Oak Ridge National Laboratory Energy Storage Program Capabilities

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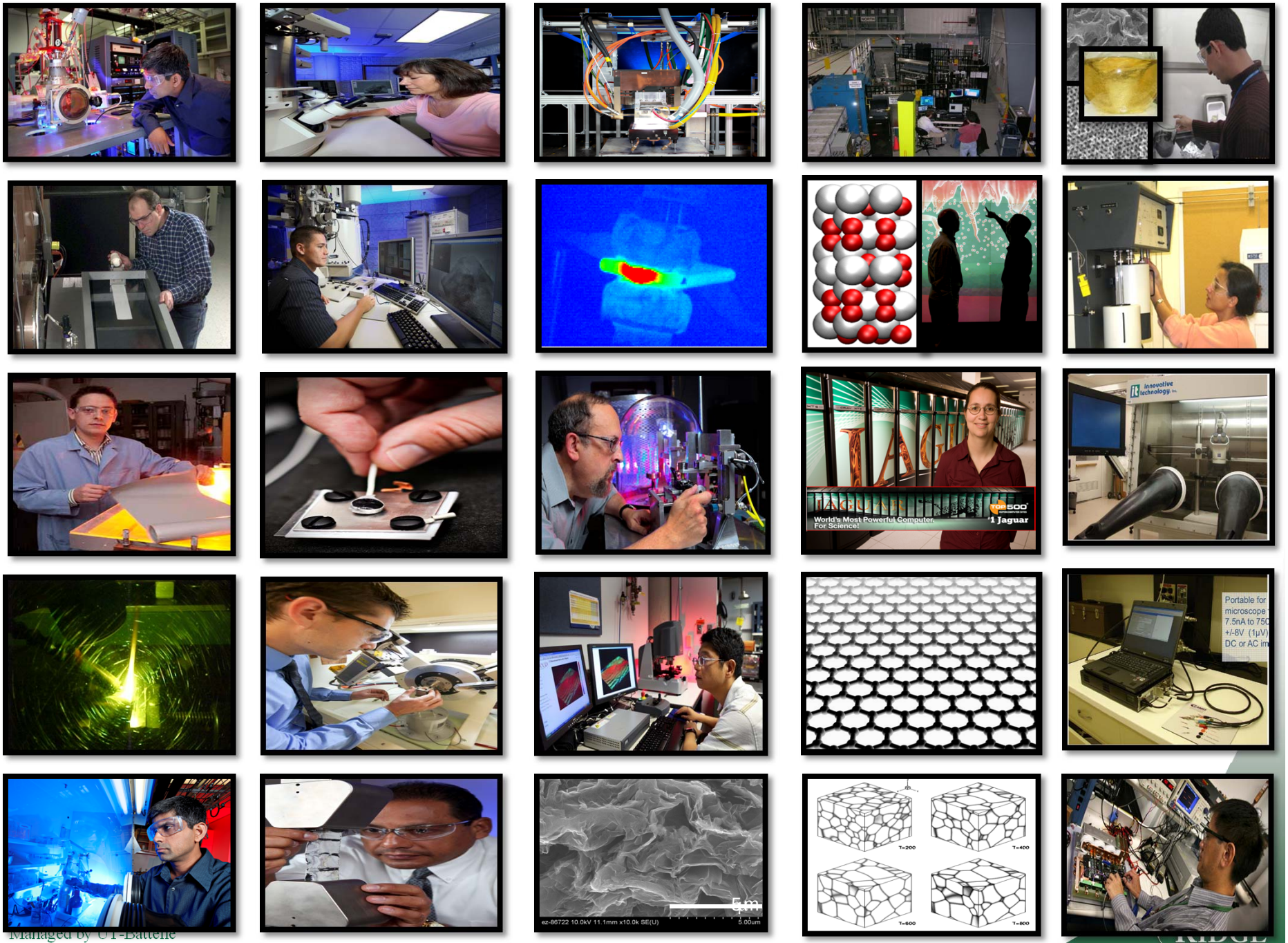
Energy Storage Program Manager

March 23, 2010



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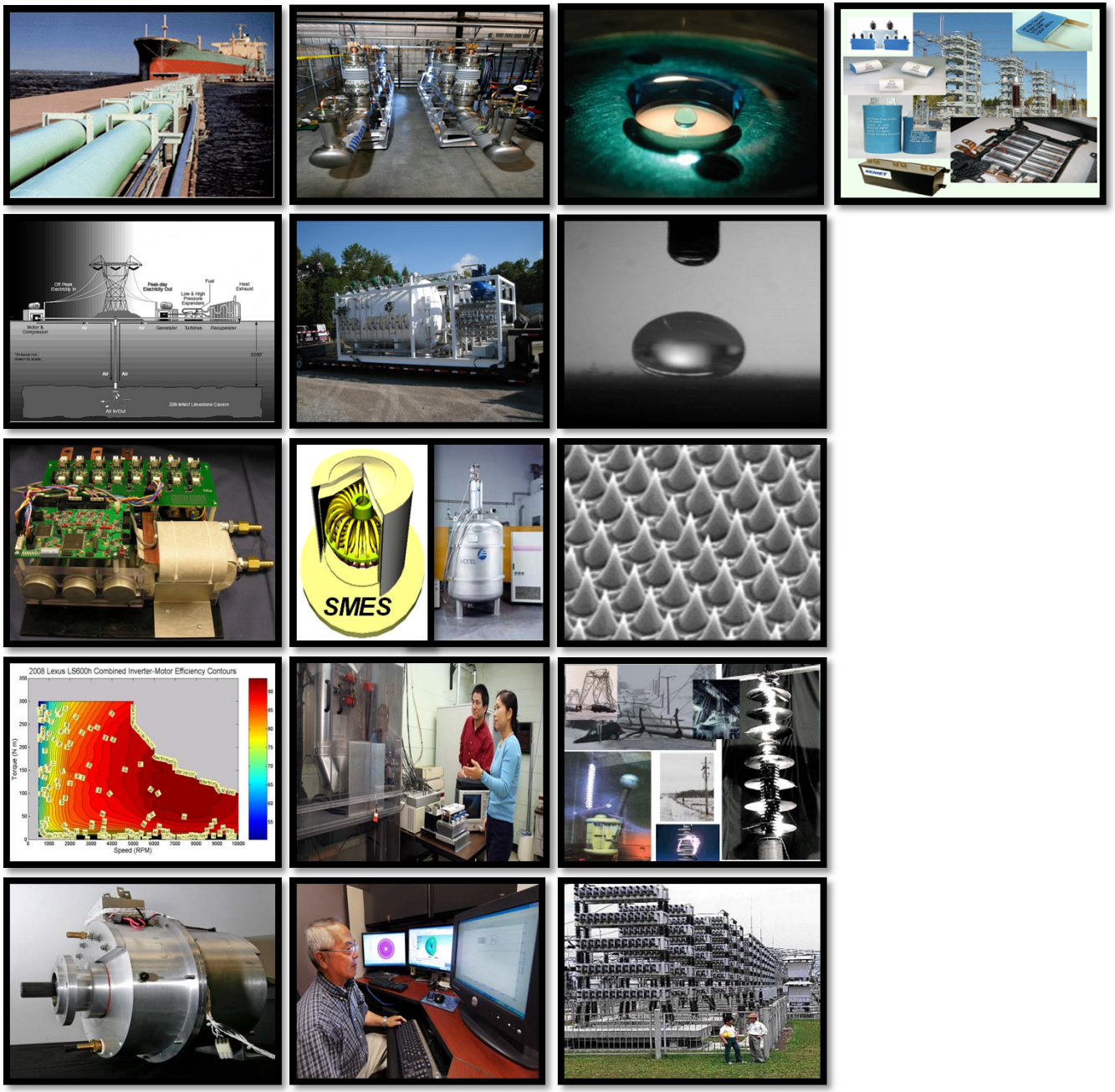
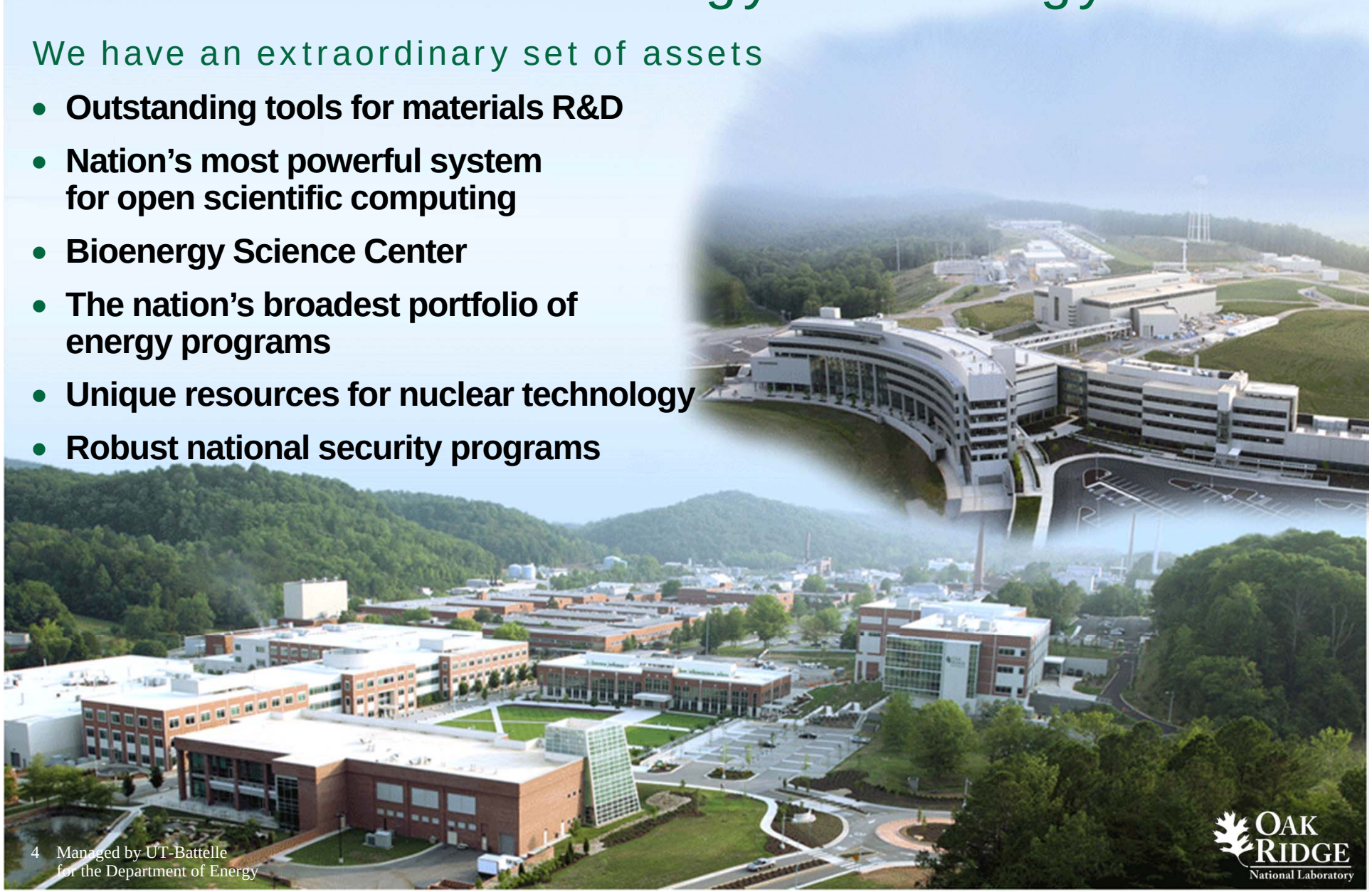


