USDRIVE

DRIVING RESEARCH AND INNOVATION FOR
VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

# U.S. DRIVE Highlights of Technical Accomplishments

2022

# U.S. DRIVE
# Highlights of Technical Accomplishments Overview

*Through precompetitive collaboration and technical exchange, U.S. DRIVE accelerates the development of energy-efficient advanced automotive and energy infrastructure technologies.*

U.S. DRIVE (*Driving Research for Vehicle efficiency and Energy sustainability*) is a voluntary government-industry partnership focused on precompetitive, advanced automotive and related infrastructure technology research and development. Partners are the United States Department of Energy (DOE) and leaders in the automotive industry (United States Council for Automotive Research LLC, the collaborative technology company of Ford Motor Company, General Motors, and Stellantis); energy industry (BP, Chevron, Phillips 66, ExxonMobil, and Shell); and electric utility industry (American Electric Power, DTE Energy, Duke Energy, Southern California Edison, and the Electric Power Research Institute).

The Partnership benefits from a history of successful collaboration across multiple technical areas, each focused on a key area of the U.S. DRIVE portfolio (see below). These teams convene the best and brightest scientists and engineers from across the Partnership to discuss key technical challenges, identify possible solutions, and evaluate progress toward goals and targets published in technology roadmaps. By providing a framework for frequent and regular interaction among technical experts in common areas of expertise, U.S. DRIVE accelerates technical progress, helps to avoid duplication of efforts, ensures that publicly funded research delivers high-value results, and overcomes high-risk barriers to technology commercialization.

U.S. DRIVE teams selected the highlights in this document from many hundreds of DOE-funded projects conducted by some of the nation's top research organizations. Each one-page summary represents what Partnership experts collectively consider to be significant progress in the development of advanced automotive and infrastructure technologies. The report features technical highlights in two general categories:

Vehicles
- Electrical and Electronics
- Electrochemical Energy Storage
- Materials
- Vehicle and Mobility Systems Analysis

Infrastructure and Integration
- Grid Integration
- Integrated Systems Analysis
- Net-Zero Carbon Fuels

More information about U.S. DRIVE, including prior-year accomplishments reports and technology roadmaps, is available on the DOE (https://www.energy.gov/eere/vehicles/us-drive) and USCAR (www.uscar.org) web sites.

# Contents

## VEHICLES

# Electrical and Electronics

# Development of a Cost-Effective Manufacturing Process for High-Performance Soft Magnetic Materials

*Scalable Processing of High-Silicon Steel Laminates and Stator Shapes.*

## *Ames National Laboratory*

Ames National Laboratory (AMES) researchers have developed a highly simplified, cost-effective method of manufacturing 6.5% silicon (Si) steel for electric drive motor applications. The steel typically used today, which has 3.2% Si, gives rise to high core (power) losses, especially at higher motor speeds (Figure 1). Using steels with high Si content improves the efficiency, thanks to the steels' higher capacity for magnetism and greater electrical resistivity, which helps overcome core loss. However, steel with high Si content is brittle and hard to manufacture. The AMES approach is based on a method that solidifies steel at high rates of cooling, bypassing the transition that leads to brittleness. This 6.5% Si steel has higher electrical resistivity than 3.2% Si steel and higher saturation magnetization than other advanced/costly soft magnetic materials, e.g., nanocrystalline or amorphous alloys.

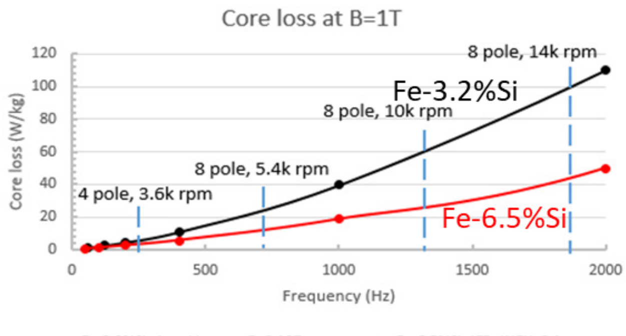


**Figure 1**. Comparison of motor core loss of commercially available Fe-3.2Si and Fe-6.5Si in a motor setting.

AMES researchers used rapid solidification to prepare thin ribbon made of an iron–silicon alloy with 6.5% Si (Fe-6.5%Si). They formulated and optimized a wire bundle concept for near-net-shape fabrication of stator segments (Figure 2) using the melt-spun 6.5% Si steel ribbon. Ribbons are insulated by a self-grown oxide, which the AMES team is currently optimizing.

Regarding production challenges, the 6.5% Si steel sheet is a drop-in replacement for conventional 3.2% Si steel laminate production. The 6.5% Si steel can eliminate many heating and rolling steps typically used (Figure 3) and is likely to offer significant cost and energy savings.

This wire (ribbon) bundle concept not only simplifies the manufacturing process but also contributes to enhanced magnetic flux density and reduced core losses. However, making full-width Fe-6.5%Si laminate foil presents technical challenges. It has a high melting point and requires improved wetting on the quench wheel without lowering saturation magnetization.

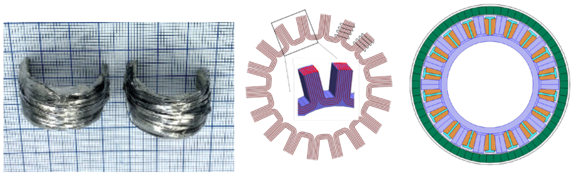


**Figure 2**. a) Demonstration of AMES wire bundle concept; b) wire bundle stator, c) stator and rotor assembly (Oak Ridge National Laboratory).

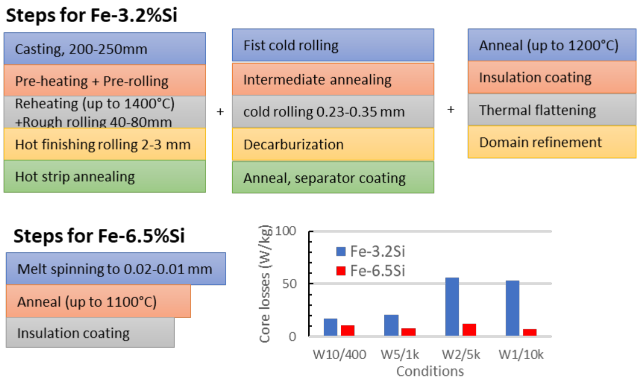


**Figure 3**. Number of steps needed to make Fe-3.2%Si and Fe-6.5%Si, as well as their iron losses at various conditions.

*2022 U.S. DRIVE Highlight*

# Electric Motor Cooling Concept for Increased Power Density

*Cooling end windings of electric motors.*

## *National Renewable Energy Laboratory, and Georgia Institute of Technology*

The National Renewable Energy Laboratory (NREL) and Georgia Institute of Technology (Georgia Tech) have collaborated to develop an electric motor cooling concept to cool electric motor end windings directly. Advanced thermal management designs are needed to increase motor power density. Power density increases efficiency and reduces material costs, but it is often limited by the magnet wire used in electric motors because of the temperature limit of the magnet wire coating. The end windings of a motor, in particular, produce considerable heat. They have irregular surfaces, making it difficult to incorporate a proximate thermal management strategy. End windings are a common hot spot and limiting factor in motor thermal management.

The NREL–Georgia Tech team retrofitted the cooling concept shown in Figure 1 to a commercial electric vehicle motor (Nissan Leaf). The concept included an end cap, separation wall, and channel cavity and was fitted into a commercial water jacket, as shown in Figure 1. A water–ethylene glycol (WEG) mixture (50–50 by volume) at 65°C temperature was circulated through the channel cavity to provide cooling. The channel cavity was filled with a high-performance potting compound to facilitate heat transfer from the end windings to the concept cooler. The concept appears sufficiently robust to work with different coolant temperatures that might be encountered within an automotive environment.

The cooling concept demonstrated a 30%–45% decrease in motor end-winding temperatures relative to the commercial baseline. This result should enable increased motor power density. Furthermore, the concept is straightforward to incorporate into the existing cooling loop and thus is scalable for commercial production. The concept might also enable integration of the electric motor and power electronics thermal management system utilizing the WEG coolant.

With the cooling concept, the copper content (windings) in the motor can be reduced, and the separate oil pump and heat exchanger could potentially be eliminated. Future work could investigate the torque characteristics of the motor incorporating this concept. The channels could also be incorporated into the motor housing.

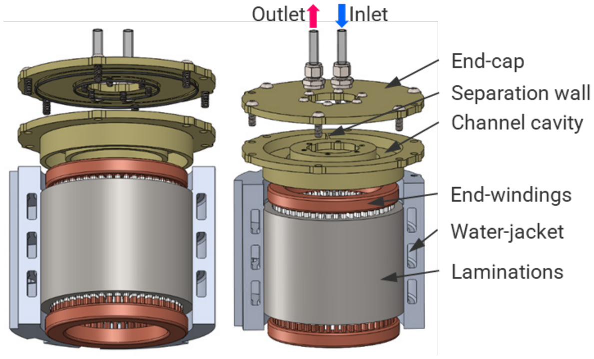


**Figure 1.** Section view of proposed motor end-winding cooling concept.

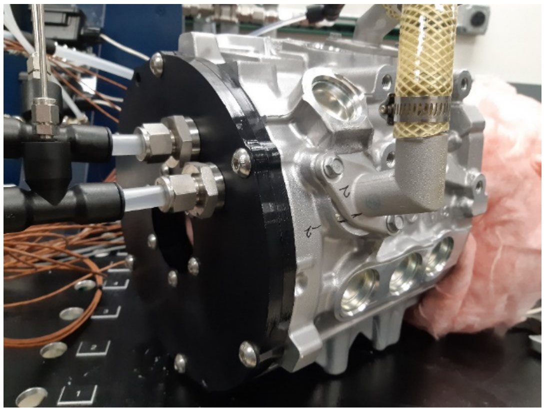


**Figure 2.** Assembled motor end-winding cooler at NREL. Photo Credit: Sebastien Sequeira, Georgia Tech/NREL.

*2022 U.S. DRIVE Highlight*

# DC-Ripple-Energy Adaptive-Minimization (DREAM) Modulation for a High-Power Density Inverter

*A new modulation scheme that reduces capacitor current by up to 70%.*

***Oak Ridge National Laboratory***

Researchers have developed a method to reduce ripple current in an electric drive system: DC-ripple-energy adaptive-minimization (DREAM). DREAM addresses a major power-density and reliability hurdle of these systems: the direct current (DC) bus capacitor. Drive systems include a motor drive inverter with switches that regulate current and voltage, and these switches generate large ripple currents; the DC bus filter capacitor absorbs the currents for a constant flow into the battery. The capacitor takes up much space in the inverter but, because it must be sized to meet the ripple current, is hard to shrink. A dual-inverter-based segmented drive can reduce the ripple current by 47% (vs. a non-segmented drive); DREAM can increase this reduction.

Figure 1 shows a segmented drive system with two inverters. The dual three-phase inverter system comprises six power switches (S1–S6) for each inverter and a DC bus filter capacitor. In one switching period, the motor currents (ia, ib, ic) are relatively constant, and the inverter DC side current iinv is determined by the switching state of the six switches through modulation. Since the capacitor current iCbus equals ibat – iinv, it is minimized when ibat stays close to iinv. The DREAM modulation can achieve this by selecting the optimal switching states of S1 to S6 adaptively across different motor operating conditions, so the DC ripple energy in the capacitor Cbus is always minimized.

Figure 2 (top) shows the normalized capacitor currents, comparing non-segmented, traditional segmented, and DREAM modulation. The DREAM modulation reduces the worst-case capacitor current by 46% more than the traditional segmented scheme. Experimental waveforms (bottom) show that DREAM reduces capacitor current magnitude by 38% against the traditional segemented scheme and by 70% against the non-segemented scheme.

The reduction in capacitor current ratings can lead to smaller capacitor size, which will improve the overall inverter power density. For example, film capacitor volume can be reduced by 77% when the rated current is cut by 70%.

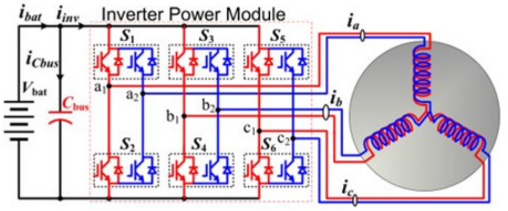


**Figure 1**. A segmented drive system (top) and its possible inverter current values $i_{inv}$ for a given battery current $i_{bat}$ (bottom).

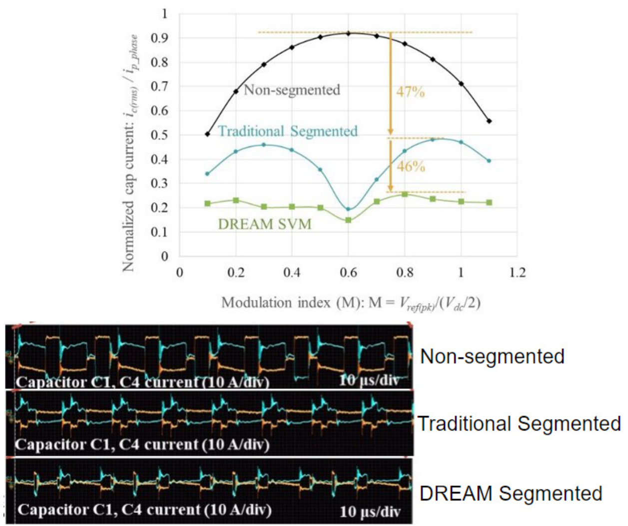


**Figure 2**. Simulated performance (top) and experimental waveforms (bottom).

*2022 U.S. DRIVE Highlight*

# Power Block for Integrated Electric Drive

*High-power-density power block for integrated drive.*

## *Oak Ridge National Laboratory*

Researchers have designed a building block for power electronics (Figure 1). The “power block” contains a silicon carbide (SiC) power module, gate driver, capacitor, and busbars—components needed for the technology to operate independently. Traditionally, these components are designed separately and integrated to form an inverter–converter system, but this approach can lead to voltage spikes. To achieve better performance , power electronic components must be co-optimized and co-designed. Oak Ridge is using multiple power blocks to develop an inverter–converter with little or no compromise on performance.

