



**NETL**  
Science & Technology  
**ACCOMPLISHMENTS**  
**2021**



U.S. DEPARTMENT OF  
**ENERGY**



NATIONAL  
ENERGY  
TECHNOLOGY  
LABORATORY

# MESSAGE FROM THE DIRECTOR

I am pleased to present the National Energy Technology Laboratory's (NETL) *FY 2021 Science & Technology Accomplishments*. The projects described in the following pages represent just some of our outstanding successes and contributions toward meeting clean energy goals calling for a net-zero carbon emission electricity sector by 2035 and economy-wide net-zero emissions by 2050.

These accomplishments demonstrate the impressive impact made possible through research aligned with the Department of Energy's Office of Fossil Energy and Carbon Management's nine research, development, demonstration, and deployment (RDD&D) priorities:

- Demonstrate and Deploy Point Source Carbon Capture
- Advance Carbon Dioxide Removal and Low-Carbon Supply Chains for Industry
- Low-Carbon Industrial Supply Chains
- Accelerate Carbon-Neutral Hydrogen
- Reduce Methane Emissions
- Advance Critical Minerals, Rare Earth Elements, and Mine Remediation
- Increase Efficient Use of Big Data and Artificial Intelligence
- Address the Energy Water Nexus
- Invest in Thoughtful Transition Strategies

A significant portion of the NETL research portfolio includes collaborative efforts conducted through partnerships, cooperative research and development agreements, financial assistance, and contractual arrangements with universities, research organizations, the private sector, and other national laboratories. Together, coupled with our own research, these efforts serve to focus the nation's wealth of scientific and engineering talent to create commercially viable solutions to help solve national and global energy and environmental challenges.

NETL's research competencies and portfolio of successes constitute a robust national asset that is poised to meet the aggressive decarbonization goals required to mitigate the climate crisis and directly support the administration's initiatives.

I'm proud of the many benefits our research and talent are providing to enable environmental sustainability for all Americans, advance environmental justice and revitalize economies, and deliver technological solutions for a prosperous clean energy future. Thank you for supporting our work.

Sincerely,

**Brian J. Anderson, Ph.D., Director**  
*National Energy Technology Laboratory*



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Department of Energy's Office of Fossil Energy and Carbon Management  
Research, Development, Demonstration, and Deployment

# FECM RDD&D PRIORITIES



## DEMONSTRATE AND DEPLOY POINT SOURCE CARBON CAPTURE

RDD&D for CCS in the power and industrial sectors to enable wider, strategic commercial deployment to meet net-zero emissions goals by 2050.



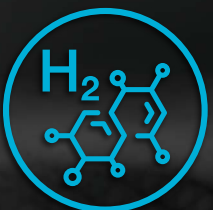
## ADVANCE CARBON DIOXIDE REMOVAL AND LOW-CARBON SUPPLY CHAINS FOR INDUSTRY

Air capture and mineral carbonization projects and develop novel approaches to recycle carbon emissions.



## LOW-CARBON INDUSTRIAL SUPPLY CHAINS

Develop novel approaches to recycle carbon emissions into value-added products such as concrete, steel, chemicals, and fuels using systems-based carbon management approaches consistent with realizing a net-zero carbon economy by 2050.



## ACCELERATE CARBON-NEUTRAL HYDROGEN (H<sub>2</sub>)

Develop technologies that leverage the natural gas infrastructure for H<sub>2</sub> production, transport, storage, and use, coupled to carbon management.



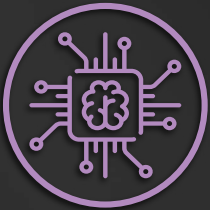
## REDUCE METHANE EMISSIONS

Develop technologies and deploy regional initiatives to monitor and reduce methane emissions from fossil fuel infrastructure including coal, oil, and gas.



## ADVANCE CRITICAL MINERALS, RARE EARTH ELEMENTS (REE), AND MINE REMEDIATION

Improving REE separation/recovery technologies to manufacture products from CO<sub>2</sub> and carbon ores and to address current market and process economics. Advancing R&D to address abandoned mines.



## INCREASE EFFICIENT USE OF BIG DATA AND ARTIFICIAL INTELLIGENCE

Use AI, machine learning, and data analysis to create learning algorithms within large dataset to help discover new material, optimize processes, and run autonomous systems.



