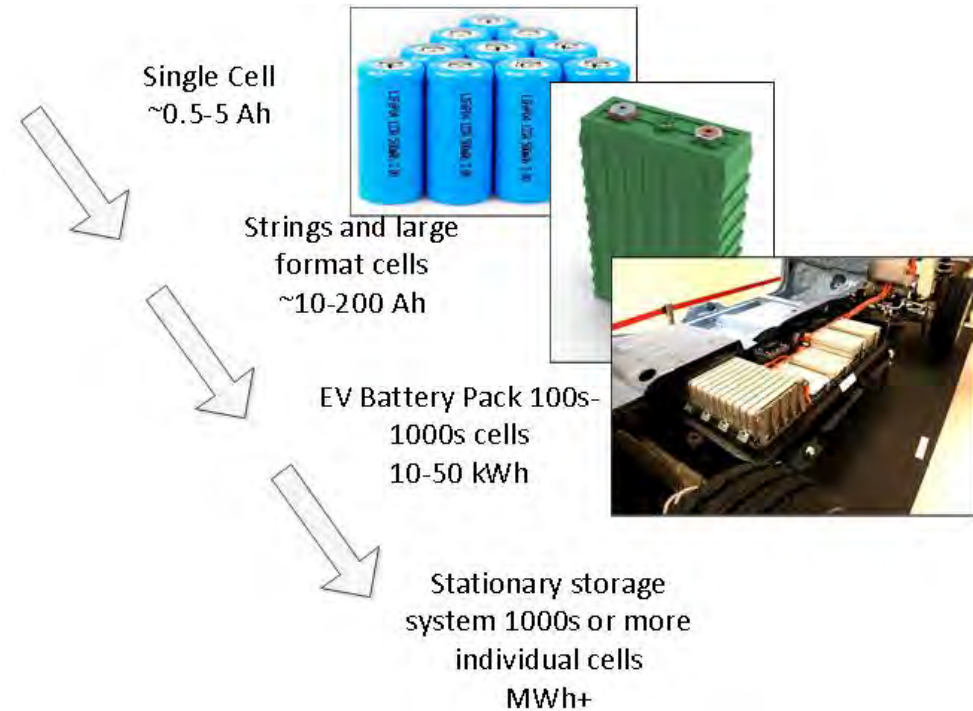
SAND2017-10933 C



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Validated reliability and safety is one of four critical challenges identified in 2013 Grid Energy Storage Strategic Plan

- Failure rates as low as 1 in several million,
- Potentially many cells used in energy storage.
- Moderate likelihood of 'something' going wrong,



- A single cell failure that propagates through the pack can have an impact even with low individual failure rates.

- **How do we decrease the risk?**

www.nissan.com
www.internationalbattery.com
www.samsung.com
www.saft.com



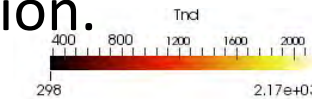
Approaches to designing in safety

The current approach is to test our way into safety¹

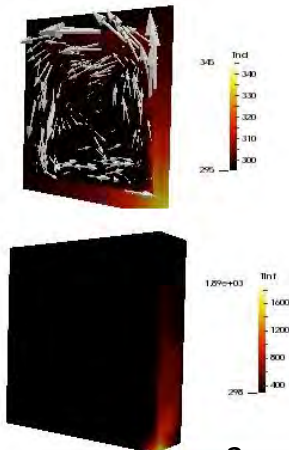
- Large system (>1MWh) testing is difficult and costly.

Consider supplementing testing with predictions of challenging scenarios and optimization of mitigation.

- Develop multi-physics models to predict failure mechanisms and identify mitigation.
- Build capabilities with small/medium scale measurements.
- Still requires some testing and validation.

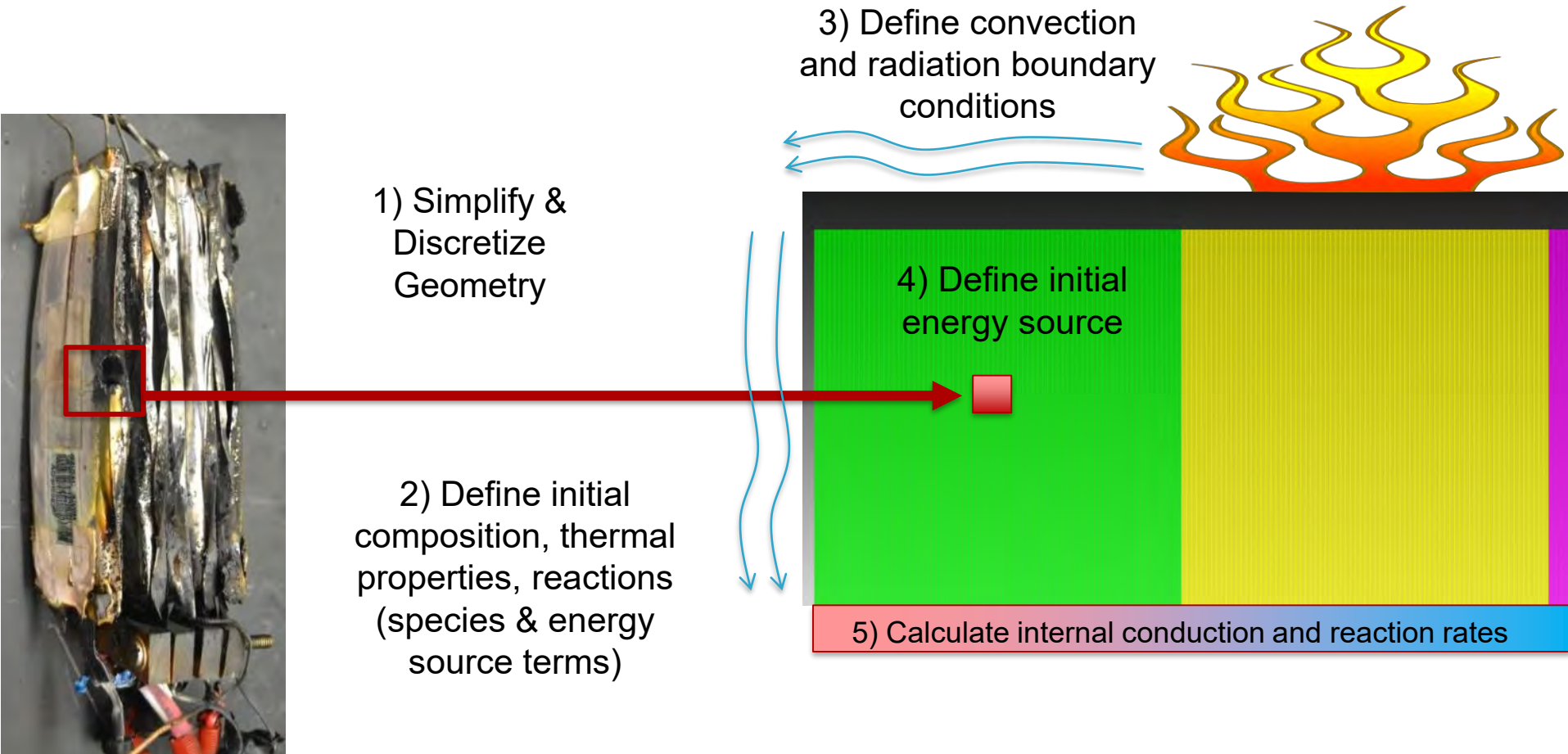


Time: 46.683046



¹ 'Power Grid Energy Storage Testing Part 1.' Blume, P.; Lindenmuth, K.; Murray, J. EE – Evaluation Engineering. Nov. 2012.

How Do We Model Thermal Runaway in Batteries?



Models Need Parameters

- Preliminary chemistry model from literature
 - Based on Dahn group from 2000, 2001
 - Derived from calorimetry data (ARC and DSC)
 - Needs to be recalibrated

- Empirical chemical reactions
 - SEI decomposition $2 \text{ROCO}_2\text{Li} \rightarrow \text{Li}_2\text{CO}_3 + \text{prod}$
 - Cathode-electrolyte $\text{CoO}_2 + \text{C}_3\text{H}_4\text{O}_3 \rightarrow \frac{1}{3}\text{Co}_3\text{O}_4 + \text{prod}$
 - Electrolyte-salt $\text{C}_3\text{H}_4\text{O}_3 + \text{LiPF}_6 \rightarrow \text{prod}$
 - Anode-electrolyte $\text{C}_6\text{Li} + \text{C}_3\text{H}_4\text{O}_3 \rightarrow \text{Li}_2\text{CO}_3 + \text{prod}$

- This model form has been utilized repeatedly, but requires calibration for each system because it is not expressed in terms of fundamental cell characteristics.

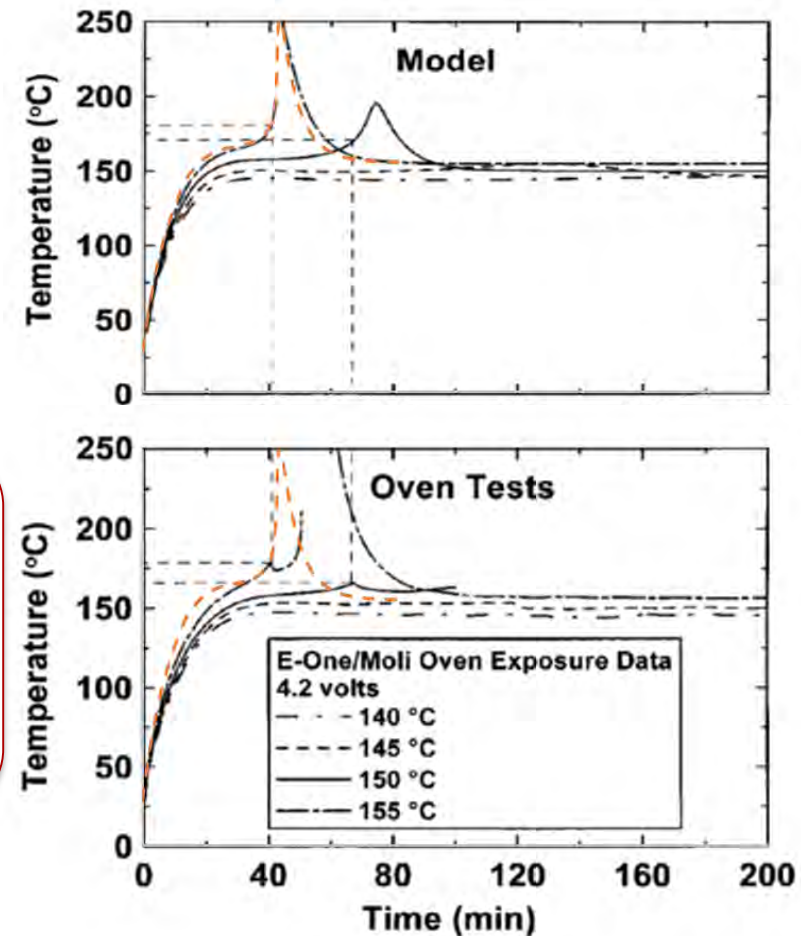
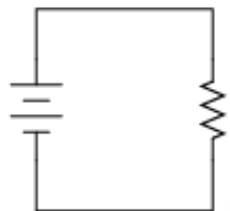
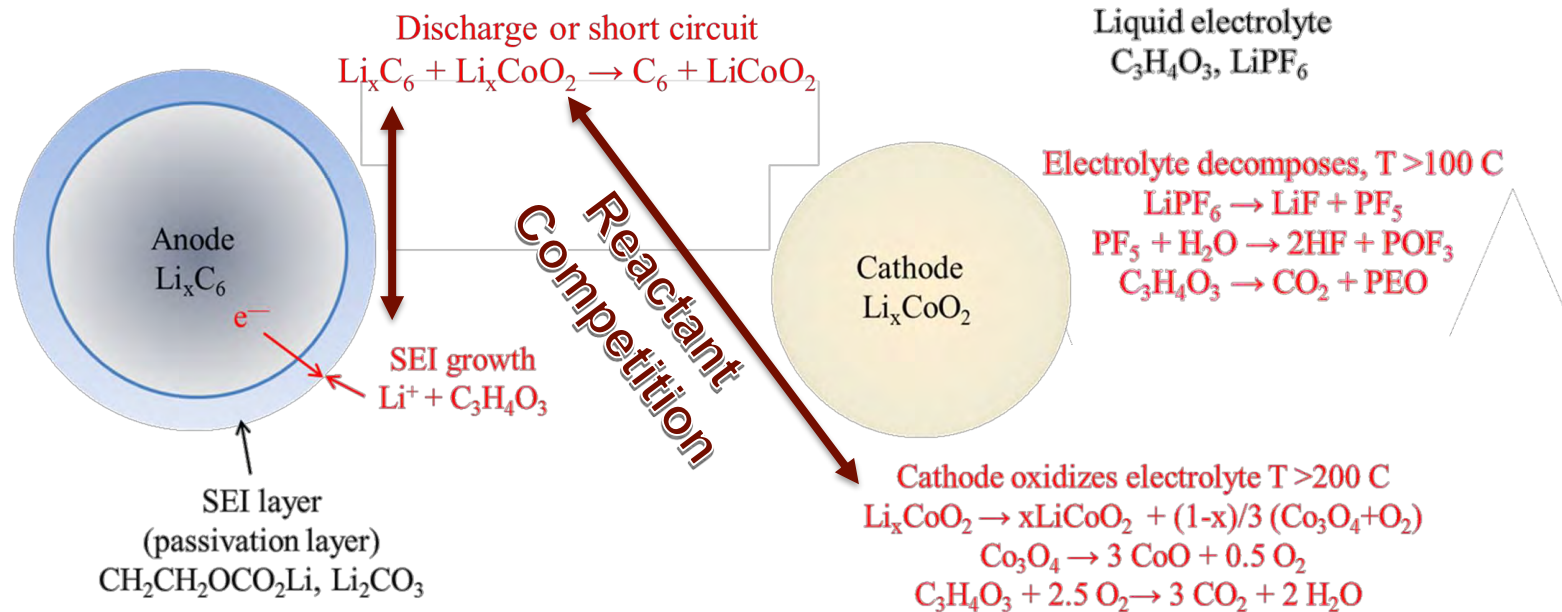
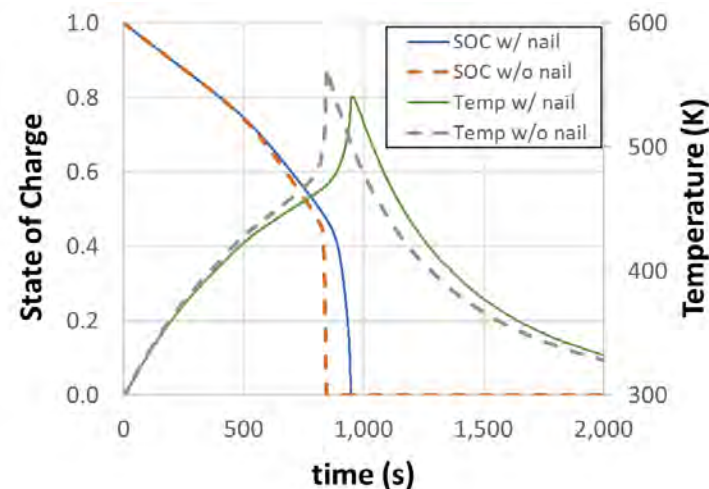
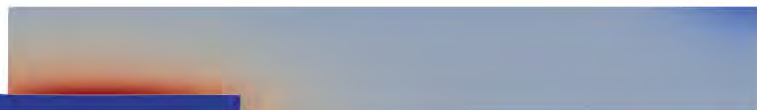


Figure 2. A comparison of oven exposure test results to model predictions: (top) model predictions and (bottom) oven test results for 18650 E-One/Moli Energy cells charged to 4.2 V.

Thermal and electrochemical reactants are same



Simulated short circuit plus thermal runaway

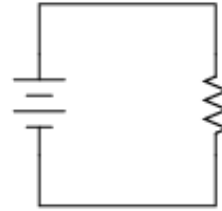


Limits of thermal runaway in high-temperature environments and under internal short-circuits

Simulated oven test



high temp environ



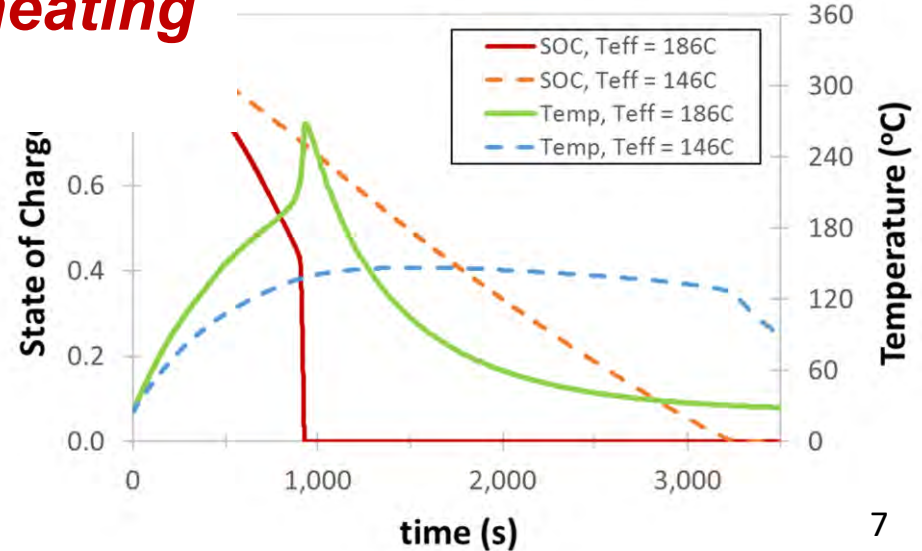
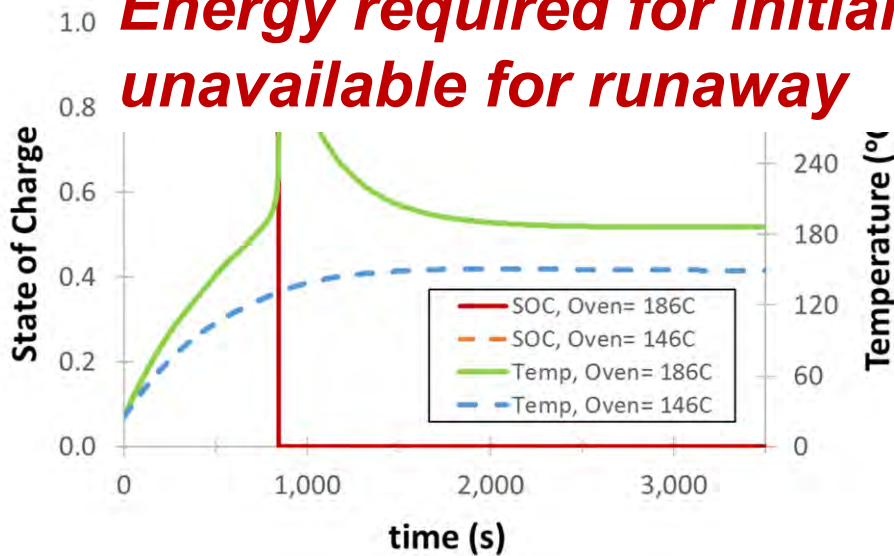
Simulated short circuit analogy with oven temperature



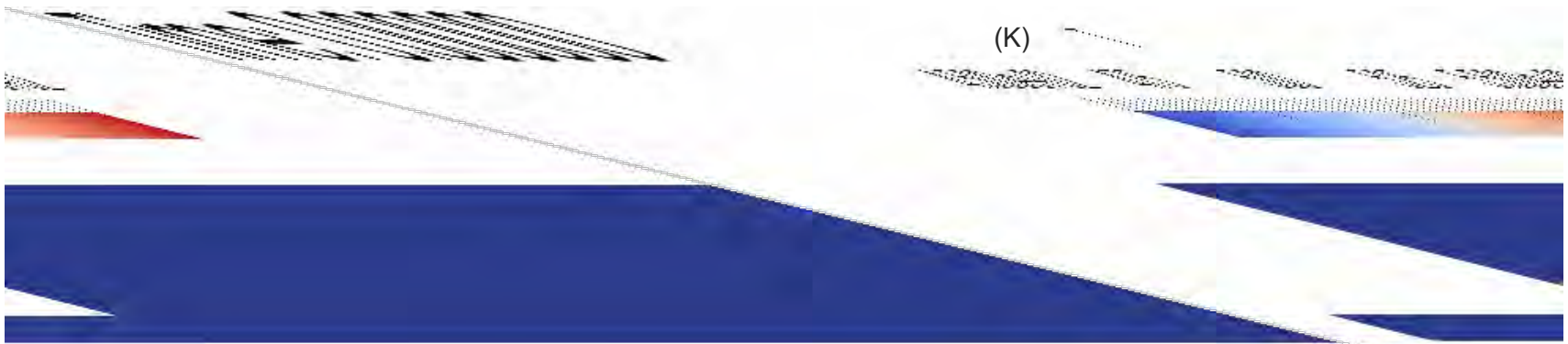
$$P = \frac{V^2}{R}$$

$$T_{eff} = T_{\infty} + P / h_{net} A$$

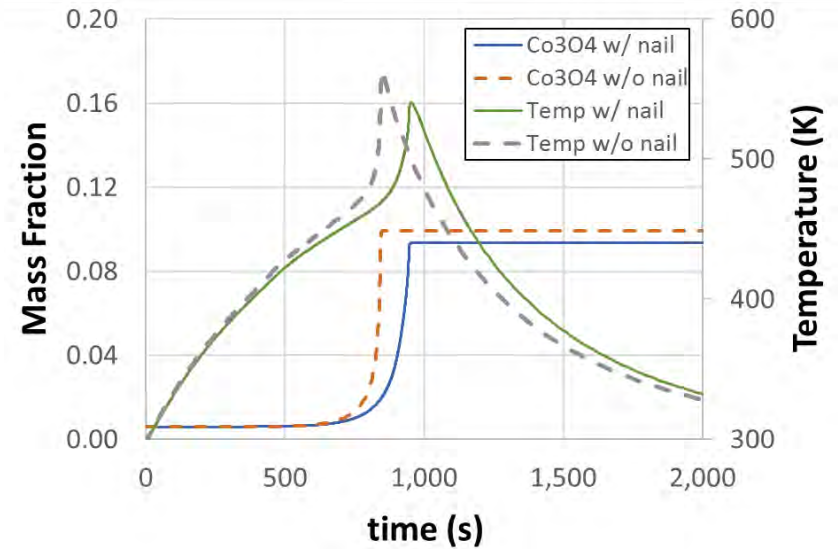
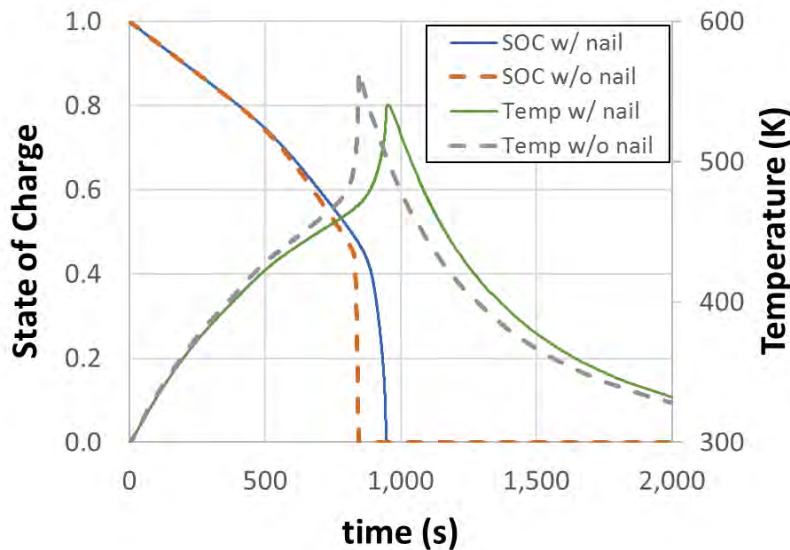
Energy required for initial heating unavailable for runaway



Short-circuit induced runaway in meshed 18650 with nail



$R = 1.4 \text{ ohm}$, $h = 7 \text{ W/m}^2/\text{K}$, Meshed 18650 with 50% heat release in nail



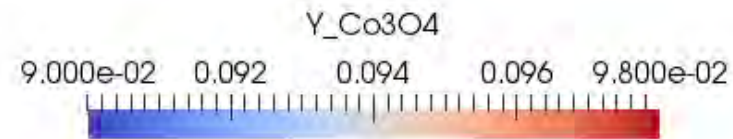
- Effects of inhomogeneity increase as scale increases beyond the lumped-capacitance regime.

Relative importance of short-circuit versus thermal reactions

$R = 1.4 \text{ ohm}$, $h = 7 \text{ W/m}^2/\text{K}$, Meshed 18650 with 50% heat release in nail

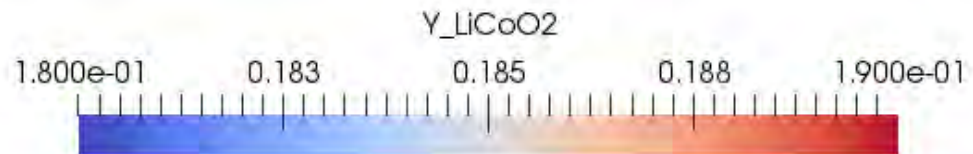
Time: 1004.759876

Thermal Reaction Cathode Product



Time: 1004.759876

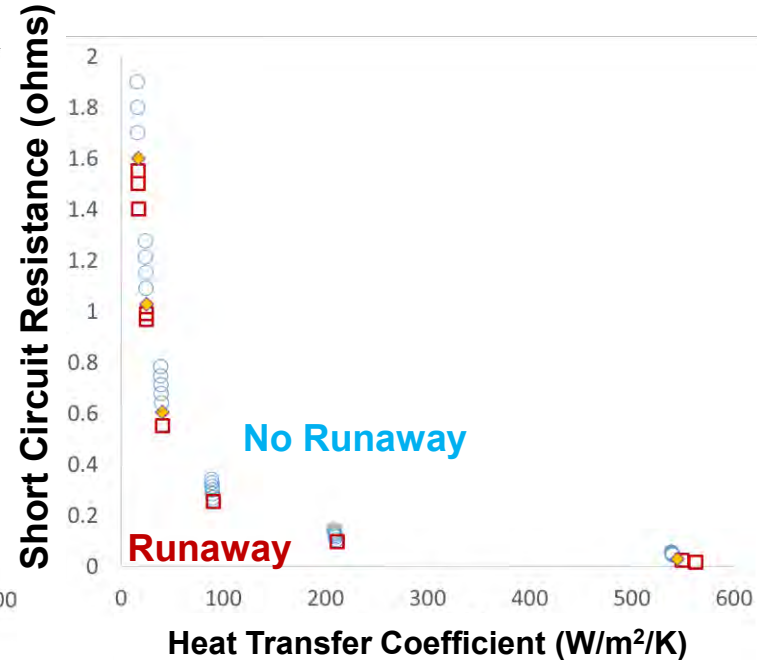
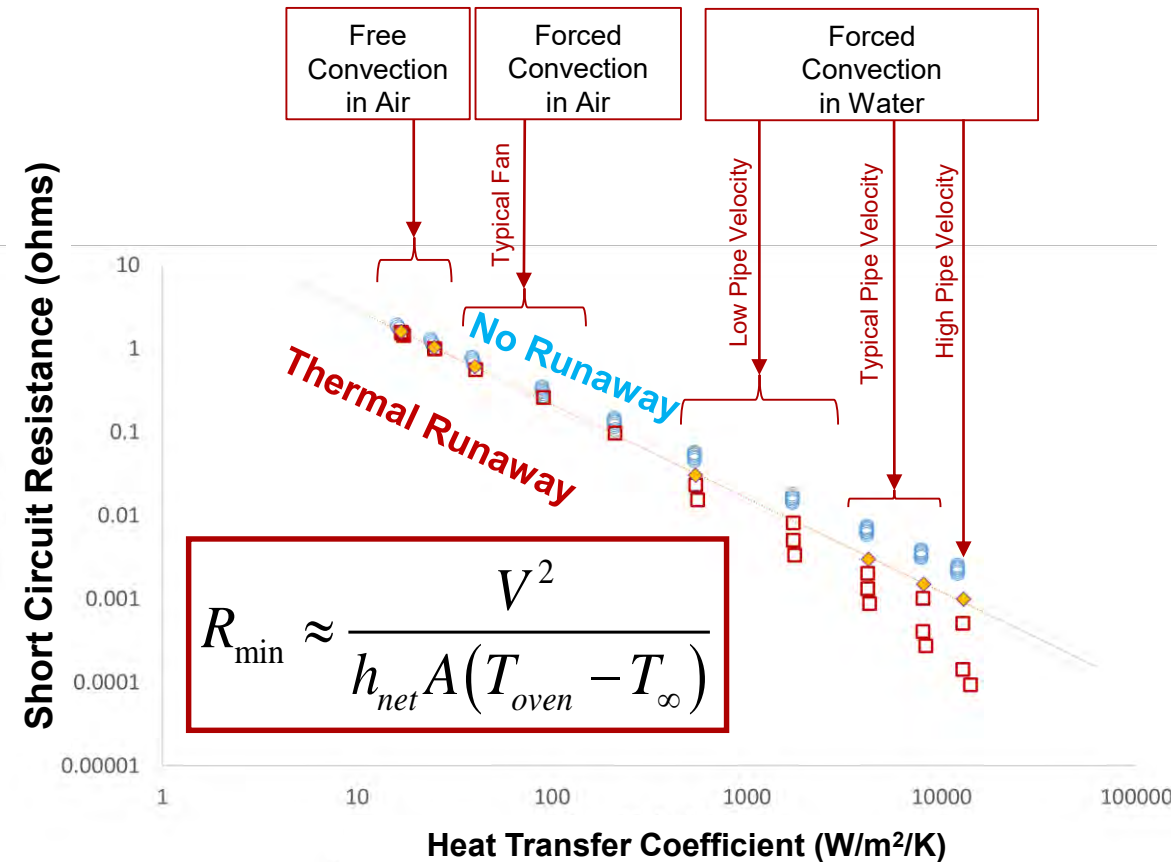
Short Circuit Cathode Product



How Much Cooling to Suppress Runaway with Internal Short Circuit?

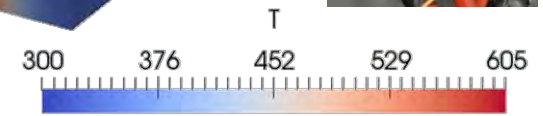
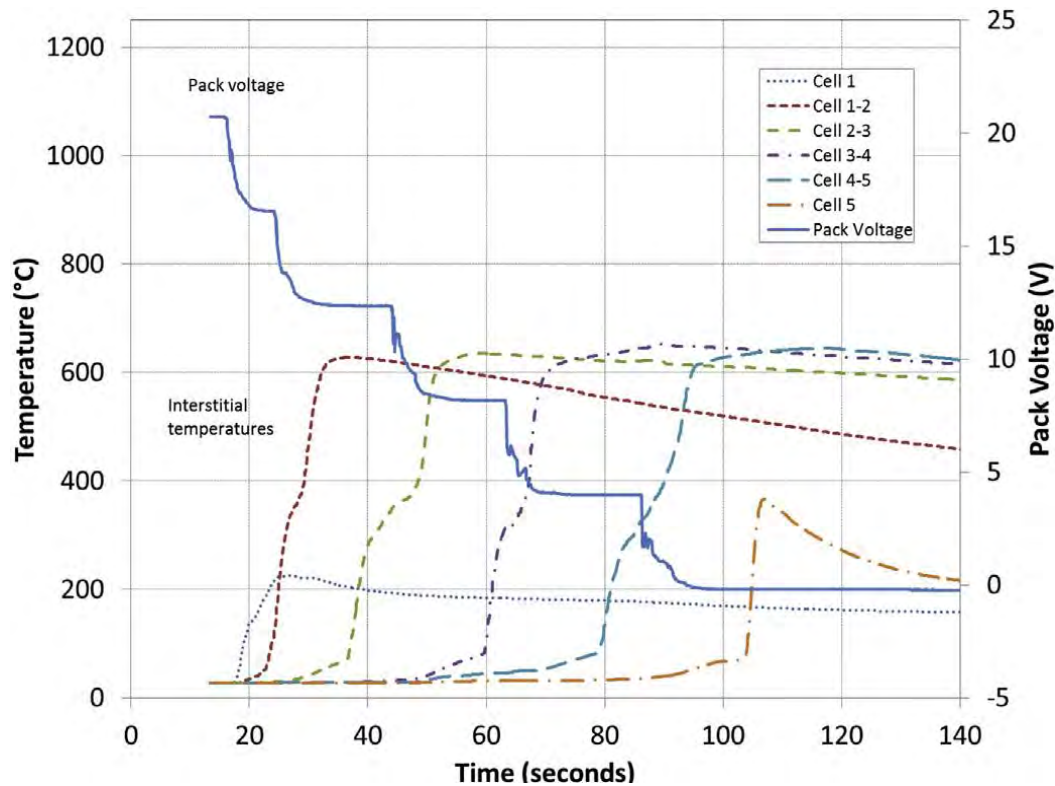
$$T_{eff} = T_{\infty} + P / h_{net} A$$

$$P = \frac{V^2}{R}$$

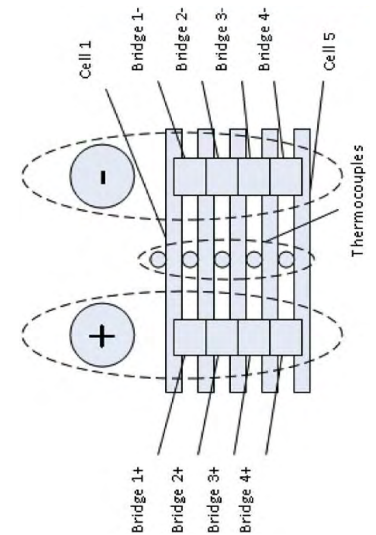


- Models can be used to estimate cooling requirements
 - Simulation shows homogeneous heating of 18650 cells (varying short resistance and cooling)
 - Internal temperature variation will be worse for large format systems and localized shorts

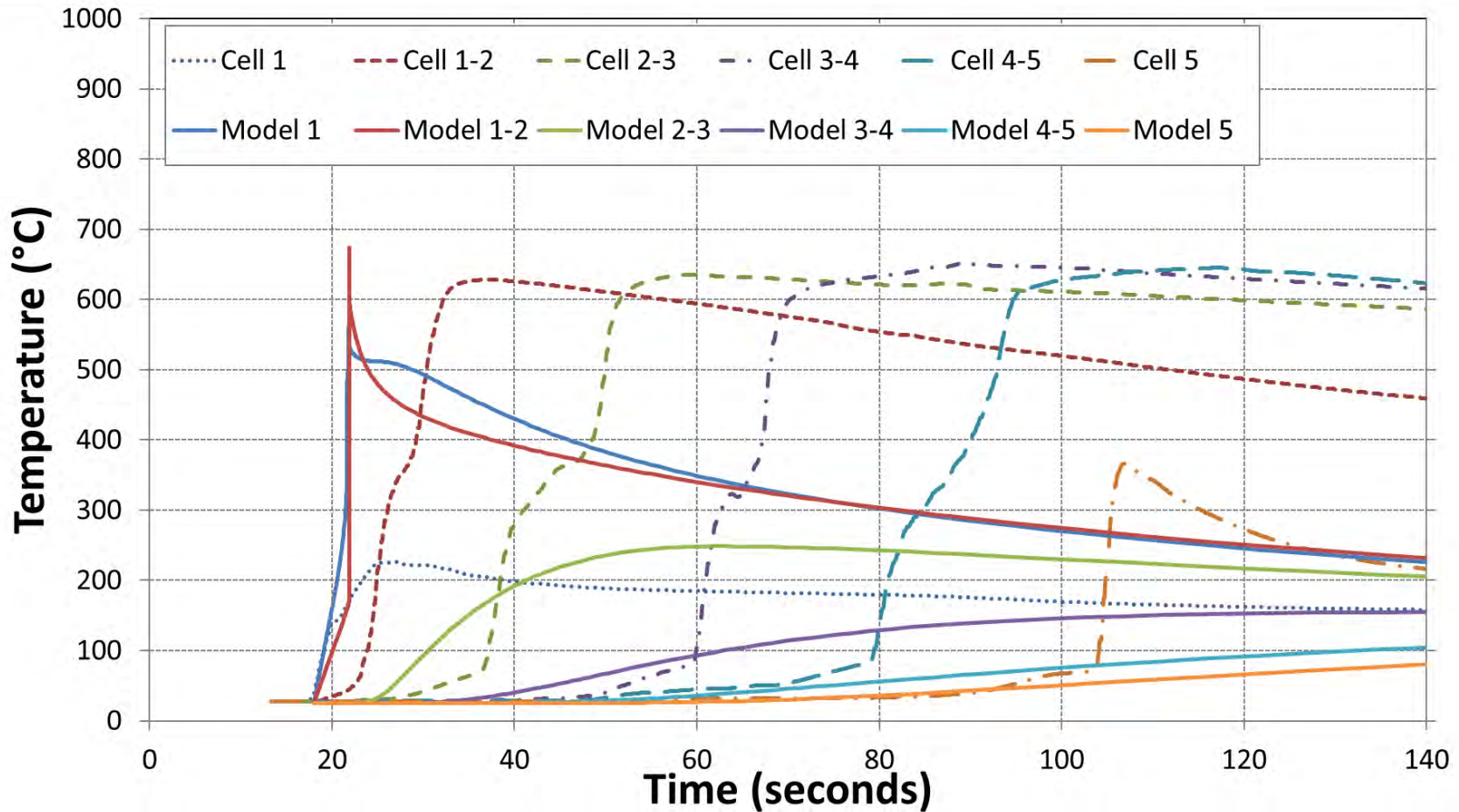
Cascading Propagation Observed in Li-Ion Packs



- Experimental propagation in 5 stacked pouch cells at Sandia
- Investigating effects of
 - State of charge
 - Intermediate layers
 - Cell geometry
- Good pack-scale model validation cases

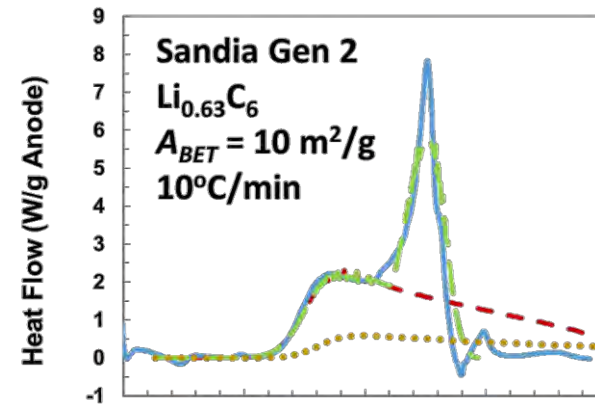
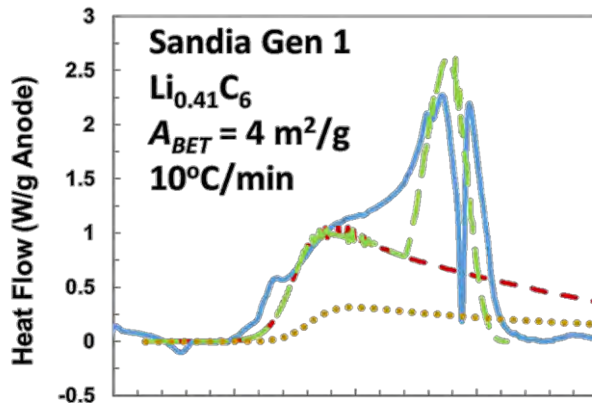


Decrease high-temperature reaction rate by 2x again

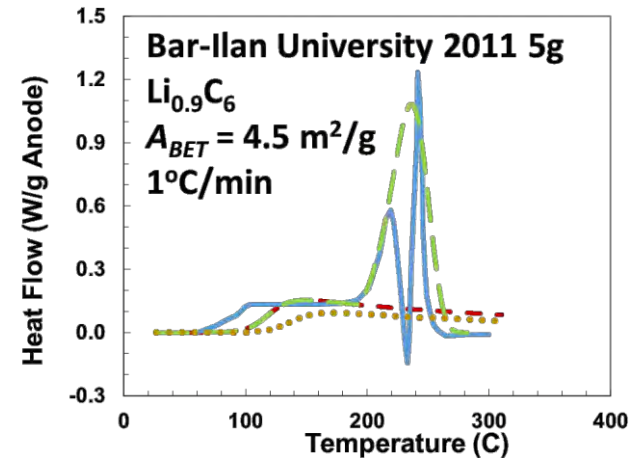
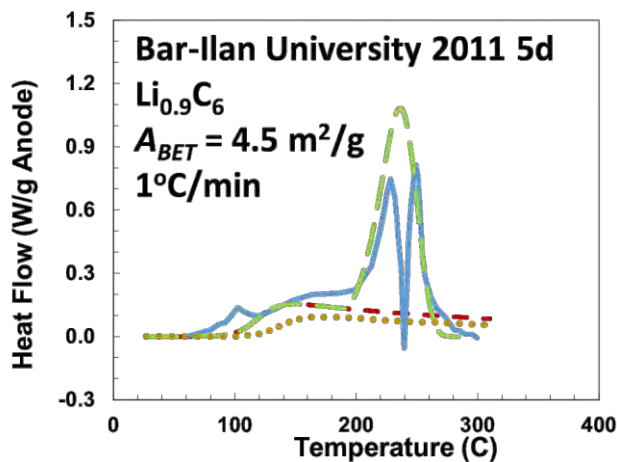


- Propagation predictions will improve with fidelity of high-temperature chemistry

Prior models provided incomplete accounting of heat release – example for anode.



Data **Dahn Model** **Area-Scaled** **Critical Thickness**

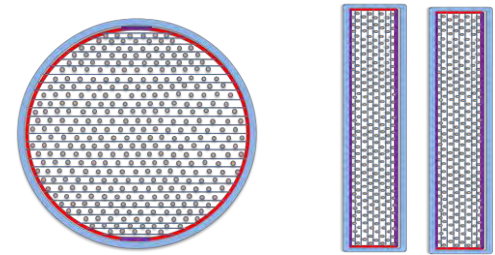





Key anode model improvements

Area-Scaled Model

- SEI Passivation layer inhibits lithium reduction of electrolyte, $\exp(-z)$.
- H_{rxn} thermodynamically consistent with $2\text{LiC}_6 + \text{EC} \rightarrow 2\text{C}_6 + \text{C}_2\text{H}_4 + \text{Li}_2\text{CO}_3$
- Reaction scales with effective surface area.

$$\frac{dz}{dt} \propto \frac{A_{rxn,ref}}{A_{rxn}} \approx \left(\frac{A_{BET,ref}}{A_{BET}} \right)^{n_1}, n_1 < 1$$

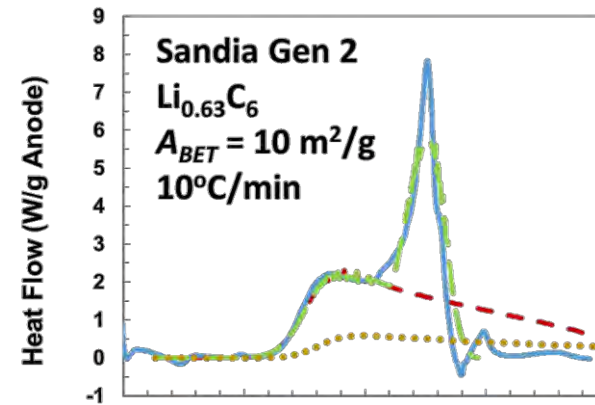
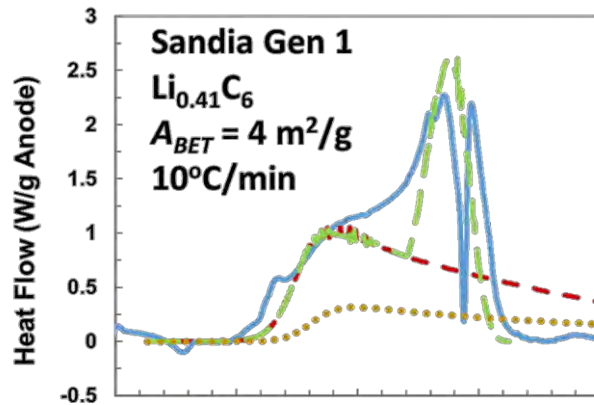


-  = Graphite Basal Planes (smooth)
-  = Graphite Edges (rough)
-  = SEI Layer

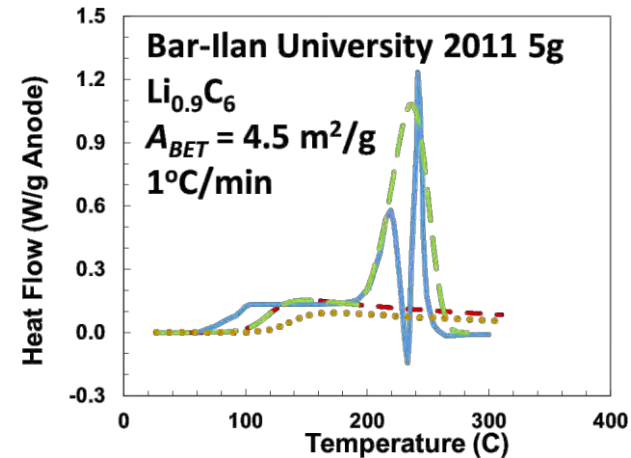
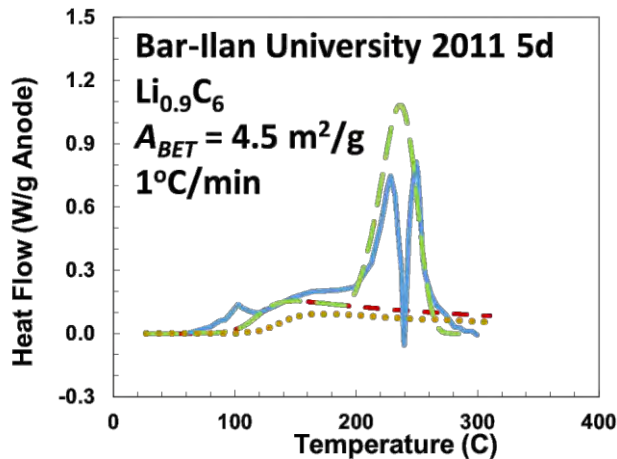
Critical Effective Layer Thickness $z = \min(z, z_{crit})$ where $z_{crit} \propto x_{sei,crit} \left[\frac{A_{BET}}{A_{BET,ref}} \right]^{n_2}$

- Limit to passivation layer growth with heating.
 - Endothermic defoliation (or other process) observed. Fracture, cracking?
 - Defects in SEI more likely on on edges.

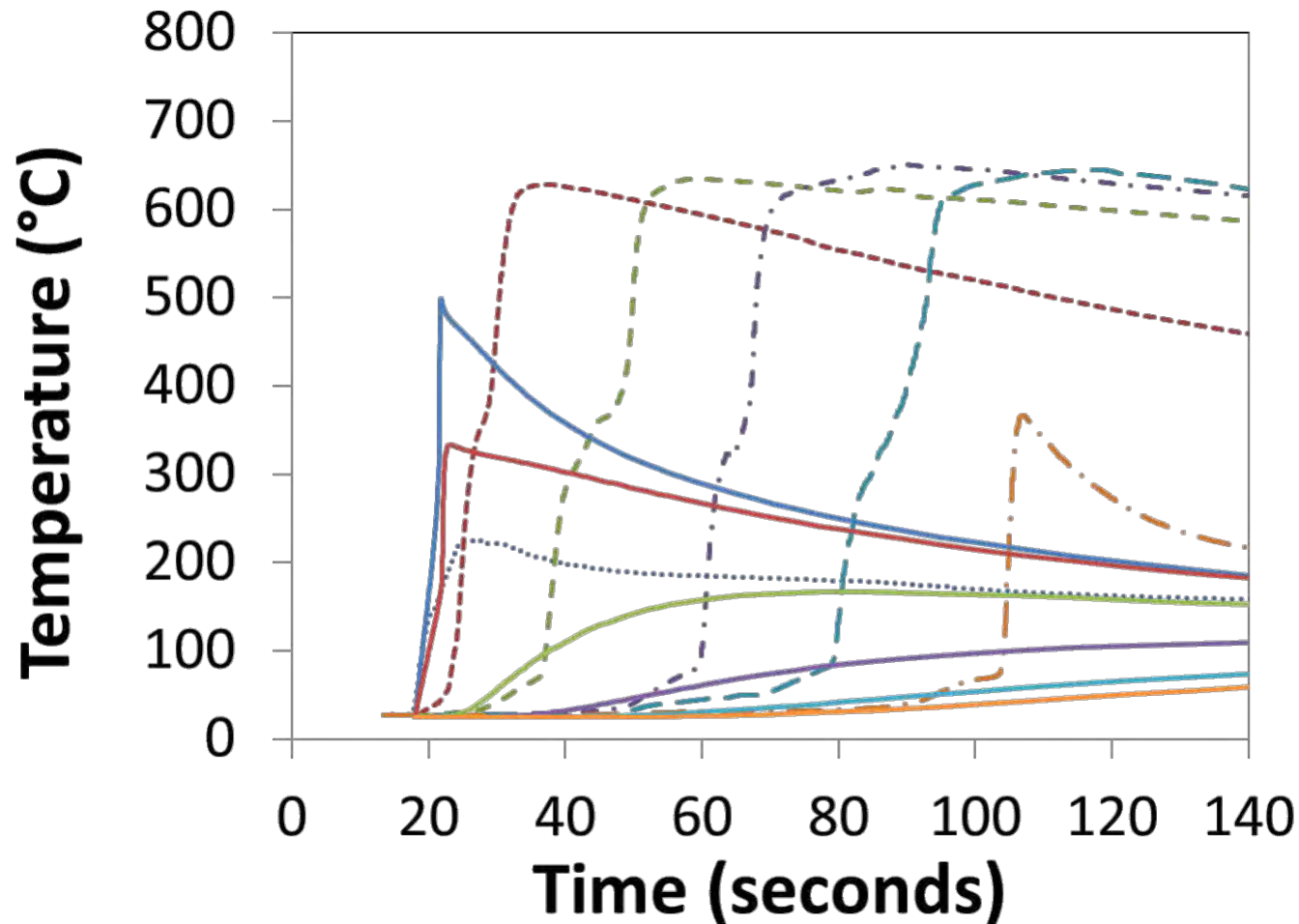
New model based on measurable quantities and thermodynamic material properties



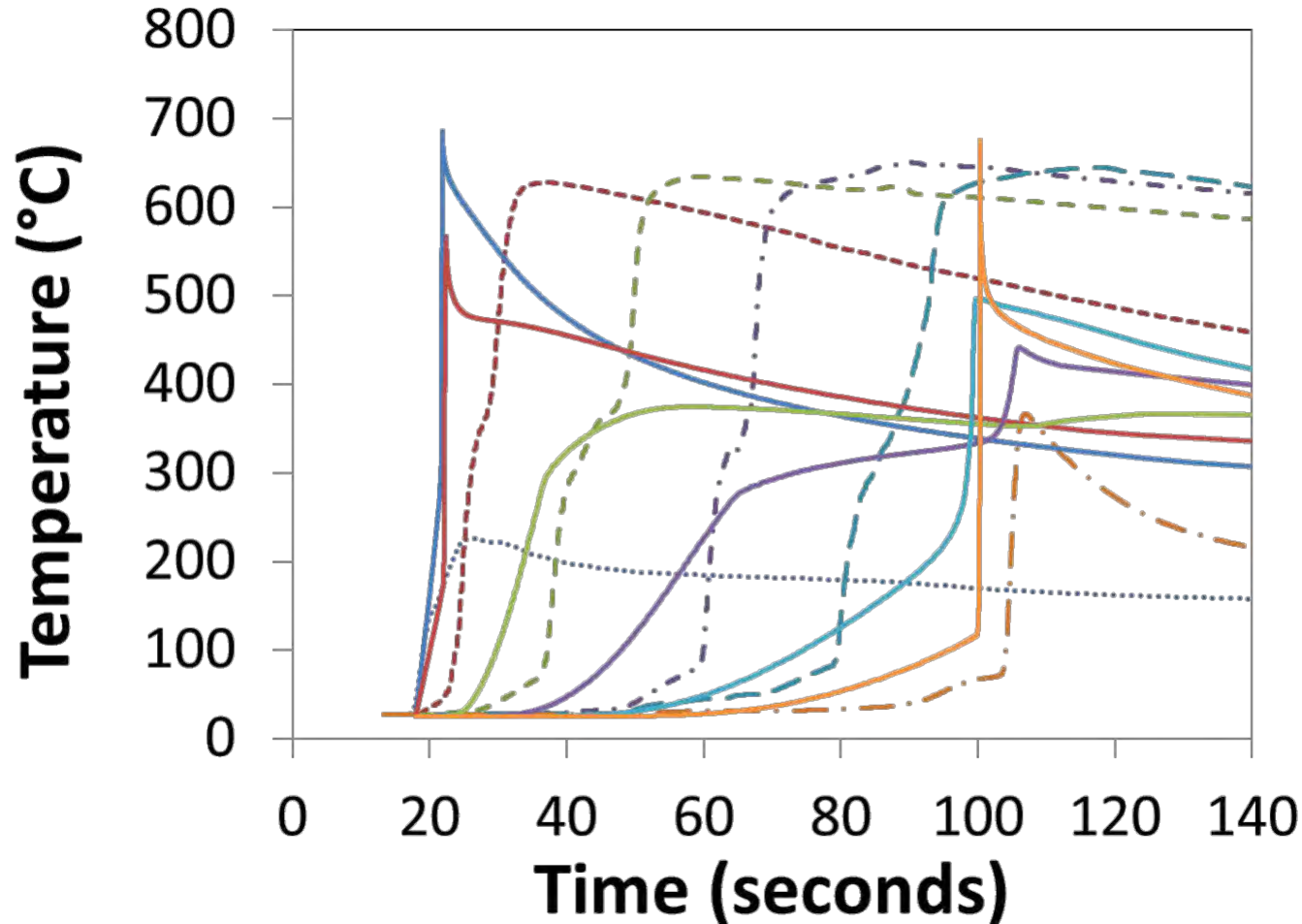
Data **Dahn Model** **Area-Scaled** **Critical Thickness**



Dahn Model (Hatchard et al. 2001)



Dahn + New Anode Model, Alternate Anode Parameters



■ Publications

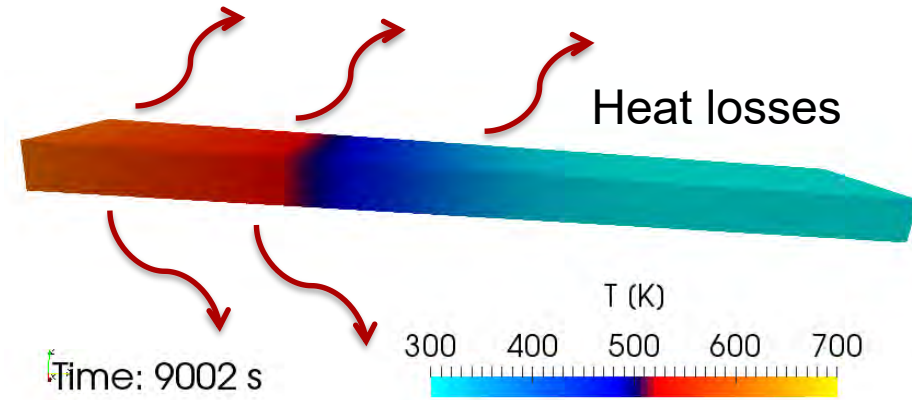
- J. C. Hewson, R. Shurtz, “Modeling Thermal Runaway in Lithium-ion Packs as a Function of Scale and Heat Source,” *Proceedings of the 10th US National Combustion Meeting*, 2017.
- Hewson, J.C., *Understanding the limits of thermal runaway in lithium-ion battery systems*, in *Interflam*. 2016: London, UK.
- Ferreira, S.R., et al., *Fundamental aspects of the safety of large-scale energy storage systems, Paper 5.3*, in *Power Sources Conference*. 2016: Orlando, FL.

■ Presentations:

- Shurtz, R. and J. Hewson, “Modeling Thermochemical Sources for a Broader Range of Materials and Conditions,” 231st Electrochemical Society Meeting, New Orleans, (May 28-June 2, 2017)
- Shurtz, R. and J. Hewson, “Modeling Thermal Runaway in Li-ion Packs as a Function of Scale and Heat Source,” 231st Electrochemical Society Meeting, New Orleans, (May 28-June 2, 2017)
- J. C. Hewson, R. Shurtz, “Modeling for understanding and preventing cascading thermal runaway in battery packs,” FAA Triennial Fire and Cabin Safety Research Conference, Atlantic City, NJ, October 2016.
- J. C. Hewson, R. Shurtz, “Understanding and preventing cascading thermal runaway in battery packs,” 2017 Energy Storage Systems Safety & Reliability Workshop in Santa Fe, NM, February 2017.
- J. C. Hewson, R. Shurtz, “Modeling Thermal Runaway in Lithium-ion Packs as a Function of Scale and Heat Source,” *Proceedings of the 10th US National Combustion Meeting*, April 2017.

Future work

- Fit calorimetry data from a variety of battery chemistries (Sandia team and literature) to kinetic models.
- Identify configurations that inhibit initial ignition.
- Continue modeling thermal interaction of battery pack configurations.
 - Cascading versus isolated failure.
 - Inhomogeneous packs with losses.
 - Focus on heat losses required to mitigate propagation.
- Intermediate term
 - Demonstrate simulation as tool for risk-cost trade space studies through distributed sensing versus mitigation response.
 - Predict contributions of battery thermal runaway to overall fire load and as source of hazardous products.
 - Integrate reacting thermal model of battery packs with fire models in Sierra to evaluate safety of representative geometries and scenarios.
- **Ultimate goal: *Employ modeling as design tool for optimal mitigation strategies.***



In closing

- Thermal runaway is a risk and potential barrier to development and acceptance.
- Heat release rates are moderate relative to potential dissipation.
- Multi-physics thermal models can potentially identify critical ignition and propagation trends.
- Quality measurements are key to parameter identification.
- Progress this term
 - Relate chemical source to fundamental material properties, allowing simultaneous short-circuit and thermal runaway.
 - Identify thermal mitigation to prevent thermal runaway with short circuits.
 - Advance chemical models of thermal runaway processes to predict high-temperature processes.
 - Identification of thermal ignition criterion for cell-to-cell (EESAT).
 - Cell-to-cell propagation and cooling for mitigation along homogenized pack structures (EESAT).

Acknowledgements

- Supported by Imre Gyuk and the OE Electrical Energy Storage Program.
- Collaborative discussions with Heather Barkholtz, Lorraine Castro, Summer Ferreira, Josh Lamb, Chris Orendorff and Dave Ingersoll have been instrumental in understanding the range of possible topics that might be addressed.

