VEHICLE TECHNOLOGIES PROGRAM

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

# DOE Research on Technologies Relating to Electric Vehicle Safety

Meeting of the group on Electrical Vehicle Safety - Global Technical Regulation (EVS-GTR)– Washington, DC, *13--15-May-2014*

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# Outline

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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- Cabin Climate Control
- Grid Integration
- Wireless Power Transfer
- Power Electronics
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  - Age Effects on PEV Charging and ESS
- AVTA Testing Status
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# Executive Summary

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- DOE sponsors research promoting EV Vehicle Safety that addresses a range of issues
- Has experience with EVs at the integrated systems and technology component levels
- Sponsors Investigations of technology related safety issues to include events and formulation of Lessons Learned
- Is actively collecting additional data to address gaps regarding safety issues for existing and emerging EV technologies.

# Office of Vehicle Technologies Program Structure

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- **OVT/PHEV Program Mgmt.**
  - **Industry/Gov't Collaboration**
  - **Technology Assessment**
    - Benchmarking
    - Analytical Studies
    - Risk Assessment
  - **Research & Development**
    - Energy Storage
    - Power Electronics & Electric Motors
    - Engines and Fuels
    - Vehicle Efficiency Technologies
  - **Testing & Validation**
    - Standard Procedures
    - Lab Testing and Validation
    - Field Reliability Testing and Validation
    - Field Testing and Demonstration
  - **Deployment Issues**
    - Grid Interactions
    - Automotive-Utility Industry Interactions
    - Incentives
    - Education and Learning Demonstration
    - Codes & Standards

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# EDV Safety and Cabin Climate Control

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## Challenge

- Climate control usage reduces electric range
- If preference is given to battery cooling or heating, less energy is available for the cabin
  - Hot weather is a battery degradation issue
  - Cold weather is a vehicle performance (battery capacity) issue

## Risks

→ Drivers stranded along a road in a dangerous situation

→ Drivers are uncomfortable and experience vigilance and attentiveness issues

→ Driver turns off climate control system to maximize range and experiences driver vigilance issues as well as increases the risk of fogging or icing impairing visibility

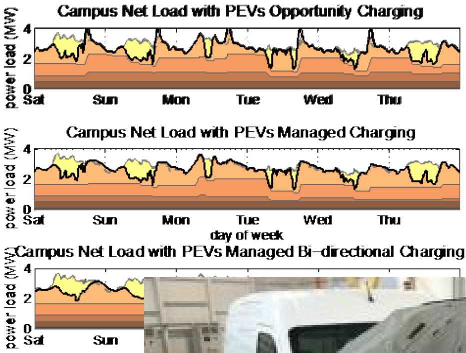
## Technical Objectives

*EV Everywhere* should focus on advanced climate control technologies (passenger comfort and window defrost/ defog) that use less energy to achieve the same level of climate control, allowing for a smaller, less expensive battery

# EDV Safety and Cabin Climate Control



- DOE is working with NREL and the automotive industry to develop solutions
  - Thermally precondition the battery while plugged in
  - Cabin thermal load reduction and higher efficiency climate control systems to reduce climate control energy consumption and increase range
    - Develop new Heating Ventilating and Air Conditioning (HVAC) component models compatible with Autonomie
    - ANL quantified the impact of cabin climate control systems on the energy consumption of a HEV, PHEV, and BEV at different temperature settings and in different ambient temperature environments.(E.g. EPA 5 cycle label fuel economy test conditions
- Two industry projects are focused on developing innovative heating and cooling technologies that reduce battery demands and improve range by 20 to 30 percent (Halla Visteon and Delphi Automotive, FY 2013-16)
- Additional industry projects are pending FOA award process (FY 2014-17)




**Scenario Simulation**


**Tech Development**


**System Confirmation**

V2G system desired benefits,

- ~$2K-$3K/mo of electricity cost reduction
- Improved Renewable Energy micro-grid integration

**5x 60kW Bi-directional Stations Integrated with Micro-grid Operations**

V2G standards under development to address safety risks associated with

Source: Burns &McDonnell

- Connection during outages
- Aiding distribution line stability and recovery
- Heating of components, connectors, & transmission lines during high power transfer
- Increased security vulnerabilities due to communications with electric grid