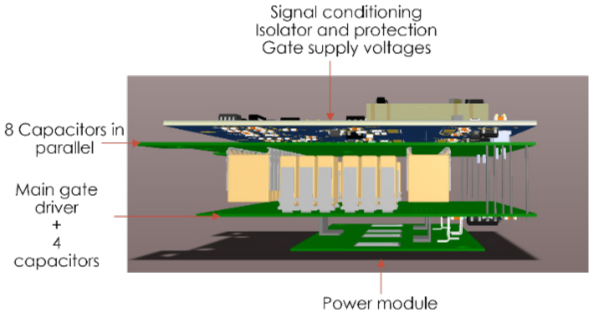


**Figure 1**. Assembled power block containing an SiC module, capacitor, gate driver, and protection circuitry.

The power block components are shown in Figure 2. The module was designed to handle 800 V and 150 A currents. A gate driver board with decoupling capacitors was added on top of the module to reduce the gate loop and power loop inductance (a primary cause of voltage overshoot). A secondary capacitor board on the gate driver board handles higher currents and suppresses voltage oscillation. The entire capacitor board was designed to handle more than 80 A ripple current. The capacitors were also placed symmetrically from the termination to achieve low layout inductance and equal current-sharing among the parallel capacitor branches. Finally, a gate driver power supply board with protection circuitry is placed.

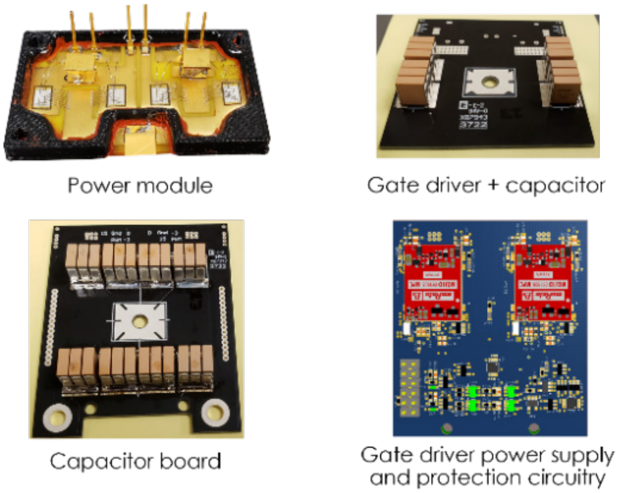


**Figure 2**. Power block components.

The team then evaluated the power board using a double pulse test setup where the DC bus was 800 V and the current was 150A (Figure 3). The test measured output/inductor current, showing 250 V overshoot at 800 V (1050 V at the device terminal) and 150 A operation—well within the manufacturer voltage limit of 1200 V. Researchers calucated total power loop inductance (≈ 27 nH) and power module inductance (20 nH) and estimated the layout inductance of the capacitor board and busbars (7 nH). The module inductance dominates the power loop inductance and can be further optimized.

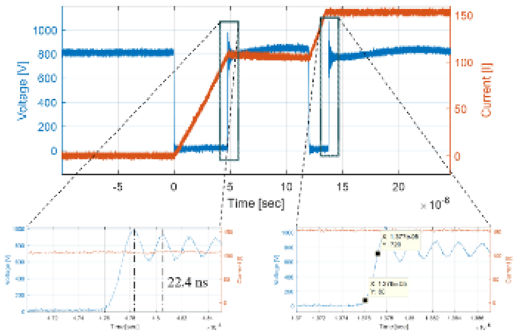


**Figure 3**. Double pulse test results showing 800 V up to 150 A operation with fast voltage rise to minimize switching loss.

# Edge Termination for Vertical Gallium Nitride Power Devices in Electric Drivetrains

*Power devices with increased efficiency and power density to support next-generation electric drivetrains.*

## *Sandia National Laboratories*

Next-generation power electronics are leveraging the advantages of wide-bandgap semiconductors to push for higher power densities and higher efficiency. In electric vehicle drivetrains, this translates to lighter-weight systems and more miles per charge. Vertical gallium nitride (GaN) power devices promise an advantage over silicon, or even silicon carbide, by leveraging a large breakdown electric field and, compared to lateral GaN, offer increased power densities for high-voltage and high-current applications.

A key aspect of designing high-voltage vertical power devices is minimizing electric field crowding at the periphery of the device, which otherwise causes premature device breakdown. Because of limitations surrounding selective-area doping in GaN, many conventional methods for edge termination are not viable. The Sandia team has developed a process for edge termination in vertical GaN power devices and has reported a multipoint fit from theory to experiment, which marks a milestone of maturity for these devices.

The Sandia edge termination strategy consists of a multi-zone junction termination extension (JTE) where the charge in the edge termination is proportional to the electric field at breakdown. To correctly design a multi-zone JTE, it is necessary to understand the optimal design point for a single-zone JTE and the sensitivity of breakdown voltage to JTE thickness, and to adjust for any offsets due to non-idealities.

This study (Figure 1) demonstrates the impact of charge in the passivation on edge termination design (Figure 2) and the impact of JTE thickness on breakdown voltage (Figure 3), allowing for an optimized JTE design that maximizes the potential of vertical GaN devices.

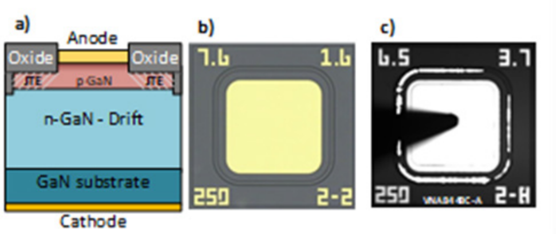
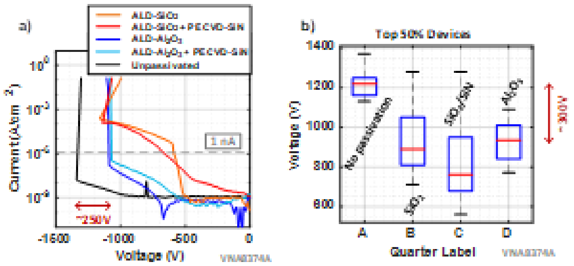


**Figure 1**. Representative structure (a) of the single-zone JTE vertical GaN on fabricated diodes, (b) an optical image of the fabricated device, and (c) electroluminescence of the diode under high reverse bias during avalanche showing emission at the outer edge of the JTE as predicted by the modeling.



Theory: 200-300V drop every 4e12 cm⁻² charge

**Figure 2**. Results from a passivation study showing (a) reverse current-voltage characteristics comparing various passivation films against an unpassivated "baseline" device, and (b) the statistical breakdown data nominally demonstrating a ~300 V drop in breakdown voltage for passivated devices.

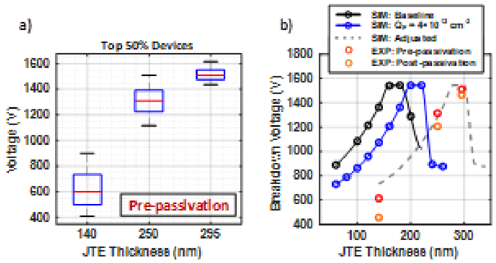


**Figure 3**. Results from the JTE study showing (a) statistical breakdown data versus JTE thickness (pre-passivation), and (b) a comparison between the theoretical model and experimental results showing an excellent fit of the experimental data to the shape of the theoretical curve, with an x-offset of ~100 nm compared to the unmodified baseline.

# Electrochemical Energy Storage

*2022 U.S. DRIVE Highlight*

# Enhanced Performance of High Energy Cobalt-Free $LiNiO_2$ Enabled by Optimized Synthesis Conditions

*Insights into the synthetic mechanisms of pure $LiNiO_2$ show that this cathode is not inherently unstable as compared to NMC counterparts, opening the door to more stable Ni-rich cathode designs.*

## Argonne National Laboratory

$LiNiO_2$ (LNO) has been of interest as an alternative to its layered counterparts (e.g., NMC and $LiCO_2$) for many years because of its intrinsically high energy and lack of expensive cobalt. However, LNO has never achieved commercial success due, in part, to cycling instabilities at high states of charge (>~60%). These instabilities have been presumed to be inherent to LNO, and compositional and structural modifications with Mn, Co, and other dopants (e. g. Al, Mg) have been deemed necessary. However, due to the extreme sensitivity of LNO to synthesis conditions such as precursor control, temperature, and atmosphere, virtually all LNO cathodes studied contain substantial defects with respect to ideal $LiNi^{3+}O_2$. Some of the defects are anti-site disorder ($Li^+/Ni^{2+}$), mixed $Ni^{2+}/Ni^{3+}$, off-stoichiometry, and surface contamination. Work at Argonne National Laboratory (ANL) has shown that near-ideal, 'defect-free' LNO can be synthesized through better control of synthesis parameters and these findings are shedding light on the optimal performance of pure $LiNi^{3+}O_2$, as well as questioning conventional thinking about the mechanisms of dopants in LNO.

Figure 1a shows the excellent performance of ANL's 'defect-free' LNO cycling at high capacities (>220 mAh/g) over many cycles without dopants, coatings, or electrolyte additives. Such high performance, including very low initial irreversible capacity (~96%), has never been reported for LNO. Key to achieving such results was precise control of synthesis parameters including novel precursor preparation/calcination conditions that facilitate minimum local defects ($Li^+/Ni^{2+}$ mixing, $O_2$ vacancies, stacking faults), optimized primary and secondary particle morphologies, which also result in a higher resistance to secondary particle cracking (See Figure 1b).

Surprisingly, synthesis of 'defect-free' LNO could be enabled within a wide range of $O_2$ partial pressures, even as low as 0.2 atm (Inset of Figure 1a). The data suggests that, in contrast to general belief, high $O_2$ partial pressures may not be necessary when other synthesis conditions are optimized. Full-cell tests with graphite anodes and Gen 2 electrolyte (1.2 M $LiPF_6$ in ethylene carbonate/ethyl methyl carbonate (EC:EMC) (3:7 by weight)) showed performance on par with $LiNi_{0.9}Mn_{0.05}Co_{0.05}O_2$, when cycled over similar states of charge, Figure 1c. Note that three-hour holds at the top of every charge were used to push stability limits. Overall, this work challenges the conventional knowledge on $LiNiO_2$ and provides new insights for the development of next-generation cathode materials.

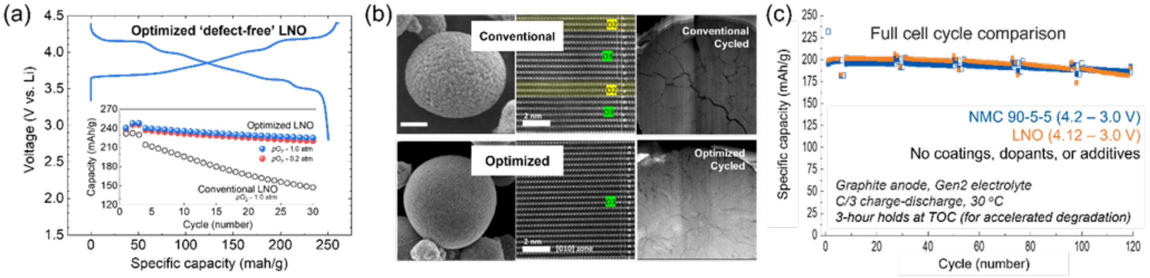


**Figure 1.** (a) Li half-cell performance (initial voltage profiles and cycling stability); (b) physicochemical properties (morphology, stacking faults, and cycle-induced cracks) of optimized LNO vs. conventional LNO; (c) Full-cell performance comparison of optimized LNO vs. $LiNi_{0.9}Mn_{0.05}Co_{0.05}O_2$.

*2022 U.S. DRIVE Highlight*

# Li-metal Anodes Enabled by Solvation-Protection Strategy Electrolyte Innovations

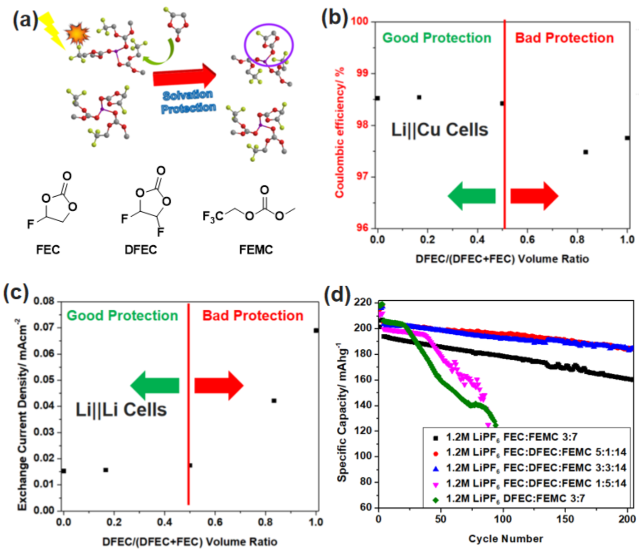
*Achieving solvation-protection using "protecting" solvents provides a new strategy for stabilizing lithium metal anode-based cells.*

## *Argonne National Laboratory*

The development of a stable electrolyte system is critical to the successful application of lithium (Li) metal batteries (LMBs). Recently, fluorinated electrolytes have attracted attention as components of high-voltage LMBs because of their high anodic stability and robust solid electrolyte interphase (SEI)-forming capability. However, the arbitrary utilization of fluorinated solvents without a deep understanding of their underlying solution chemistry may lead to non-ideal performance.

In this work, researchers at Argonne National Laboratory have developed a new "solvation-protection" strategy for developing a novel fluorinated electrolyte system. As illustrated in Fig. 1a, fluoroethylene carbonate (FEC) was introduced into the difluoroethylene carbonate/fluoroethyl methyl carbonate (DFEC/FEMC) electrolyte system to serve as a solvation protection agent. Although DFEC is known to enable stable cycling of a lithium metal anode, a Li||$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811) cell with DFEC/FEMC electrolyte (and no FEC) displays inferior cycling because of the presence of a significant quantity of lithium complexes solvated solely by FEMC. These complexes subsequently decompose on the Li surface to form detrimental by-products. Owing to the relatively high solvating power of FEC, the solution structures of lithium complexes can be altered readily by introducing FEC to the electrolyte. Through the precise control of the solvation number (SN > 1) of fluorinated cyclic carbonate (*i.e.*, FEC:DFEC > critical ratio), the undesired FEMC complexes can be effectively eliminated.

The ternary FEC/DFEC/FEMC system not only maintains the beneficial effect of DFEC in forming a robust SEI on the Li anode, but also confers outstanding anodic stability provided by FEMC, as evidenced by the improved lithium plating/stripping capability of Li||Copper (Cu) (Fig. 1b), Li||Li cells (Fig. 1c) and the stable cycling of Li||NMC cells (Fig. 1d). This ternary system outperforms the FEC/FEMC and DFEC/FEMC binary systems in facilitating the stable cycling of LMBs.



| Electrolyte (1.2M $LiPF_6$ in FEC:DFEC:FEMC) | SN (FEMC) | SN (FEC) | SN (DFEC) | SN (FEC + DFEC) |
|---|---|---|---|---|
| 1:5:14 | 2.23 | 0.34 | 0.22 | 1.72 > 1 |
| 3:3:14 | 2.05 | 1.07 | 0.21 | 1.28 > 1 |
| 5:1:14 | 1.95 | 1.59 | 0.13 | 0.56 < 1 |

**Figure 1.** (a) Schematic illustration of solvation-protection strategy through the use of FEC as protecting solvent. (b) Coulombic efficiency *vs.* the ratio of DFEC:(DFEC + FEC) for Li||Cu cells. (c) Exchange current density *vs.* the ratio of DFEC:(DFEC + FEC) for Li||Li cells. (d) Cycling performance of Li||NMC811 cells using 1.2M $LiPF_6$-FEC/DFEC/FEMC in different ratios.