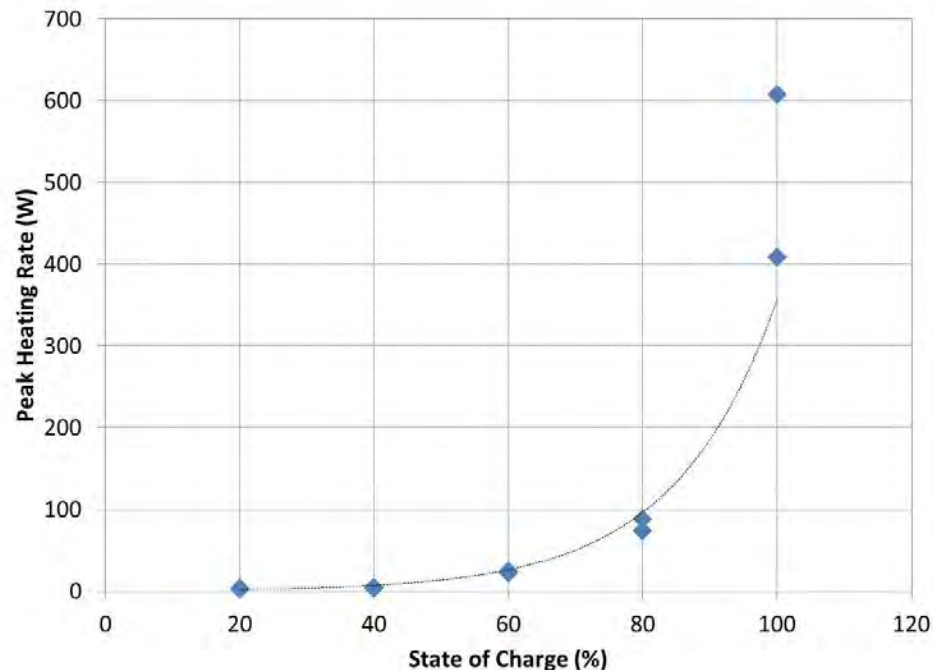
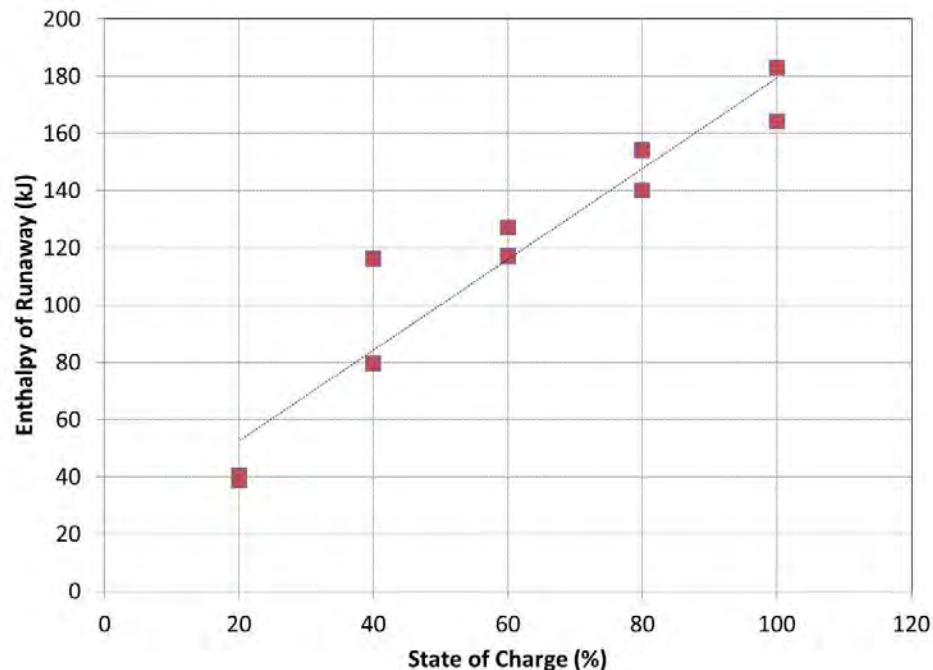
THANK YOU

QUESTIONS:

JOHN HEWSON

jchewso@sandia.gov

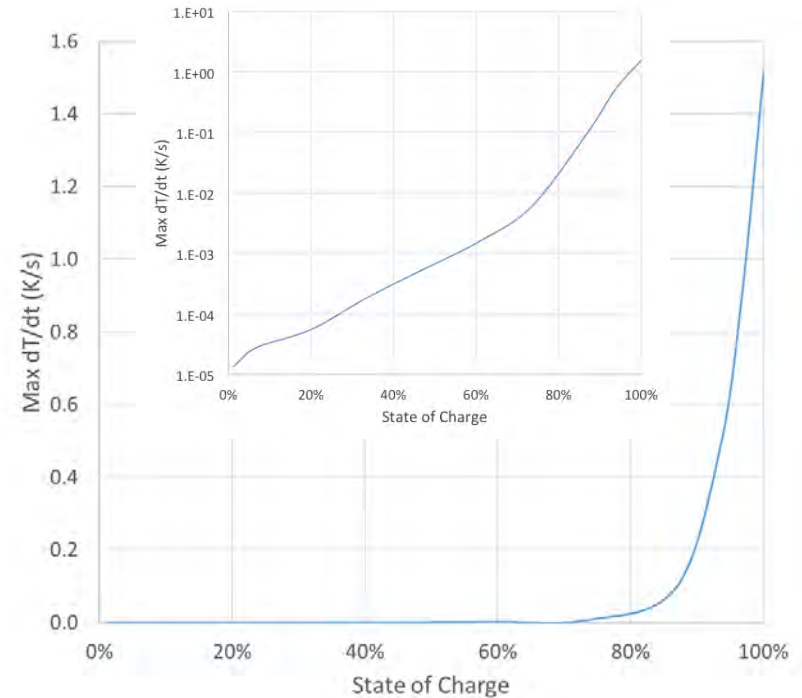
Impact of SOC on Runaway – Josh Lamb Expts.



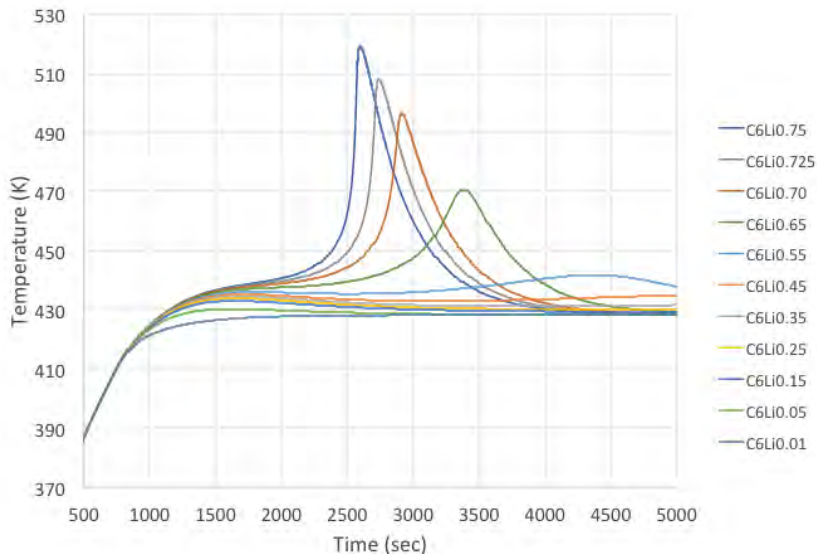
- Results show a nearly linear relationship between total heat release (kJ) and cell SOC – similar to data for cell size this suggests that failure enthalpy is based largely on the stored energy available
- Heat release rates (e.g. runaway reaction kinetics) follow an almost exponential relationship with cell SOC – again this is traditionally thought to cause a greater risk of thermal runaway
- Could a runaway still occur with large numbers of low SOC cells or cells in well insulated conditions?

Increasing stored energy (SOC) leads to exponentially faster heat release rates

- Fully charged cells observed to undergo more violent exothermic reactions.
- Charged fraction of cathode and anode are reactive component
 - CoO_2 vs LiCoO_2 ; LiC_6 vs C_6
- Greater heat release associated with greater fractions of active material (greater SOC).



- Higher temperatures give exponentially greater heat release due to Arrhenius rate constants.



How are Different Heat Sources Analogous?

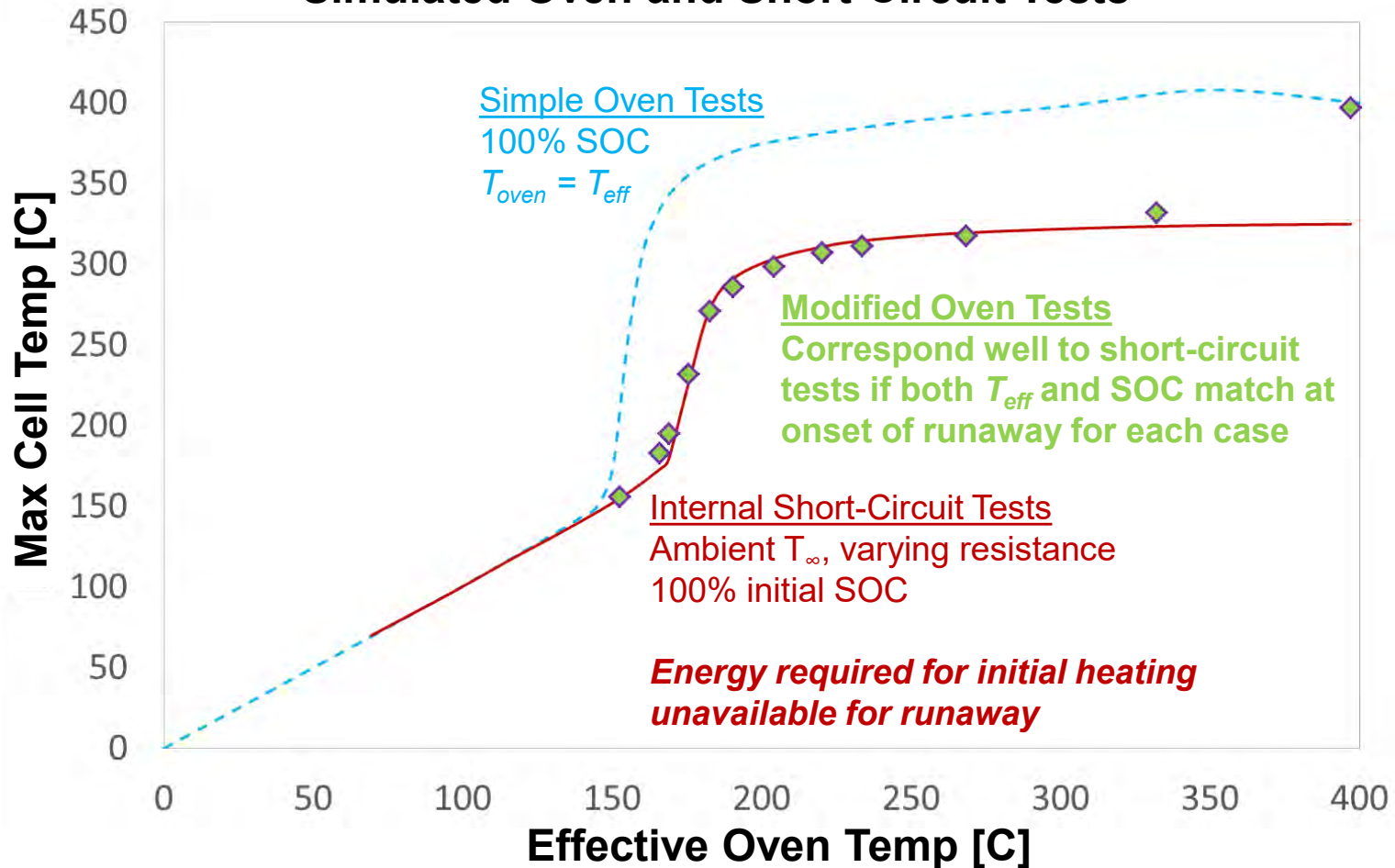
Energy balance on a cell yields:

$$T_{eff} = T_{\infty} + P / h_{net} A$$

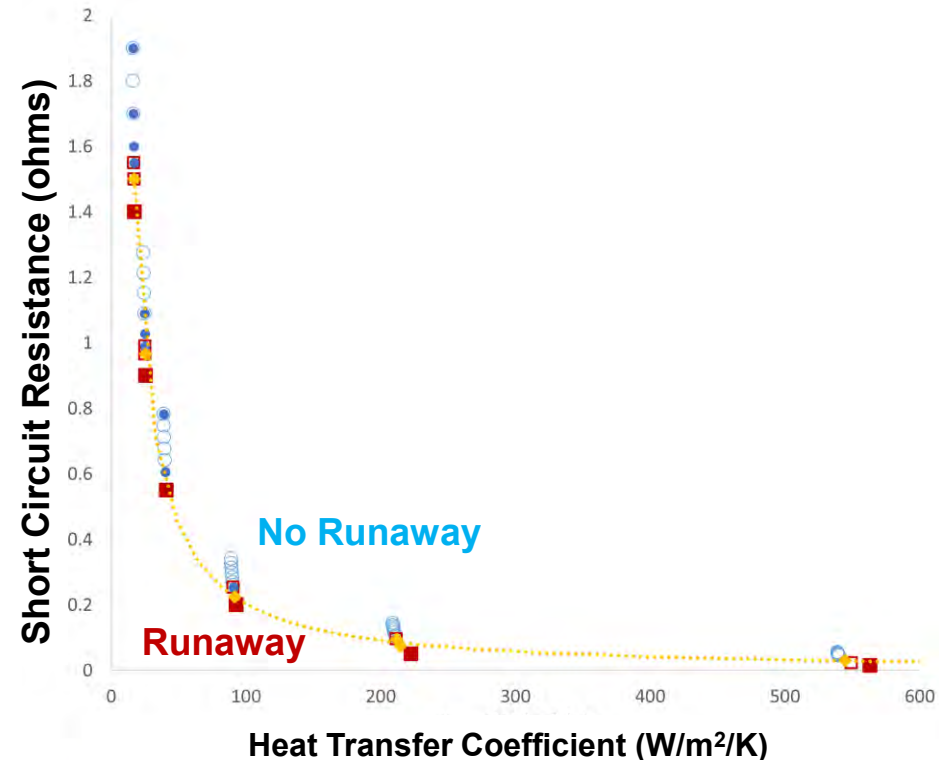
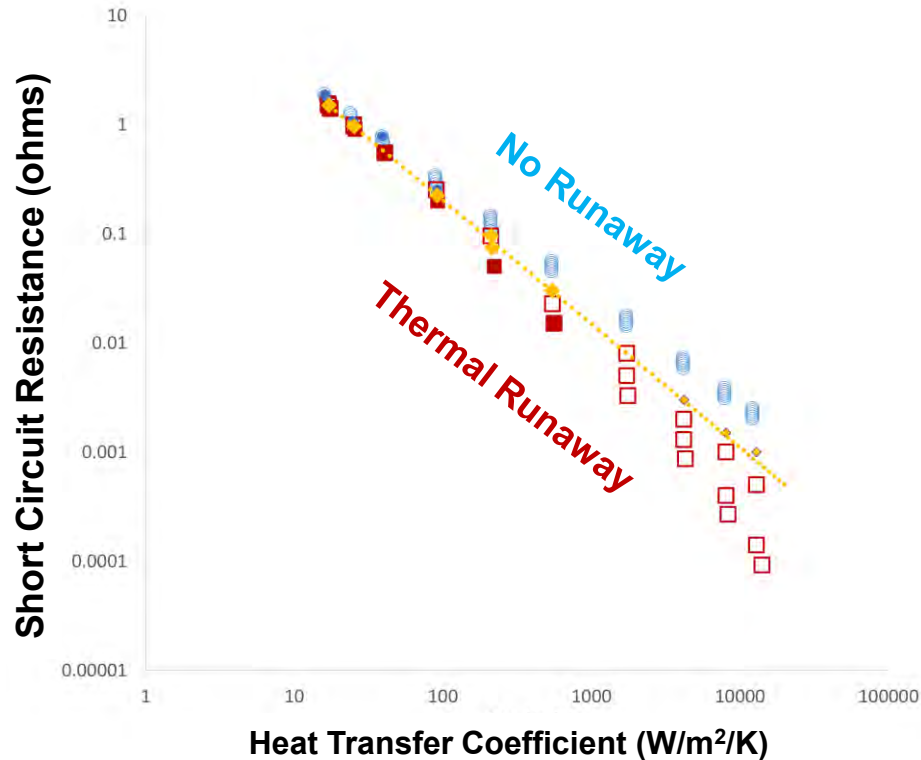
$$P = \frac{V^2}{R}$$

$$h_{net} = h + h_{rad} = h + \epsilon\sigma(T_w^2 + T_{\infty}^2)(T_w + T_{\infty})$$

Simulated Oven and Short-Circuit Tests



R vs h Relationship Holds for Localized Short



Lumped Cell
Meshed Cell

○ No Runaway

□ Runaway, dT/dt

◇ Transition Runaway

● Meshed no Runaway

■ Meshed Runaway

◆ Meshed Transition

- Lumped capacitance previously reported as good approximation for this battery
- Transition region becomes more gradual due to inhomogeneous competition for reactants

Assessment of Battery Reliability Data and Research Needs

**David Reed, Daiwon Choi, Qian Huang, Vilayanur Viswanathan,
Bin Li, Alasdair Crawford, Vijay Murugesan and Vincent Sprenkle.**

Pacific Northwest National Laboratory

Support from DOE Office of Electricity Delivery & Energy Reliability
Energy Storage Program

OE Energy Storage Systems Program Review
San Diego, CA
October 9th-10th, 2017

Outline

- ▶ Background
- ▶ Program Objectives and Accomplishments
- ▶ Initial Li-ion Battery Evaluation
- ▶ Vanadium Redox Flow Battery Reliability Study
- ▶ Reliability Laboratory at PNNL

Reliability Testing Needs

- ▶ Accelerating the development and deployment of energy storage into the electric infrastructure.
- ▶ Critical for increased acceptance of the technology.
- ▶ The performance and lifetime of storage systems under grid duty cycles should be quantified and disseminated throughout the industry.
- ▶ Duty cycles from field deployed systems must be used to direct research related to degradation and aging of the technology.



Program Overview

► Program Objective

- Predict lifetime of battery components by understanding degradation mechanisms.
- Establish a battery testing facility (duty cycles for grid services, accelerated testing, etc.) that leverages a strong on-site characterization facility (NMR, XPS, EBSD, TEM, etc.).
- Material ↔ Performance relations for various battery technologies
- Provide Battery operation guidelines to end users to maximize battery lifetime

► Accomplishments

- Impact of Frequency Regulation on Degradation of Commercial Li-ion Batteries*
- Reliability Studies of Vanadium Redox Flow Batteries

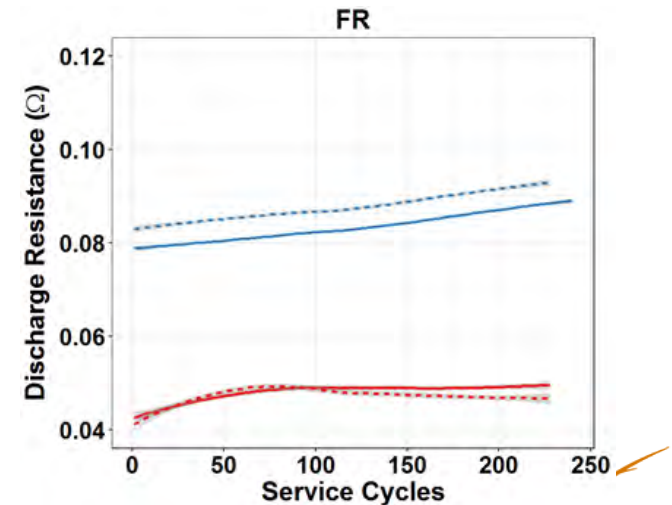
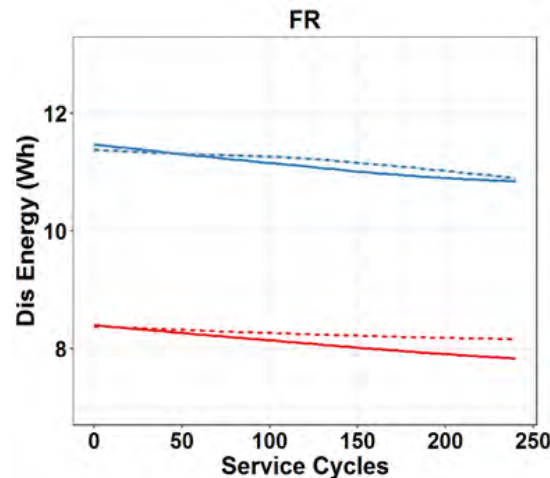
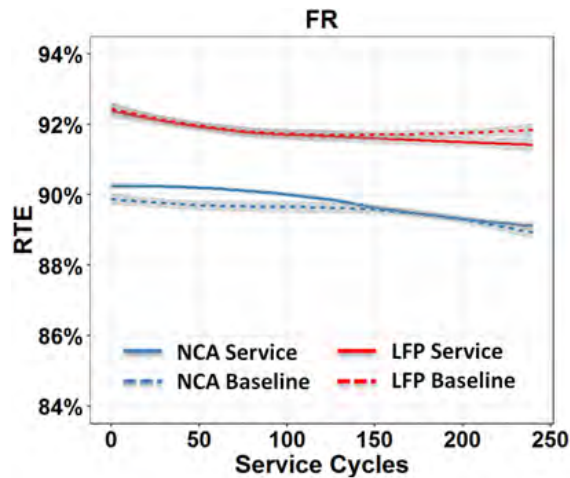
* Lifecycle Comparison of Selected Li-ion Battery Chemistries under Grid and Electric Vehicle Duty Cycle Combinations
A. Crawford^a, Q. Huang^a, M. CW. Kintner-Meyer^a, J. Zhang^a, D. Reed^a, V. Sprenkle^a, V. Viswanathan^{a*}, D. Choi^{a*}
submitted for publication

Impact of Frequency Regulation on Degradation of Commercial Li-ion Batteries

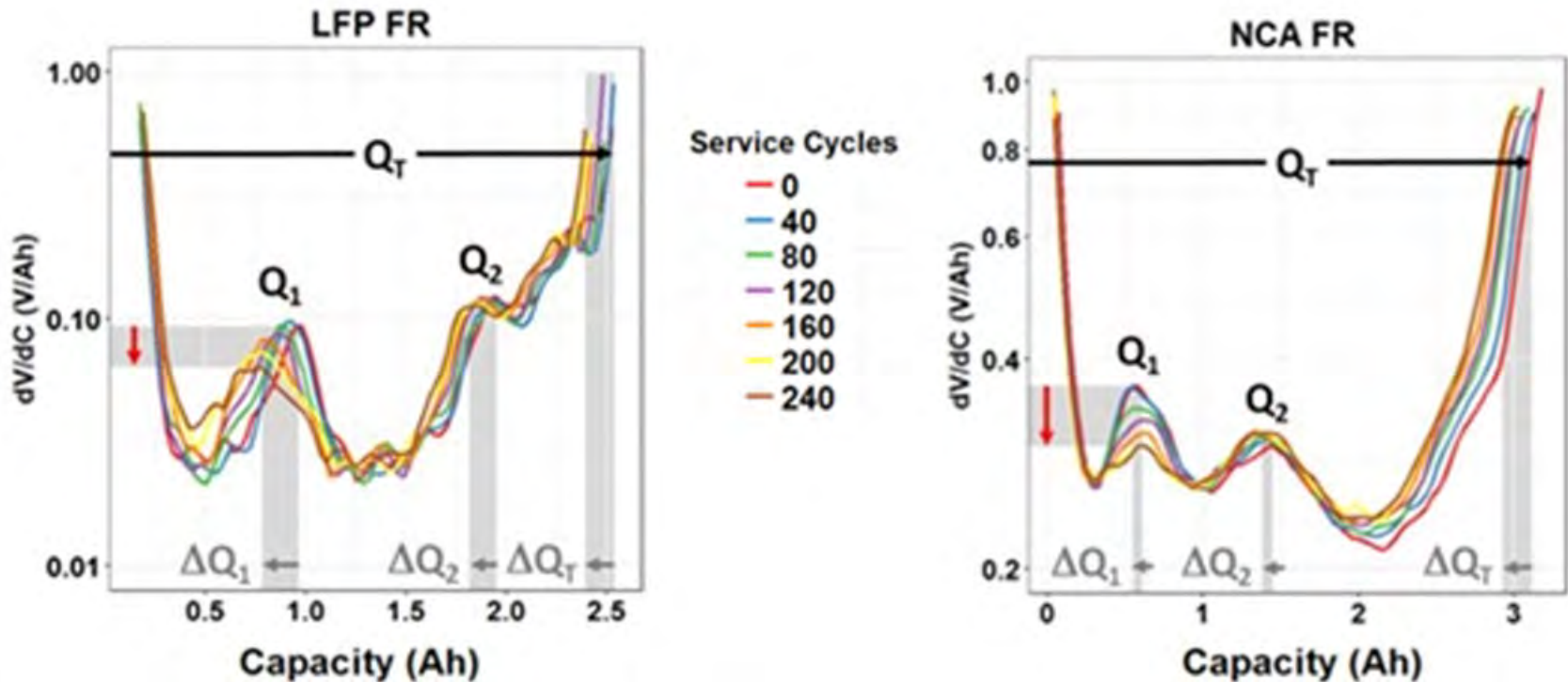
► Objectives

- Reliability of two different Li-ion battery chemistries (NCA and LFP) under frequency regulation (FR) grid service and combination of electric vehicle (EV) drive cycle and frequency regulation (FR) or peak shaving (PS).
- Fundamental understanding of degradation mechanism and limitations of the two Li-ion battery chemistries.
- SOH monitoring

— NCA Service — LFP Service
- - - NCA Baseline - - - LFP Baseline



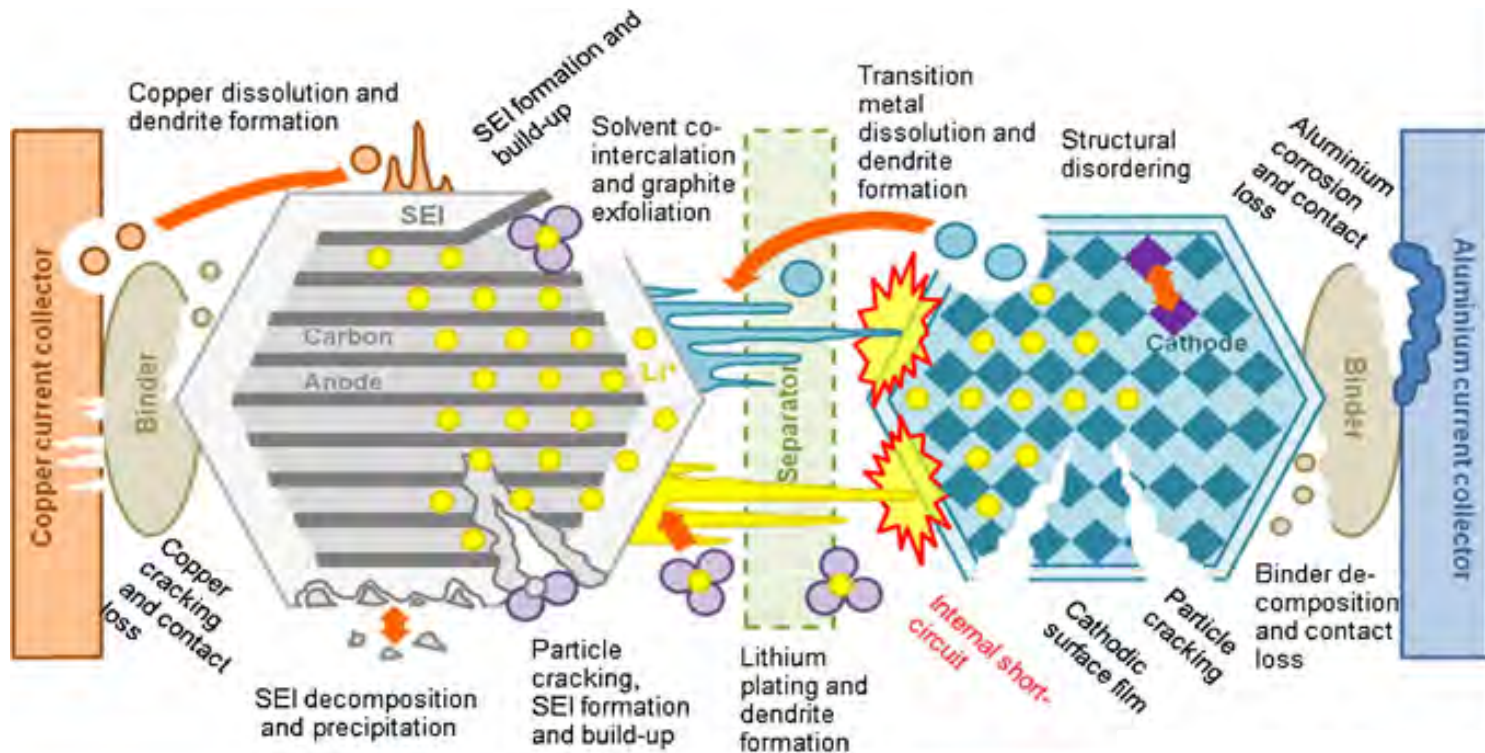
Impact of Frequency Regulation on Degradation of Commercial Li-ion Batteries



➤ Poster session – Daiwon Choi

Impact of Frequency Regulation on Degradation of Commercial Li-ion Batteries

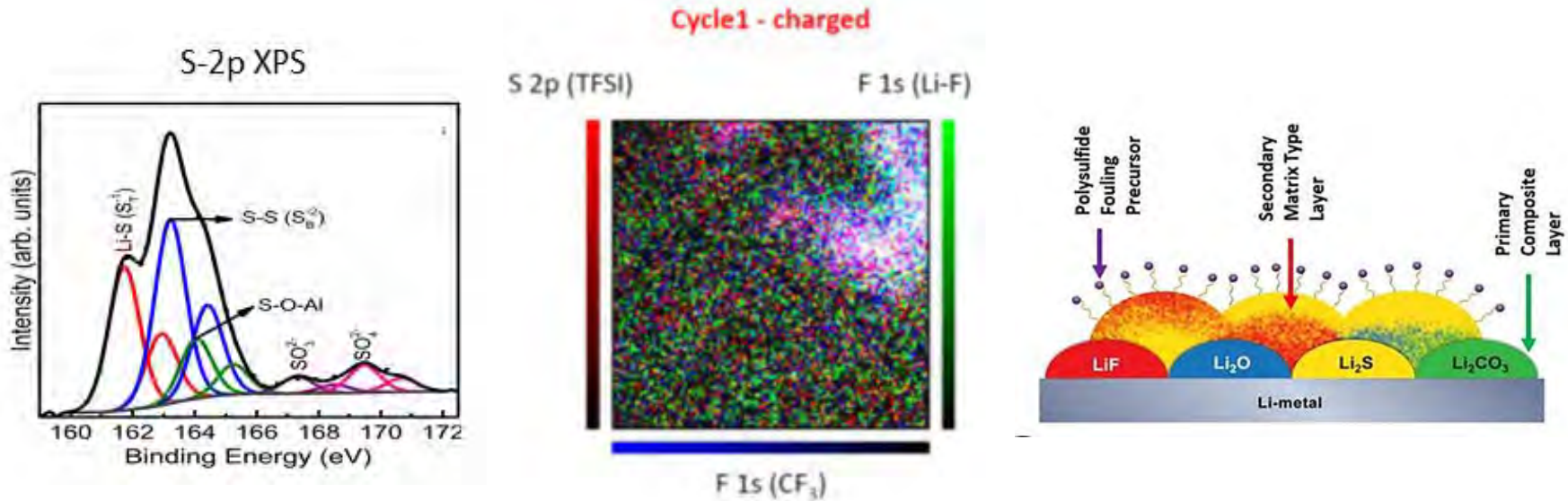
Degradation mechanisms in Li-ion batteries



Christoph Birkel, Energy and Power Group, University of Oxford, 2014

Impact of Frequency Regulation on Degradation of Commercial Li-ion Batteries

SEI layer evolution using XPS imaging



- Establishing the links between physical degradation mechanisms and their effects on performance deterioration
- State of Health monitoring

* In-Situ Chemical Imaging of Solid Electrolyte Interphase Layer Evolution in Li-S Batteries, M. Nandasiri, L E Camacho-Forero, A. Schwarz, V. Shutthanandan, S. Thevuthasan, P. Balbuena, K. Mueller, V. Murugesan, *Chem. Mater.* 2017, 29, 4728-4737.

Reliability Study of Vanadium Redox Flow Battery using a Stable Reference Electrode

► Objectives

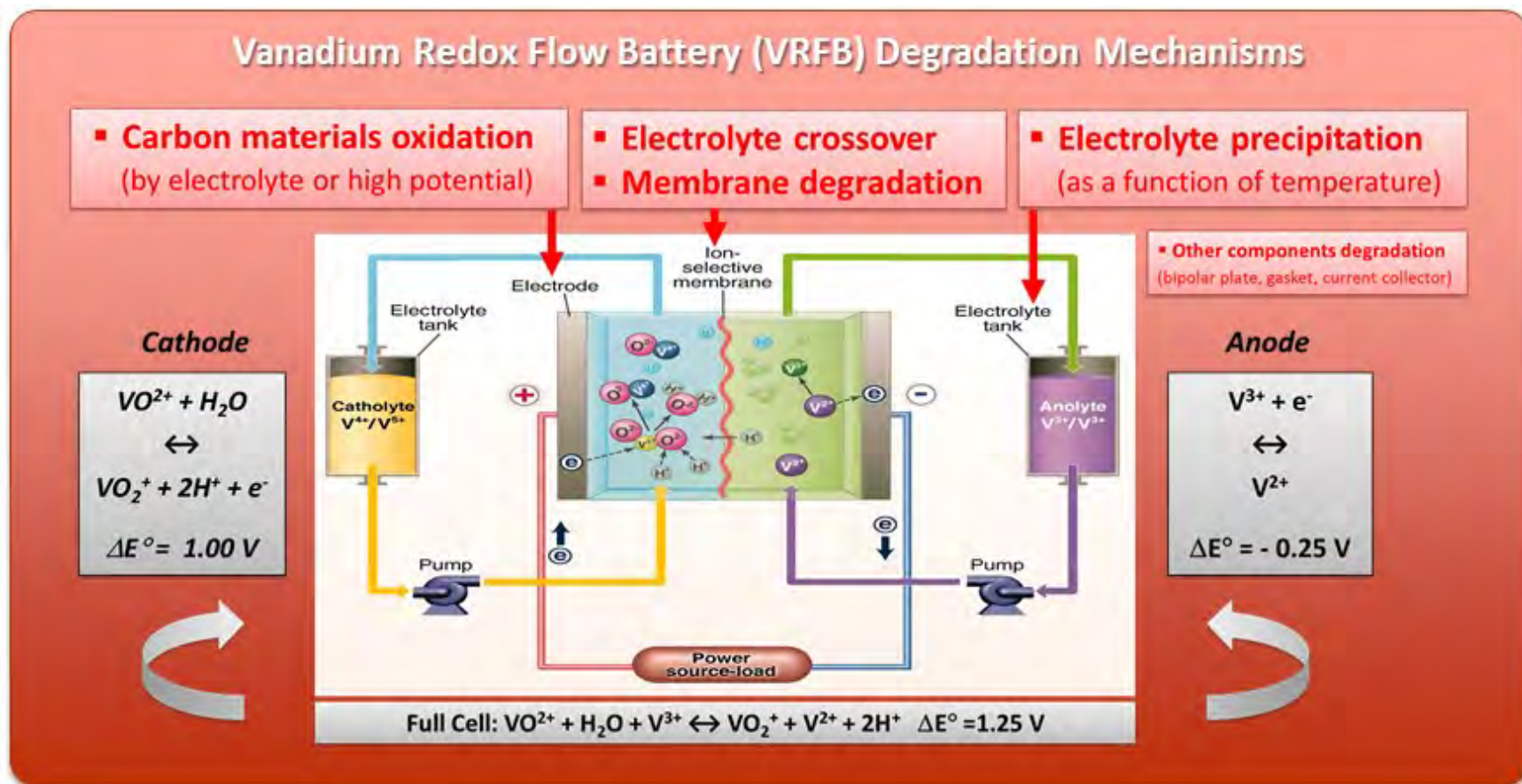
- Develop a stable reference electrode to decouple the anode and cathode during long term testing.
- Fundamental understanding of degradation mechanism of VRFB component and system.

► Joint Project with National Research Council Canada (NRC) and Fraunhofer

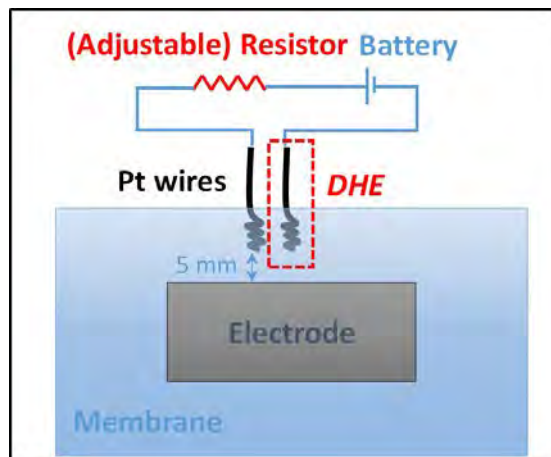
- Common cell design, materials, and electrolytes will be developed for all partners with validated baseline performance testing.
- After baseline performance testing, each partner will evaluate specific cell components and accelerated degradation protocols.

Reliability Study of Vanadium Redox Flow Battery using a Stable Reference Electrode

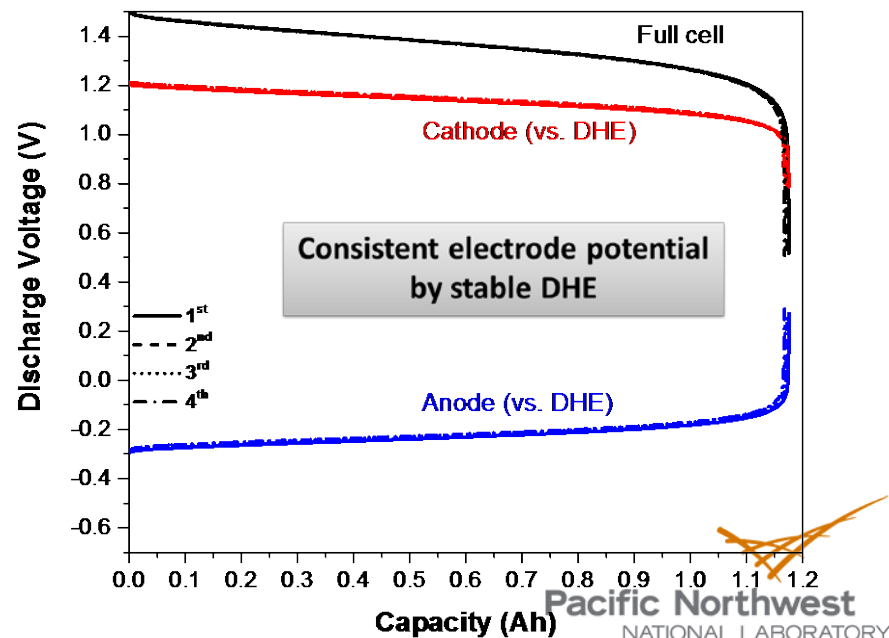
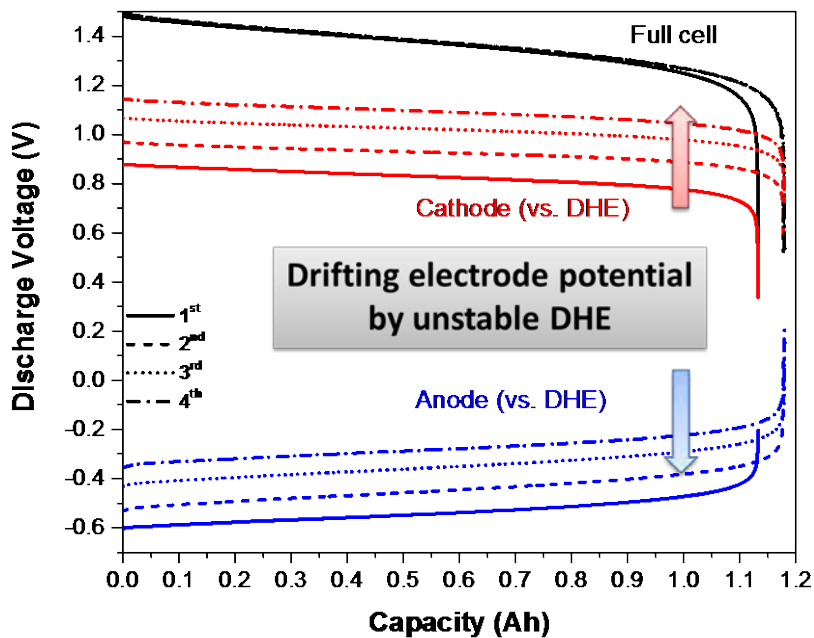
Degradation mechanisms in VRFB



Reliability Study of Vanadium Redox Flow Battery using a Stable Reference Electrode



- Sandwich between laminated membranes
- Optimized design with adjustable resistor
- In-situ monitoring



Reliability Study of Vanadium Redox Flow Battery using a Stable Reference Electrode

► Future Work

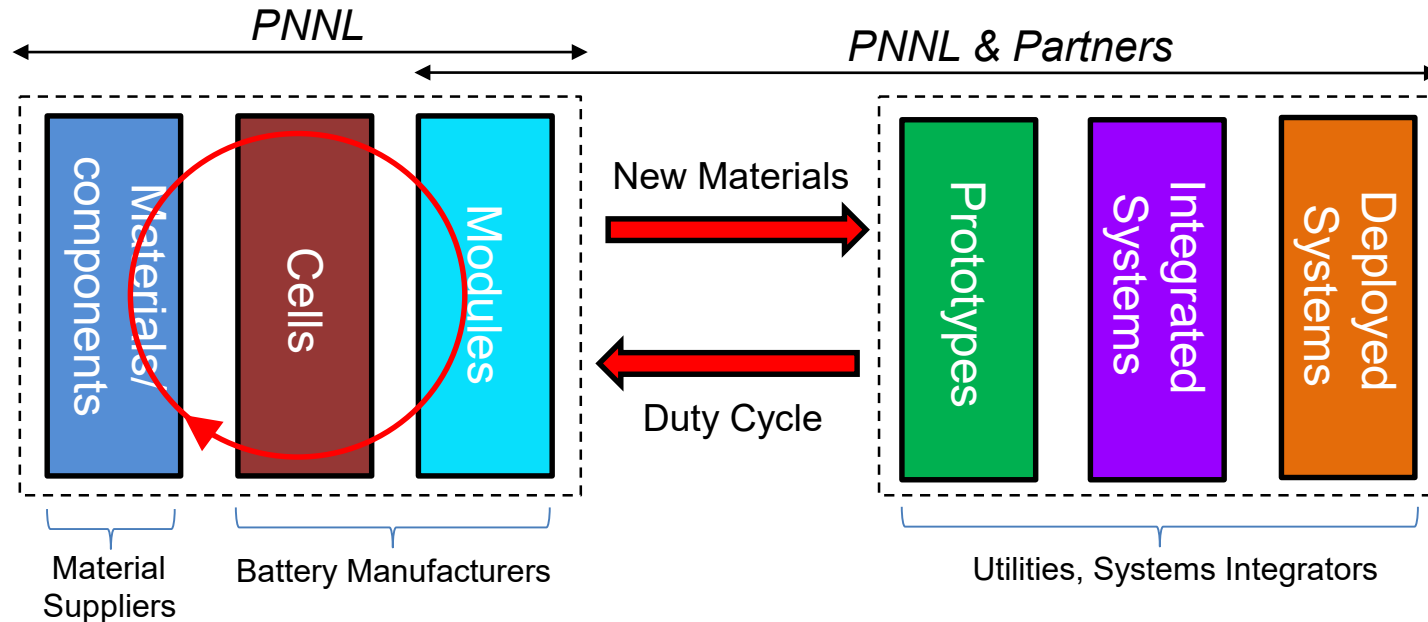
- Single or multi-stressors will be studied (temperature, current density, SOC, DOD and catholyte and anolyte starvation).
- Develop accelerated testing protocol for redox flow batteries in collaboration with NRC-Canada and Fraunhofer-ICT
- Establishing the links between physical degradation mechanisms and their effects on performance deterioration

➤ Poster session – Qian Huang

Reliability Test Laboratory

- Collaboration with other institutes to test duty cycles in field deployed systems.
- Capable of testing stationary energy storage technologies based on Li, Na, Zn, Mg, etc. and various flow battery technologies.
- Testing with simulated grid use cases to investigate the impact of grid services on energy storage lifetime.
- Characterization of fundamental degradation mechanisms for emerging energy storage technologies.

Reliability Test Laboratory



Goals

- Predict lifetime of battery components by understanding degradation mechanisms
- Establish a world class battery testing laboratory (duty cycles for grid services, accelerated testing, supplier and battery manufacturer testing, etc.)
- Utilize strong on-site characterization facilities (TEM, NMR, XPS, APT, etc.)
- Create innovative material solutions to existing technologies to increase reliability by understanding Material ↔ Performance relations for various battery technologies
- Provide battery operation guidelines to end users to maximize battery lifetime

Acknowledgements

- Support from US DOE Office of Electricity Delivery & Energy Reliability
- Dr. Imre Gyuk, Energy Storage Program Manager

Energy Storage Safety and Reliability Forum 2018

March 2018
Seattle, WA



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Update on Energy Storage System Safety Roadmap Codes and Standards Activities

David R. Conover
Pacific Northwest National Laboratory

Support from DOE Office of Electricity Delivery & Energy
Reliability Energy Storage Program

DOE OE Peer Review
San Diego, CA
October 10, 2017



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Purpose and Expected Outcome

Purpose

- ▶ Reinforce the relevance and continuing importance of ESS safety-related codes and standards work in fostering successful expansion of energy storage technology development and deployment.

Expected Outcome

- ▶ An understanding of the value of the work and the foundation laid through past successes that will continue to support future efforts.



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Energy Storage Safety Challenge

Achieving desired growth of energy storage in the built environment that is minimally affected by safety-related incidents due to the availability of updated codes and standards that support the technology, are founded on robust research and field data, and are known to and supported by all relevant stakeholders.



OR



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Roadmap to ESS Safety and Reliability

DOE OE Energy Storage Systems Safety Roadmap

GOAL

Foster confidence in the safety and reliability of energy storage systems.

BACKGROUND

Energy Storage Systems (ESS) are in increased demand for stationary applications. The aggressive adoption in the U.S. of stationary ESS has raised concerns about the degree of risks they pose, and questions about how to best understand and mitigate such risks. Stationary energy storage can bring with it risk management concerns and increase challenges associated with ensuring public safety. There is no expectation that the rapid evolution of stationary storage associated with energy storage technologies will slow as the costs continue to fall, new applications continue to be discovered, and policy initiatives continue to spur ESS implementation. There has been and continues to be a pressing need for coordinated, industry-wide action to improve the safety and reliability of energy storage systems.

In 2013, with the release of the Grid Energy Storage Strategy, the U.S. Department of Energy's, Office of Electricity Delivery and Energy Reliability (DOE OE) identified the challenges to widespread deployment of energy storage.¹ One of the central challenges identified was a concern about the risks associated with energy storage. This challenge provided the motivation for holding an energy storage safety workshop sponsored by DOE OE in 2014.² A wide range of stakeholders attended this workshop, and with their input, the DOE Energy Storage Safety Strategic Plan was developed and released in late 2014. DOE has fostered a number of efforts to address energy storage risk assessment and mitigation, including numerous publications, educational materials, communications and meetings organized under an ESS Safety working group. The working group was comprised of three sub-groups focusing on research and development (R&D), codes and standards, and education and outreach. Through their efforts, research has been facilitated, codes and standards have been updated, and information on risk identification and management has reached those having an impact on the deployment of energy storage systems. With a significant increase in R&D activities and in the number of

codes and standards that relate to ESS safety, Sandia National Laboratories held the ESS Safety Forum in early 2017. This brought together the energy storage community to share past efforts and research, as well as helped to identify the most critical needs going forward.

Understanding and mitigating safety risks associated with ESS are receiving greater attention. It has been identified that organizational work and collaborative efforts needed around safety can benefit if they are coordinated by an entity that does not represent any specific ESS development or implementation stakeholder. The DOE OE, through the national labs who support its activities in ESS safety, are shepherding these activities, facilitating efforts to identify and mitigate risks in ESS, and establishing the foundation needed to foster communication and collaboration amongst all ESS stakeholders.

INTRODUCTION

This document is the result of past efforts as described above and most notably the Energy Storage Safety Forum held in late February 2017 which had over 100 attendees representing a wide range of stakeholders associated with ESS development and adoption.

The primary focus of this roadmap is to establish a goal and then a path toward achieving that goal. The roadmap provides a specific goal and three distinct objectives identified to reach that goal. Each objective has specific tasks identified to enable successful realization of the objective. The tasks outlined under each objective fall naturally into the past activities associated with the ESS Working Group and are in line with other initiatives being undertaken by the wide range of stakeholders. The roadmap objectives fall into the following categories: research/development, codes/standards, and collaborative resources.

The areas of focus throughout the roadmap that are relevant to all three objectives include electrical safety, fire, and smoke hazard detection and mitigation, health and environmental hazards, natural and man-made disasters, ventilation and thermal management, and system controls. These areas of focus are addressed beginning with system development

¹Grid Energy Storage, US DOE, December, 2013. http://www.sandia.gov/ess/docs/other/Grid_Energy_Storage_Dec_2013.pdf

²Energy Storage Safety-Strategic Plan, US DOE, December, 2014. http://www.sandia.gov/ess/docs/other/DOE_OE_Safety_Strategic_Plan_Dec_2014_final.pdf

GOAL

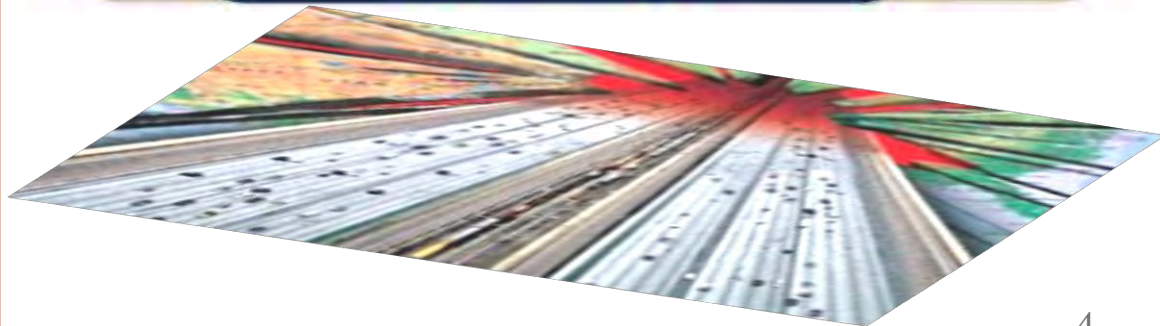
Foster confidence in the safety and reliability of energy storage systems.

OBJECTIVES

R&D

C/S

CR



Research and Development

DOE OE Energy Storage Systems Safety Roadmap

▶ **Objective** – Ensure that the most needed research is identified, prioritized, and communicated so the community can best minimize consequences from potential system failures. Facilitate collaboration through information and results sharing.

▶ **Activities**

- Identify gaps such as testing that is needed, what should be measured and how, shortcomings of current information, and need for new test methods.
- Facilitate collaboration to design research and information gathering efforts to address the identified gaps.
- Identify available information, best practices, test results, etc. and facilitate the inclusion of relevant information into an ESS collaborative repository (CR).

Codes and Standards

DOE OE Energy Storage Systems Safety Roadmap

- ▶ **Objective** – Apply research and development to support efforts that are focused on ensuring that codes and standards are available to enable the safe implementation of energy storage systems in a comprehensive, non-discriminatory, and science-based manner.
- ▶ **Activities**
 - Review and assess codes and standards that affect the design, installation, and operation of ESS systems.
 - Identify gaps in knowledge that require research and analysis that can serve as a basis for criteria in those codes and standards.
 - Identify areas in codes and standards that potentially need revision or enhancement and can benefit from activities conducted under research and development.
 - Develop input for new or revisions to existing codes and standards through individual stakeholders, facilitated task forces, or through laboratory staff supporting these efforts.

Codes and Standards

DOE OE Energy Storage Systems Safety Roadmap



The goal of the DOE OE ESS Safety Roadmap¹ is to foster confidence in the safety and reliability of energy storage systems.

There are three interrelated objectives to support the realization of that goal: research, codes and standards and communication/coordination. The objective focused on codes and standards is.....

To apply research and development to support efforts that are focused on ensuring that codes and standards are available to enable the safe implementation of energy storage systems in a comprehensive, non-discriminatory and science-based manner.

The following activities are intended to support that objective and realization of the goal:

- Review and assess codes and standards which affect the design, installation, and operation of ESS systems.
- Identify gaps in knowledge that require research and analysis that can serve as a basis for criteria in those codes and standards.
- Identify areas in codes and standards that are potentially in need of revision or enhancement and can benefit from activities conducted under research and development.
- Develop input for new or revisions to existing codes and standards through individual stakeholders, facilitated task forces, or through laboratory staff supporting these efforts.

The purpose of this document is to support the above activities by providing information on current and upcoming efforts being conducted by U.S. standards developing organizations (SDOs) and other entities that are focused on energy storage system safety (IEC efforts are listed on the last page).

For the purposes of presenting this information the model codes, standards and other documents (guidelines, recommended practices, etc.) covered are classified in relation to their scope relative to energy storage systems from the 'macro to the micro' as indicated below, noting that more 'macro' documents are likely to adopt by reference more 'micro' documents. **Changes in current activity from the prior edition are shown in bold italics.**



- Overarching Codes and Standards-- the built environment at large that includes but is not limited to energy storage systems.
- Codes and Standards for ESS Installations-- the installation of the energy storage system in relation to other systems and parts of the built environment.
- Codes and Standards for a Complete ESS-- the entire energy storage system in the aggregate.
- Codes and Standards for ESS Components-- components associated with the energy storage system.

What's Noteworthy?

The opportunity to provide public input on NFPA 855 will close October 4, 2017 see www.nfpa.org/855next for more information.

IEEE has initiated the development of a "Recommended Practice for Stationary Battery Electrolyte Spill Containment" (IEEE P1578)

Additional requirements for PV Rapid Shutdown Equipment and Systems are being proposed to UL 1741. STP ballots and all comments are due October 2, 2017.

Inclusion of information related to standards being developed by NEMA

► Accomplishments

- Identification of all ESS relevant C/S development activities (ASME, CSA, DNV GL, ICC, IEEE, FM Global, NECA, NEMA, NFPA and UL)
- Review of C/S activities and communicating about them to all interested parties
 - Monthly C/S Reports
 - Webinar featuring presentations from 10 relevant SDOs on their activities
 - Conference presentations
 - Ongoing information transfer



Codes and Standards

DOE OE Energy Storage Systems Safety Roadmap

► Accomplishments

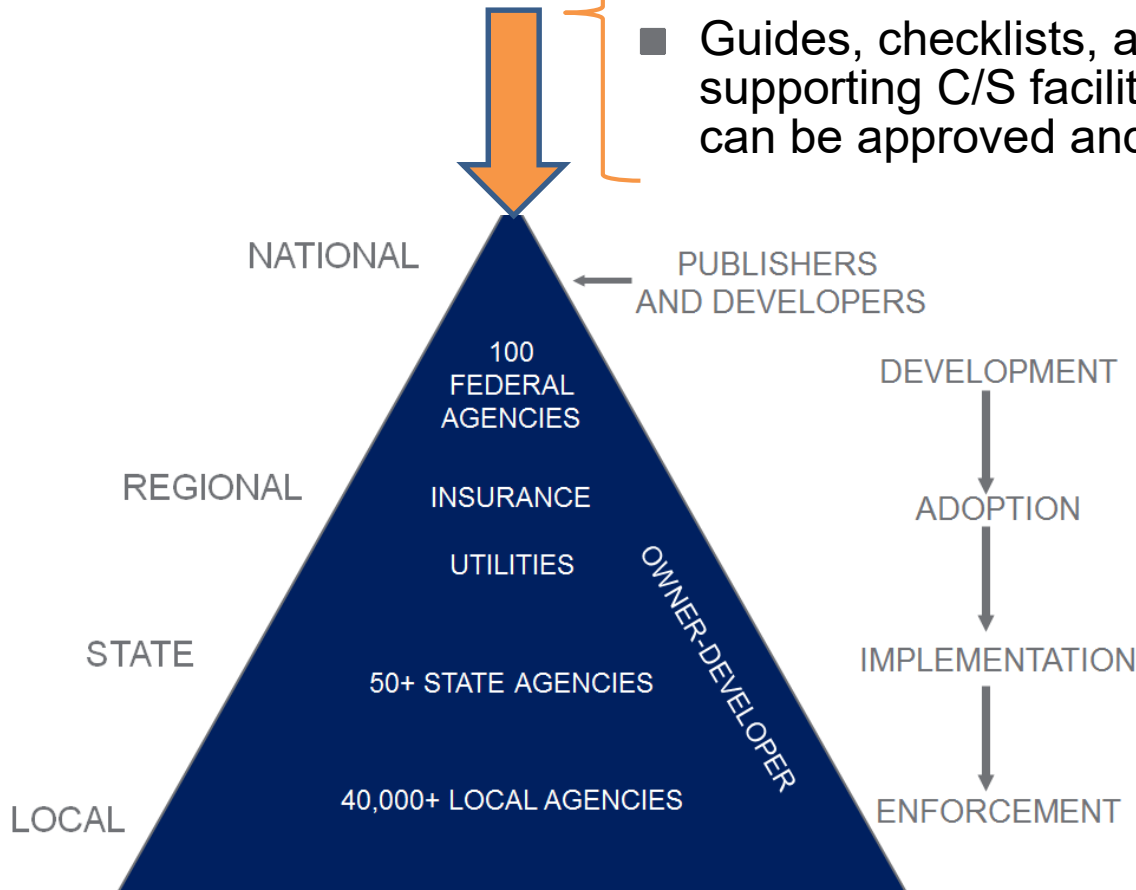
- Involvement in C/S development (committee or task force member and/or submission of proposed changes)
 - ASME TES-1 Safety Standard for Thermal ESS (development of initial draft)
 - DNV GL GRIDSTOR (development of 2nd edition)
 - IEEE 1578 Recommended Practice for Stationary Battery Electrolyte Spill Containment and Management (development of initial draft)
 - NECA 416 Recommended Practice for Installing Stored Energy Systems (submission of comments)
 - NFPA 70 National Electrical Code (development of new Article 706 on ESS in the 2017 edition and proposed changes to create the 2020 edition)
 - NFPA 855 Standard for the Installation of Stationary ESS (development of a first draft open for public input)
 - ICC International Residential Code and Fire Code (development of proposed changes on ESS in the 2018 editions and proposed changes to create the 2021 editions)
 - UL 9540 Energy Storage Systems and Equipment (development of the first edition and proposed changes to the next edition)
 - UL 1974 Evaluation for Repurposing Batteries (development of the first edition)

Codes and Standards

DOE OE Energy Storage Systems Safety Roadmap

► Outcomes

- New and updated codes and standards are adopted and become the minimum safety metric affecting the timely acceptance of ESS.
- Guides, checklists, and educational materials supporting C/S facilitate the ease with which ESSs can be approved and implemented.



