INL Electrochemical Performance Testing

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Idaho National Laboratory

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Project ID: ES202

Overview

Timeline

- Established in 1985
- Activity On-going

Barriers

- Cost – System Cost
- Performance – Energy, Power
- Reliability and Ruggedness - Vibration
- Life – Performance over time and cycles

Budget

- FY 2015: $3.0M (AES)
- FY 2016: $3.0M (AES)

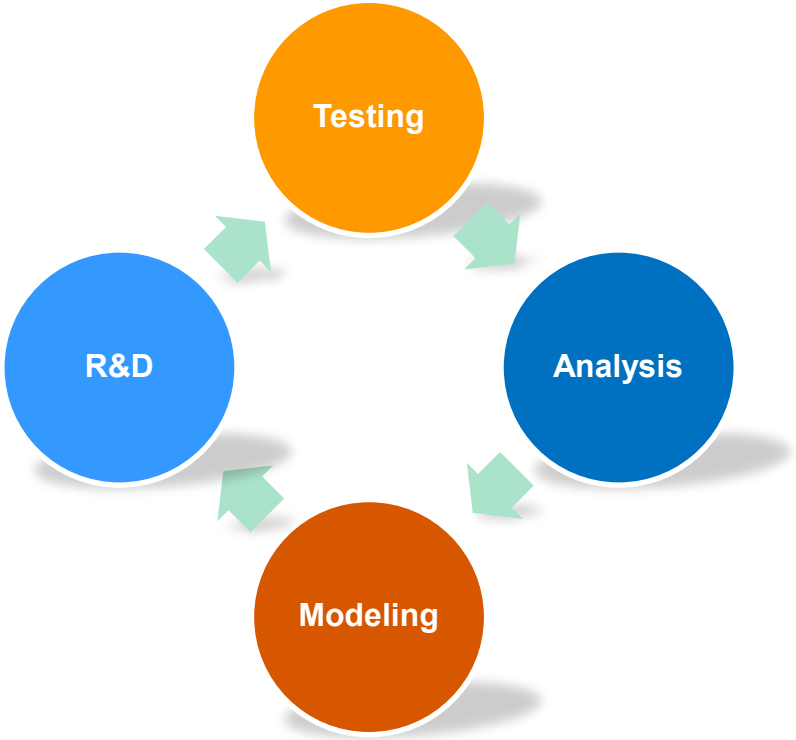
Partners

- U.S. Advanced Battery Consortium
  - FCA Ford General Motors
- U.S. DOE National Labs
  - ANL SNL NREL
- Others
  - AVTA DOT (NHTSA) Private Industry

Relevance

Technical Challenge

- Advanced battery chemistries intended for vehicles are being introduced to the automotive industry at an accelerated rate
  - DOE supported battery research is a major reason for this positive trend
  - Transitioning chemistries from the lab to the consumer often fails due to inadequate testing early in the R&D cycle



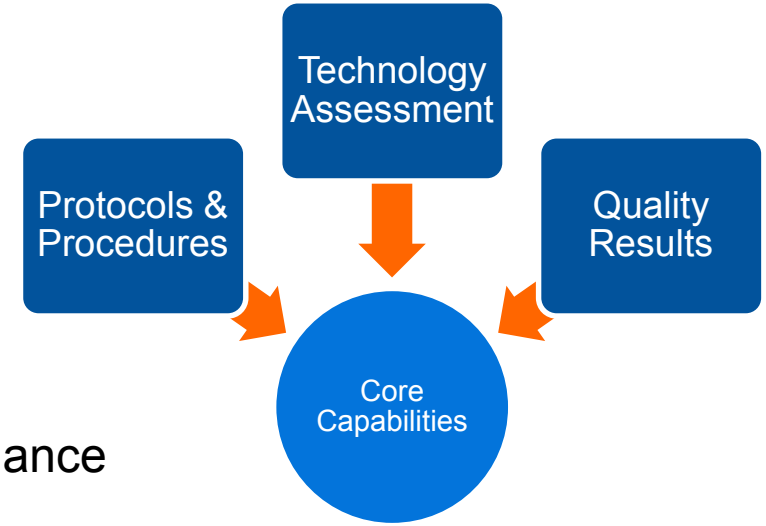
Quality testing/validation/analysis is critical for adoption/success in the market

Relevance

Objective

***Independent**, science-based performance assessment of energy storage devices.*

- Precise environmental control
- Software analysis tools for data analysis and reporting.
- Standards developed for data acquisition, analysis, quality, and management.



