Past R2R Processing Successes at ORNL and Current/Future Opportunities

Presented by

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ORNL Is Addressing R2R Processing Issues Relevant to Industry

- Annealing of materials on temperature-sensitive substrates (solid-state lithium-ion cathodes for large-scale thin-film batteries); Planar Energy Devices, 2010-2012.
- Primary drying (solvent removal) of dispersion cast coatings (replacing hazardous NMP organic solvent with water); PPG Industries, various binder suppliers, coating equipment suppliers, battery producers, 2010-2015.
- Dramatic reduction of secondary drying (removal of adsorbed moisture) time of lithium-ion electrodes in preparation for cell assembly; A123 Systems, 2012.
- UV and electron beam (EB) curing of high-solids dispersions into thick films; Miltec, 2011-Present; COMET – Plasma Control Technologies 2015-Present.
- On-line and off-line non-destructive evaluation (NDE) for coating quality control (QC) improvement and long-term performance enhancement; NREL, battery makers, equipment suppliers, 2012-Present.
- R2R slot-die deposition of thick films for lithium-ion electrodes with graded and patterned architectures; Palo Alto Research Center (PARC), binder companies, battery producers, 2014-Present.
- Optimization of web speeds for different deposition methods and applications; ongoing.

Selected Industrial Partners

FRONTIER

SHARP

LOCKHEED MARTIN

NAVITAS SYSTEMS

PLANAR Energy Devices

EASTMAN

ASHLAND

XALT Energy

MILTEC

saft

POROUS POWER TECHNOLOGIES

APPLIED MATERIALS

SOLVAY Specialty Polymers

BTU

FMC Lithium

Ford

COMET

GM

سابك
sabic

PPG

parc
A Xerox Company

Vorbeck Materials
realizing graphene's possibilities

Maxwell TECHNOLOGIES

A123 SYSTEMS

JSR Micro
MATERIALS INNOVATION
JSR

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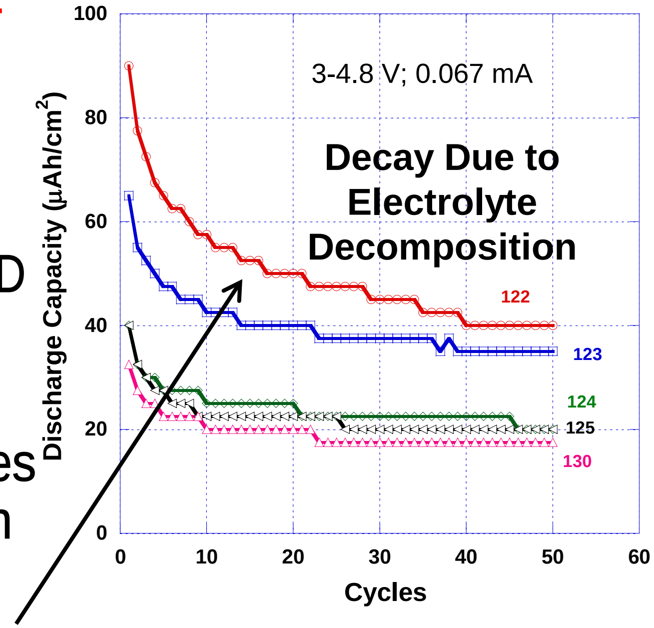
Planar Energy Highlight – Solid-State Cathode Processing

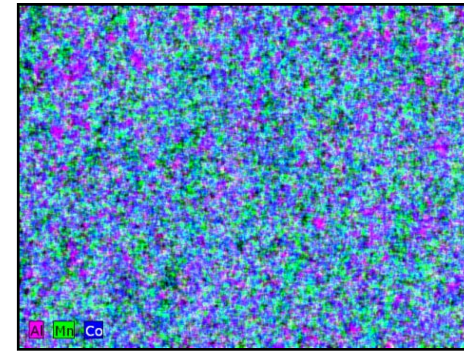
PLANAR Energy Devices

- <u>Goal:</u> to replace PVD and high-T furnace annealing with room-T atomized spray deposition and photonic (UV/IR) annealing.
- Current processing involves PVD for ~1 h and 650°C furnace annealing for 20 min.
- New processing involves minutes of room-T deposition and <1 min of photon exposure.