## ADDRESS THE ENERGY WATER NEXUS

Improve our efficient use of scarce water resources advance water remediation technologies to address the environmental impacts related to produced or displaced water associated with oil, gas, and coal industries, in addition to that associated with dedicated CO<sub>2</sub> storage.



## INVEST IN THOUGHTFUL TRANSITION STRATEGIES

Invest in technologies and approaches and deploy regional initiatives to help create an equitable and just transition to a net-zero carbon economy in energy communities.

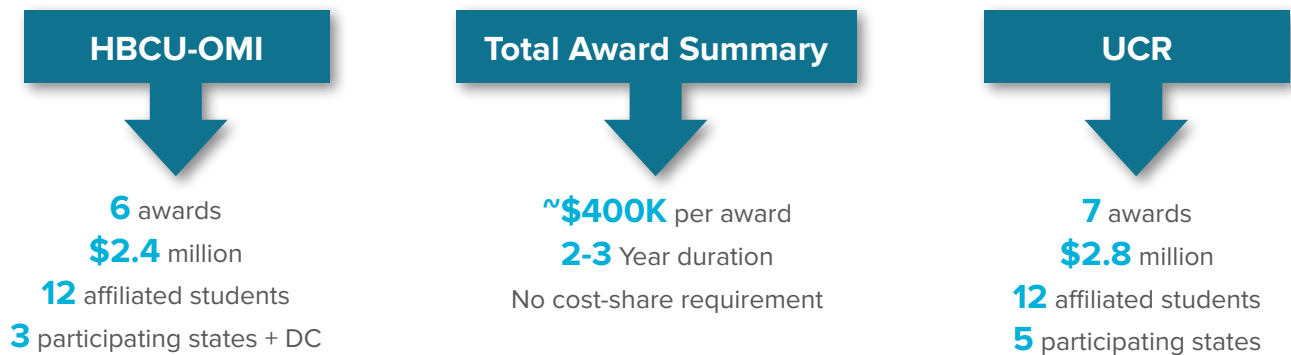
# DOE INVESTS \$5 MILLION TO INVESTIGATE HYDROGEN PRODUCTION, WATER-ENERGY NEXUS, MATERIALS SUPPLY CHAIN, AND 5G WIRELESS TECHNOLOGIES

Special emphasis placed on diversity and inclusion, providing opportunities in STEM fields for traditionally underrepresented communities.

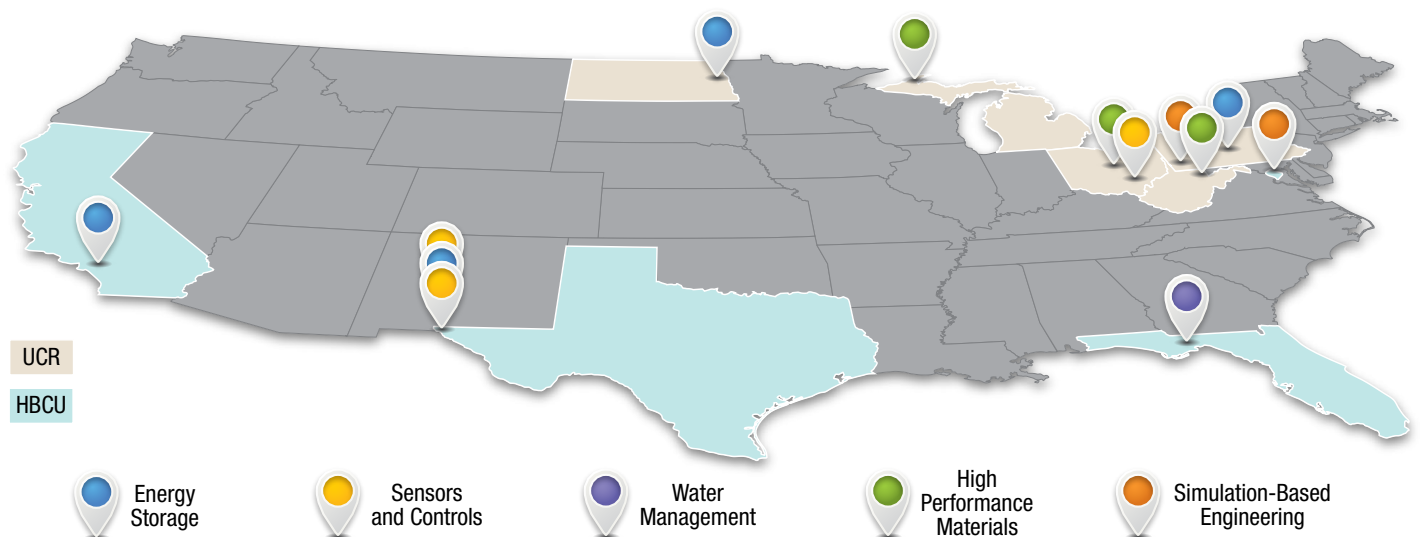
The University Training and Research (UTR) program portfolio supports novel, early-stage research at U.S. colleges and universities that advances the Office of Fossil Energy and Carbon Management’s mission of delivering integrated solutions related to minimizing the environmental impacts of fossil fuels while working toward net-zero emissions and negative emission power generation facilities.