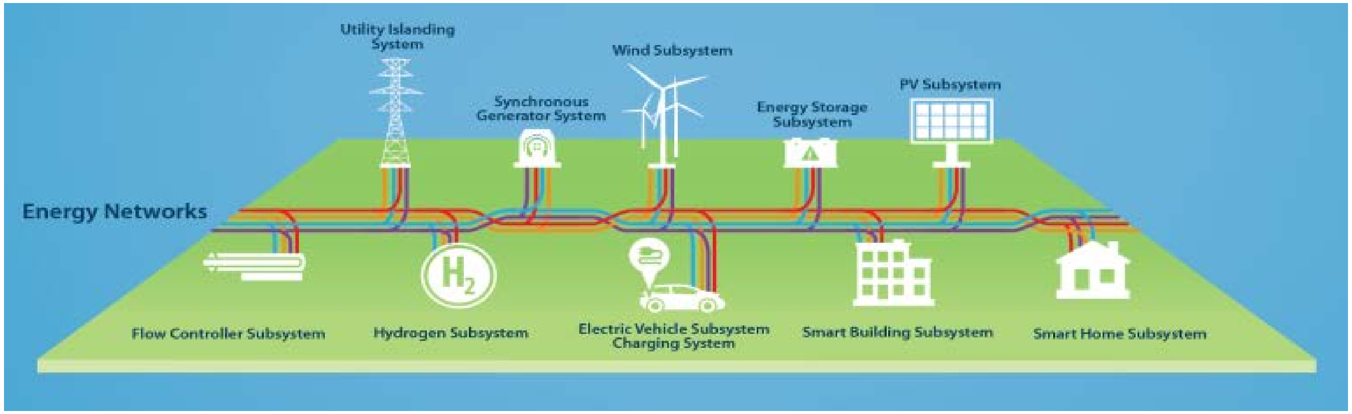
# INTEGRATE

*Integrated Network Test-bed for Energy Grid Research and Technology Experimentation*

Enable EERE technologies to increase the hosting capacity of the grid by providing grid services in a holistic manner using an open source, interoperable platform.

INTEGRATE project will:

a. Characterize the grid services and grid challenges associated with EE and RE technologies when integrated into the grid at scale
b. Utilize an open-sourced, interoperable platform that enables communication and control of EERE technologies both individually and holistically
c. Develop and demonstrate high value grid services that EE and RE technologies can provide holistically at a variety of scales