Codes and Standards

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DOE OE Energy Storage Systems Safety Roadmap

► Accomplishments

- Publication of resources to facilitate compliance with C/S
 - ESS Safety Plan Review and Inspection Checklist
 - ESS Guide for Compliance with Safety Standards



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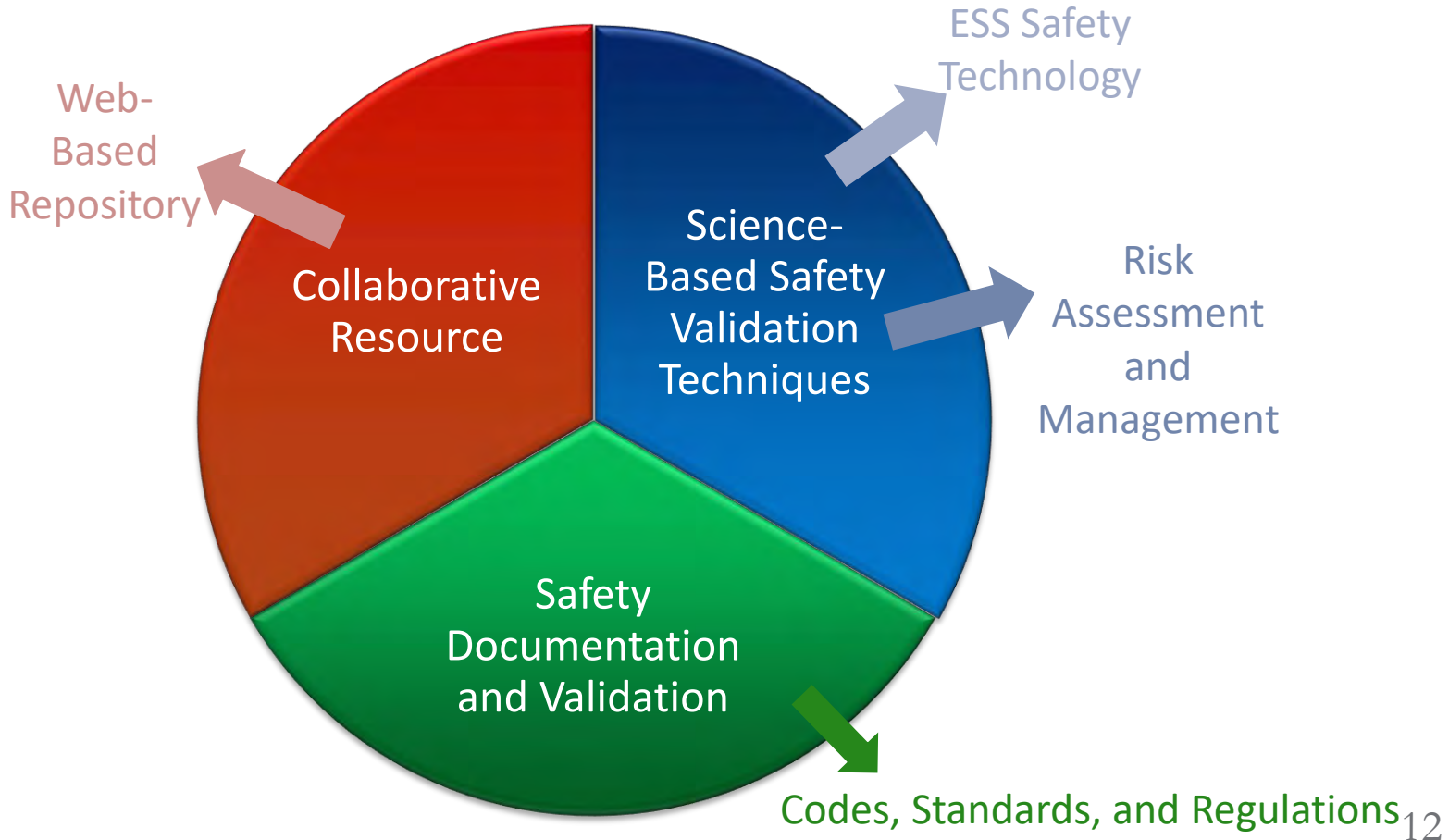
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Collaborative Resources

DOE OE Energy Storage Systems Safety Roadmap

- ▶ **Objective** – Create a conduit for effective communication using traditional and evolving media that will serve as a forum for involvement, information sharing, and collaboration that allows stakeholders to be informed of activities being undertaken in support of energy storage safety and the roadmap.
- ▶ **Activities**
 - Develop and deploy an ESS collaborative repository strategy.
 - Secure a commitment from stakeholder associations and organizations to participate in the development and deployment of the activities planned in the ESS collaborative repository strategy.
 - Create a web-based information resource (Repository).
 - Collect relevant information concerning energy storage system risks for inclusion in the Repository. Create resources to inform the community based on the results of objectives one and two. Organize the Repository for easy access and efficient navigation by all stakeholder groups.
 - Foster the update and enhancement of the Repository information on an ongoing basis to facilitate communication regarding energy storage system risk assessment and mitigation.
 - Monitor efforts associated with communication and collaboration, report on successes and identify and address areas where increased communication and collaboration are needed.

Interconnected Paths to Safe Energy Storage Systems



Stakeholder Observations

- ❖ *“I believe that that the work DOE has been undertaking in the safety area has been beneficial to the industry as a whole. In particular as an employee of a Standards Development Organization, the ESS Codes/Standards Reports, Roadmaps and Presentations allow me to see what work other SDOs are undertaking. This helps to prevent duplication of efforts and allows for cross referencing.”*
 - Kate Hyam, PE S&C Project Engineering Advisor, Safety ASME
- ❖ *“From FDNY's perspective, DOE OE has been instrumental in collaborating with the response community throughout the nation on ESS research, code and standard development, data analysis and testing. DOE OE bring together a critical partnership comprised of industry, first responders, code officials, and standard development organizations. Without these initiatives, the ESS industry would be hard-pressed to move forward.”*
 - Lt. Paul Rodgers, FDNY Haz Mat Operations
- ❖ *“The NEMA Energy Storage Section has worked closely with the national laboratory’s involved in OE’s ESS safety work. The Storage Section values the safety work because it brings together a broad group of stakeholders in various forums and produces outreach materials. These activities are helping to improve safety of energy storage systems.”*
 - Brian Marchionini, Senior Program Manager NEMA



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Stakeholder Observations

- ❖ *"Fire protection engineers and code officials will be looking for data-based evidence from large scale fire testing to assist in the design and permitting of ESS to better understand the risks to occupied structures. The DOE OE's continued support for this and additional safety performance data will be vital. Electrical infrastructure resiliency is critical to life safety as witnessed in the recent weather events."*
 - Matt Paiss IAFF Standards Representative to NFPA 70 and 855.
- ❖ *"DOE's work in ESS Safety is foundational to the success of the energy storage industry because it serves as an impartial hub for information collection and knowledge sharing."*
 - Ryan Franks, Manager, Global Energy Storage, CSA Group
- ❖ *"The DOE OE ESS safety effort focusing on codes and standards has been very beneficial as it provides information on the what is going on in the codes and standards world related to energy storage. I certainly am aware of what UL is doing, but I find it helpful to hear about the work of other organizations, since there are many that I am not involved in and their work can impact what we do at UL. There is so much going on in this arena that it helps to have one source of information to keep up-to-date."*
 - Laurie Florence, Principal Engineer – Stationary/Motive Batteries, Fuel Cells and Capacitors, UL



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Acknowledgment

Dr. Imre Gyuk

DOE-Office of Electricity Delivery and Energy
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15

Q/A and Further Information



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<http://www.sandia.gov/energystoragesafety/>



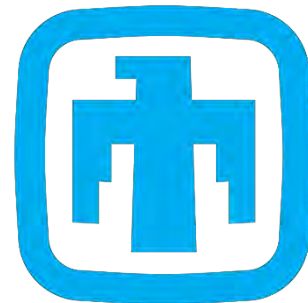
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PNNL-SA-129601

Determining the internal pressure in 18650 format lithium ion batteries under thermal abuse

Frank Austin Mier^a, Dr. Michael Hargather^a,
Dr. Summer Ferreira^b

(a) New Mexico Tech, (b) Sandia National Laboratories



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Laboratories**

Presented at Peer Review, October 10, 2017

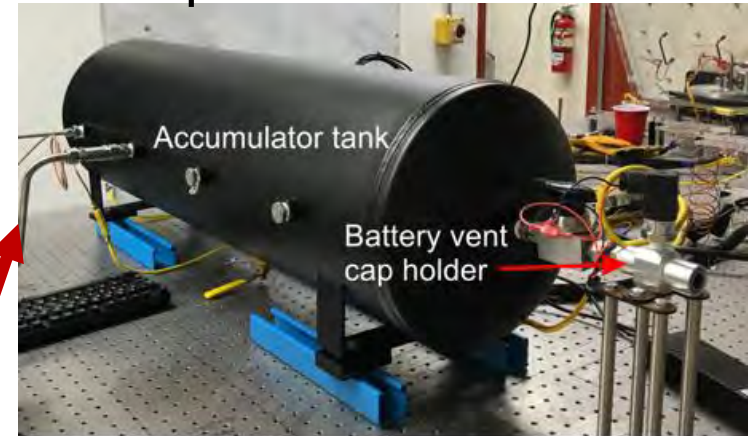
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2017-10800 C

Describing the external dynamics of venting starts with quantifying pressure

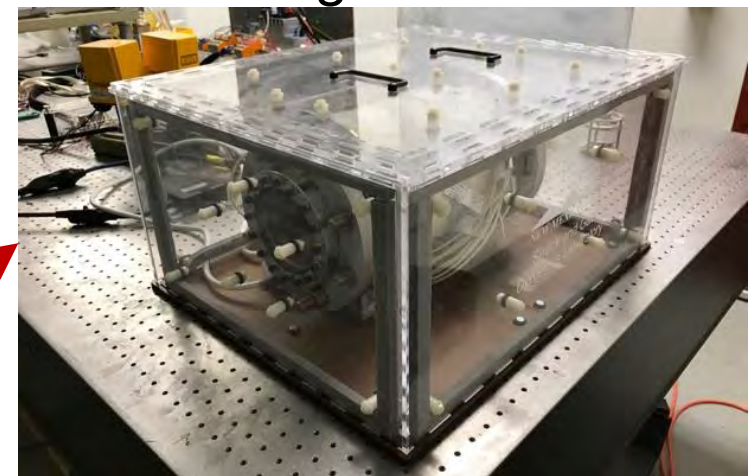
- Batteries are designed to vent under extreme abuse
- Presents safety concerns such as flammability

Designed two experiments:

Direct pressurization of vents:



Strain during thermal abuse:



- Measurements:
 - Vent area, burst pressure
 - Battery internal pressure



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Impact of Frequency Regulation on Degradation of Commercial Li-ion Batteries

Daiwon Choi, Alasdair J. Crawford, Vilayanur V. Viswanathan, Qian Huang, Michael CW. Kintner-Meyer, Ji-Guang Zhang, David M. Reed, Vince L. Sprenkle

Pacific Northwest National Laboratory

Support from DOE Office of Electricity Delivery & Energy Reliability Energy Storage Program

DOE Office of Electricity Delivery & Energy Reliability Peer-Review
San Diego, CA, Oct. 9-10, 2017

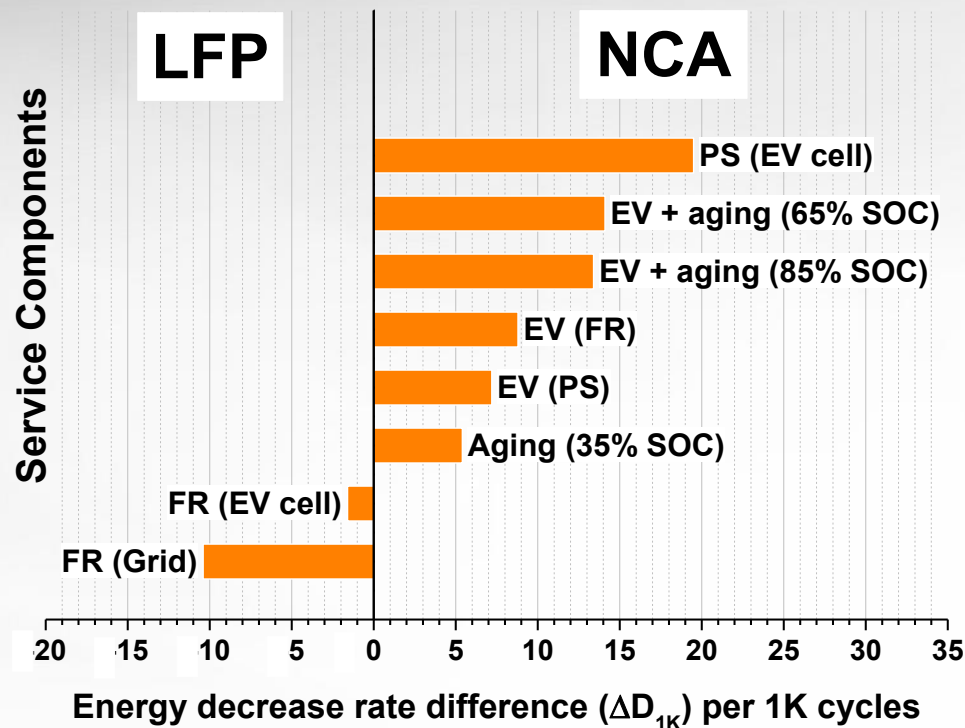
Project Overview

▶ Program Objectives

- Reliability of two different Li-ion battery chemistries (NCA and LFP) under frequency regulation (FR) grid service and combination of electric vehicle (EV) drive cycle and frequency regulation (FR) or peak shaving (PS).
- Fundamental understanding of degradation mechanisms and limitations of the two Li-ion battery chemistries.

▶ Accomplishments

- Round trip efficiency, resistance, capacity and energy changes were studied.
- Different service components were separated to understand effect of specific application on Li-ion battery chemistries.
- Degradation mechanisms of the two different Li-ion battery chemistries were analyzed and proposed.

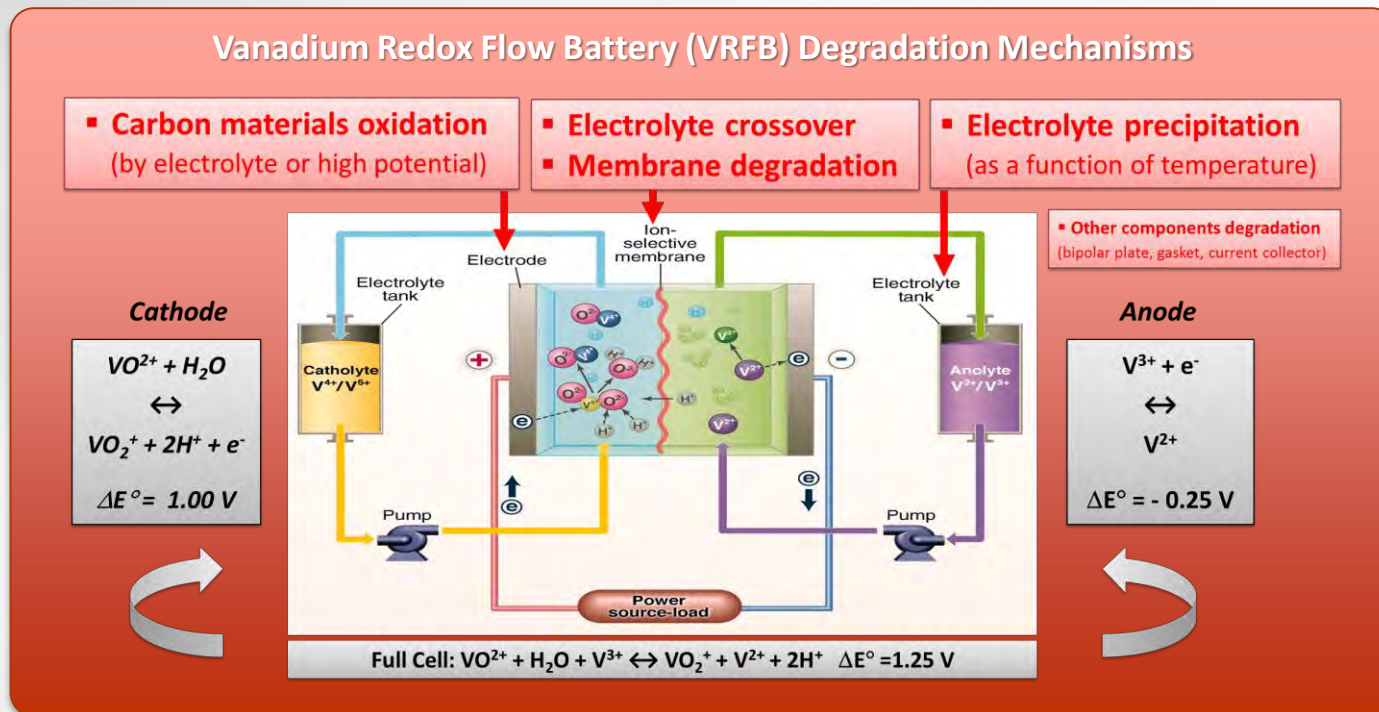


Reliability Study of Vanadium Redox Flow Batteries by Superior Stable DHE

Qian Huang ^a, Bin Li ^a, David Reed ^a, Chaojie Song ^b, Alison Platt ^b, Khalid Fatih ^b,
 Zhengming Jiang ^b, Christina Bock ^b, Darren Jang ^b

^a Electrochemical Materials & Systems Group, Pacific Northwest National Laboratory, Richland, WA 99352

^b Energy, Mining & Environment, National Research Council Canada, Vancouver BC V6T 1W5



Project Overview



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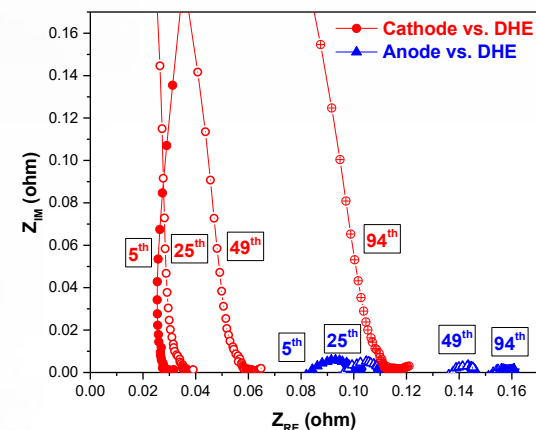
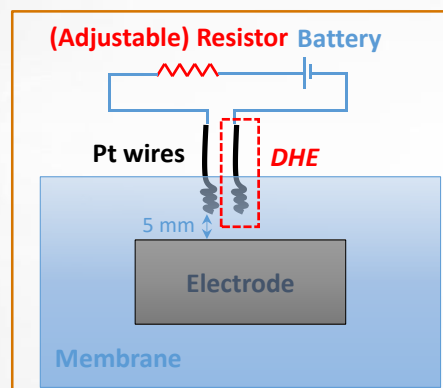
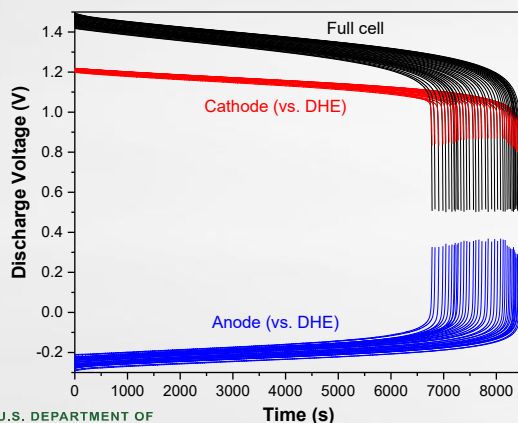
Objectives & Approaches:

- Stable reference electrode development to decouple the cathode and anode during long-term testing of VRFB;
- Accelerated stressor lifetime testing (ASLT) protocol development for VRFB;
- Fundamental understanding of degradation mechanism of VRFB component and system.

Summary & Perspective:

- A dynamic hydrogen electrode (DHE) based reference electrode has been developed for VRFB, which demonstrates a superior long-term stability by optimized design with adjustable resistor;
- In-situ* monitoring single electrode potential has been achieved by the extraordinarily stable DHE throughout 100 cycles of VRFB charging-discharging;
- By DHE approach, the full cell performance decay (such as capacity, overpotential and impedance distribution) during long-term cycling is dissected into individual electrodes;
- The newly developed DHE approach in scaled commercial VRFB is under validation.

Single Electrode Potential Measurement DHE: Optimized Design with Adjustable Resistor Single Electrode Impedance Measurement





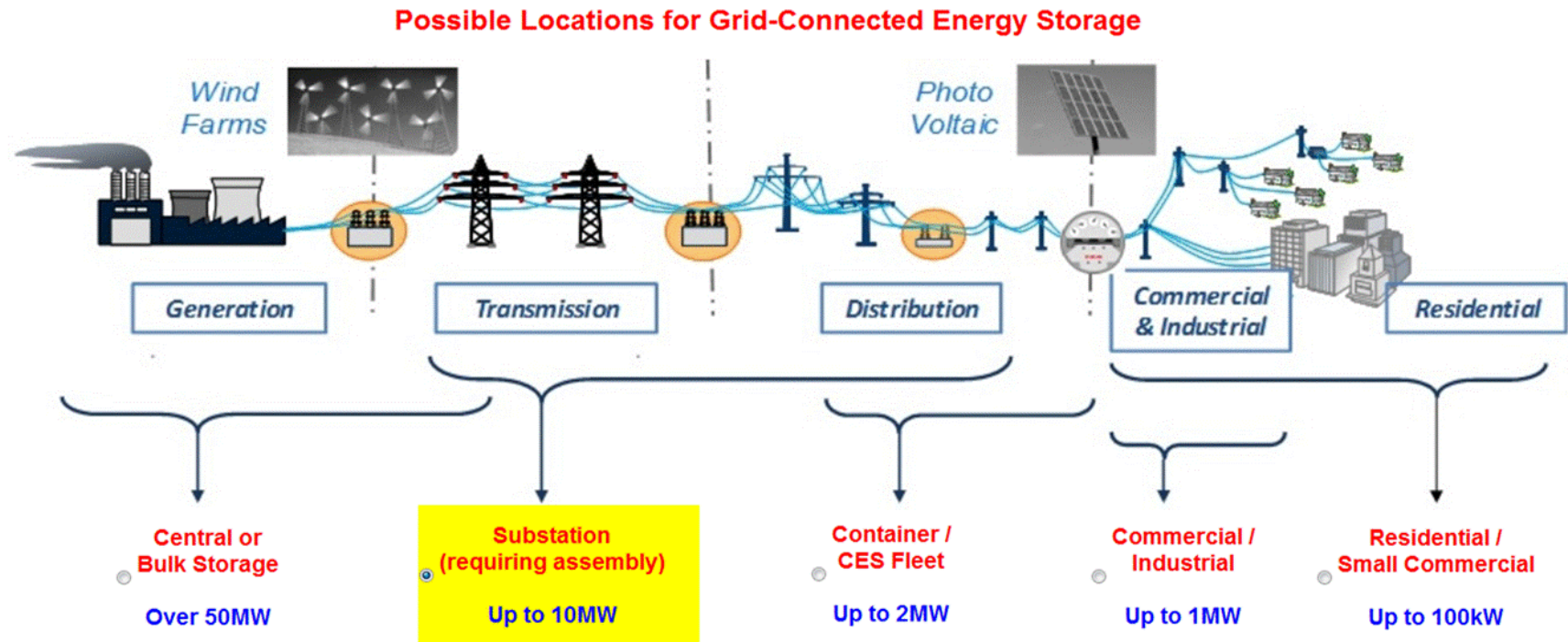
3300 V SiC MOSFETs for Energy Storage Power Electronics

Ranbir Singh and Siddarth Sundaresan
GeneSiC Semiconductor Inc.

Acknowledgement: The authors thank Dr. Imre Gyuk for funding this work and Dr. Stan Atcitty for technical contributions. Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SBIR Phase II Grant DE-SC0013816

GeneSiC
SEMICONDUCTOR

Energy Storage Opportunities at Medium Voltages (3-20 kV)

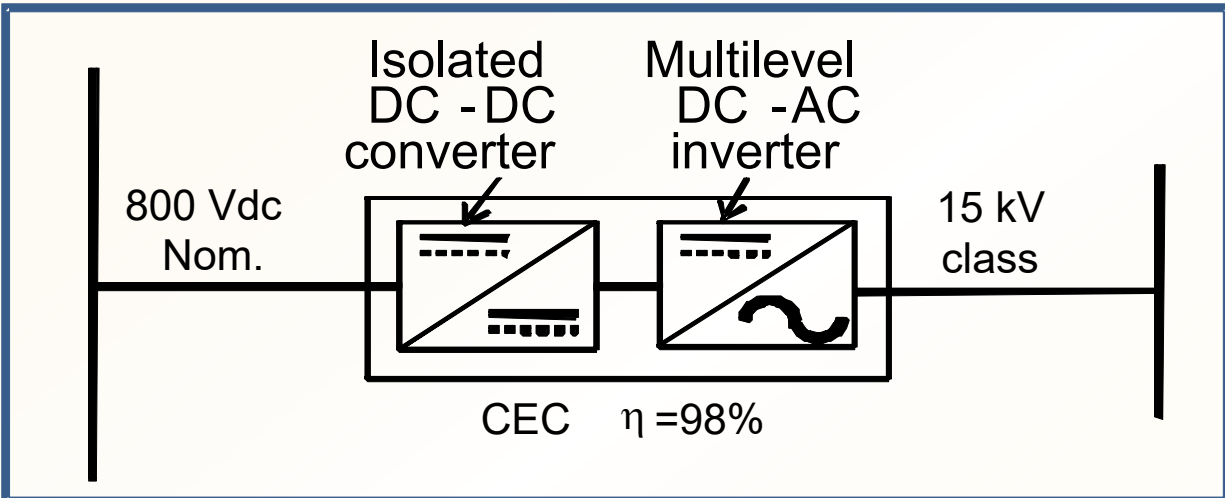
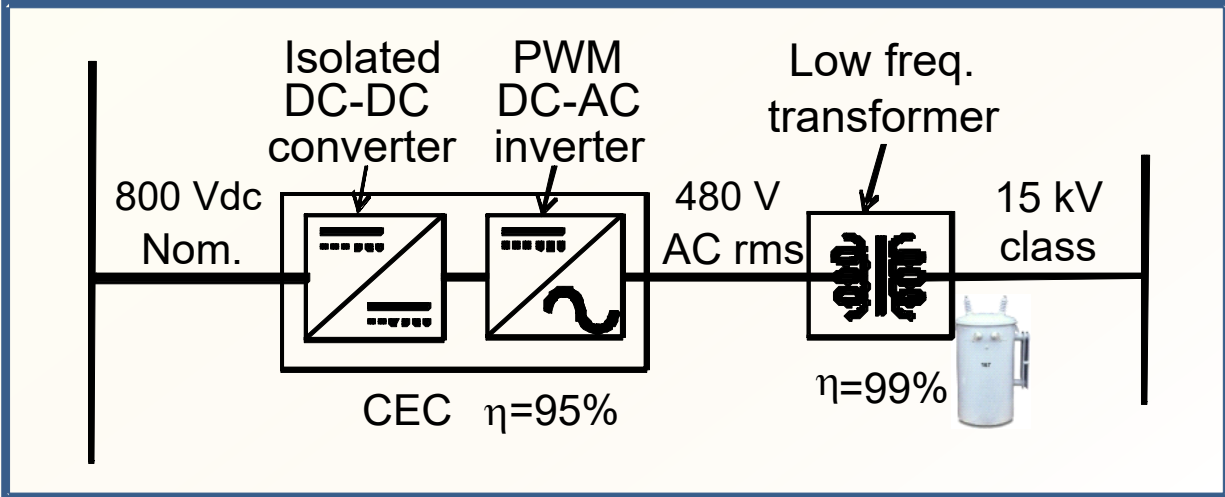


- Many Energy storage opportunities require power electronics that can enable conversion efficiencies needed for making energy storage viable
- Silicon Carbide high voltage devices will play a pivotal role

Why MV SiC Power Devices?

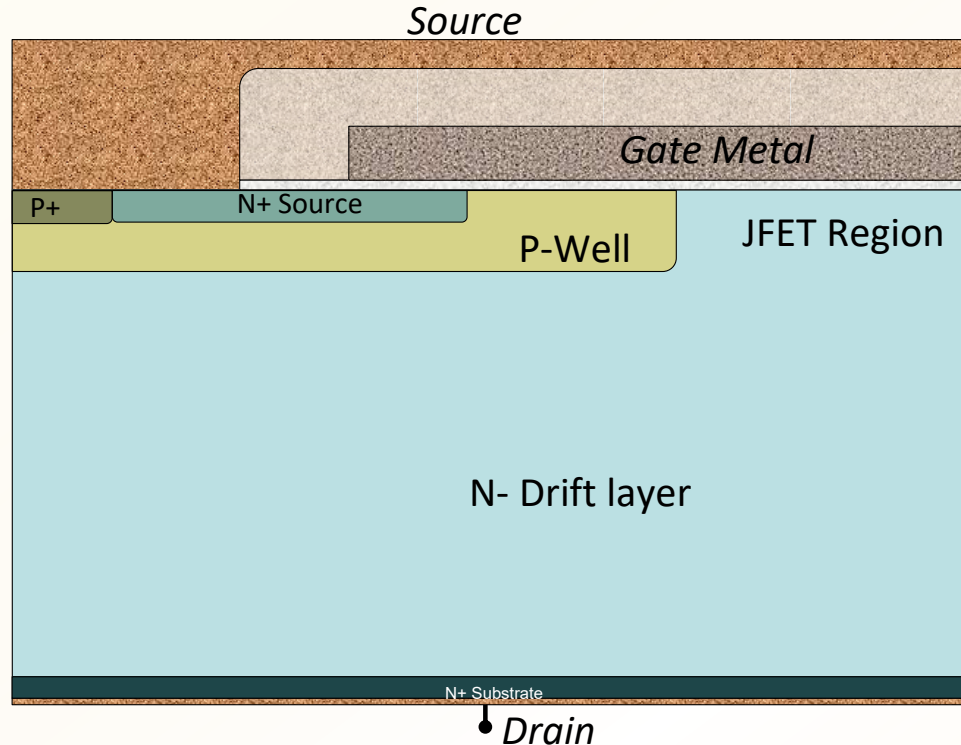
Properties SiC vs Si	Performance of >10kV SiC Devices	Impact on Power Circuits
Breakdown Field (10X)	Lower On-state Voltage drop (2-3X)	Higher Efficiency of circuits
Smaller Epitaxial Layers (10-20X)	Faster Switching speeds (100-1000X)	Compact circuits
Higher Thermal Conductivity (3.3-4.5 W/cmK vs 1.5 W/cmK)	Higher Chip Temperatures (250-300°C instead of 125°C)	Higher pulsed power Higher continuous current densities,
Melting Point (2X)	High Temperature Operation (3X)	Simple Heat Sink
Bandgap (3X) (10¹⁶X smaller n_i)	High Intrinsic Adiabatic Pulsed Current Level (3-10X?)	Higher Current Capability

Battery Energy Storage Power Electronics Architectures



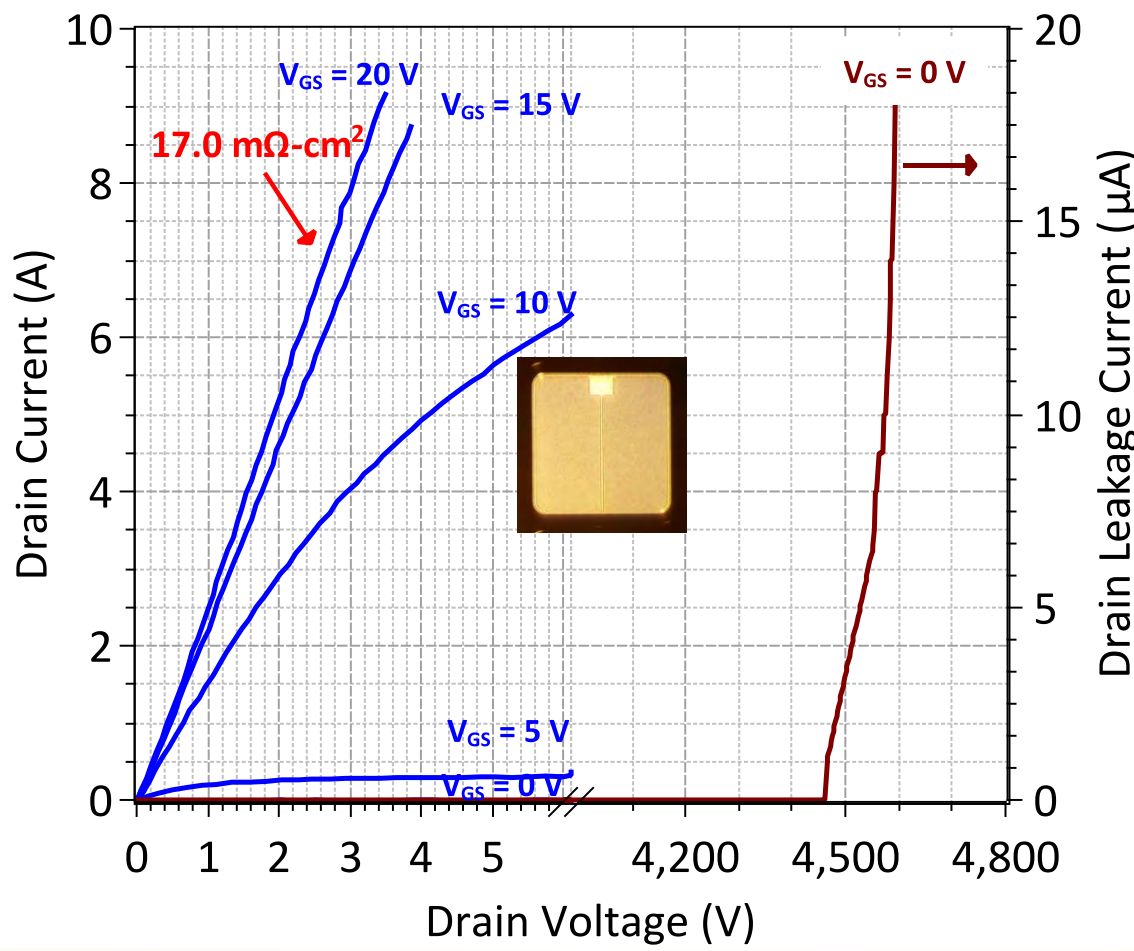
- Bidirectional, isolated DC-AC Power Conversion systems needed
- High Efficiencies are needed due to two-way power flow
- Compact systems help in wider deployments
- Low Frequency Transformer occupies space

Device Design and Fabrication



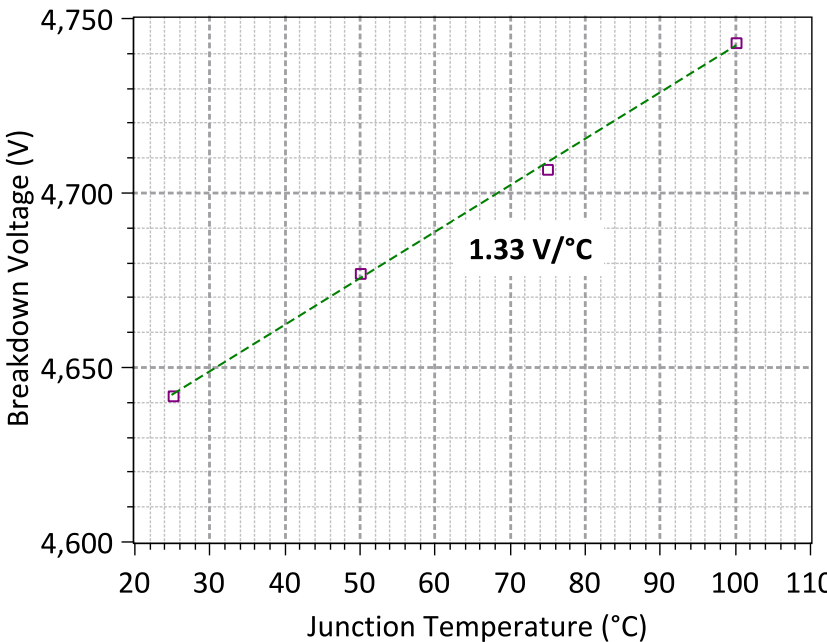
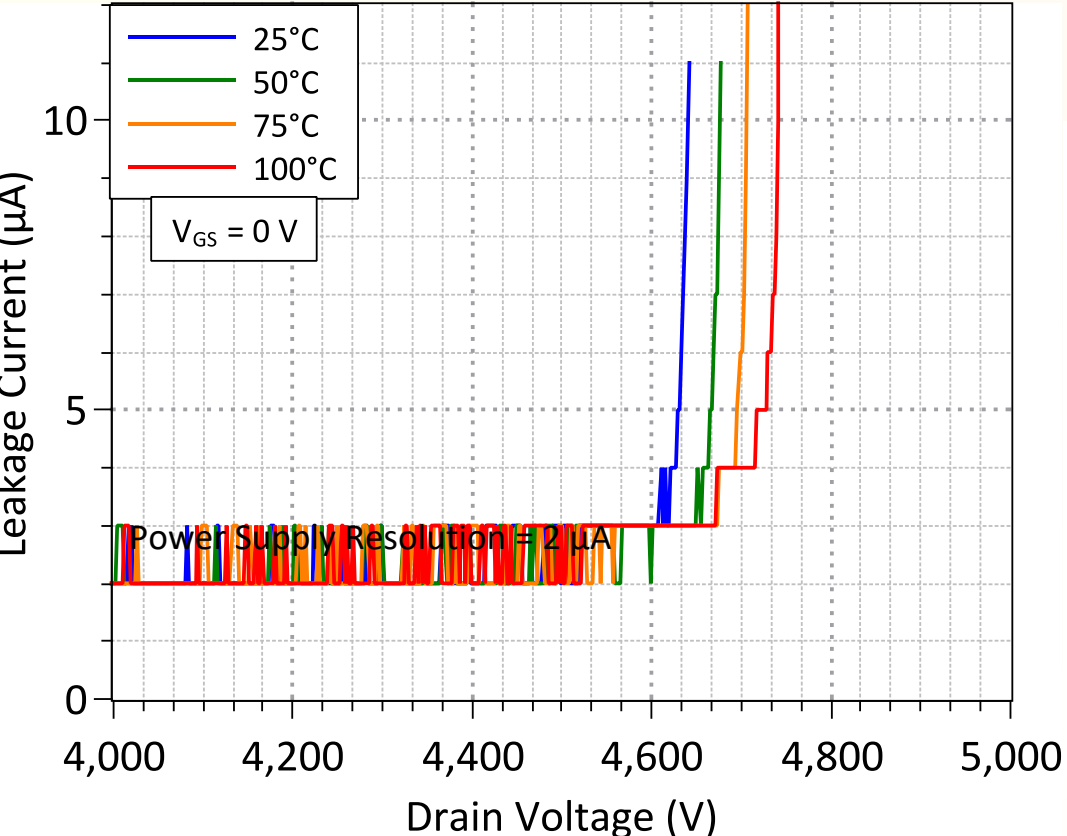
- SiC Planar DMOSFETs fabricated on 35 μm thick, $\approx 2.8 \times 10^{15} \text{ cm}^{-3}$ doped N- drift epilayers
- The device design space constituted different JFET Doping Profiles, Channel Lengths and JFET spacings

Output and Blocking Characteristics



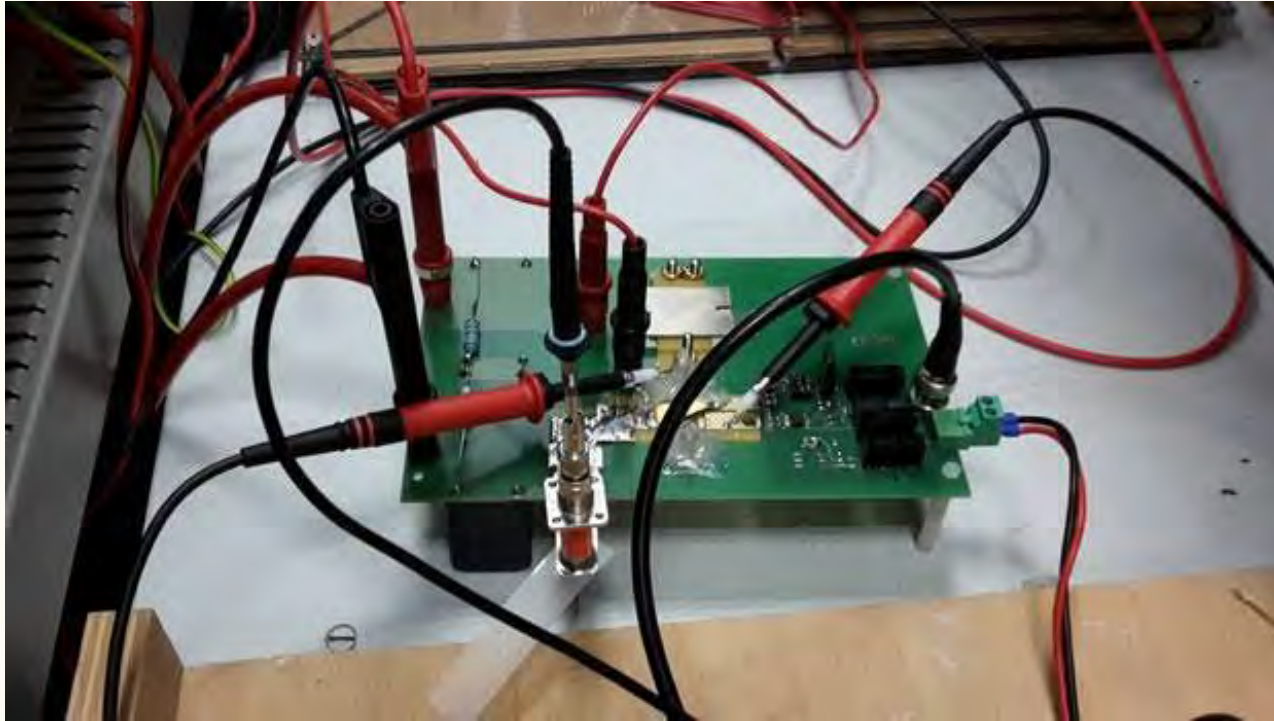
- 2.74 mm x 2.74 mm die
 - Active Area = 0.046 cm²
- R_{on,sp} of 17.0 mΩ-cm², and breakdown voltage of 4600 V measured at 25°C
- BV close to theoretical limit for 35 µm/3x10¹⁵ cm⁻³ thick N- drift layer
- V_{TH} extracted as 2.4 V (at I_D = 5 mA)

Breakdown Voltage Variation with Temperature



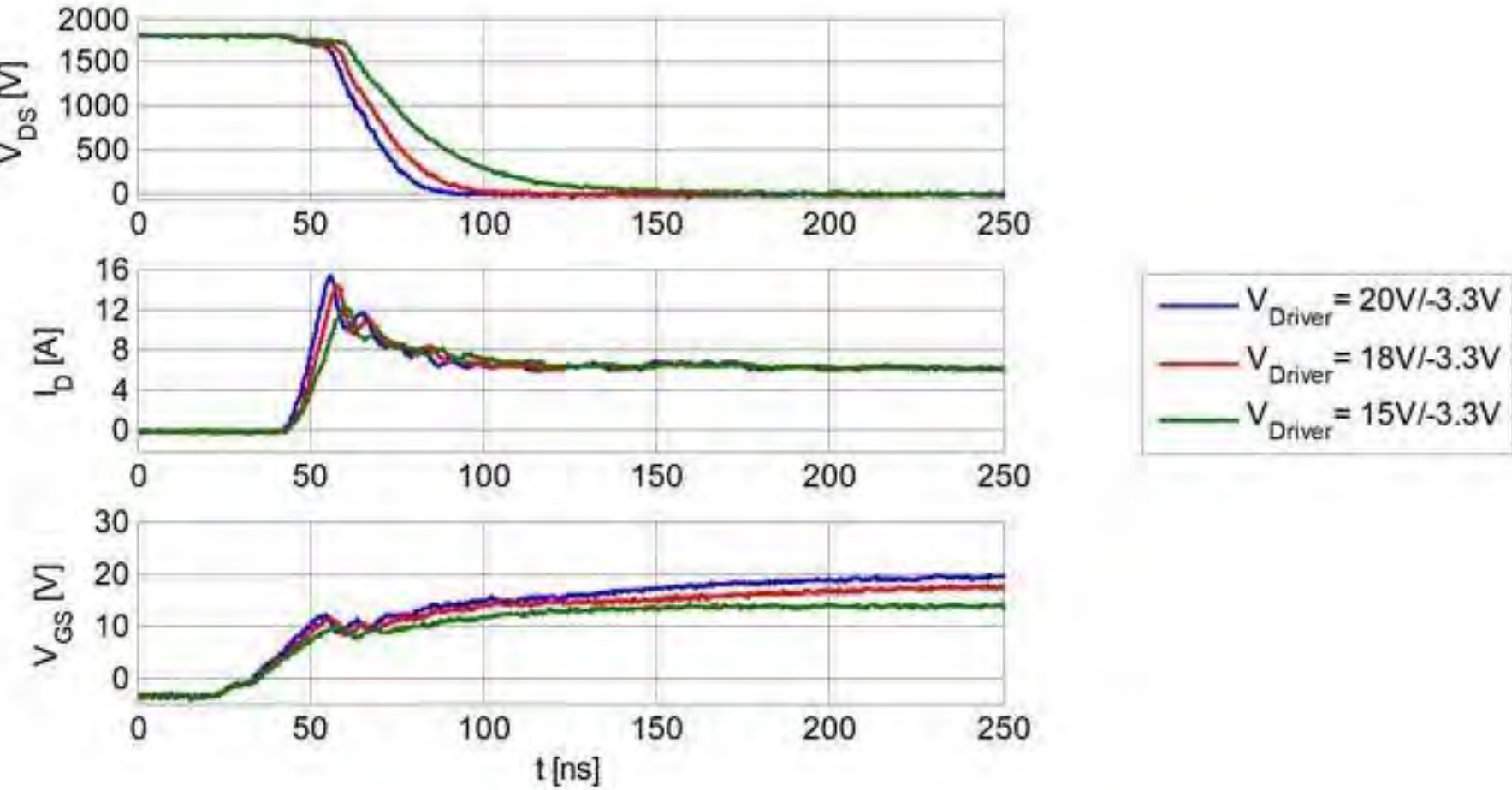
- Breakdown voltage increases linearly with measurement temperature
- Extracted temperature co-efficient of avalanche breakdown as 1.33 V/ $^{\circ}\text{C}$

Double Pulse Switching Characterization



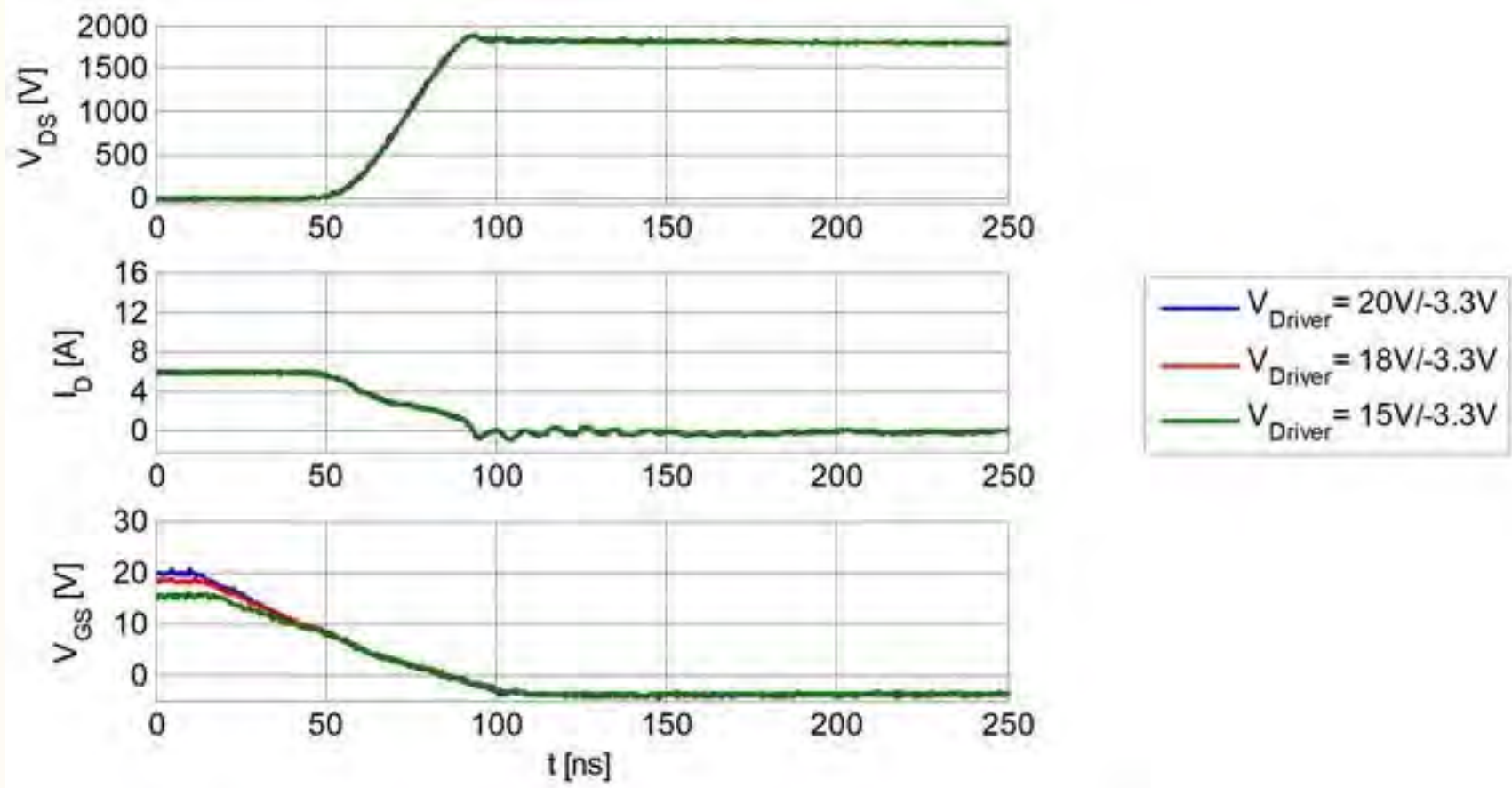
- Double-pulse testing for high-voltage switching of GeneSiC DMOSFETs
Studied impact of V_{drive} in the range of +15-20 V, and (external) gate resistance in the range of 10-30 Ω on switching characteristics
- Performed switching measurements at DC link voltage of 1800 V and $I_D = 6$ A
 - The body diode of a second MOSFET was used as the FWD

Double Pulse Switching Characterization



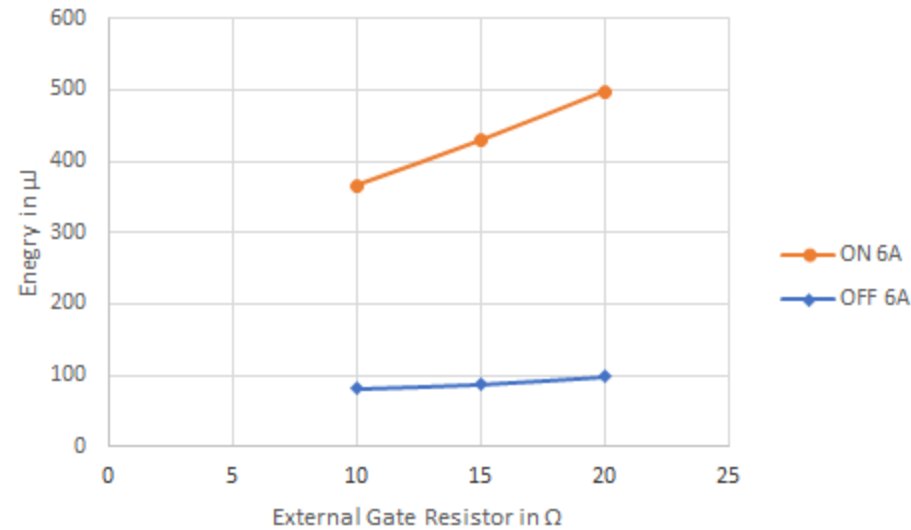
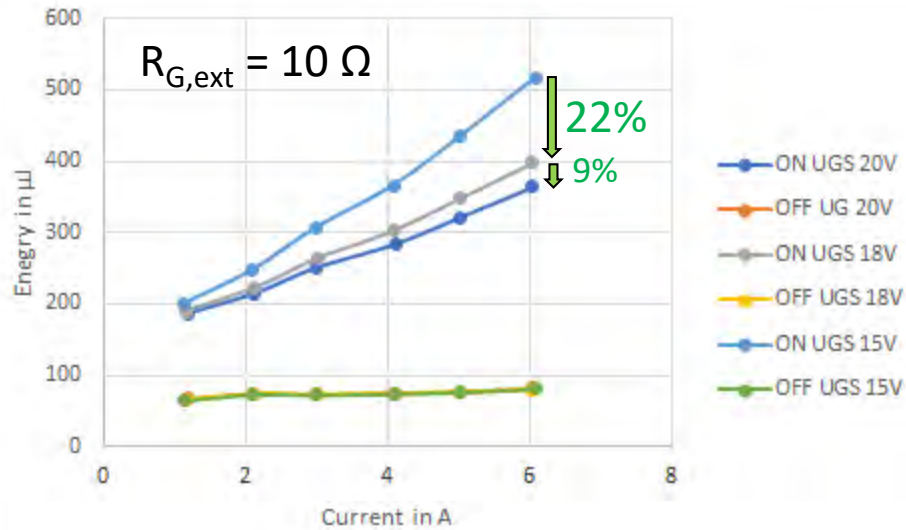
- V_{DS} fall time = 30 ns achieved for switching at 1800 V and 6 A, with +20 V drive voltage and $R_{G,ext} = 10 \Omega$

Double Pulse Switching Characterization



- V_{DS} rise time = 30 ns achieved for switching at 1800 V and 6 A, with -3.3 V Gate Drive Voltage

Double Pulse Switching Characterization



- Energy Losses are extracted from switching waveforms measured at various drain current levels and different gate drive voltages
- 22% decrease in E_{ON} observed, when gate drive voltage is increased from +15 V to +18 V
- Further increase of drive voltage from +18 V to +20 V only yielded 9% improvement in E_{ON}

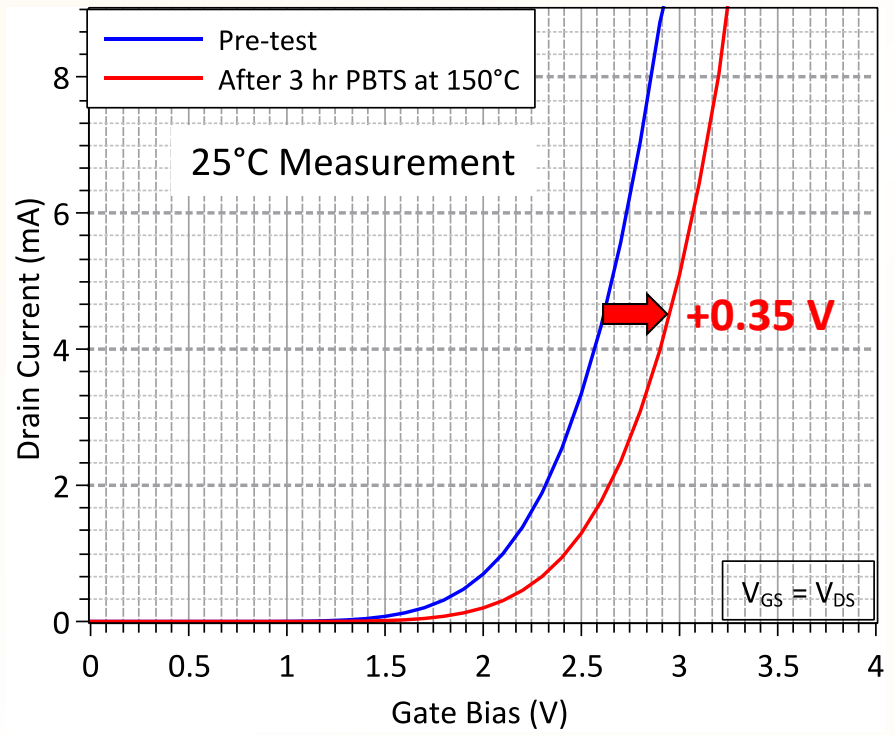
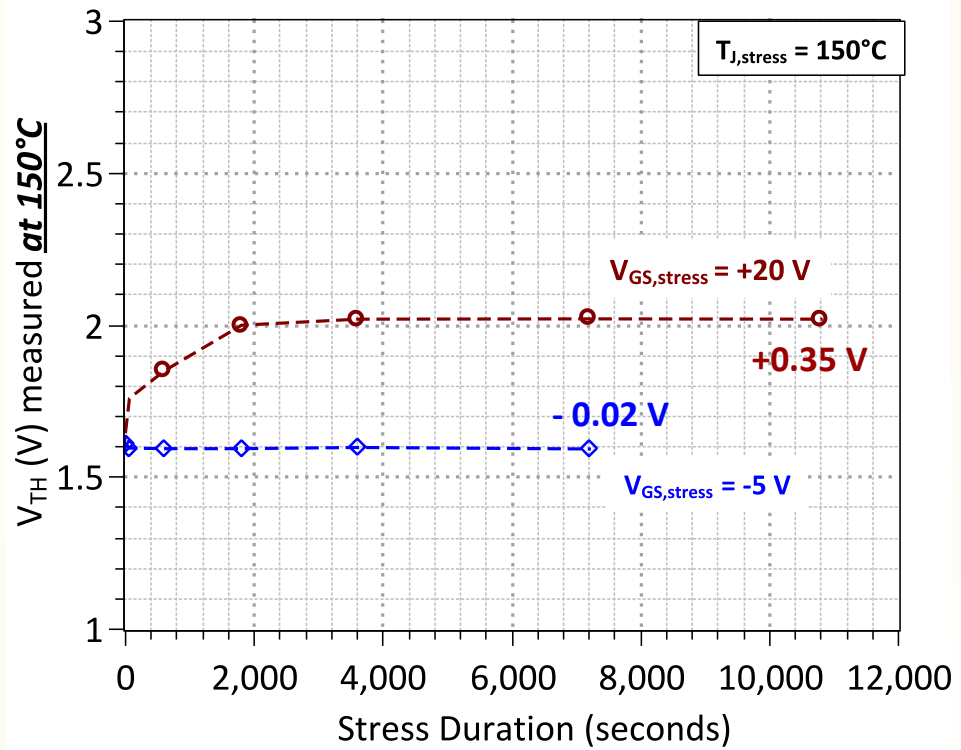
Status and Future Efforts

- Current Status
 - Technology developed for commercially viable 3300 V SiC MOSFETs
 - Up to 4600 V SiC MOSFETs demonstrated
 - Phase I Project July 2015 – March 2016
 - Phase II Project started Aug 1, 2016
- Future Efforts in Phase I
 - Scale up the voltage ratings to 6500 V
 - Scale up Current ratings to 50 A
 - Quantify the impact of All-SiC based power electronics on grid-tied energy storage systems
 - Work with commercialization partners by making a 400 kW demonstration