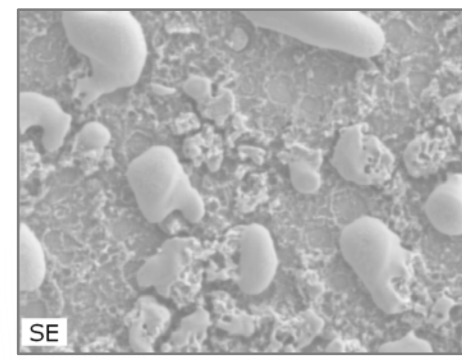


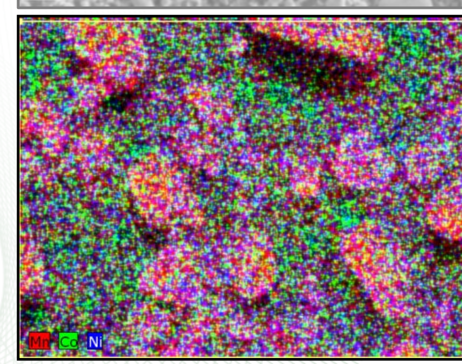
- Best performance of 38% furnace annealing baseline was achieved with single voltage plateau and multiple pulses on the PulseForge 3300.
- Pulse thermal processing conditions were refined to include combinations of pulse duration ramping, 2) multiple voltage plateaus, 3) number of pulses at each voltage.
- CRADA results were sufficient for Planar Energy to make the business decision to pursue the technology for microbattery applications (i.e. sensors, smart cards, etc.).