*2022 U.S. DRIVE Highlight*

# Developing Low-cost Rechargeable Lithium-Sulfur Batteries

*Battery500 Consortium researchers combine innovative electrolytes and advanced diagnostics to enable low-cost lithium-sulfur batteries.*

## *Battery500 Consortium*

The Battery500 Consortium has advanced the performance of a lithium-sulfur (Li-S) battery through innovation in battery electrolytes and improved understanding of a polymer-derived sulfur cathode. A 2 Ah pouch cell with an energy density of 250Wh/kg (which is comparable with current lithium-ion EV cells) has been demonstrated.

Sulfurized Polyacrylonitrile (SPAN) is a low-cost material containing no critical materials and can be readily made by heating sulfur with PAN, an industrial product, at 300°C-500°C. Unlike elemental sulfur-based cathodes, SPAN appears to avoid the generation of soluble polysulfide species, which lead to capacity decay and performance sensitivity to electrolyte amounts, an ongoing challenge for elemental sulfur battery systems.

To enable a long-life Li-SPAN battery, electrolytes need to be stable at both the Li anode and the SPAN cathode. For this purpose, the Consortium has developed a localized concentrated electrolyte consisting of 1.8 M lithium bis(fluorosulfonyl)imide (LiFSI) in diethyl ether (DEE) and bis(2,2,2-trifluoroethyl) ether (BTFE). This electrolyte forms a protective layer on the SPAN surface that prevents loss of sulfur to the electrolyte. In addition, Li also cycles stably due to the formation of a LiF-rich solid electrolyte interphase. Both Li and SPAN show high stability through nearly 1,000 cycles in coin cells using this new electrolyte.

To further improve the capacity and reversibility of SPAN, it is essential to understand its molecular structure and working mechanism in a battery. Using chemical analysis, electron microscopy, and surface analysis, we established that SPAN undergoes an irreversible transformation during the 1st cycle that reduces its residual hydrogen content and produces a more extended conjugated molecular structure. As a result, its electronic conductivity increases by > 100x and raises the working potential. This structural feature may serve as a blueprint for the design of next-generation polymer materials.

Electrolyte innovation and electrode engineering developed under the Consortium have allowed the fabrication of a first generation 2 Ah Li-SPAN battery with an energy density of 250 Wh/kg which demonstrates stable cycling (Figure 1). Cycling ended when the Li metal anode caused an internal short which the team is currently working to address. Work is in progress to further increase the capacity of SPAN and formulate new electrolytes with the potential to extend the cycle life of Li-SPAN batteries. Team members are now scaling up SPAN cathode materials to enable more pouch cell manufacturing and testing.

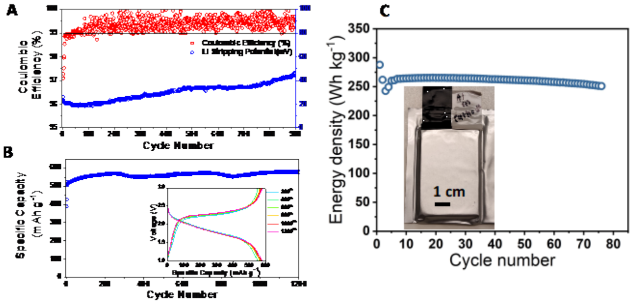


**Figure 1.** Progress of developing a low-cost Li-S battery by the Battery500 Consortium. The sulfur cathode is sulfurized polyacrylonitrile (SPAN). (a) and (b), Stable cycling of Li and SPAN in a localized concentrated electrolyte, respectively. (c) Demonstration of a 1st Generation Li-SPAN pouch cell of 2 Ah with an energy density of 250 Wh/kg.

# Rapid Identification of Failure Modes by the Use of Synthetic Data and Deep Learning

*Leveraging synthetic data and deep-learning techniques enable fast and robust classification and quantification of battery aging.*

## *Idaho National Laboratory*

A key challenge for lithium-ion batteries (LiBs) is the ability to effectively identify the dominating aging modes (e.g., loss of lithium inventory and loss of active material), unique mechanisms, and with high confidence. Early identification of battery aging modes/mechanisms will enable more accurate forecasting of battery life with the goal of reducing the research and development cycle time for new battery designs.

An Idaho National Laboratory (INL) team developed a deep-learning (DL) algorithm for rapidly classifying and quantifying battery aging modes. The DL framework is trained on thousands of synthetic data sets and generates an efficient incremental capacity battery model. The DL framework automatically classifies and quantifies the dominant aging modes upon training with the synthetic data. The DL framework classified the dominant aging modes for Graphite/$LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$ (NMC532) cells undergoing fast charge in less than 100 cycles. Upon classification, the framework tracked the evolution of the aging modes through 600 cycles at different charging rates (1C–9C) (Figure 1). The method has been used for NMC532, NMC811 and $Li_4Ti_5O_{12}$/$LiMn_2O_4$ (LTO/LMO) cells to show broad applicability.

An advantage of this framework is that it enables fast and robust classification and quantification of battery aging modes without requiring expensive teardown and post-mortem tests. Automatic classification and quantification provide significant benefits over manual analysis, which requires substantial time, effort, and experimentation. The proposed framework will help advance rapid LiB technology validation, early design improvement, and reliable diagnostic and prognostic methods.

INL will continue developing this DL-based framework to incorporate additional lithium ion active materials, cell designs, and usage conditions to enhance its cross-functionality. INL team is also collaborating with National Renewable Energy Laboratory to enable aging mode classification and quantification during cell cycling using fast-rate charge/discharge responses; reducing dependence on much more slowly acquired and sparse reference performance test data.

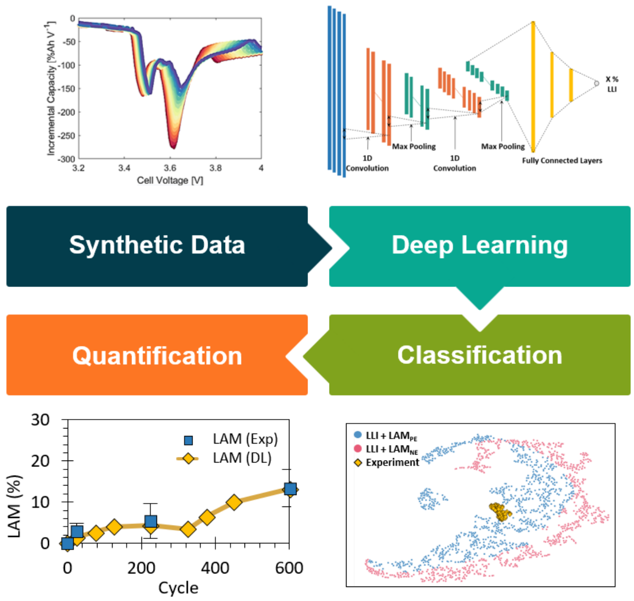


**Figure 1.** A flow of synthetic–data-based DL modeling framework to classify and quantify the dominant aging modes.

*2022 U.S. DRIVE Highlight*

# All-Solid-State Cell Chemistries with High Energy Densities and Practical Cycle Life

*All-solid-state batteries (ASSBs) are strong candidates as future energy storage technologies. In this work, we demonstrate a high-energy ASSB cell design achieving 1000 cycles with nearly 90% capacity retention.*

***Lawrence Berkeley National Laboratory***

While conventional lithium (Li)-ion batteries continue to progress, the presence of organic liquid electrolytes brings with it necessary system or performance trade-offs to accommodate abuse tolerance challenges. All-solid-state batteries (ASSBs) consisting of a 4 V-class cathode active material (CAM), a solid-state electrolyte (SSE) and a Li-metal based anode are capable of higher energy densities and may provide improved abuse tolerance in some areas, both key metrics. The use of Li-metal ASSBs, however, comes with challenges. The current barriers to commercialization include dendrite issues at the anode for Li-metal systems, as well as cathode instabilities due to oxidative degradation of SSE, reactivities between SSE and CAM, and loss of mechanical integrity.

Here, we report novel cathode structures incorporating: 1) conductive halide SSEs with high oxidative stability to enable use of 4 V-class CAM without any coating and 2) single-crystal CAM particles to eliminate intergranular cracking associated with volume changes and mechanical instability. As an example, results obtained on ASSB cells with a single-crystal LiNi$_{0.8}$Mn$_{0.1}$Co$_{0.1}$O$_2$ (SC-NMC) CAM, a 300-um thick Li$_3$YCl$_6$ (LYC) SSE, and a Li-In alloy anode are shown in Figure 1, along with a comparison with equivalent ASSB cells with a commercial polycrystalline NMC811 (PC-NMC) CAM. The SC-NMC cell demonstrated significantly improved cycling performance. At the C/2 rate, the capacity decreased from ~105 to 80mAh/g after 830 cycles in the PC-NMC cell and ~140 to 125mAh/g after 1000 cycles in the SC-NMC cell, a retention of ~76% and 89%, respectively. Similar values were obtained on the discharge energy. The initial capacity difference may be due to a surface coating (which is present on most commercial 811 CAM) on the PC-CAM, but diagnostics could not be performed on this material to confirm that). Post-mortem analysis reveals superior mechanical stability of the SC-NMC cathode whereas significant morphological changes were observed on the cycled PC-NMC, including extensive cracking and disconnections between the LYC and NMC. The design principle described here might be expandable to ASSB cells with other types of halide SSEs and CAMs.

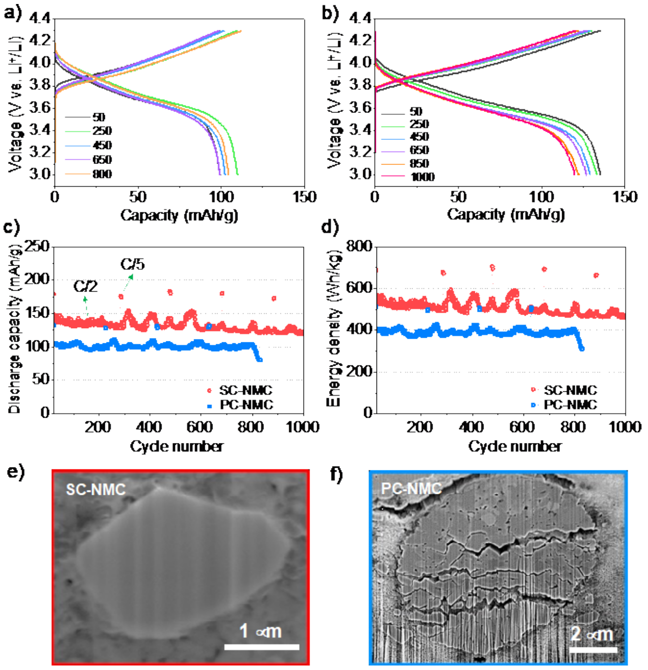


**Figure 1.** a-b) Voltage profiles of PC-NMC and SC-NMC ASSB cells, respectively. c-d) Discharge capacity and energy density retentions of the ASSB cells, respectively. e-f) Cross-sectional SEM images showing better mechanical stability of 9.04 mg/cm2 SC-NMC cathode composite upon cycling. All cells were cycled at room temperature at C/2 rate for 200 cycles followed by 3 cycles at C/5. This sequence was repeated throughout the testing. The performance fluctuation shown in c) and d) is due to room temperature variation in the laboratory, which ranged from 25±5 oC during the test.

# Polymer catholyte for solid state batteries enhanced by residual solvent

*The use of residual solvent dramatically influences cathode performance and improves capacity retention in ASSBs.*

**_Lawrence Berkeley National Laboratory_**

All-solid-state batteries (ASSB) promise high energy density through the use of a Li metal anode, and possibly improved safety due to the absence of a flammable liquid electrolyte. Favorable cathode performance and durability are two challenges with using solid electrolytes. Here, we show that retained residual solvent dramatically improves the performance of a cathode containing solid polymer binder. A very small amount of solvent retained in the polymer/Li-salt composite plasticizes the polymer, thereby greatly increasing Li-ion conductivity. The cathode was combined with a solid sintered ceramic separator and Li metal anode (Figure 1), demonstrating a pathway to a viable ASSB.

Drying the cathode to different extents greatly impacts conductivity of the composite and therefore total cathode performance (inset to Figure 2). By optimizing the amount of residual solvent and polymer/Li-salt ratio, promising performance and capacity retention was achieved (Figure 2). The positive effect of residual solvent was observed over a very wide temperature range from -10°C to 60°C. Multiple solvents produced a similar effect, providing flexibility to select the solvent based on cost, safety, reactivity, and manufacturing considerations. The cycling data were obtained using a $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ cathode ($2 mg/cm^2$ loading), Li metal anode, and a 300-micron thick $Li_{6.25}Al_{0.25}La_3Zr_2O_{12}$ electrolyte in an approximately 100mAh coin cell. It was found that, without the residual solvent, the cell impedance was too high to cycle the cell.

The sensitivity of cathode performance to small variations in solvent content may explain some of the disparate reports in the literature, where uncontrolled drying leads to unknown levels of residual solvent.

This work supports the goal of ASSBs with high energy density and may pave the way for future work to design a truly liquid-free cell.

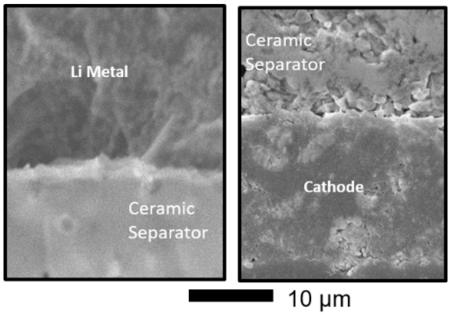


**Figure 1.** Cross-section image of the separator/cathode structure. The separator is an oxide ceramic and the cathode is a solid composite of NMC active material, carbon, polymer catholyte, and trace residual solvent.

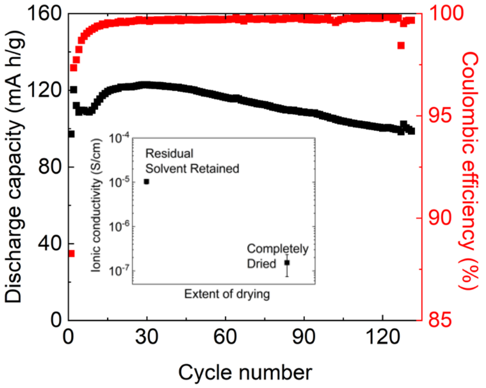


**Figure 2.** Capacity retention of a cell with residual solvent cycled at 25°C and 20 hour full charge/discharge cycle. The inset shows the conductivity of the polymer/Li-salt composite with and without residual solvent.