# Health and Safety on WPT Research

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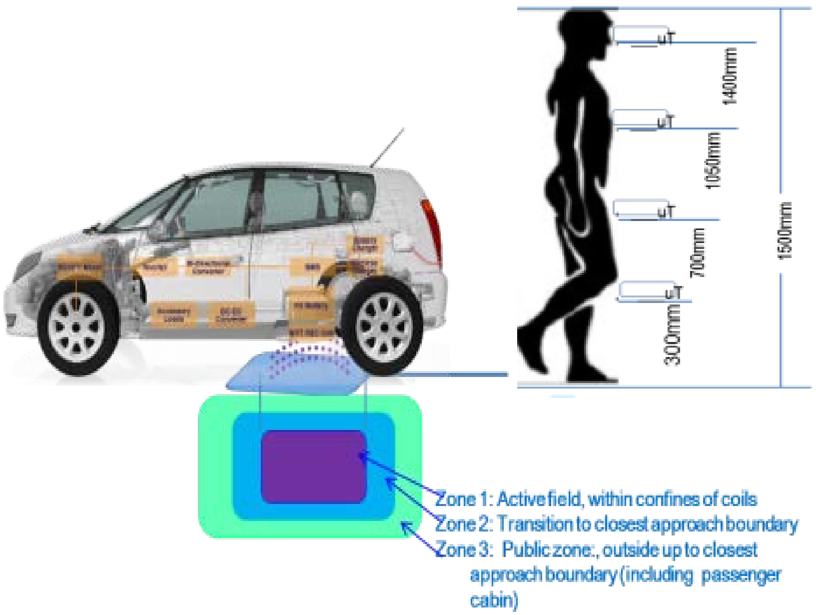
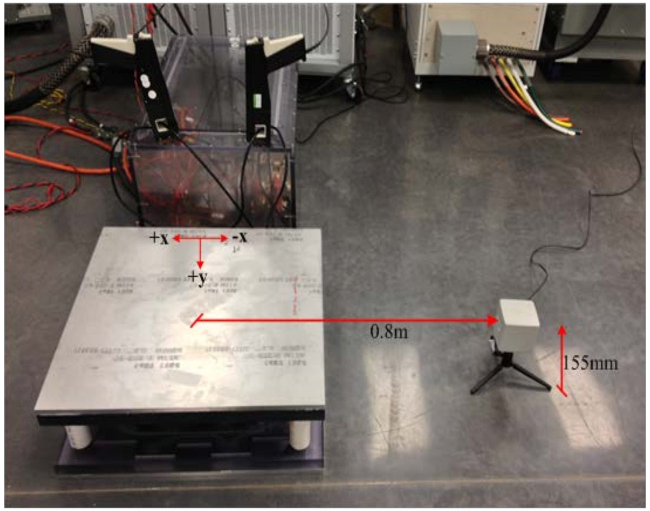
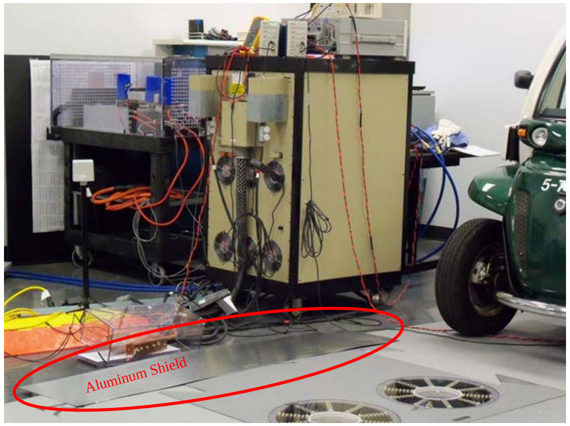
- In all WPT coil and grid side unit developments, electric (E) and electromagnetic field (B) measurements are performed around the coils, high frequency cables, tuning capacitors, grid side unit enclosure, around the vehicle, and inside the vehicle including floorboard, driver seat, and headrest area.
- Recognition of national and international guidelines defined by IEEE and ICNIRP (International Commission on Non-Ionizing Radiation Protection).
  - ICNIRP public exposure limits are B=6.25 µT and E=87 V/m measured at a distance of 0.8 meters from the center of the primary coil
  - Current guidelines need to be integrated into a cohesive approach
- ORNL is actively researching:
  - Advanced coil designs with better efficiency and reduced fringe/leakage fields.
  - Advanced understanding of magnetic fields gained from ITER fusion reactor program
  - High power WPT up to ~200 kW for MD and HD industry. Very little is known at these power levels with regards to leakage fields and health effects



# Health and Safety on WPT Research

- Example field measurement positions:

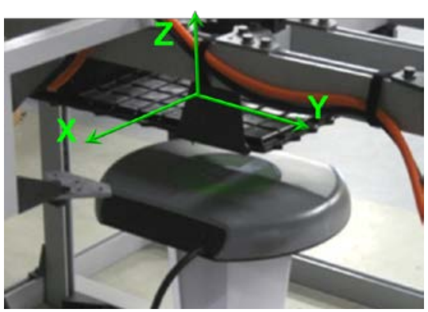


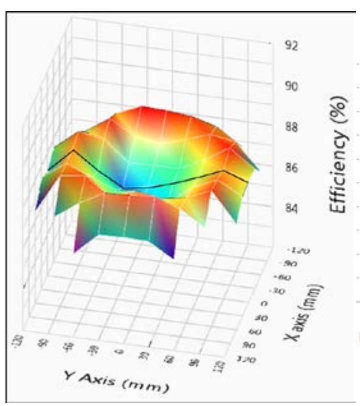

- Current international standards do not define all required safety related power electronics and related features
  - ORNL WPT R&D incorporates a high frequency transformer based galvanic isolation stage that adds another level of safety and protection to the driver, passengers, and the WPT equipment.
  - ORNL R&D in power electronic converters for WPT applications explores built-in and external protection schemes for over-voltage, over-current, short-circuit, and over-temperature events.
- ORNL is developing metallic, non-metallic, and magnetic object detection systems with measurement and sensing devices.