Grant Details

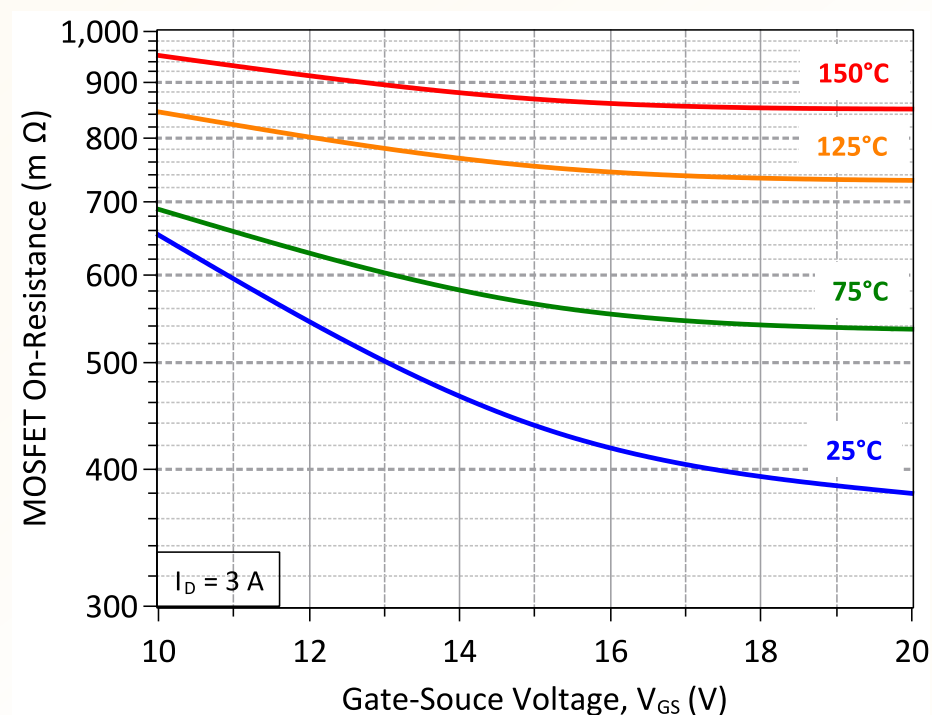
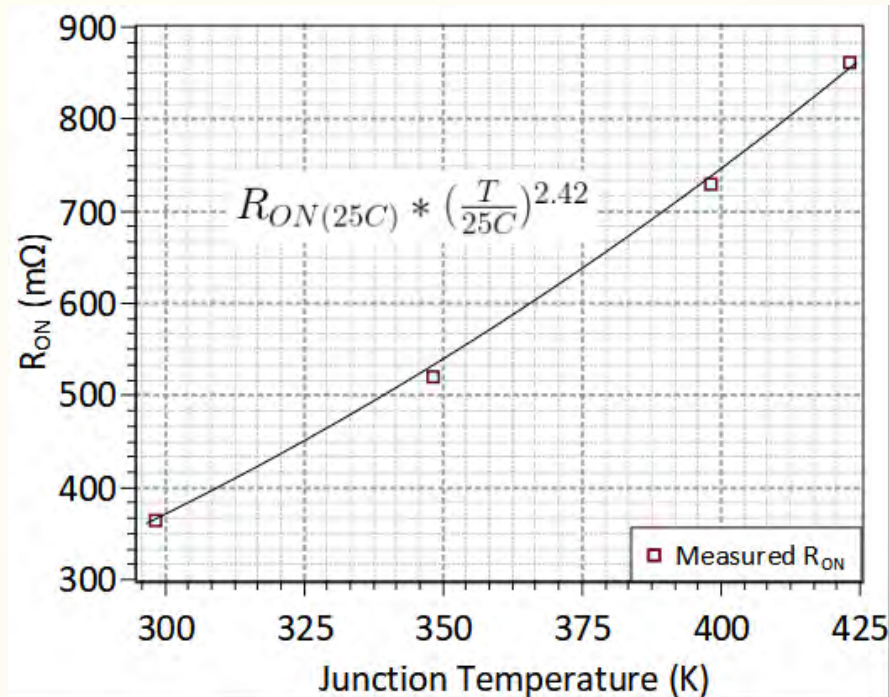
- Principal Investigator: Dr. Ranbir Singh
- Program Manager: Dr. Ranbir Singh
- Grantee:
 - GeneSiC Semiconductor Inc. and North Carolina State University
 - 43670 Trade Center Place
 - Suite 155
 - Dulles VA 20166
 - +1 703 996 8200 (ph)
 - ranbir.singh@genesicsemi.com

High-Temperature Gate Bias Stressing



- Stress Bias applied with device on a 150°C hotplate
- Transfer I-V measured at 150°C within 5 seconds after interruption of stress bias
- V_{GS} shifts by +0.35 V during the PBTS sequence
- V_{GS} shifts by -0.02 V during the NBTS sequence

$R_{DS,ON}$ at High Temperatures

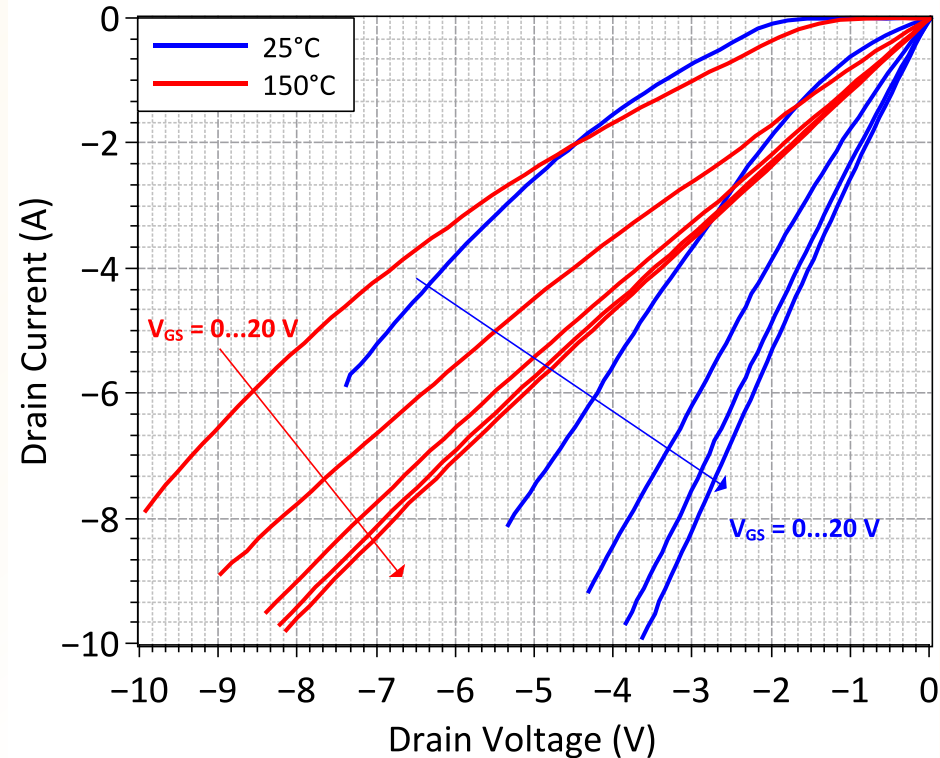
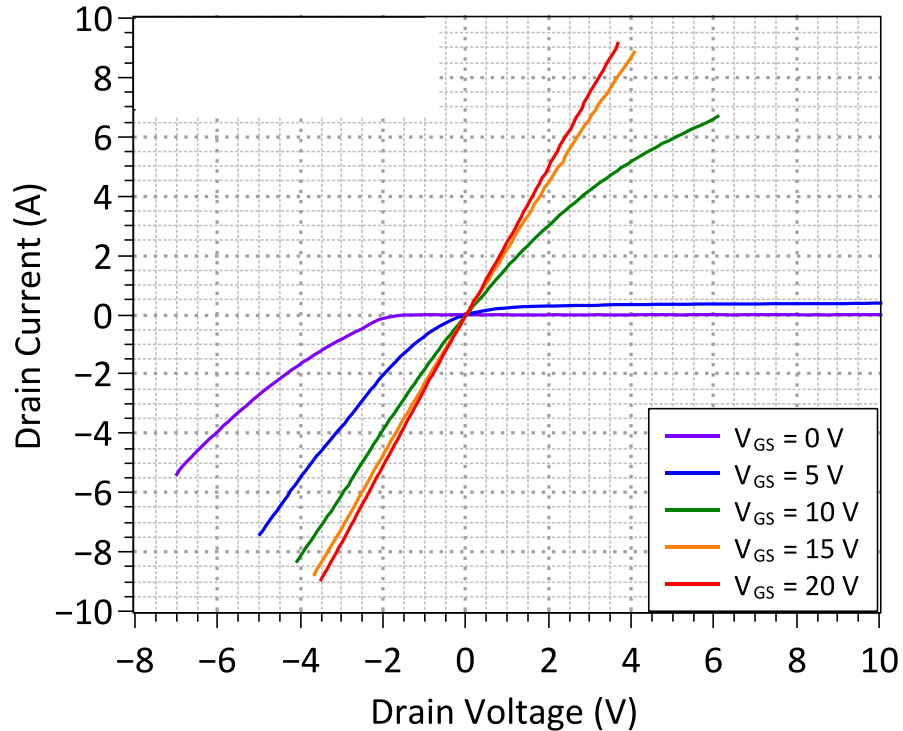


- The temperature co-efficient of R_{on} tracks very closely to the temperature dependence of (bulk) electron mobility
 - On-Resistance is solely determined by N- drift layer properties

- Impact of Gate Bias on $R_{DS,on}$ is less significant at higher operating temperatures

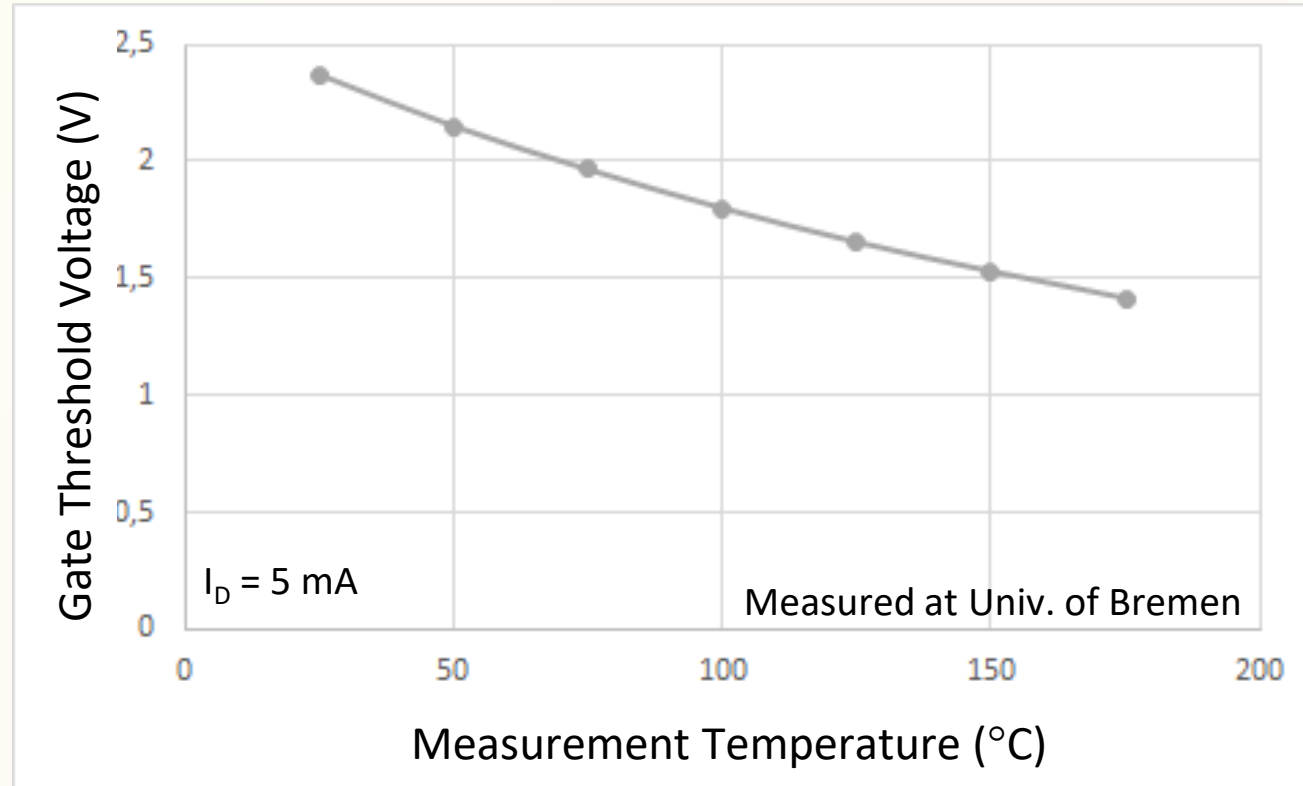
	25°C	150°C
Increasing V_{GS} from 15 V to 20 V	13.2% R_{ON} reduction	2% R_{ON} reduction

Negative Drain Bias Characteristics



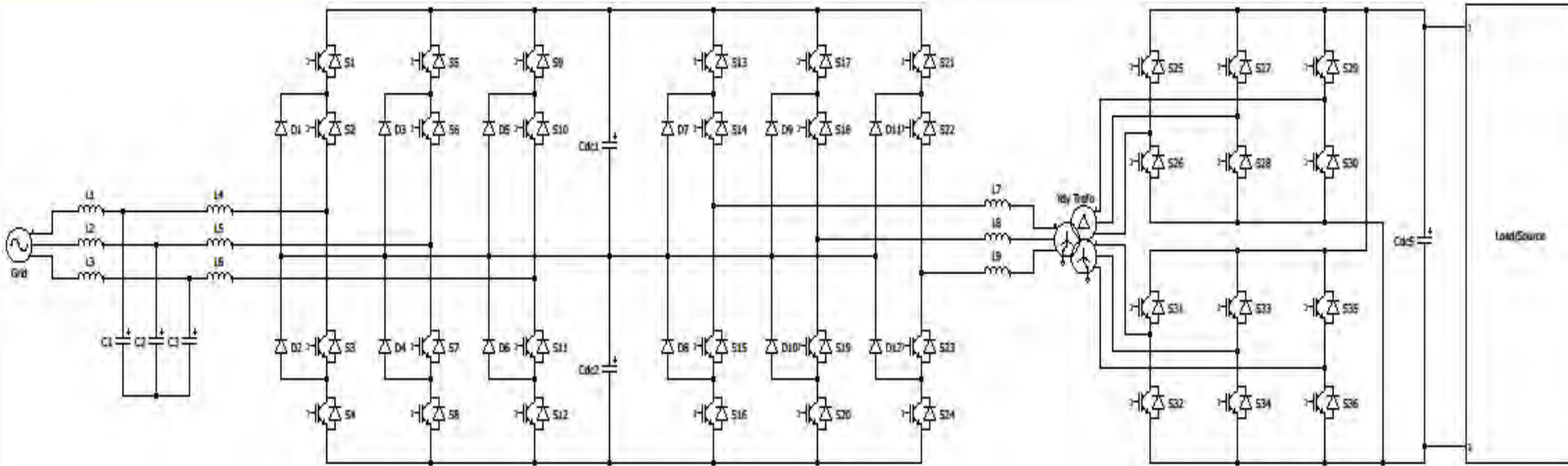
- The negative drain bias (synchronous rectifier mode) performance of the DMOSFET at 25°C and 150°C is shown
- Depending on the magnitude of the gate bias and the junction temperature, the device operates in either purely bipolar mode, purely unipolar mode, or in a mixed-mode.

Gate Threshold Voltage Variation with Temperature

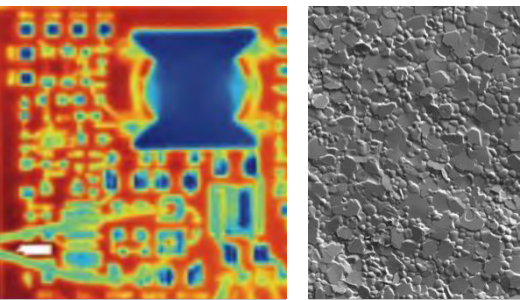


- V_{TH} decreases from 2.4 V at 25°C to 1.4 V at 175°C.
 - Linear temperature co-efficient = - 6.3 mV/°C
 - Mild temperature co-efficient of V_{th} is an indication of a low (acceptor-type) MOS interface charge

Multi-level Converters using HF/SiC Transistors at >3300 V



- Bidirectional 800 V grid-scale battery connections on secondary side
- 3300 V and 6500 V SiC devices required for high frequency secondary side connection



Obstacles to High Temperature DC-Link Capacitor Reliability

Harlan J. Brown-Shaklee, Rudeger H.T. Wilke,
Jonathan A. Bock

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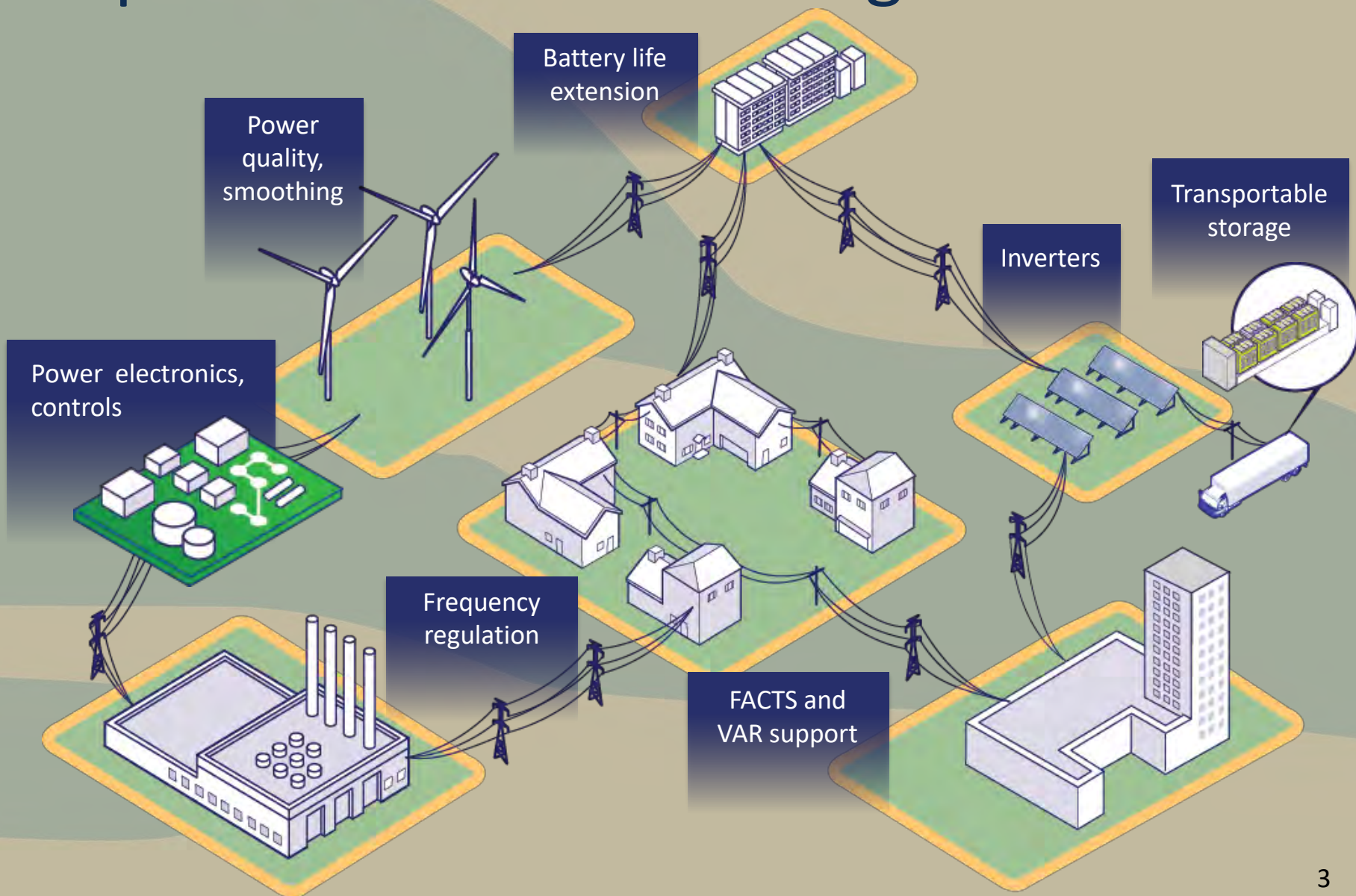
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Acknowledgements

- Funding:
 - Dr. Imre Gyuk, Department of Energy's Office of Electricity Delivery and Energy Reliability
- Team
 - Other Sandians
 - Rudeger Wilke, PhD
 - Jonathan Bock, PhD (Postdoc)
 - Carl Fitzgerald
 - Mia Blea-Kirby
 - Amber Arqitola (Summer Student)
 - Lara Draelos (Summer Student)
 - Alice Kilgo and Bonnie McKenzie
 - Terry Garino, PhD (Retired)
 - Stan Atcitty, PhD
 - TPL, Inc., Albuquerque, NM (Technology Commercialization Fund)
 - Kirk Slenes, PhD

Team combines expertise and advanced capabilities in use design, fabrication, integration, degradation and reliability, characterization, and applications

Capacitor Needs for Storage



Capacitors are required for future power electronic module designs

This R&D targets capacitor technology gaps that will impede high power inverter design breakthroughs on a 10-15 year development horizon

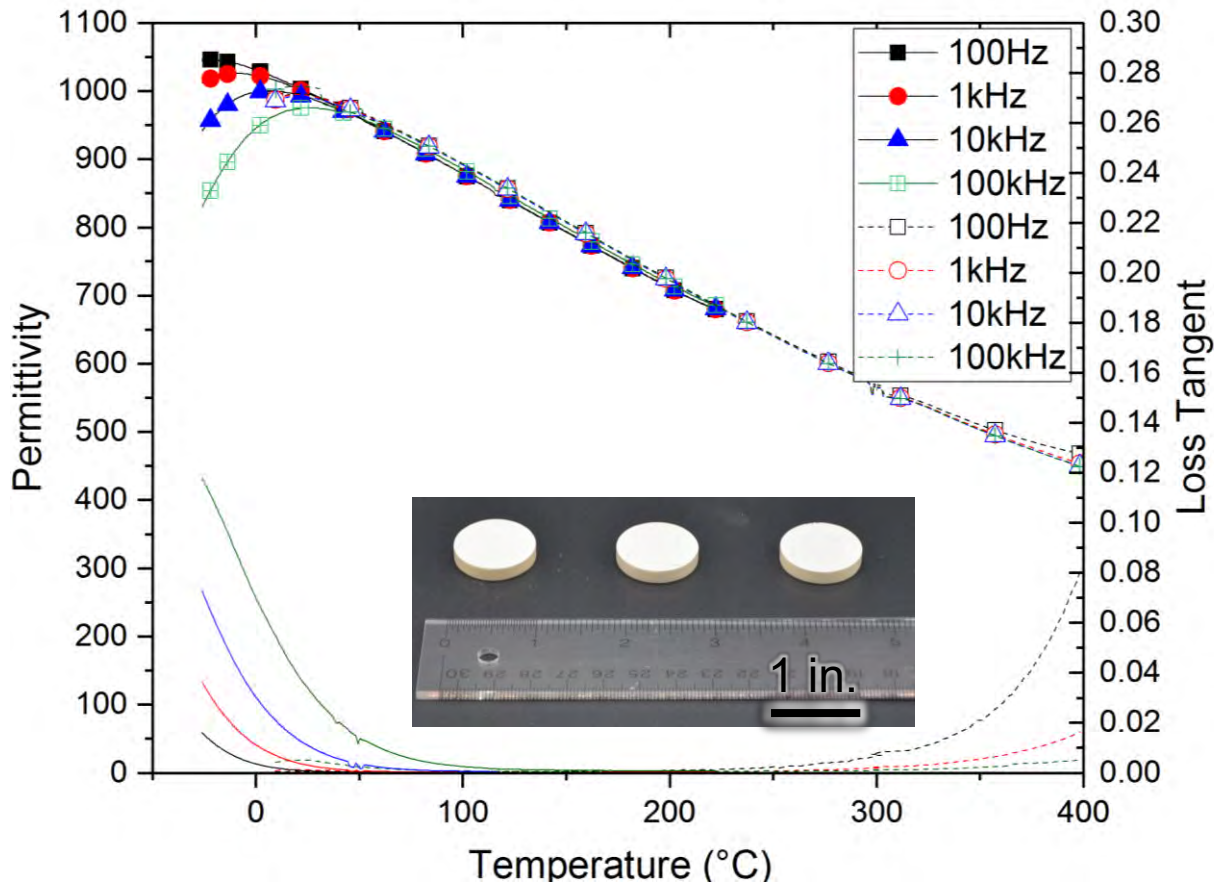
- Power electronics are required for storage and renewable insertion as well as phase, and voltage regulation
 - Current wide band gap semiconductor modules can operate with metallized polypropylene film capacitors ($T < 250^{\circ}\text{C}$)
 - Capacitors will operate at higher temperatures as cooling is eliminated and ripple currents increase from high voltage-high speed switching
- Heating from WBG die and self heating from ripple current will activate conduction and cause capacitor degradation

Capacitor Development Thrusts

- Dielectric Formulation
 - Control of insulation resistance
 - Control of voltage and temperature coefficients of permittivity
- Reliability
 - Assess time to failure of dielectric from IR reduction and breakdown
 - Understand the role of manufacturing defects
- Processing Science
 - Reduction of sintering temperatures for base metal electrode integration
- Packaging Engineering
 - Capacitor design for electric field management

Collaboration between TPL, Inc. and Sandia via DOE TCF

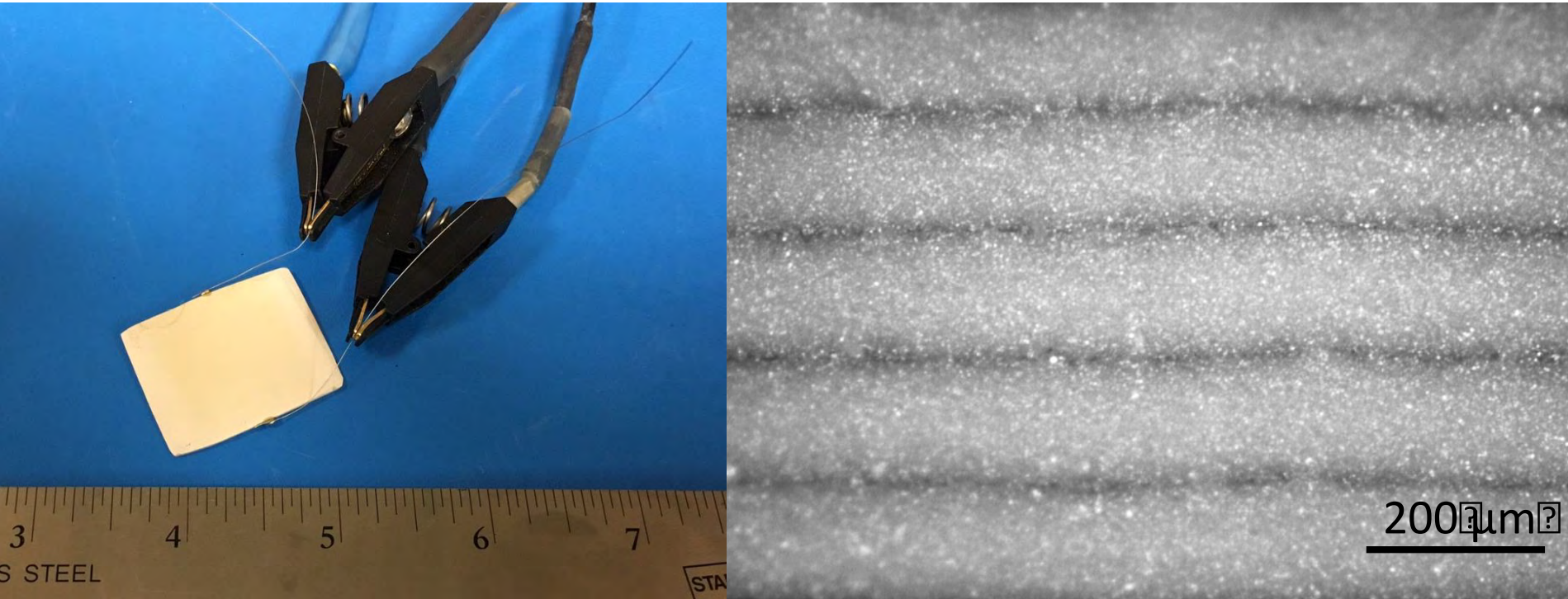
- 20%Bi(Zn_{1/2}Ti_{1/2})O₃-40%SrTiO₃-40%BaTiO₃ composition (Office of Electricity ca. 2013) transferred to TPL for processing



- Fairly large TC ϵ compared to NPO/COG
- High permittivity: $k > 500$ at 350°C
 - NPO: CaZrO₃ \rightarrow $k \sim 25$
- Typical relaxor behavior observed below room temperature
- An increase in low frequency dielectric loss above 250°C still problematic

TPL, Inc. Produced MLCC with SNL Dielectric Composition

20%Bi(Zn_{1/2}Ti_{1/2})O₃-40%SrTiO₃-40%BaTiO₃ MLLC with 150μm Dielectric Thickness



- 90nF high voltage MLCC fabricated by TPL, Inc. clearly demonstrates path to commercialization

Photo and micrograph courtesy of Kirk Slenes of TPL, Inc.

A Class II Capacitor Identification Challenge is Now Emerging

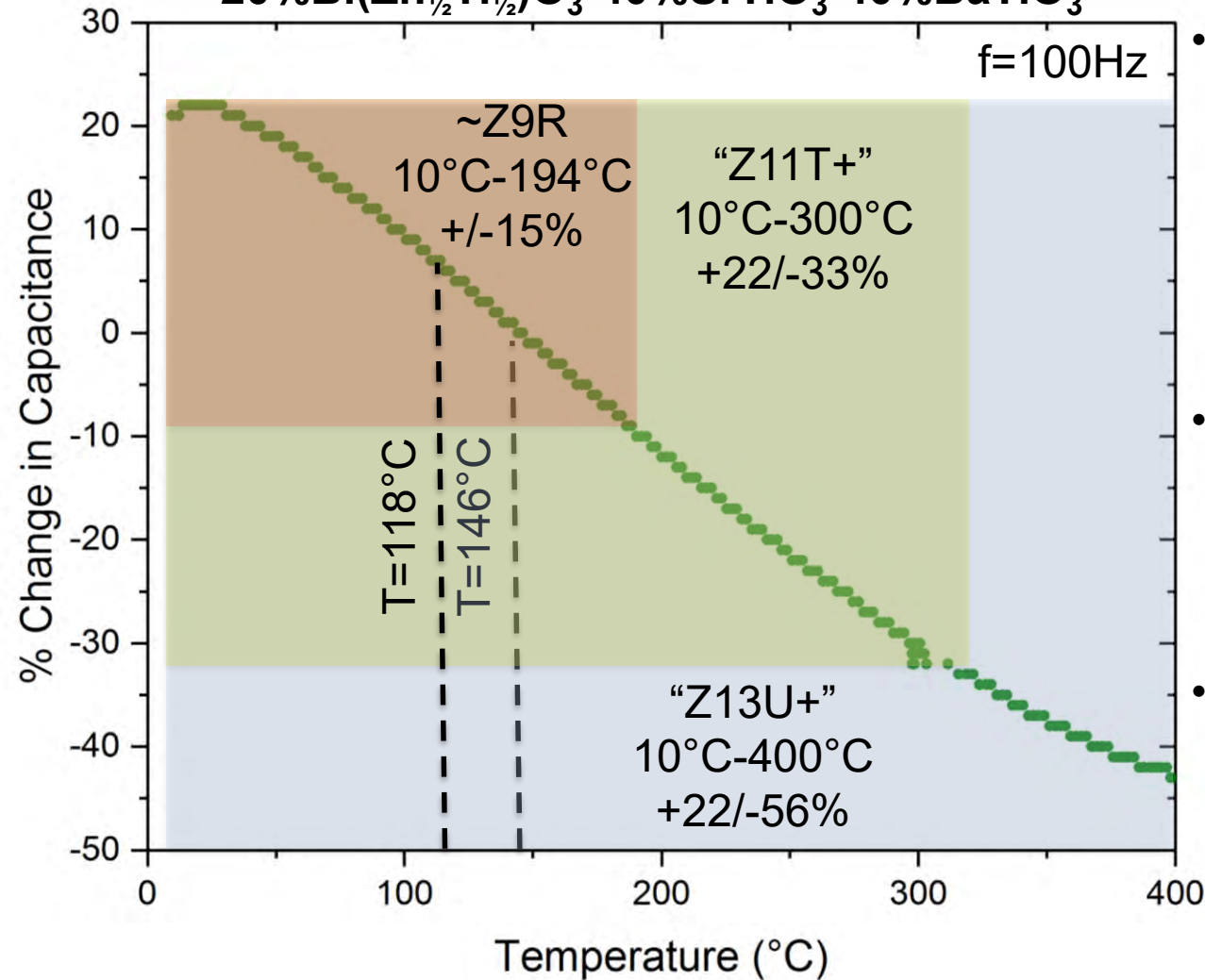
Letter code	Number code	Letter code
low temperature	upper temperature	Change of Capacitance Over the Temperature Range
X = -55 °C (-67 °F)	4 = +65 °C (+149 °F)	P = ±10%
Y = -30 °C (-22 °F)	5 = +85 °C (+185 °F)	R = ±15%
Z = +10 °C (+50 °F)	6 = +105 °C (+221 °F)	S = ±22%
AA	7 = +125 °C (+257 °F)	T = +22/-33%
BB	8 = +150 °C (+302 °F)	U = +22/-56%
CC	9 = +200 °C (+392 °F)	V = +22/-82%
DD	10=+250 °C?	W
EE	11=+300 °C?	X

Our industry standards need to capture these novel materials for use in long lifetime high temperature applications.

- Begin to report $\Delta C(T)$
- Evaluate lifetime and acceleration factors

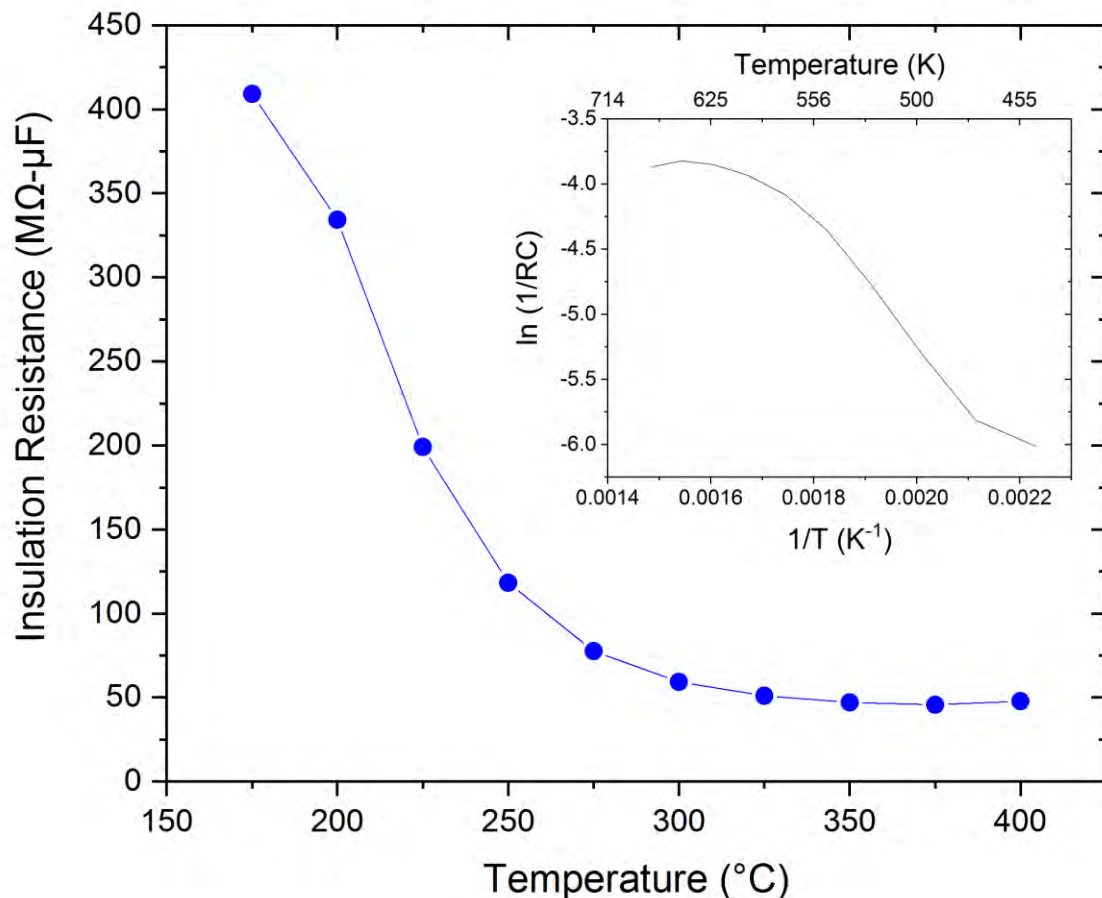
Naming New High Temperature Dielectrics to Communicate Use Intent

20%Bi(Zn_{1/2}Ti_{1/2})O₃-40%SrTiO₃-40%BaTiO₃



- Highly volume efficient dielectrics like X7R may not meet the temperature requirements of future SiC and GaN based uncooled power electronics
- Our dielectric can be classified in different ways that lead to ambiguity for the electrical designer
- We have an opportunity to promote the adoption of new high temperature naming conventions

Insulation resistance is $<1000\text{M}\Omega\text{-}\mu\text{F}$



Further improvements to high temperature RC are desired

$$RC = \frac{e_r e_0}{nem}$$



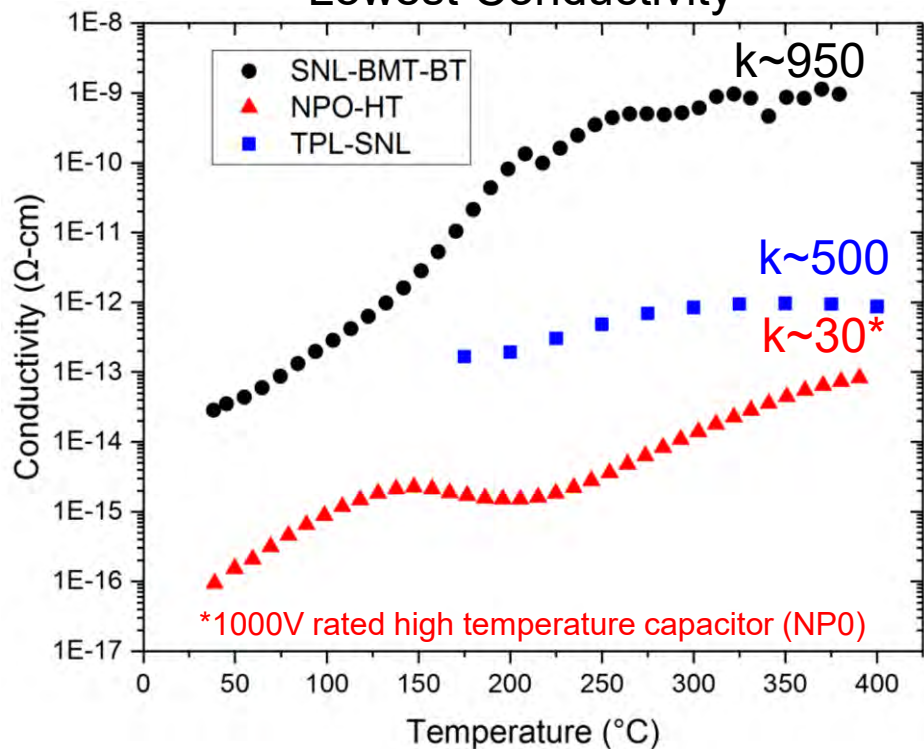
63.2% Self Discharge Time

Higher capacitor RC values are preferred and indicate that a dielectric is more insulating

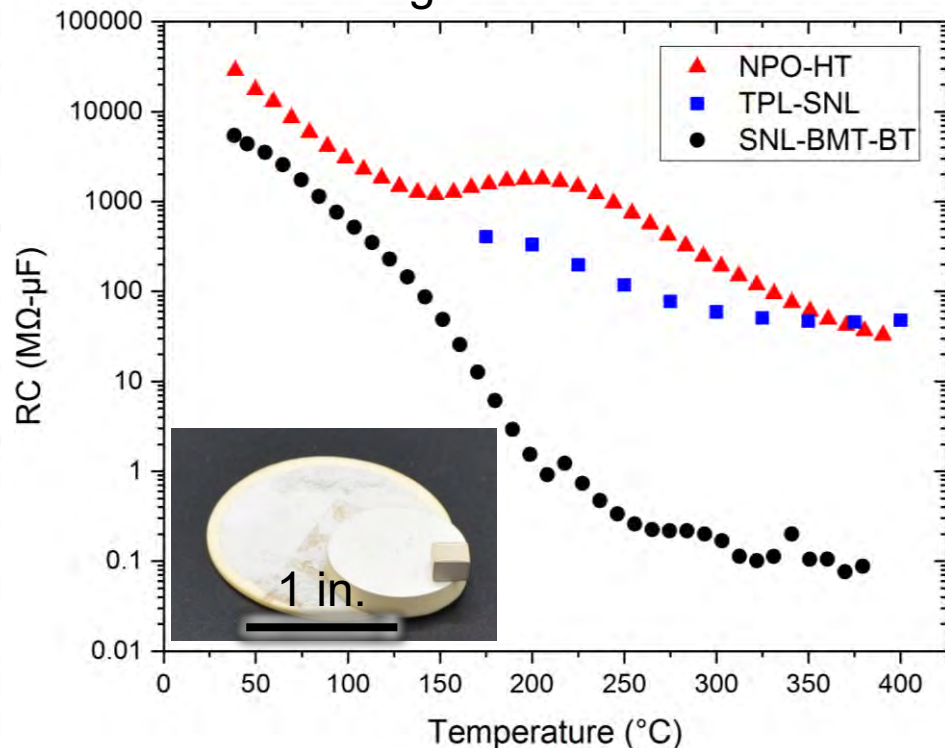
Thermally activated mobility leads to reduction of RC with increasing temperature

High Permittivity *Can* Increase RC to Affect High Temperature Self Discharge

Commercial MLCC has the Lowest Conductivity



Sandia-TPL Capacitor has the Highest RC at 400°C



$$RC = \frac{e_r e_0}{nem}$$

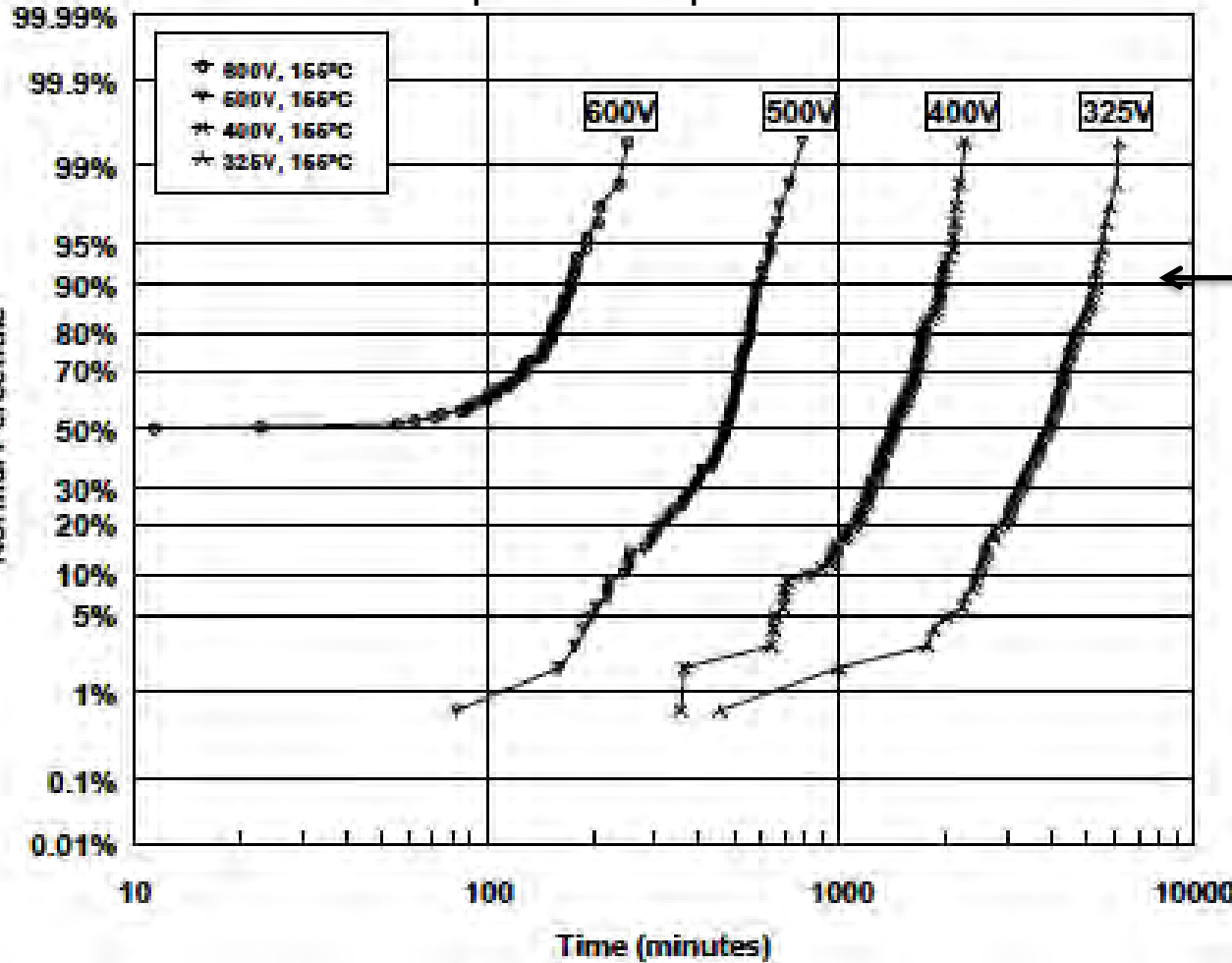
Opportunity: Systematically demonstrate RC design with Sr-substitutions in $\text{Bi}(\text{Zn}_{1/2}\text{Ti}_{1/2})\text{O}_3\text{-BaTiO}_3$

We need to understand lifetime of these capacitors

Highly Accelerated Lifetime Testing

HALT requires many samples per stress condition

Kemet BME 0.1 μ F-50V capacitors tested at 155°C



10x voltage de-rating is not uncommon to achieve reliability during operation

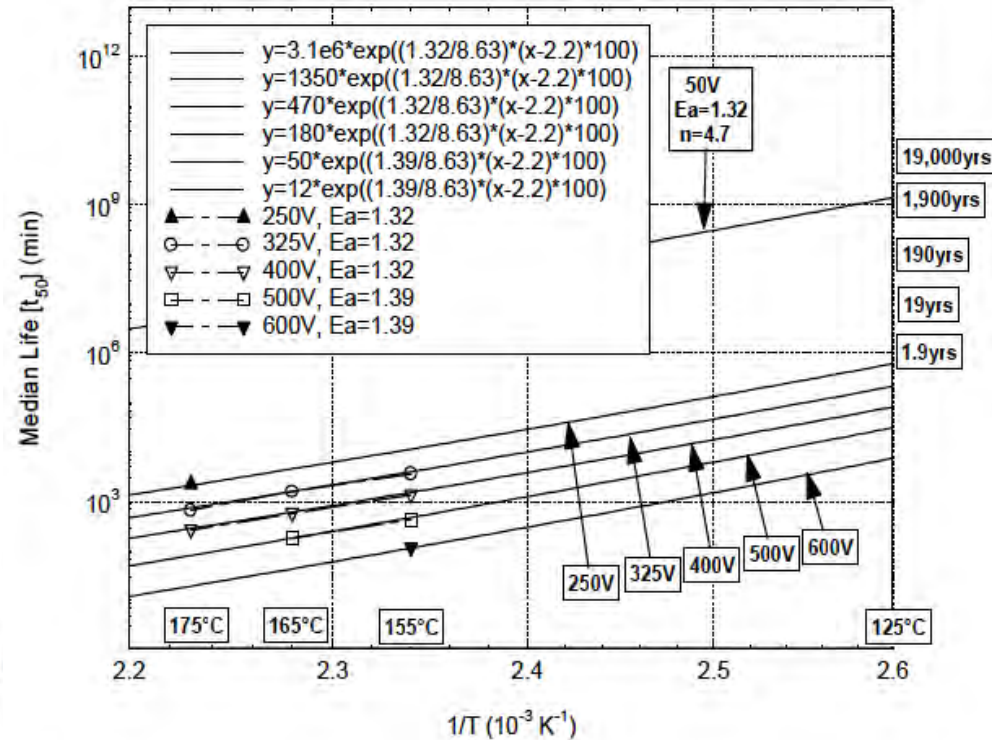
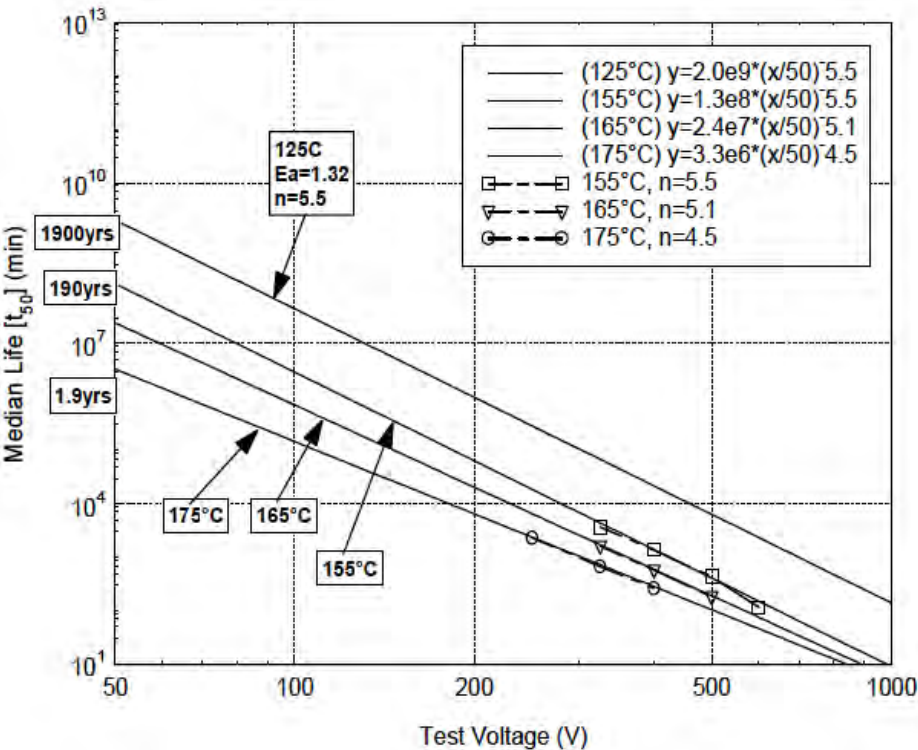
100 samples per stress condition

Commercial 10nF high voltage- High temperature capacitors cost ~\$2.60/nF

\$26,000 per line for 100nF capacitor stacks

MLCC HALT Literature Follows Prokopowicz and Vaskas

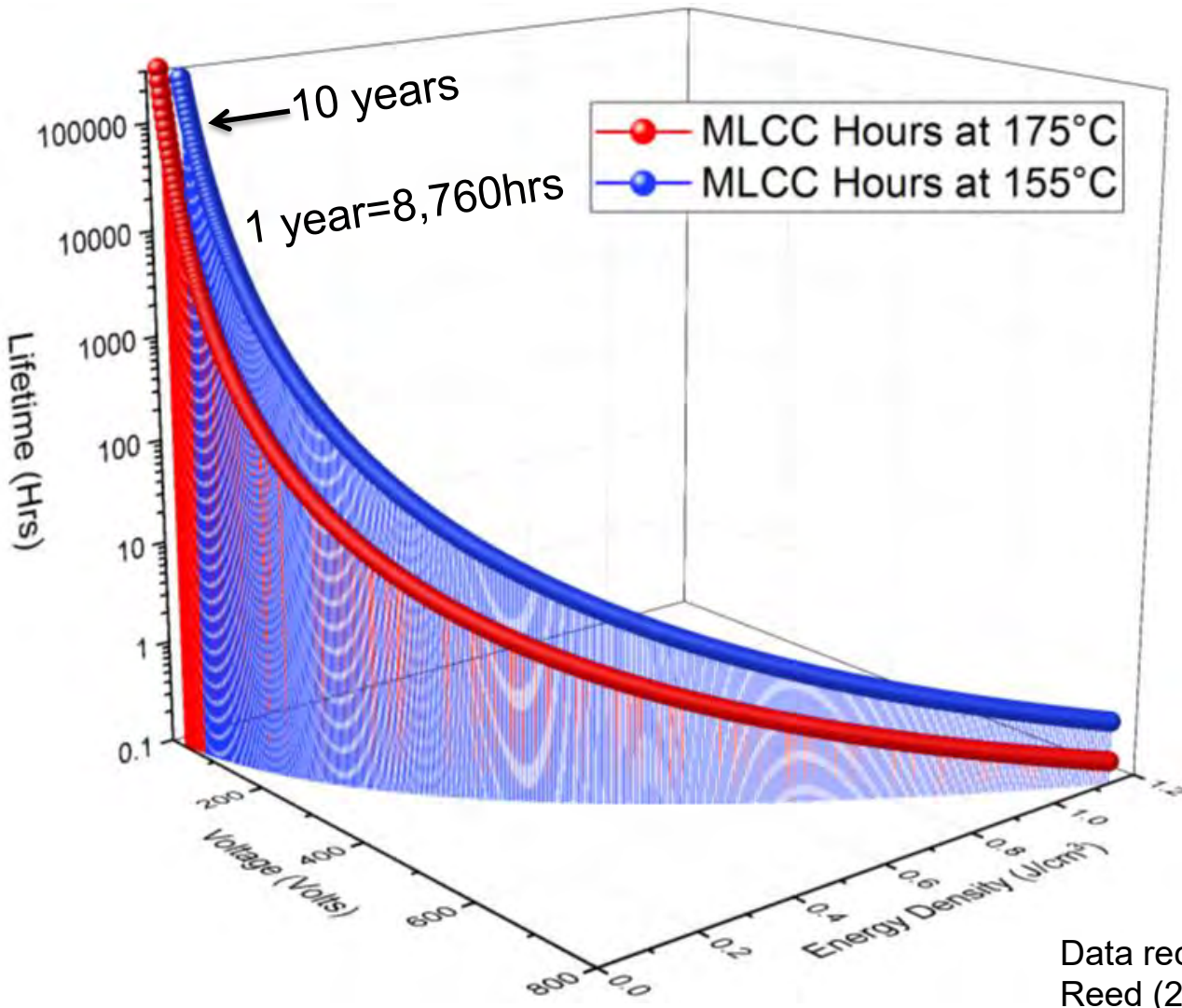
Median Life Estimates for Kemet 50V Rated 100nF X7R MLCC



$$A = \frac{t_1}{t_2} = \left(\frac{V_2}{V_1} \right)^n \exp \left[\frac{E_a}{k} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \right]$$

One can accelerate capacitor failure to predict performance, reliability, and *derating values*.

Capacitor Burnout Time is a Function of Temperature and Electric Field



- High temperatures reduce lifetime
- High electric fields reduce lifetime

$$U/vol. = \frac{CV^2}{2 * vol.} = \frac{1}{2} e_r e_0 E_{field}^2$$

You Pick Two!