*2022 U.S. DRIVE Highlight*

# Low-Cost & Fast-Charging Electric Vehicle Lithium-Ion Batteries Based on Neocarbonix Electrode Technology

*Neocarbonix electrodes eliminate conventional PVDF polymer binders, and the need to use toxic NMP solvent, resulting in improved battery performance and reduced manufacturing costs.*

## *Nanoramic Laboratories and United States Advanced Battery Consortium*

Nanoramic has re-invented the way electrodes are manufactured by removing the conventionally used polymer binder, polyvinylidene fluoride (PVDF), from the active material layer, and eliminating the need for toxic n-methyl-2-pyrrolidone (NMP) solvent, thus creating Neocarbonix (NX) technology. NX improves lithium-ion battery (LiB) performance, decreases manufacturing costs, and is a drop-in replacement for today's gigafactories. Additionally, NX simplifies the direct recycling process of cathode active material and reduces $CO_2$ emissions during manufacturing by eliminating NMP. Such benefits may enable a faster adoption of electric vehicles and the related impact on greenhouse gas emissions.

In Nanoramic's NX electrodes, a 3D nanoscopic carbon matrix works as a mechanical scaffold for the electrode active material and mimics the polymer chain entanglement. Chemical bonds are present between the surface of the carbon, the active materials, and the current collector, promoting adhesion and cohesion. As opposed to polymers, the 3D nanoscopic carbon matrix is electrically conductive, which enables very high power. This scaffold structure is also suitable for producing thick electrodes, which increases the energy density of LiB cells.

Nanoramic is optimizing its NX technology to meet the United States Advanced Battery Consortium's technical requirements and has already met several targets. Nanoramic built small format 4Ah cells capable of over 330 Wh/kg and 80% charge in 15 minutes (Figure 1). The NX electrode also enabled coating speeds three times faster than conventional cathodes using NMP solvents and PVDF binder with the same coating equipment. Figure 1 also displays the 4C-rate discharge capacity retention of ~60% even with high loading electrode ≥5.8 $mAh/cm^2$. Lastly, through NX's manufacturing processing, and high energy density advantage, the tested cells delivered a cost reduction of up to ~20%.

Nanoramic's next steps in this project will be to make further advancements in LiB cycle life and cost reduction through NX technology.

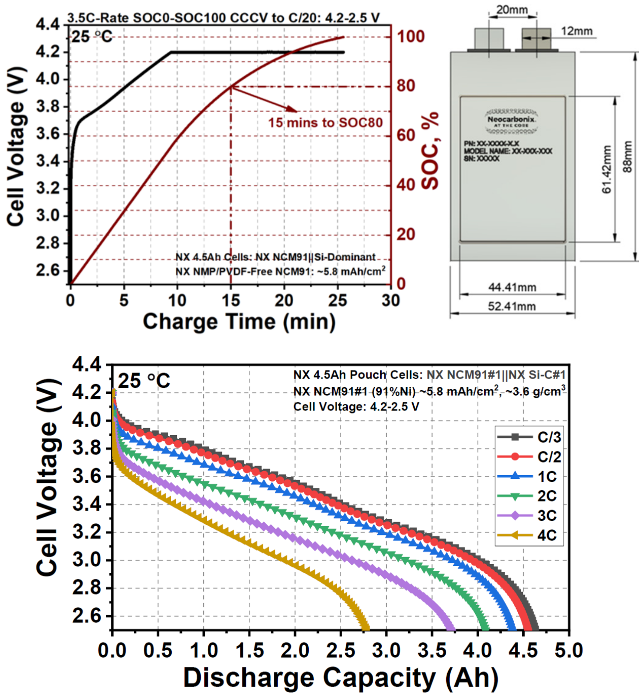


**Figure 1**. NX NCM91||SiGr 4.5Ah battery cells: 3.5C CCCV C/20 cutoff fast-charging and various C-rate discharge (C/3, C/2, 1C, 2C, 3C, 4C) performance with high-capacity electrode loading of ~5.8 $mAh/cm^2$.

*2022 U.S. DRIVE Highlight*

# Machine Learning Enhances Battery Life Prediction

*Machine-learning-assisted life models can have improved accuracy compared to human-expert models. A new algorithm reduces time required from battery subject-matter experts when sufficient and relevant chemistry-and-design-specific short-term data is used.*

## *National Renewable Energy Laboratory*

Accurate life predictions are crucial for optimizing battery system design and use. Examples include extending life, establishing fast-charge protocols, anticipating battery maintenance, and maximizing battery revenue. But developing accurate battery lifetime models is challenging because degradation rates are sensitive to many factors including temperature, maximum state-of-charge, depth-of-discharge, and dis/charging current rates.

Battery life-predictive models typically require minimum six to nine months of test data. NREL researchers developed the ‘Autonomous Identification of Battery Lifetime Models’ toolkit, AI-Batt, which uses machine-learning (ML) to autonomously identify high-performing models from tens of millions of possibilities, resulting in models that have roughly twice the accuracy of models identified by humans (Fig 1) (Gasper et al, 2021, J. Echem. Soc. 168 020502). After training life models to fit accelerated aging data, lifetime predictions can then be made for real-world applications with dynamic loads or varying use (Fig 2) (Gasper et al, 2022, J. Echem. Soc. 169 080518).

Battery life models identified via ML are used for a variety of applications, such as electric vehicle battery life prediction (Smith et al, 2021, J. Echem. Soc. 168 100530), health prediction (Gasper et al, 2022, Cell Rpts. Phys. Sci., 101184), and for stationary energy storage optimization. NREL has incorporated battery lifetime models into several open-source technoeconomic energy system simulation tools, such as REOpt ® and System Advisor Model.

Presently, NREL is merging ML-based lifetime prediction with physics-based electrochemical models. This physics/ML hybrid method promises to improve accuracy across a wide variety of use cases, including during extreme fast charge. It also enables early life prediction by requiring less test data and provides a potential future pathway to enable the transfer of data-based learnings to other cell designs and chemistries.

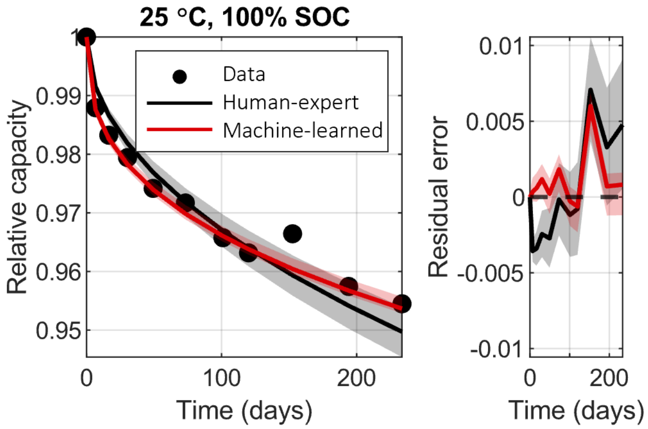


**Figure 1.** Calendar degradation of lithium-ion battery predicted by human-expert and ML models with 90% confidence intervals. ML models fit aging data with half of the error of human-expert models and have better confidence.

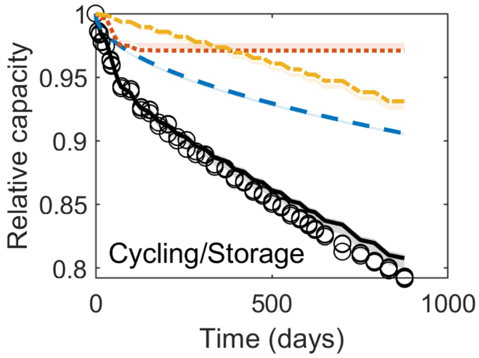


**Figure 2.** Validation of ML lithium-ion battery life model on dynamic aging test with monthly variation of cycling and storage. Total degradation is the sum of three aging modes identified from accelerated aging test data (red = “break in” cycling induced fade, yellow = longer term cycling fade, blue – calendar induced fade) and fit using ML.

*2022 U.S. DRIVE Highlight*

# A Hydrothermal Manufacturing Process for Improved and Less Expensive Cathodes for Lithium-Ion Batteries

*Cleaner, more affordable, and more efficient way to make a high-capacity cathode material used in lithium-ion batteries for energy storage application.*

***Oak Ridge National Laboratory***

Lithium (Li)-ion batteries are used in products from appliances to cell phones, and in electric vehicles (EV). As demand for EVs increases, so does the need for more sustainable production of high-voltage cathodes, a key electrochemical energy storage component. However, a variety of problems are associated with traditional methods of processing cathode materials.

The first obstacle is a reliance on cobalt, a rare metal mined and refined abroad. This dependence on foreign sources poses risks to American manufacturing supply chains and transportation infrastructure. The balance of other metals common among cathodes can also make the manufacturing process longer and more hazardous. For example, high nickel concentration has led to the widespread use of a chemical mixing method for cathode production that requires large quantities of ammonia for corrosive reactions. Use of the toxic chemical increases costs, heightens health and environmental concerns, and wastes large amounts of water to reduce acidity.

Researchers at Oak Ridge National Laboratory recently developed a new method for producing a class of cobalt-free Li-ion cathode material, $LiNi_{0.9}Mn_{0.05}Al_{0.05}O_2$, termed NMA9055 (Figure 1a), using a hydrothermal synthesis method which is ammonia-free. This novel process offers the key advantage of moving the cathode industry to cleaner and more cost-competitive production (due to the removal of expensive cobalt) while putting less burden on the environment.

This new class of cobalt-free cathode material containing nickel, manganese and aluminum is created using an ammonia-free synthesis route and is expected to provide an easy path towards more sustainable cathode production. The result is a more affordable battery through a faster process, using less-toxic materials. The developed NMA material has properties similar to conventional Co-based cathodes (NMCs/NCAs) and thus can be seamlessly manufactured and integrated into current industrial scale manufacturing techniques. In summary, the developed NMA9055 material has the potential to address key Co issues facing the battery industry in addition to providing improvements in processing cost, performance, and structural and thermal stability.

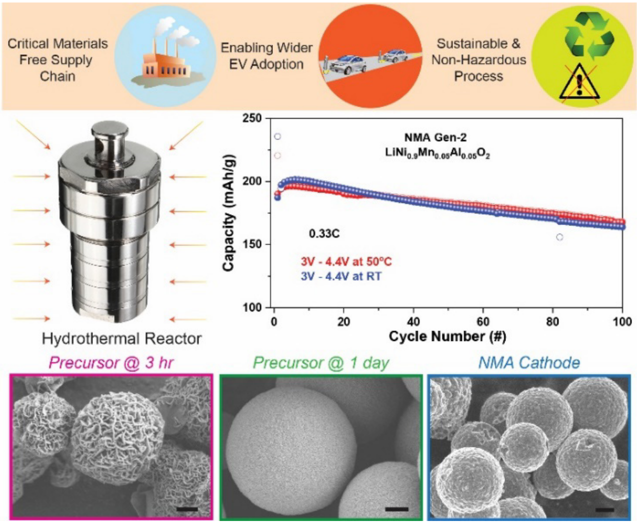


**Figure 1.** Development of Co-free cathode materials for next-generation Li-ion batteries.

*2022 U.S. DRIVE Highlight*

# High-Performance Low-Cobalt Cathode Materials for Lithium-ion Batteries

*A low-cost and effective coating has been developed to improve the cycling performance of low-Cobalt Nickel Cobalt Manganese Oxide cathodes-for lithium-ion batteries.*

***The Pennsylvania State University, Pacific Northwest National Laboratory, and Oak Ridge National Laboratory***

$Li[Ni_xCo_yMn_{1-x-y}]O_2$ (NCM) cathode materials have been one of the best choices for increasing the driving range of electric vehicles (EV) due to their high energy density and good cycling stability. However, the increased cost of cobalt (Co) over the past few years has significantly increased the price of the NCM material. Therefore, developing cathode materials with low- or no Co content while still achieving high energy density and low cost is both essential and urgent. Unfortunately, the cycling stability of many low-Co NCM cathodes is compromised by structural instability, non-uniform strain during cycling, and parasitic reactions between the cathode and electrolyte. The coating methods developed in this project are shown to be an effective strategy for alleviating these issues.

Specifically, we achieved a low-cost $LiFePO_4$ (LFP) coated NCM811 cathode (LFP/NCM811) via a dry coating approach, where the nanosized LFP is uniformly coated on the surface of NCM811 particles. Coin cell cycling (not shown) demonstrated a clear advantage of the LFP-coated NMC compared to uncoated. The 2.5 Ah pouch cells were assembled using 10 wt% LFP-coated NCM811 cathode and graphite anode. The cathode loading is 17.5 mg/cm², the N/P ratio = 1.1 and the cell achieved 450 Wh/L and 200 Wh/kg. Figure 1a demonstrates that the pouch cells cycle at room temperature (RT), with capacity retention of 76.7% after 2,413 cycles. Moreover, the cell could still achieve 67.3% capacity retention after over 1,600 cycles at 40°C.

Furthermore, the superior stability of LFP-coated NCM811 (LFP/NCM811) may improve calendar life. At 22 °C and at 100% state of charge (fully charged), the pouch cell using LFP coated NCM811 cathode shows better calendar life than uncoated NCM622 initially but appears to sustain a higher fade rate over the longer term (Figure 1b). In addition, the overall fade rate of these cells is higher than commercial cells, which is not understood at this time.

In summary, $LiFePO_4$ coating improves the cycling performance of low-Co layered structured cathode pouch cells. The team continues to investigate more effective coating materials for $Li[Ni_xCo_yMn_{1-x-y}]O_2$ cathode materials cobalt content of $\leq 0.04$.