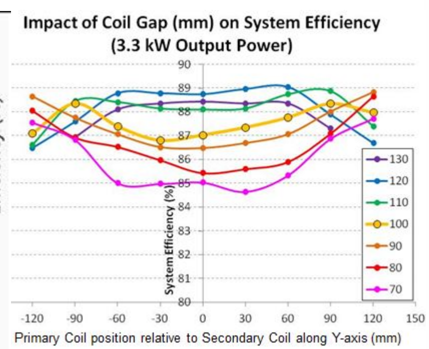
# WPT Testing Supports Standards Development



- A prototype wireless power transfer (WPT) system has been both lab and in-vehicle tested and a production vehicle with integrated WPT system will be tested next
  - Standalone device test will complete by August 2014
  - Production vehicle tests complete by Sept, 2014
- EMF fields and power quality
- Misalignment of primary and secondary coil effects
- WPT system response to debris is tested, including:
  - Paper clips, soda can, aluminum foil, rebar (3/8") which can be in the floor, coins, steel toe shoe, CD ROM disk, and other objects




# Power Electronics Related EV Safety

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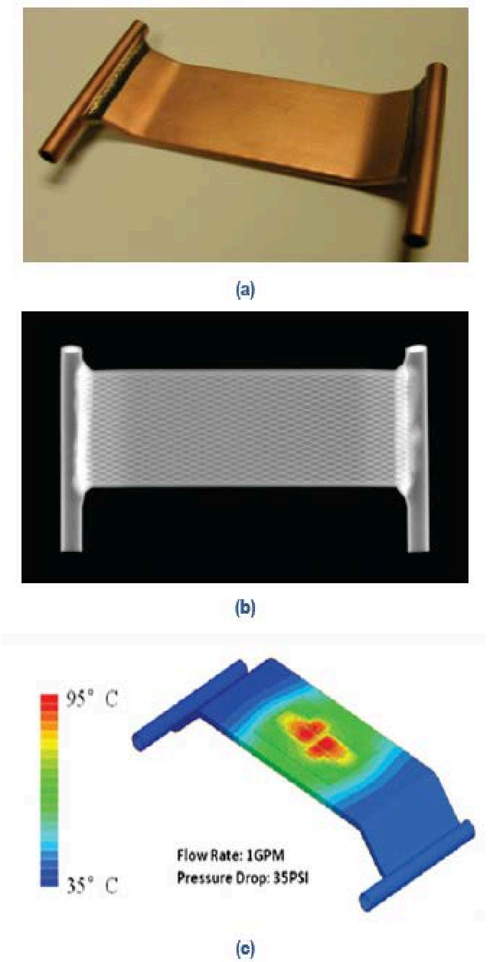
- The trend in hybrid electric vehicles (HEVs) has been to increase the traction drive bus voltage to >600 VDC.
- Electric and plug-in hybrid electric vehicle high voltage traction drives are increasing in overall power delivery capabilities
- Component design is critically important to maintain system integrity in these high voltage/power ranges.
- ORNL is engaged in R&D in the power electronic areas to address
  - Power module design for increased voltage operation and efficiency
  - Packaging of power electronics components and subsystems to reduce thermal loads and dissipate heat efficiently
  - All converters are equipped with the devices with over-voltage, over-current, short-circuit, and over-temperature situations.