1. High reliability
2. High energy density
3. High temperature

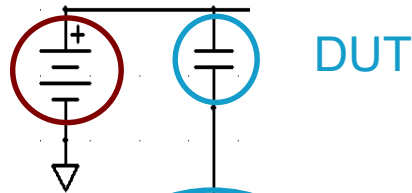
Data recreated and fit from Paulsen and Reed (2001) *50V, 100nF, X7R

Our Approach to HALT

1. Design and build a high voltage HALT system that provides high voltage and temperature headroom for our dielectrics
2. Evaluate dielectric reliability during the design/build phase to benchmark Sandia dielectrics against commercial dielectrics
3. Use HALT data to influence next generation power electronic circuit design and layout

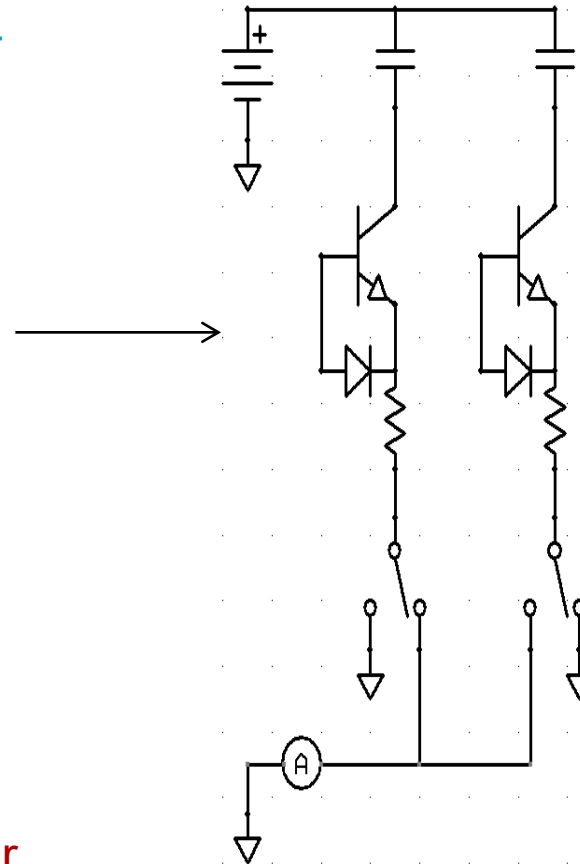
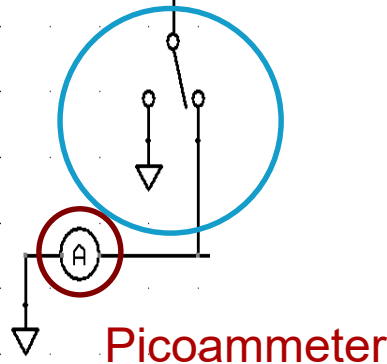
HALT circuit designed for high throughput capacitor lifetime analysis

0-3kV Power Supply



Passive current limiting circuit prevents overload of HV supply

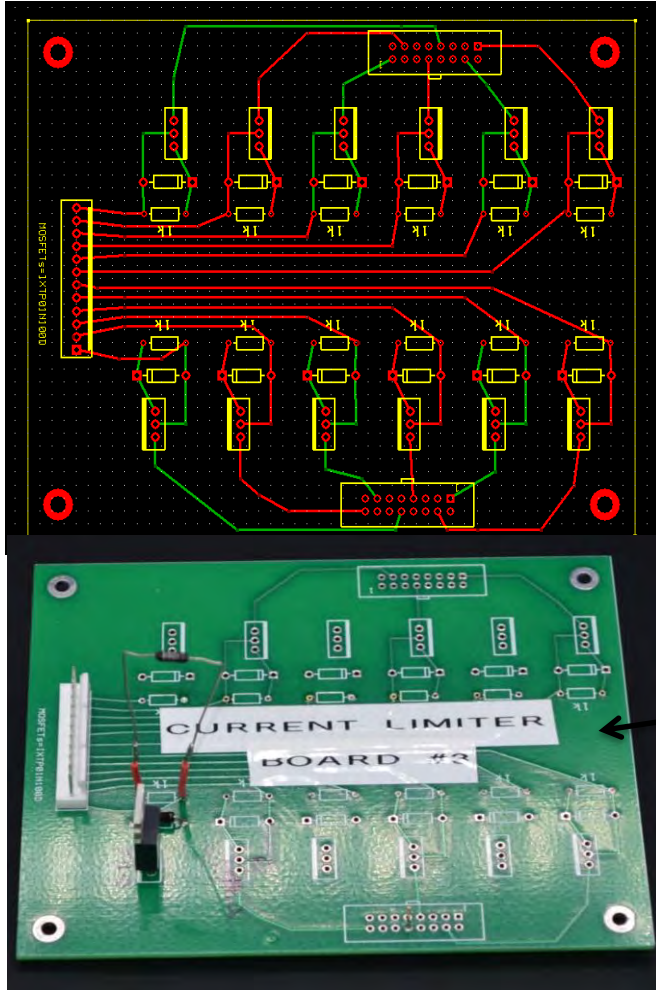
Labview control connects DUT to ground to manage data density and enable multiplexed sampling



- Design for up to **36** individual samples to be tested in parallel
- All DUTs are at V_{Hi} and switching occurs on low voltage side

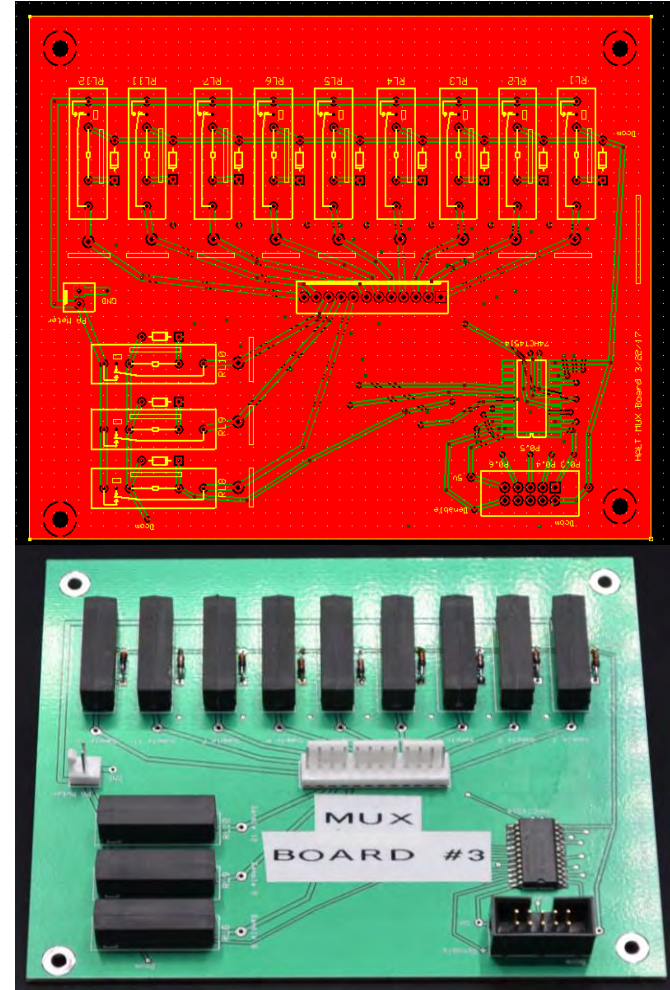
Printed HALT circuit boards designed, populated, and tested

Passive Current Limiting Board

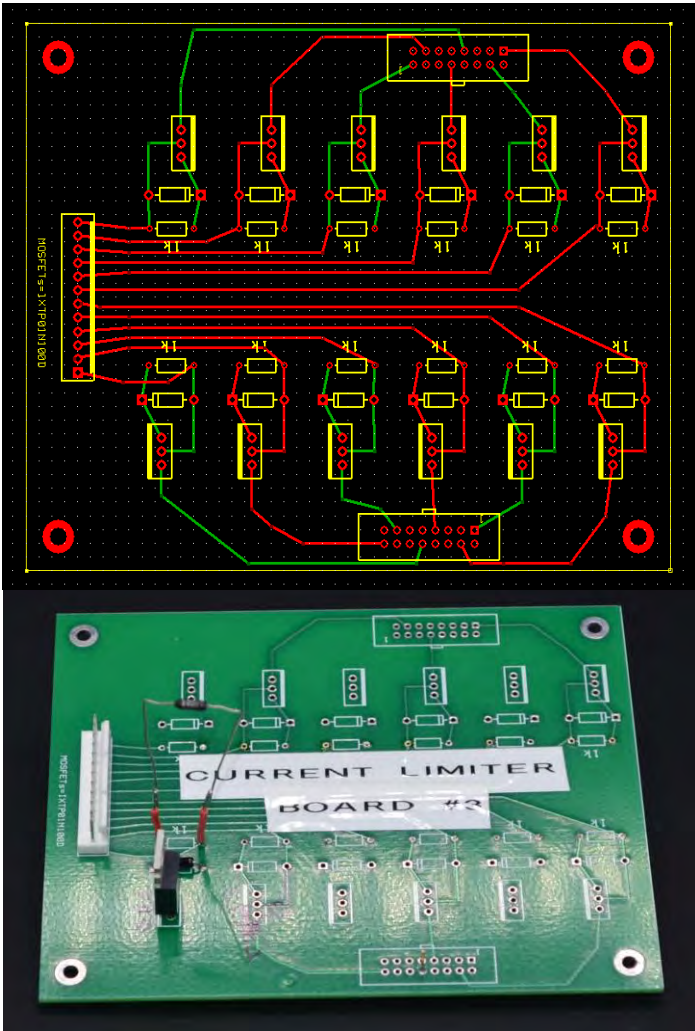


Rev 1
Single
Channel
Kluge

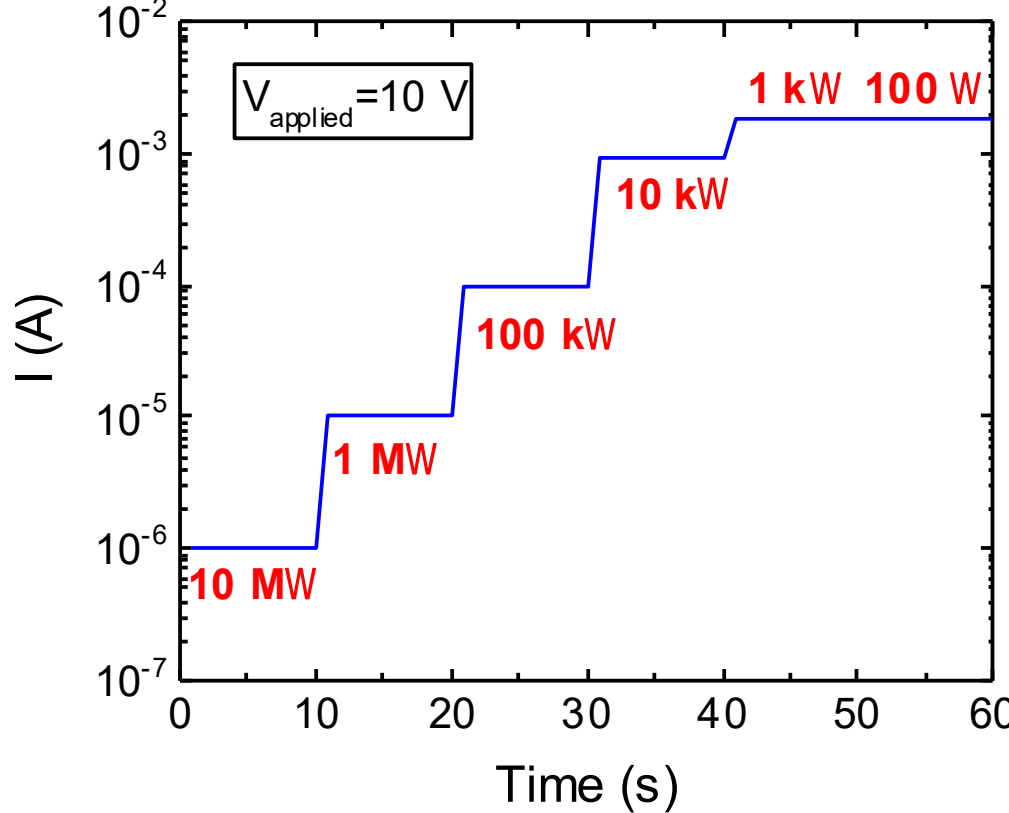
Custom High-Voltage Multiplexer



Current Limiting Circuit Demonstration



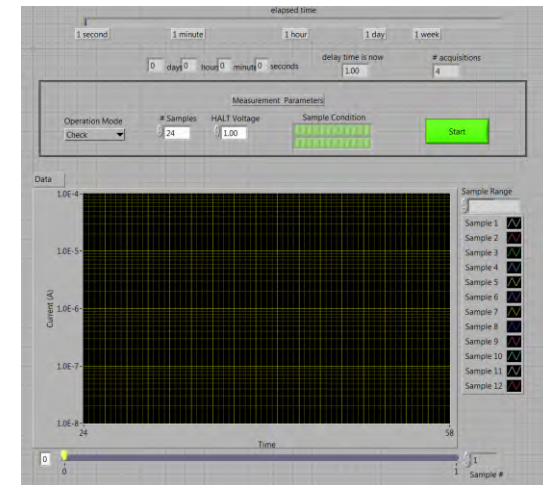
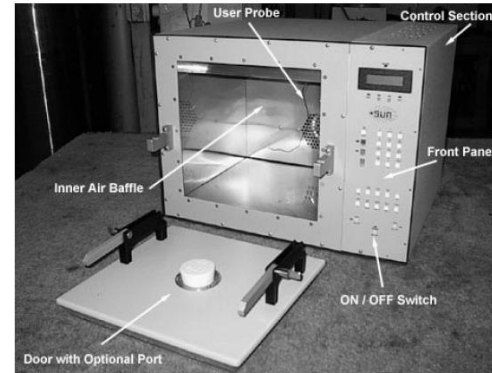
Current Drawn Through Decadal Resistance Box



Limiter shuts off current flow at <2 mA when R drops to <1 kΩ ✓

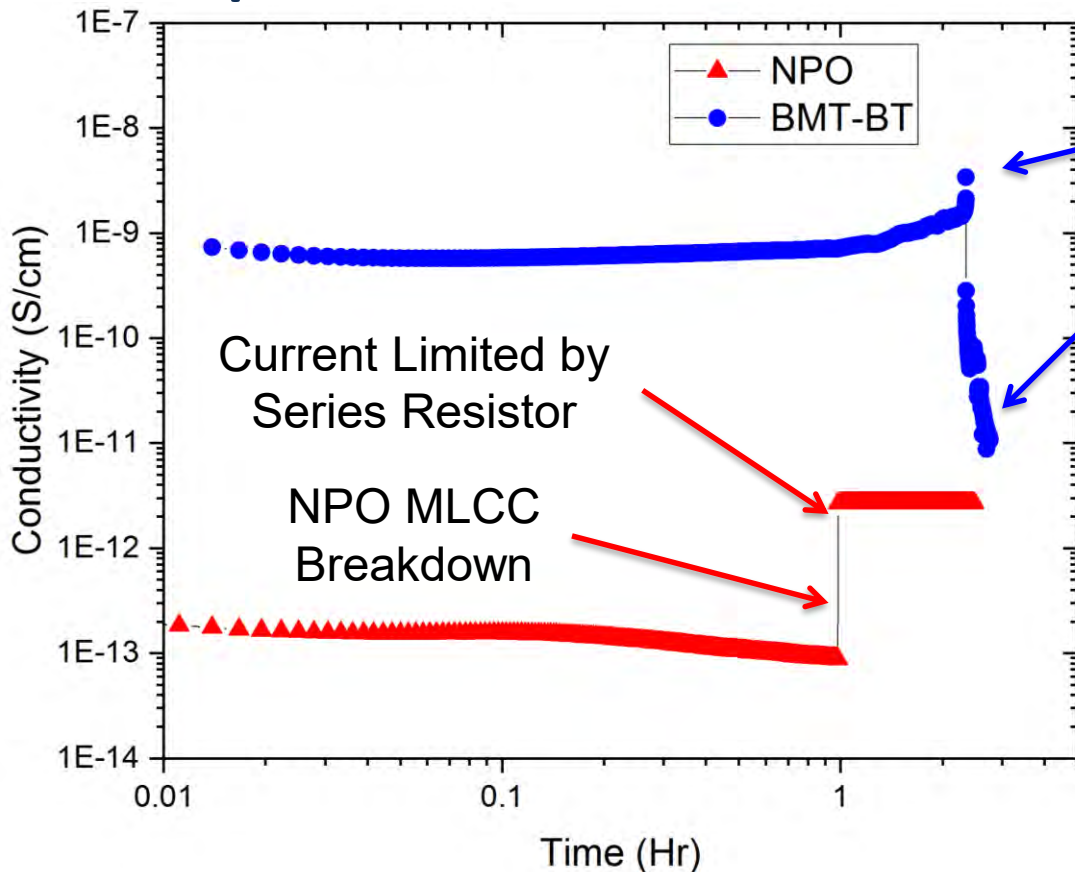
Other system components of 1kV-400° C HALT tester

- Sun Electronic Systems, Inc GPIB controlled EC1.3W environmental chamber (-100°C to +400°C) ✓
- Labview controlled data logging and instrumentation control with GPIB
- National Instruments USB DAC card for HV multiplexer circuit control ✓
- Test fixture (n=36) machined from high resistivity Al_2O_3 ✗



Integration of HALT tester components to be completed Dec 2017

Commercial High Temperature Capacitors Fail in 1 hour at 385°C



Disc Capacitor Breakdown

Current Limited by Layer Gap (1.05 mm)

$$E_{B,Air} \sim 30 \text{ kV/cm}$$

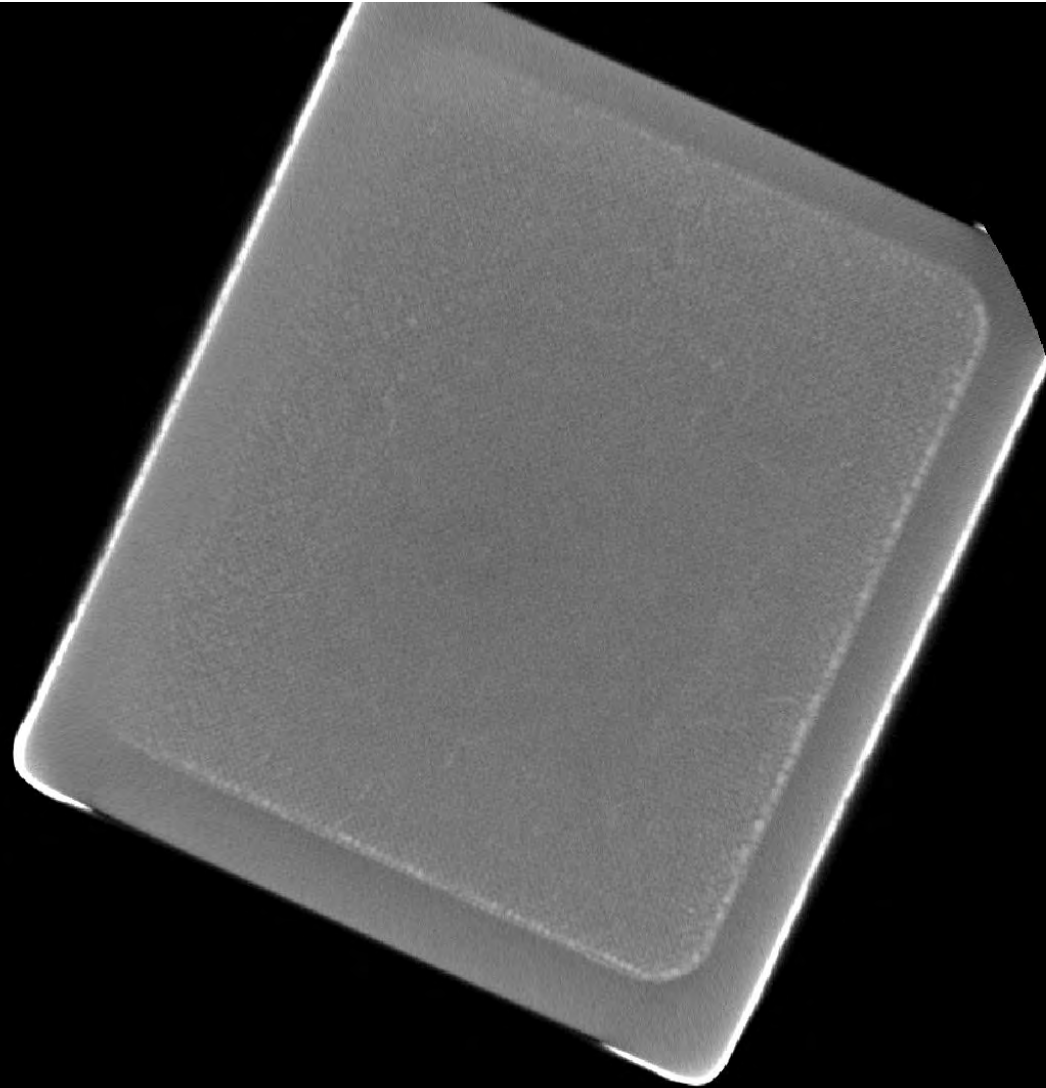


Commercial HALT Benchmark

	NPO MLCC	BMT-BT
A (cm ²)	18.6	10.9
T (cm)	0.005	0.105
E _{field} (kV/cm)	200	10
Permittivity	30	950
U/vol. (J/cm ³)	0.053	0.0038
TTF (Hr)	1	2.3

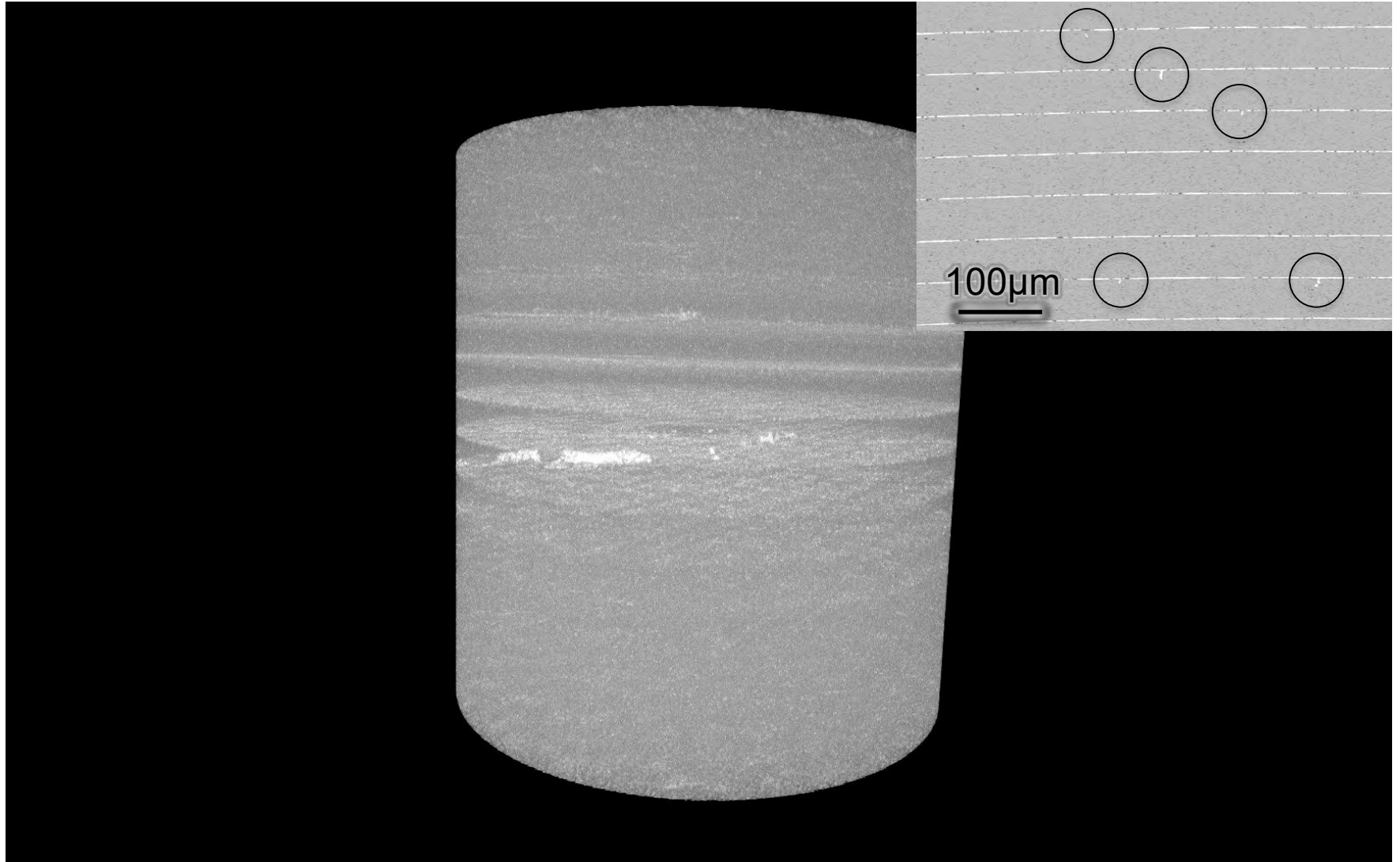
- BMT-BT must be at 35.5kV/cm (3.7kV) to match the energy density of the NPO MLCC
- BMT-BT C~8.7nF and NPO MLCC is C=10nF

HALT Breakdown Origin Identified with X-ray μ -Computed Tomography



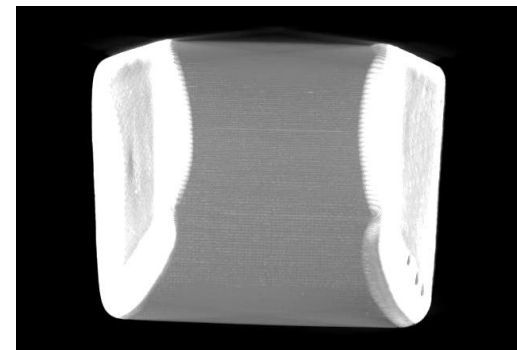
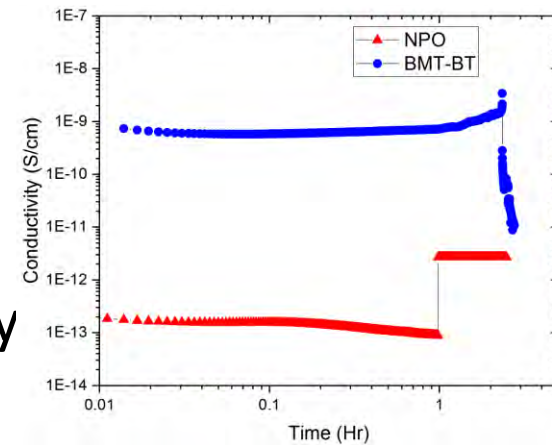
XY
620 / 1016
C 28655 W 13874

HALT Breakdown Origin Identified with X-ray μ -Computed Tomography



Summary

- Sandia developed dielectrics from an industrial partnership have been evaluated
 - Insulation resistance is competitive with industrially mature NPO MLCCs at $T > 350^\circ\text{C}$ and exceeds performance of $\text{Bi}(\text{Mg}_{1/2}\text{Ti}_{1/2})\text{O}_3\text{-BaTiO}_3$
- *Only* rigorous lifetesting will determine the feasibility of high temperature-high reliability high energy density capacitors
 - Preliminary HALT data shows $\text{Bi}(\text{Mg}_{1/2}\text{Ti}_{1/2})\text{O}_3\text{-BaTiO}_3$ dielectrics do not outperform commercial NPO lifetimes
 - NPO lifetimes may be limited by manufacturing defects that enhance electric fields



Next Steps: FY18 Milestones

- Cold sintering ($T < 400^{\circ}\text{C}$) demonstrated for scalable multilayer fabrication
 - Target Completion-Feb 2018
- HALT data (3000V, 20-400 $^{\circ}\text{C}$) collected for Sandia capacitors
 - Target Completion-June 2018
- 3000V, 300 $^{\circ}\text{C}$, 20nF multilayer ceramic capacitor with 10,000 hr lifetime fabricated (Sept. 28, 2018)

Contact Information

Contact Information

PI: Nick Hudak, nhudak@sandia.gov



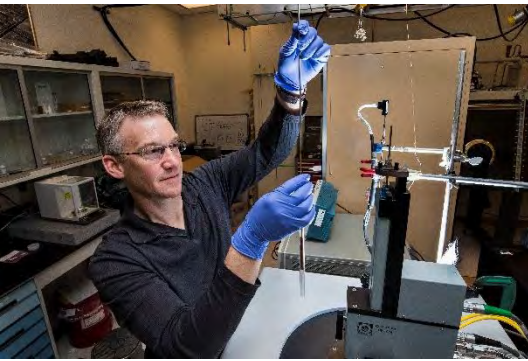
**OFFICE OF
ELECTRICITY DELIVERY &
ENERGY RELIABILITY**

The author gratefully acknowledges the support of Dr. Imre Gyuk and the Department of Energy's Office of Electricity Delivery & Energy Reliability.

Exceptional service in the national interest



energy.sandia.gov



Advanced Magnetics for High Frequency Link Converters

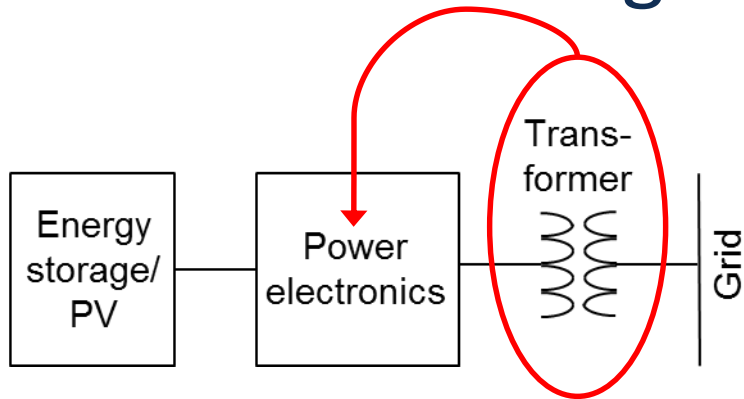
October 10, 2017

Todd Monson

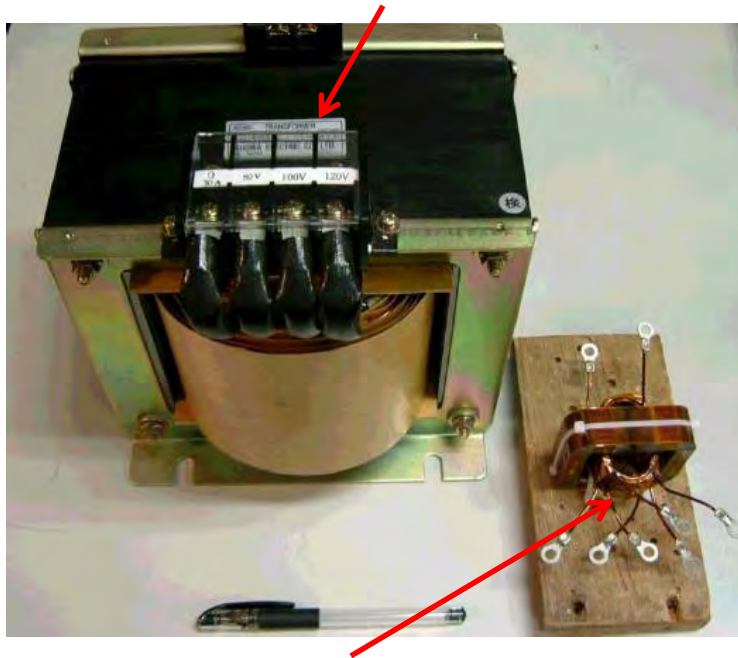


Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Benefits of a High Frequency Transformer



Line frequency (50 Hz) transformer



High frequency (20 kHz) transformer

S. Krishnamurthy, Half Bridge AC-AC Electronic Transformer, IEEE, 1414 (2012).

- Integrate output transformer within power conversion electronics
- Leverage high switching speed, voltage, and temperature performance of WBG semiconductors
- Core materials for high frequency transformers have been an afterthought (no current material meets all needs)

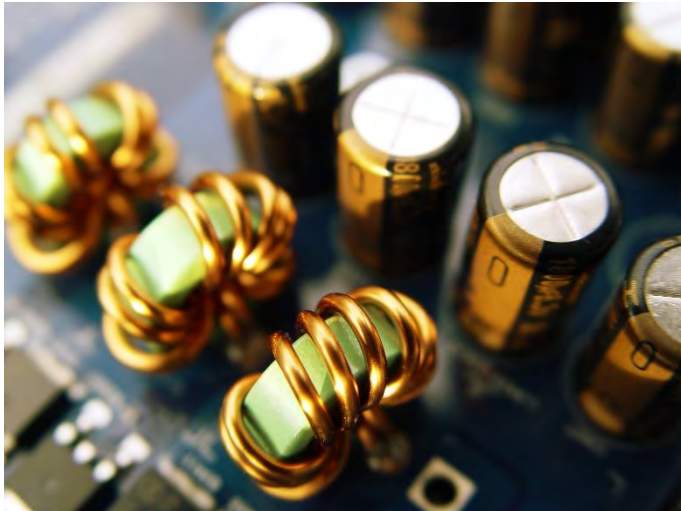
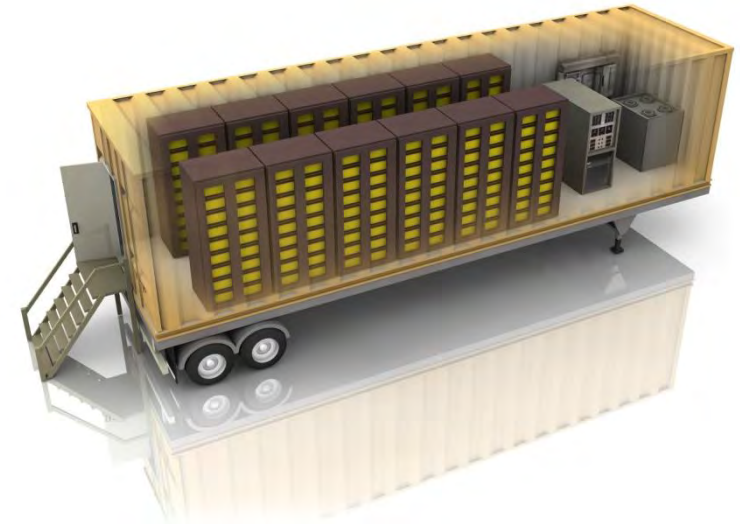
Material requirements:

- Low loss over 10-200 kHz frequency range
 - low coercivity, high ρ
- High $J_s \rightarrow$ high power density
- High temperature performance
- Scalable & Affordable
- **Increased reliability and better SWaP**

Transportable Energy Storage and Power Conversion Systems (PCS)

Benefits of Energy Storage:

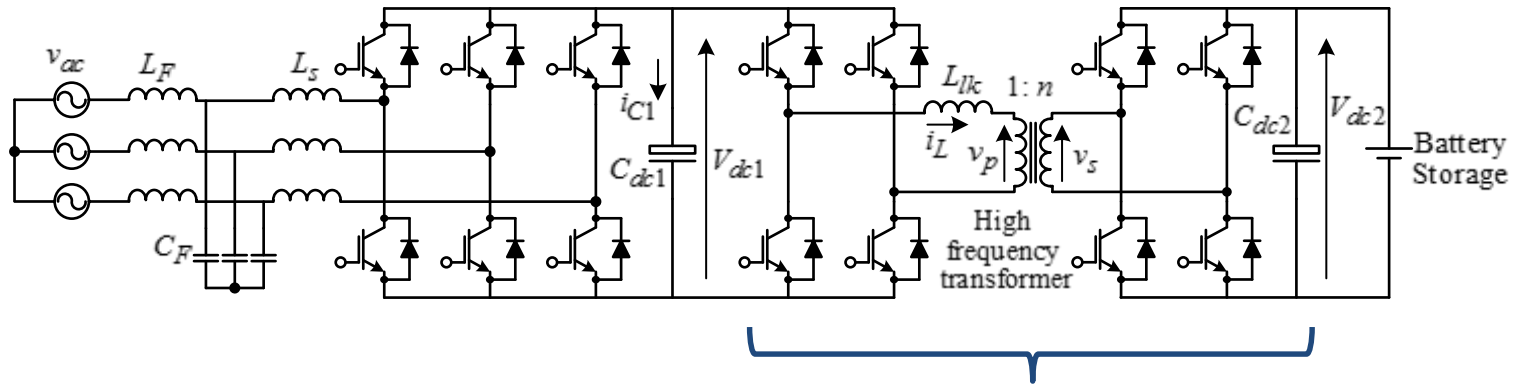
- **Maintain power quality and reliability**
 - Improve stability and defer upgrades
 - Enhanced agility and control (load leveling, power factor control, frequency and voltage regulation)
- **Increase deployment of renewable energy**



Benefits of Transportable Systems:

- **Lower cost**
- **Modular design reduces assembly and validation time**
- **Faster installation at renewable energy generation sites**

High Frequency Link Power Conversion System

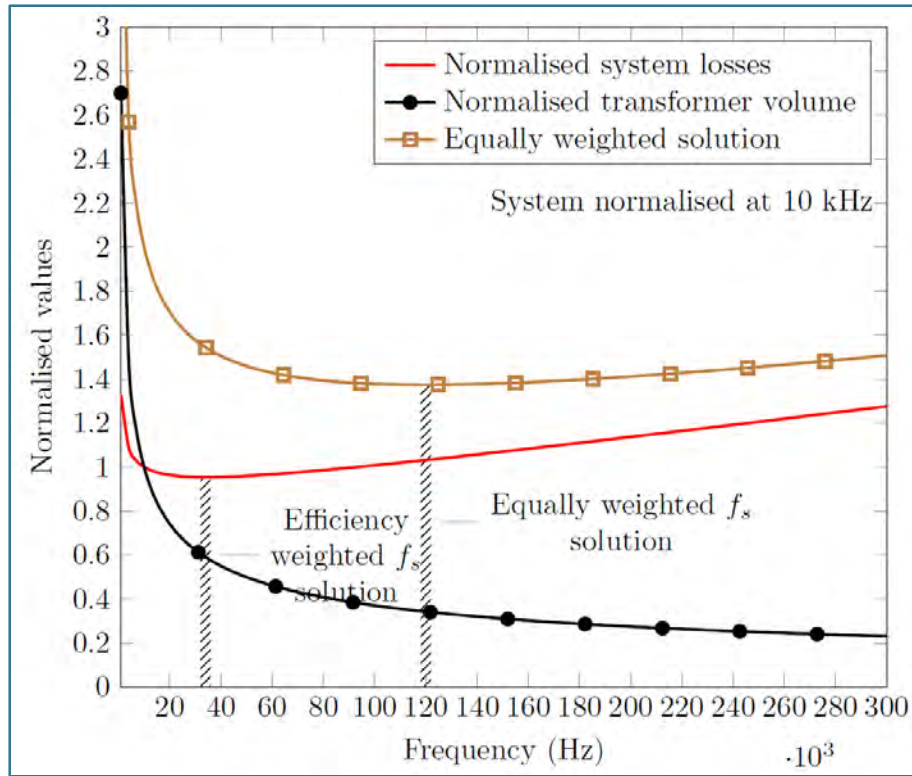


Volume occupied by heat sinks and non-magnetic components were not considered !!

Optimal frequency based on:

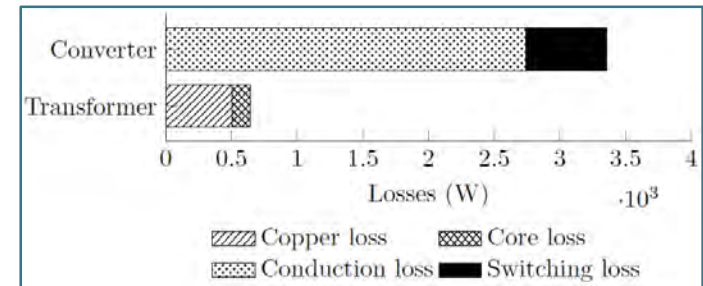
- Switching and conduction losses in semiconductors
- Volume of the transformer
- Losses in the transformer
 - Winding (copper) losses
 - Core losses

Optimum Frequency with SiC MOSFETs



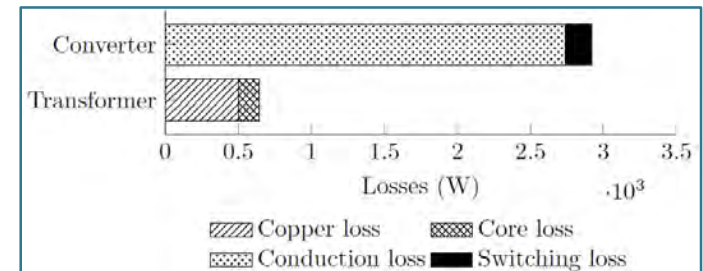
Equally weighted solution:

The converter has optimal solution at a frequency of **120 kHz** with equal weights on volume and losses

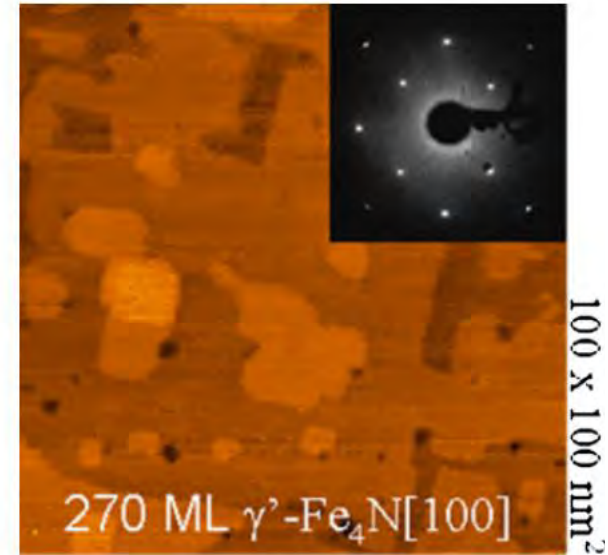
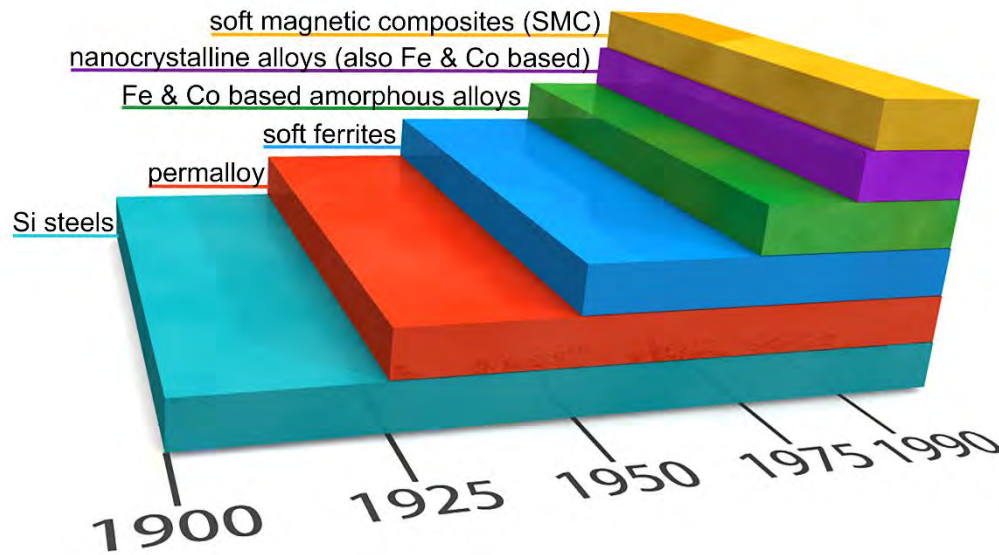


Efficiency driven solution:

The optimal solution for minimum loss condition is **35 kHz**



Soft Magnetic Material Development



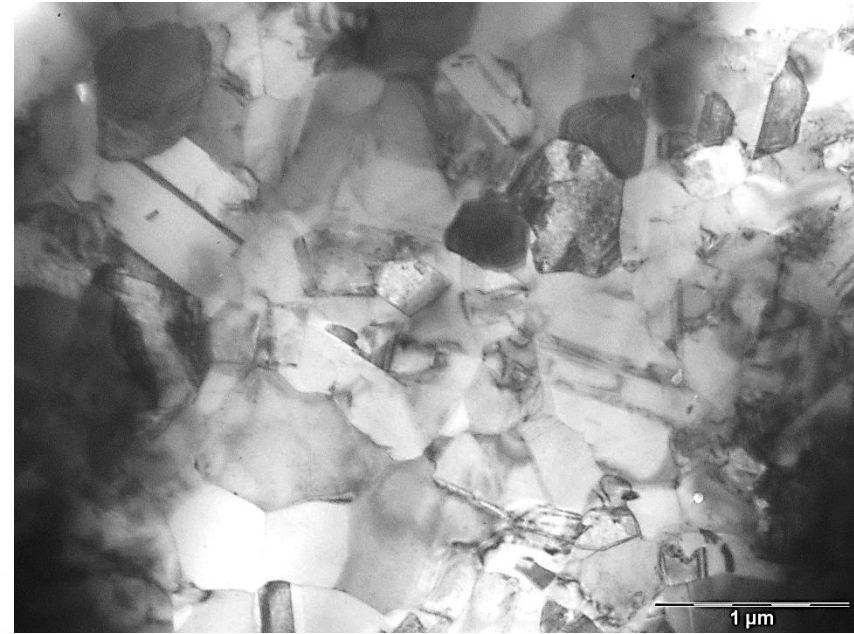
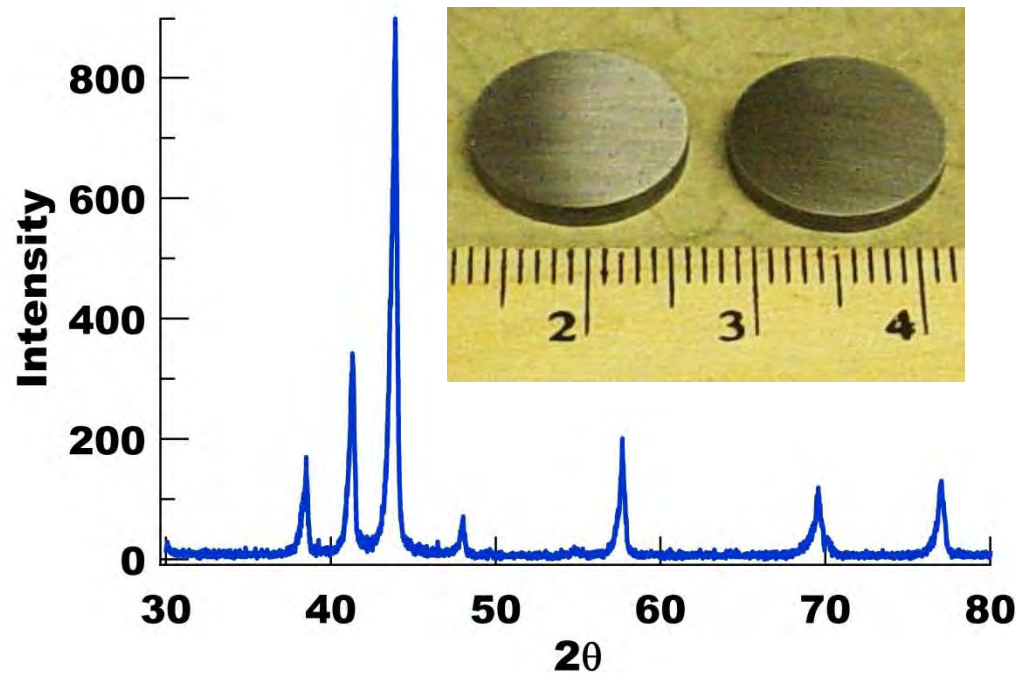
adapted from: L.A. Dobrzański, M. Drak, B. Ziębowicz, Materials with specific magnetic properties, Journal of Achievements in Materials and Manufacturing Eng., 17, 37 (2006).

D. Ecija, et. al., "Magnetization reversal of epitaxial films of γ' -Fe₄N on Cu(100)", J. Magn. Mag. Mat., 316, 321 (2007).

Magnetic Material	J_s (T)	ρ ($\mu\Omega\cdot m$)	Cost
VITROPERM (Vacuumschmelze)	1.20	1.15	High
Metglas 2605SC	1.60	1.37	High
Ferrite (Ferroxcube)	0.52	5×10^6	Low
Si steel	1.87	0.05	Low
γ' -Fe ₄ N	1.89	~200	Low

- ➔ γ' -Fe₄N can meet all requirements of high frequency power electronics

World's first bulk γ' -Fe₄N!



- Fe nitride powders well consolidated with little porosity
- Grain sizes 200 nm – 1 μm
 - Refining grain size to reduce losses
- γ' -Fe₄N primary phase
- Fe₃N secondary phase from mixed phase starting material

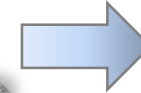
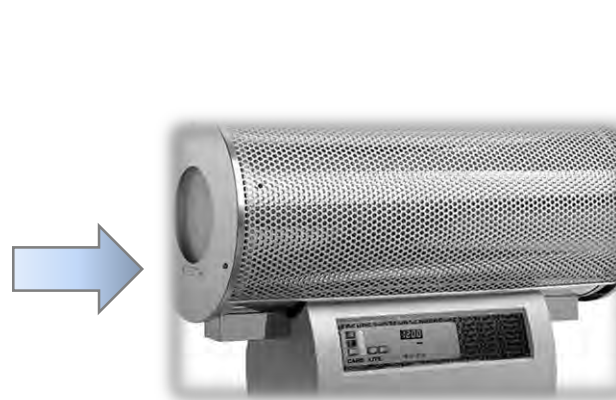
γ' -Fe₄N Synthesis and Processing

U.S. Patent Filed January 2016 (#15/002,220)



SPS Consolidation

Fluidized Bed Furnace



- Pressure and pulsed current assisted sintering process
- Precision control over heat and pressure
- Restrain grain growth
- Full densification



Coercivity as a Function of Particle Size

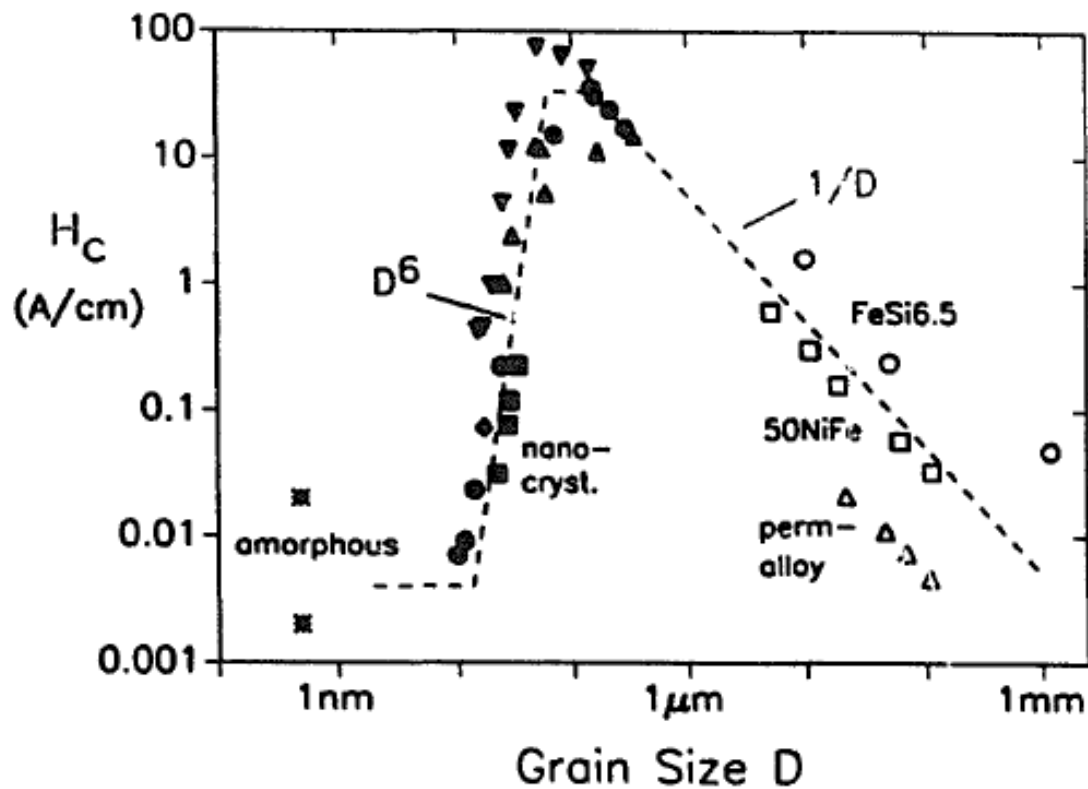
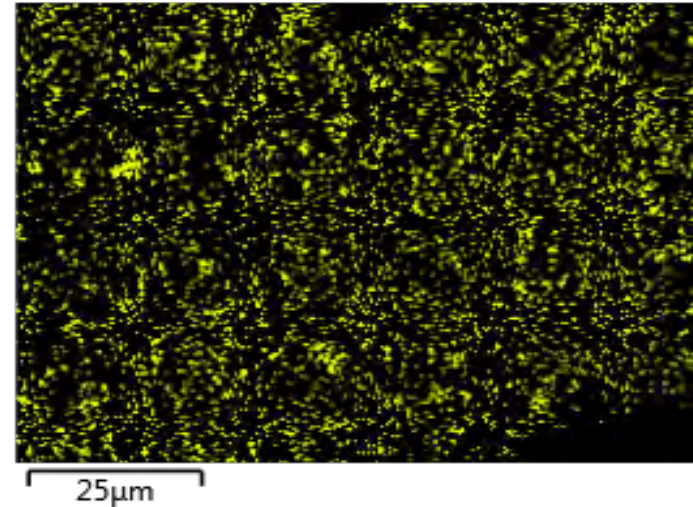
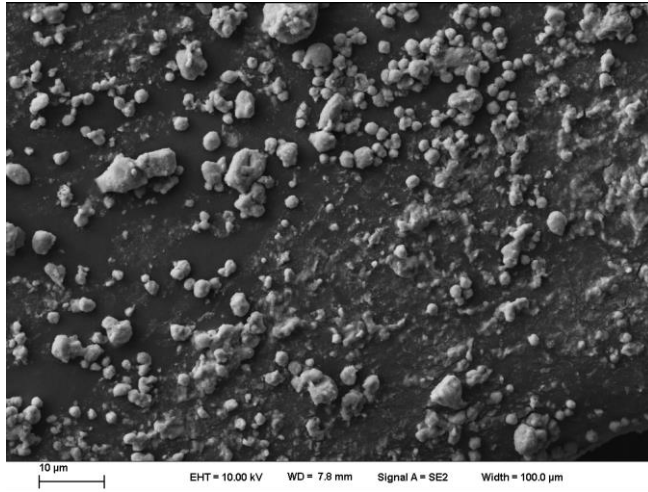


Fig. 2. Coercivity H_c vs. grain size for various soft magnetic metallic alloys. The data of the nanocrystalline material refer to (▲) FeNbSiB and (●) FeCuNbSiB [14], (◆) FeCuVSiB [15], (■) FeZrB [4] and (▼) FeCoZr [16].

G. Herzer, Nanocrystalline Soft Magnetic Materials, J. Magn. Mag. Mat., 112, 258 (1992).

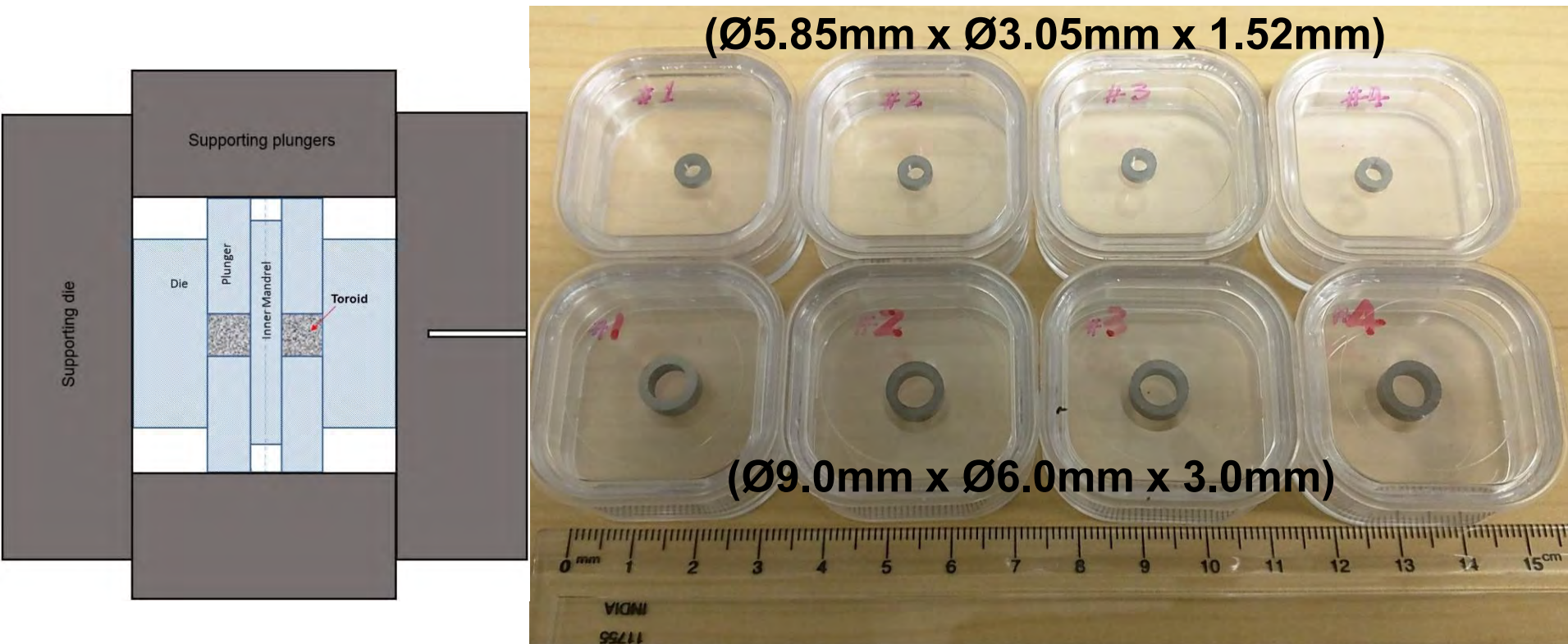
Synthesis of fine grained γ' -Fe₄N



- SEM-EDS confirms nitrogen content
- Optimizing conditions to yield phase pure material

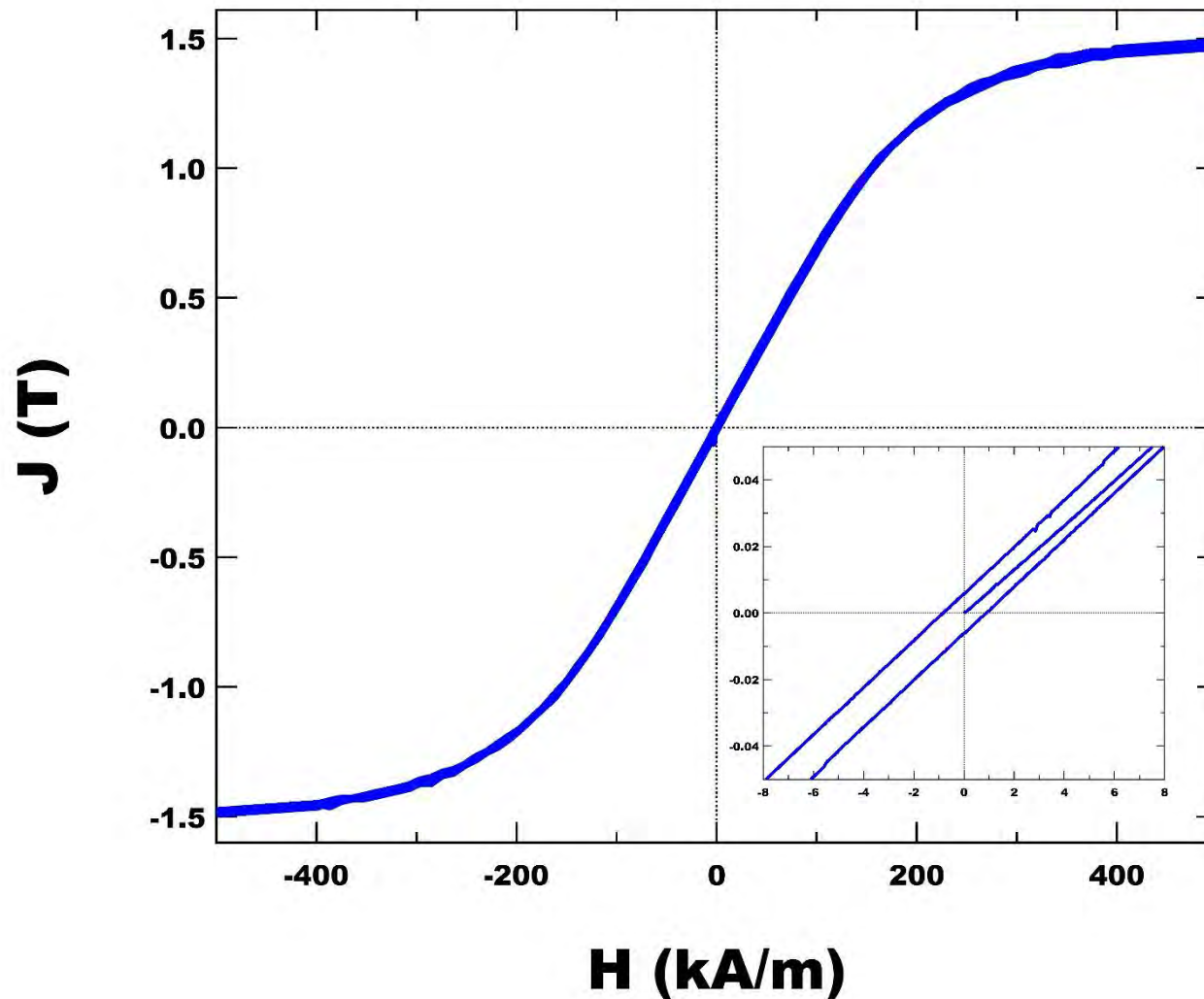
See more in Tyler Steven's poster at EESAT
poster session Wed. evening!

Net-Shaping of Transformer Cores



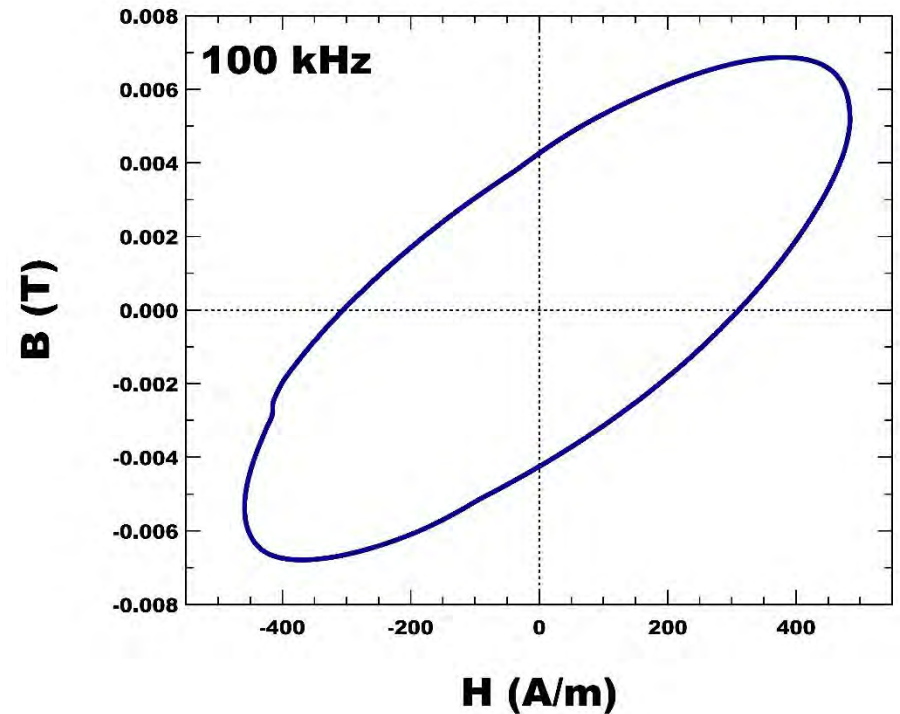
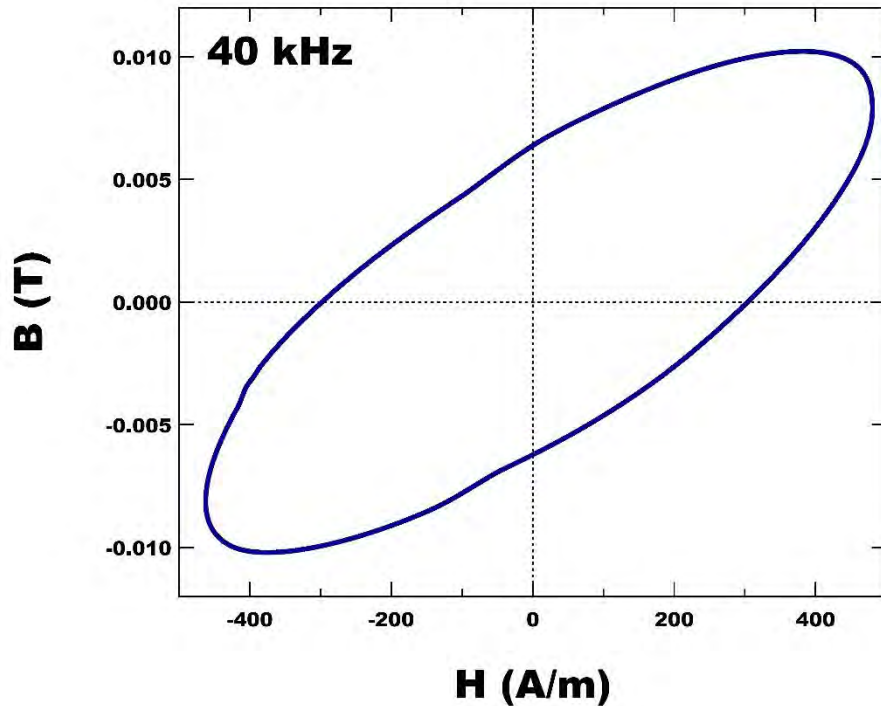
- Can sinter toroids and other shapes directly (net-shaping)
- Eliminates the need for any machining

Magnetic Characterization



- SPSeD at 550°C and 100 MPa
- $J_s = 1.62$ T
- Theoretical $J_s = 1.89$ T (SiFe is 1.87 T)
- $H_c < 1000$ A/m

High frequency characterization



- Cannot saturate toroids with current B-H analyzer amplifier
- New 5 A amplifier delivered and being unpacked now

Summary/Conclusions

- γ' -Fe₄N has the potential to serve as a new low cost, high performance transformer core material
 - $J_s >$ Si steel
 - Increased field and current (and therefore power) carrying capability
 - Resistivity 200X greater than nanocrystalline and amorphous alloys
 - Only requires low cost and abundant elements (Fe & N)
 - High temperature (T) operation complementing development of high T capacitors and WBG semiconductors at DOE/OE

Patents:

T. C. Monson, K. Waldrip, "Electrochemical Solution Growth of Magnetic Nitrides," U.S. Patent Application # 14/531,075.

T. C. Monson, E. J. Lavernia, B. Zheng, Y. Zhou, "Method to Synthesize Nanocrystalline Iron Nitride," U.S. Patent Application # 15/002,220

Presentations:

2017 Spring MRS, MS&T 2016, TMS 2016, MMM-Intermag, Advances in Magnetism, Magnetism 2015, IECON 2014

Manuscript in review at IEEE Magnetism Letters

Acknowledgements

We thank Dr. Imre Gyuk and the Energy Storage Program in the Office of Electricity Delivery and Energy Reliability at the US Department of Energy for supporting this work

Questions?