Business Sensitive

ORNL is uniquely positioned to deliver science and technology for energy

We have an extraordinary set of assets

- **Outstanding tools for materials R&D**
- **Nation's most powerful system for open scientific computing**
- **Bioenergy Science Center**
- **The nation's broadest portfolio of energy programs**
- **Unique resources for nuclear technology**
- **Robust national security programs**



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Energy Storage Capability Matrix

Grid Component	Fundamental Research Areas					Applied Research Areas									
	High Perfomance Computing	Neutron Imaging	Materials Development Characterization	Materials Reliability	Nanomaterials	Standards	Electrical Interfaces	Sensors & Controls	System Design Integration	Regulatory	Materials Processing/Fab	Device Testing	Thermal Management	Socio-Econ Benefits / Behavior Eval.	Environmental Assessment
Electrochemical Energy Storage - Batteries															
Electrochemical Energy Storage - Ultracapacitors															
Hydro-electric Energy Storage															
Compressed Air Energy Storage															
Thermal Energy Storage															
Grid Interaction & Ancillary Services															
Flywheels															
Superconducting Storage															

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Unique Energy Storage Capabilities

- **Thin-film Rechargeable Lithium Batteries**
- **Material synthesis**
- **Powder characterization**
- **Slurry coatings**
- **Innovative material processing**
- **Thermal processing**
- **Micro-joining**
- **Carbon, graphite, and carbon fibers**
- **Modeling, Simulation, and super computing**
- **Large Format Li-ion, Metal-air and Flow Batteries**
- **Super-capacitors**
- **Pumped Hydro**
- **Compressed Gases**
- **Flywheels**
- **Super Magnetic Energy Storage**
- **Power Electronics**
- **GRID energy storage integration**
- **Ancillary Services**

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Thin-Film and Slurry Deposition

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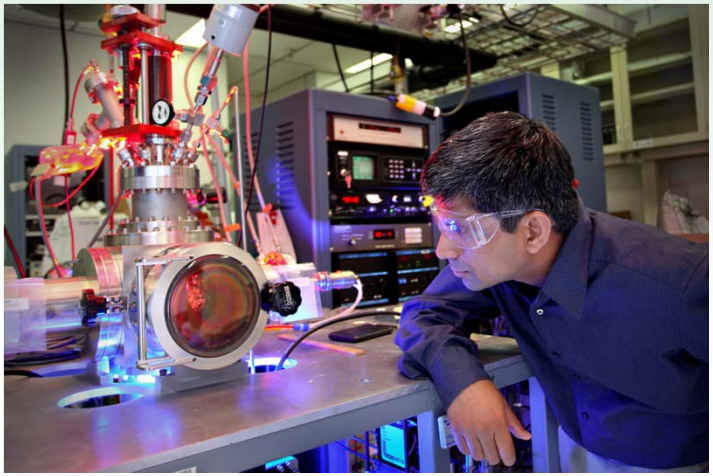
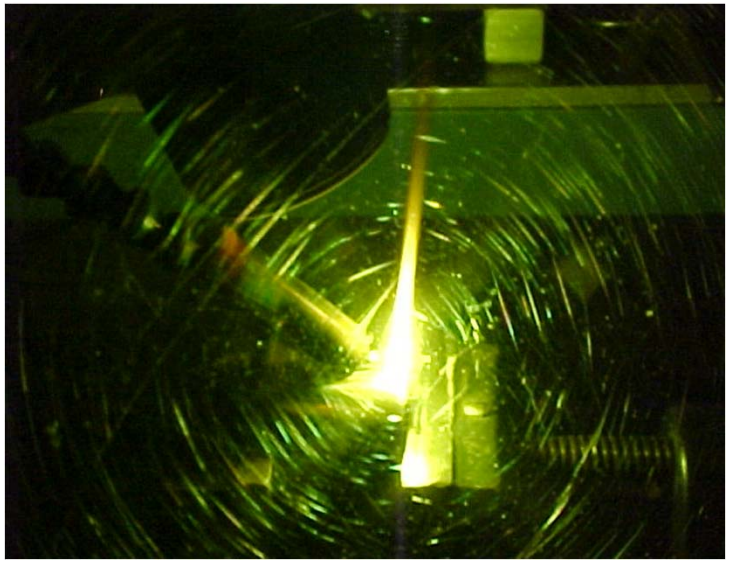


A sputtering technique is used to study **thin film deposition** of battery materials and solid electrolytes.

Tape casting of **slurry based** materials is used to obtain coatings for electrodes in batteries and other applications.

Wet and Dry Coating and Ultrasonic Joining

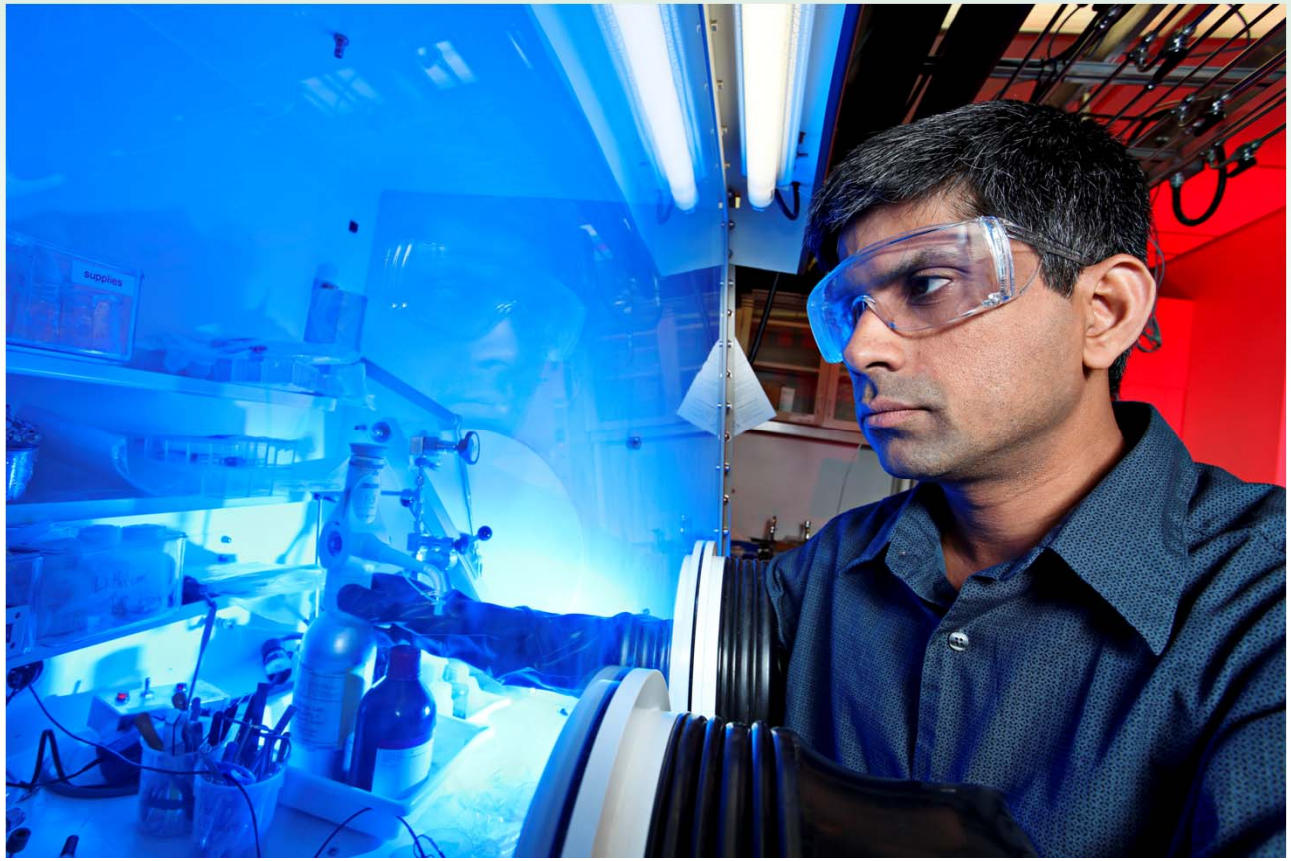
ORNL is doing research on **wet and dry coating** technologies that could reduce the time and energy needed for typically used formation procedures after the battery is assembled.



Micro laser welding

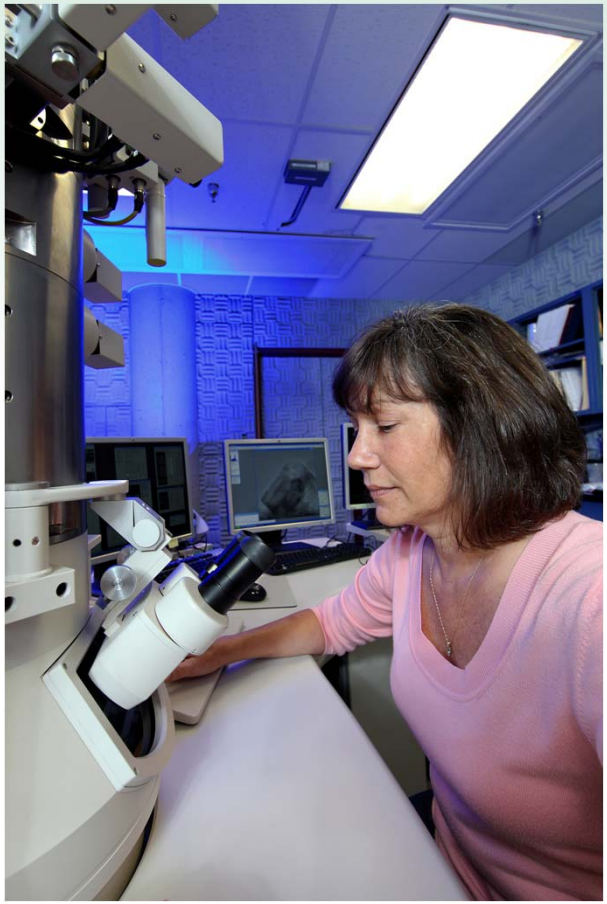
Low thermal impact joining is of very high importance for batteries. Devices are assembled and filled with thermally sensitive materials, then must be joined and sealed. **Ultrasonic joining** is one technique for such an application. ORNL is doing research on advanced joining techniques and understanding the thermal impact of those techniques.