As Received

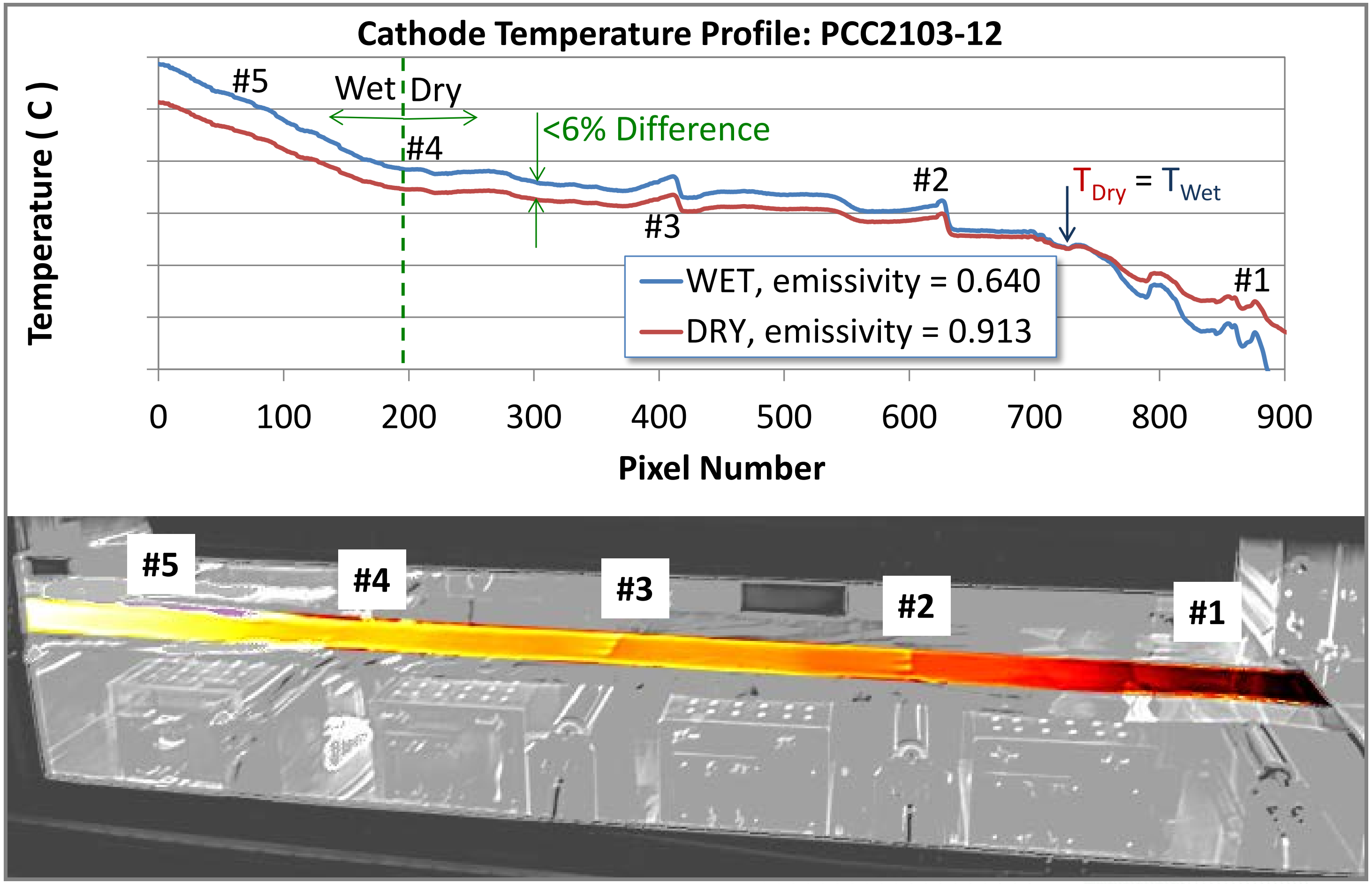


Phase Segregation Must Be Avoided After Annealing



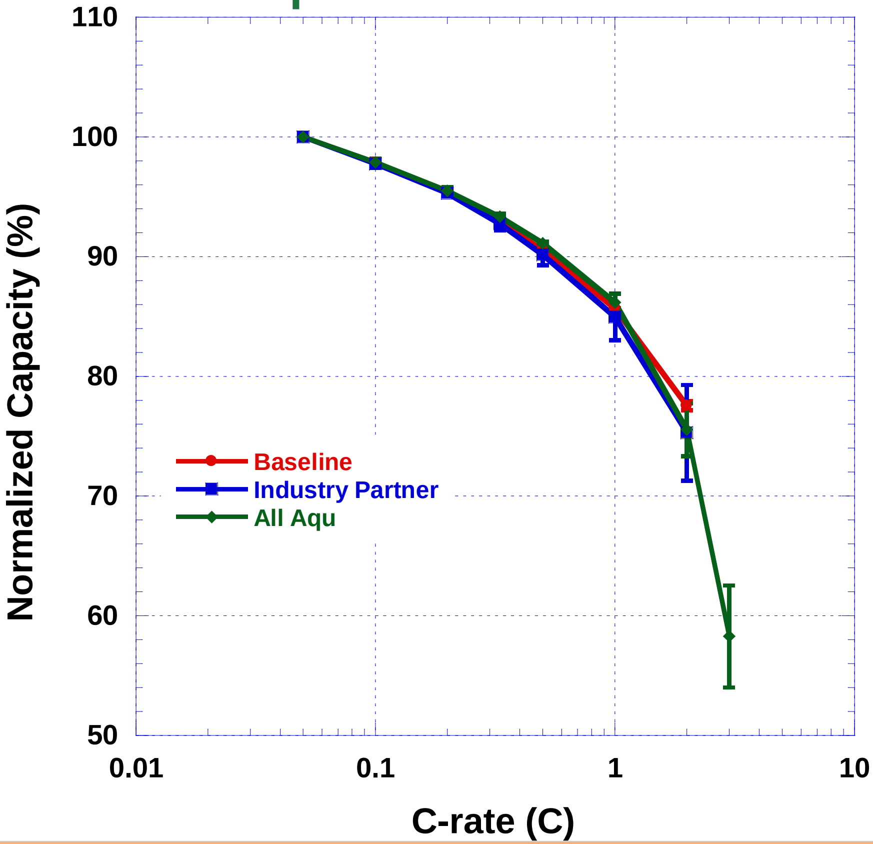


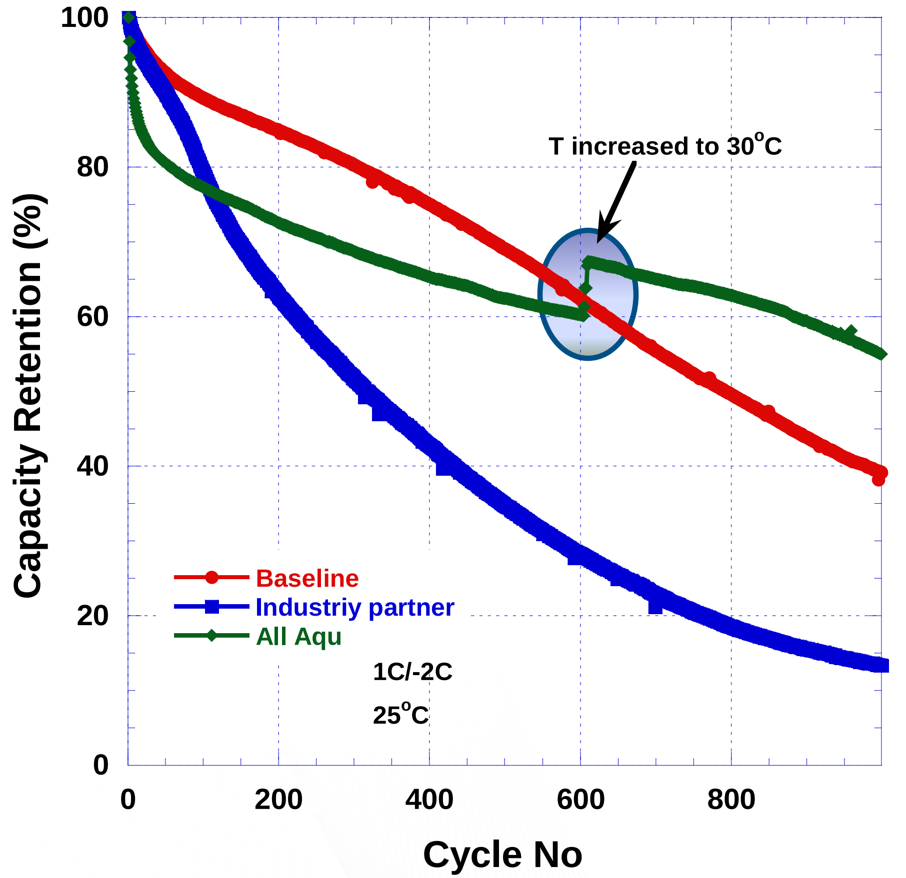
IR Imaging of Electrode Coating Line Reveals Wet-toDry Transition Points