Principal Investigator Contact Information:

Todd Monson

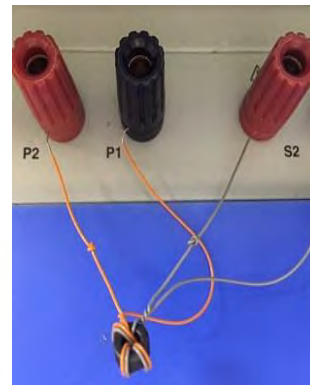
tmonson@sandia.gov



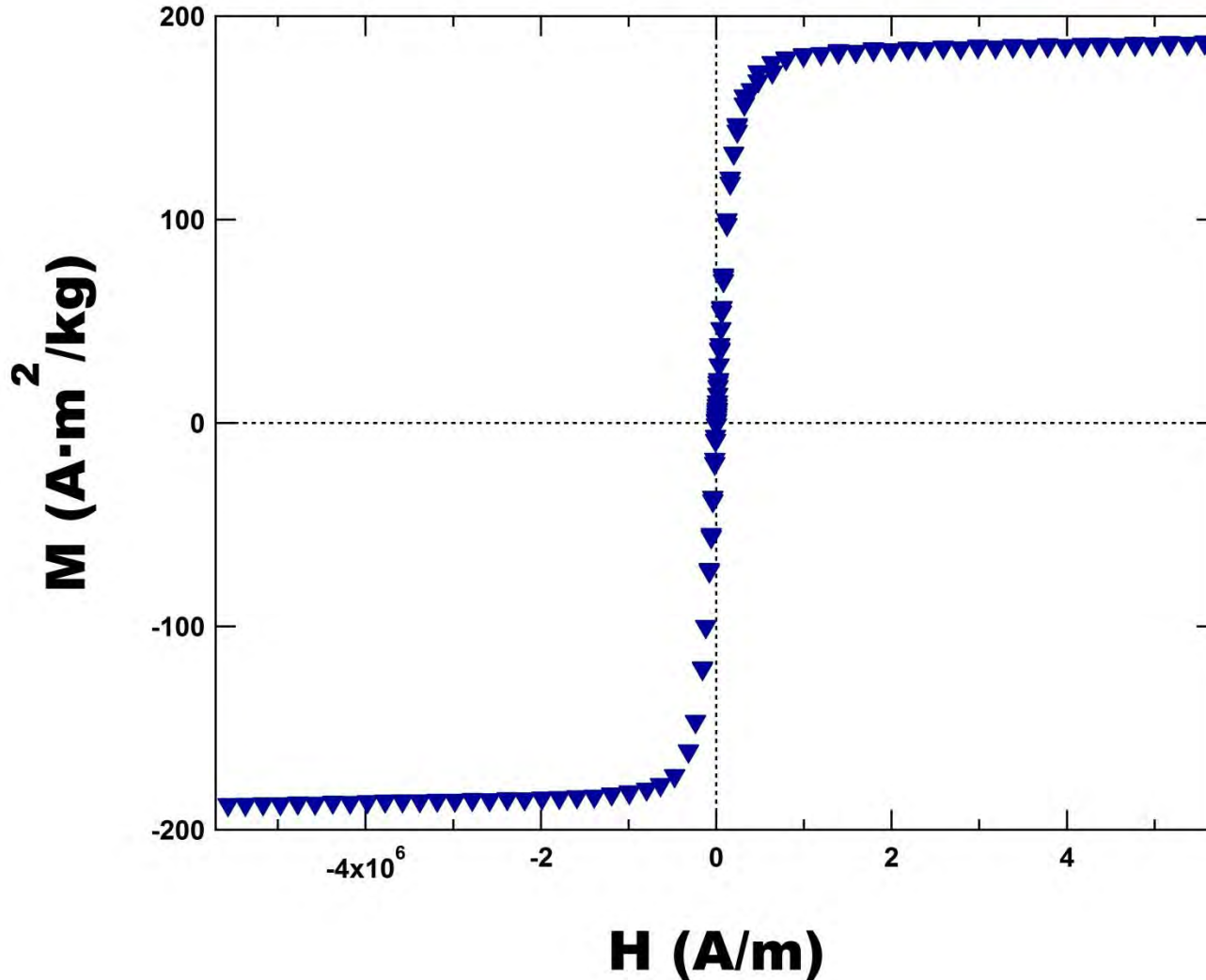
Extra Slides

Ongoing Tasks

- SPS processing parameters are being modified to improve phase purity, grain structure, and magnetic performance
- Parallel development of improved synthesis route to pure nanocrystalline γ' -Fe₄N raw powders
- Evaluation and comparison of transformers at high frequency and elevated temperatures



Magnetic Characterization

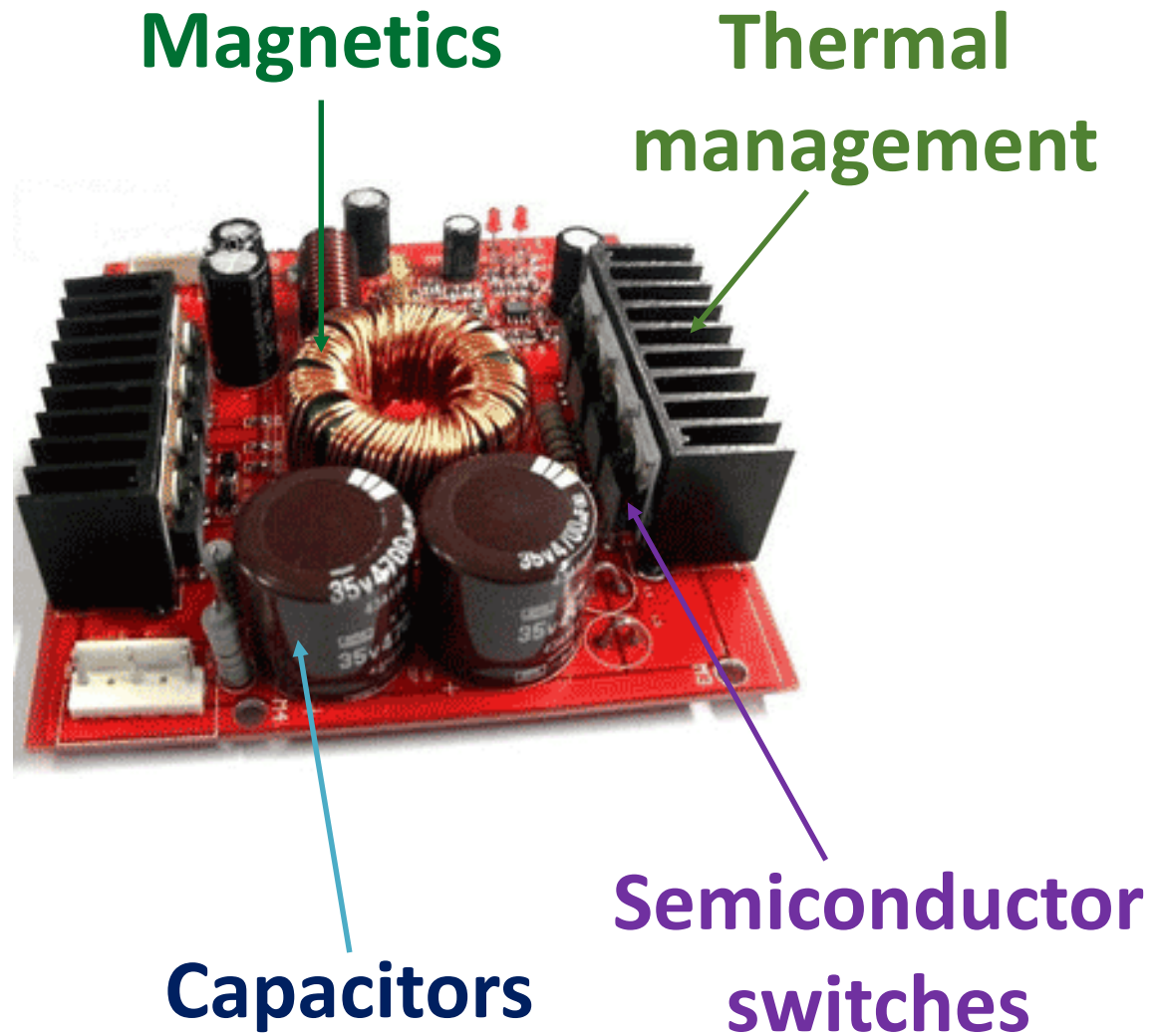


- Fe_4N SPSed at 550°C and 100 MPa achieved an M_{sat} of $188 \text{ A}\cdot\text{m}^2/\text{kg}$.
- Predicted M_{sat} of bulk γ' - Fe_4N is $209 \text{ A}\cdot\text{m}^2/\text{kg}$ (Fe is $217 \text{ A}\cdot\text{m}^2/\text{kg}$)
- Negligible coercivity

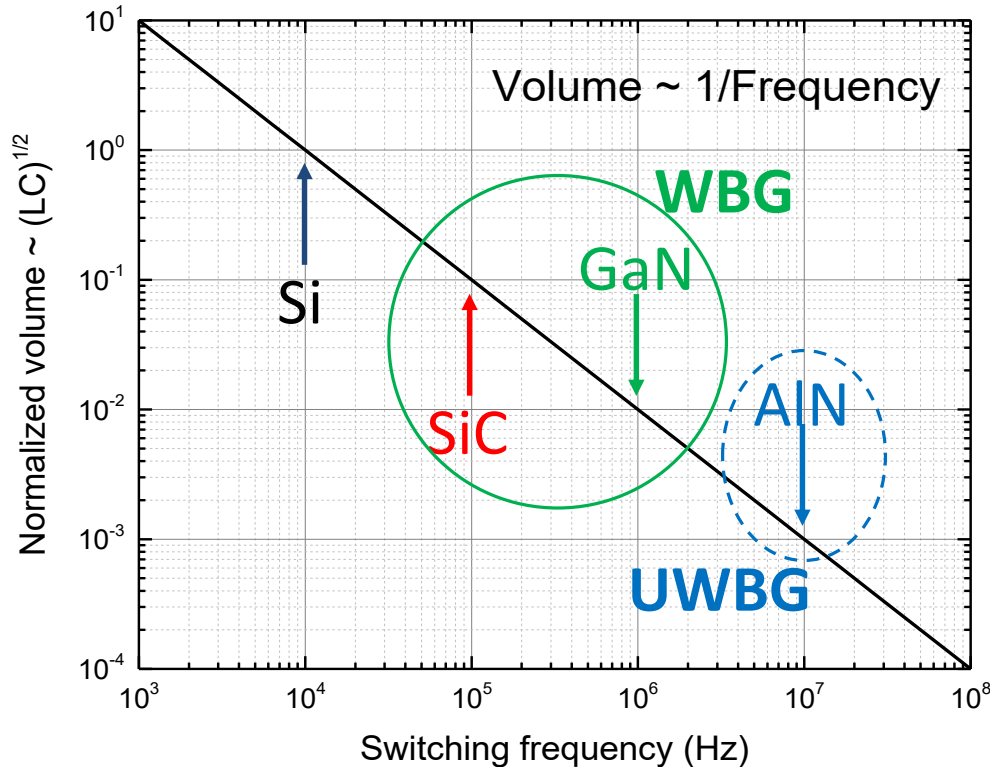
Magnetic Devices Impact Power System Volume and Weight

Passive elements and thermal management comprise the bulk of the volume and mass of a power converter

WBG/UWBG materials enable higher switching frequency and better thermal management



Higher Frequencies Decrease Inductance Requirements, However...

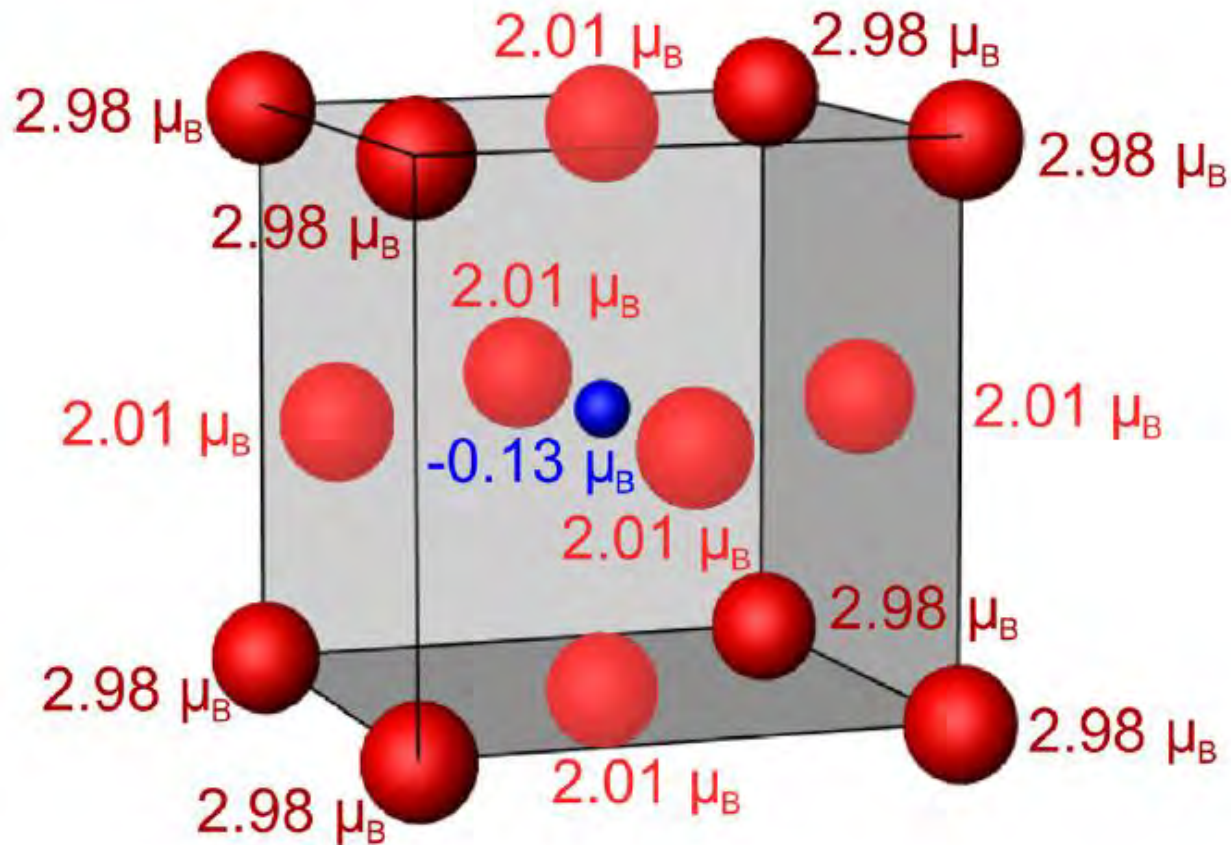


- Higher switching frequency is enabled by scaling properties of WBG/UWBG materials
- Ideal 1/f SWaP dependence (true dependence likely weaker 1/fⁿ with n < 1 due to nonidealities)
- Other benefits exist, e.g. higher voltage without series stacking of devices, and higher temperature operation
- *UWBGs may be required for specialized applications such as pulsed power*

Inductive core materials have essentially been an afterthought and new magnetic materials are needed

Adapted from Bob Kaplar (SNL)

γ' -Fe₄N Unit Cell



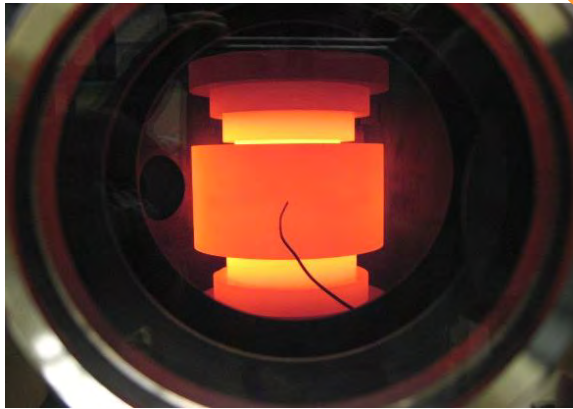
fcc γ Fe structure stabilized by interstitial nitrogen in the body center

G. Scheunert, et al., A review of high magnetic moment thin films for microscale and nanotechnology Applications, *Appl. Phys. Rev.*, 3, 011301 (2016).

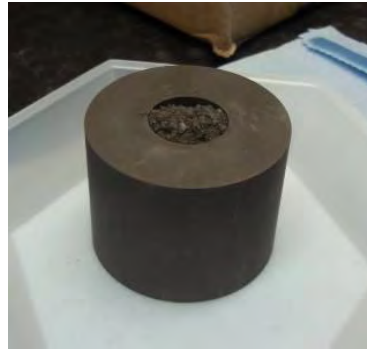
J.M.D. Coey, *Magnetism and Magnetic Materials* (Cambridge University Press, Cambridge, UK, 2012).

Spark Plasma Sintering (SPS)

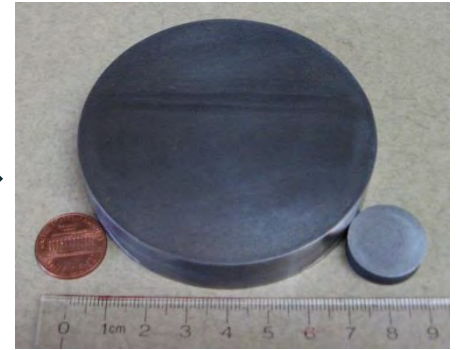
SPS Model: SPS-825S Dr. Sinter® at UCD



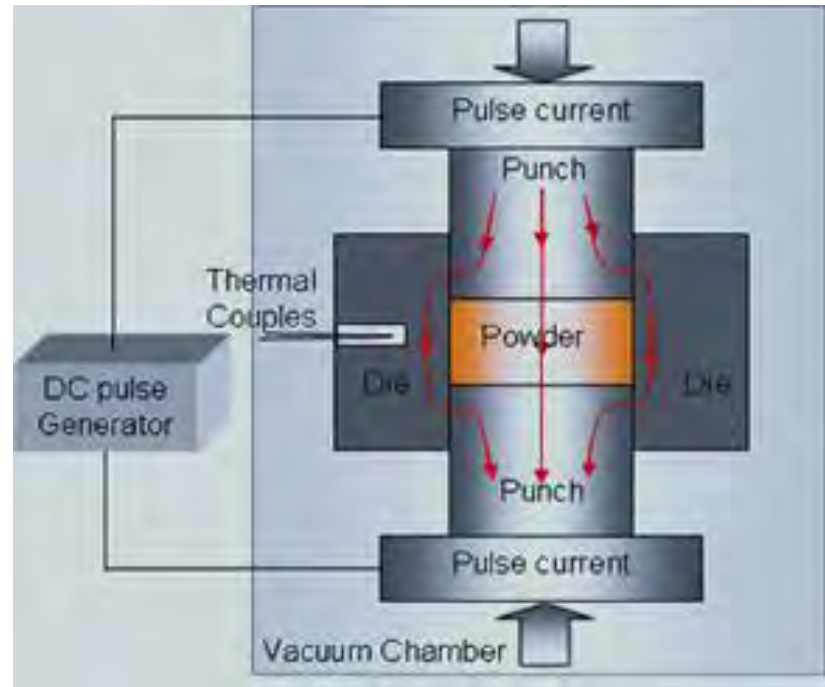
SPS Chamber



Starting Powder in Die



End Product



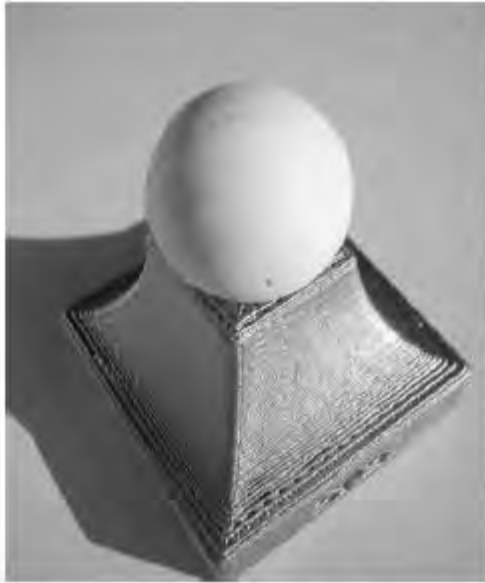


Fig. 9. Al_2O_3 sphere obtained in one single step by SPS¹⁶³¹

J. Galy, Private Communication, 2007.

Hungría et. al., Adv. Eng. Mater. Vol. 11 (2009) 616;
DOI: 10.1002/adem.200900052

SPS System Manufacturers:

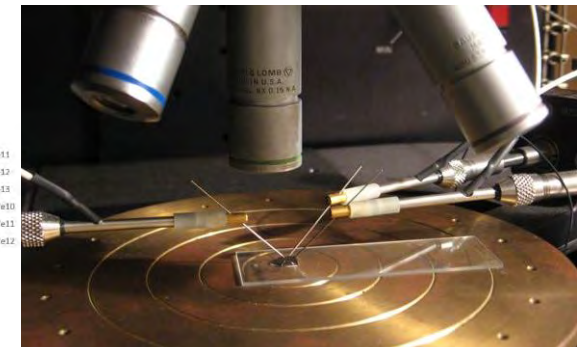
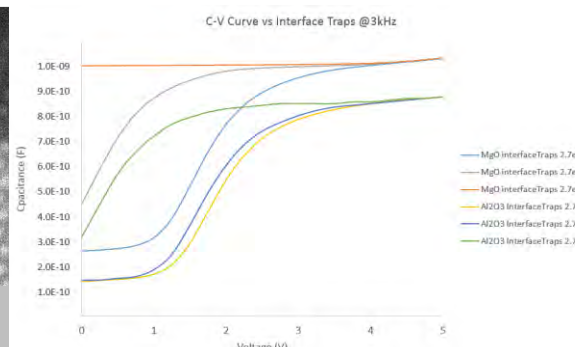
- Fuji Electronic Industrial Co. (Japan)
- FCT Systeme GmbH (Germany)
 - Can make components up to 500 mm (~20") in diameter
- Thermal Technology LLC (Santa Rosa, CA)

- **Size of equipment increasing to accommodate commercial needs**
- **Technology for continuous SPS under development**
- **A large number of companies have acquired SPS but often request this info to not be made public to maintain a competitive advantage**

Exceptional service in the national interest



Paisley *et al.*, J. Appl. Phys. **115**, 2014



Gate Oxide Sentaurus Model for Wide-bandgap Devices



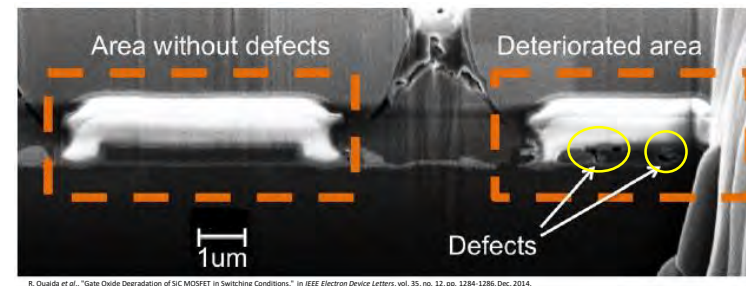
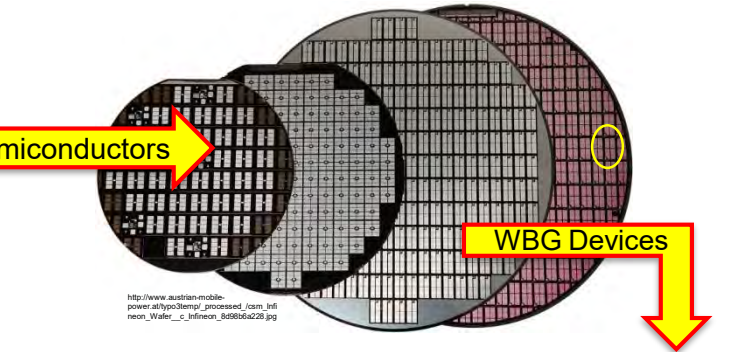
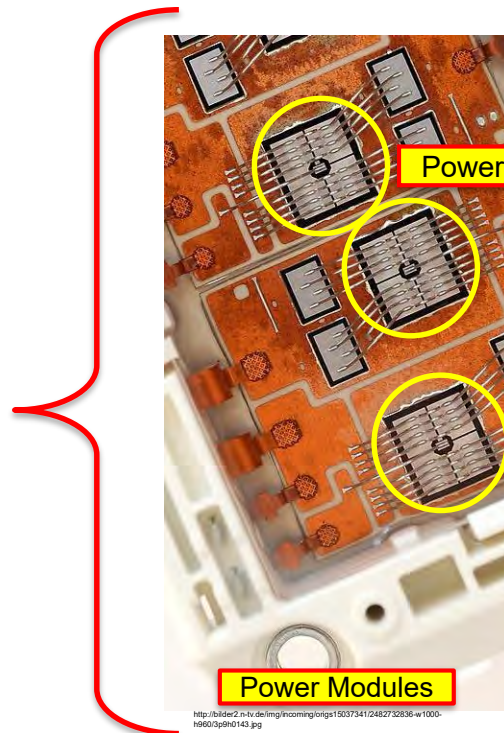
Adam Morgan, Stan Atcitty, Peter Dickens, Jon Ihlefeld

2017 DOE/OE Peer Review Conference

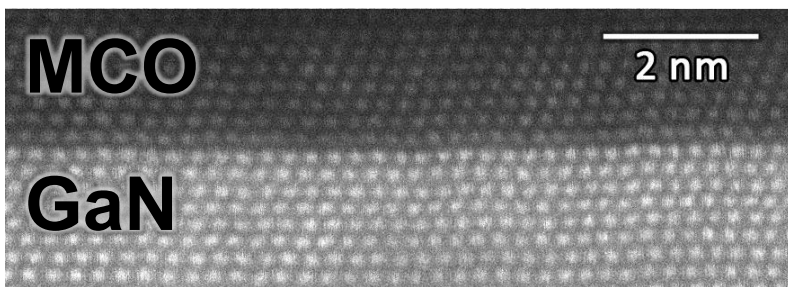


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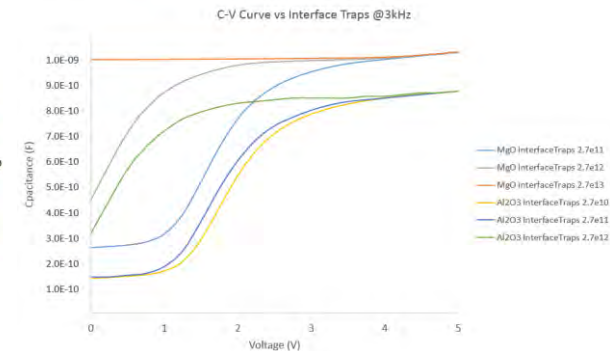
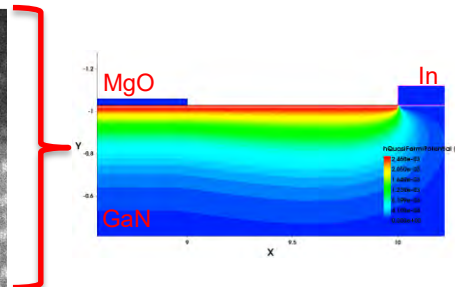
Power Conversion Systems Research at the Molecular Level



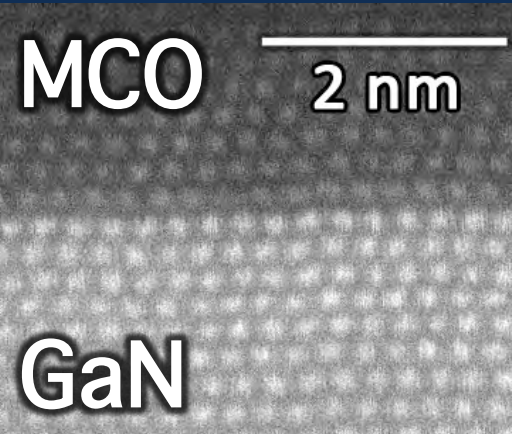
R. Ouda et al., "Gate Oxide Degradation of SiC MOSFET in Switching Conditions," in IEEE Electron Device Letters, vol. 35, no. 12, pp. 1234-1236, Dec. 2014.



Paisley et al., J. Appl. Phys. **115**, 2014



Reliable High-Performance Gate Oxides for Wide Band Gap Devices



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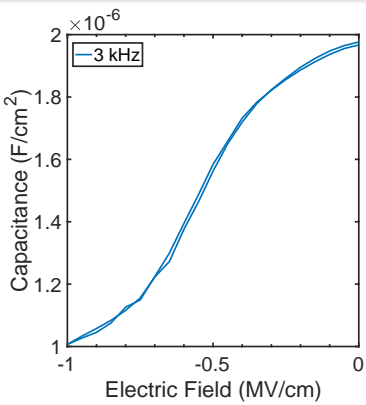
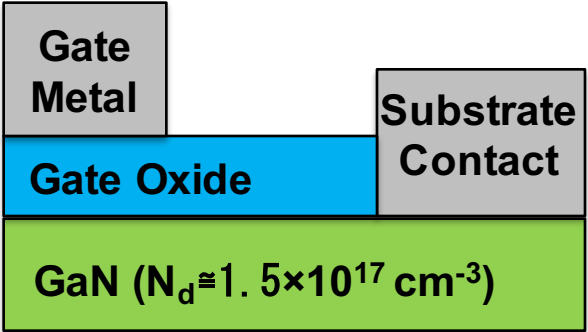
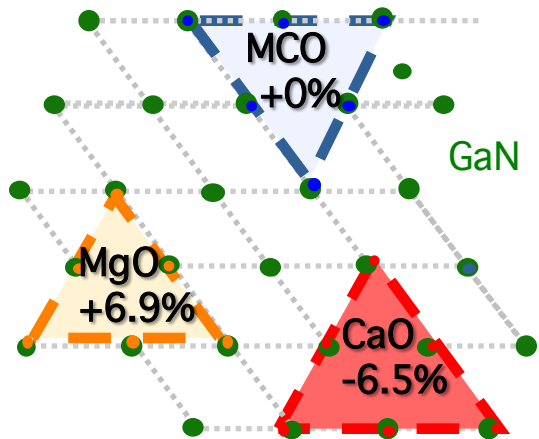


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Reliable Wide Band Gap Gate Dielectrics



Purpose

- Gate dielectrics are a key limiter in GaN- and SiC-based power electronics technology
- Engineered gates will enable the development of robust and reliable MOSFETs and MOSHEMTs for use at elevated temperatures

Results

- Comparison of MgO/GaN MOScap properties to $\text{Al}_2\text{O}_3/\text{GaN}$ devices
 - MgO/GaN exhibits fewer defects
- Improvement of MgO/GaN devices via post-growth anneals
 - Lower interface state density
 - Reduced leakage current

Impact

- Increased performance, efficiency, and reliability
- Reduced system cost
- Reduced power electronics size

High Temperature Optocoupler for 3D High Density Power Module



08/15/2016 – 08/14/2019
Electrical Engineering Department
University of Arkansas,



Dr. Zhong Chen, Assistant Professor
Dr. Shui-qing (Fisher) Yu, Associated Professor
Dr. Alan Mantooh, Distinguished Professor

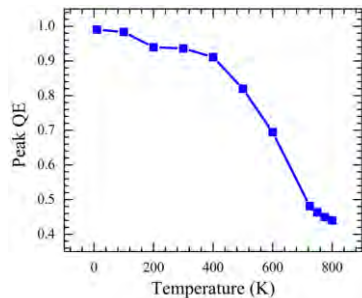
Sandia National Labs Collaborators: Dr. Stan Atcitty, Dr. Robert Kaplar

Project Goal: Develop a reliable high-temperature (250°C) optocoupler to replace gate transformers as a galvanic isolation system

Optocouplers at High Temperatures

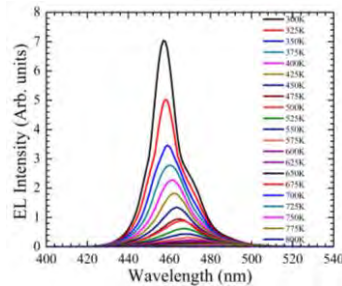
Material-level (LED)

- Quantum efficiency
- PL intensity
- Power dependent analysis



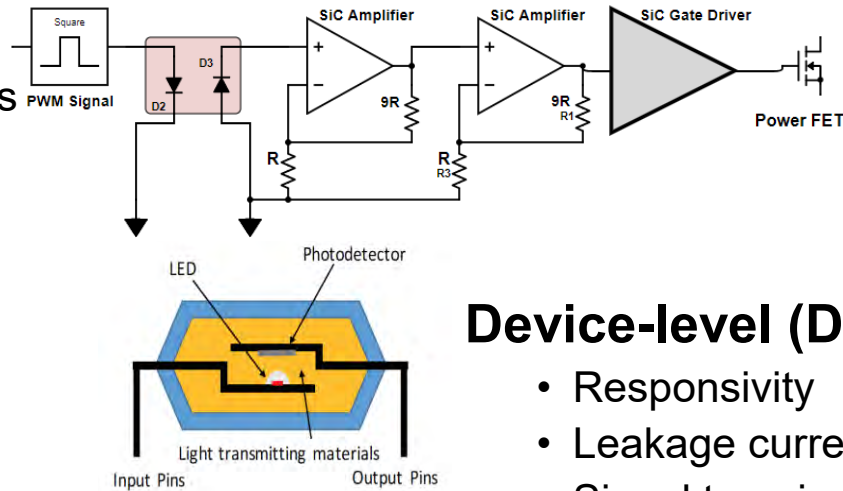
Device-level (LED)

- Light intensity
- Quantum efficiency
- Injected current
- long-term reliability



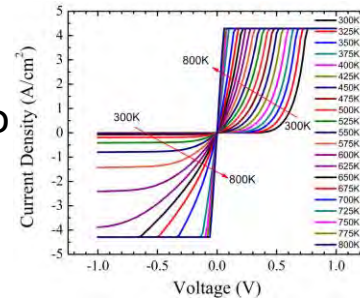
Circuit-level with gate driver

- SNR requirements
- HT amplifier
- HT gate driver



Device-level (Detector)

- Responsivity
- Leakage current
- Signal to noise ratio



Component-level (packaging)

- Device architecture
- HT Insulation materials
- Dielectric properties

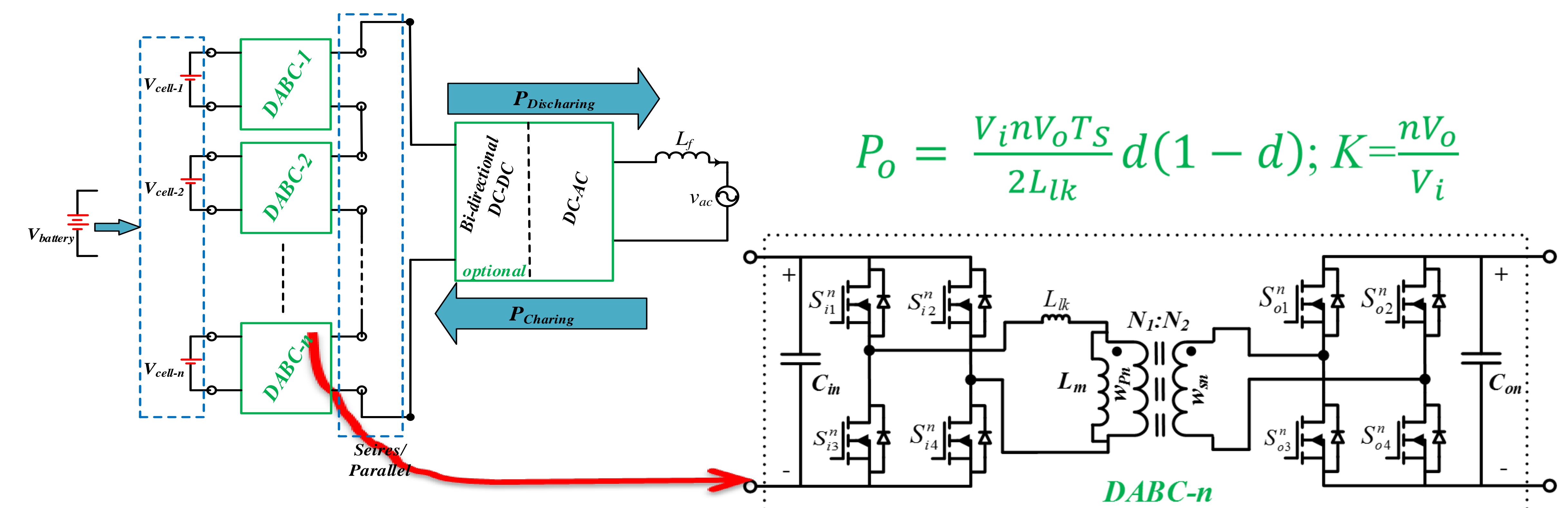
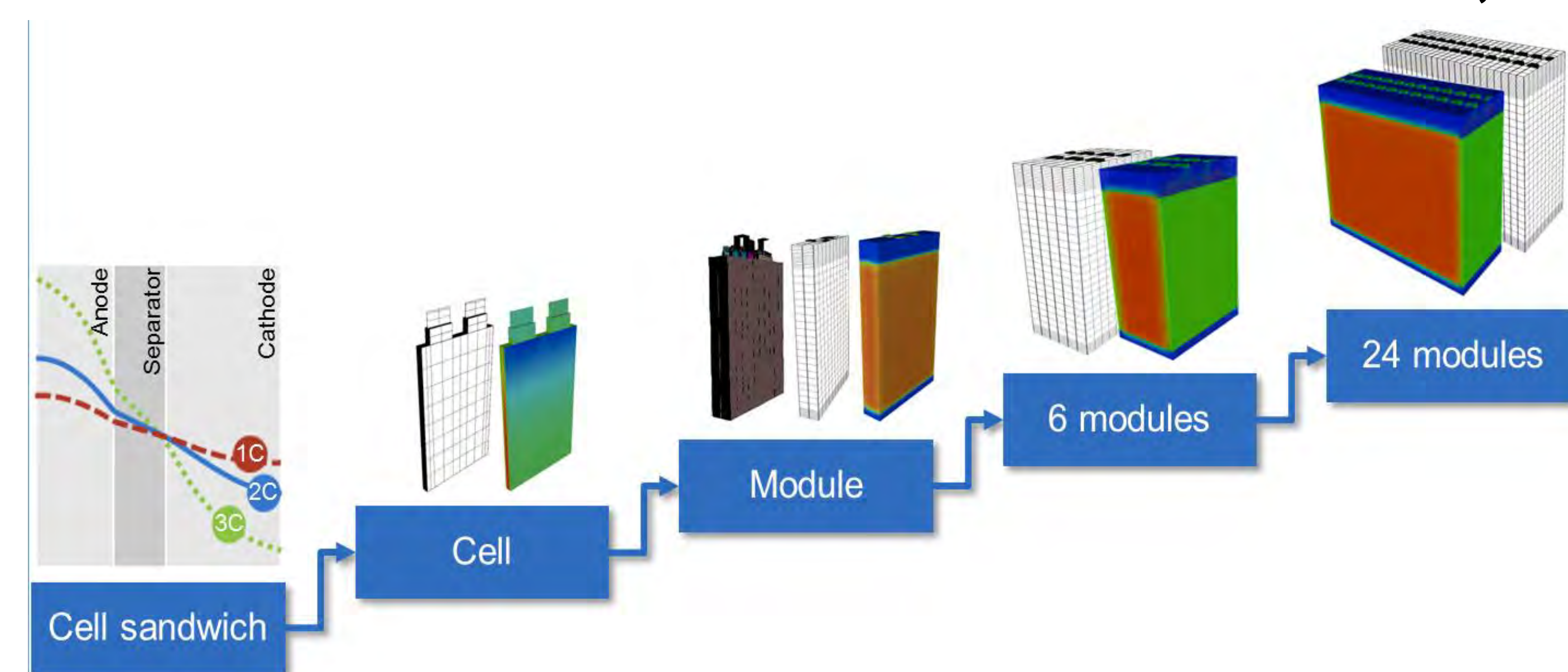
Component-level (optocoupler)

- Bandwidth
- Isolation voltage
- Propagation delay

Distributed power processing for Li-ion batteries

Nataraj Pragallapatti Satish Ranade Javier Alvidrez Ankith Nadella Jose Tabarez
Klipsch School of Electrical Computer Engineering New Mexico State University,
Las Cruces, NM

Stan Atcitty M A Moonem
Sandia National Laboratories
Albuquerque, NM



$$P_o = \frac{V_i n V_o T_s}{2L_{lk}} d(1-d); K = \frac{nV_o}{V_i}$$

Purpose and Impact

Investigate potential benefits of processing energy at the unit level (battery, cell) with subsequent series parallel connections

- improved efficiency of the overall stack?
- improved safety and reliability through battery level analytics?

Description

Design and development of Distributed Power Conversion circuits based Battery Energy Storage System (DPCC-BESS) for the stationary, grid-tied applications.

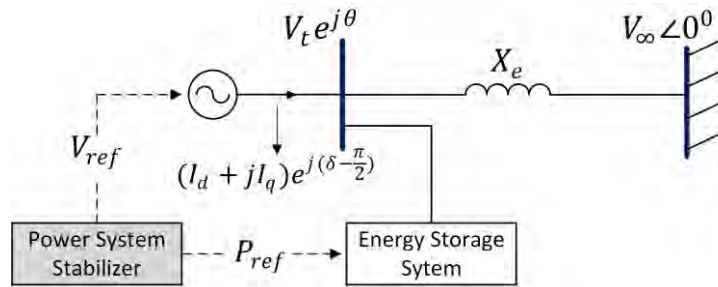
- Optimized Power processing battery/cell level.
- System efficiency improvement by the use of advanced power electronics devices.
- Optimized PCB close to the size of battery/cell.
- High-frequency Transformer design and Bi-directional power control of DAB at battery/cell level.

This work is supported by the Department of Energy, Energy Storage Program management by Dr. Imre Guyk.

Optimal Control of Energy Storage for Transient Stability

David Rosewater (SNL), Quan Nguyen (UT Austin), and Surya Santoso (UT Austin)

Single Machine Infinite Bus (SMIB) model of a power system with a generator, power system stabilizer, and energy storage system.

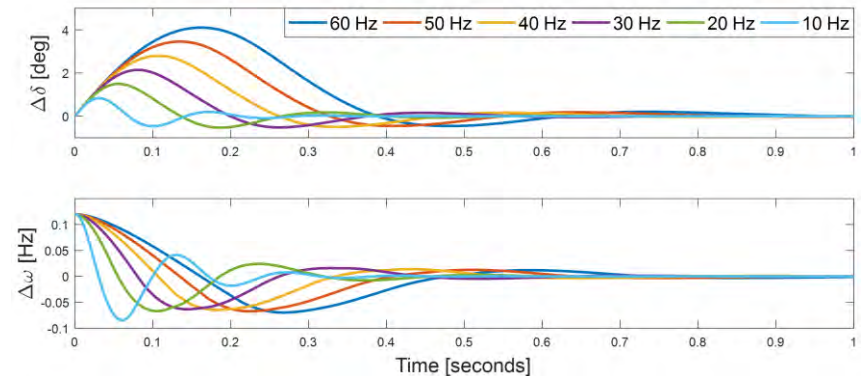


Calculate optimal state feedback control gain to minimize generator angle and frequency disturbances over an infinite horizon.

$$L = \frac{1}{2} \int_0^\infty \left[(\Delta\delta)^2 + (\Delta\omega)^2 + r_1 (\Delta V_{ref})^2 + r_2 (\Delta P_{ref})^2 \right] dt$$

$$\mathbf{u}^* = [\Delta V_{ref} \ \Delta P_{ref}]^T \quad \mathbf{u}^* = -\mathbf{K}\mathbf{x}, \mathbf{K} = \mathbf{R}^{-1}\mathbf{B}^T\mathbf{S}^*$$

Explore how the state response changes on low frequency transmission systems.



The stability improvements achieved by conventional power system stabilizers (PSS), energy storage system (ESS) damping, and low-frequency high-voltage alternating current (LF-HVAc) transmission are stackable.

Sandia National Laboratories Energy Industry Acceptance - Storage Projects

Daniel Borneo, P.E.
Sandia National Laboratories

DOE-OE Peer Review
October, 2017

Program Sponsor: DOE/OE Stationary Energy Storage Program - Dr. Imre Gyuk



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SAND2017-10991 C



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Six Sandia Thrust Areas to Meet Grid Challenges



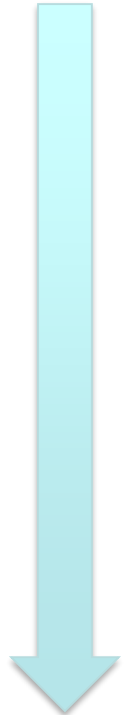
U.S. DEPARTMENT OF
ENERGY



Sandia
National
Laboratories

- **Materials and Systems Development**
 - Leading the **development** of next-generation technologies
 - Improving current **technology** (flow batteries, flywheels, etc.)
- **Power Electronics**
 - **Developing** and testing new wide-bandgap power-electronic devices
- **Component and systems analysis and safety**
 - Analysis from battery cells through MW size ES systems
 - ES system testing protocols
 - ES system safety R&D
- ***Industry Acceptance (IA)***
 - ***ES System Field deployments and commissioning***
 - ***State-Initiated Demonstrations***
 - ***Technical support***
- **Grid Analytics and Policy**
 - Providing **assessments** of the impact of storage placement
- **Outreach** - Leading publications and meetings to **help** educate the Grid Energy community

Nanoscopic



Macroscopic

SNL Industry Acceptance Team/Partners



- Sandia Team
 - Ben Schenkman
 - Ray Byrne
 - Cole Benson
 - Meghann ManGold
 - Tu Nguyen
 - Frank Maldonado
 - Megan Brace
- Clean Energy States Alliance
 - Todd Olinsky-Paul
- OE Lab Partners
 - PNNL - Patrick Balducci
 - ORNL - Michael Starke
- Industry Partners:
 - Matt Lazarewicz (HELIX)
 - Jim Glass (EPB)
 - Will Price/Matt Ibaracki (EWEB)
 - HELCO
 - Laurence Sombardier (NELHA)
 - Jeremy Lewis (EMNRD)
 - Diane Broad (Oregon DOE)
 - Josh Castonguay (GMP)
 - Marc Mueller-Stoffels (UoA)
 - Los Alamos County DPU
 - UniEnergy Technology
 - East Penn/ECOULT
 - GS Yuasa
 - Energy Market Authority of Singapore (EMA)

SNL Industry Acceptance – ES Projects Team

MISSION STATEMENT: Encourage investment in Energy Storage

APPROACH: - Work with national and international entities to:

- Develop and Deploy Energy Storage Projects
- Support State and International renewable/resiliency/Energy Storage initiatives

** Partnering relationship with sister Labs – PNNL, ORNL, NREL

SNL Industry Acceptance – ES Projects Team



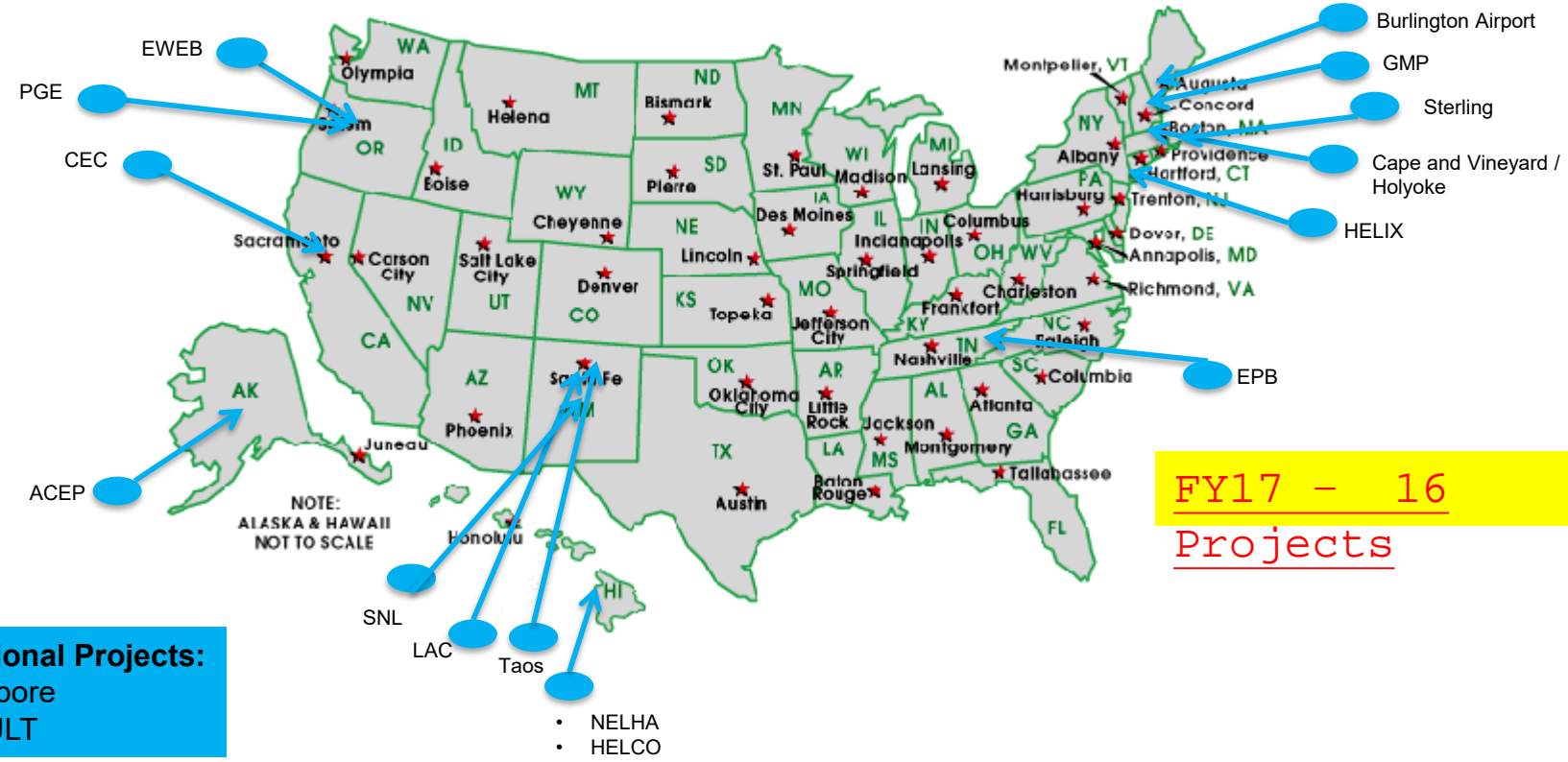
Capabilities

- Project Development and Implementation
 - RFI & RFP
 - Project designs and specifications
 - Data Acquisition Systems (DAS)
 - Technical support during the construction
 - ESS commissioning/testing plan development and implementation.

- System monitoring
 - Remote monitoring and data acquisition
 - Analysis of operational test data

- Policy, regulatory and state support through CESA resources
 - Webinars, Papers, Presentations

SNL Industry Acceptance - ES Projects 2017



Stock Image source: <http://www.devarticles.com/c/a/Web-Services/Cooking-With-Web-Services-PHP-and-GD/3/>

Thanks

Dan Borneo - drborne@sandia.gov

CESA State Projects and Policy Development

DOE-OE Peer Review
San Diego, CA
October 9-10, 2017

Todd Olinsky-Paul
Project Director
Energy Storage Technology Advancement Partnership
Clean Energy States Alliance



Agenda for this presentation:

- Introduction to CESA and ESTAP
- Current projects
- Policy work
- Outreach

Clean Energy States Alliance (CESA)

www.cesa.org



Department of Commerce
Innovation is in our nature.



Energy Storage Technology Advancement Partnership (ESTAP)

- A project of Clean Energy States Alliance (CESA)
- Conducted under contract with Sandia National Laboratories, with funding from US DOE-OE

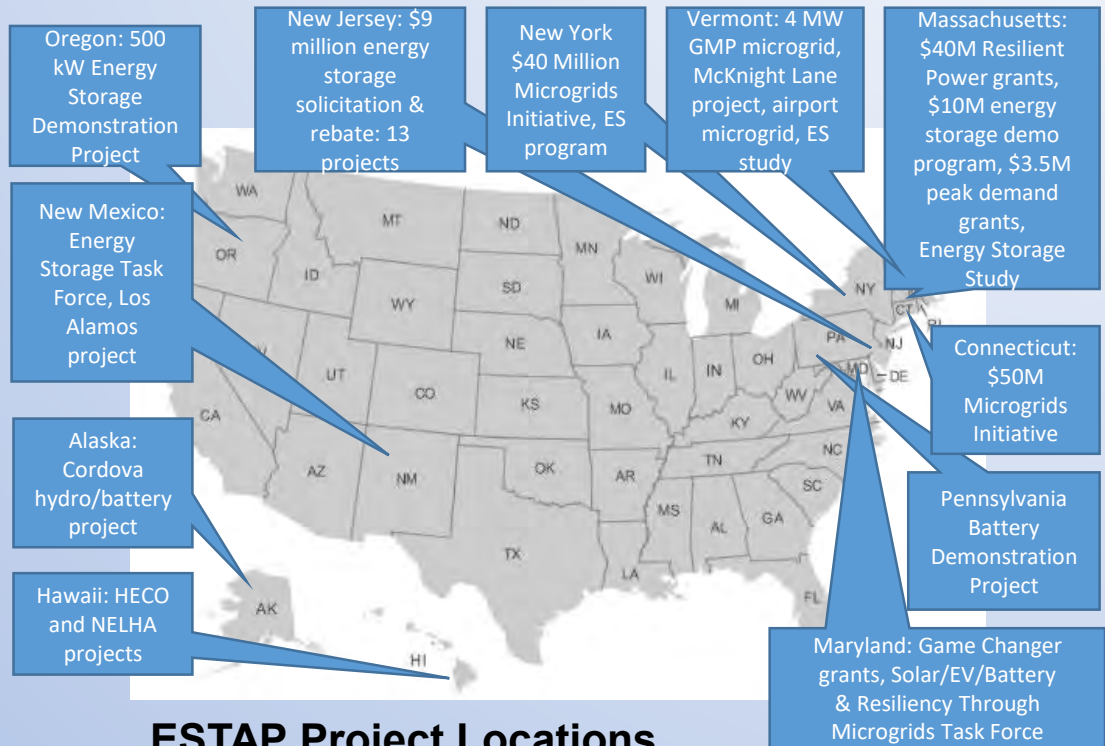
ESTAP Key Activities:

1. Facilitate public/private partnerships to support joint federal/state energy storage project deployment
2. Disseminate information to stakeholders
 - ESTAP listserv >3,000 members
 - Webinars, conferences, information updates, surveys.
3. Support state energy storage efforts with technical, policy and program assistance

Thank You to:

Imre Gyuk, US DOE-OE

Dan Borneo, Sandia National Laboratories



ESTAP Project Locations



Current ESTAP Projects

- Massachusetts
 - Sterling Municipal Light Department
 - Cape & Vineyard Electric Cooperative
 - Holyoke Gas & Electric
 - Northampton
- Vermont
 - McKnight Lane Redevelopment Project
 - Burlington International Airport Microgrid
- Oregon: Eugene Water & Electric Board (EWEB)

Massachusetts: Sterling Municipal Light Department 2MW/3MWh energy storage project



Project partners: SMLD, DOER, DOE-OE, SNL, CESA

Project timeline: Groundbreaking in October 2016, commissioning in December, 2016

Project Summary: 2 MW / 3 mWh lithium ion battery project, connected with 3.4 MW solar PV at utility substation; islanding capability to support municipal police and emergency dispatch facility.