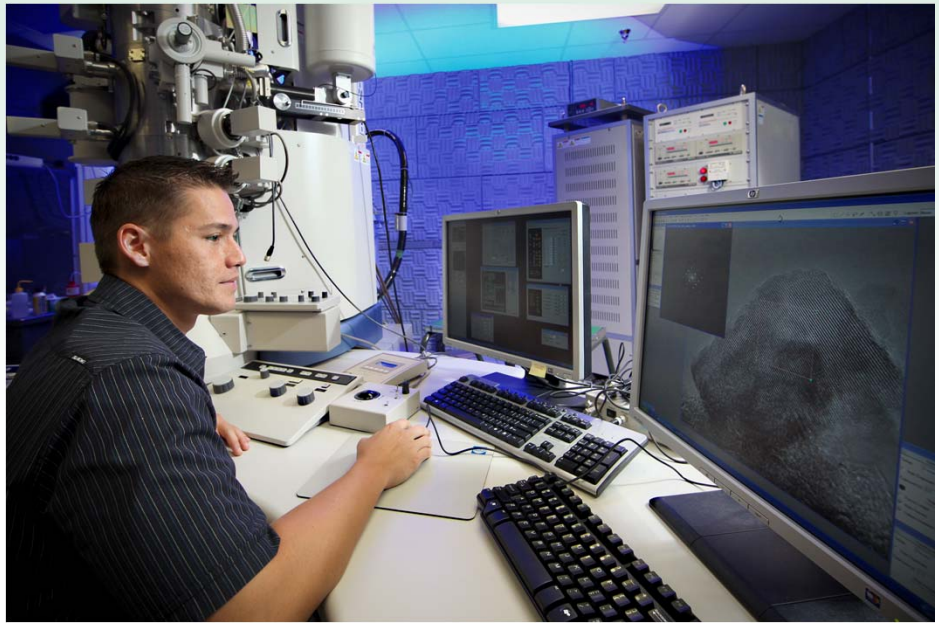
Battery Development & Assembly



Lithium-ion **cell assembly** for performance testing inside the glove box.

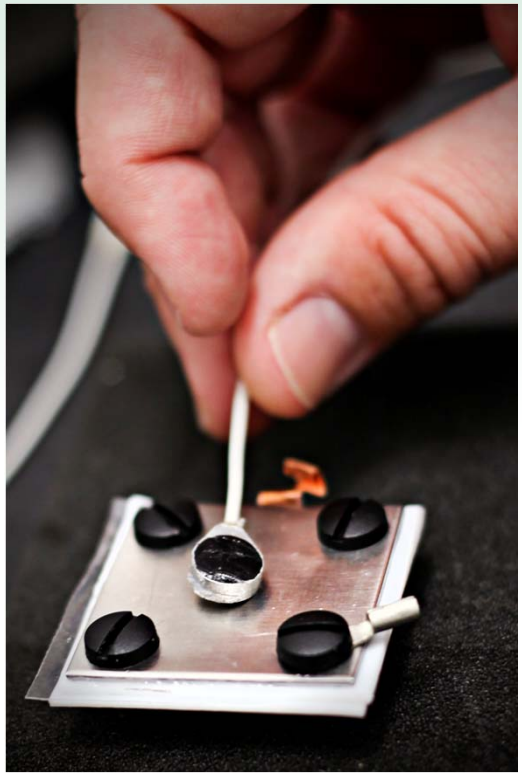
In-situ characterization using Transmission Electron Microscopy (TEM)





Transmission electron microscopy for **in-situ characterization** studies evaluates the stability of battery electrode materials during rapid charge-discharge cycling.

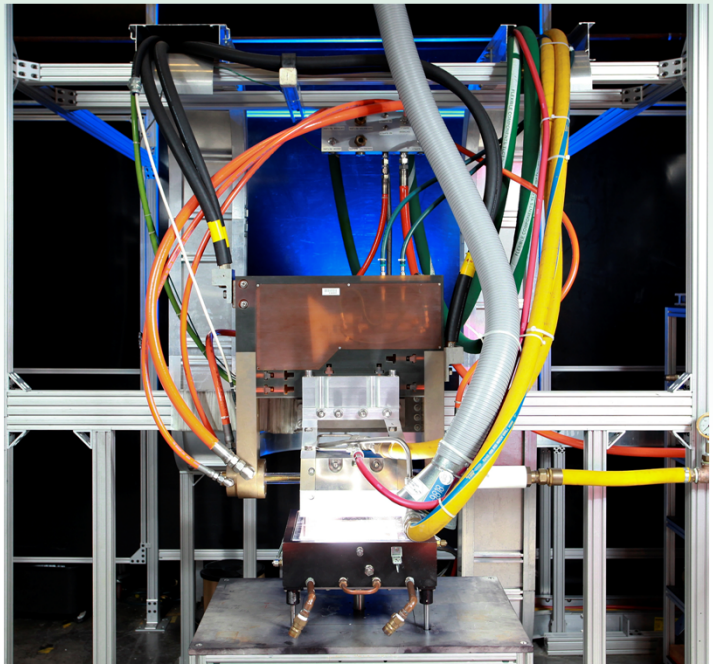
In-situ acoustic emission spectroscopy and **X-ray diffraction**



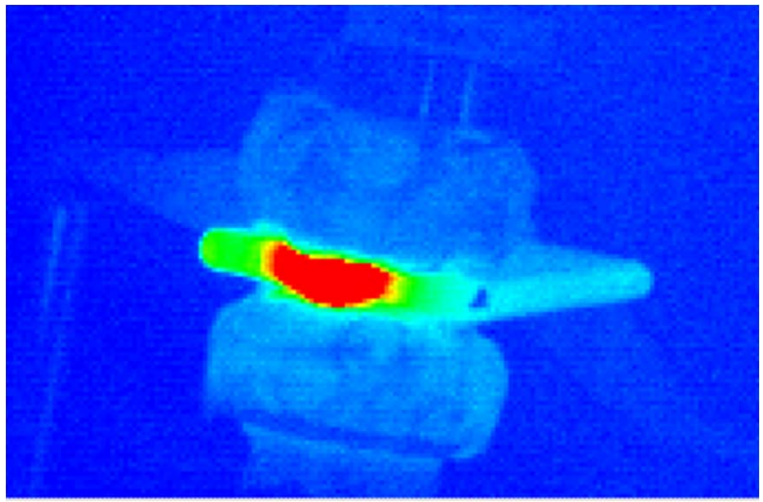
The plate is the top of a specially designed battery cell for **in-situ acoustic emission spectroscopy** and **X-ray diffraction** studies to investigate and better understand mechanical degradation as a means of capacity fading during charge and discharge.

An X-ray diffractometer is used to evaluate how battery materials change during charges and discharges.

Advanced Photonic Processing and Infra-red Imaging

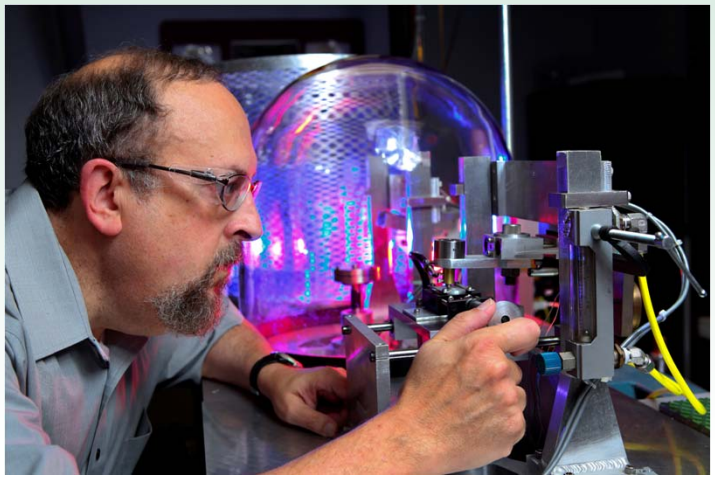


Pulsed thermal processing and other **advanced photonic processing** methods allow new and advanced technologies to dry, solidify, and sinter coatings and layers used in batteries and other applications.

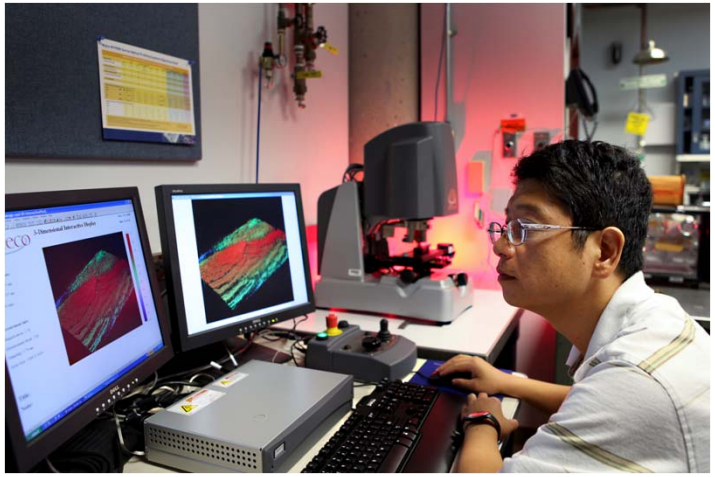


An infrared imaging tool is used to determine temperature distribution inside batteries during internal short circuit testing to prevent **thermal runaway** in lithium ion batteries.

Tribology and 3-D Surface Profiling



Tribology measures the friction forces between battery materials. Repeated charging and discharging can cause internal chafing between layers, which in turn can lead to short circuits and reduced battery life.



A vertical scanning interferometer precisely measures fine-scale surface features, and construct high-resolution **3-D surface profiling** maps. Unlike a scanning electron microscope that requires putting materials into a high vacuum chamber, the phase-shift imaging features of this system enable nanometer-resolution images to be obtained in air.

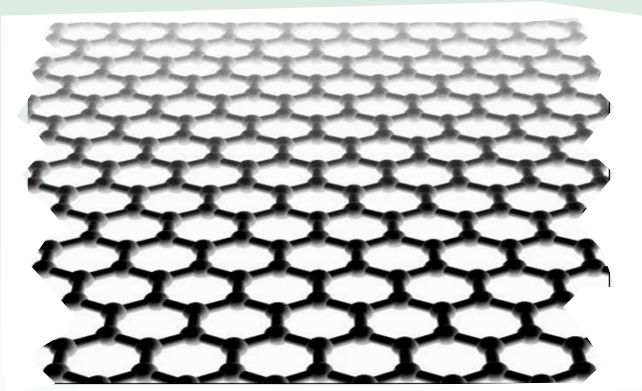
Mechanical Testing

A **mechanical testing** machine is used to characterize the stress-strain response of a polymeric electrolyte for a Li-ion battery. Information obtained from these tests, and from similar tests on other battery components, is important to understand the mechanisms that limit their durability and to identify strategies to improve it. This information is also necessary to support the development of multi-physics models to describe the operation of these batteries.

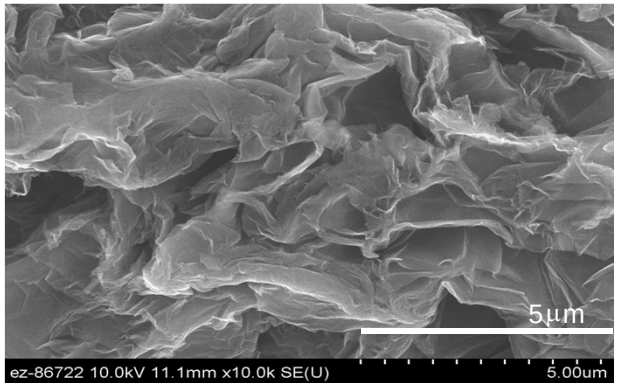
Carbon, Graphite, and Carbon Fiber Composites, and Material Synthesis

Use of **carbon, graphene, and carbon fiber composites** helps improve the thermal and electrical conductivity of battery materials.

Through **materials synthesis**, researchers are working to identify industrially viable technologies for the large-scale application of electrochemical double-layer capacitors for electrical energy storage. The materials can be produced using scalable chemical and materials processing operations, helping enable cost-effective manufacturing processes.