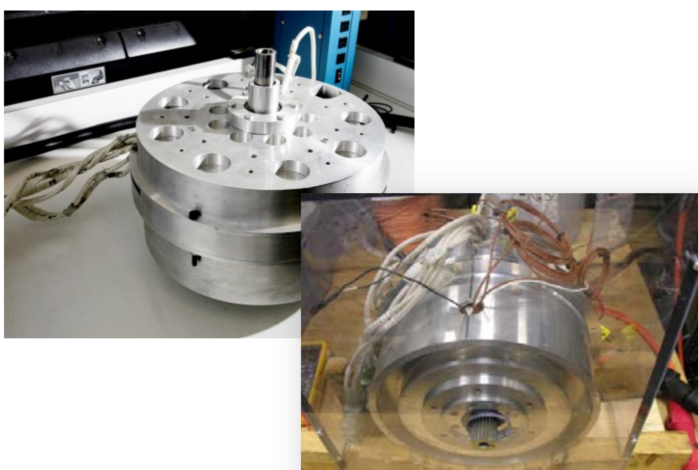


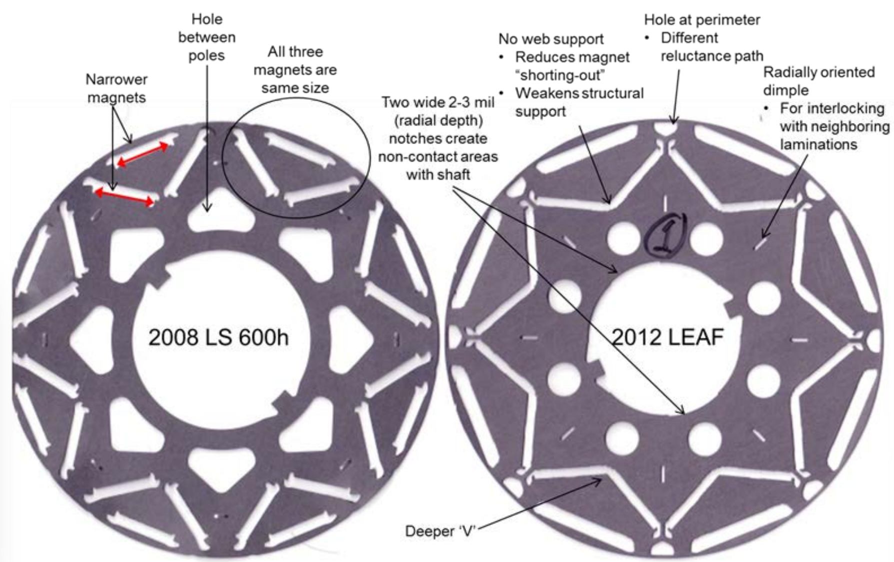

**Cold-base plate and thermal performance: (a) photo of the integrated cold-base plate; (b) x-ray image of the plate; and (c) temperature distribution of the power module on the integrated cold-base plate.**

# Electric Machines Related EV Safety



- In order to increase the specific power density of electric machines in EV and HEV traction drive systems, industry has focused on high speed electric machines (> 12,000 RPM)
  - Complimentary electromagnetic FEA must be conducted since there is often a tradeoff between mechanical integrity and electromagnetic performance
  - High speed operation is a challenge for many non-rare earth designs require rotors
- Motor winding failure is one of the most common and potentially dangerous fault conditions
  - Both short and open winding failures can be dangerous, they are caused by various mechanisms
    - Breakdown due to voltage spikes
    - Degradation from abrasive chemicals/artifacts (oil, metal shavings, etc.)
    - Mechanical wear from vibration
    - Degradation from high temperatures near or above motor wire insulation rating
- ORNL is researching materials and methods to avoid winding failure, while gaining power density and specific power advantages with the same method





# AVTA Background

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- U.S. Department of Energy's Advanced Vehicle Testing Activity (AVTA) is DOE's field, lab and track benchmarking program for advanced technology electric drive vehicles
  - Conducted by the Idaho National Laboratory (INL) and Intertek's Center for the Evaluation of Clean Energy Technology
  - Testing is often conducted with other DOE National Laboratories and industry groups
- Since 2010: 129 million test miles accumulated on 8,200 plug-in electric vehicles (PEVs) representing 19 models
- Since 2010: 17,000 EVSE & DC Fast Chargers accumulated 6 million charge events using 48,000 MWh of electricity
- AVTA PEVs include preproduction and production vehicles from OEMs and a few conversion PEVs

# AVTA's PEV Data Parameters

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- All PEVs provide multiple data parameters
- AVTA collects 65 parameters as inputs for analysis and report generation. Examples include:

| | | |
|---|---|---|
| A/C Power Factor (Calculated) | Onboard charger mode | Charge duration time |
| AC Input to Charger – Current | Odometer Reading | Cumulative charge time |
| AC input to Charger – Voltage | Latitude, Longitude | Brake status switch |
| Accelerator Pedal Position | Vehicle Speed | Planned end SOC for HVB |
| A/C Compressor Watts | Engine Coolant Temperature | Propulsion system status |
| Accessory Power Consumption | Engine RPM | Watt hours per charge event |
| Average Ambient Temperature | Traction battery temperature | Total miles driven in EV mode |
| Average Filtered Fuel – Liters | Active charging time | Trip distance |
| 12V Battery Voltage | High voltage battery current | Long term mpg (PHEVs) |
| DC Output of Charger – Current | High voltage battery (HVB) SOC | Short term mpg (PHEVs) |
| DC Output of Charger – Voltage | High voltage battery voltage | Charge start time |
| Distance traveled regen energy | J1772 Status | Charge end time |
| Charge Sustaining Mode Status | Cumulative kWh charge HVB | % EV miles (PHEVs) |
| Ignition Switch Status | Cumulative kWh discharge HVB | Regen energy recovered |