The UTR program consists of two budget lines under Crosscutting Research: (1) Historically Black Colleges and Universities and Other Minority Institutions (HBCU–OMI), and (2) University Coal Research (UCR).

## FY21 UTR AWARDS BY BUDGET LINE



## FY21 UTR AWARDS: PARTICIPATING STATES BY KEY TECHNOLOGY





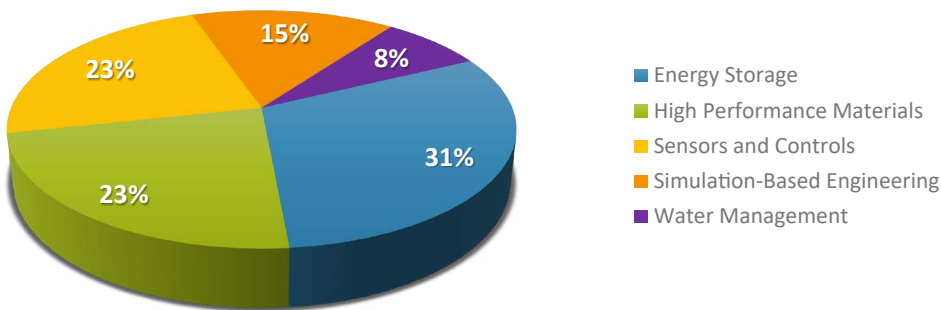
## UTR PROGRAM MISSION

- To increase research and development opportunities for traditionally underrepresented communities within the United States and tap into the innovative and diverse thinking of student researchers at HBCU-OMI institutions of higher learning.
- To educate and train the next generation of engineers and scientists to help develop and contribute to a highly skilled, inclusive, and competitive U.S. workforce and economy.
- To support novel, early-stage research at U.S. colleges and universities that advances the Office of Fossil Energy and Carbon Management’s mission of delivering integrated solutions related to fossil energy and carbon management and enable transformation to a sustainable, low-carbon energy future.
- To ensure that students are being equipped with cutting-edge, translatable skill sets that will allow them to contribute to the U.S. workforce and greater economy over the course of long and enduring careers.

## FY21 FUNDING OPPORTUNITY ANNOUNCEMENTS TECHNOLOGY FOCUS

PROMOTING THE INFLUX OF FRESH IDEAS AND ENSURING CONTINUED TRAINING OF FUTURE SCIENTISTS AND ENGINEERS

- Energy-water nexus implications and opportunities of a hydrogen economy.
- Electromagnetic energy-assisted approaches to convert fossil fuels to low-cost hydrogen.
- Process and materials co-optimization for the production of blue hydrogen.
- Addressing high-temperature materials supply chain challenges.
- 5G wireless technologies for power generation.



AWARD NUMBER  
**DE-FE002398**

### PROGRAM BUDGET



- DOE (UCR) .....\$2,797,885
- DOE (HBCU-OMI) .....\$2,399,878

### CONTACTS

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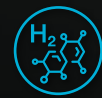
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### FECM RDD&D PRIORITIES



ADDRESS THE ENERGY WATER NEXUS



ACCELERATE CARBON-NEUTRAL HYDROGEN (H<sub>2</sub>)



INCREASE EFFICIENT USE OF BIG DATA AND ARTIFICIAL INTELLIGENCE

### PARTNERS



# GASIFICATION HANDBOOK AND TOOLSET – ENABLING GASIFICATION TECHNOLOGY FOR PRODUCTION OF ENERGY AND CLEAN HYDROGEN

Unprecedented planning and design resource for gasification-based systems for power, hydrogen, and liquid fuels production.