Project Benefits and Revenue Streams:

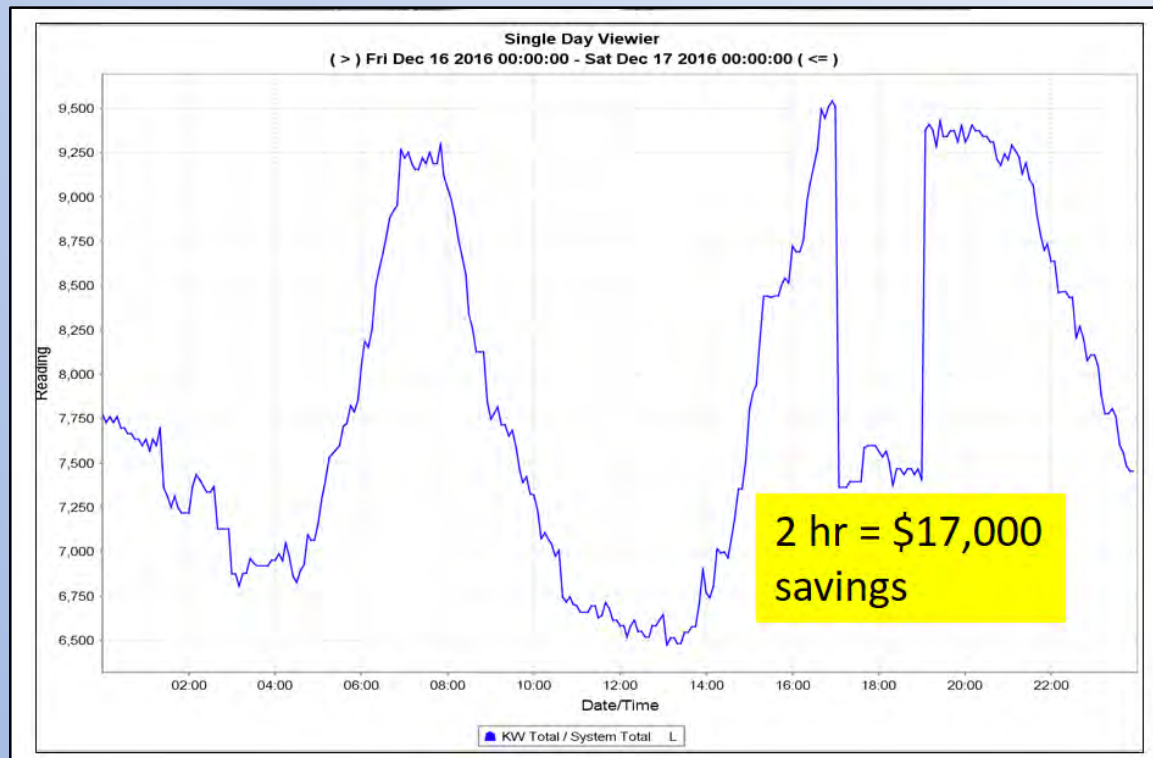
- Backup power to support town police station / dispatch center during grid outages
- Cost savings through reduction of SMLD's capacity and transmission obligations to ISO-NE
- Revenues from arbitrage
- Integration of solar PV



Sterling project demonstrates value of peak shaving in ISO New England: 9 months of service = \$358,460 saved

Projected annual savings = \$400,000

Simple payback: 2.5 years (7 years without subsidies)



Sterling follow-on projects

The Sterling project has received visitors from all over the world, and is being emulated by a number of other municipal utilities in Massachusetts

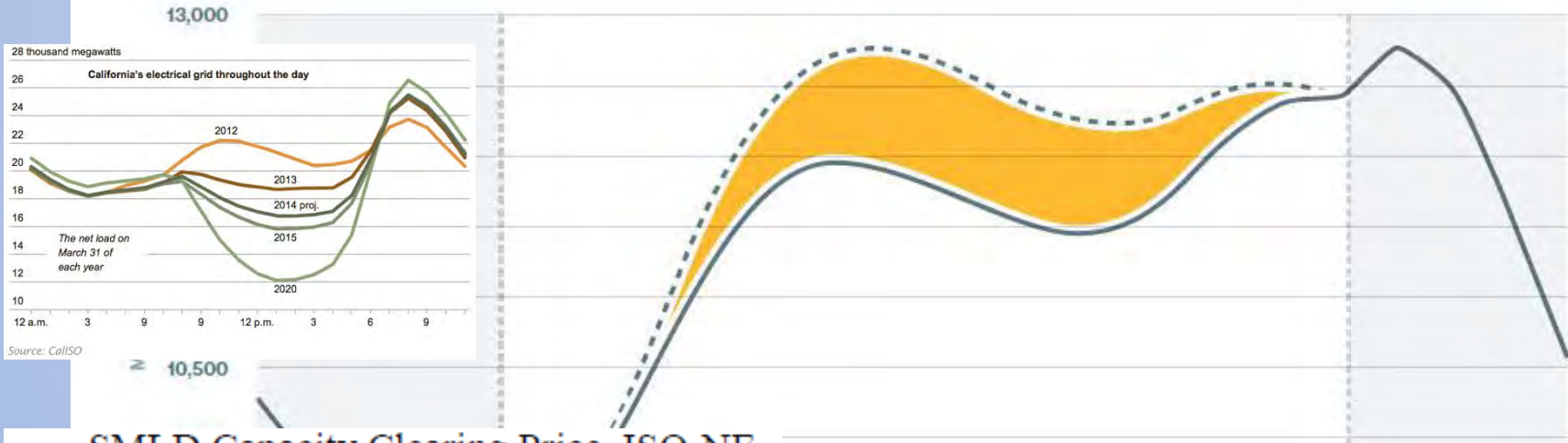
In addition, Sterling is in the process of adding more energy storage to its system

Holyoke Gas & Electric is developing what will be the largest energy storage project in the state, based on the economic case demonstrated by Sterling and GMP

Massachusetts Municipal Wholesale Electric Company (MMWEC) is developing a program to provide energy storage and ES support services to its members (other MA municipal utilities)

ISO New England Demand

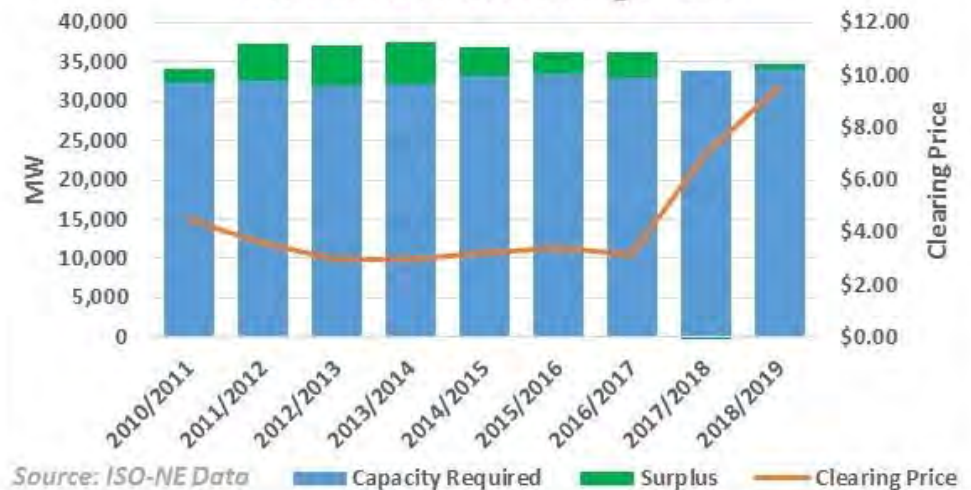
Solar Power's Effect on Regional Electricity Demand
May 23, 2015



SMLD Capacity Clearing Price, ISO-NE.

Year	Price (\$/kW-Month)
2010-2011	\$4.254
2011-2012	\$3.119
2012-2013	\$2.535
2013-2014	\$2.516
2014-2015	\$2.855
2015-2016	\$3.129
2016-2017	\$3.150
2017-2018	\$7.025
2018-2019	\$9.551

ISO-New England FCM Auctions:
MW Procured & Clearing Prices



Vermont: McKnight Lane Residential Redevelopment Project, Waltham VT

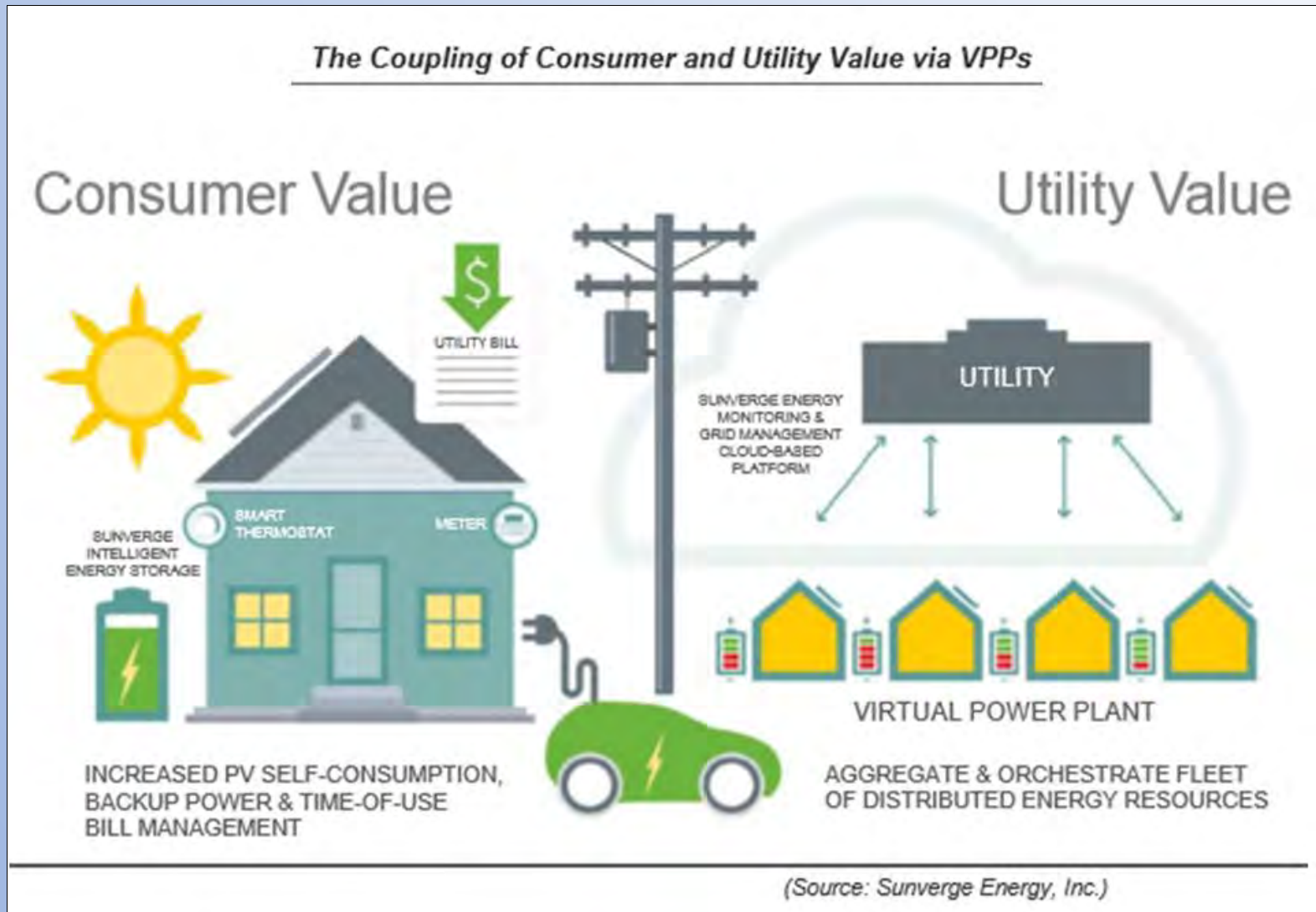


- Defunct trailer park redevelopment
- 14 high efficiency, all-electric affordable modular homes
- Each equipped with solar+storage (6 kW Li Ion)
- Tenants receive resiliency benefits
- Utility dispatches batteries to reduce costs





McKnight Lane operates as a Virtual Power Plant (utility and customers share benefits)



Values to utility: control of batteries for peak shaving, grid congestion relief/T&D investment deferral, and arbitrage

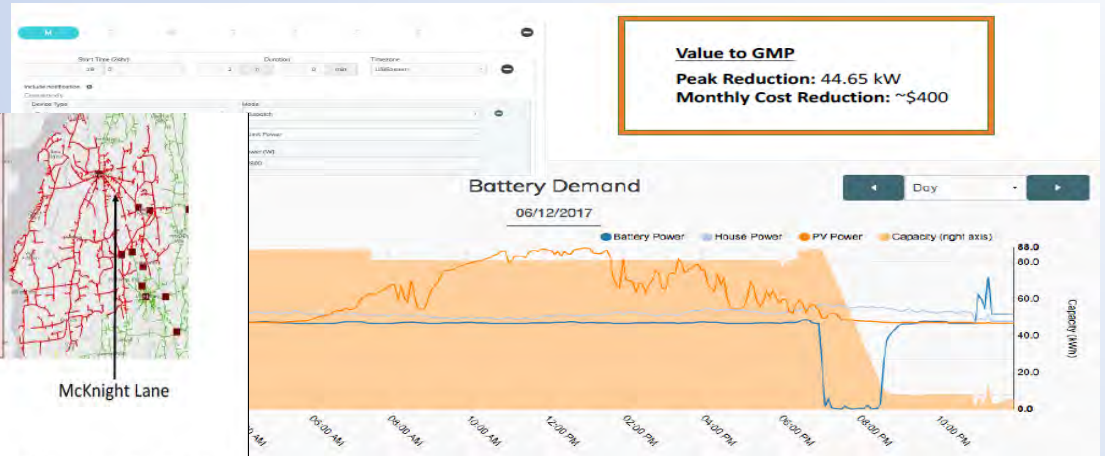
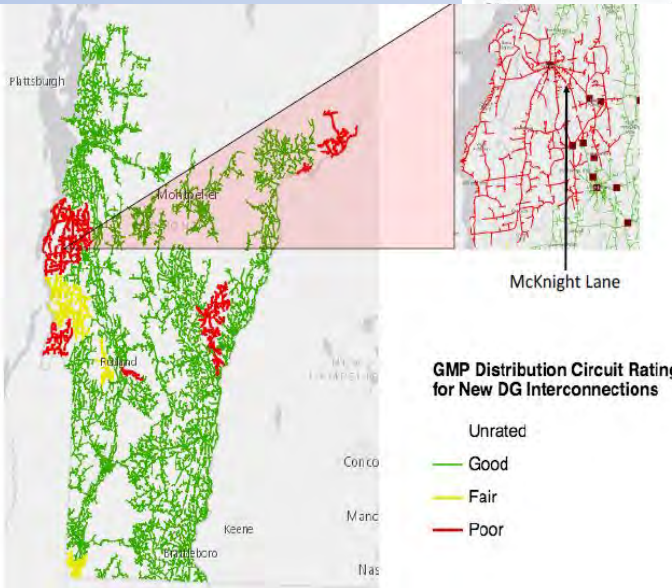
Additional Benefits to GMP

Grid Congestion from PV

Store energy at time of high PV penetration to "Soak Up" excess solar in a certain area

T&D Deferral

Small amounts of distributed energy storage may delay, or completely alleviate the need for wire or transformer upgrades that may be overkill for a small increase in capacity in a given area



Arbitrage

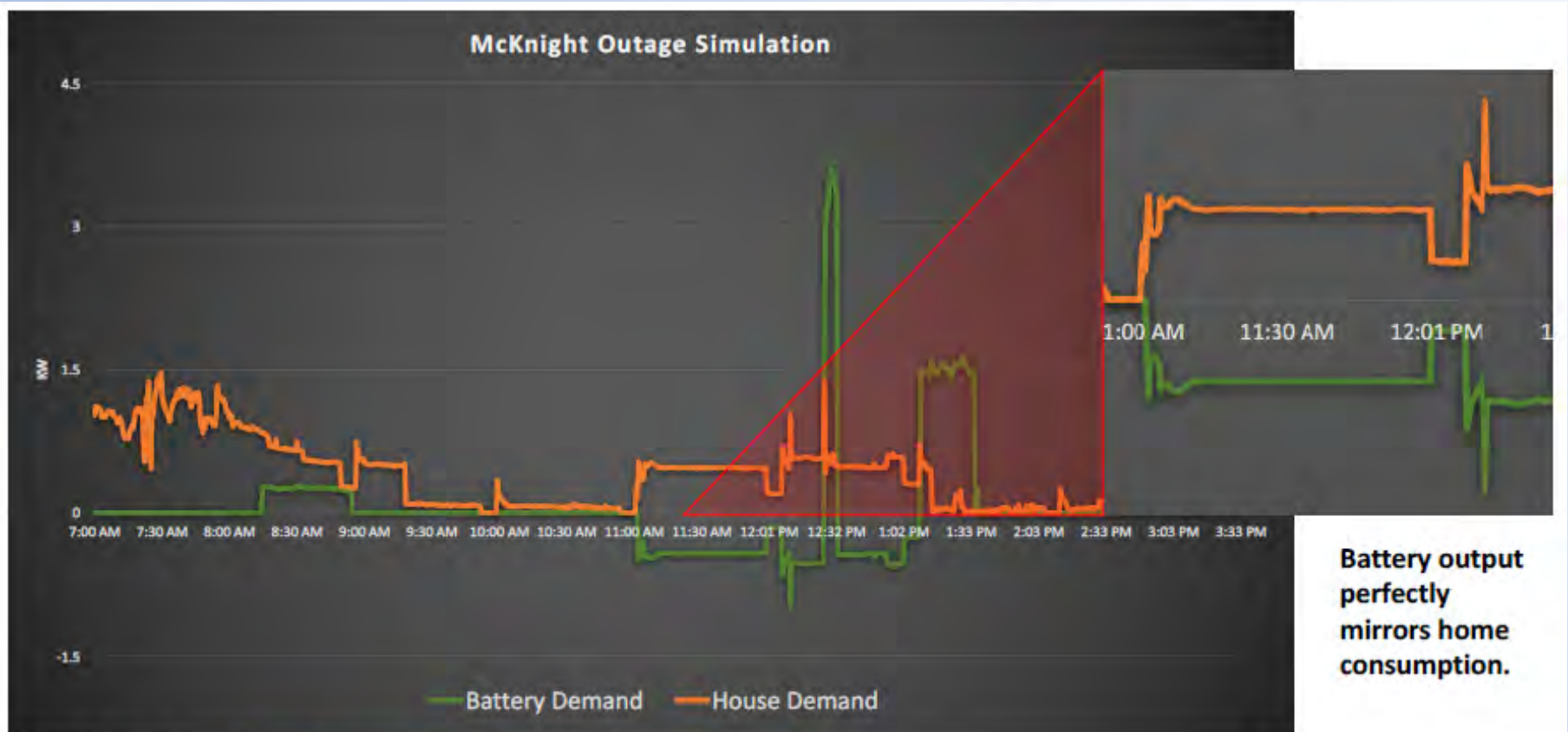


Energy Arbitrage is the process of charging or discharging the batteries based on market prices of energy. This represents a new value stream available to GMP.

GMP has partnered with Virtual Peaker to provide this functionality and is close to making arbitrage with these systems a reality.



Value to tenants: backup power supports critical loads when grid goes down



Event Schedule:

Time	Event	Duration
11:00 am	Grid Outage	2 hours
1:00 pm	Grid Connection	-

CESA's role:

- Provide technical assistance
- Collect and analyze project data
- Document the project in case study
- Create a replicable project template



Project partners:

- US Department of Energy, Office of Electricity
- Sandia National Laboratories
- Addison County Community Trust
- Cathedral Square
- Efficiency Vermont
- Green Mountain Power
- High Meadows Fund
- Sonnen Batterie
- VerMod
- Vermont Community Foundation - Sustainable Future Fund



McKnight Lane follow-on projects

- CESA is working with Housing Vermont, the state's largest affordable housing developer, to equip multifamily affordable housing facilities with solar+storage for resiliency and demand charge management
- VEIC is in talks with Vermod and Tesla to develop an affordable modular home with solar+storage



Vermont: Burlington International Airport Microgrid

- Burlington Electric Department intends to install 1 MW/4 MWh battery connected to existing 500 kW solar PV
- Municipal utility will use storage to reduce costs through peak shaving (capacity and transmission cost reductions) and other applications (arbitrage, frequency regulation)
- Airport will receive backup power during grid outages

Status:

- BED has received project proposals and is in the process of selecting a vendor
- RFP sought turnkey and third-party ownership with PPA
- Project likely to be third party with PPA



CESA Policy and Technical Assistance

- New England States Energy Storage Policy Collaborative: ME, MA, NH, VT, CT, RI
- CESA States Energy Storage Working Group: DC, OR, CA, WI, CT, RI, MA, MD, WA, IA
- Connecticut
 - Assistance with microgrids grant program
- Massachusetts
 - Technical assistance to state resiliency grantees (Sterling, Northampton, Holyoke, Cape&Vineyard, Beverly, Wayland)
 - Assistance with microgrids program development
 - Assistance with energy storage grant solicitation (ACES)
 - Energy storage rebate proposal (in progress)
- Oregon
 - Assistance with state energy storage grant program
- Vermont
 - Assistance with state energy storage study
 - Testimony before VT Legislature, Energy Committee
- Washington
 - Assistance with state grid modernization grant program

CESA Outreach Activities

Reports:

Energy Storage Procurement Guidance Documents for Municipalities, by Daniel R. Borneo, Todd Olinsky-Paul, Maria Blais Costello, Sarah Galbraith, Henry Misas and Nick Turchak (September 2016)

The Value Proposition for Energy Storage at the Sterling Municipal Light Department, by Ray Byrne, Sean Hamilton, Daniel R. Borneo, Todd Olinsky-Paul and Imre Gyuk (February 2017)

Solar+Storage for Low- and Moderate-Income Communities: A Guide for States and Municipalities, by Todd Olinsky-Paul (March 2017)

Green Mountain Power (GMP): Significant Revenues from Energy Storage, by Susan Schoenung, Raymond H. Byrne, Todd Olinsky-Paul and Daniel R Borneo (May 2017)

Video: Sterling Municipal Light Department Energy Storage System – A Revolution for the Electric Grid

Blogs and Articles:

Steps states can take to advance energy storage, Todd Olinsky-Paul, *PV Tech Power Magazine*, September 2017

Financing for Solar Plus Storage, Todd Olinsky-Paul, *Green Energy Times*, August 2017

How One Small US Town Will Save Millions with a Microgrid, Todd Olinsky-Paul, *Renewable Energy World Magazine*, Vol. 20, Issue 4, July 2017

Small Community Saves Big with Energy Storage, Todd Olinsky-Paul, April 2017

Bringing the Benefits of Solar+Storage to Low-Income Communities: A Guide for States and Municipalities, Todd Olinsky-Paul, March 2017

How Utilities Can Bring Storage to Scale in Massachusetts, Todd Olinsky-Paul, December 2016

Sterling, Massachusetts Breaks Ground on a Resilient Energy Storage System, Todd Olinsky-Paul, October 2016

Massachusetts Goes All-In on Energy Storage, Todd Olinsky-Paul, September 2016

Webinars:

Webinar Title	Date	Attended
McKnight Lane Project Updates	9/27/17	139
Identifying Potential Markets for Commercial Behind-the-Meter Battery Storage	9/19/17	311
SolarResilient: A New Tool for Resilient Solar+Storage Design	8/3/2017	183
Solar Risk: How Energy Storage Can Preserve Solar Savings in California Affordable Housing	6/15/2017	117
ESyst: Optimizing Energy Storage Savings with Geli's New Online Tool	5/24/2017	197
Is Energy Storage Right for Our Community-Based Solar Project? A Solar+Storage 101 Webinar	5/12/2017	46
The Value Proposition for Energy Storage at the Sterling Municipal Light Department	4/27/17	284
Tools for Building More Resilient Communities with Solar+Storage	4/6/2017	131
NYC's Policy Target and Roadmap for Resilient Solar+Storage	4/4/2017	115
Solar+Storage Industry Perspectives: JLM Energy	3/22/2017	151
Comparing the Abilities of Energy Storage, PV, and Other Distributed Energy Resources to Provide Grid Services	3/13/17	354
Developing an Energy Storage Project: A Technical Perspective	3/8/2017	310
American Samoa's Solar+Storage Microgrid	2/16/2017	182
GTM Energy Storage Market Updates	1/27/17	320
McKnight Lane: A Rural Low-Income Resilient Solar+Storage Housing Project	12/14/2016	266
Energy Storage for Public Health	11/2/2016	114
Mass Energy Storage Study and Legislation	10/27/16	237
Sterling Microgrid Project	10/25/2016	260
Resilient Power Retrofit: How a Minnesota Nature Center Became a Solar+Storage Community Shelter	10/19/2016	80

Conferences and Presentations:

States Energy Storage Policy Panel, Renewable Energy Vermont, Burlington, VT
October 2017

State Energy Storage Policy panel, Council of State Governments policy
workshop, Washington, DC September 2017

Sterling, MA Energy Storage Project video and panel, Solar Power International
conference, Las Vegas, NV, September 2017

“Microgrids for Resiliency: State of the States.” National Governors Association
webinar, August 29, 2017

“New England States’ Energy Storage Policy Collaborative Meeting.” Barr
Foundation, Boston, MA, July 2017

“Microgrids as a Resiliency Strategy.” Clean Energy States Alliance Meeting,
Washington, DC, June 2017

“State Energy Storage Policies and Program Tools.” Clean Energy States Alliance
Meeting, Washington, DC, June 2017

“Bridging the Gap between Yesterday's Legacy Grid and Tomorrow's Smart
Grid.” Microgrids East conference, Boston MA, April 2017

Conferences and Presentations, continued

“State Energy Storage Policy.” Testimony before the Vermont House Committee on Energy & Technology, April 2017

“Solar Plus Storage in Boston: An Economic Analysis,” NESEA BuildingEnergy conference, Boston MA, March 2017

“Energy Storage: The Game-Changer.” National Conference of State Legislatures Capital Forum, Washington, DC December 2016

“CESA State Projects and Policy Development.” DOE-OE Peer Review, Washington, DC, September 2016

“How Solar + Energy Storage Builds Resilience.” Carolinas Climate Resilience Conference, Charlotte, NC, September 2016

“McKnight Lane Redevelopment: A Residential Solar + Storage Project for Rural Vermont.” Renewable Energy Vermont Conference, Burlington, VT. October 2016

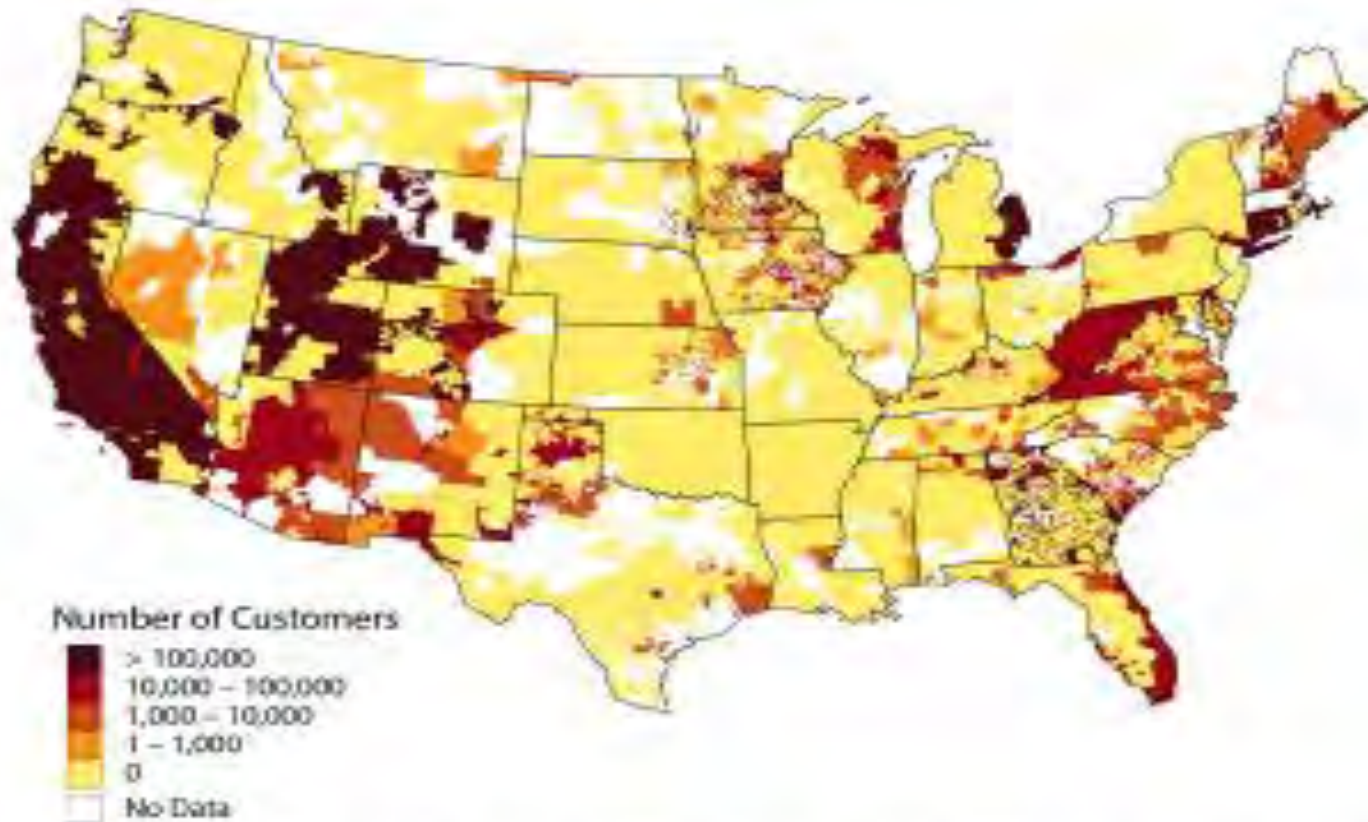


Figure 1. Number of commercial electricity customers who can subscribe to tariffs with demand charges in excess of \$15/kWh.

Darker areas on map = more customers paying high demand charges

Thank You to:

Imre Gyuk, US DOE-OE

Dan Borneo, Sandia National Laboratories

Todd Olinsky-Paul

Project Director

CEG/CESA

Todd@cleanegroup.org

ESTAP Website: <http://bit.ly/CESA-ESTAP>

ESTAP Listserv: <http://bit.ly/EnergyStorageList>



Sterling Municipal Light Dept.



2017 DOE Peer Review

value of Energy Storage to Sterling Ratepayers

October 10, 2017

Matthew Stelmach PE, Chairman SMLD Commission



Ice Storm 2008



Value of Battery Energy Storage

- Grid Resiliency-Police and Dispatch Center
- Smoothing Intermittent Resources (Solar)
- Regional Network Service (RNS) -Monthly Peak
 - Captured 7/9 monthly peaks (to 8/31/2017) for a value of \$106k
- Capacity Load Obligation Payments –Annual Peak
 - Captured Annual Peak (6/13/2017) for a value of \$240,660
- Energy Arbitrage-Value to Date \$8k, 16 Round Trip operations
- Total Value to date \$354,660 (less \$3,500 operating expenses)

● Source: The Value proposition for Energy Storage for Sterling Municipal Light Department

● Author Dr. Raymond Byrne, Sandia National Laboratories. www.energysterling.com

Ma. DOER. Community Clean Energy Resiliency Initiative Grant

- Received \$1.463 million from Ma. DOER.
- Received \$250k from Dept. of Energy.
- With Grant -SMLD \$807k payback is 2 years.
- Interconnect work performed by SMLD crews.
- Cooperative effort by Town of Sterling Depts., Selectmen/TA (Grant), Fire Dept. Design & Inspection of System, DPW –Road and Base compaction, Police Dept.-container delivery/testing, Wire Insp. Building Insp.
- Shovel in ground to operation- 33 working days

Resiliency Benefits

2mw/3.9mwhr -Battery Energy Storage System

1. BESS provides Power up to 12 Days.
2. BESS Located in Main Substation.
3. Substation 2,300' from Critical Facility.
4. Separate Circuit for BESS and Critical Facility
5. MicroGrid Capable with Solar.
6. Live Test Performed April 27,2017



Police & Dispatch Facility

Chocksett Substation

Wiles Rd 2 MW solar array

Micro Grid Capable

© 2014 Google

Google

Imagery Date: 9/20/2010 42°27'00.86" N 71°44'14.78" W elev 434 ft

SEPA Solar Watts Per Customer Comparison

SEPA 2013

SEPA 2015

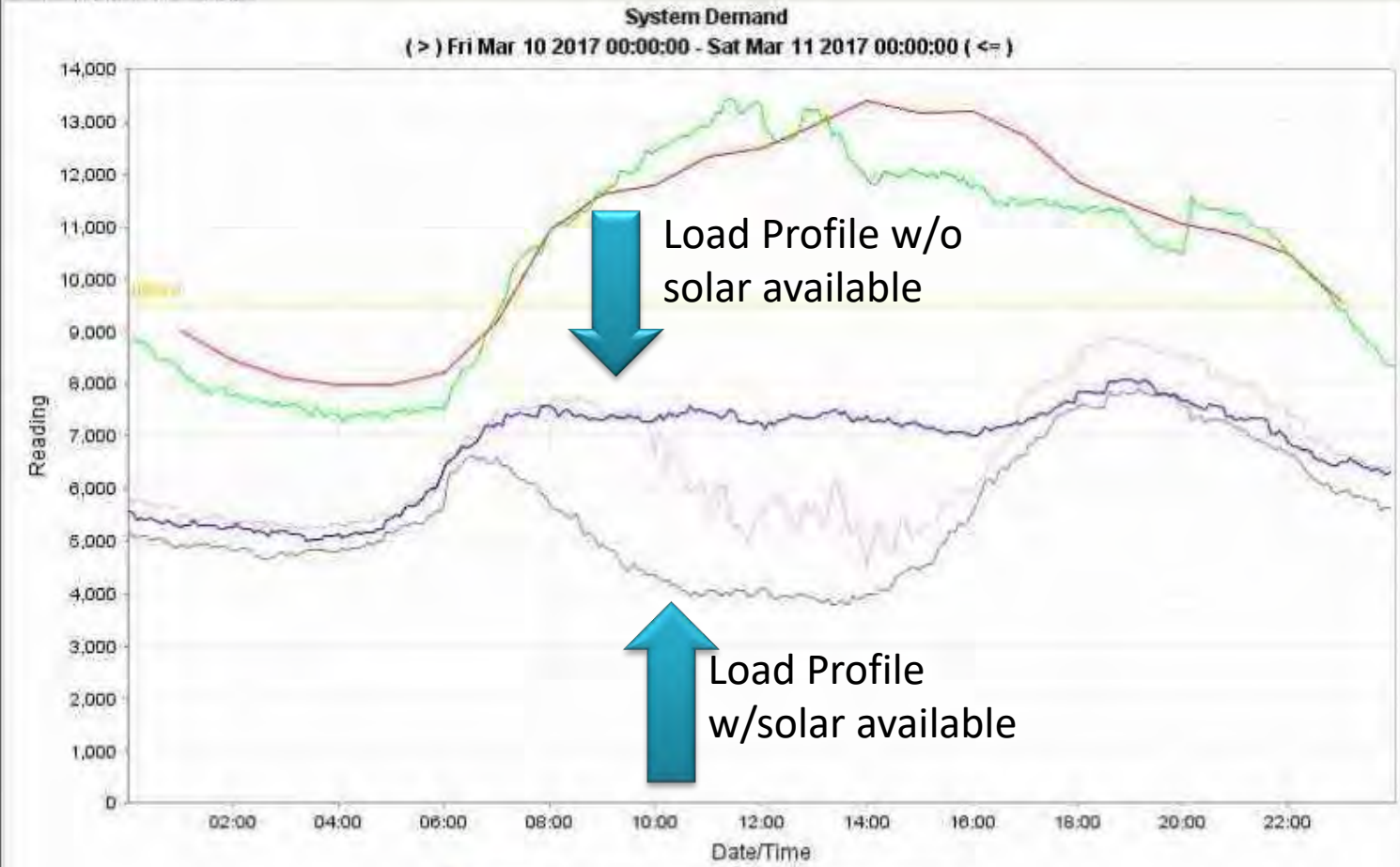
Rank	Utility	W/C	Village of Minster (OH)	2,104
1	Sterling Municipal Light Dept (MA).	831	2	City of Palo Alto Utilities (CA) 1,846
2	San Diego Gas & Electric Company (CA)	461	3	Roseville Electric Utility (CA) 1,416
3	Silicon Valley Power/City of Santa Clara (CA)	427	4	Carey Municipal Electric Utility (OH) 1,351
4	Arizona Public Service (AZ)	368	5	Vineland Municipal Electric Utility (NJ) 1,318
5	Hawaiian Electric Company, Inc. (HI)	329	6	Ashburnham Municipal Light Plant (MA) 1,079
6	Pacific Gas and Electric Company (CA)	281	7	Sterling Municipal Light Department (MA) 848
7	Hawaii Electric Light Company (HI)	182	8	Imperial Irrigation District (CA) 750
8	Maui Electric Company Ltd (HI)	178	9	Guam Power Authority (GU) 710
9	Kauai Island Utility Cooperative (HI)	167	10	Silicon Valley Power (CA) 613
10	Imperial Irrigation District (CA)	159		

Sort By: Trends

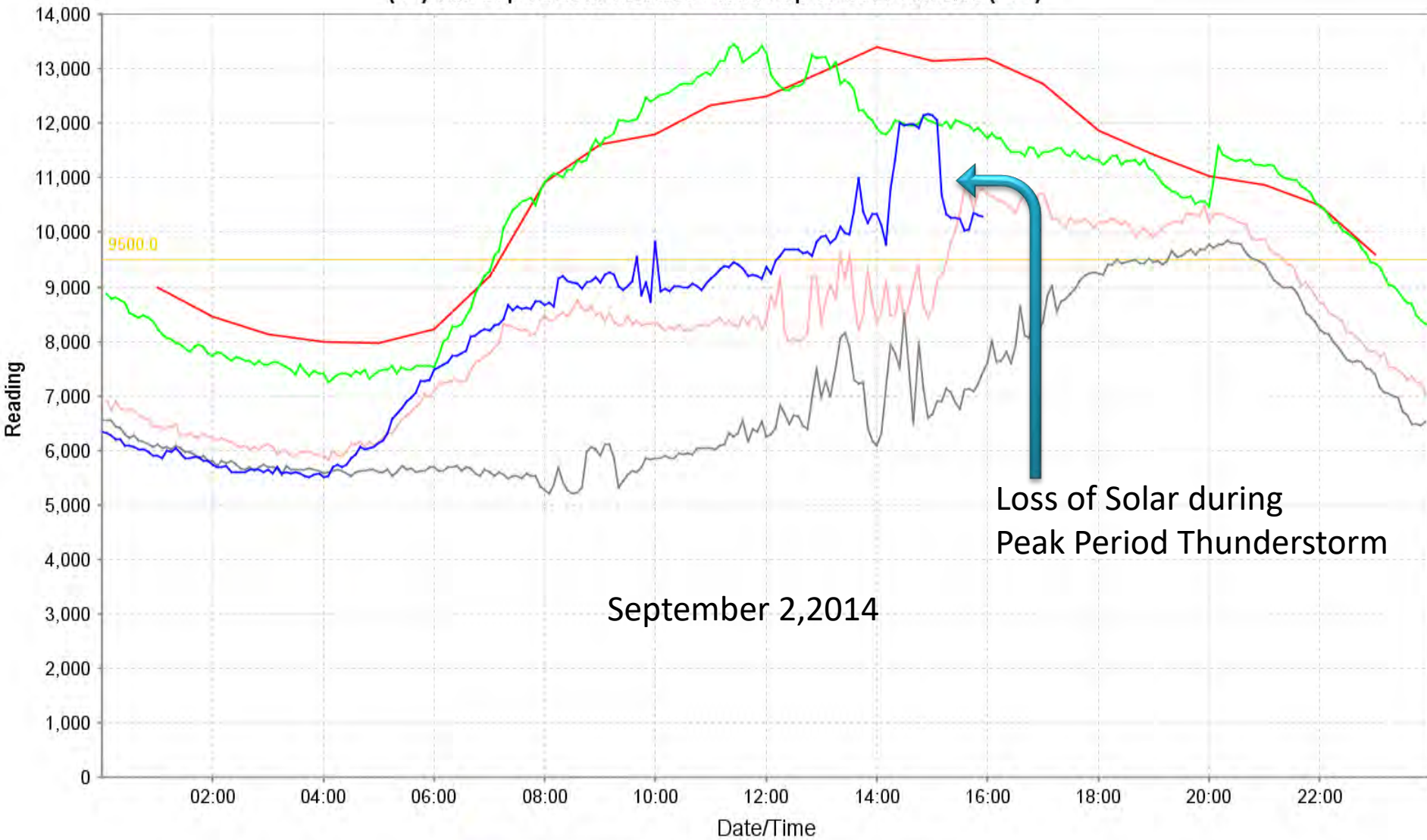
- Hourly Demand
- Hourly system demand
- Load Observation
- Single Day Viewer
- System Demand**

Refresh Current Historical Time Period: 1 Day Start Date: Mar 10, 2017 Number of Events: 20

Graph Tabular Summary



- Today System Total kW L
- 2011 Coincident Peak 1.975MW SHD [Fri Jul 22 2011] L
- Yesterday System Total kW [Thu Mar 09 2017] L
- March 2016 Peak Day [Wed Mar 02 2016] L
- System Peak kW [Wed Aug 02 2006] L
- Threshold L



- Today System Total KW L
- 2011 Coincident Peak 1.975MW SHD [Fri Jul 22 2011] L
- Yesterday System Total KW [Mon Sep 01 2014] L
- August 2013 Peak [Wed Aug 28 2013] L
- System Peak KW [Wed Aug 02 2006] L
- Threshold L

Final Real-Time Locational Marginal Prices (\$/MWh) 9/2/2014

Note Hour 14 During Thunderstorm

Hour	HUB	WCMA	NEMA	SEMA	CT	RI	NH	VT	ME
1	44.23	44.35	44.48	44.03	44.40	44.39	43.85	43.75	41.88
2	38.15	38.31	38.22	37.84	38.36	38.17	37.74	37.75	36.11
3	32.98	33.11	33.01	32.68	33.09	32.96	32.67	32.54	31.54
4	28.23	28.34	28.26	28.01	28.26	28.19	28.02	27.90	27.13
5	28.06	28.19	28.07	27.83	28.17	27.97	27.89	27.81	26.98
6	32.97	33.10	32.98	32.67	33.11	33.09	32.86	32.82	31.77
7	37.33	37.46	37.49	37.03	37.51	37.24	37.44	37.29	36.38
8	40.87	40.99	41.07	40.62	41.05	40.90	41.01	40.86	39.96
9	35.01	35.09	35.25	36.10	35.06	41.63	35.25	34.96	34.33
10	45.85	45.99	46.13	46.51	46.09	50.20	46.07	45.92	44.34
11	73.81	74.12	74.15	73.39	74.69	73.55	74.11	74.15	71.31
12	89.80	90.11	90.35	89.45	93.48	89.51	90.14	89.86	86.67
13	185.70	186.25	187.11	185.44	190.47	185.53	186.15	184.95	178.01
14	554.71	555.62	560.77	555.12	558.00	555.55	555.69	551.95	530.00
15	206.54	206.72	209.37	207.47	308.93	207.60	206.72	205.66	196.51
16	70.45	70.57	71.51	70.86	158.68	70.91	70.15	70.67	65.38
17	86.23	86.34	87.48	86.72	168.94	86.71	85.96	86.14	80.60
18	133.90	134.22	135.05	134.18	174.45	134.14	133.38	133.73	126.21
19	72.92	73.14	73.35	72.90	107.74	72.81	72.65	73.38	68.10
20	75.16	75.35	75.60	75.14	82.61	75.08	75.14	75.41	71.28
21	74.36	74.62	74.61	74.20	75.75	73.96	74.14	74.76	70.18
22	55.07	55.27	55.32	54.86	55.76	54.56	54.81	54.91	52.16
23	38.60	38.75	38.82	38.36	39.02	38.21	38.48	38.42	36.99
24	54.55	54.76	54.98	54.15	55.00	54.01	54.41	54.12	52.48
AVG	88.98	89.20	89.73	88.98	104.53	89.45	88.95	88.74	84.85

Monthly Peak Alert Notice	
Date:	12/15/2016
ISO Projected Peak:	19,500
ISO Projected Hour:	18
Threshold:	18,282
Alert Rating:	5
Turn on Battery?	yes
Hours to Run:	18-19

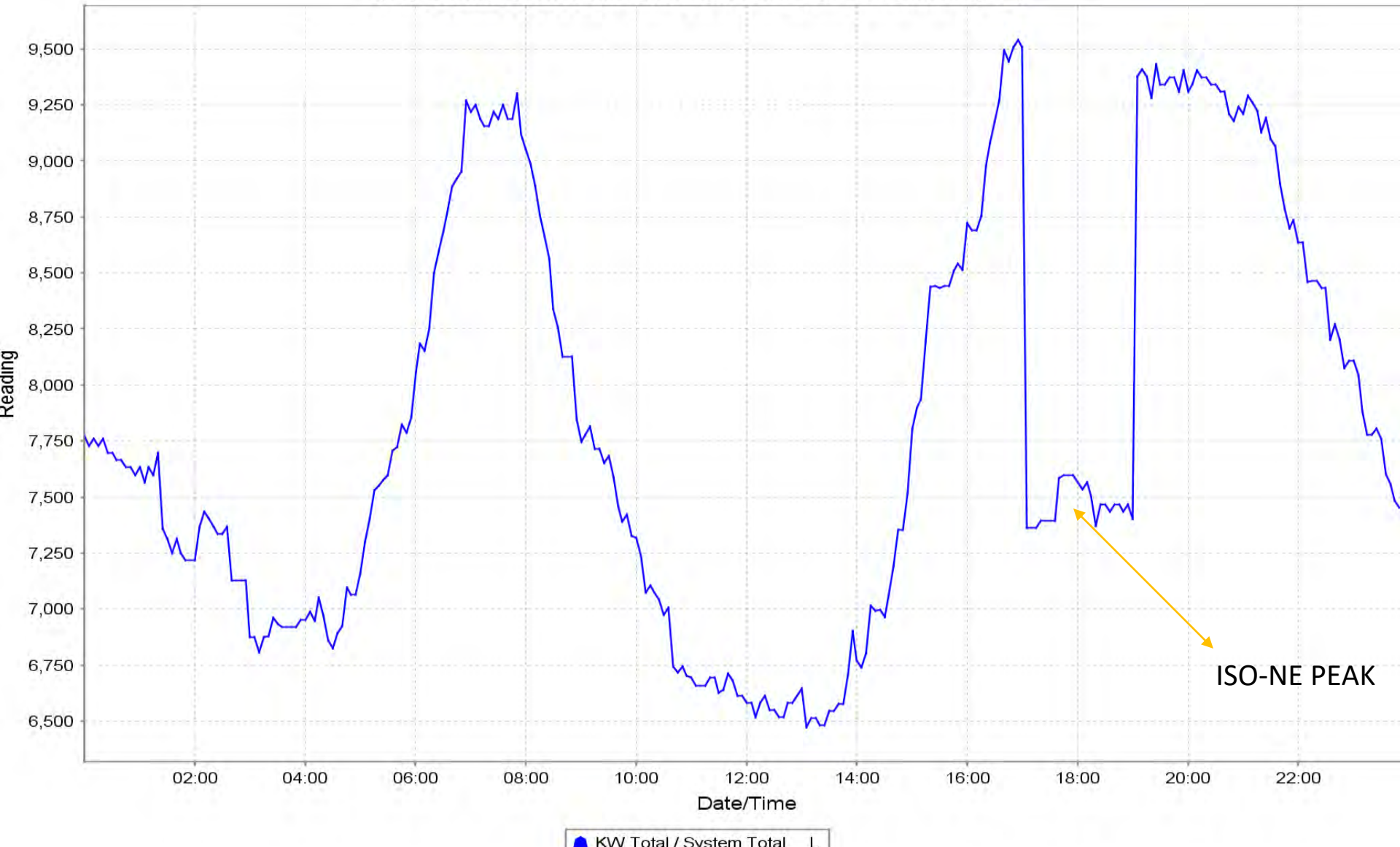
Alert Ratings Explained		
<i>Rating</i>	<i>Definition</i>	<i>Advice</i>
0	Projected peak is below the threshold by greater than 1,000 MW.	Take no action. This will not be the peak day.
1	Projected peak is below the threshold by an amount between 500 and 1,000 MW.	Take no action. Barring a dramatic miss by ISO this will not be the peak day.
2	Projected peak is below the threshold by an amount less than 500 MW.	Be aware of the situation. Peak load is approaching threshold, but will most likely not be the peak.
3	Projected peak is above the threshold by an amount less than 500 MW.	Send alert. Today has a chance of being the peak day
4	Projected peak is above the threshold by an amount between 500 and 1,000 MW.	Send alert. There is a strong chance that today will be the peak day
5	Projected peak is above the threshold by an amount greater than 1,000 MW.	Send alert. There is an extremely high probability that today will be the peak day.

Began Construction 10-12-2016

Reduces RNS Peak on 12-16-2016

Single Day Viewer

(>) Fri Dec 16 2016 00:00:00 - Sat Dec 17 2016 00:00:00 (<=)







UTILITY ENERGY STORAGE RANKINGS

TOP 10 ANNUAL WATTS-PER-CUSTOMER

1	Sterling Municipal Light Department 	533 Watts-per-customer
2	Glasgow EPB	248 W/C
3	Imperial Irrigation District	198 W/C
4	American Samoa Power Authority	109 W/C
5	Indianapolis Power & Light Company	42 W/C
6	Duke Energy Ohio	23 W/C
7	Maui Electric	17 W/C
8	San Diego Gas & Electric	12 W/C
9	Green Mountain Power	8 W/C
10	Commonwealth Edison, an Exelon Company	6 W/C

Special Thanks to :

- SMLD General Manager Sean Hamilton – Spearheaded this project
- Town of Sterling - For their continued support
- Judith Judson – MA DOER Commissioner
- Dr. Imre Gyuk – U.S. DOE Office of Electricity, ES Program Director
- Sandia National Laboratories - Daniel Borneo PE., Dr. Raymond Byrne
- Todd Olinsky-Paul – Project Director for CSEA and CEG.
- MMWEC - Market Analysis
- Scott Reynolds, OPM and Mike Barrett, PLM, Design Engineering
- Jared Carpenter, Jim Frawley-Grant Technical Information



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State Regulatory Efforts

REBECCA O'NEIL, PATRICK BALDUCCI, ALAN COOKE, KENDALL MONGIRD

Energy and Environment Directorate

OE Energy Storage Program Peer Review

October 9-10, 2017



State Regulatory Policy: Why It Matters

- ▶ Policy development is taking place at federal, state, and local (utility) levels, but leadership is at the state level

- ▶ What is the policy basis for storage?
 - Completely different kind of resource
 - Need for flexibility in the power system
 - “Fit” with traditional operating paradigm
 - Customer advocacy
 - Economic development and technology industry growth
 - Enabling technology for clean energy
 - Resiliency and grid independence
 - Natural next step for emerging delivery models



State Drivers for Storage

- ▶ New revolution in state regulatory engagement in energy storage
 - Closely connected to distribution system planning, resiliency, and grid modernization
 - Value stacking and co-optimization are essential, which do not fit traditional resource planning and modeling paradigms
 - Customers and stakeholder-driven agendas with legislation increasingly common
 - Cost declines make storage more competitive with alternatives

- ▶ Storage has the potential to fit the utility business model – an owned asset that meets the regulatory compact



State Regulatory Approach

- ▶ Equitable Regulatory Environment topic (OE Energy Storage Program strategy *Grid Energy Storage*, December 2013)
- ▶ Objectives
 - Expand the technical capacity of states interested in engaging with storage in ground-breaking ways
 - Share best practices and principles
 - Support more informed regulatory outcomes
- ▶ FY17 Projects
 1. Partnership with the Oregon Public Utilities Commission (Oregon PUC) and Washington Utilities and Transportation Commission (Washington UTC)
 2. Valuation Handbook (initiated FY17)
 3. Salt Lake Seminar (initiated FY17)



Oregon Overview

- ▶ Oregon energy storage requirement
 - Oregon legislature passed HB 2193 in 2015 session
 - Directs Oregon commission to create procurement guidelines for storage by 2017 and for utilities to propose projects that meet those guidelines.
 - Required to propose storage but not necessarily to build: Commission can determine that proposals are not acceptable
 - Capacity/energy terminology in law: projects should have “the capacity to store at least five megawatt-hours of energy” but constitute no greater than 1 percent of peak load (38 MW PGE; 26 MW PacifiCorp)
 - Oregon commission set procurement guidelines in March 2017 and draft project proposals are due by December 2017.
 - Utilities must also provide the commission with a “system evaluation” to determine what storage is appropriate for the system. Utilities submitted draft evaluations in July 2017.



Oregon Use Cases for Benefit Stacking

Category	Service	Value
Bulk Energy	Capacity or Resource Adequacy	The ESS is dispatched during peak demand events to supply energy and shave peak energy demand. The ESS reduces the need for new peaking power plants.
	Energy arbitrage	Trading in the wholesale energy markets by buying energy during low-price periods and selling it during high-price periods.
Ancillary Services	Regulation	An ESS operator responds to an area control error in order to provide a corrective response to all or a segment portion of a control area.
	Load Following	Regulation of the power output of an ESS within a prescribed area in response to changes in system frequency, tie line loading, or the relation of these to each other, so as to maintain the scheduled system frequency and/or established interchange with other areas within predetermined limits.
	Spin/Non-spin Reserve	Spinning reserve represents capacity that is online and capable of synchronizing to the grid within 10 minutes. Non-spin reserve is offline generation capable of being brought onto the grid and synchronized to it within 30 minutes.
	Voltage Support	Voltage support consists of providing reactive power onto the grid in order to maintain a desired voltage level.
	Black Start Service	Black start service is the ability of a generating unit to start without an outside electrical supply. Black start service is necessary to help ensure the reliable restoration of the grid following a blackout.
Transmission Services	Transmission Congestion Relief	Use of an ESS to store energy when the transmission system is uncongested and provide relief during hours of high congestion.
	Transmission Upgrade Deferral	Use of an ESS to reduce loading on a specific portion of the transmission system, thus delaying the need to upgrade the transmission system to accommodate load growth or regulate voltage or avoiding the purchase of additional transmission rights from third-party transmission providers.
Distribution Services	Distribution Upgrade Deferral	Use of an ESS to reduce loading on a specific portion of the distribution system, thus delaying the need to upgrade the distribution system to accommodate load growth or regulate voltage.
	Volt-VAR Control	In electric power transmission and distribution, volt-ampere reactive (VAR) is a unit used to measure reactive power in an AC electric power system. VAR control manages the reactive power, usually attempting to get a power factor near unity (1).
	Outage Mitigation	Outage mitigation refers to the use of an ESS to reduce or eliminate the costs associated with power outages to utilities.
	Distribution Congestion Relief	Use of an ESS to store energy when the distribution system is uncongested and provide relief during hours of high congestion.
Customer Energy Mgmt Services	Power Reliability	Power reliability refers to the use of an ESS to reduce or eliminate power outages to utility customers.
	Time-of-Use Charge Reduction	Reducing customer charges for electric energy when the price is specific to the time (season, day of week, time-of-day) when the energy is purchased.
	Demand Charge Reduction	Use of an ESS to reduce the maximum power draw by electric load in order to avoid peak demand charges.

Source: Modified from Akhil et al. 2015.



Partnership with the Oregon PUC

- ▶ Memorandum of Understanding signed December 15, 2016
- ▶ Areas of Cooperation
 - Use cases and services derivation; calculation methodologies; review of system benefit analysis.
 - Technology capability validation.
 - Staff support, subject matter expert for sound policy development.
- ▶ **Key Results:** Informed multiple Staff memos, earning quick ALJ and Commission approvals; system evaluations and project proposals will drive storage modeling advances; Staff empowered to engage in secondary storage actions, e.g. planning and procurement guidelines
- ▶ **Docket Status (UM 1751)**
 - Staff Recommendations on Draft System Evaluations Submitted to Commission
 - Draft Project Proposals due January 1, 2018

- ▶ Washington commission issued a draft policy statement in March 2017
- ▶ Built on years of utility analysis, staff white paper, and public workshops

Service Date: March 6, 2017

**BEFORE THE WASHINGTON STATE
UTILITIES AND TRANSPORTATION COMMISSION**

In the Matter of the Washington
Utilities and Transportation
Commission's Investigation into
Energy Storage Technologies.

DOCKETS UE-151069 AND U-161024

DRAFT REPORT AND POLICY
STATEMENT ON TREATMENT OF
ENERGY STORAGE TECHNOLOGIES
IN INTEGRATED RESOURCE
PLANNING AND RESOURCE
ACQUISITION

I. INTRODUCTION AND PROCEDURAL BACKGROUND

- 1 On May 18, 2015, regulatory staff of the Washington Utilities and Transportation Commission (Commission) initiated a staff investigation into the role of energy storage in electric utility planning and procurement.¹ Commission Staff (Staff) initiated the investigation based on a Staff white paper that identified barriers to energy storage created by the way that Washington's investor-owned utilities modeled such technologies

UTC Draft Policy Statement

Key Recommendations



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- ▶ **Establishes energy storage as Commission policy.** “It is the policy of this Commission that energy storage is a key enabling technology for utilities to comply with the state’s energy policies, and that Washington’s investor-owned utilities should be diligently working to identify and pursue cost-effective opportunities to incorporate energy storage into their systems.”
- ▶ **Utilities must evaluate storage in order to make a major investment.** Utilities seeking a prudence determination (the usual pre-requisite for seeking rate recovery for an investment) “must be able to demonstrate that their analysis of resource options included a storage alternative.”
- ▶ **Encourages transparency of data and for utilities to procure storage systems competitively.** This is a nod to third-party ownership and an interest in increasing visibility and creating more methodological consistency in estimating the value of ancillary services within vertically integrated utilities.
- ▶ **Directs utilities to consider a range of storage technologies, and to use learning curves, or reducing cost curves, when estimating storage in the future.**
- ▶ **Directs utilities to transition to sub-hourly models for future IRPs, and adopts a “net cost” approach in the interim.**



Partnership with the Washington UTC

- ▶ MOU signed March 4, 2017
- ▶ Areas of Cooperation
 - Record analysis and development.
 - Modeling approach
 - Drafting consultation and publication.
- ▶ **Key Results:** Timely and credible delivery of storage technology information; advisory role in weighing the merits of multiple approaches in a draft policy statement; continuous updates and engagement to facilitate final policy statement development.
- ▶ **Status:** Final Policy Statement anticipated in 2017.



Valuation Handbook

- ▶ Aggregates collection of work in FY17
 - National review of IRPs for cost estimates, modeling practices, and portfolio selection
 - Evolved practice of project, utility and system valuation
- ▶ Proposed publication in FY18
 - Supports a collective understanding of current practices and establishes principles for future practices
 - Instructive case studies and infographics
 - Broad review of state of practice in utility and market proceedings, including planning, procurement, and rate recovery



Salt Lake Seminar

- ▶ Scheduled for November 8, 2017 at the Western Electricity Coordinating Council's offices in Salt Lake City, Utah
- ▶ Eight states in the Western Interconnection confirmed, additional invitations pending.
- ▶ Purposes:
 - Stage an educational opportunity tailored to state regulatory commissions
 - Share the OE research program with independent lens
 - Offer states an opportunity to communicate with each other directly
- ▶ Active state dockets related to storage include:
 - Grid Modernization
 - Legislated Procurement Target
 - PURPA Avoided Cost
 - Exploring Capacity Needs
 - Distribution System Planning
 - Integrated Resource Planning



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Thank you

Rebecca O'Neil
rebecca.oneil@pnnl.gov

Learn more about our research at www.pnnl.gov

GMLC: Secondary Use Energy Storage

Michael Starke, Oak Ridge National Laboratory

October 2017



Supported by the DOE Office of Electricity:

– Dr. Imre Gyuk, Energy Storage Program Manager

Background: Grid Modernization Initiative

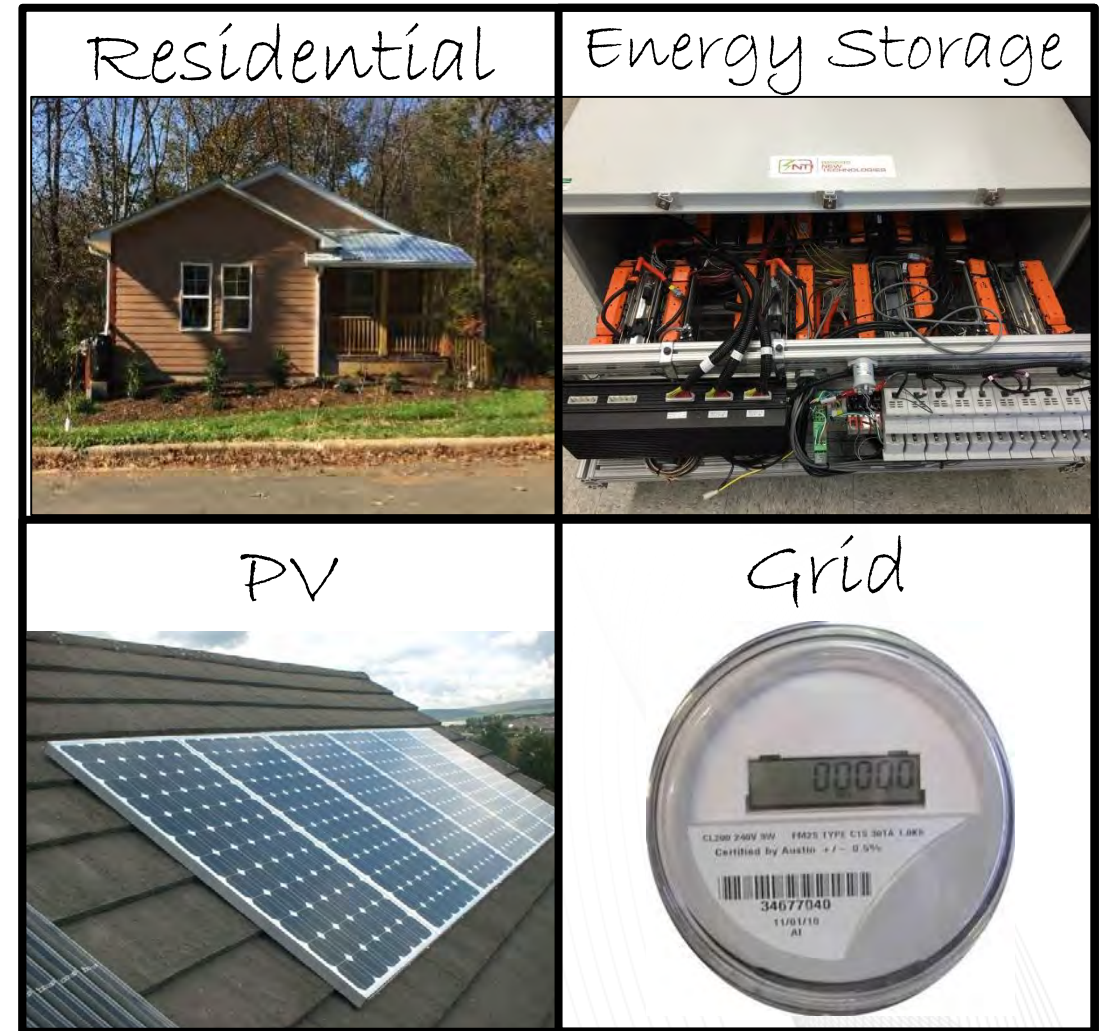
The vision of DOE's Grid Modernization Initiative (GMI) is:

- A future grid that will solve the challenges of seamlessly integrating conventional and renewable sources, storage, and central and distributed generation.
- The future grid as a critical platform for U.S. prosperity, competitiveness, and innovation in a global clean energy economy.
- A future grid that will deliver **resilient, reliable, flexible, secure, sustainable, and affordable** electricity to consumers where they want it, when they want it, how they want it.