- **Protocols & Procedures**
  - Internationally accepted manuals for performance assessment of energy storage systems.
  - **Lead National Laboratory** for technical content and authorship with support from DOE and USABC.
- **Quality Results**
  - Flexible state-of-the-art energy storage test facility capable of supporting current and future development activities.
  - Rigorous NIST traceable calibration procedures for in depth uncertainty analysis
  - Temperature controlled testing for reliable and repeatable results.

Milestones

Year	Program	Description	Status
2015	USABC / DOE	Deliverables testing Q1 quarterly status report	Complete
2015	USABC / DOE	Deliverables testing Q2 quarterly status report	Complete
2015	USABC / DOE	Deliverables testing Q3 quarterly status report	Complete
2015	USABC / DOE	Deliverables testing Q4 quarterly status report	Complete
2015	USABC / DOE	Technology trending (progress and performance) for developer test articles; Report results to USABC and DOE	Complete
2015	USABC / DOE	Conduct feasibility study on low-temperature assessment of rapid impedance measurements; Report to USABC and DOE	Complete
2015	USABC / DOE	Host a Tech-to-Market (T2M) workshop for industry providing tutorials and demonstrations of Electric Drive Vehicle battery performance, testing protocols, and data analysis.	Complete

Milestones

Year	Program	Description	Status
2016	USABC / DOE	Q1 Deliverables testing status report	Complete
2016	USABC / DOE	Q2 Deliverables testing status report	Complete
2016	USABC / DOE	Q3 Deliverables testing status report	On-Track
2016	USABC / DOE	Q3 Report assessing performance of cells before and after vibration testing	On-Track
2016	USABC / DOE	Q4 Annual deliverables testing status report	On-Track
2016	USABC / DOE	Q4 Next generation electrochemical couples report	On-Track

Approach

- **INL Battery Test Center (BTC)**
  - Cell, Module, and Pack Performance and Life Assessment
  - Testing and Analysis Procedures
  - Data Quality Standards

- **Advanced Vehicle Testing Activity (AVTA)**
  - On-Road Demonstration and In-Lab Component Analysis
    - EV, PHEV, and HEV battery pack testing through life

INL Role: Quality Testing and Applied Research

Technical Accomplishments/Progress

- World Class Facilities:
  - Wide range of test equipment allows the Battery Test Center (BTC) to assess the performance of many different deliverable configurations from small cells to modules to full vehicle packs while minimizing uncertainty.
- Data Quality and Procedures:
  - Rigorous calibration procedures improve data quality
  - Standard lab operating procedures reduce setup variability
  - Active members of USABC TAC and workgroups
- Results:
  - Results reported to USABC, DOE and Manufacturers
  - The INL Battery Test Center (BTC) evaluated 461 cells, 12 modules, and 3 packs for a total of 476 articles in FY-15 and FY-16-to-date.
- Performance Science:
  - Understanding system performance based upon the intended environment, application, chemistry.