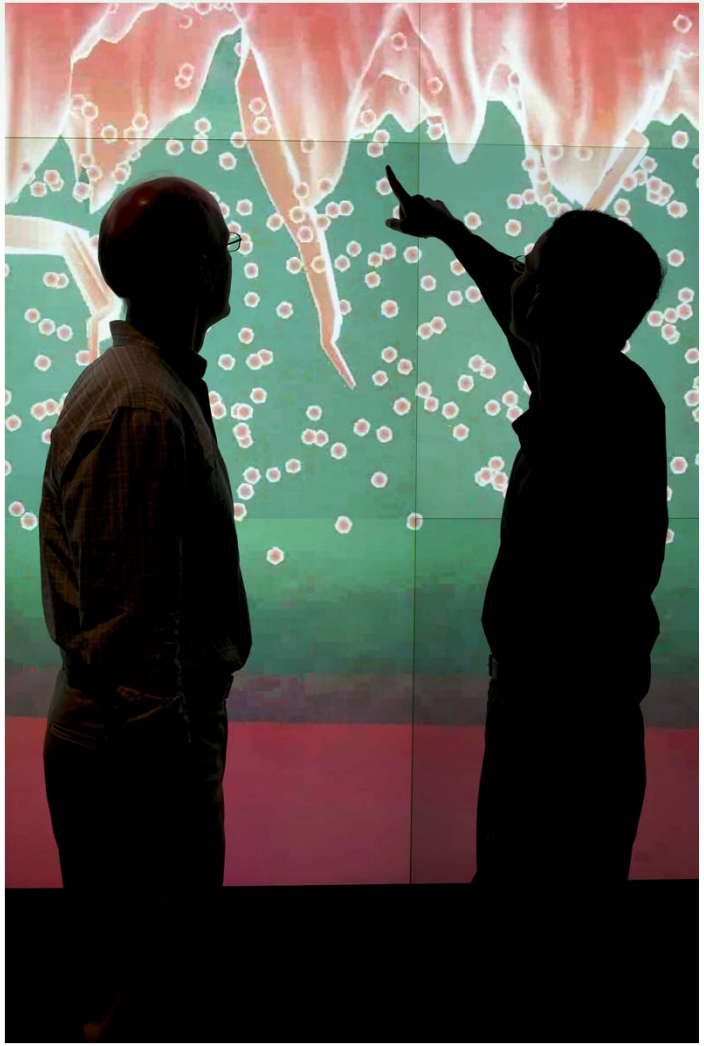


Graphenes: 2-D networks of carbon atoms



Scanning electron microscopy shows wrinkled and curled graphenes sheets allow access of electrolyte to the internal surface

Modeling, Simulation and Computational Science



Growth of lithium dendrites of rechargeable lithium-metal batteries (illustrated in the background animation) is a well known problem that can lead to performance degradation and safety hazards due to battery cell short-circuiting. Through extensively validated predictive simulation tools, researchers hope to understand these phenomena in order to design safer hi-performance batteries.

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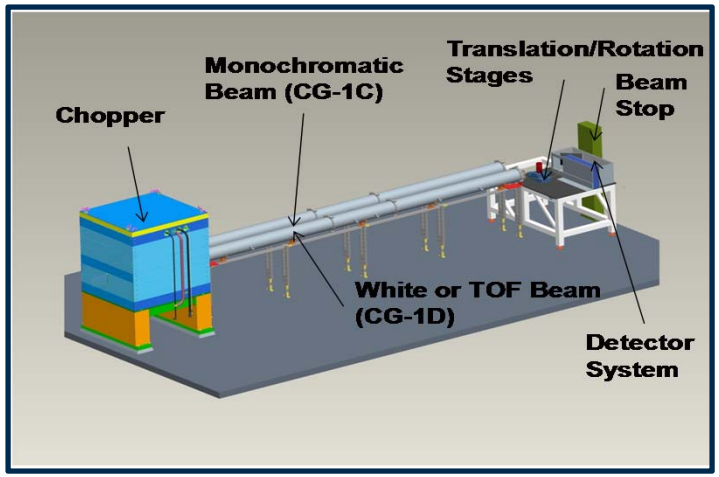
State-of-the-art experimental, characterization and computational facilities



ORNL has extensive experimental and characterization capabilities related to material science, catalysis and various electrochemical conversion devices. The main **characterization tools** include in-situ and atomic-force microscopy, SNS **and** HFIR **Neutron sources**, atomic force microscopy.

State-of-the-art computational software, algorithms and hardware to make predictive simulations feasible by bridging computations from atomistic to continuum scales. The simulations will be integrated with the experiments and characterization to have a validated suite of tools for metal-air battery design.

State-of-the-art experimental, characterization and computational facilities

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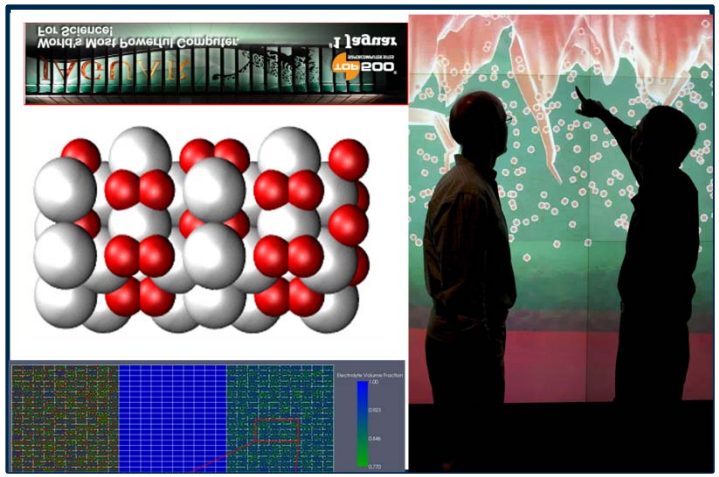
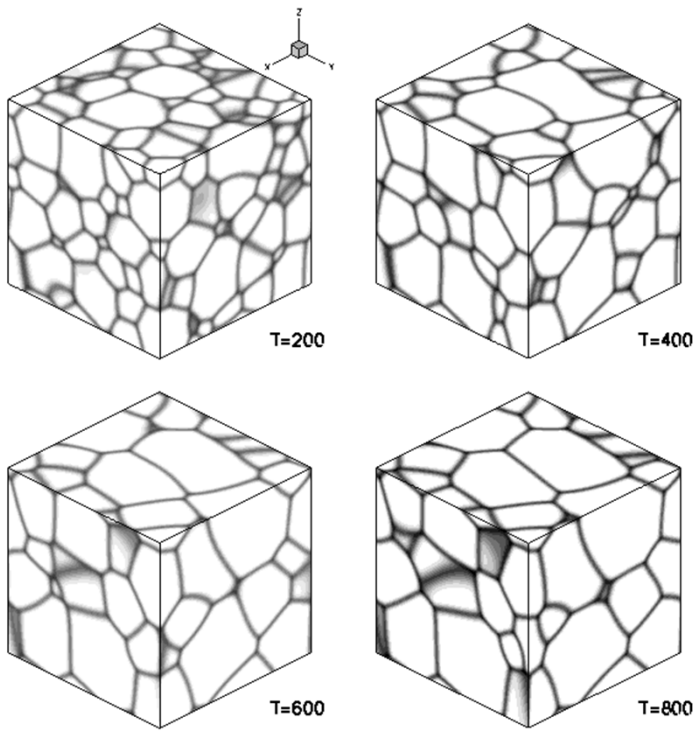


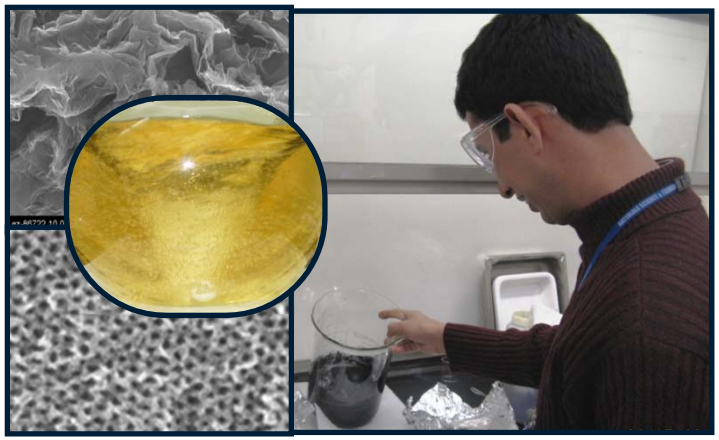
State-of-the-art computational software, algorithms and hardware to make predictive simulations feasible by bridging computations from atomistic to continuum scales. The simulations will be integrated with the experiments and characterization to have a validated suite of tools for flow battery design.

Mesoscale Modeling for Batteries: Phase field approach used for modeling grain growth in metals



Phase field approach has been used to model curvature driven, three-dimensional grain growth grain growth in metals taking advantage of the high performance computing facilities at ORNL. Figure shows the use of a **novel approach to eliminate grain coalescence** during grain growth modeling.

Advanced materials for supercapacitors



Synthesis of Novel Materials: Using high throughput wet chemistry methods, **templated carbons and graphene materials** as well as tailored electrolytes are being synthesized and tailored for use in electrical double-layer capacitors. The electrode materials can be produced from available chemicals and using scalable processing operations, enabling **cost-effective nanomanufacturing processes.**

Materials Characterization: **Gas adsorption analysis** is used for measuring the **surface area** and the **distribution of pores** of nanometer size in electrode materials. In addition, information **on surface chemical functions** is obtained from thermodesorption combined with mass spectrometric analysis (TPD-MS).

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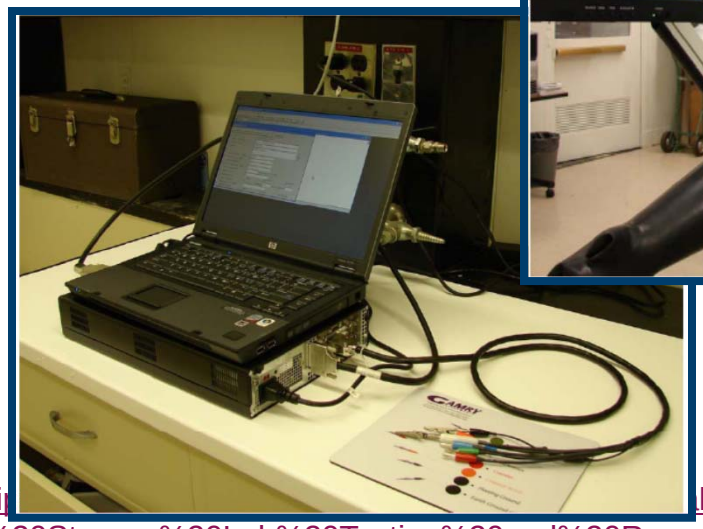
Advanced materials for supercapacitors

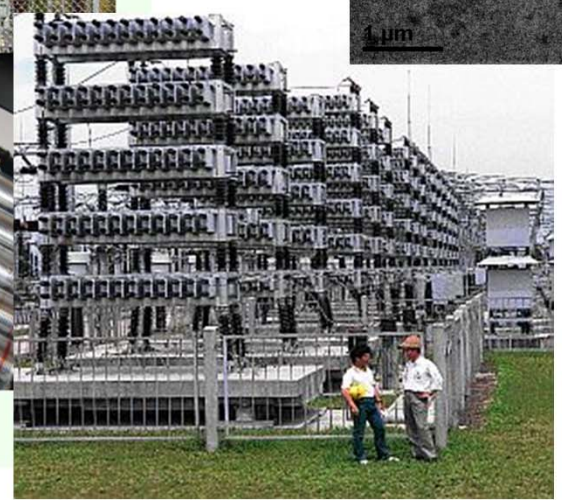
Electrochemical Testing: The performance of novel materials for electrochemical capacitors – including electrode materials and tailored electrolytes – is tested under realistic conditions in a dedicated laboratory for energy storage measurements. Cells assembled in an inert-atmosphere dry box can be cycled using industry-standard test systems under temperature-controlled conditions.