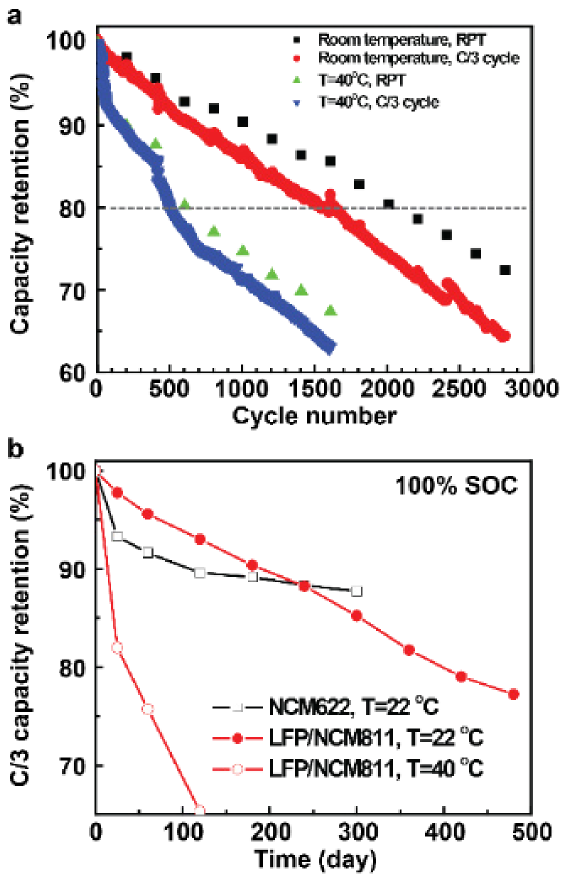


**Figure 1.** (a) Capacity retention pouch cells during C/3 cycling at RT and 40°C. (b) C/3 capacity retention of the LIBs using different cathodes during storage at different temperatures.

*2022 U.S. DRIVE Highlight*

# Zero-Cobalt, Zero-Strain, High-Rate Cathodes with Improved Thermal Stability

*A novel cathode formulation with no cobalt demonstrates good cycling stability in Li ion cells, while undergoing zero strain, a possible advantage for future solid state cell designs.*

## *University of California, Irvine*

Cobalt (Co) is considered the highest material supply chain risk for electric vehicles (EVs). However, eliminating Co from $LiNi_xMn_yCo_zO_2$ (NMC) cathodes can exacerbate thermal and chemo-mechanical instabilities due to presence of the high-nickel (Ni) concentrations of the cathode material, particularly at the surface where it is exposed to reactive electrolyte. In addition, the volume change during cycling that exists in high-Ni cathode materials can cause both structural degradations and mechanical failures. Another drawback is that nearly all high-Ni cathodes, irrespective of Co-level, suffer from intrinsically poor thermal tolerance in the charged (delithiated) state, owing to the combination of the strong oxidizability of $Ni^{4+}$ and oxygen release. Although increasing Ni content in cathodes enables higher capacities, it inevitably results in lower stability and reduced abuse tolerance, particularly at elevated voltages.

To address the thermal, electrochemical stability-capacity trade-off and volumetric change issue, the team at UC Irvine has developed a new class of concentration-complex stoichiometric layered oxides that have 1) zero cobalt content, 2) zero strain (<1% relative volume change) within a 2.5V – 4.3V charge window, and 3) high thermal stability[1]. At the same time, they can deliver equal or greater specific capacity, energy density, and rate capability as their NMC counterparts that have the same Ni content. Two zero-cobalt chemistries have been demonstrated. The first has high Ni content (Ni content = 80%, HE-N80) targeting high-power and long-range EV applications. Differential scanning calorimetry (DSC), capacity, rate capability, and cycling data for HE-N80 is shown in Figure 1 and demonstrates the advantage as compared to NMC811. A second cathode with lower Ni content (Ni content = 50%, HE-N50) targeting medium-range EV applications, is comparable in energy to NMC-532. Both cathodes have excellent cycle life in lithium-ion cells due to the combined effect of zero strain, high oxygen retention, suppressed phase transformation and reduced transition metal (TM) dissolution. It is worth noting that the manufacturing processes of these cathodes are the same as NMC-811 and NMC-532 respectively allowing them to be quickly scaled up in domestic manufacturing facilities. Some of these cathodes contain small amounts (less than 3%) of rare elements such as Nb and Mo, the cost of which must still be assessed.

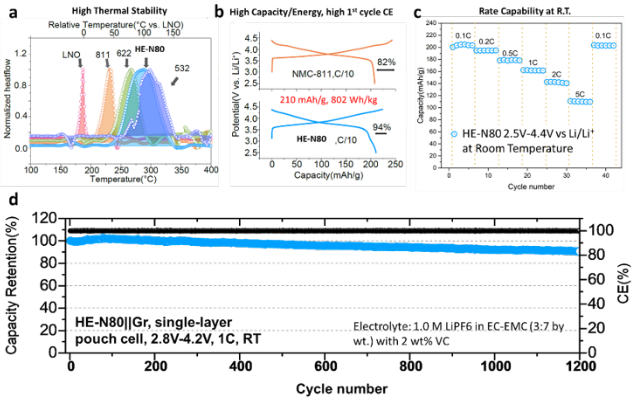


**Figure 1.** The electrochemical and thermal stability performance of UCI's HE-N80 cathode (Ni content 80%). (a) DSC measurements of charged cathodes. (b) Comparison of HE-N80 and NMC-811. (c) Rate capability. (d) Cycle life measurement in a single layer Li-ion pouch cell.

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[1] https://www.nature.com/articles/s41586-022-05115-z.

*2022 U.S. DRIVE Highlight*

# Enabling Long Cycle Life in High Voltage Co-Free Spinel Oxide Cathode

*A dry electrode fabrication method and all-fluorinated electrolyte are developed to achieve high loading spinel oxide cathode with improved battery life.*

## *University of California San Diego*

LiNi$_{0.5}$Mn$_{1.5}$O$_4$ (LNMO) is a promising cobalt-free cathode for next generation lithium-ion batteries due to its high operation voltage (~4.7V). However, it still faces challenges such as poor cycle life and low electronic conductivity.

In this work, researchers at UCSD developed a dry electrode fabrication method to enable high areal loading LNMO (up to 9.5 mAh/cm$^2$, over two times that of current electric vehicle battery cells) as shown in Figure 1A. Compared to 3 mAh/cm$^2$ loading, the cell performance at this high loading is comparable at low (C/10) rate. This fabrication method is also a solvent-free process, rendering it more environmentally benign. Researchers also used plasma focused ion beam scanning electron microscopy (PFIB-SEM) to investigate phase uniformity which shows that active materials and conductive carbon are uniformly distributed (Figure 1B) which may promote fast electron transport.

To address high voltage stability, computations on different facets (Figure 1C) of the material showed that fluoroethylene carbonate (FEC) molecules have the highest energy barrier among the candidates considered which provides stronger oxidation stability at high voltage. Together with novel all-fluorinated electrolyte, the C/3 cycling stability of the LNMO/graphite full cell is also significantly enhanced (Figure 1D).

This dry electrode processing approach, which may be more cost-effective, environmentally benign, and sustainable, can be applied to other cathode materials operating with voltages higher than 4.5 V.

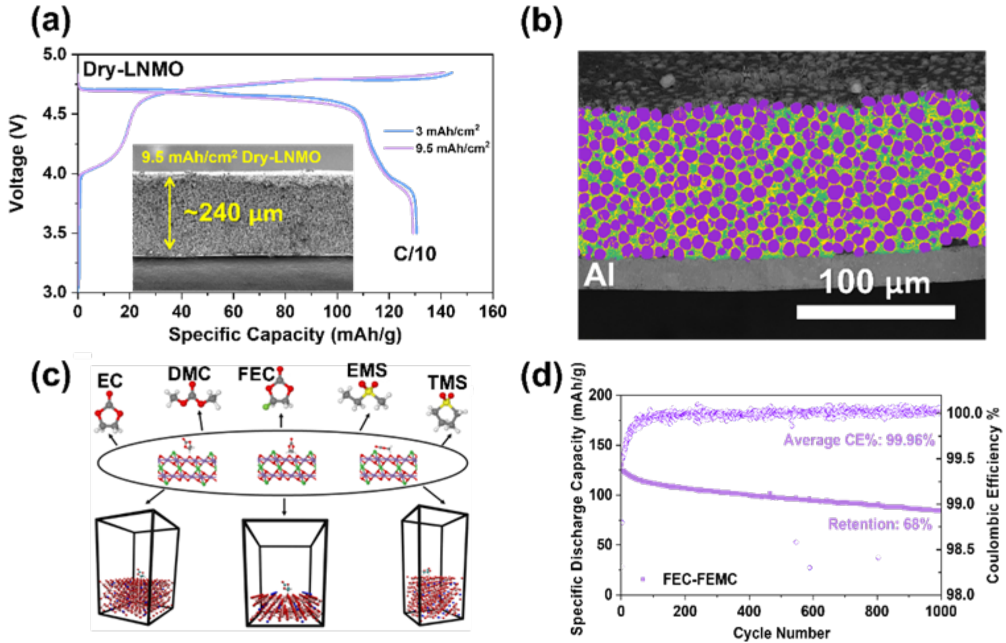


**Figure 1.** (A) Electrochemical performance of both low and high loading LNMO and the SEM cross-sections. (B) FIB-SEM of dry-LNMO. Purple represents LNMO, green represent carbon and yellow represents porosity. (C) A three-component framework for the computational screening of electrolyte/cathode interface materials (D) Long-term cycling of dry-processed LNMO full cell.

# Materials

*2022 U.S. DRIVE Highlight*

# Next Gen High-Efficiency Boosted Engine Development

*Completed design and fabrication of an engine targeting 23% reduction in fuel consumption and 15% reduction in weight using advanced materials and manufacturing techniques.*

## *Ford Motor Company, FEV North America, and Oak Ridge National Laboratory*

This project explores and develops engine efficiency and weight-saving technologies. While the market share of battery electric vehicles is increasing, many vehicles will continue to use conventional or hybrid powertrains well beyond 2030. Improvements in engine efficiency and reductions in powertrain weight will reduce vehicle-related $CO_2$ emissions for decades to come.

Addressing the dual goals of increased efficiency and reduced weight required a comprehensive reevaluation of all engine systems. In many cases, the technology implemented to improve efficiency increased engine weight. The team leveraged advanced materials, additive manufacturing techniques, and architectural features to offset these weight increases.

Advanced materials were selected for several key components. A glass and recycled carbon fiber filled polypthalamide was selected for the structural oil pan. The pan was manufactured using extrusion compression molding and achieved more than 30% weight reduction.

Stiffness of the engine block main bearing caps was enhanced using an aluminum ladder frame bonded to an additively manufactured windage tray. A high-performance polyetherimide thermoplastic was selected for the windage tray reducing mass by more than 50%.

Additive manufacturing techniques enabled designs not possible with traditional methods. Printing the cylinder head casting cores reduced the number of cores, eliminated the need for draft angles, and facilitated reentrant features all of which reduced weight.

Packaging the engine's active pre-chamber ignition system presented several challenges. The pre-chamber bodies were printed using AISI 8620 steel which provided the required material properties and complex geometry in a small volume.

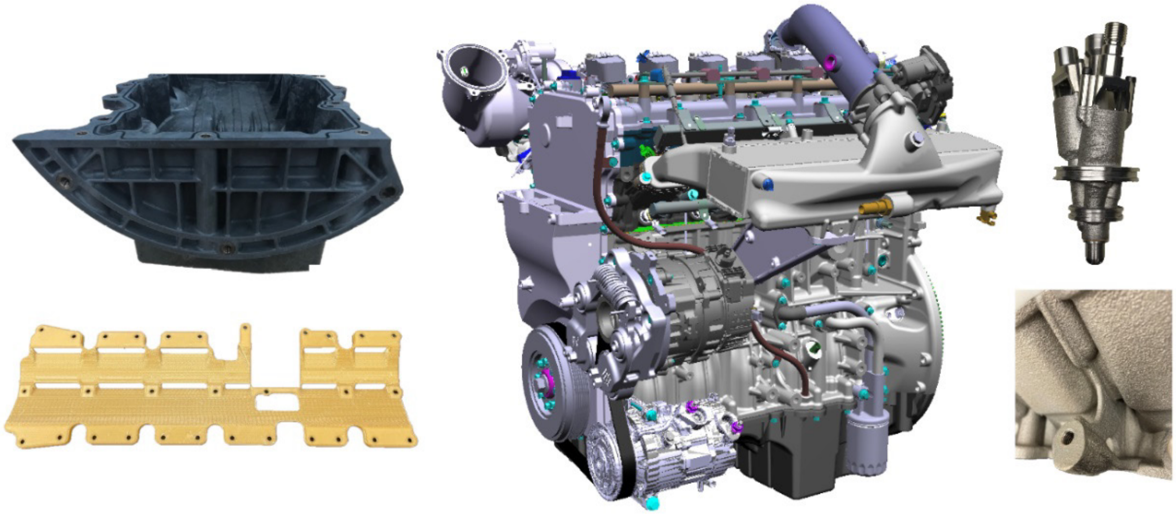


**Figure 1.** Oil pan, windage tray, engine assembly, pre-chamber ignition system, and reentrant casting features.

*2022 U.S. DRIVE Highlight*

# Low-Mass and High-Efficiency Engine for Medium-Duty Truck Applications

*Project to develop advanced materials and combustion technologies capable of achieving ≥10% fuel efficiency improvement and ≥15% engine weight reduction compared with a baseline L96 engine.*

## *General Motors*

Today's transportation vehicle customers are demanding manufacturers to produce engines with lower weight and improved efficiency to reduce fuel consumption, emissions and costs associated with vehicle use, while maintaining or even increasing engine performance. Developing the next generation of high-efficiency, very-low-emission internal combustion engines thus requires a combination of new combustion strategies, advanced materials, and new materials processing techniques to further increase engine efficiency and reduce weight.

This is a collaborative project between General Motors, Oak Ridge National Laboratory, The Ohio State University, Michigan Technological University and ECK Inc. The team has developed several advanced materials and manufacturing technologies to reduce mass and improve performance. A novel low pressure precision sand casting (LPPSC) process has been developed to cast high quality Al cylinder head and engine block. The high cycle fatigue (HCF, 10^7 cycles) strength of the LPPSC heads at 250°C has improved by >20% compared to the baseline heads for the same alloy used. Similar improvement is also seen in the cast Al block, which is 58.3kg lighter than the cast iron baseline block.

High strength Al-Ce based (DuAlumin3D) alloy has been developed and additively manufactured (AM) into piston which is 11g lighter than the cast Al baseline piston. The HCF strength of the AM pistons at 300°C is increased by >50% compared to the cast Al pistons. The improvement in low cycle fatigue is more pronounced for the AM pistons (Figure 1).

High strength cast steel alloy and high modulus cast nodular iron alloy have been developed to replace costly forged steel cranks. Both alloys have been cast into quality hollow crankshafts with the optimal gating/riser systems and casting process developed. The cast steel crank is very comparable to the forged steel baseline crank in terms of fatigue performance. After hot isostatic pressing, the cast steel crank shows higher fatigue strengths (5-10%) than the forged one. The cast steel and cast nodular iron cranks are 240g and 800g lighter than the forged baseline, respectively.

Through process modeling and local material property simulation, following the integrated computational materials engineering approach, has been conducted for all casting parts and AM pistons to ensure their designs to meet the performance and durability requirements (Figure 2).