# AVTA Experience with Thermal Events



- During 20 years of testing, the AVTA has never experienced a thermal event with a production vehicle from an OEM
- AVTA's direct experience with unintentional thermal events include
  - Passenger battery electric bus
  - Conversion company conversion of a HEV sedan to a PHEV
  - Conversion company conversion of a HEV SUV to a PHEV
  - Preproduction PHEV

# HEV to PHEV Conversion Events

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- These vehicles were third party conversion vehicles, not OEM vehicles

# Overall Vehicle Safety

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## PEVs are not unique when it comes to vehicle based thermal anomalies in the U.S.

- Average number of highway vehicle fires per day
  - 1225 for the period 1980 - 1982
  - 514 for the period 2009 - 2011

Conventional vehicle fire

Port of Newark, Sandy event

Impact of salt water flooding

Source:(http://avt.inel.gov/pdf/energystorage/FinalReportNFPA.pdf)

# Field Lessons Learned



- Full battery thermal events can be suppressed or “finished” by:
  - Disassembling the pack (thus discharging) and applying water to the cool the pack to avoid in-pack and in-vehicle combustible materials from burning
  - Allowing the event to continue unsuppressed and ensuring personnel and facility safety. Will ultimately result in all combustible materials burned and vehicle destroyed (but the fire will be out!)
  - Using trained electrical safety worker to discharge the pack after applying cooling water to stop combustible materials from burning (INL’s most recent experience)
    - However, this should only be undertaken by electric safety trained workers with large battery pack safety and equipment experience
    - Vehicle can remain in a location that is hazardous to safety workers for several hours or days

# Field Lessons Learned – cont'd

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- The need for first responder training was recognized by U.S. DOE, U.S. DOT (NHTSA), and National Fire Protection Association (NFPA).
- DOE, DOT, NFPA, and INL developed a vehicle fire suppression lessons-learned program
  - OEMs, through the Alliance of Automobile Manufacturers, participated and contributed vehicle-sized lithium ion battery packs
  - Packs were used to demonstrate suppressed outcomes via the NFPA fire trainer vehicle
  - Target audience was first responders
  - Film is part of the education and training materials

# NFPA Project - Goal

- Identify full-scale heat release rate (HRR) and fire suppression testing of PEVs with large format Li-ion batteries
- In particular, members of the emergency response community had questions regarding
  – Appropriate personal protection equipment (PPE) to be used for responding to PEV fires
  – Tactics for suppression of fires involving PEV batteries
  – Best practices for tactics and PPE to be used during overhaul and post-fire clean-up operations
- One laboratory test was conducted to determine HRR
- Six full-scale fire suppression tests were conducted to collect data and evaluate any differences associated with PEV fires as compared to traditional ICE vehicle fires
  – Three of the Battery “A”, 4.4 kWh lithium ion battery pack
  – Three of the Battery “B”, 16 kWh lithium ion battery pack

# NFPA Project - HRR Test



- The objective of the heat release rate (HRR) testing was to determine the amount of energy released from the battery alone when it was ignited by an external ignition source
- Secondary testing objective was to verify the battery could be induced into thermal runaway with the external ignition source (propane fueled burners positioned beneath the battery) for use during the full-scale fire suppression tests and to collect data as to the indications that the battery was experiencing thermal runaway
- Based on a review of NFPA data on vehicle fire risk, flammable or combustible liquids or gases were the first item ignited in 31% of U.S. highway vehicle fires, resulting in 70% of civilian deaths, 58% of civilian injuries, and 31% of the direct property damage. As such, a pool fire scenario under the PEV was selected as the likely ignition scenario where the batteries become near fully involved and "burning on their own."
  (http://avt.inel.gov/pdf/energystorage/FinalReportNFPA.pdf)

# NFPA Fire Suppression Project

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Figure 72 Off gassing of Battery A3 approximately 22 hours after the conclusion of the test

- 22 hours after testing – the pack ‘self-reignited’
- At the conclusion of testing, to prepare for shipping, the PEV batteries were fully submersed in a salt bath for 24 hours