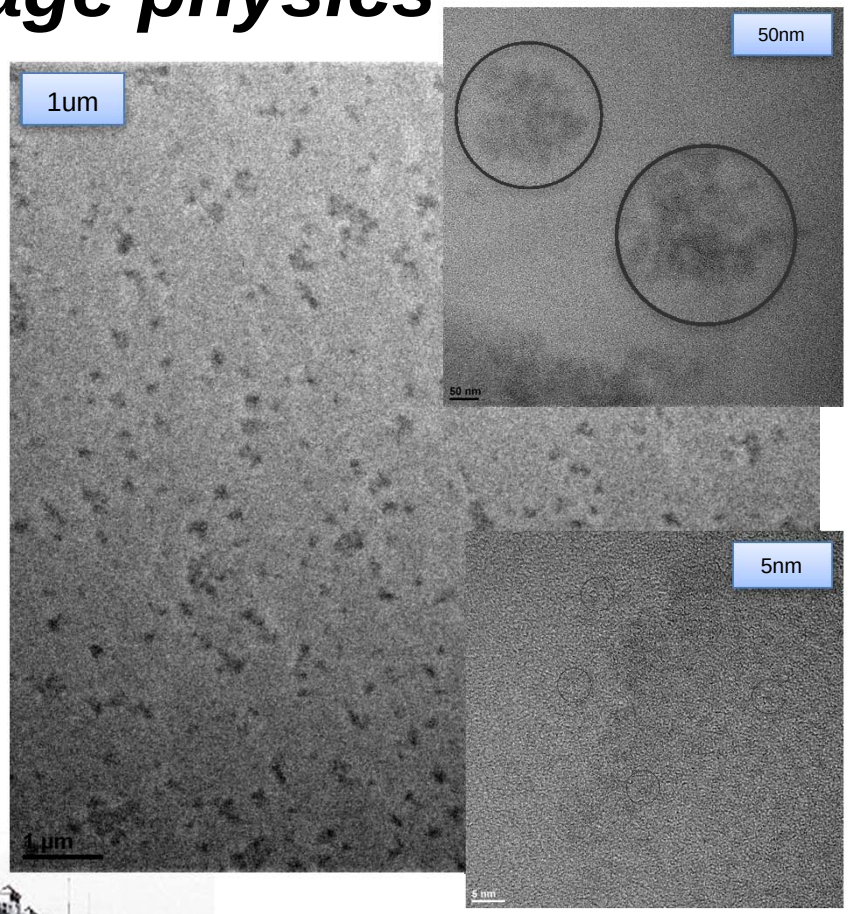


Pictures added from https://portal.ornl.gov/sites/leadership l%20Meeting%20-%20April%202/1%20Energy%20Storage%20Lab%20Testing%20and%20Research%20-%20Nancy%20Dudney.pdf

Dielectrics and high voltage physics

Dielectric capacitors of different sizes are employed in various **high voltage** power electronics and grid applications.





Nanodielectrics with better electrical insulation properties are employed as energy storage material in capacitors. Transmission electron microscopy is used to determine uniformity in nanodielectrics.

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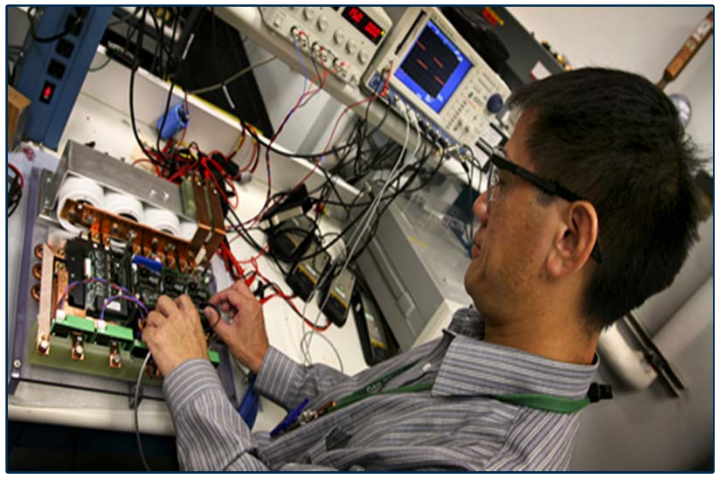
Power Electronic Conversion for Energy Storage

ORNL owns its own distribution system.



The **Power Electronics and Electric Machinery Research Center** encompasses more than 9,000 square feet of space for developing, building, and testing the next generation prototypes of power electronics and electric machine technology.

The **DECC laboratory** is equipped for developing methods of incorporating distributed energy resources that can produce reactive power locally and for injecting into the distribution system. The benefit of this system is to be able to provide voltage regulation and dynamic reactive power reserves without the use of extensive communication and control systems.

Power Electronics Innovation

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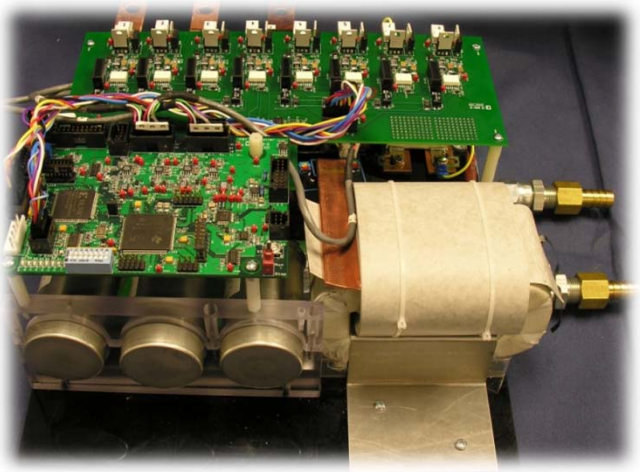
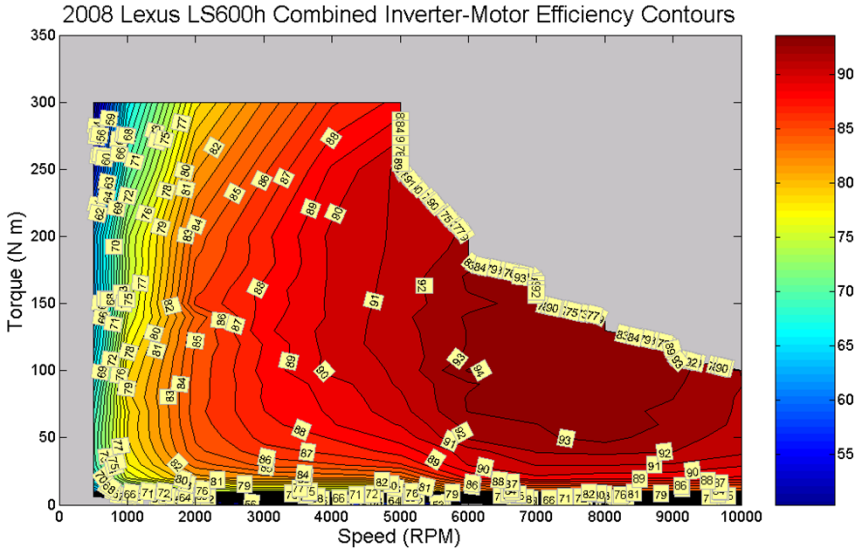


Power electronics (PE) advances produce technologies that address critical vehicle PE needs. Topologies that minimize passive components, are temperature tolerant, integrate functionality (incorporate boost into inverter), and innovative packaging lead to reductions in cost, volume, and mass required for mass market adoption.

Testing of commercially available hardware and understanding of advanced designs allows accurate models to be developed.



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Advanced Electric Motor Design and Modeling

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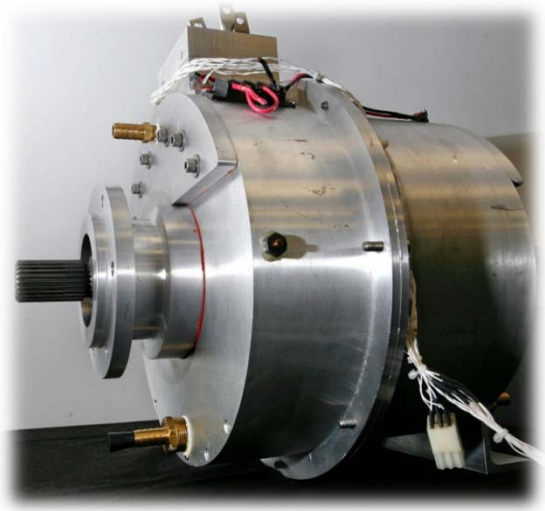

16,000 rpm Brushless Field Excitation (BFE) Motor

Electric motor advances focus on cost reductions by increasing speed, developing motors that use no permanent magnets, and improving permanent magnet motor designs. Motor designs also developed to match current requirements optimally for power need.

Extensive capability to model motors and determine performance.

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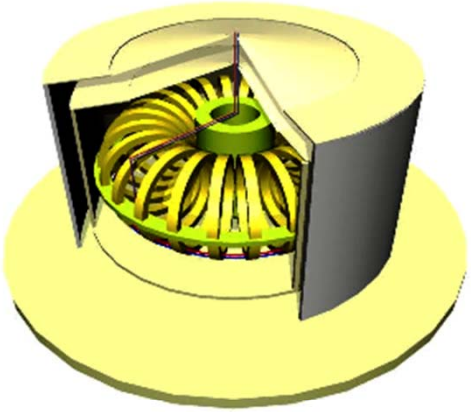
Superconducting Magnetic Energy Storage (SMES) for Grid Applications – Types of SMES units



SMES

- **Ultra SMES**
  - **Energy→ 2-5 MJ**
  - **Current→ 1 kA; B-field 4-5 T**
  - **Max Power→ 800 kW**

- **Mid SMES**
  - **Energy→ 1000-5000 MJ**
  - **Current → 10-20 kA; B-field 5-15 T**
  - **Max Power→ 10-50 MW**

- **Large SMES**
  - **Energy 3000-4000 GJ**
  - **Need a loop of 100 miles radius of land to install this one (possible health effects; size; manufacturing; critical current and refrigeration issues)**