Technical Accomplishments/Progress

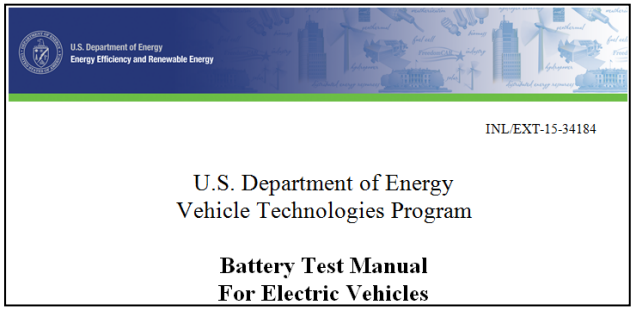
- INL Battery Test Center (BTC)
  - **700** test channels
    - 671 cell level
    - 22 module level
    - 7 pack test channels
  - >100 controllable thermal chambers
  - Vibration test system

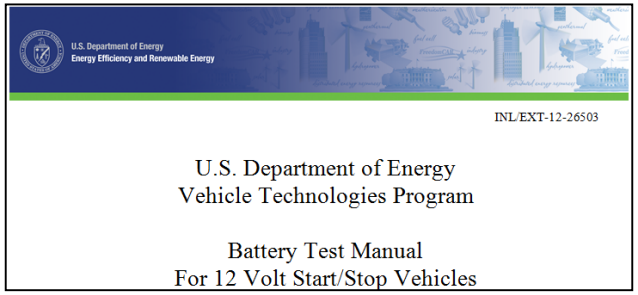
Battery Test Center named DOE Core Capability for Electrochemical Performance Testing

Progress

Test Manuals

- **Published:**
  - Battery Test Manual for Electric Vehicles, Revision 3, June 2015
  - Battery Test Manual for 12V Start/Stop Vehicles, Revision 1, June 2015
- **In progress:**
  - 48-V Manual, Revision 0
- **Noteworthy Item:**
  - Lead National Laboratory for technical content and authorship with support from DOE and USABC.





Internationally referenced and accepted manuals for performance assessment of energy storage systems.

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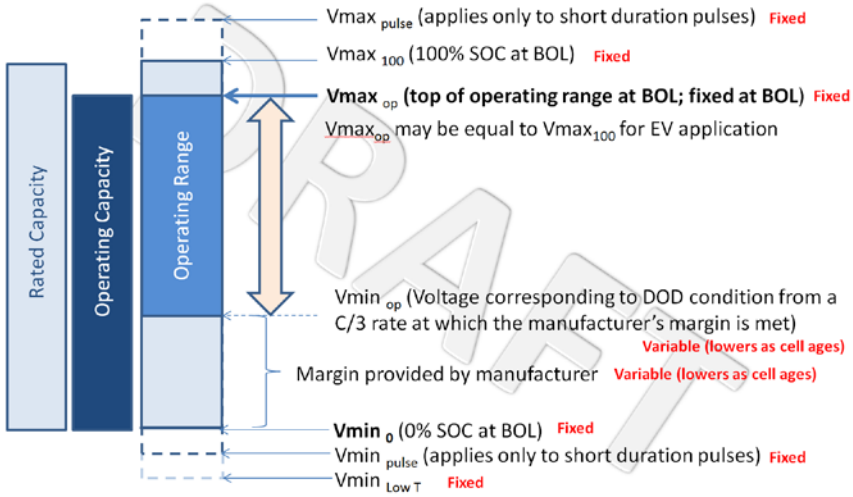
Test Manuals: EV Rev. 3

Notable updates to Battery Test Manual for Electric Vehicles, Revision 3

- Operating range defined
  - Difference allowed between maximum rated and operational voltage limits
- Power capability assessed at energy target through life
- Regen power goal added
- Last revision in 1996
  - Basis for updates and additions to harmonize with other manuals



Manuals harmonized across programs to clarify testing and support similar analysis methods.