## GASIFICATION HANDBOOK COMPLETED

NETL has completed work on the Gasification Handbook, **designed to educate investors and developers on the benefits of and best practices for the development of gasification systems**, including those for power generation and hydrogen and liquid fuels production.

## DIGITAL TOOLSET FOR PLANT SYSTEMS ANALYSIS

Delivering a quick and easy way to evaluate gasification-based systems

The Gasification Handbook is accompanied by a **modeling toolset** based on Microsoft Excel® that can model various gasification-based systems.

Choices that can be analyzed include:

- Power generation by steam turbines, combustion turbines, or both (i.e., combined cycle) or by reciprocating engines.
- **Hydrogen production.**
- Fischer-Tropsch synthesis of fuels.

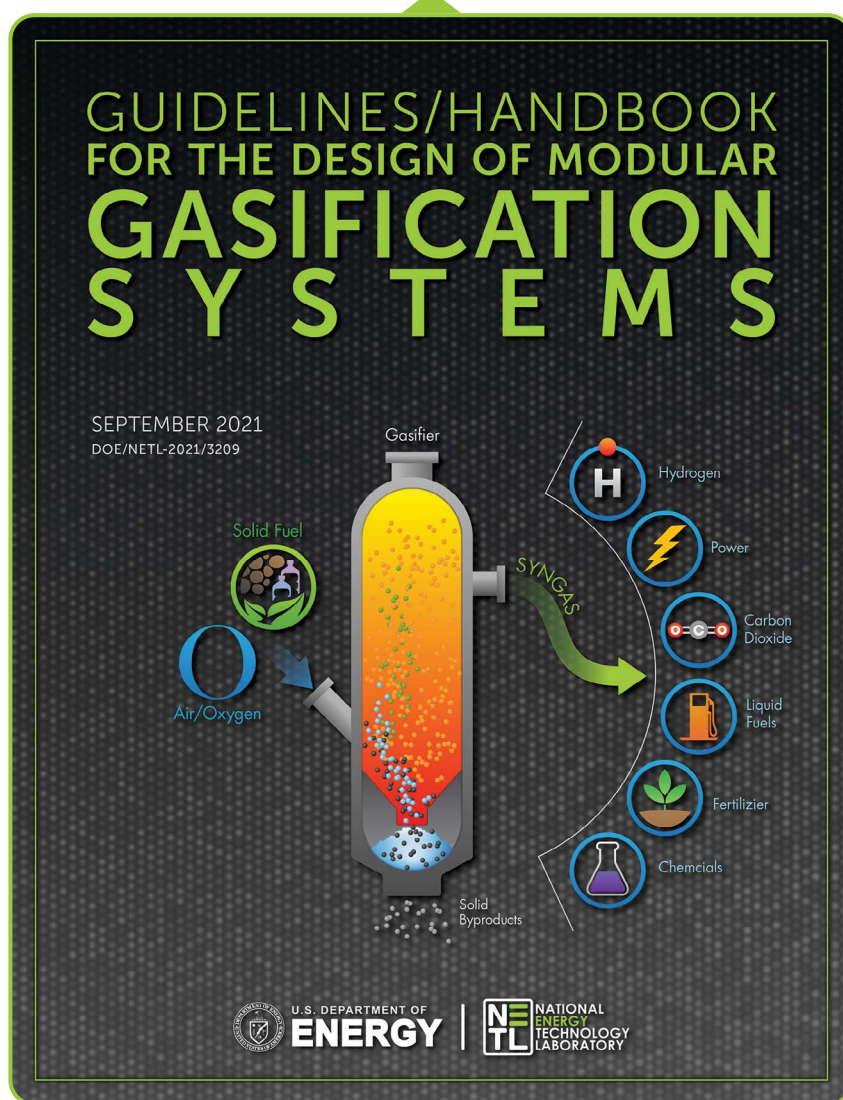
Once the user specifies the basic system by type and fuels utilized (coal/biomass/wastes), the **toolset automatically calculates basic process flows, amounts of products or power produced, system efficiencies, and costs.**

Major plant/system units are activated as applicable for the specified system; the main ones include:

- Gasifier
- Gas cleanup
- Turbines and steam generation
- Cooling tower/condenser
- Power generation

The toolset **features a user-friendly graphical user interface** to make the program easier to navigate and populate with input data.