2 MJ SMES

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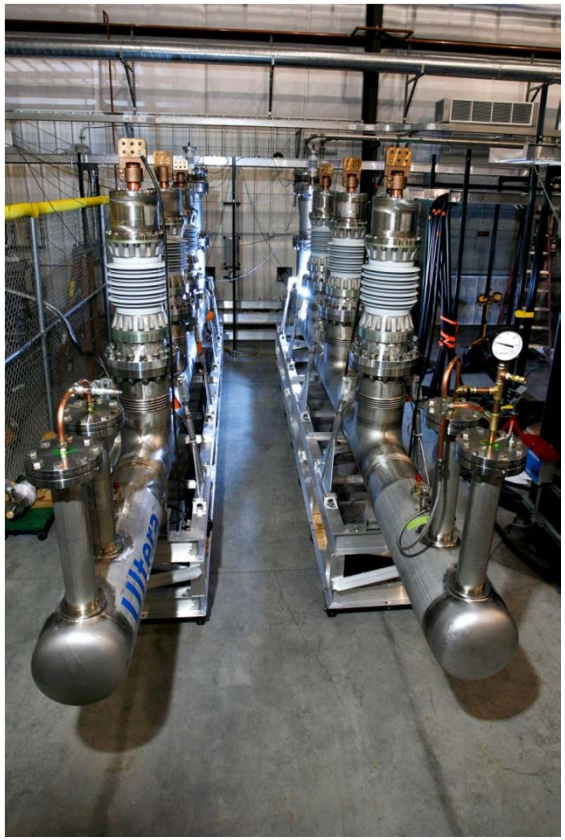
ORNL Test Capability for SMES

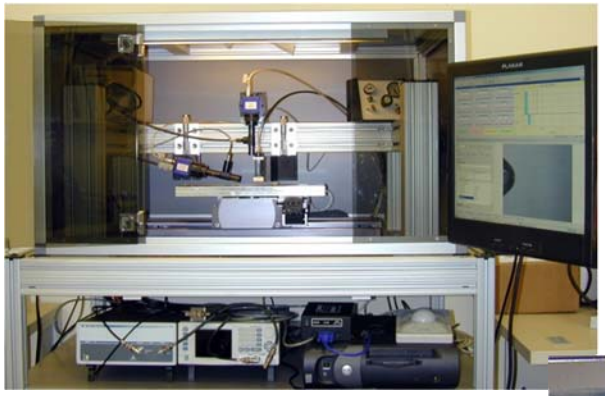


- **High Currents: 25 kA dc and 5 kA_{rms} ac**
- **High voltage: 200 kV BIL, ac/dc withstand to 100 kV**
- **Fault Current: 60 kA_{rms} at 1 kV**
- **Refrigeration: 6 kW at 70 K, 40 gpm flow rate at 16 bar**

ORNL HTS Wire Fabrication Capabilities

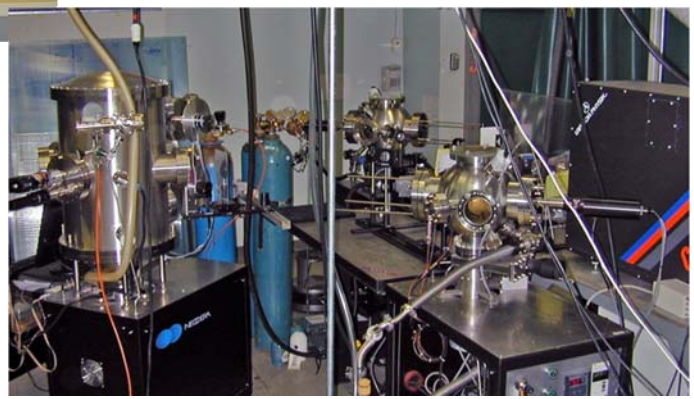
Expertise and capabilities in synthesis of 2nd Gen. HTS Wires

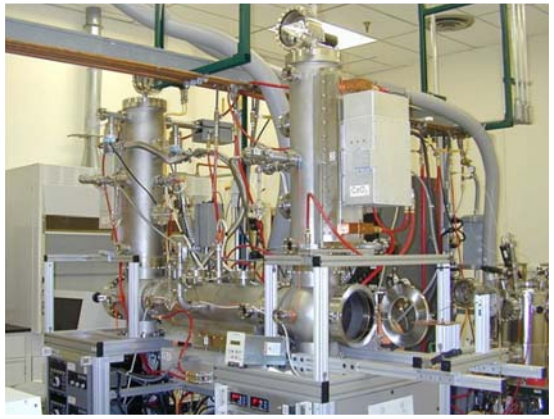
- Long-length thermo-mechanically crystalline metal templates for superconductor wires
- Multilayer coatings for buffer layers, oxide superconductors, and metal overlayers



Coating Deposition

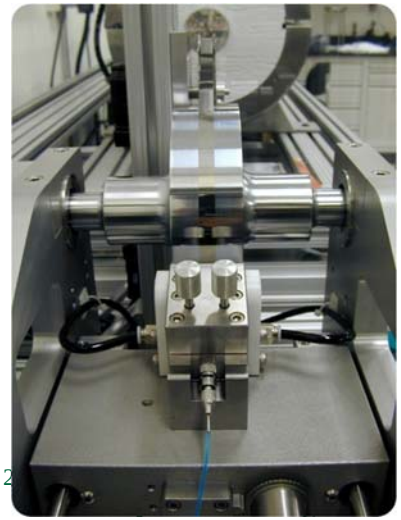
3-chamber PLD system





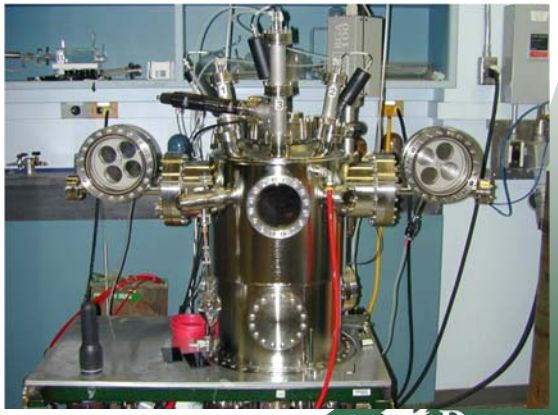
Solution coating by inkjet printing

Multi-layer *rf* sputtering (3 systems)



Solution coating by slot die (reel-to-reel)

3-source e-beam co-evaporation (2 systems)



ORNL HTS Wire Fabrication Capabilities

Materials Processing and Characterization

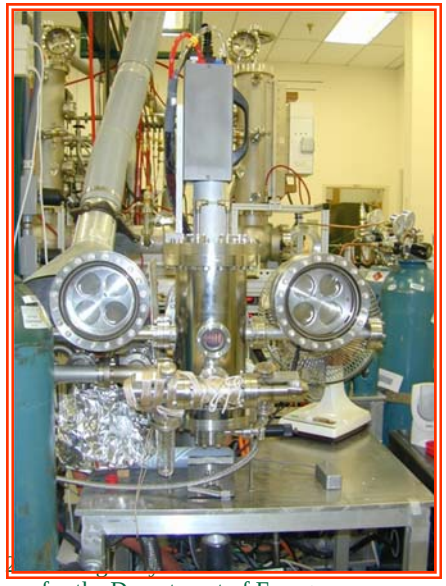
Class 1000, 4-High Rolling Mill

Magnetic-field electrical properties systems (3 total)

SQUID-based Magnetometer with 7 Tesla Field

Laser scriber (sample patterning)

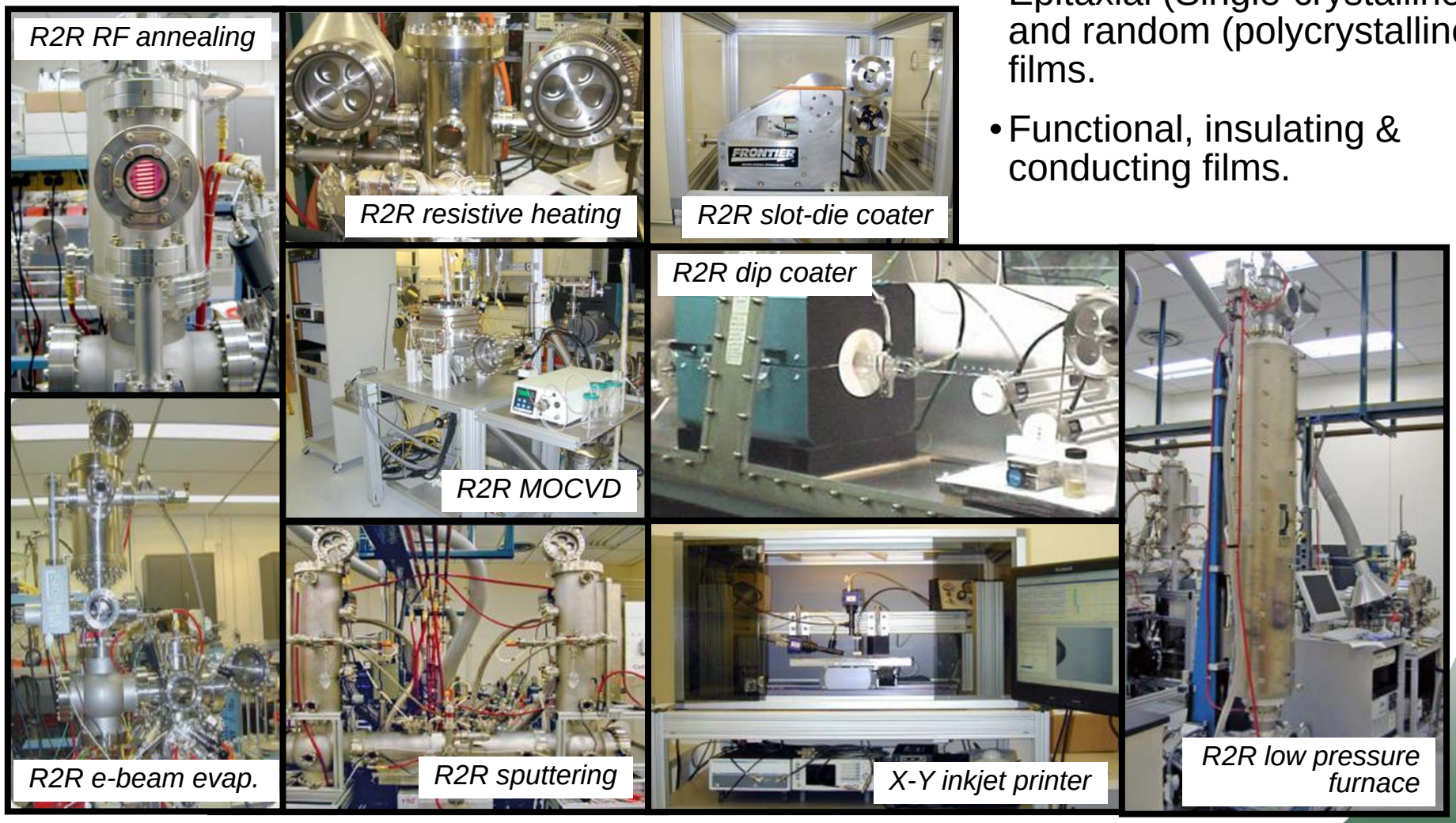
Reel-to-reel e-beam and Auger spectroscopy



1500°C vacuum thermal processing

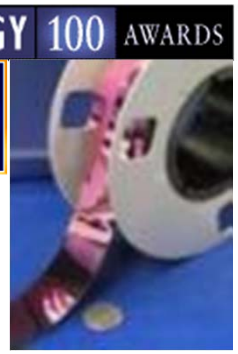
A large variety of high-temp reel-to-reel & batch film processing equipment is available.

- Epitaxial (Single-crystalline) and random (polycrystalline) films.
- Functional, insulating & conducting films.

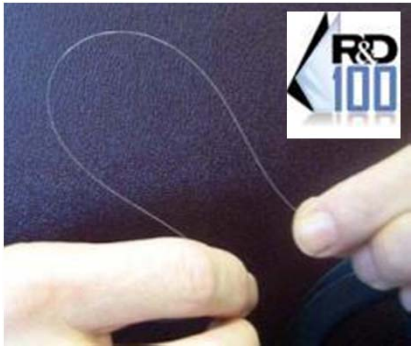


Demonstrated track record in providing innovative solutions to materials challenges.