IR imaging of Dow Kokam pilot coating line showing uniform drying of cathode. The "Dry" temperature curve crosses the "Wet" temperature calibration curve at 100°C ($T_{Wet} = T_{Dry} = 100°C$).

Aqueous Electrode Processing – Sufficient Primary and Secondary Drying Protocols Developed





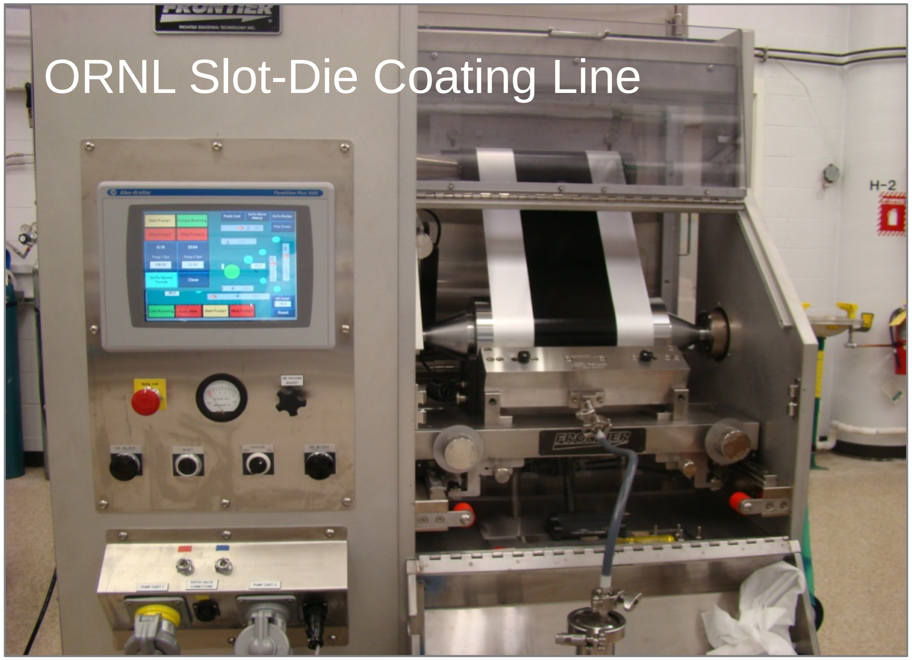
NMC532 & CP-A12 graphite

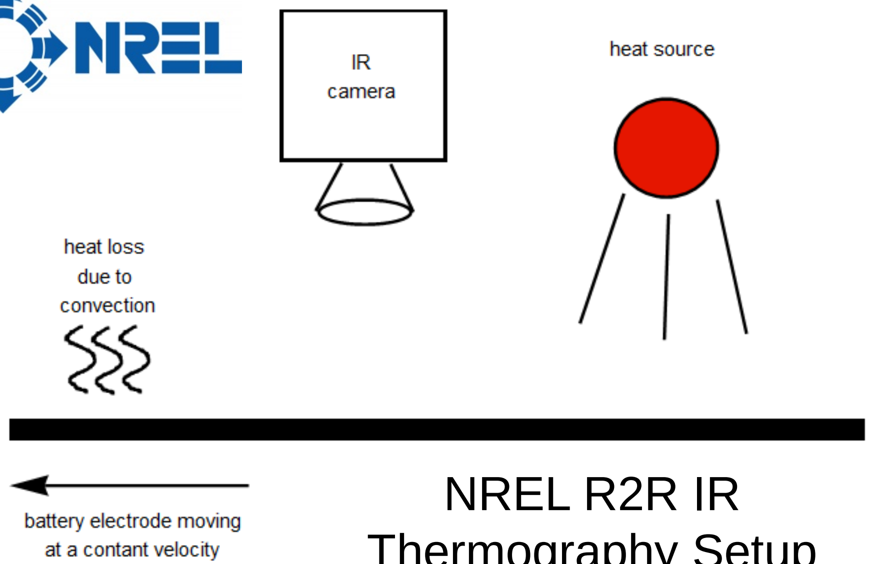
- Baseline-all NMP based processed electrodes
- Industry partner-NMC cathode via aqueous processing
- All aqu—all aqueous processed electrodes

- Similar rate performance
- Baseline cells—best early cyclability
- Slope changes indicate different degradation mechanisms.