Gasification Handbook Cover



# SUPPORTING CLEAN ENERGY AND THE HYDROGEN ECONOMY

## Helping Developers and Investors Decide on Value Propositions for Gasification-based Systems

The handbook and toolset are expected to:

- **Accelerate gasification** systems development, deployment, and adoption.
- Give developers and investors an **improved understanding of gasification systems** and components.
- Enable gasification technology to **contribute clean energy** in a hydrogen-based economy.

The toolset is designed to provide a quick assessment that allows easy comparisons to evaluate value propositions for gasification-based hydrogen or energy production plants.

The gasification-based systems choices featured in the Gasification Handbook and Toolset are aligned with the **urgent need for clean energy systems** as the United States economy drastically reduces carbon emissions to meet climate goals. The syngas-based systems all allow pre-combustion capture that can **help in attaining net-zero emissions** characteristics. Biomass can be included as feedstock in all system options to improve carbon footprint performance.

The hydrogen production option from gasification of low-cost solid feedstocks and wastes is especially relevant to the envisioned hydrogen economy of the future, offering an **alternative to expensive electrolysis-based hydrogen**.

Conceptual Gasification System



## GASIFICATION SYSTEMS

### PROJECT BUDGET

FY21 FUNDING



● DOE ..... \$500,000

### CONTACTS

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### FECM RDD&D PRIORITY



ACCELERATE CARBON-NEUTRAL HYDROGEN (H<sub>2</sub>)

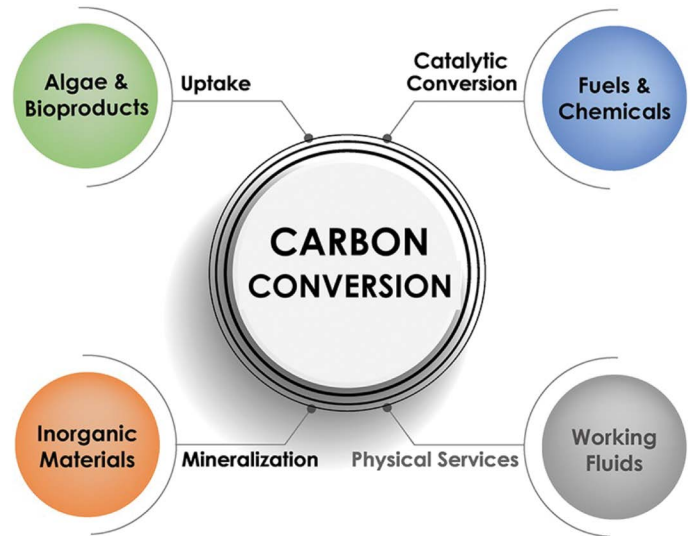
# MAJOR ADVANCEMENTS IN LCA GUIDELINES FOR CARBON UTILIZATION TECHNOLOGIES

Updating NETL LCA guidance to foster better decision making and leading global discussion to align carbon utilization LCA best practices

## CARBON UTILIZATION TECHNOLOGIES TRANSFORM CAPTURED CO<sub>2</sub> INTO ARRAYS OF VALUABLE PRODUCTS

Carbon utilization, also called carbon conversion, can reduce greenhouse gas emissions by transforming captured carbon dioxide (CO<sub>2</sub>) emitted from power and industrial sources into valuable products (e.g., chemicals, polymers, and mineral products) for various applications (e.g., agriculture, construction, and manufacturing). Carbon dioxide utilization (CO<sub>2</sub>U) is an emerging research area that encompasses many possible pathways, including biological uptake, catalytic conversion, and mineralization.

### Major Carbon Utilization Product Pathways



Physical services R&D is supported through the Carbon Storage and Transport Program

## NETL RELEASED NEW VERSION OF CO<sub>2</sub>U LCA GUIDANCE TOOLKIT

Life cycle analysis (LCA) can support the evaluation of the potential environmental impacts of CO<sub>2</sub>U technologies compared to existing alternatives in the marketplace from a consistent and unbiased viewpoint. In the interest of supporting the creation of useful and consistent LCAs of CO<sub>2</sub>U projects, the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) has developed a *CO<sub>2</sub>U LCA Toolkit* and recently released version 2.0.

Version 2.0 includes, but is not limited to, updated LCA guidelines to reflect more CO<sub>2</sub> sources, guidelines for inclusion of land use change impact, and other necessary updates. The associated tools were also updated to improve usability and knowledge transfer.