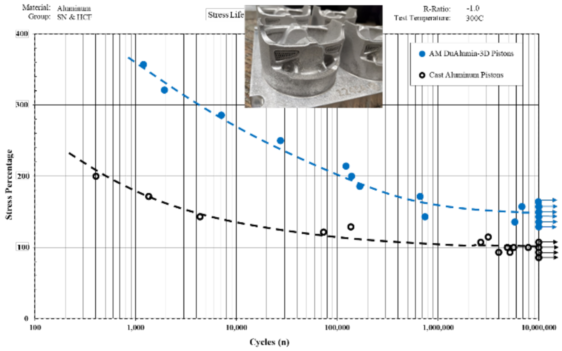


**Figure 1.** S-N fatigue data of cast Al and AM pistons at 300°C.

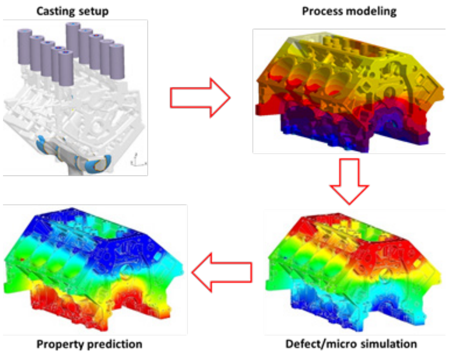


**Figure 2.** Through process modeling approach flow for cast aluminum block made by LPPSC process.

*2022 U.S. DRIVE Highlight*

# New Fatigue-Resistant Aluminum Alloys via Additive Manufacturing

*Lightweighting electric vehicles for energy efficiency.*

***Oak Ridge National Laboratory***

Range-anxiety is a barrier towards wider adoption of electric vehicles (EVs). To mitigate that barrier, manufacturing lighter EVs with increased use of lightweight Al alloys in place of heavier steels (~3X heavier) is an increasingly attractive option. Additive Manufacturing (AM) can augment the benefits of Al alloys by printing components with complex geometries that are also lighter than the simpler geometries possible with conventional manufacturing. Thinner sections are possible with printed alloys, since the non-equilibrium processing conditions in AM can produce alloys with superior microstructure and mechanical properties.

Fatigue performance of AM alloys has been a major concern because various defects (lack of fusion, gas porosity, hot-tear cracks, etc.) produced during AM can reduce fatigue strength. A new Al-Ce-Ni-Mn alloy has been designed by ORNL specifically for laser powder bed AM. The processing parameters were optimized to achieve >99.8% relative density. Figure 1a shows high cycle fatigue properties of the alloy at 350 °C. The fatigue strength at 350 °C is comparable to those of the most-fatigue resistant wrought Al alloys at 315 °C. Surprisingly, fatigue cracks were found to initiate at oxide inclusions in the alloy instead of porosity. Figure 1(b, c) compares the size of pores and inclusions in the alloy measured by x-ray computed tomography (XCT). The largest pores are smaller in size compared to the largest oxide inclusions, which is consistent with fatigue cracks initiating at the latter sites. This result demonstrates that with proper alloy design and optimization of processing parameters it is possible to minimize defects and achieve fatigue performance in AM Al alloys that is notably superior to wrought alloys.

The Al-Ce-Ni-Mn alloy was developed for higher temperature environments that can find application in EV regenerative brake systems. The insights gained from this work, however, have wider implications for pathways toward deploying superior lightweight AM alloys for EVs. A path forward towards additional improvement in fatigue strength would require minimizing oxide inclusions which either originate during powder atomization, powder handling and storage, and/or printing.

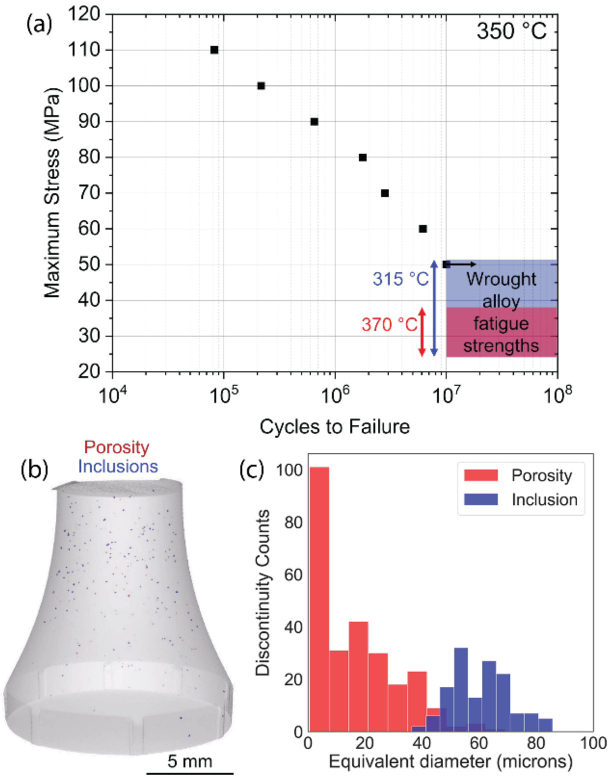


**Figure 1.** (a) Maximum applied stress vs. cycles to failure for the Al-Ce-Ni-Mn alloy during fatigue tests at 350 °C. Stress ratio, R was -1 and sample runout was considered at $10^7$ cycles (horizontal arrow). (b) XCT reconstruction of a tested fatigue specimen showing pores and inclusions with the corresponding distribution shown in (c).

*2022 U.S. DRIVE Highlight*

# New Frontier in Polymer Matrix Composites via Tailored Vitrimer Chemistry

*Unraveling a path for multi-cycle recycling of tailored carbon fiber-reinforced vitrimer composites.*

## *Oak Ridge National Laboratory*

Manufacturing transformation toward a net-zero carbon society demands polymeric composite materials to be reprocessable in circularity in an energy-efficient and stable manner. Carbon-fiber-reinforced polymers (CFRPs), are strong, lightweight materials that can help lower fuel consumption and reduce emissions in critical areas such as transportation. However, unlike metal competitors, CFRPs are not typically recyclable, meaning wider adoption could present waste challenges. While advances have been made for recycling CFRPs, conventional recycling technologies are energy intensive, and their mechanical properties are typically much lower than the original product. As a consequence, recycling rates remain very low, and the poor recyclability of CFRPs is the major bottleneck for wider adoption of lightweight materials.

Oak Ridge National Laboratory scientists have identified the tailored resin system with exchangeable disulfide bonds for CFRPs to overcome such intrinsic chellenges. The strategy involves the incorporation of dynamic disulfide bonds bridging between ductile polyurea segment and mechanically robust epoxy network (Figure 1). The dynamic polyurea/epoxy (DPE) vitrimers were synthesized by reacting tailored ratios of aliphatic polyisocyanate and diglycidyl ether of bisphenol A using 4-aminophenyl disulfide as dynamic crosslinks (Figure 1). The ductile polyurea not only improved the mechanical properties (e.g., toughness, resilience, ductility) but also decreased the processing temperature, which thus ultimately improved recyclability. Because of the rapid exchange reactions and the efficient polyurea/epoxy chain rearrangement, the DPE resins exhibited superior reprocessability with a rapid processing rate and excellent recovery of mechanical strength compared with conventional epoxy vitrimers (DE). For example, the DPE vitrimer exhibits 6 times faster bond rearrangement and ~40°C lower reprocessing temperature, which enables full recovery of the mechanical strength throughout 6 reprocessing cycles, while the conventional vitrimer lost ~63% of strength (Figure 1). Moreover, the CFRPs prepared with the DPE vitrimers exhibit facile multi-cycle processability and repairability. These findings provide a solution to the fundamental challenges of high energy/carbon intensiveness and mechanical deterioration upon recycling of thermoset composites.

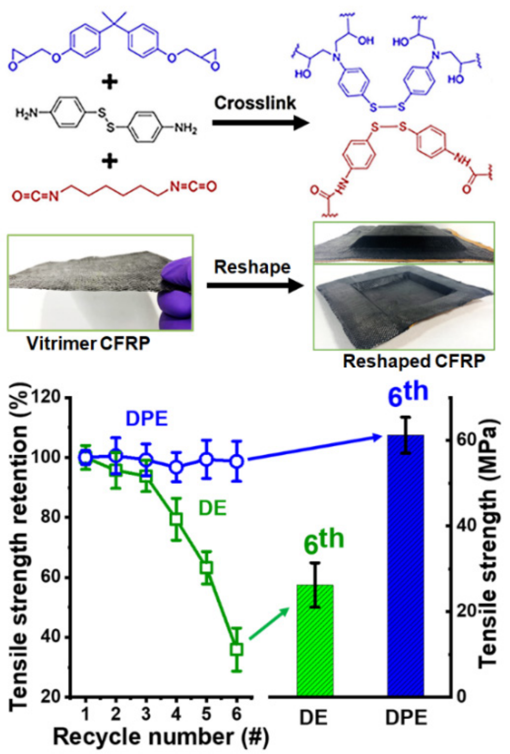


**Figure 1.** Synthesis of crosslinked DPE resin (Top), The multi-layered composite is reshaped to a 3D shape after the compression molding process (middle), and Summarized tensile strength values of reprocessed DE and DPE (Bottom).

*2022 U.S. DRIVE Highlight*

# Surface Modifications for Improved Joining and Corrosion Resistance

*Description: Laser and plasma surface modifications improved joint strength and corrosion resistance.*

## *Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Argonne National Laboratory*

Lightweight multi-materials vehicles have been a new paradigm for decarbonization. To achieve this concept, higher specific strength materials, such as high strength aluminum (Al) alloys, magnesium (Mg) alloys, carbon fiber reinforced polymers (CFRP), and advance/ultrahigh strength steels (AHSS/UHSS), are being integrated into vehicle structures. Integrating such multi-material systems into a vehicle raises joining and corrosion issues. To address these critical challenges, Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Argonne National Laboratory (ANL) teamed up to develop novel surface modification techniques to improve the joint performance and mitigate corrosion. Several joining techniques for multi-material joints were developed by ORNL and PNNL under Joining Core Program funded by the Department of Energy Vehicle Technology Office. High velocity riveting, friction based riveting, adhesive, and hybrid (with adhesive) were used to join 2T or 3T lap joint configurations.

The researchers from ORNL and PNNL developed laser and atmospheric plasma surface treatment to form the desired oxide layer on Al, CFRP, and dual phase (DP) steels substrate to increase surface energy for enhanced adhesion between adhesive and surface modified substrate and improve corrosion performance. To further investigate the phases on the surface advanced characterization was performed using at the advanced photon source located at ANL. Figure 1 shows STEM EDS maps for atmospheric plasma treated AA7075 alloy, indicating formation of thick and dense oxide layer on the surface. Electrochemical impedance spectroscopy was used to evaluate the improvement in macroscopic corrosion resistance of due to surface treatment. The improvement in corrosion resistance ranged from 4x to 75x compared with non-treated sample. This also led to a 14% increase in adhesive bond strength in Al7075-DP980 joint after plasma treatment.

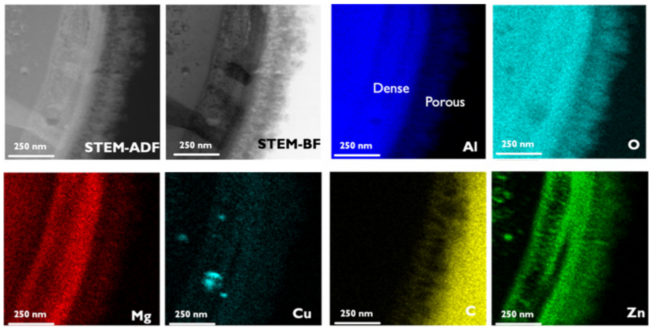


**Figure 1.** Scanning transmission electron microscopy (STEM) with element dispersive spectroscopy (EDS) images showing thick and dense Al, Mg, Zn oxide formation on AA7075 alloy after atmospheric plasma treatment.

Researchers at PNNL and ORNL also utilized ASTM B117 standard testing to evaluate corrosion performances of these multimaterial joints with surface modifications. Localized surface corrosion measurements by scanning electrochemical cell microscopy show a greater corrosion resistance (up to 2500% increase) for plasma treated Al, DP590 and CFRP surfaces. Joint performance evaluated after 1400 hours of ASTM corrosion tests indicated 70% more resistance to corrosion in these surface modified hybrid multimaterial joints.

*2022 U.S. DRIVE Highlight*

# Enhancing Aluminum Conductivity for Lightweight EVs

*Manufacturing Technology that Enables Higher Functionality in Aluminum Composites.*

## *Pacific Northwest National Laboratory*

With the focus on EV performance, cost, and range extension, the automotive industry is eagerly seeking materials with enhanced functionality such as electrical conductivity—or how well a material transports an electric charge—over the standard copper material. This need is compounded by copper supply chain concerns and interests to develop alternative materials. The goal—to improve efficiency, weight, power density, and reduce cost of stators, rotors, windings in electric machines like motors and wireless charging components.

Pacific Northwest National Laboratory (PNNL) researchers are developing enhanced conductivity aluminum-graphene composites using PNNL's Shear-Assisted Processing and Extrusion technology (ShAPE™). In the aluminum-graphene composites, the graphene additives serve as 'high-velocity' pathways for energy carriers in the composite. Previous attempts at manufacturing aluminum-graphene composites have not been successful owing to the propensity for carbon (from graphene) to react with aluminum to form an insulating intermetallic that is detrimental to enhancing conductivity. An effective manufacturing process is critical for distributing the graphene in the aluminum matrix, synthesizing the composite with minimal porosity, and preventing the interfacial reaction to minimize carrier scattering, especially at higher operating temperatures.

Recent advances in PNNL's ShAPE technology provide the key to manufacturing—at industry scale—with the desired interface and graphene placement within the aluminum matrix to enhance electrical properties. ShAPE is also key to enable the use of lower cost reduced graphene oxide particles as additives for enhancing metal conductivity instead of the high-cost ultra-pure graphene foils–the process can facilitate the delamination and distribution of the lower cost additives more effectively compared to other processes.

The project, sponsored by the U.S. DOE Vehicle Technologies Office, fabricated over 10-m-long aluminum-graphene composite wires measuring 1-2 mm diameter. Electrical conductivity increased as the graphene content increased. Even at such low graphene concentrations as 0.1 wt.%, the composites showed 65.4% IACS electrical conductivity, which is >7% higher than commercial AA1100 alloy used typically in electric motor windings. The wires also showed >12% lower temperature coefficient of resistance compared to AA1100, making them more efficient at operating temperatures of ~200°C. These wires can be drawn down to desired forms for motor windings, with minimal loss to electrical performance. The team is also developing atomistic and mesoscale material models to guide the development of composites with even more improved electrical performance.