Approach with NREL

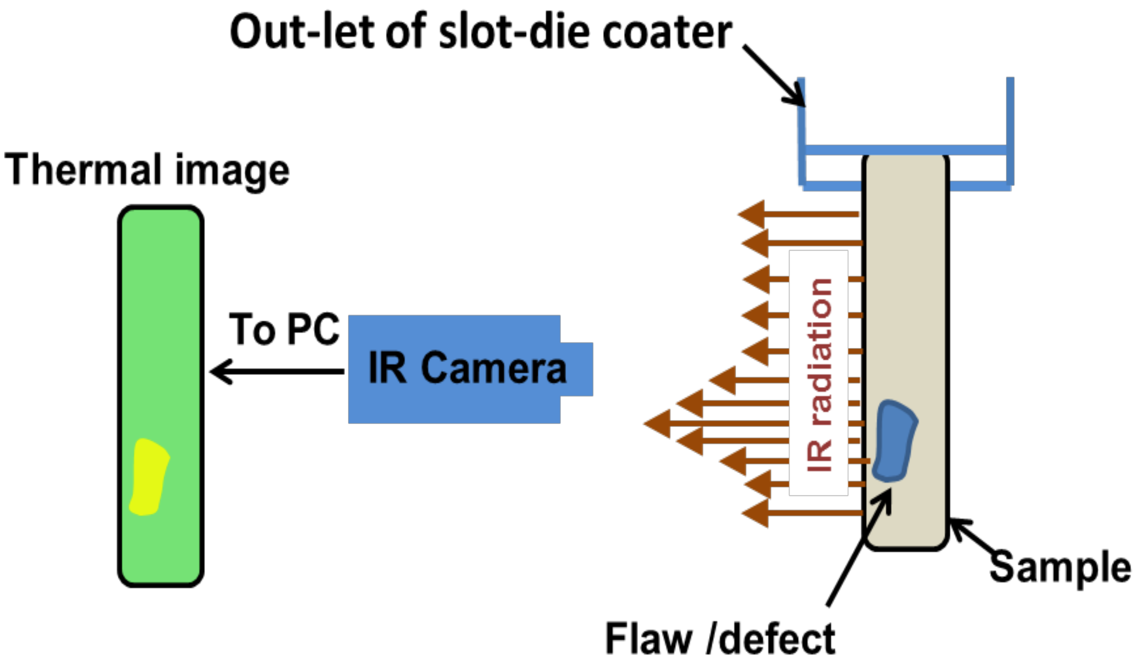
- Problems:
  - Electrode coating defects are currently identified by optical CCD cameras, which miss many of the subtle inhomogeneities.
  - A ***low-cost*** method for ***in-line*** thickness and porosity is needed for optimal electrode coating QC.
  - Useful feedback loops must be developed based on IR thermography input information to ***prevent*** coating defects and inhomogeneities.
- Overall technical approach and strategy:
  1. Use white light or thermal excitation of electrode coatings to generate a IR emissivity signature from electrode coatings.
  2. Take measured IR emissivity and correlate it to a coating T profile for input into a mathematical model based on electrode physical properties (IR absorbance, heat capacity, thermal conductivity, bulk density, etc.).
  3. Use model and measured heat loss down the web to generate a porosity and thickness profile.