# NFPA - Best Practices

A small sample of findings are listed below

- Use standard vehicle firefighting equipment and tactics in accordance with department SOPs/SOGs
- All personnel should wear and utilize full PPE and self contained breathing apparatus (SCBA) as required at all vehicle fires
- Use water or other standard agents for PEV fires
- The use of water does not present an electrical hazard to firefighting personnel
- If a PEV battery catches fire, it will require a large, sustained volume of water
  - Battery A required 275 to 1,060 gallons
  - Battery B required 1,165 to 2,639 gallons
- If a Lithium Ion (Li-Ion) HV battery is involved in a fire, there is a possibility that it could reignite after extinguishment. If available, use thermal imaging to monitor the battery. Do not store a vehicle containing a damaged or burned Li-Ion HV battery in or within 50 feet of a structure or other vehicle until the battery can be discharged

# NFPA Report

- NFPA Final Report  and Appendices
  – http://avt.inel.gov/energystoragetesting.shtml
- NFPA Final Report only
  – http://avt.inel.gov/pdf/energystorage/FinalReportNFPA.pdf
- NFPA Appendix A
  – http://avt.inel.gov/pdf/energystorage/AppendixBthruE1NFPA.pdf
- NFPA Appendix B
  – http://avt.inel.gov/pdf/energystorage/AppendixBthruE1NFPA.pdf


# PEV Charger and ESS Temperature Testing



- Goal is to benchmark temperature and age impacts on battery charge acceptance
  - During dynamometer, normal Level 2 testing collects battery and charger performance at -7ºC, 22ºC and 32ºC when the PEVs and batteries are new
  - During fleet testing, DC Fast Charger testing collects battery and charger performance at 0ºC, 25ºC and 50ºC when the PEVs are new and at end of fleet testing. Mid-mileage testing to be determined by PEV technology.
  - Parameters collected during both types of testing include:
    - Current, voltage, SOC, time to charge X Kwh, battery temperature and ambient temperate (which is set)
  - PEVs soak at target temperature for at least 24 hours prior to test
- Early results show that charge rate is affected by temperature

# Overall AVTA Status of Projects

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- Continuing data collection on PEVs, EVSEs, and DC Fast Chargers (DCFC) use characteristics
- Investigating grid impact from distributed energy storage and workplace sites
- PHEV and BEV accelerated testing will analyze traction battery degradation rates, battery and power electronics safety issues, and general wear impacts
- Several hundred additional PHEV pickups and vans will start providing data during 2014
- Additional wireless power transfer testing will identify safety & FCC compliance at high power & various frequencies
- Additional Level 2 and DCFC testing includes cyber security vulnerabilities, efficiencies, and power quality issues

# Codes and Standards Near Term Gaps ANSI EV Roadmap 2.0

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- Vehicle Systems (6 near-term)
  - Functional safety in the charging system
  - Delayed battery overheating events
  - Safe storage of li-ion batteries
  - Packaging and transport of waste batteries
  - Battery recycling
  - Audible warning systems

DOE R&D helping to address gap

# Codes and Standards Near Term Gaps ANSI EV Roadmap 2.0



- Charging Systems (12 near-term)
  - Wireless charging
  - Battery swapping – safety and interoperability
  - Power quality
  - EVSE charging levels
  - Off-board charging station / portable EV cord set safety in North America
  - EV coupler safety in North America
  - EV coupler interoperability with EVSE globally
  - Conformance programs for EV coupler interoperability in the U.S.
  - Electromagnetic compatibility
  - Vehicle as supply / reverse power flow
  - Use of alternative power sources

# Codes and Standards Near Term Gaps ANSI EV Roadmap 2.0



- Communications (7 near-term)
  - Charging of roaming EVs between EV service providers
  - Access control at charging stations
  - Communication of standardized EV sub-metering data
  - Standardization of EV sub-meters
  - Coordination of EV sub-metering activities
  - Cyber security and data privacy
  - Telematics smart grid communications
- Installation (0 near-term)

# Codes and Standards Gaps ANSI EV Roadmap 2.0



- Support Services-Education & Training (5 near-term)
  - EV emergency shutoff – high voltage batteries, power cables, disconnect devices; fire suppression, fire fighting tactics and personal protective equipment
  - Labeling of EVSE and load management disconnects for emergency situations
  - Electrical energy stranded in an inoperable RESS
  - Battery assessment and safe discharge following an emergency event
  - Workforce training – charging station permitting