These results constitute a disruptive approach to light-weighting electric machines such as motors, without sacrificing performance. These composites have several potential applications and can replace conductor-grade metals in electric machines, busbars, EV charging systems, and electronics to enhance conduction efficiency, improve performance, or light-weighting, depending on product need.

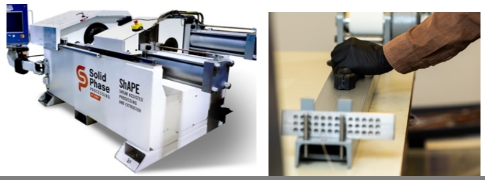


**Figure 1.** ShAPE™ equipment at PNNL (left) used to make 10-m-long aluminum-graphene wires that can be drawn down (right) similar to commercial motor windings.

*2022 U.S. DRIVE Highlight*

# Variable Wall Thickness Extrusion

*Development of Shear-Assisted Processing and Extrusion to achieve tailored wall thickness along the length of an extrusion for improved formability, joining, and energy absorption.*

## *Pacific Northwest National Laboratory*

As automakers drive toward lighter vehicles and more streamlined manufacturing, there is a need for components that improve performance and downstream integration. An emerging approach to satisfy these often-competing objectives is the development of components with locally modified properties. For example, advanced roof rails may benefit from reduced wall thickness in the bends to improve formability, and increased wall thickness at the ends to improve joining and energy absorption. To this end, Pacific Northwest National Laboratory (PNNL) is developing Shear Assisted Processing and Extrusion (ShAPE™) technology that is capable of tailoring wall thickness along the length of a product.

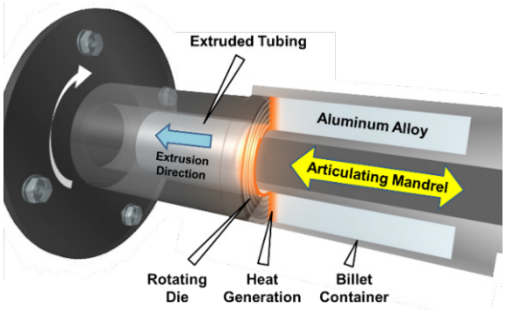
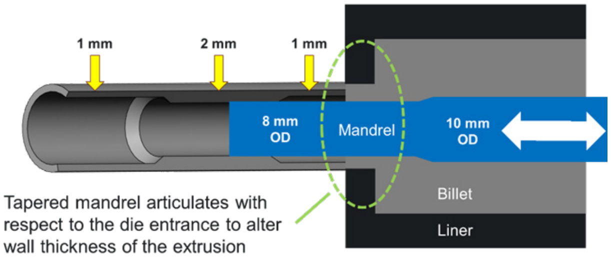


**Figure 1.** Schematic of ShAPE process with articulating mandrel to actively control wall thickness during extrusion.

ShAPE is an extrusion technology where feedstock material is rammed against a rotating die, resulting in heat generation and severe deformation of the material (Figure 1). The combined effect of axial force and rotational shear at elevated temperature promotes extensive refinement of the metal grain structure and achieves better compositional uniformity. Until now, round profiles extruded by ShAPE have been limited to uniform wall thickness. For this project, an articulating mandrel has been integrated with ShAPE to enable active control over wall thickness during extrusion (Figure 2.)



Tapered mandrel articulates with respect to the die entrance to alter wall thickness of the extrusion

**Figure 2.** Tapered mandrel for tailoring wall thickness along length.

For this project, aluminum alloy (6061, 6111, and 5182) tubing was extruded with 12 mm outer diameter and wall thickness transitioning back and forth between 1–2 mm along a 2-meter length (Figure 3). Extrusions were performed over a range of extrusion speeds from 1.2-4.9 meters/min with dimensional stability of the wall within 0.004”.

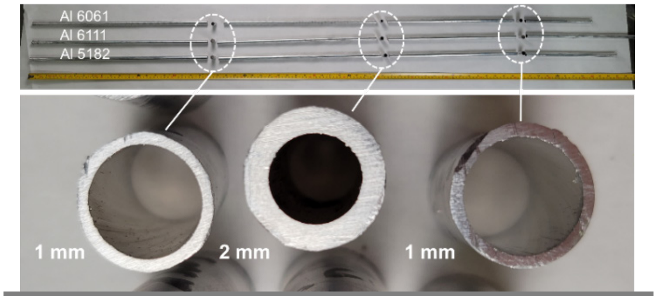


**Figure 3.** Cross sections of aluminum alloy tubing with wall thickness tailored to 1mm and 2mm along the extrusion length.

Future efforts will focus on scaling to larger extrusion profiles using a higher capacity ShAPE 2.0 machine currently being manufactured by Bond Technologies. ShAPE 2.0 is expected to be operational at PNNL in FY23 Q4 and eventually capable of full-scale roof rail components with tailored wall thickness.

*2022 U.S. DRIVE Highlight*

# Cast Magnesium Local Corrosion Mitigation

*Developed novel local surface alloying processes to mitigate corrosion in magnesium high pressure die cast samples.*

## *Pacific Northwest National Laboratory and Oak Ridge National Laboratory*

Magnesium alloys are excellent candidates for automotive light weighting applications due to their high specific strength. High Pressure Die Casting (HPDC) is the most widely used manufacturing process to produce Mg alloy parts as it is economical, fast and produces complex geometries. However, their poor corrosion performance under harsh automotive conditions prevents large scale implementation. Additionally, joining of Mg alloys with aluminum alloys or steels is challenging due to their susceptibility to localized galvanic corrosion. Surface coating methods are an excellent strategy to overcome these challenges. However, currently used coating methods designed to protect the surface of Mg alloys are often expensive, non-localized, time consuming and lead to the formation of porous surface films. To over this challenge, researchers at PNNL and ORNL are collaboratively utilizing surface alloying techniques such as cold spray and reactive coating processes, respectively. The current work is focused on modifying the surfaces on commercial products with curved and complex geometries to improve the corrosion and wear resistance. These coatings are also amenable to recycling and place no extra burden on the existing material recycling pipeline.

Cold spray is a solid phase coating method wherein powders of a coating material are ejected from a nozzle at supersonic velocities and additively deposited (layer-by-layer) onto the substrate surface. This process is capable of faster coating deposition and greater coating deposition efficiency compared to existing coating methods. Optimization of coating parameters produced highly dense aluminum alloys and zinc coatings on AZ91 and AM60 Magnesium alloy substrates (Figure 1a). These coatings had more than 1000% improvement in corrosion properties as compared to the base untreated magnesium alloy. Moreover, these coatings were metallurgically bonded to the substrate and their wear resistance was more than 25% better than the substrate.

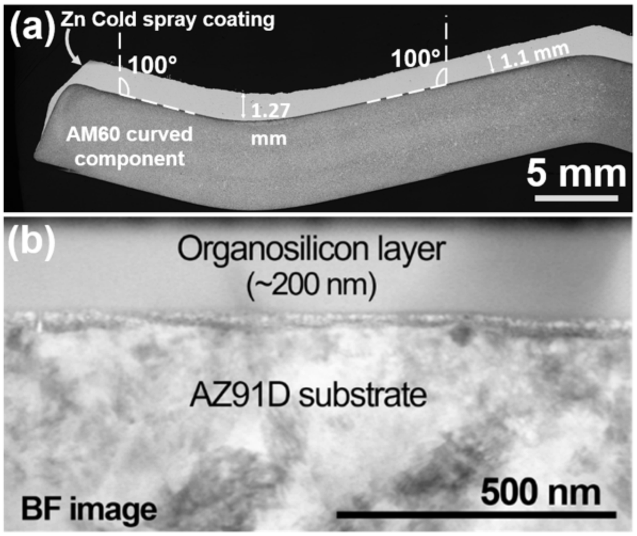


**Figure 1.** (a) Cross section of a curved automotive component of AM60 magnesium alloy cold spray coated with pure Zinc, (b) Cross section of an AZ91D magnesium alloy coupon with a 200nm thick organosilicon coating.

The surface modified $CO_2$/Li treated and organosilicon coated AZ91D formed a 2~3 µm thick carbonate layer with uniformly dispersed lithium rich Mg-O-C layers. Meanwhile, plasma-assisted organosilicon coating was ~200 nm thick (Figure 1 b), with no notable defects at the interface with AZ91D substrate and composed of Si, O and C. Corrosion evaluation exhibited 10x or greater corrosion resistance in the samples with optimized treatment compared to the untreated AZ91D alloy. Moreover, wear resistance of $CO_2$/Li treated AZ91D showed 10% improvement with respect to the untreated alloy, demonstrating another technical benefit of this treatment on Mg alloys for automotive application.

# Polymer Fiber-reinforced Polymer Composites

*Development of thermoplastic composites with the reinforcement of thermoplastic polymer fibers to achieve high-recyclability, weight reduction, and high specific mechanical properties for vehicles.*

***Pacific Northwest National Laboratory and Oak Ridge National Laboratory***

Polymer composites, which are lighter than metals and combine strong carbon fibers and tough plastics, have been widely used to fabricate structural components in automobile, aviation, and infrastructure. However, the efficient solutions for dramatically increased polymer composites waste have been encountering challenges. To this end, Pacific Northwest National Laboratory (PNNL) and Oak Ridge National Laboratory (ORNL) are co-developing polymer-fiber-reinforced polymers (PFRPs) to displace carbon/glass fibers, achieve high-recyclability, and lower the vehicle cost and weight. PFRPs can be used as a bumper and interior panels of a vehicle structure for crash resistance.

In this project, our investigation has been ranging from the individual component in composites (*i.e.*, polymer fiber, polymer matrix) to thermoplastic PFRPs. For instance, reinforcing polypropylene (PP) fibers were fabricated through melt-fiber spinning and subsequent multiple fiber drawing process. As shown in Fig. 1, the melting onset temperature of the fiber was elevated from 130 to 160℃ due to the changes of internal crystal structures. Other properties such as strength, ductility, thermal shrinkage, morphology, and crystallinity of different thermoplastic polymer fibers and matrices (*e.g.*, polyethylene (PE), polyamide (PA), PP, etc.) were also characterized to study their effects on composites.

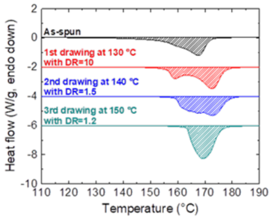


**Figure 1.** Melting peaks for as-spun and multiple drawn PP fibers.

For composites, we investigated different combinations of fibers and matrices to produce PFRPs with similar or dissimilar polymers. Various fabrication methods and processing parameters were studied. For example, thanks to multiple drawings of ultra-high-molecular-weight-polyethylene (UHMWPE) fibers leading to the increased melting peak temperature up to 160℃, a processing window between fiber and HDPE matrix then can be generated to fabricate composites (Fig. 2). However, high temperature can significantly reduce the composite strength to HDPE matrix strength due to reinforcing fibers melting (Fig. 2). Likewise, other methods (*e.g.*, infrared heating, injection molding, etc.) and related parameters (*e.g.*, pressure, cooling, injection speed, etc.) were also studied in this project.

Also, we studied failure behavior and morphology of different thermoplastic PFRPs with high fiber volume fractions in quasi-static and impact loads. The specific impact energies for the penetration of thermoplastic PFRPs are 20 to 70J/mm/(g/cm$^3$), whereas carbon-/glass-/aramid-fiber-reinforced polymers are about 5-20 J/mm//(g/cm$^3$). Surface modifications of fibers were also studied in this project to further enhance the mechanical behavior of thermoplastic PFRPs.

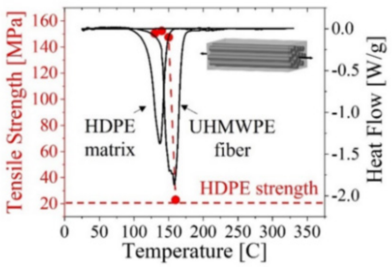


**Figure. 2.** Effects of processing temperature on tensile strength of uni-directional 5wt% UHWMPE fiber-reinforced HDPE composites.

# Vehicle and Mobility System Analysis

*2022 U.S. DRIVE Highlight*

# Vehicle Automation Impact on Land Use

*This study quantified the impact of Adaptive Cruise Control (ACC) and Coordinated Adaptive Cruise Control (CACC) when deployed at scale across a wide range of metrics, including mobility, energy, emission, greenhouse gases, and land usage.*

## *Argonne National Laboratory*

We studied the impact of various automated driving technology deployments on mobility, energy and emissions utilizing the POLARIS-centered SMART Mobility workflow, developed under the DOE Energy Efficient Mobility Systems program. Extending previous work from 2021, we assessed the potential influence of vehicle automation on land usage. The mobility system model allowed us to study potential consequences such as changes in Vehicle Miles Travelled (VMT) and land usage, and associated policy solutions such as carbon pricing.

All results were obtained from a simulation of the Austin metro area from 2015 to 2040 with evolving vehicle fleet and technology penetration varying from 1% to 90% deployment of:

- Adaptive Cruise Control – highway only
- Level 2 Cooperative Adaptive Cruises Control (CACC) for highway only
- Level 4 Automated Driving with CACC (highway only)

Key Findings

1. Level 4 automation potentially leads to employment density/land-use reduction in the urban core, while increasing employment density in the ex-urbs (Fig. 1)

2. U.S. DRIVE program success (High Tech) for advanced vehicles further reduces fuel consumption, increasing MPGe by up to 29% by 2040 (Fig. 1). This impact is counteracted somewhat by L4 automation as drivers adapt – fuel consumption for High Tech L4 case is the same as Business-as-Usual Baseline case (Fig. 2)

3. CACC with high automation (L4) increases congestion, reducing speeds by 5%, due to longer travel distances driven by reduction in driving burden, with VMT increasing 7%

4. Policy changes in the form of carbon pricing of fuels, can reduce some of the VMT increase by counteracting the value of travel time reduction from L4 automation

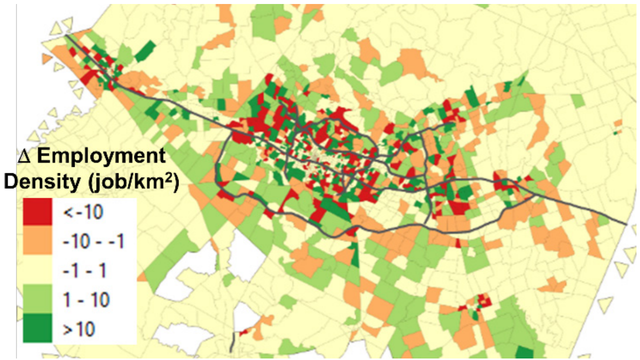


**Figure 1**. Change in employment density by 2040 for L4 vs. L2 CACC.

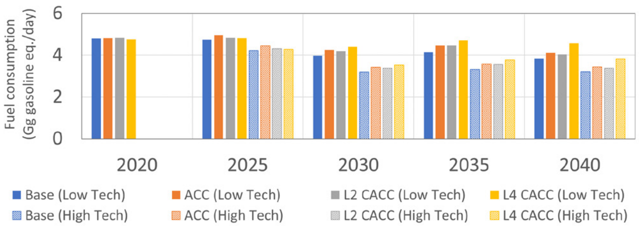


**Figure 2**. Fuel Consumption by Technology & Automation Type.

INFRASTRUCTURE AND INTEGRATION

# Grid Integration

*2022 U.S. DRIVE Highlight*

# The EVs@Scale Lab Consortium: Accelerating the Full-Scale Electric Vehicle Transition

*A DOE consortium conducting R&D to address challenges and barriers for high-power electric vehicle charging infrastructure that enables greater safety, grid operation reliability, and consumer confidence.*

## *Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Office*

With tens of millions of light-, medium-, and heavy-duty electric vehicles (EVs) projected to hit American roads by 2030, establishing a secure, affordable, and scalable infrastructure is necessary to support the transition to an electric fleet. The U.S. Department of Energy's (DOE) Electric Vehicles at Scale (EVs@Scale) Laboratory Consortium brings together six national laboratories—Argonne, Idaho, Oak Ridge, Pacific Northwest, Sandia National Laboratories, and National Renewable Energy Laboratory—to conduct infrastructure research and development (R&D) to accelerate this full-scale electric vehicle transition. Key stakeholders also help pinpoint R&D needs and mitigation strategies as partners from federal agencies, non-profits, academia, and industry. This collaboration produces world-class research that is responsive to a rapidly changing industry without regard to organizational boundaries and has the greatest chance for near-term market impact.