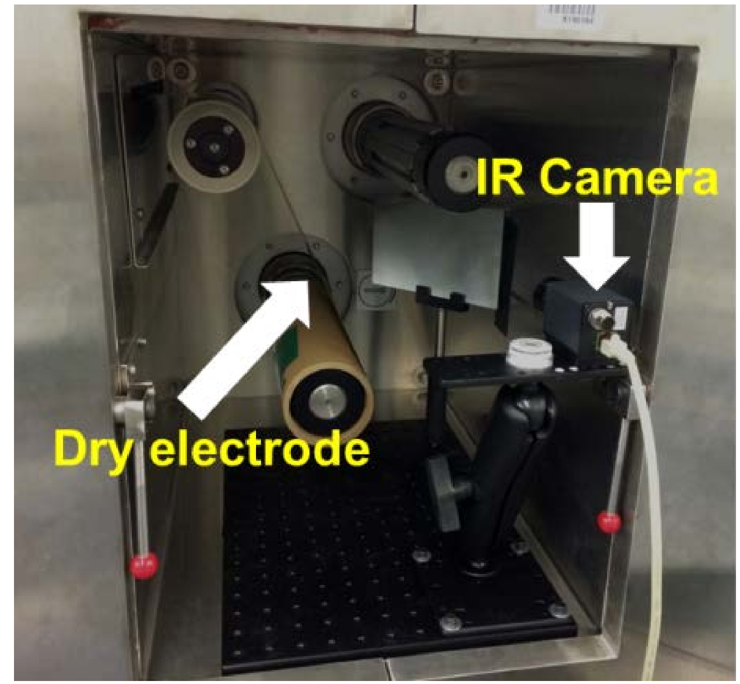

ORNL Slot-Die Coating Line



NREL R2R IR Thermography Setup

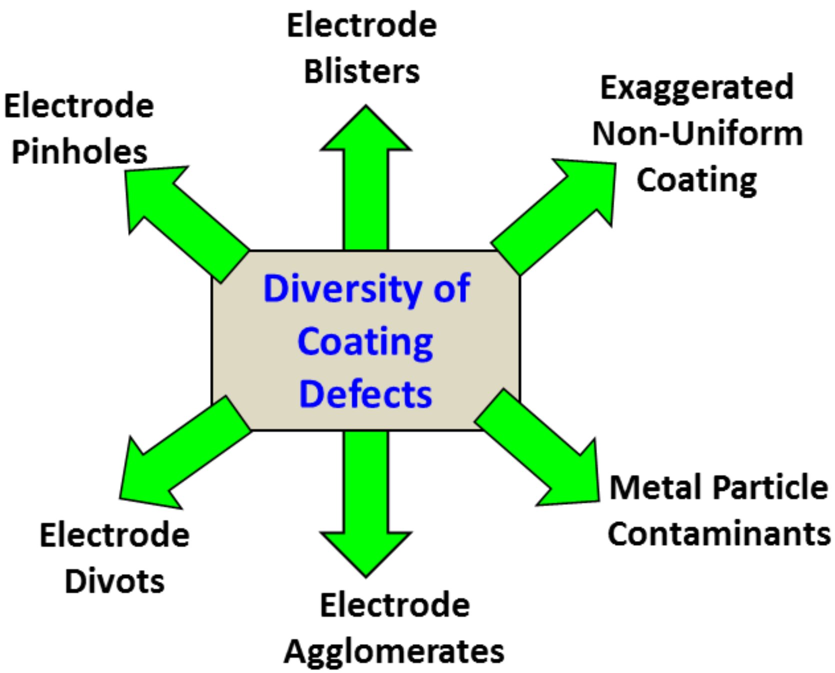
Technical Accomplishments – IR camera Installation on Slot-Die Coater