NETL CO<sub>2</sub>U LCA Guidance Document Version 2.0

## NETL CO-LEADS INTERNATIONAL CCU ASSESSMENT HARMONIZATION GROUP

Evaluation of environmental and economic opportunities and associated risks is vital for promoting research, development, and commercialization of carbon capture, utilization, and storage (CCUS) technologies. LCA and techno-economic analysis (TEA) are means to quantify these opportunities and risks. For consistent conduct and transparent reporting, a common framework for LCA and TEA is required.

NETL has teamed with the Global CO<sub>2</sub> Initiative (GCI) to lead the International CCU Assessment Harmonization Group, a diverse alliance of 30 international researchers that will create a harmonized framework by bringing together related efforts, analyzing differences, and eliminating discrepancies. NETL co-led multiple sub-teams in this effort and presented outcomes and recommendations during GCI's May 2021 webinar series.

Outcomes included:

- The launch of the [AssessCCUS website](#).
- Glossary of accepted TEA and LCA terms for CCUS.
- Recommendations to conduct LCA and TEA for CCUS technologies at low technology readiness level.
- Strategy to define comparison product system representatives.
- Guidelines to evaluate the technology learning curve and its implications on future performance.

NETL is contributing as a guest editor of a special issue the *Frontiers in Climate* journal, which will include multiple journal articles based on findings from this collaboration effort.

This international effort continues today to support the development of consistent guidelines to advance the commercialization of products produced from captured CO<sub>2</sub> to reduce the environmental impact to local and global communities to ensure a sustainable future.

**Consistent, unbiased, and detailed guidance is crucial for helping project developers assess and communicate the climate benefits of their technology to enable commercialization and acceptance of CO<sub>2</sub>-derived products in the marketplace.**

### CONTACTS

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### FECM RDD&D PRIORITY



**ADVANCE CARBON DIOXIDE REMOVAL AND LOW-CARBON SUPPLY CHAINS**

## INTERNATIONAL CCU ASSESSMENT HARMONIZATION GROUP

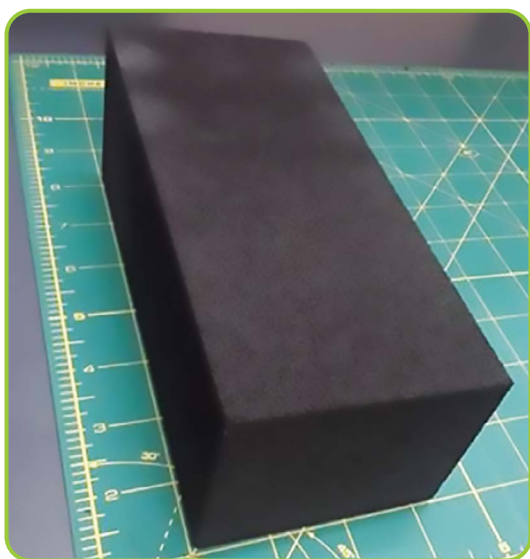


# PRODUCTION OF BUILDING PRODUCTS FROM COAL AND COAL WASTE BEGINS IN WEST VIRGINIA

Coal-derived building materials will create jobs in Appalachian coal communities.

## X-MAT BEGINS SMALL-SCALE PRODUCTION AND TESTING

**X-MAT**, an NETL Carbon Ore Processing Program recipient, began small-scale production and testing of **Coal-Derived Building Materials (CDBM)** at a new facility in Bluefield, West Virginia. The technology uses proprietary ceramic forming resin to **encapsulate coal and coal-waste particles into composite materials for application in building products** such as roofing tiles and siding.



Sample of Full-Size X-BRIX - Coal-Derived Building Block of the Future, Licensed from Partner, Semplastics



Set of 10 Coal-Based Ceramic Roof Tiles (Containing 70% Coal) Developed by Semplastics

The X-MAT CDBM exhibits high-performance characteristics, including **high strength** (five times the flexural strength of the best commercial brick, and more than twice the compressive strength of construction-grade concrete block), **lower density**, improved mechanical durability and **abrasion resistance**, very high temperature stability, **and resistance to chemicals, acids, salts, and water**.