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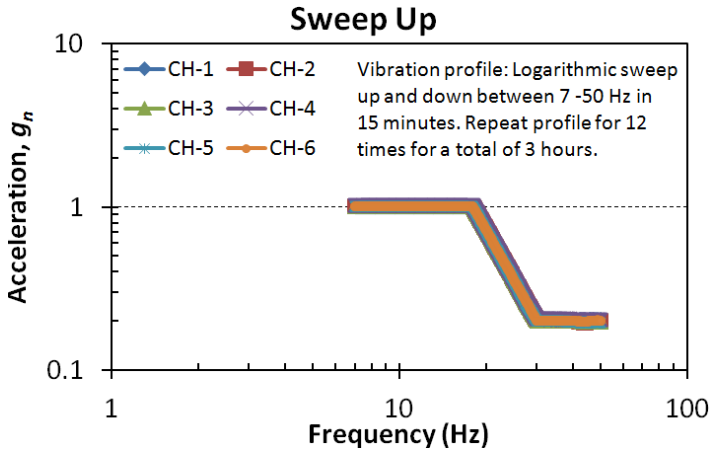
Vibration Testing – Safety

- Commercial EV cells tested under UN ECE-R100 vibration safety test as first live test
- USABC EV cells performed same test
- Open-circuit voltage, and cell temperature monitored
- Pre/Post Vibration capacity, power and EIS tests followed by cycle life aging



Data collected from the vibration-test cells will support a milestone performance assessment report.

Progress

Tech-to-Market Workshop

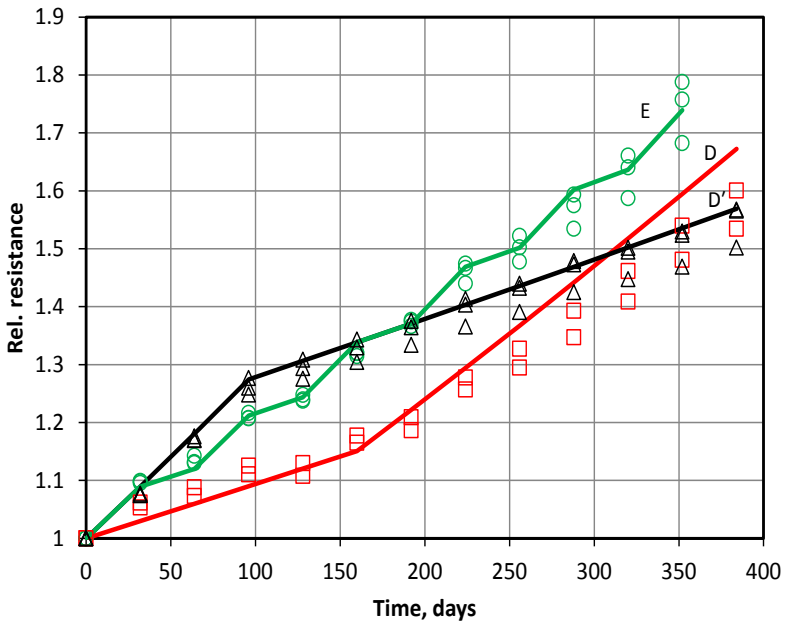
- 30-40 Participants attended the workshop at INL in May, 2015. Attendees included:
  - U.S. OEMs, Battery suppliers, Academia, DOE, National Labs
- Presentations and Tours focused on energy storage topics including:
  - Safety
  - Testing
  - Analysis
  - Best Practices

Industry provided positive feedback on the workshop, which was a 2015 milestone

Progress

Memoryless Aging Study

- Li(Mn,Co,Ni)O2 + Li-Mn-O spinel cathode with graphite anode 18650 cells were aged in groups under thermal conditions ranging from 45-55°C.
- Resistance rise over an interval was attributed to the thermal conditions for that period, and was not found to be affected by the previous temperature condition.
- "*Memoryless Degradation of Lithium-ion Cells under Non-isothermal Conditions*" under review for publication in Journal of Power Sources in collaboration with ANL, SNL, LBNL



Results suggest that the degradation process for resistance under calendar aging for the chemistry tested is essentially memoryless