Project Objectives

- General Project Objectives:
 - Broadening the customer base with a low cost energy storage solution.
 - Integrated energy system to increase value of storage.
 - Overcoming secondary-use energy storage challenges.
- Three year Project
- Current Project Deliverable:
 - Initial Prototype with Testing Plan



Why Secondary Use?



What do we do with vehicle batteries once the vehicle is retired?

Reuse?



Repurpose?



Where to next?

Recycle?



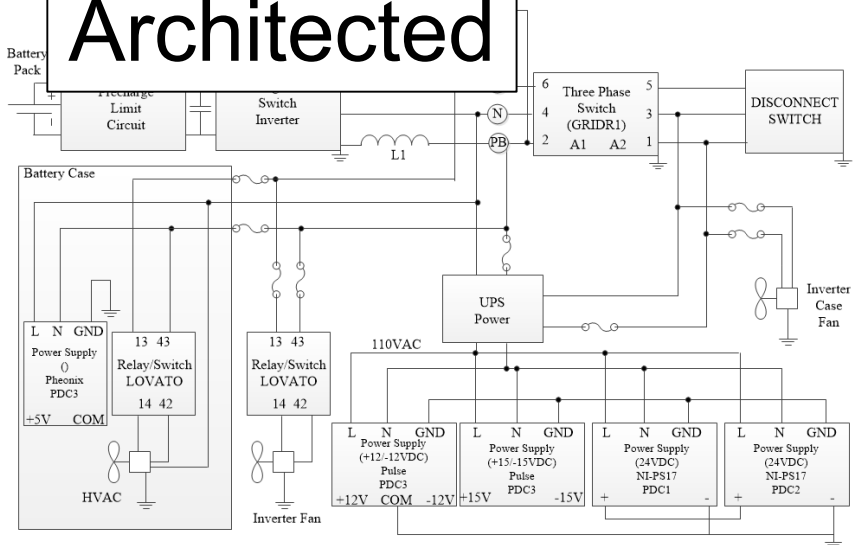
Approach

September 2016

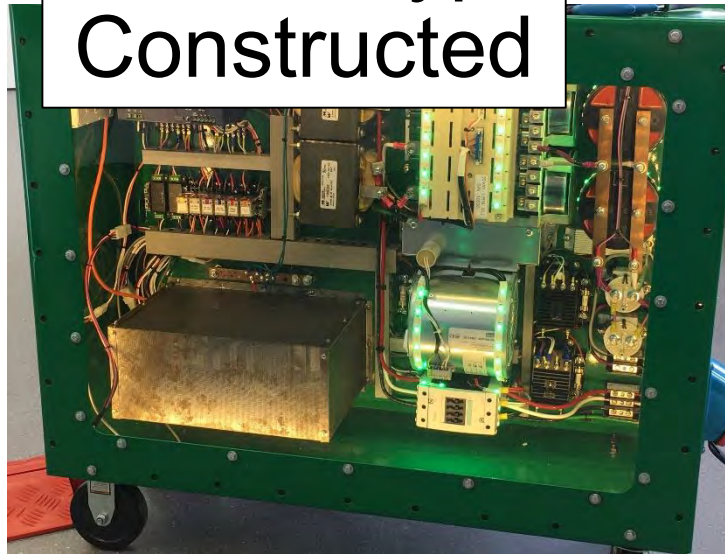
Goal: Prototype system to identify potential challenges with final system design

September 2017

Design Architected



1st Prototype Constructed



Test Plan Ready

Table 2: Test set point conditions

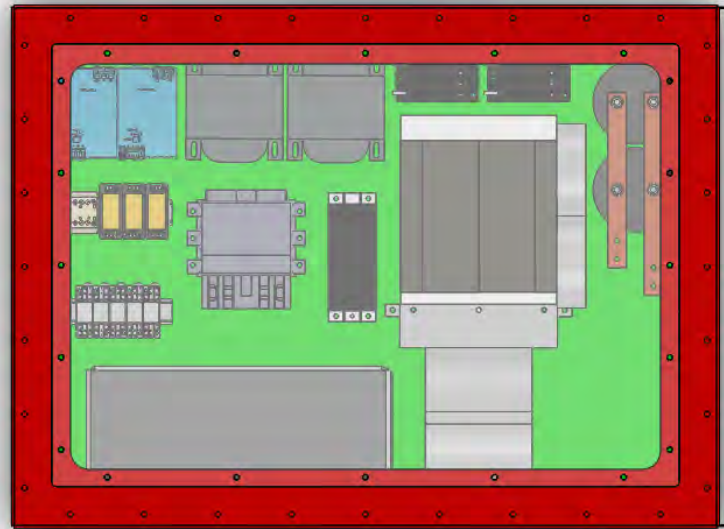
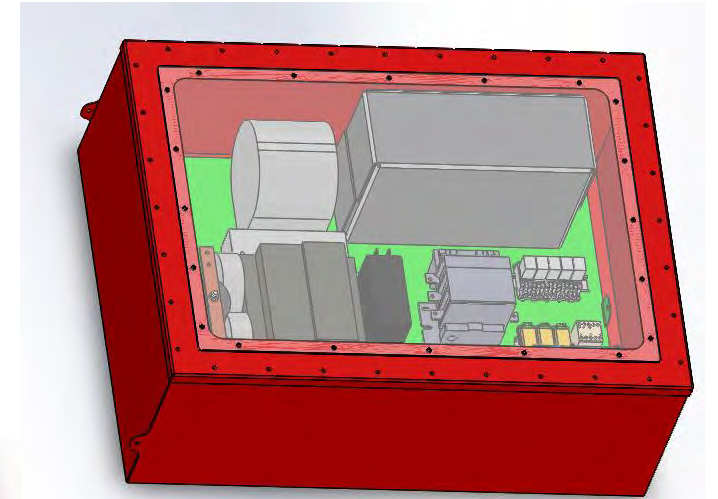
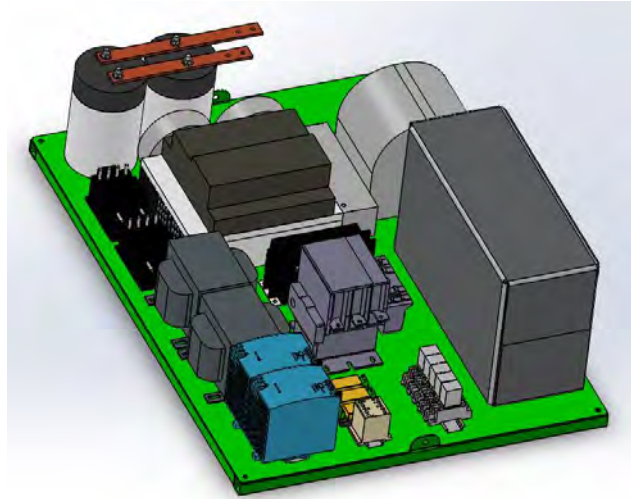
Real Power	Reactive Power
1 kW	0.5 kVAR
2 kW	0.8 kVAR
5 kW	1.5 kVAR
10 kW	2.5 kVAR
15 kW	3.5 kVAR
20 kW	4.5 kVAR

Table 3: Test set point conditions

Real Power	Reactive Power
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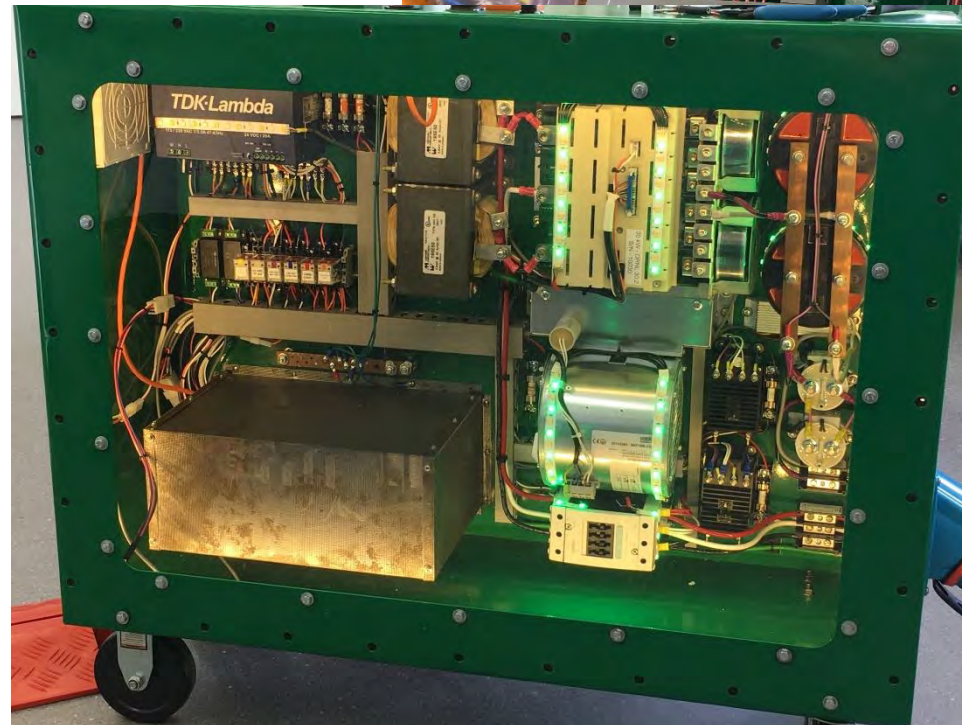
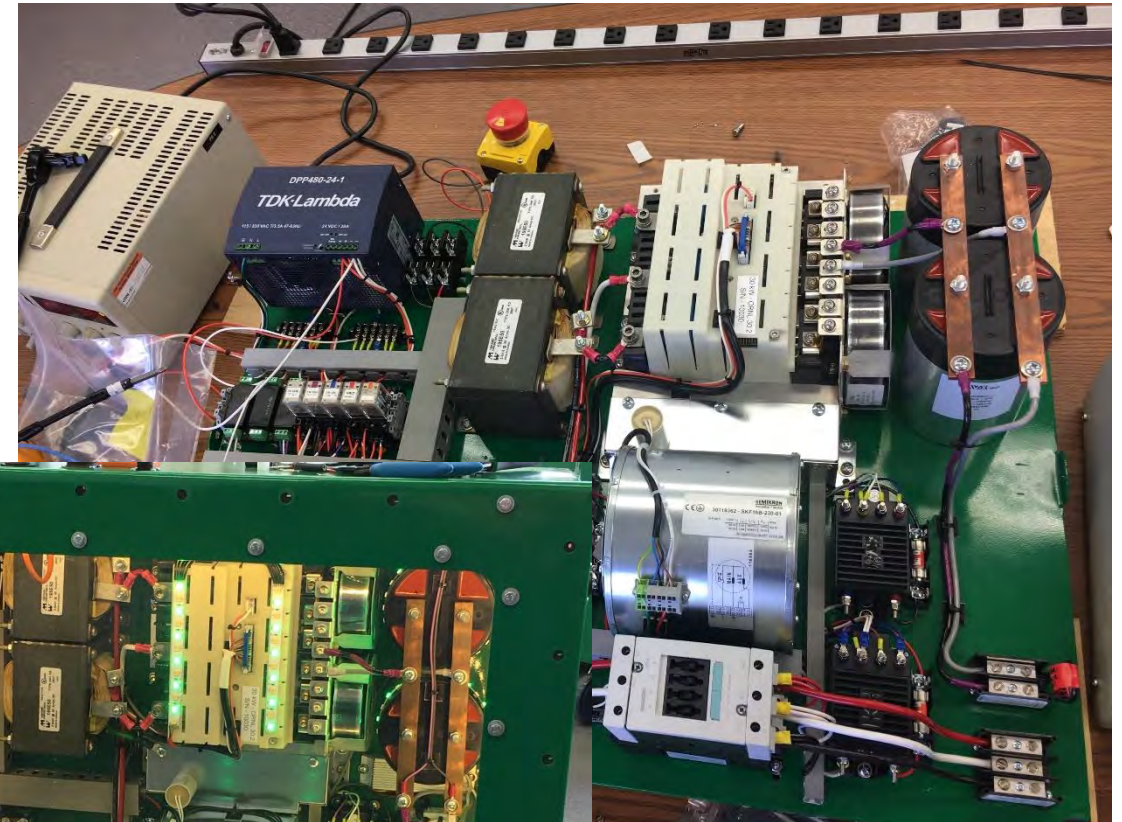
Power Conditioning System Design

- Previous year:
 - Use cases included energy arbitrage, demand charge, and resiliency
 - Sized according to use cases
 - Published Conference Paper
- CAD was used to layout and design power conditioning system based on previous year schematics
- Designed to match the battery system in form factor.



Power Conditioning System Construction

Task	Feb 27 – Mar 3					Mar 6-10					Mar 13-17					Mar 20-24				Mar 27-31				
	27	28	1	2	3	6	7	8	9	10	13	14	15	16	17	20	21	22	23	24	27	28	29	30
Final Layout of Components																								
Drill/Mount Components																								
Wire Power Supplies / Test Power On																								
Wire Agile Interface Board / Comms Test																								
Wire relay controls/ test relays																								
High Power wiring																								
Move unit to DECC																								
DC Link testing (power, contactor, measurements)																								
Grid-side AC measurements																								
Close contactor, inv-side AC measurements																								
Push power to load bank from DC pwr supply																								
Push power to load bank from battery																								
Pull power from grid to battery																								
Capture data from testing																								
Compile presentation for GMLC Y1																								



- Schedule was constructed and testing of hardware is performed on each stage of construction.
- Preliminary non-battery testing of functions completed

Battery System Construction

- Built by partner Spiers New Technologies
- Composed of Graded Nissan Leaf Batteries
- Emergency systems integrated
- System tested at SNT before delivery with basic self protection and control systems.



Failure Mode Effects Analysis (FMEA)

- In-depth study of all possible failure modes for the system was completed
- Asked three major questions:
 - What can go wrong?
 - How does the system automatically respond to this failure?
 - What happens if the system fails to properly respond to the failure?
- Rated results on a “likelihood vs. risk” square to ensure that overall risk stayed low and safe

Node: A		Node Description: Inverter Container						
Drawing(s): Mechanical and Electrical					Session Date: 5/19/2017			
Node Intended Operating Parameters: Start-up, push energy to grid, pull energy from grid, idle, shutdown								
Nominal Temperature: Up to 50C		Nominal Pressure: N/A		Nominal Flow: N/A				
Other: Nominal AC voltage – 240 V _{AC} 1Ø, Nominal DC voltage – 400VDC (324v to 425v)								
Item	Failure	Causes	Consequences	L	S	Risk	Safeguards	Recommendations
A.1.1	Inverter fan does not turn on	Blown fuse, bad relay, mechanical failure	Inverter can exceed 50C operating temperature	O	V	OV	Inverter has overtemp controls, will automatically shut-down	
A.1.2	Inverter fan develops internal short	Wear and tear, mechanical failure	Short across hot phases of 240 V _{AC}	R	L	RL	Inverter fan is fused at 1.5 A on both legs of the 240 V _{AC} power supply	
A.2.1	Case fan does not turn on	Blown fuse, bad relay, mechanical failure	Limited, container operating temp. not critical	O	V	OV		
A.2.2	Case fan develops internal short	Wear and tear, mechanical failure	Short across hot phases of 240 V _{AC}	R	L	RL	Case fan is fused at 1 A on both legs of the 240 V _{AC} power supply	
A.3.1	CRIO does not power on	No power applied from internal 24VDC supply or auxiliary 24VDC supply or CRIO has failed	Unit will not power on, no devices will actuate	R	V	RV	With no control power to the unit, nothing will turn on/work (all contactors are normally open except E-stop)	
A.3.2	CRIO powers on, does not connect/activate controls	CRIO software failure	Unit will not power on, no devices will actuate	R	V	RV	With no control power to the unit, nothing will turn on/work (all contactors are normally open except E-stop)	
A.4.1	Short across inverter AC terminals (while running or idle)	Metal debris, impact to container, loose wire	Dead-short from p1-n, p2-n, or p3-n, arc, fire	R	H	RH	Inverter has over-current protection controls and will automatically shut-down or there is no gnd reference a	
A.4.2	Short across inverter AC terminals (while starting)	Metal debris, impact to container, loose wire	Dead-short from p1-p2 or p1-n, arc, fire	R	H	RH	Exterior Circuit breaker will sense short and open	
A.4.3	Short across inverter DC terminals (while running or starting)	Metal debris, impact to container, loose wire	Short from DC+ to DC-, arc, fire	R	H	RH	Inverter has under-voltage controls, will automatically shut-down and AC contactor will open. Battery has 100A mid-pack fuse that will blow if the inverter does not automatically shut down	
A.4.4	Inverter control board - does not trigger fault logic	Inverter FPGA freezes, fault settings not set properly	Arc, electrical fire	U	M	UM	100A mid-pack fuse protects DC link from over-current situation. 60A fuse on "grid" disconnect switch	

High (H)	High (H) Rare (R)	High (H) Unlikely (U)	High (H) Occasional (O)	High (H) Frequent (F)
Medium (M)	Medium (M) Rare (R)	Medium (M) Unlikely (U)	Medium (M) Occasional (O)	Medium (M) Frequent (F)
Low (L)	Low (L) Rare (R)	Low (L) Unlikely (U)	Low (L) Occasional (O)	Low (L) Frequent (F)
Very Low (V)	Very Low (V) Rare (R)	Very Low (V) Unlikely (U)	Very Low (V) Occasional (O)	Very Low (V) Frequent (F)
	Rare (R)	Unlikely (U)	Occasional (O)	Frequent (F)

Preliminary Test-Plan Development

- Split into four parts:
 - Low power functionality testing (relays, communications)
 - High power battery-less testing (Open loop to load bank, push to grid, etc)
 - High power testing with battery (full functionality testing at full rated power levels)
 - Use Case Testing – leveraging existing PNNL/Sandia reports

The image shows three overlapping pages from a test plan document. The top page is titled '2 General Testing' and describes testing the inverter and battery system. The middle page is titled '3 Low Power Inverter System Testing' and includes sub-sections for 'Power AUX 24VDC line', 'Network Communications Test', and 'Relay "Click" Test'. The bottom page is titled '4 High Power Inverter System Test' and includes sub-sections for 'Install AC fuses', 'Open-Loop Controls Test', 'Verify AC powered inter', and 'Verify Internal Power Supply'. The right page shows a table of test set-point conditions and a section for 'Grid Connected Testing Discharging Battery'.

Table 2 Test set-point conditions.

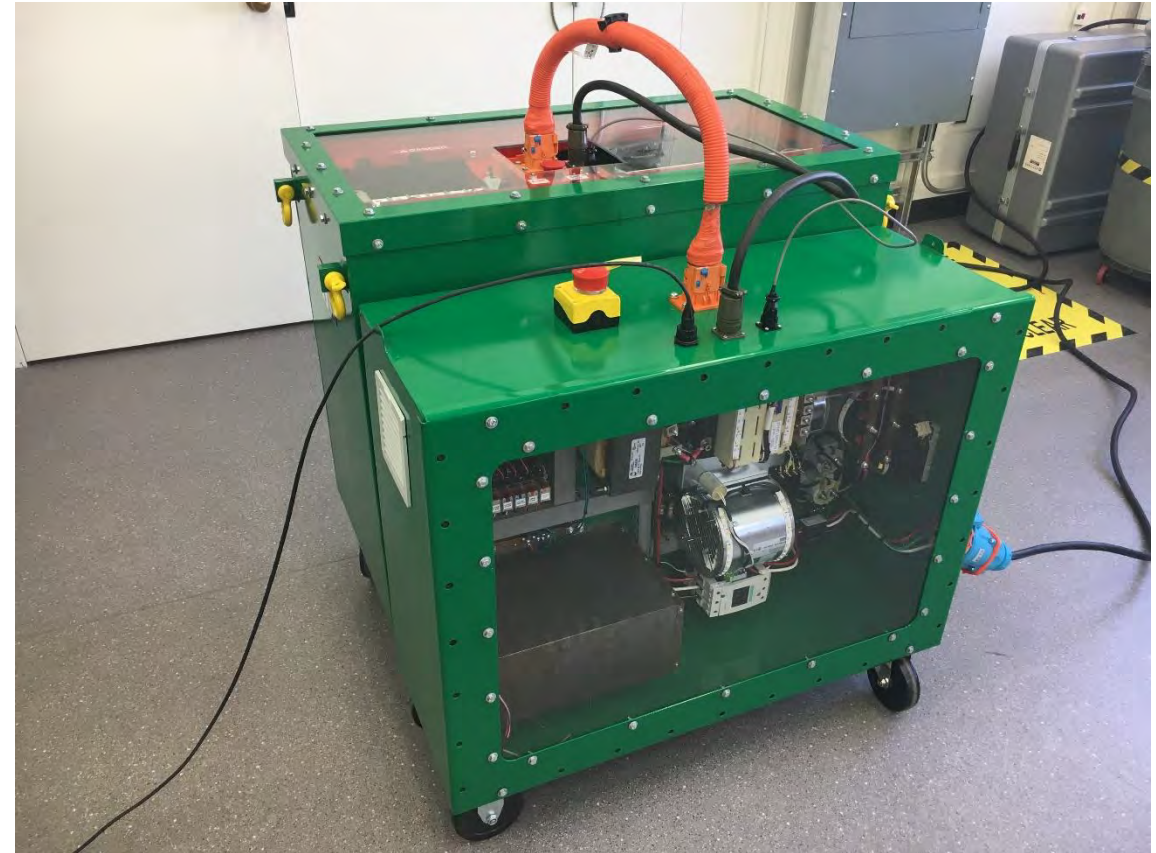
Real Set-point	Reactive- Set-point
1 kW	0 kVar
2 kW	0 kVar
5 kW	0 kVar
10 kW	0 kVar
15 kW	0 kVar
20 kW	0 kVar
1 kW	0.5 kVar
2 kW	1 kVar
5 kW	2.5 kVar
10 kW	4.8 kVar
15 kW	7.5 kVar
20 kW	9.5 kVar

Table 3 Test set-point conditions.

Real Set-point	Reactive- Set-point
Real Power Only	
1 kW	0 kVar
2 kW	0 kVar
5 kW	0 kVar
10 kW	0 kVar
15 kW	0 kVar
20 kW	0 kVar
Real Power Leading PF	
1 kW	0.5 kVar
2 kW	1 kVar
5 kW	2.5 kVar

Battery Functionality Testing

- Inverter connected to battery and Load Bank for testing
- Able to test open-loop and off-grid discharge from DC to AC
- Completed testing of “off-grid” functionality.
- Issue detected on battery system that resulted in inoperable system.
- Began root-cause analysis to determine failure of systems.

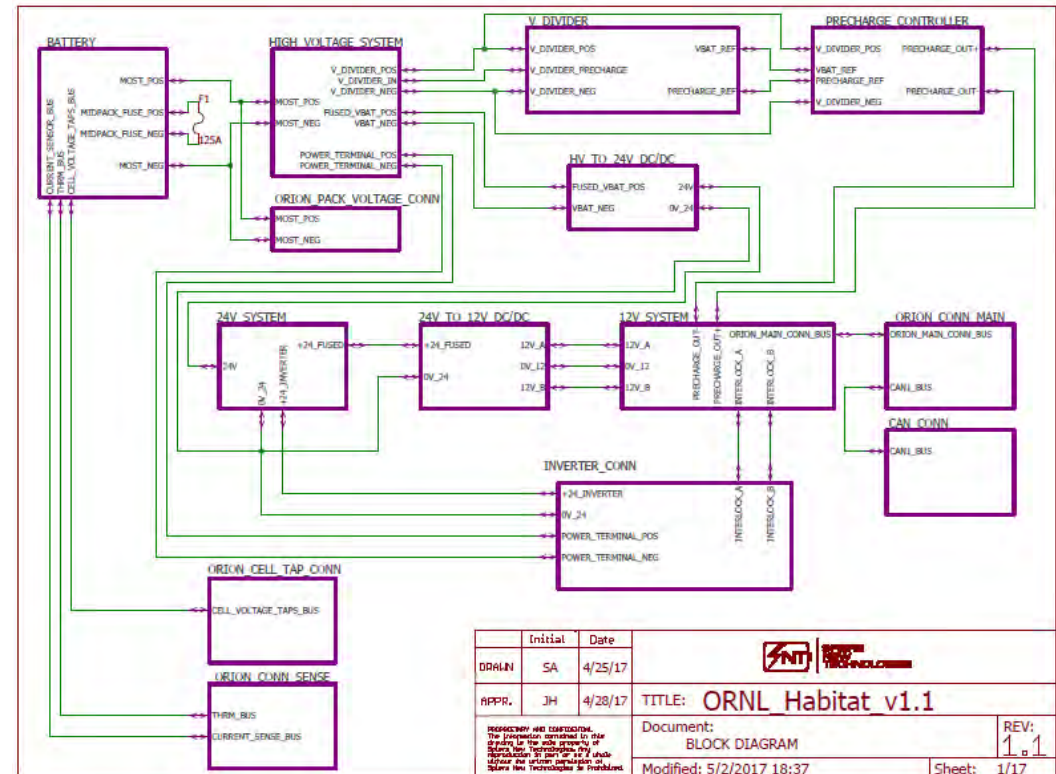


Root-Cause Analysis

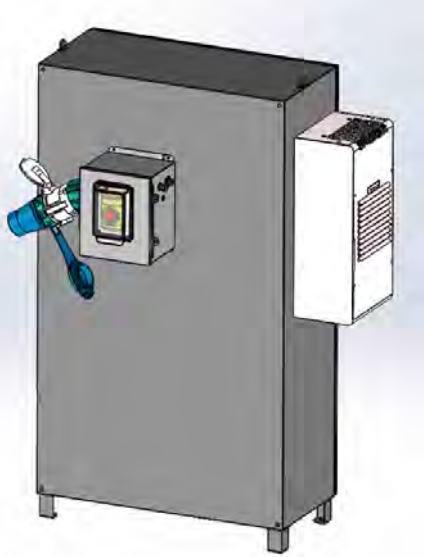
- Once mid-pack fuse was installed, no way to de-energize control circuitry
- Control circuitry predicted to use 4-7 W while idle
- Actually consumed 40-50 W
- Battery voltage dropped to non operational levels
 - DC must meet or exceed minimum level to prevent uncontrolled charging of battery
- Analog circuitry would not allow for charging from DC supply

Table 2 – Interlock Cause and Effect

Interlock Cause & Effect	HV Output and Indicator	High Side Contactor (K1)	Precharge Contactor (K2)	Low Side Contactor (K3)	HV to LV DC/DC Converter	BMS Powered
Mid-Pack Fuse Removed	deactive	open	open	open	deactive	deactive
BMS Controlled Disable	deactive	open	open	open	active	active
Main Cable Interlock Open	deactive	open	open	open	active	active
E-Stop Open	deactive	open	open	open	active	active
Case Switch Open	deactive	open	open	open	active	active
Precharge Unbalanced *	deactive	open	closed	closed	active	active



Battery Prototype v. 1.5



- Battery redesigned to allow controls to power down
- Include contactors with status feedback
- Container redesigned to better handle thermal cycling by including an HVAC for temperature control.
- Controls are able to be bypassed to allow for DC charging of battery
- Currently undergoing testing at SNT

Next Steps

- Begin testing of power conditioning system
- Development of final version of system
- Design and Plan commissioning of system

Acknowledgements and Collaboration

This work is supported by Dr. Imre Gyuk, Manager, Energy Storage Program, Office of Electricity Delivery and Reliability, Department of Energy.

- SNT team for working diligently to meet deadlines and provide updates.
- Habitat for Humanity for being a willing partner on this project



**SPIERS
NEW
TECHNOLOGIES**



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Energy Storage Data Submission Guidelines

Cole Benson

October 10th, 2017



Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Objectives and Future Outlooks

- Standardize data submission
- Faster and more robust data analysis
- Apply these guidelines to our recent ESTP installation
- Test feasibility/refine which data points are useful



This work was generously supported by Dr. Imre Gyuk through the Department of Energy Office of Electricity Delivery and Energy Reliability

GMLC: Use Case and Economic Evaluation of Regional Energy Storage Projects (EPB)

Michael Starke

Oak Ridge National Laboratory



Supported by the DOE Office of Electricity:

– Dr. Imre Gyuk, Energy Storage Program Manager

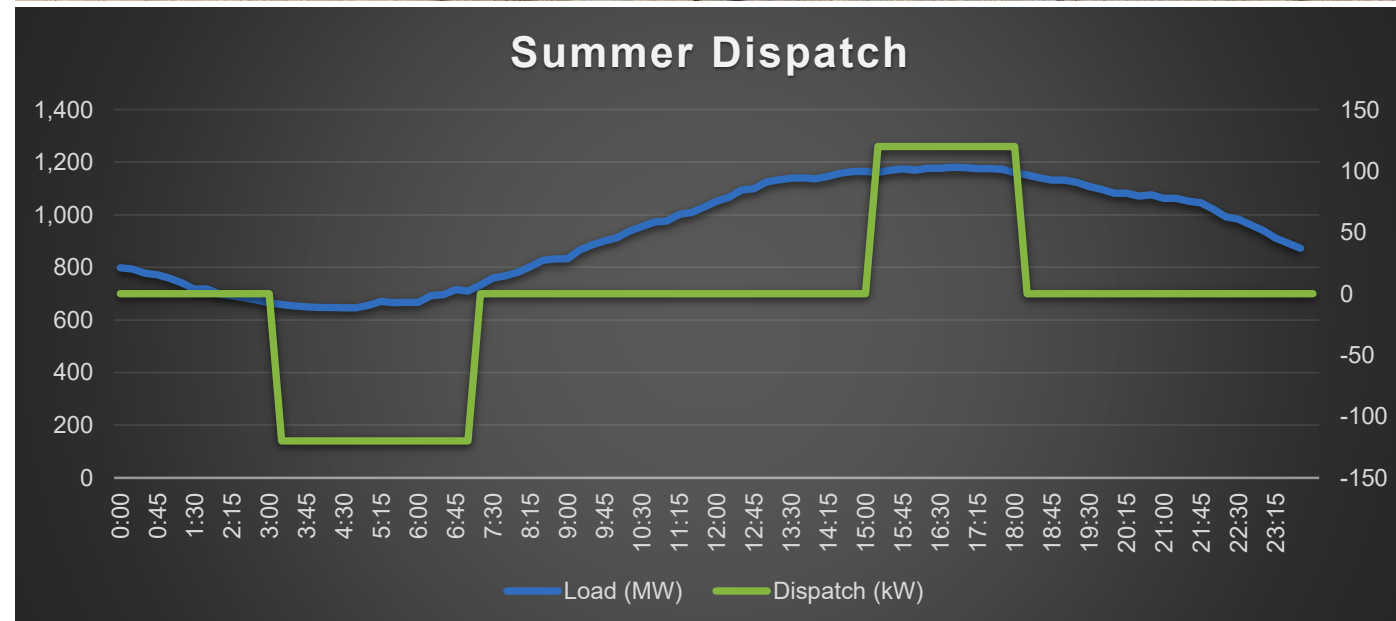
ORNL is managed by UT-Battelle
for the US Department of Energy

GMLC: Use Case and Economic Evaluation of Regional Energy Storage Projects

- ORNL with Sandia and PNNL are providing an
 - system integration support,
 - economic use cases, and
 - testing procedures

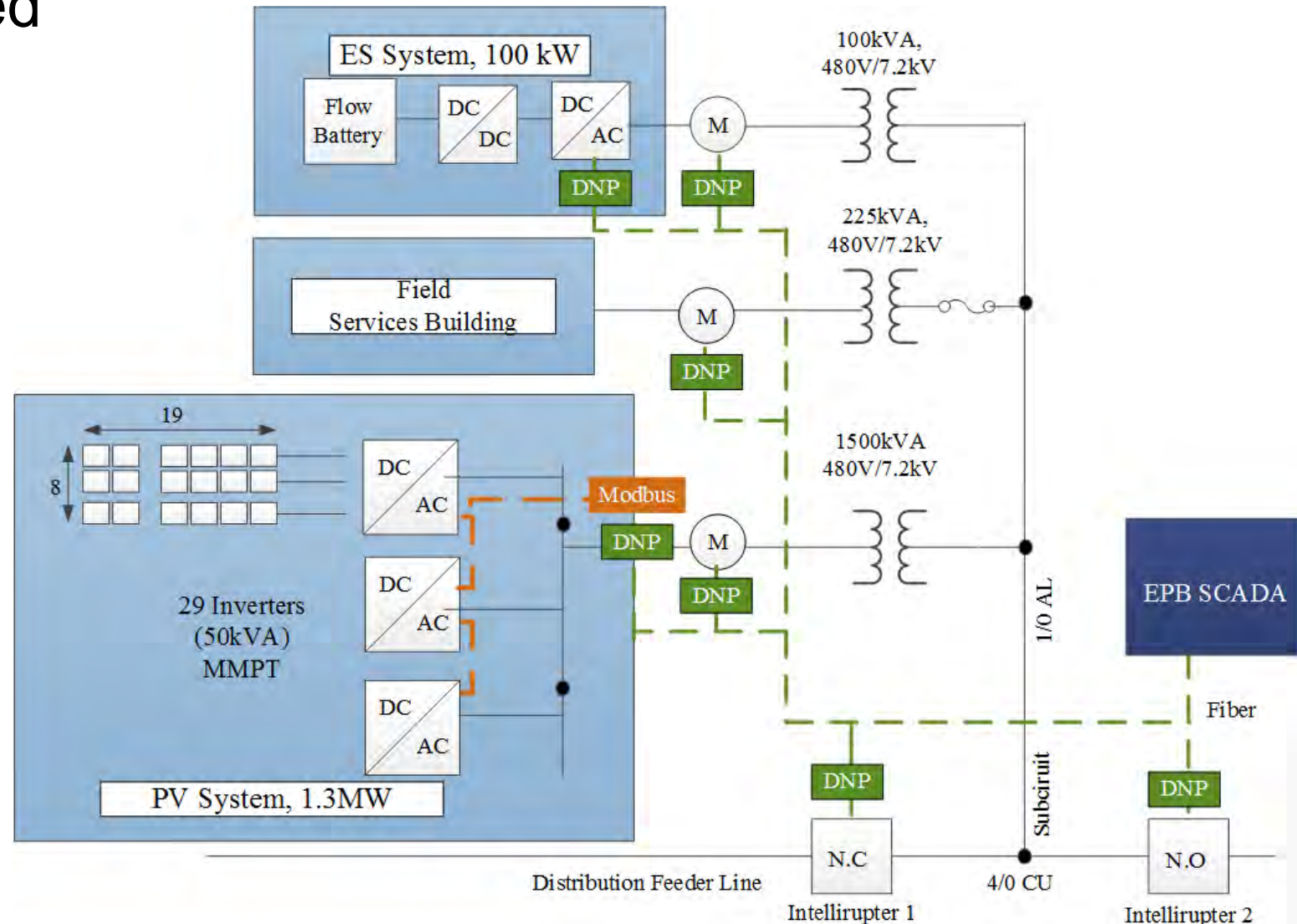
to evaluate a UET
100kW/400kWh flow battery.

- Use cases include: Energy Arbitrage, Peak Management, Reliability, and Solar Integration.



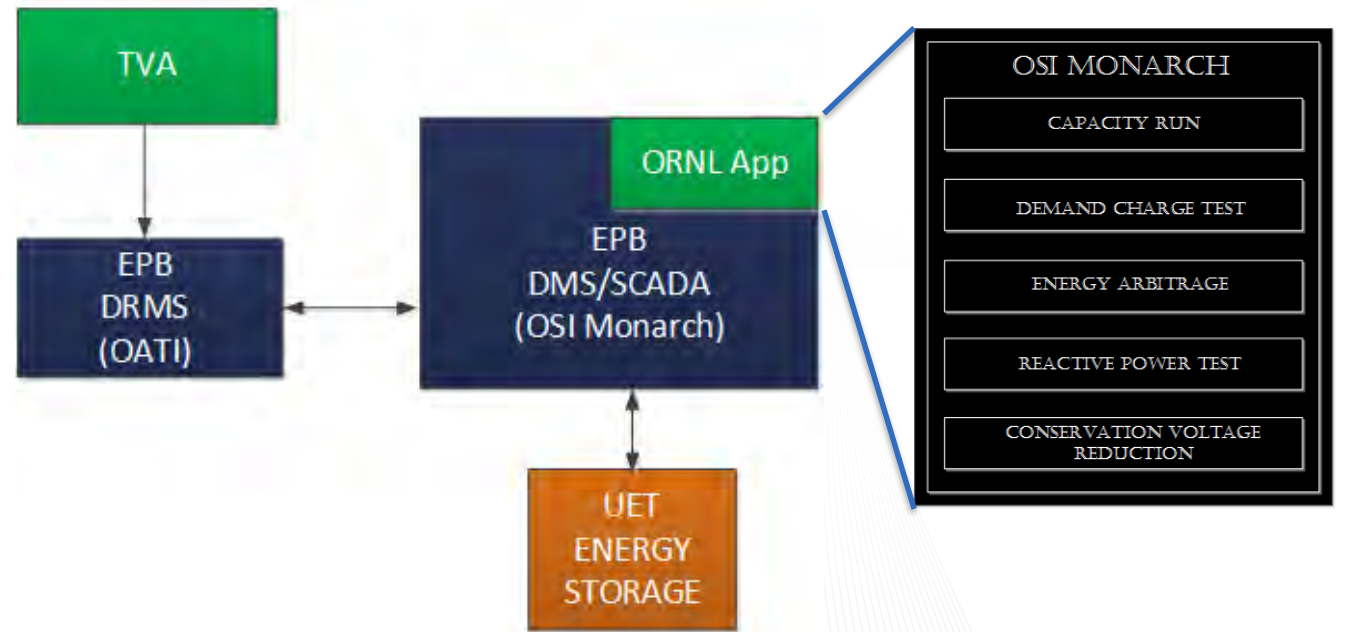
Electric Power Board of Chattanooga System

- EPB has a highly advanced distribution system composed of fiber communications and distributed automation.
- Recently commissioned 1.3MW PV system (July 2017)
- Local EPB building
- Intellirupter technology



Integration of Use Cases

- EPB utilizes OSI Monarch system for their SCADA
- OSI provides programmable interface to access SCADA data.
- ORNL is developing applications in this interface that follow the PNNL test procedures.
- Working with Sandia to replicate and look at new potential use cases.



Acknowledgements

- US DOE Office of Electricity – Dr. Imre Gyuk, Energy Storage Program Manager
- EPB for providing us direct access to their systems
- National Lab Partners, Sandia and PNNL



HOST Park

Hawaii Ocean Science & Technology Park

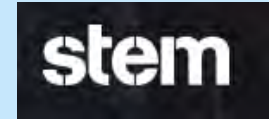
administered by the Natural Energy Laboratory of Hawaii Authority

Peer Review October 10, 2107

Update on the Natural Energy Laboratory of Hawaii Authority ESS Projects

Laurence Sombardier

NELHA Energy Storage System Test Bed



Research Campus Microgrid Development

Grid Scale 100kW UniEnergy Technologies Installation



Value of High Power, Short Duration Energy Storage



Helix Power



EESAT 2017 / DOE Peer Review

San Diego, CA

Matt Lazarewicz, President

| Email: lazarewicz@helixpower.com



Value of High Power, Short Duration Energy Storage

■ Regenerative braking on NYC Transit Trains

- NYC Transit is single largest energy user in NYC – **opportunity**
- Regen Braking in use >30 years–for lower operating cost–**not efficiency**
- 30%-50% reduction in propulsion energy – **untapped**
- Eliminating 350,000 tons of CO2 annually – **untapped**
- Many secondary value streams exist – **untapped**

■ Biggest technical issues - **Manage Heat**

- 125+ cycles/day at + 100% DoD
- Manage high full power cycling
- Different from load shifting application

	Energy Storage Segments		
	Power Mgmt.	Grid Balance	Load Shifting
C-Rate	40	4	0.4
Cycle Life	1,000,000	100,000	10,000



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Portland General Electric (PGE) Storage Analysis

Patrick Balducci
Chief Economist

Other members of the project team: Vish Viswanathan, Di Wu, Jan Alam, Alasdair Crawford, Mark Weimar, Abhishek Somani, Kendall Mongird, and Kevin Whitener (PGE)

2017 US Department of Energy, Energy Storage Peer Review
San Diego, CA
October 10th, 2017



DISCOVERY

in action



PGE Storage Analysis Summary

Problem and Study Objective

- Problem: Capacity constraints and penetration of renewables pose challenges requiring grid flexibility → energy storage
- Objective: Collaborate with states, utilities, and energy storage system (ESS) providers to help elucidate storage benefits and integration challenges, find solutions

Salem Smart Power Center – 5 MW / 1.25 MWh Li-Ion ESS

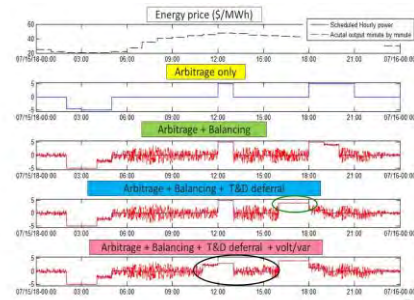
Nine use cases defined at multiple points in grid

Battery Performance Test Results

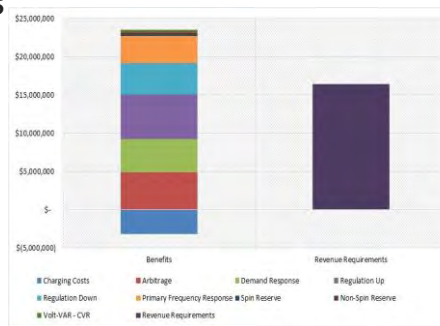
- RTE without counting auxiliary power for the ESS ranged from 78–85%
- The AC power delivered by all ESS blocks was quite uniform
- When operated in a normal manner, ESS took 12–13 seconds to reach rated power; ESS ramp rate was in the range of 67 to 100 percent of rated power in one second when the ESS was set in the special ramp mode

Economic Results

- ESS is currently underutilized, optimal operation could generate an additional \$170,000 in value annually
- Initial ESS design/cost does not generate positive return on investment (ROI); however, a modified design and operation could yield positive ROI
- A small number of power-intensive applications generate significant value over a small number of hours of operation
- ROI maximized at an energy to power ratio of 2.0



Bundling Services



Value of Optimally Bundled Services

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Sandia's Energy Storage Projects Status



Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Projects Status Update



Use Case Test Results for Battery Energy Storage Systems

VILAYANUR VISWANATHAN, MD JAN ALAM, DI WU, PATRICK BALDUCCI, ALASDAIR CRAWFORD, VINCENT SPRENKLE AND MICHAEL KINTNER-MEYER

Pacific Northwest National Laboratory

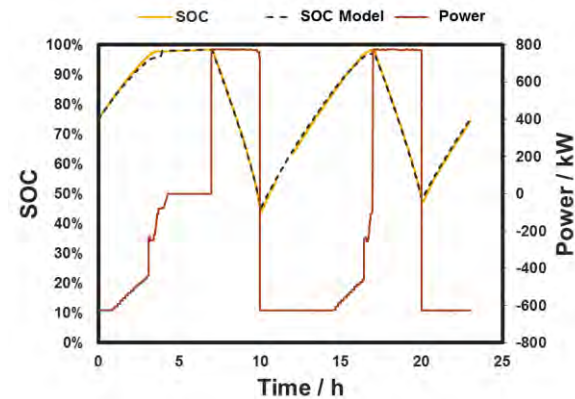
Poster Presentation US DOE-OE Peer Review October 9-10, 2017

The project team gratefully acknowledges the support of the DOE-OE Energy Storage Program managed by Dr. Imre Gyuk.

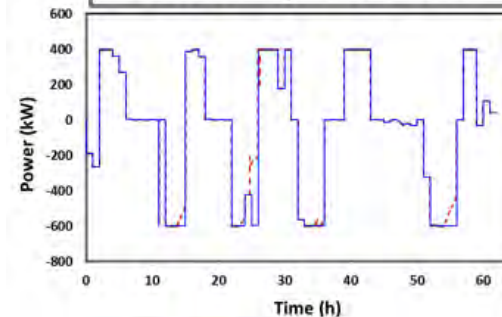
- Battery energy storage system (BESS) integration with the grid is key to increasing grid reliability and penetration of renewables.
- Baseline BESS performance metrics were evaluated using the US DOE-OE Energy Storage Performance Protocol.
- Multiple use cases were conducted to evaluate BESS performance, with performance metrics developed for each use case.
- Data at various levels including power flow at the Power Conversion System (PCS), Auxiliary load, DC battery power flow, DC battery state of charge (SOC), temperature was analyzed.

Results and takeaways

- ▶ A battery model was developed and validated to predict SOC as a function of time at various power levels, temperature and SOC.
- ▶ Incorporation of these findings in economic models allows optimum allocation of the BESS to various services to maximize benefits.
- ▶ Use cases ranged from Arbitrage – non-volatile duty cycle to Frequency Regulation – highly volatile
- ▶ Round Trip Efficiency (RTE) calculated with and without Rest, with and without Auxiliary Load consumption
- ▶ Signal tracking highly dependent on communication latency – RMSE 1% of rated power for one system and 16% of rated power for another
- ▶ RTE for Frequency Regulation 35 to 40% for one system, and 86% for the other.

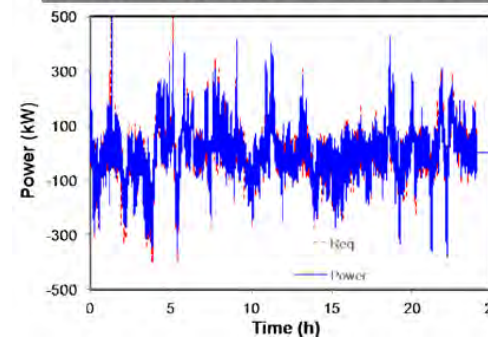


Arbitrage Use Case



RTE 74%
80% w/o Aux

Frequency Regulation Use Case



RMSE 10 kW
Or 1% of
rated power

Optimal Control for Battery Storage Using Nonlinear Models

Di Wu

Pacific Northwest National Laboratory

October 10, 2017



Pacific Northwest
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Introduction

- ▶ Applications of battery storage
 - T&D: energy arbitrage, balancing services, capacity value, distribution system upgrade deferral, outage mitigation
 - Customer-side: energy and demand charge reduction
- ▶ Optimal scheduling
 - Battery models to capture limited power & energy capacity
 - Look-ahead optimization to capture interdependent operation over time
- ▶ Battery models in existing optimal scheduling methods
 - Fixed energy and power rating
 - Constant efficiencies

Abstract

- ▶ Develop nonlinear battery model
 - Varying charging/discharging power & energy rating as a function of SOC
 - SOC change rate as a function of power and SOC
- ▶ Develop optimization using nonlinear model
 - Nonlinear and nonconvex optimization problem
 - Algorithm based on dynamic programming method
- ▶ Case study
 - 1 MW/3.2 MWh vanadium redox battery
 - Energy arbitrage and energy imbalance reduction
- ▶ Conclusion
 - Nonlinear battery model better captures varying power & energy rating and efficiencies
 - Inaccurate battery model could result in significant errors in economic assessment, and even infeasible operation

Green Mountain Power: Significant Revenues from Energy Storage

Dr. Susan Schoenung

Longitude 122 West, Inc.

ESS Peer Review / 2017 EESAT

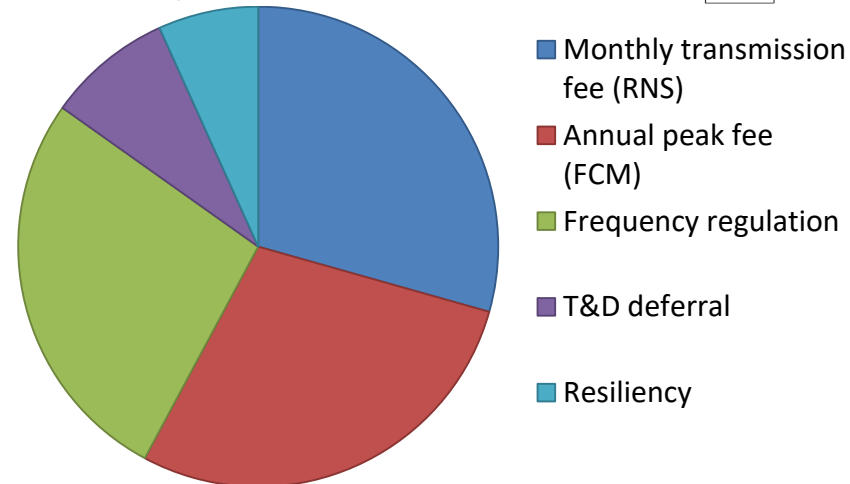
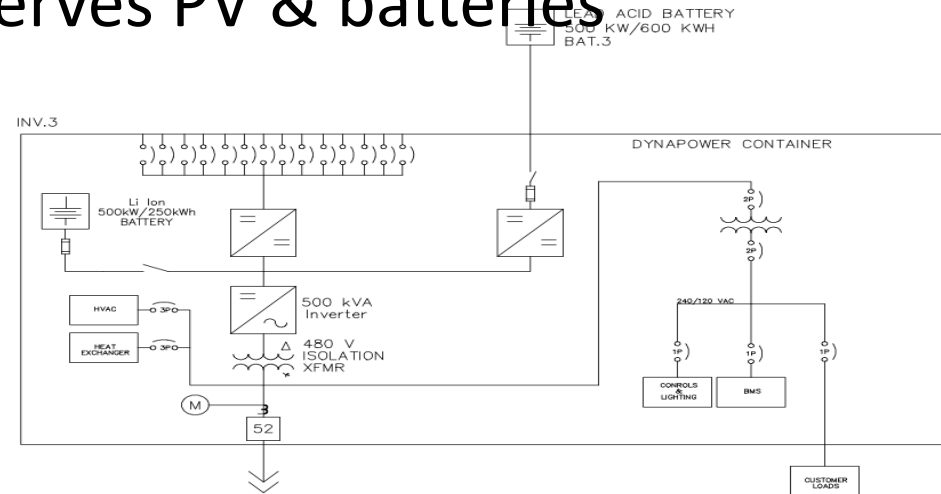
San Diego, CA October 10-11, 2017

With Contributions from Todd Olinksky-Paul (CESA), Ray Byrne and Dan Borneo (Sandia), Josh Castonguay and Dan Belarmino (GMP)

4MW / 3.4 MWh Battery Storage installed for Resiliency

- Objective: to assess and document operation of Energy Storage system at Stafford Hill, VT.
- Operations designed for peak shaving, frequency regulation and islanding.
- Potential benefits / payback period calculated. (~8years)

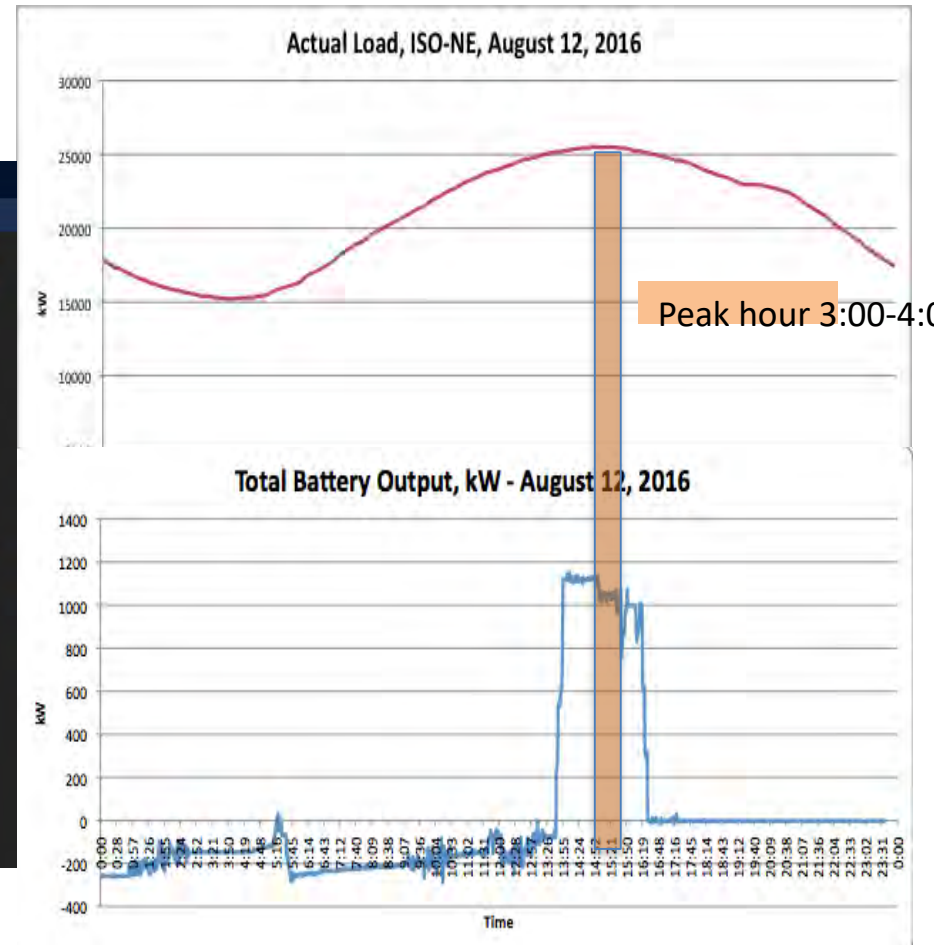
Multi-port inverter topology serves PV & batteries



Current revenues from annual peak, monthly peak, frequency regulation



Frequency regulation using 4 500-MW Li-ion batteries



Shaving the annual peak in 2016

Update on Oregon Energy Storage Demonstration

“Grid Edge” Demonstration

Battery Energy Storage Enhancing Resilience

Project Partners

Sandia National Lab: Dan Borneo

Pacific Northwest National Lab: Patrick Balducci

EWEB: Will Price, Matt Ibaraki

ODOE: Diane Broad

CESA: Todd Olinsky-Paul

Acknowledgement

Funding from US DOE, Dr. Imre Gyuk Energy Storage Program Manager



Grid Edge Energy Storage Demonstration

Enhancing Resilience

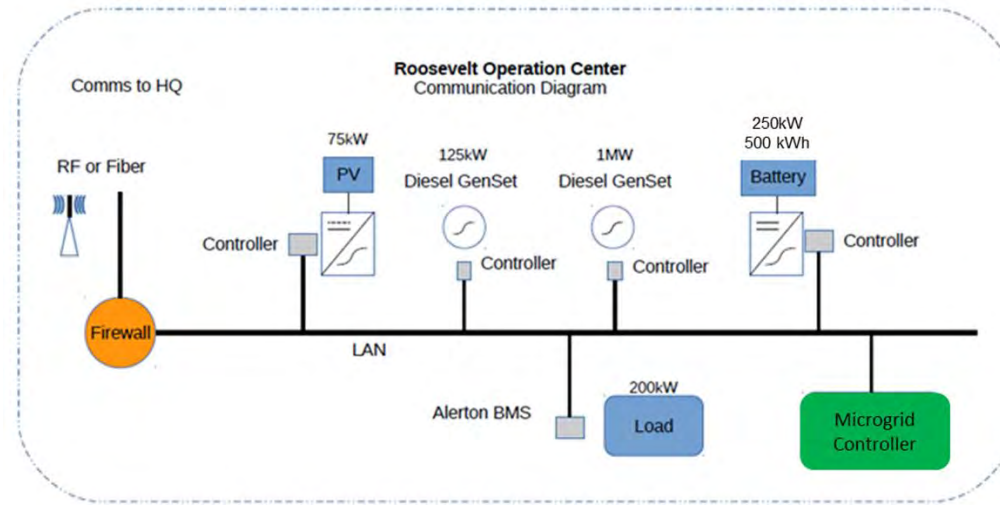
Eugene Water and Electric Board (EWEB) is a consumer-owned utility. The project balances utility needs and community benefits.

10-year Strategic Priorities

- Emergency Preparedness and Disaster Recovery
- Electric Resource Choices

Value Stream Validation

The Pacific Northwest lacks an organized energy market. Stacking energy storage values is essential to gaining wide-spread deployment. The Grid Edge energy storage demonstration started with evaluation of 5 use cases. At this time, 4 additional use cases are being evaluated. EWEB considers the use case with the highest value that can be monetized as the driver for future programs.



Microgrid Optimization

Operation of the energy storage systems will be optimized for maximum value [day-ahead, hour-ahead] as well as energy availability to the sites.

Grid Edge Energy Storage Demonstration

Abstract

Battery energy storage systems, sized at approximately 500 kW, are deployed at two sites with an emphasis on enhancing resilience of the energy and water systems of the utility. The ESS are managed by a microgrid controller that optimizes dispatch and mode considering up to 9 use cases. The use cases span benefits to customers, the distribution utility, and the transmission operator.

The project is located in Oregon, and the utility does not have opportunity to participate in an organized energy market. Some of the use cases are difficult to evaluate and monetize without markets for the system benefits of ESS. One objective for the demonstration is to determine if there is a particular use case that is highly valuable, can be easily monetized, and would result in wide-spread deployment at the utility. Use cases include:

- Peak Demand Reduction / T&D Deferral
- Energy Resiliency / Back-up Power
- Voltage/VAR Support
- Frequency Regulation
- Renewable energy ramping, firming
- Energy Arbitrage
- Outage Mitigation
- Reduction of Transmission Charges (reduction of utility co-incident peak)
- Reduction of Transmission Charges (generation imbalance)

The project sites include renewable energy sources (solar PV), diesel generation and battery energy storage. Optimization of dispatch of the battery and diesel generators depending on availability of solar output and local load is a key outcome.

Diane Broad, P.E. – Diane is a Sr. Policy Analyst at the Oregon Department of Energy where she focuses on grid modernization and integration of renewable energy. Prior to joining the Department, Diane was an engineering consultant serving electric utilities and renewable energy developers. Ms. Broad has a BS in Electrical Engineering from Colorado State University and is a registered Professional Engineer in the State of Oregon.

Will Price – Energy Resource Analyst, Power and Strategic Planning

Will brings 25 years of experience in the electric utility sector, specializing in Research and Development (R&D) projects as foundational proof of concept prior to launching full scale utility programs. He brings over 20 years of experience as an energy management engineer, working with EWEB's commercial and industrial customers. He has a deep level of expertise in controls, measurement and verification (M&V), contracts, and energy systems. Mr. Price holds a Bachelor of Science degree in Physics from Georgetown University, Washington DC.

Matthew Ibaraki, P.E. – Staff Electrical Engineer, Electric Systems Engineering

Matt's 7 years of utility experience comes from working Substation Engineering and Distribution Engineering departments at EWEB. Some of his current responsibilities include managing EWEB's Distribution Analysis Model using CYME, supporting EWEB's electrical SCADA system, providing engineering approvals for residential and commercial solar projects, and managing substation construction projects. Mr. Ibaraki is also a member of the team in charge of rebuilding the City of Eugene's downtown secondary grid.