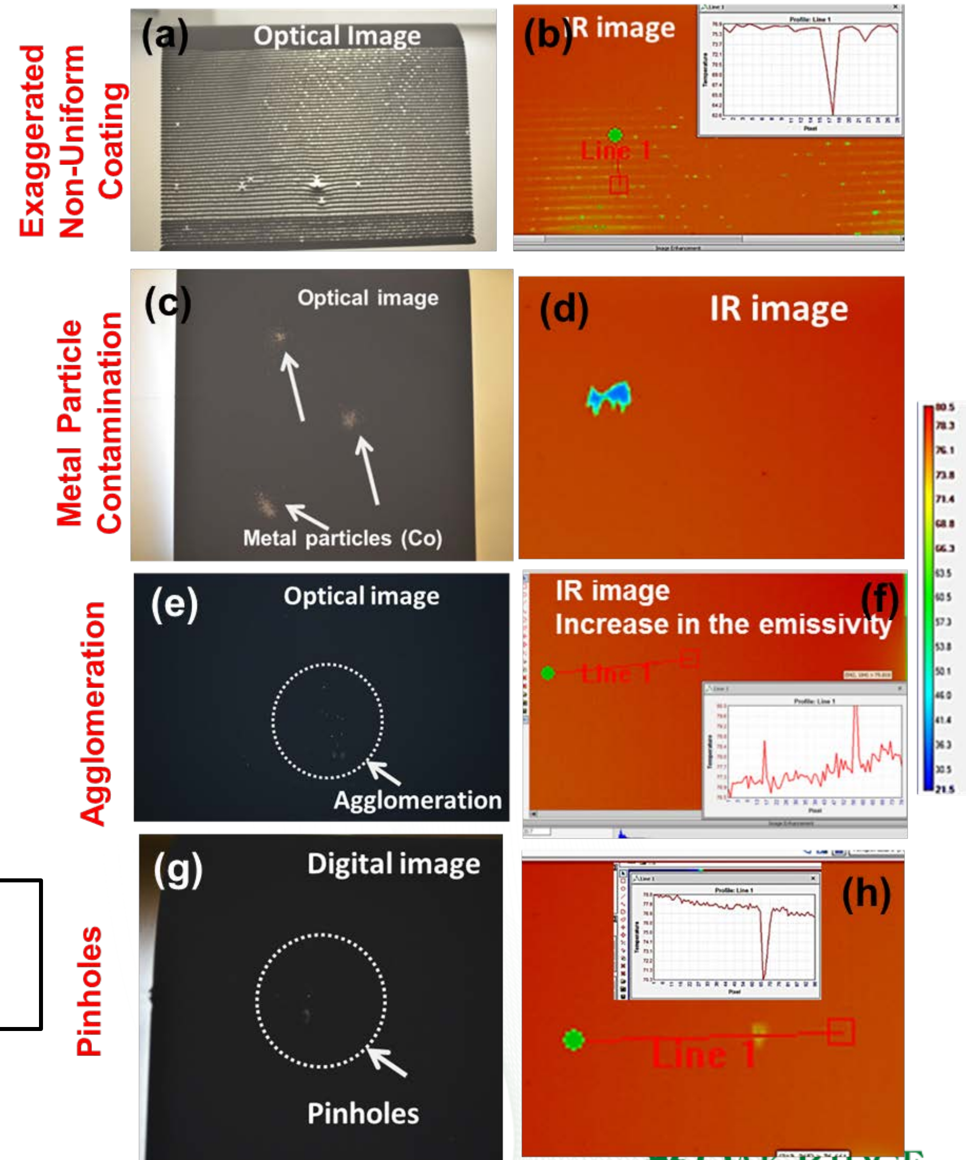




Monitor temperature profile of dried electrodes detecting any potential defects such as divots, pinholes, agglomerates, etc.

Systematic Study of Electrode Coating Defects Reveals Differing Performance Effects





6 types of defects are being studied to determine relative importance.

Low-Cost, Multi-Sensor Wireless Platform for SMART Buildings

Current wireless sensor Platform: $150-$300/node → **Proposed Advanced Sensors Platform**: $1-$10/node

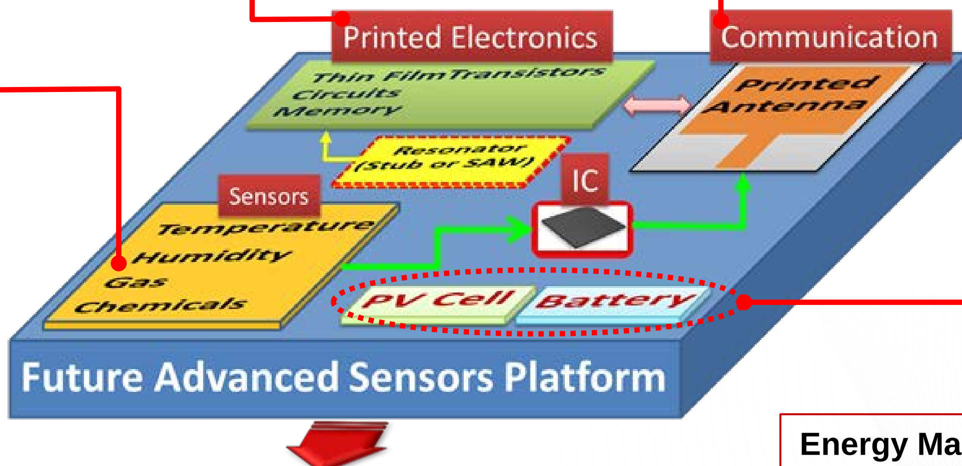
Infrastructure investment already made
- Financial support and resources required for timely development

Proposed R&D

Core Components
- High performance thin films
- Low temperature integration
- R2R processing setup

Proposed R&D

Extensive Capabilities at ORNL
- Modeling
- Design
- Test and Measurements

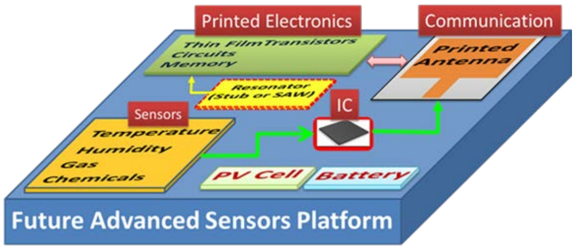


Energy Management Technologies
- Extensive know-how at ORNL
- Resources required to target low temperature material/device development

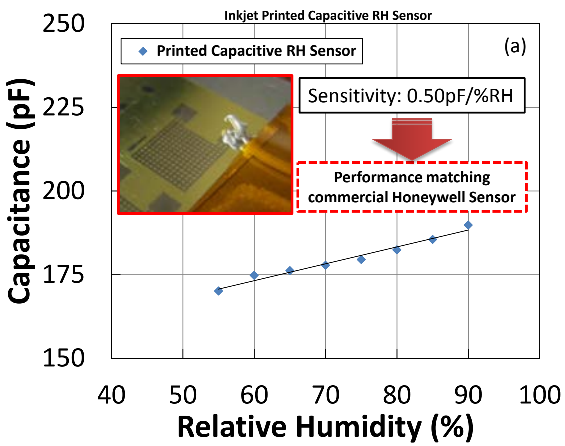
Market Potential: Not just an improvement over existing technology
- Prospects of New market, • Enhanced Functionality