Progress

FY-15/16- Deliverables Tested: USABC

Manufacturer	Type	Number of Articles	Rating (Ah)	Application	Status
LG CPI	Cell	5	6.0	HEV	Complete
	Cell	5	15	PHEV 10	Ongoing
	Cell	23	60	PHEV 40	Ongoing
	Pack	2	15	PHEV 10	Complete
	Pack	1	60	PHEV 40	Ongoing
	Cell	12	20	12V S/S	Ongoing
Maxwell	Cell	8	1.1	LEESS	Complete
Envia	Cell	6	22	EV	Complete
	Cell	14	21	EV	Complete
K2	Cell	8	45	EV	Complete
Leyden	Cell	13	1.7	EV	Ongoing

Progress

FY-15/16- Deliverables Tested: USABC (continued)

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
Saft	Cell	13	12.5	HEV	Ongoing
	Cell	15	10	12 V Start/Stop	Complete
	Cell	12	10	12 V Start/Stop	Complete
Amprius	Cell	20	2.6	EV	Ongoing

The INL Battery Test Center (BTC) evaluated 157 cells, and 3 packs for USABC in FY-15/16-to-date.

Progress

FY-15/16- Deliverables Tested: DOE Benchmark

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
Axion	Module	12	45	HEV	Complete
Hydro-Quebec	Cell	13	1.0	HEV	Ongoing
EIG	Cell	20	5.0	12 V Start/Stop	Ongoing
Sanyo	Cell	10	1.2	PHEV	Complete
Shandong Wina	Cell	3	50	EV	Complete
LG Chem	Cell	10	25.9	PHEV 40	Ongoing
Toshiba	Cell	4	20	EV	Ongoing
AESC	Cell	8	33.1	EV	Ongoing

The INL Battery Test Center (BTC) evaluated 68 cells and 12 modules for DOE Benchmark in FY-15/16-to-date.

Progress

FY-15/16- Deliverables Tested: DOE FOA-2011

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
Miltec (ANL)	Cell	18	0.1/0.26	PHEV	Ongoing
Nanosys	Cell	16	1.2	PHEV	Complete
	Cell	4	1	EV	Complete
	Cell	4	2.5	EV	Complete
	Cell	4	4	EV	Complete
	Cell	10	60	EV	Complete
Penn State	Cell	16	3	PHEV	Complete
	Cell	24	2	PHEV	Complete
Applied Materials	Cell	44	0.035/0.0042	PHEV	Complete
Amprius	Cell	16	2.3	PHEV	Complete

The INL Battery Test Center (BTC) evaluated 156 cells for DOE FOA-2011 in FY-15/16-to-date.

Progress

FY-15/16- Deliverables Tested: DOE FOA-ARRA

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
Saft	Cell	4	45	EV	Complete
	Cell	4	47	PHEV	Complete
Enerdel	Cell	5	16	PHEV	Complete
LG Chem	Cell	5	47.7	EV	Complete

The INL Battery Test Center (BTC) evaluated 18 cells for DOE FOA-2011 in FY-15/16-to-date.

Progress

FY-15/16- Deliverables Tested: DOE ABR-IC³P

Manufacturer	Type	Quantity	Rating (Ah)	Application	Status
ANL	Cell	12	0.25	EV	Ongoing
ANL	Cell	14	0.447	PHEV	Ongoing
Envia Systems	Cell	12	0.93	PHEV	Ongoing
Farasis	Cell	12	1.6	EV	Complete
Penn State	Cell	12	2.0	EV	Ongoing

The INL Battery Test Center evaluated 62 cells for DOE ABR-IC³P in FY-15/16-to-date.