This consortium addresses five key R&D opportunity areas. The first is developing grid planning strategies and vehicle control methods, also known as vehicle-grid integration and smart charge management, to mitigate the increase in higher-power electric vehicle supply equipment that could cause higher cost and delays without a managed approach. The second is to expand high-power charging opportunities, including improving long-term efficiencies of design and reliability, reducing investment and operation costs, and increasing charging equipment power densities. The third is to advance the dynamic wireless power transfer technology required to transition proof-of-concept technology to practical real-world applications and assess key performance metrics to ensure safe, secure, and efficient power transfer. The fourth is to address the evolving threats and challenges to the EV charging ecosystem through cyber-physical security research and validating the most feasible solutions to ensure safe, secure, and resilient charging operation. The fifth is to harmonize codes and standards by identifying and addressing challenges and barriers, such as infrastructure reliability, created by conflicting standards and requirements, to help integrate at-scale EV charging with the grid.

The consortium engages the public on its work and encourages partnership to increase visibility and impact. Through hosting the Biannual Stakeholder Meeting, External Steering Committee, and Deep Dive technical meetings, the consortium received feedback from and shared R&D targets, opportunities, and challenges with the larger research and stakeholder communities, both virtually and in person. The events saw high attendance and made a positive impact on the achievements of this consortium in its first year.

The EVs@Scale Lab Consortium also established an online presence to further engage the public, stakeholders, and potential partners. Webpages that include consortium research area descriptions, publications, and opportunities for partnerships, are live on the Vehicle Technologies Office website.

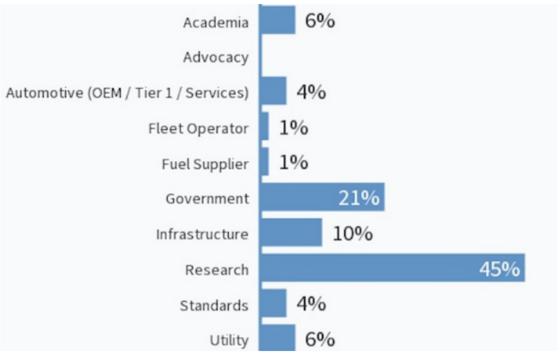


**Figure 1.** Participation in first Consortium stakeholder meeting.

*2022 U.S. DRIVE Highlight*

# NextGen Profiles: Characterizing High Power Charging

*A DOE initiative for assessment and validation of the next generation of electric vehicle High Power Charging profiles.*

## *Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Office*

In both commercial and consumer electric vehicle (EV) segments there are concerted efforts by EV and Electric Vehicle Supply Equipment (EVSE) Original Equipment Manufacturers (OEMs) to increase charge energy delivered while simultaneously decreasing charging time. To accomplish these goals, innovations must be made to increase the peak charging power of EVs. As the first 200kW+ High Power Charging (HPC) systems are emerging, it is apparent that HPC profiles can vary greatly by EV. To intelligently integrate HPC systems within co-located loads and sources and to minimize grid impacts it is critical to quantify and characterize the charging profiles that these systems will present.

The U.S. Department of Energy (DOE) has funded the NextGen Profiles project to quantify and characterize current and next-generation HPC EV profiles and EVSE characteristics. This project assesses both conductive and inductive charging topologies across light-, medium-, and heavy-duty vehicle classes. The output from this project will provide critical inputs to several ongoing efforts including modeling of electrified transportation systems, battery design, standardization best practices, and grid energy management systems.

EV charge system characterizations within the project fall into three distinct categories:

- **EV Profile Capture** – Determination of EV charging demand and performance while fixing boundary conditions.
- **EVSE Characterization** – Quantifying performance metrics that include efficiency, thermal management, and charge control.
- **Fleet Utilization** – Temporal analysis and trend tracking of electrified fleet charging.

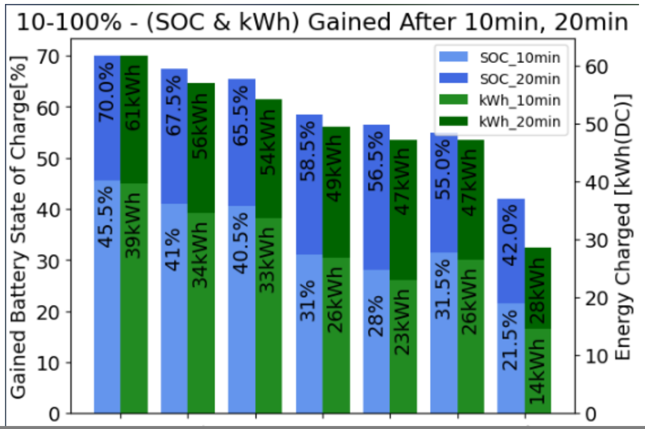


**Figure 1.** State-of-Charge (SOC) percentage and energy capture per vehicle within 10-minute and 20-minute timeframes. Vehicles include models from Tesla, Porsche, Hyundai, and Audi.

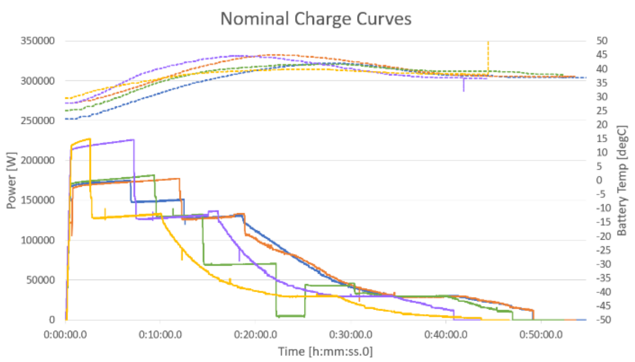


**Figure 2.** Power demand and battery temperature curves for various EVs under controlled boundary conditions.

To date 44 profiles from 14 EVs have been collected, 3 XFC systems are under test, and data is being collected from 4 fleet partners. A public report that includes a full categorical analysis is planned to be released near the end of the calendar year 2023.

# Integrated Systems Analysis

*2022 U.S. DRIVE Highlight*

# Under High Technical Progress Scenario, Future Electrified Propulsion Options Deliver Lower Emissions at Lower Cost

*A lifecycle techno-economic analysis of current and future vehicle-fuel technology pathways.*

## *Integrated Systems Analysis Technical Team*

The Integrated Systems Analysis Technical Team (ISATT) assessed greenhouse gas emissions and levelized cost of driving over a range of vehicle-fuel technology pathways for CURRENT (2020) and FUTURE (2030-2035) timeframes. For the FUTURE assessment, the team applied several sets of assumptions on rates of technical progress that lead to improvements in vehicle efficiency and/or cost reduction. The team applied a similar approach to future fuels, modeling a range of cost and carbon intensity outcomes for combustion fuels, electricity, and hydrogen. Argonne National Laboratory's Energy Systems Division published the full analysis into the public domain in June.

A key conclusion of the analysis is that under a scenario where high rates of technical progress are realized, vehicle electrification delivers a "win-win" to society in the form of lower emissions levels at lower lifetime cost.

As illustrated in Figure 1, moving from a conventional internal combustion vehicle (Conv) to a hybrid electric vehicle (HEV), with both vehicles still running on today's gasoline, reduces cradle-to-grave greenhouse gas (GHG) emissions by over 20% while also reducing the present value of lifetime cost for vehicle and fuel by several thousands of dollars. A similar Conv to HEV relationship holds in the cases of low-carbon liquid fuels, though the benefit of lower emissions comes with higher fuel costs.

In the case of battery electric vehicles (BEVs) charging on low-carbon electricity or fuel cell electric vehicles (FCEVs) using clean hydrogen, cradle-to-grave GHG emissions are reduced by over 70% relative to the conventional internal combustion vehicle (Conv). BEVs with modest ranges of 300 miles or less can also achieve lower lifetime costs than conventional vehicles. FCEVs with longer ranges are modestly higher in cost but achieve faster fill times, comparable to conventional vehicles .

The full report also quantifies similar cost metrics on a shorter 3-year timeframe, as this shorter timeframe tends to reflect first-buyer preferences. The same relationships can be seen in the 3-year analysis, indicating that high degrees of future technical success serve to align the first-buyer choice of vehicle-fuel systems with the societally optimal choice.

In FY23, ISATT is completing follow-on analysis to evaluate the cost and emissions of medium- and heavy-duty BEVs and FCEVs relative to conventional trucks.

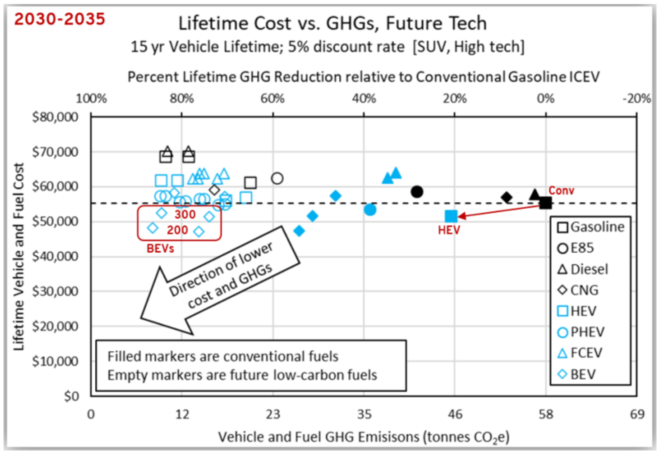


**Figure 1.** Modeled lifetime cost and greenhouse gas (GHG) emissions for a small SUV in the 2030-2035 timeframe. Assumes high rate of technical progress on underlying vehicle subsystems.

# Net-Zero Carbon Fuels

*2022 U.S. DRIVE Highlight*

# Exploring the Regional Opportunities and Needs for Net-Zero Fuels Deployment Across the United States

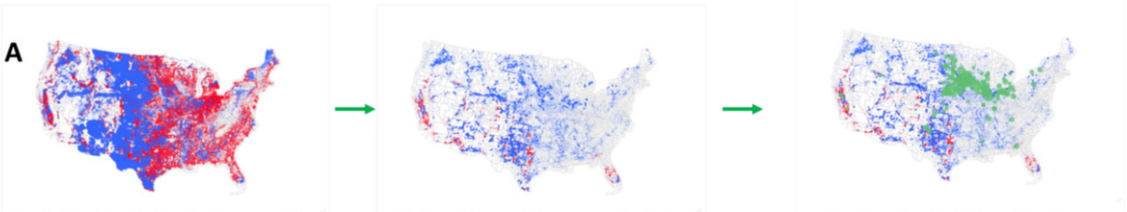
*Understanding the geographic implications of deploying several different net-zero carbon fuel technologies and the resulting impact on lifecycle GHG emissions as well as economics.*

***Argonne National Laboratory, Lawrence Livermore National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory***

Researchers at the national labs evaluated several pathways for their potential to produce “net-zero carbon” fuels. These pathways were optimized for reducing carbon intensity (CI) and their economics were assessed to understand the associated cost of carbon mitigation. Several advanced carbon management strategies were investigated for their potential to lower the CI of fuels and to understand their implementation costs. Over the first two years of the Technical Team, numerous unique fuel pathways were selected for scrutiny to discern their costs and benefits and their ability to provide net-zero carbon fuels.

The NZTT is now focused on a two-year investigation of a select subset of net-zero fuel technologies for their region-specific potential for siting future facilities. Such analyses draw on geographically relevant resource sets to examine the commercial viability of certain solutions in specific areas across the country. The specific fuel pathways explored in this regional analysis include 1) $CO_2$-to-fuels 2) hydrothermal liquefaction of wet wastes 3) biomass gasification and 4) cellulosic sugar fermentation.

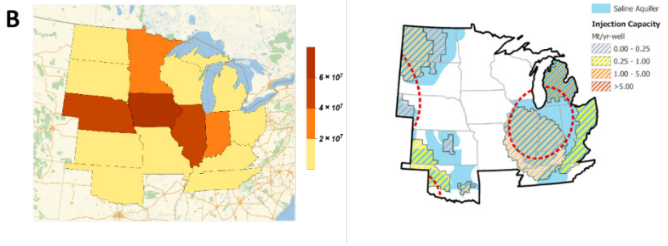
To understand the location-specific dynamics in deploying such technology in different areas of the U.S., the Team is exploring the regionality of several key resources essential to net-zero fuels. This includes feedstock availability, renewable energy/electricity potential, water, and geological storage capacity. The degree to which such resources do or don’t coincide is then considered and such scenarios are analyzed from a TEA and LCA perspective. This type of information will help assess the barriers to commercializing net-zero fuels.



Wind (blue) and solar (red) potential across the US

Refined for sufficient capacity factor and transmission infrastructure

Overlayed with high purity $CO_2$ point sources



Cellulosic biomass availability

Geologic storage potential

**Figure A**. The regionality of e-fuels technology relating to the availability of concentrated $CO_2$ and renewable electricity. Such information can help determine the actual economic viability and infrastructure needs of commercial net-zero carbon fuels deployment. **Figure B.** Understanding the regionality of cellulosic biomass and how it overlaps with geologic storage potential for $CO_2$ sequestration to enable net-zero fuel production.