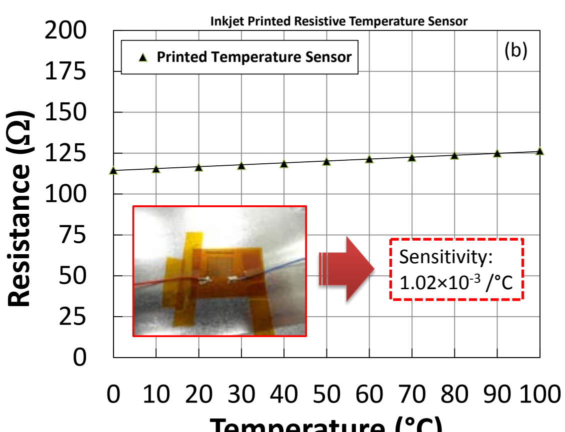
DOE Interests
- Buildings technology program (BTP),
- Advanced manufacturing office (AMO)

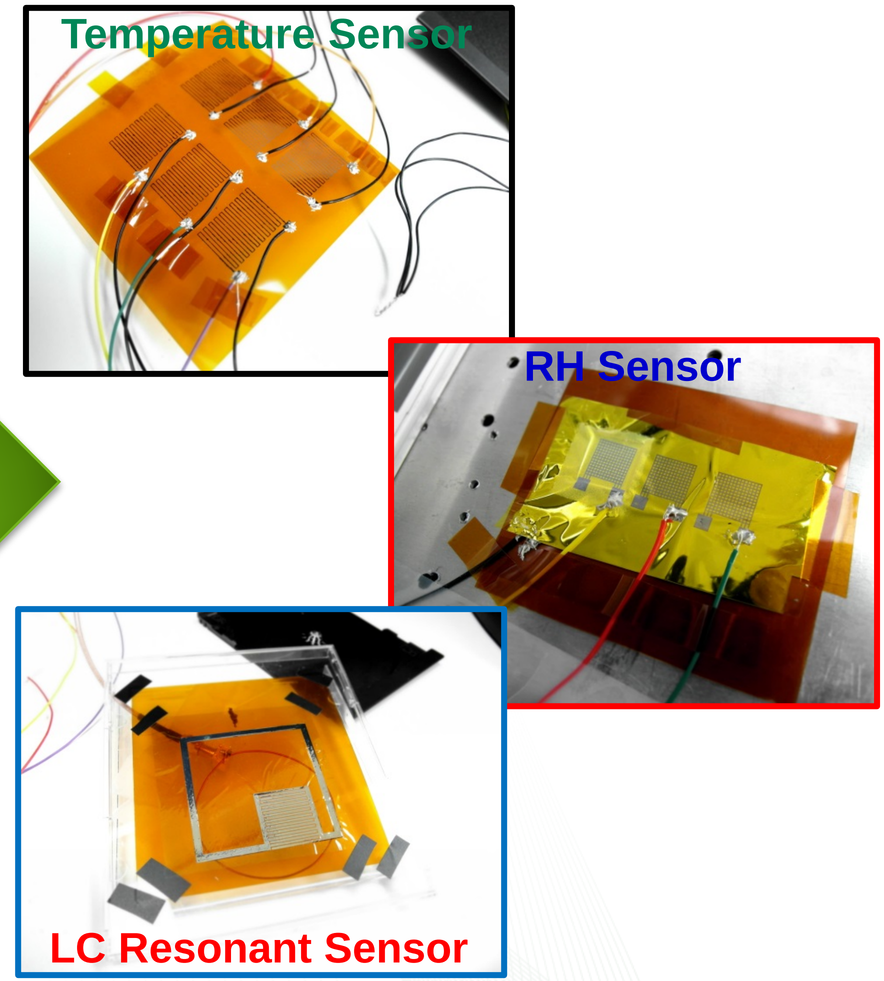
Multi-Sensor Integration and Performance Evaluation



- Discrete T and RH Sensors







Multi-sensor Printing and Calibration for system level integration underway

Future Challenges and Opportunities

- Raw material variation effects on coating deposition quality and associated device performance.
- Can similar equipment and approaches be used thick and mid-range coatings (~1-1000 μm)?
- Addressing difficulties of developing R2R thin-film (nm-scale) deposition processes.
- Identification of locations in R2R processes where in-line QC is needed.
- Successful technology transfer of developed in-line NDE and QC methods to industry.
- Understanding effects of defects on device performance; what constitutes a defect worth detecting?
- At ORNL, translate battery R2R processing successes to other applications such as supercapacitors, energy conversion (fuel cells and membrane electrolyzers), flexible displays, and flexible sensors.
- New R2R methods needed for 2-D material production.

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