Progress

FY-15/16 Deliverables Tested: Summary

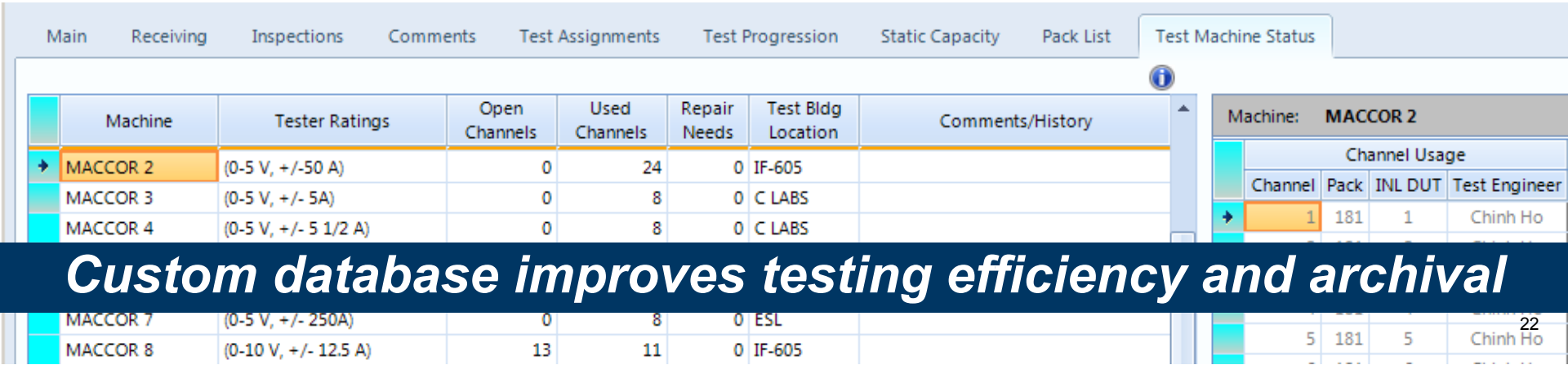
Program	Type	Quantity
USABC	Cell	157
	Pack	3
DOE Benchmark	Cell	68
	Module	12
FOA-2011	Cell	156
FOA-ARRA	Cell	18
ABR-IC^{3}P	Cell	62

The INL Battery Test Center evaluated 461 cells, 12 modules, and 3 packs for a total of 476 articles in FY-15/16-to-date.

Progress

Testing Flow and Data Management Tools

- The number of articles tested present logistical and data challenges
- Database tools developed for tracking testing and data management
  - Track cells from planning stage through testing and return to developer and archive for future reference
  - All test data archived in a secure, redundant location
  - Improve efficiency of tester channel and hardware asset utilization and time-to-test
- Data from multiple test engineers and programs is accessible by PIs for analysis from a single location



Custom database improves testing efficiency and archival

Response to Previous Year Reviewers' Comments

- Reviewer Comment:
  - The reviewer called the publication of manuals and patents impressive, but would have liked to have seen contributions to the peer-reviewed literature and considered that this seemed like a great opportunity to reach the broader public as well, perhaps through collaborative publications with science writers. The reviewer was unsure, however, if that is something DOE requires through this funding mechanism.
- Battery Test Center (BTC) Response:
  - While many of the results generated through testing of USABC development program deliverables are subject to non-disclosure agreements beyond DOE and the USABC, the BTC strives to increase publication in peer-reviewed journals when appropriate. Related work through INL's energy storage performance science focused work will focus on increased scientific publication that can leverage the test methods and analysis techniques that have evolved directly from execution of this program.

Response to Previous Year Reviewers' Comments

- Reviewer Comment:
  - "Unless the funds are used to procure/upgrade equipment, the reviewer said, they seem to be a bit on the high side.
- Battery Test Center (BTC) Response:
  - A portion of annual funds are indeed used to procure and upgrade equipment, along with maintenance of existing hardware. Significant resources are required to maintain 100+ thermal chambers and 700 channels across 43 testers in three labs. This equipment is maintained to the high standards required to produce high quality data with quantifiable certainty.
- Reviewer Comment:
  - "Testing of articles that were used to predict life, the reviewer urged, should be continued as long as possible to generate a robust baseline data set."
- Battery Test Center (BTC) Response:
  - Packs from legacy programs are continued as resources allow through end of life to strengthen the data available to support life modeling. Two sets of cells on test this year have been testing for several years in support of these goals.