Flexible single-crystal templates by the kilometer



Metallic ribbons



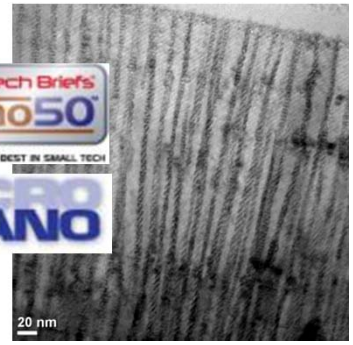
Sapphire fibers (Ribbons)

- World-renowned scientists – 4 Res. Div., 6 Res. Groups.
- Leadership roles to affect research directions and trends:
  - 11 professional society Fellows
  - 19 journal Editors
  - 5 int'l conf advisory Committee Members
  - 5 Board Directors
  - 16 Officers in prof/trade/ industry org.
- Awards winning R&D.

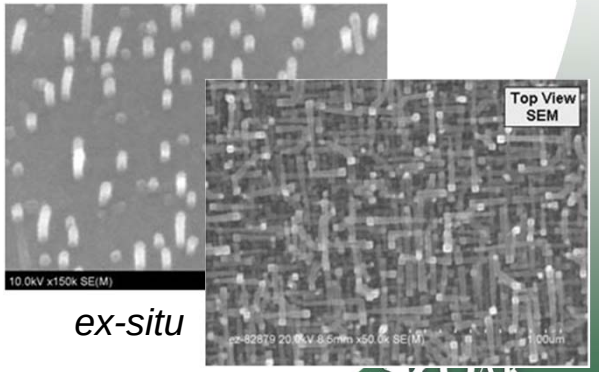
Large-scale functional tapes

> 1 kilometer piece-length near- single crystalline (3,000X higher current density)

Self-assembled nano-engineered structures to enhance performance



in-situ



ex-situ

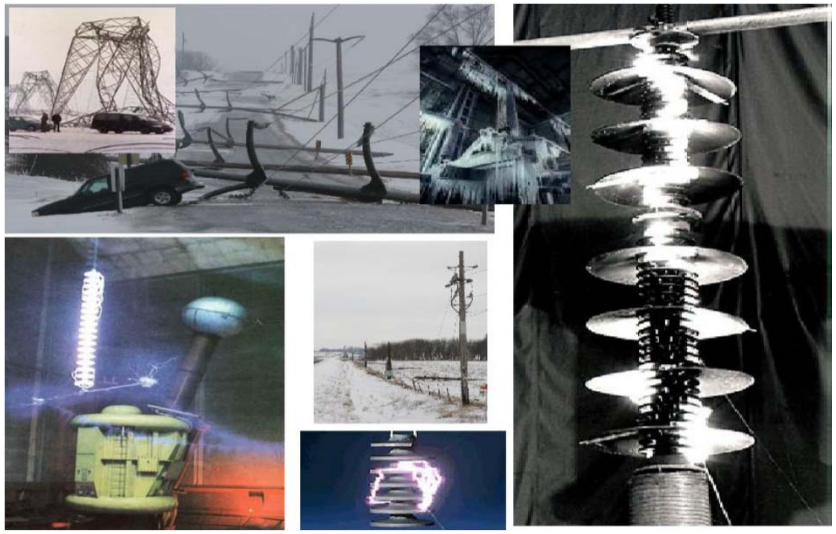
(Further > 2.5X improvement)

ORNL is pioneering development of novel enabling materials to enhance reliability.

Superhydrophobic (SH) coatings

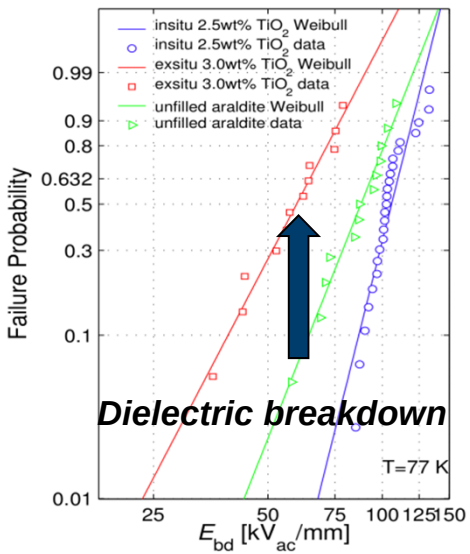
Surface nano-structure | *Contact angle* | *"Moses effect"*

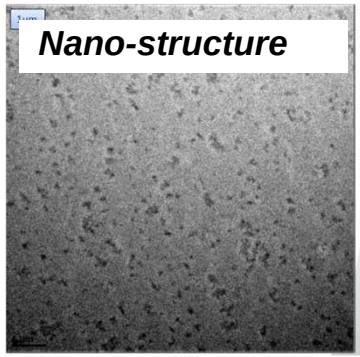
Anti-icing… ***… Self-cleansing***

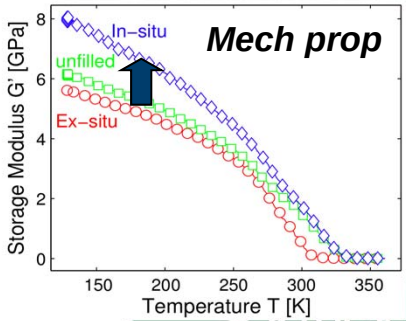


- What "new materials" can be developed to achieve a combination of desired properties?
- What materials/technologies can be applied to enhance reliability? Smartness? Self-mitigating? Self-healing?

Tailor-made dielectric nano-composites







ORNL is the go-to place for prototype power equipment development & testing.

Innovative triaxial cable design

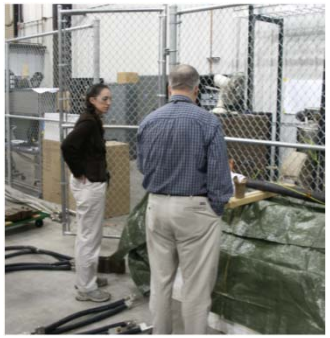
Highest power density, most compact, one-half the cost

VS.

ORNL-Southwire *Typical*

- Cables, connectors, fault-current, transformers, motors, generators
- Multiple sponsors & users:
  - ☑ DOE, DHS, DoD
  - ☑ EPRI, Southwire, Waukesha Electric, Siemens, 3M, ConEd…

Testing under combination of (extreme) conditions

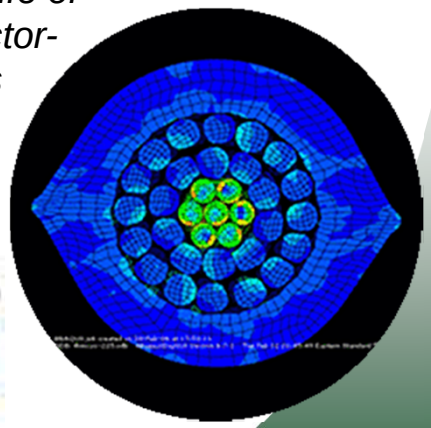


Cable Test Facility – *High voltage, high current, high fault current, cryogenic*

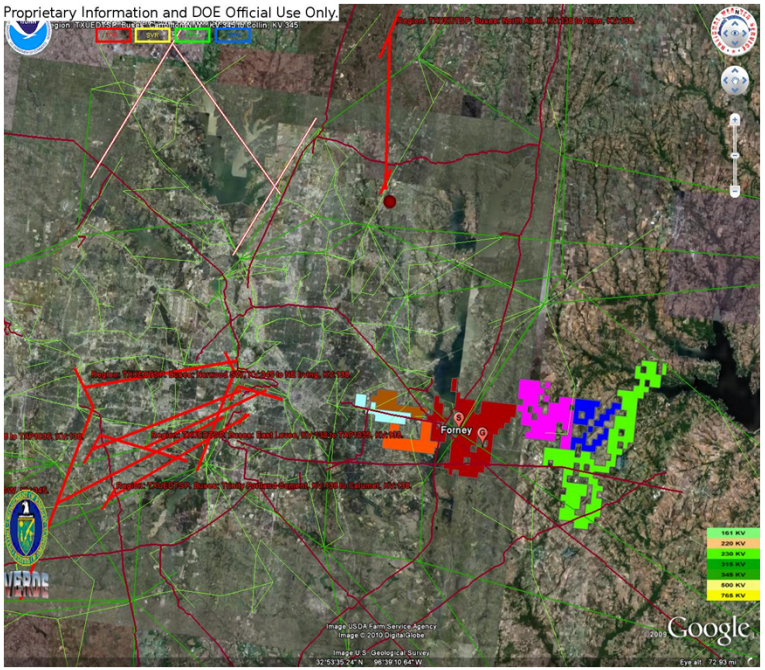
Powerline Conductor Accelerated Test Facility – *Outdoor, heating, high DC current*

Simulation & predictive modeling

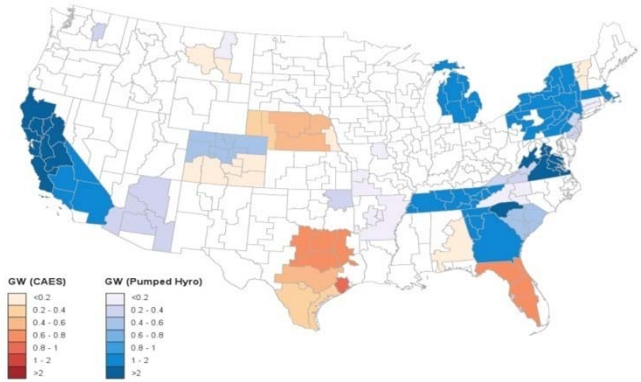
MELCOT: Methodology for Estimating the Life of Power Line Conductor-Connector Systems Operating at High Temperatures



Analytical Models and Visualization



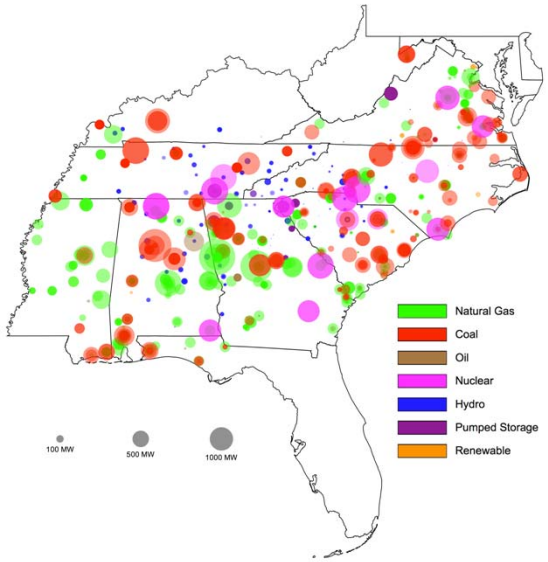
ORNL is bringing to the table modeling and simulation environment that supplies and stores electrical energy for neighboring utilities in the Dallas region. This example shows the **critical service areas, impacted transmission lines and substation locations of a disruption** to the Forney (Dallas region) natural gas city gate.



Compressed Air Energy Storage (CAES) is most appealing in certain geological formations with variable generation resources nearby. ORNL has developed analytical techniques to **identify likely cost-effective locations across the country**.