# Summary



- DOE will continue researching
  - Cabin Climate Control
  - Grid Integration
  - Wireless Power Transfer
  - Power Electronics
  - Electric Machines
  - Energy Storage System (ESS)
    - Thermal Runaway
    - Age Effects on PEV Charging and ESS
  - Codes and Standards Near Term Gaps

# Backup Slides

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# AVTA Testing Emphasis

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- While vehicle-based, the AVTA focuses:
  - Energy storage systems performance, life-cycle throughput, charge acceptance, auxiliary loads, and safety
  - Grid impacts and demands by PEV and charger technologies
  - Petroleum use reductions contributions from electric drive vehicle technologies and charging practices
  - Charging technologies and profiles at private and public locations and how grid impacts can be lessened via distributed energy storage and economic incentives
  - Safety issues that arise are fed back to OEMs
  - Focus on providing testing based factual results to the industry and regulatory groups

# Overall AVTA Status of Projects

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- EV Project data 8,200 PEVs and 12,300 EVSE and DC Fast Chargers (DCFC)
  - Benchmarks Time of Use rates can impact charging start times
  - Benchmarks work place charging use rates
  - Benchmarks different use profiles for battery electric and extended range electric vehicles
  - Benchmark cost to use public charging infrastructure impacts on use rates
  - Research continues as full data set collection of 124 million test miles and 4.2 million charging events was just completed 3 months ago
- Grid impacts for EVSE and DCFC use
  - Project to benchmark distributed energy storage at 55 locations with distributed energy storage is being developed
  - Additional EV Project analysis to benchmark workplace charging grid impacts during peak demand will be identified at 109 workplace sites

# Overall AVTA Status of Projects – cont'd

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- PHEV and BEV Accelerated Testing
  - 38 PHEVs and BEVs, representing 10 models, are currently in testing and each vehicle is operated for 60,000 to 195,000 miles each to benchmark lifecycle costs, maintenance requirements, petroleum reductions, and traction battery degradation rates
  - Accelerated BEV and PHEV testing will benchmark any safety issues at very high individual vehicle mileage accumulation
  - Includes battery and power electronics safety issues and general wear impacts
- Several hundred additional PHEV pickups and vans will start providing data during 2014
  - This is a class of vehicles that have high potential for adaption by electric utilities and other users of work vehicles requiring payloads higher than standard light-duty passenger vehicles

# Overall AVTA Status of Projects – cont'd



- Additional wireless power transfer testing will identify safety issues, including:
  - At high power transfer levels (25 to 50 kW, and possibly higher)
  - Various frequencies
  - Compliance with FCC 300-meter testing requirements
- Level 2 and DCFC testing
  - Cyber security testing is demonstrating non-anticipated vulnerabilities for several EVSE tested to date, with additional EVSE to be tested
  - Efficiencies and power quality issues are being identified
- Second year of BEV taxi use includes expanding the number of drivers to understand suitability of BEVs in a very rugged operating environment (New York City)
    - NYC taxi drivers are not know for their delicate use of vehicles, and they make excellent field testers

# Overall AVTA Status of Projects – cont’d

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- Federal fleet vehicles instrumented with data loggers is starting to benchmark ICE vehicles for replacement by PEVs
  - Onboard data loggers benchmark vehicle missions and maximum trip distances as well as parking locations for potential EVSE siting
- ICE vehicle accessories load Study
  - INL has instrumented internal combustion engine vehicles in order to benchmark accessory load demands for several OEMs to support their design process for new PEVs. This testing will continue for one year
- SAE interoperability testing
  - INL is managing the testing of approximately 40 EVSE and 10 PEVs to identify and benchmark SAE J1772 connector and vehicle port interoperability issues that appear to be wear and individual vehicle / connector dependent
  - Testing will document any inconsistencies in manufacturing and interpretations of recommended practices

# Overall AVTA Status of Projects – cont'd

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- DOD V2G (vehicle-to-grid) analysis and support
  - AVTA analysis of multi vehicle models deployment and V2G operations will benchmark economic and grid support opportunities for V2G deployments as well as any potential vehicle safety issues
- DC Fast Charging testing of Nissan Leafs is documenting DCFC impacts on battery capacity losses compared to Level 2 recharging
  - 50,000 miles per vehicle results are
- The AVTA is "neck deep" in demonstrating PEV benefits and areas requiring additional understanding and analysis. Based on the AVTA combination of real world and laboratory testing, testing results are also benchmarking whether laboratory testing accurately mimics real world vehicle use