Collaboration & Coordination with Other Institutions

- INL and Argonne National Laboratory continue to enjoy a close testing partnership.
  - This collaboration reduces unnecessary duplication and creates valuable overlap of capability where useful.
  - Both labs are conducting parallel experiments to identify and correct gaps in testing technique specifications that can affect variability of results
- INL supplying SNL with aged batteries with known-path histories for additional abuse testing.
- INL is very involved in several USABC activities and works closely with its partners.
  - Technical Advisory Committee (TAC), as well as the Test Methods & Definitions and Internal Short Circuit Work Groups.
- Expanded test capability creates additional opportunities for collaboration with other national labs (ANL, LBNL, SNL, NREL), government agencies, and industry and academic institutions.
  - INL hosted an Interagency Power Group meeting for theEnergy Storage Chemical and Safety Working Groups in September 2015. DOE, DOD, NASA, and other agencies were represented.

Remaining Challenges and Barriers

- Maintaining a flexible state-of-the-art energy storage device testing facility
  - Adapt to shifting targets and emerging technology
  - Continuously update/modify test protocols and analysis procedures
  - Equipment maintenance, repair, and upgrades
- Expanding lab capability for enhanced data assessment through additional equipment and expertise
- Strengthen and expand collaborative ties with existing Vehicle Technologies Office programs at INL, other national laboratories, and industry.
- Strengthening relationships with developers to ensure testing conforms to the needs of unique technologies while maintaining compatibility with USABC procedures.

Proposed Future Work

- USABC testing deliverables
  - Continue testing and analysis for existing deliverables
  - Add new deliverables
- Publish updated and new test manuals
  - 48V
  - LEESS
- Expand lab capabilities
  - Establish mild-abuse facilities and expertise
  - Additional laboratory support for industry and universities (WFOs, etc.)
  - Further develop data management system
- Expand ties with VTO on-road and laboratory testing to validate and enhance modeling capability
- Improve available safety information for first responders and regulators

Summary

- The INL Battery Test Center is the lead DOE laboratory for advanced automotive battery performance testing.
  - 20,000 square feet of lab space with 700 test channels for advanced energy storage testing.
- INL is continuing to support DOE and USABC with science-based performance testing and assessment of candidate battery technologies for various vehicle platform applications.
  - Rigorous NIST traceable calibration procedures provide for in depth uncertainty analysis.
- INL has strong capabilities in advanced battery diagnostics and prognostics for improved state-of-health assessment.
  - On-going research activities in collaboration with DOE, NHTSA, and SNL.
- *The INL Battery Test Center (BTC) evaluated 461 cells, 12 modules, and 3 packs for a total of 476 articles in FY15/16-to-date*

Technical Backup Slides

Equipment

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Tester Mfr.	Tester Capability	# of Testers	# of Channels
Maccor	0-5V, +/- 5A	1	8
Maccor	0-5V, +/- 5.5A	3	152
Maccor	0-10V, +/- 12.5A	3	72
Maccor	0-5V, +/- 25A	2	48
Maccor	0-5V, +/- 30A	1	96
Maccor	0-5V, +/- 50A	1	24
Maccor	0-5V, +/- 60A	6	144
Maccor	0-7V, +/- 90A	2	48
Maccor	0-5V, +/- 100A	1	8
Maccor	0-5V, +/- 180A	1	8
Maccor	0-5V, +/- 250A	6	47
Maccor	0-7V, +/- 250A	1	8
Maccor	0-7V, +/- 300A	1	8
PEC	0-50V, +/- 80A	1	8
Maccor	0-55V, +/- 220A	2	8
Maccor	0-65V, +/- 250A	1	4
Maccor	0-60V, +/- 275A	1	4
Bitrode	0-500V, +/- 350A	3	3
Bitrode	0-1000V, +/- 500A	2	2
Total # of Testers/Channels		39	700