OAK RIDGE National Laboratory

Analytical Models and Visualization



Generation dispatch modeling using the ORCED model can **show the plants that could be affected by a change in system demands**. Storage on the grid will mean some plants run more while others less.

ORNL, in partnership with TVA, has developed a **real-time status of the electric grid with VERDE** and can assess **inter-dependencies with critical energy infrastructure**

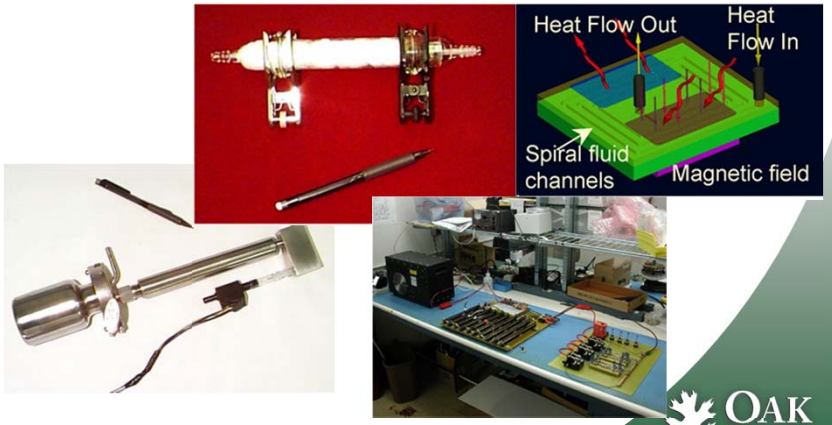
Robotics and Energetic Systems

Robotics

Human-Amplifying Machines

Power Transfer and actuation

Energy Transformation Systems



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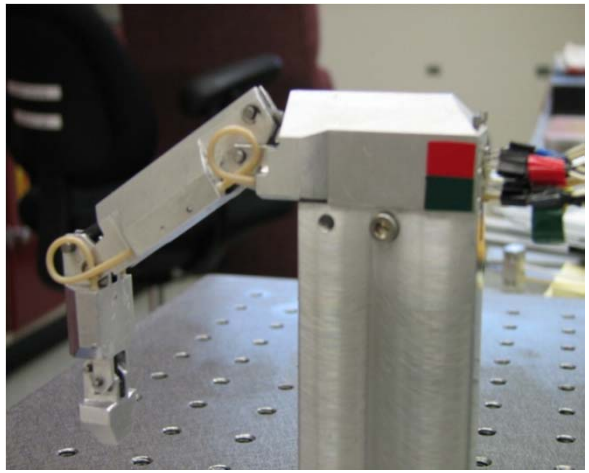
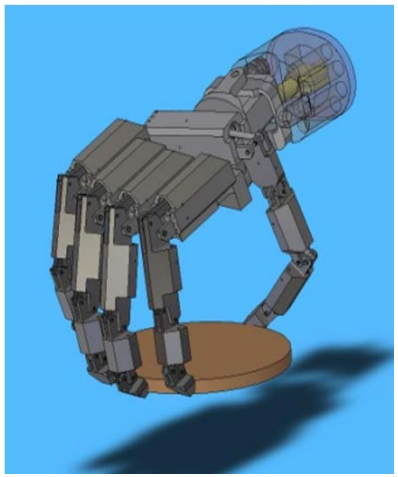
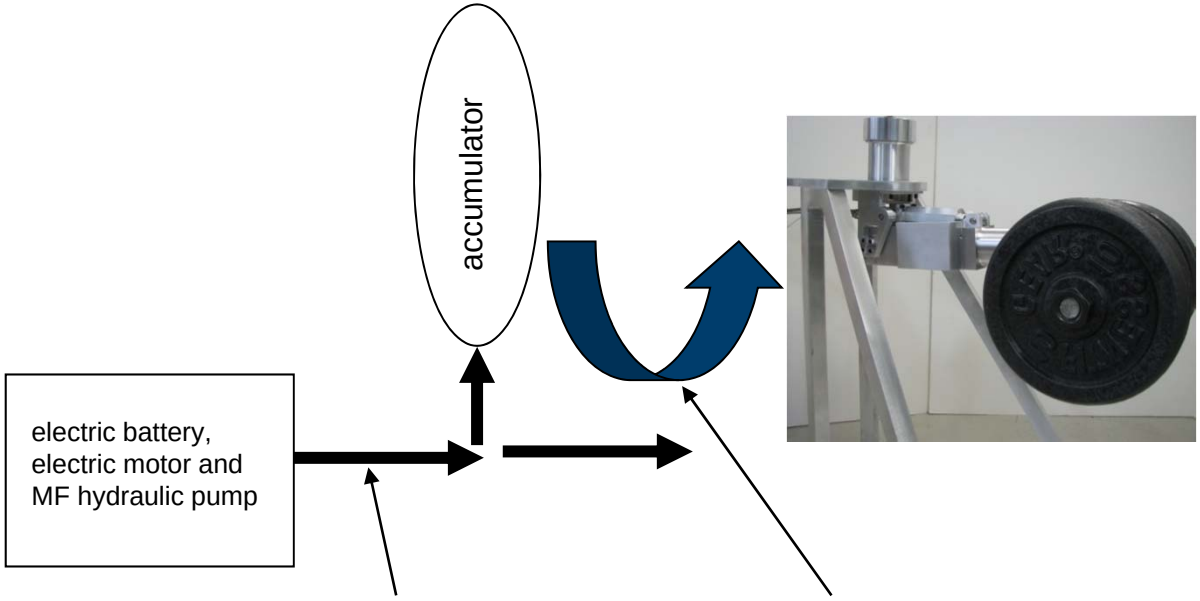
Revolutionizing Prosthetics

- **Objective – Demonstrate a human finger with intrinsic actuation and control (actuators and controls within the volume of the finger).**
- **Challenge – Need for very compact actuators, pumps and controls**
- **Approach – Mesoscale hydraulics.**
  - Began as an internal R&D activity
  - Series of pumps, actuators and control valves
  - Fit within the volume of a 50th percentile human female.
- **Operational finger capable of curling 20 lbs and weighing under 60 grams**
- **Lessons learned:**
  - The amazing scalability, simplicity and performance of hydraulics
  - Tremendous potential for energy efficiency
    - Applied hybrid hydraulics to arm (single 30 W pump for hand and wrist, charges 600 J accumulator integrated in forearm for large, low duty cycle activities)





Energy Storage is Critical for Prosthetic



Only average power

Only large transient power

- **Power requirements**
  - Average power relatively low (25 Watts, unloaded arm movements, hand) with rare peaks (up to 600 Watts for elbow and shoulder moving heavy loads)
- **It's more efficient to have a small power supply to handle average loads and an energy storage device to handle peak loads**
- **In hydraulics, energy storage is generally through an accumulator.**
  - An accumulator is a piston with compressed gas on one side, hydraulic fluid on the other
  - Can release energy rapidly for high power over short duration

CAES Development

Capabilities and Technologies

Utility-scale CAES systems involve a combination of components involving ORNL and partner research, engineering, and analysis for generators, turbines, recuperators, distribution, transmission, resident energy sources, geological structures, man-made tunnels, materials, thermodynamic properties, geothermal usage, and materials for reducing energy losses

High Voltage Insulators

Advanced power cables – superconducting wires

Power Electronics

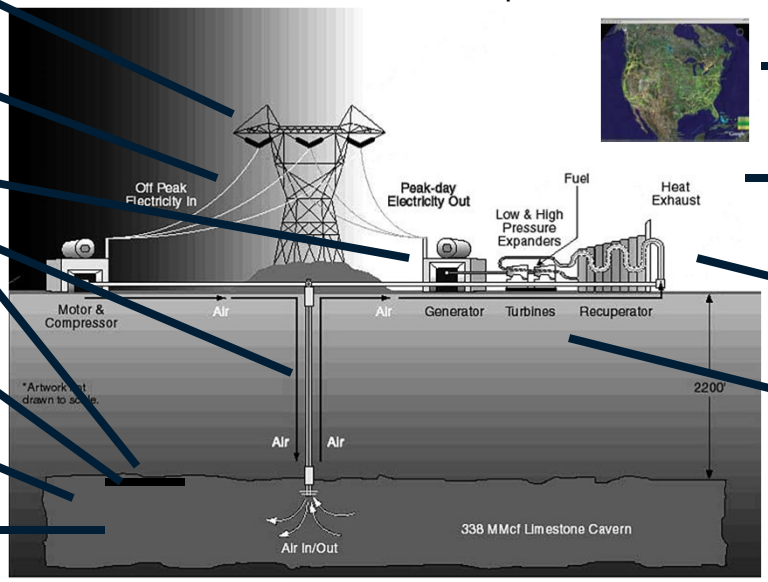
Material characterization
- sub-surface analysis
- concrete analysis

Inner Wall Material Lining

Underground facility research

Thermodynamics, compression analysis

Sustainable Campus



National-scale, Grid Situation Awareness

MicroGrid computational simulation, modeling and analysis

Heat transfer technologies
- Carbon fibers

Control System, Sensors, and engineering

Geothermal power source

Business Sensitive

Capabilities from Grid to Nuts and Bolts

Neutron Scattering has been used to inspect and improve failure analysis on items such as pipelines.

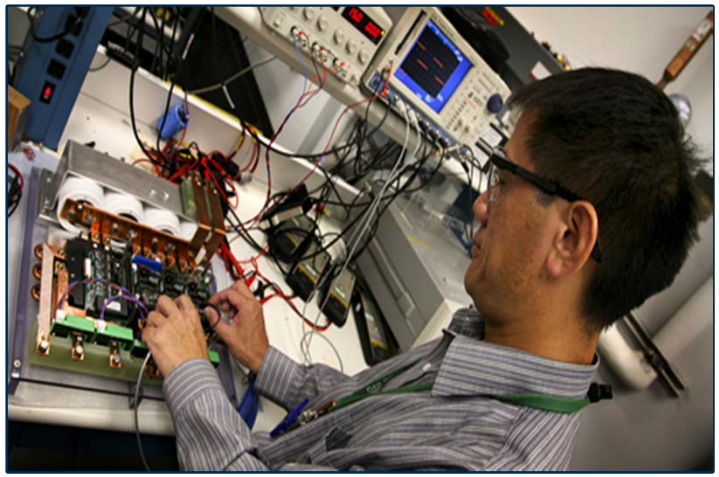
ORNL also has world-class materials science capabilities, power electronics, grid connections available for this project. This allows one to assess aspects of the project ranging from system integration down to the nuts, bolts and materials of the project.

ORNL's Jaguar is the world's fastest supercomputer, providing an unsurpassed environment for complex computations for design of systems, equipment and grid interplay. We have the hardware and we know how to use it.

OAK RIDGE National Laboratory

Pumped Hydro Energy Storage

ORNL owns its own distribution system.



The **Power Electronics and Electric Machinery Research Center** encompasses more than 9,000 square feet of space for developing, building, and testing the next generation prototypes of power electronics and electric machine technology.

The **DECC laboratory** is equipped for developing methods of incorporating distributed energy resources that can produce reactive power locally and for injecting into the distribution system. The benefit of this system is to be able to provide voltage regulation and dynamic reactive power reserves without the use of extensive communication and control systems.

Energy Storage System Requirements

All hybrid energy systems require four major components

- **The energy storage device**
- **A power conversion system (AC/DC, DC/AC)**
- **A control system to manage the state of the storage system**
- **Interconnection**