# COAL-DERIVED MATERIALS REDUCE BUILDING COSTS AND PERMANENTLY STORE CARBON

**X-MAT** has reduced the cost of CDBM by decreasing the temperature required to activate a ceramic forming resin. The process utilizes low-cost carbon in coal and coal wastes and allows the carbon to be locked away permanently.

## DESIGNING MANUFACTURED HOMES FROM COAL-BASED BUILDING MATERIALS

X-MAT is exploring applications of CDBM for higher-performance modular construction by developing a conceptual design of a CDBM-based dwelling structure and establishing and testing fastening methodologies for these building materials.



Artist's Conception of Dwelling Built Using Coal-Derived Materials (Proof-of-Concept Design)

AWARD NUMBER  
**DE-FE0031985**

### PROJECT BUDGET

FY21 FUNDING



- DOE .....\$498,442
- PERFORMER.....\$126,000

### CONTACTS

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### FECM RDD&D PRIORITY



ADVANCE CRITICAL MINERALS,  
RARE EARTH ELEMENTS (REE),  
AND MINE REMEDIATION

### PARTNERS



# RARE EARTHS AND CRITICAL MINERALS PRODUCED IN FIVE FIRST-OF-A-KIND U.S. DOMESTIC SEPARATION FACILITIES

Conventional separation technologies using unconventional feedstock resources enable our Nation's independence from foreign reliance on critical minerals and rare earth elements.

## RECOVERING DOMESTIC RARE EARTH ELEMENTS AND CRITICAL MINERALS

West Virginia University's Water Research Institute (WVWRI) and the University of North Dakota Institute for Energy Studies (UND-IES) continued to design and construct two small pilot-scale facilities that utilize acid mine drainage fluids and lignite as respective feedstock materials for separation and recovery of rare earth elements (REE) and critical minerals (CM).

The two separation facilities will soon be commissioned for production of small quantities of high-purity, mixed rare earth oxides/salts, as well as CM that contain cobalt, nickel, manganese, gallium, germanium,

REE-CM Facility at WVWRI

Courtesy of Paul Ziemkiewicz, West Virginia University



REE-CM Facility at UND-IES

Courtesy of Nolan Theaker, University of North Dakota



These new small pilot-scale facilities follow on the heels of three, first-of-a-kind, domestic bench/small pilot-scale separation facilities operating since 2019. The existing facilities also recover REE from unconventional resources including coal wastes, acid mine drainage, and fly ash.



Pilot-Scale REE Recovery Facilities

Courtesy of Rick Honaker, University of Kentucky, Roe-Hoan Yoon, Virginia Tech

Paul Ziemkiewicz, West Virginia University

Dorin Preda, Todd Beers, Prakash Joshi, David Gamliel, Winner Water Services and Physical Sciences Inc.





## PILOT FACILITIES INCORPORATE INNOVATIVE PROCESSING

The incorporation of innovative techniques such as microbial assisted production of sulfuric acid from coal pyrite for leaching of feedstock materials, separation into individual high-purity oxides, and reduction to metals, are additional advancements being made by extramural projects within the current NETL Critical Minerals Sustainability Program portfolio.



Sulfuric Acid Bioreactors

Courtesy of Rick Honaker, University of Kentucky

## REDUCING OFFSHORE IMPORTS

The new small pilot facilities are helping to address a critical need to rebuild the domestic supply chain of REEs and CMs; regain U.S. capacity for domestic production of these materials; and potentially achieve onshore manufacturing of intermediate and end-products for clean energy and national security in the future.

## ADVANCED TECHNOLOGY DEVELOPMENT AND RESOURCE ASSESSMENT

To further advance REE-CM recovery, additional R&D efforts are being focused on advanced processing of REEs and CMs for Industrial and manufacturing applications.

Additionally, the Carbon Ore, Rare Earth and Critical Minerals Initiative for U.S. Basins is being initiated with the primary focus of catalyzing regional economic growth and job creation by realizing the full potential value of natural resources across basins throughout the U.S.

### PROGRAM NAME

**CRITICAL MINERALS SUSTAINABILITY**

### PROGRAM BUDGET

FY21 FUNDING



● DOE ..... \$23,000,000

### CONTACTS

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### FECM RDD&D PRIORITY



ADVANCE CRITICAL MINERALS, RARE EARTH ELEMENTS (REE), AND MINE REMEDIATION

### PARTNERS



# U.S. DEPARTMENT OF ENERGY AND APPALACHIAN REGIONAL COMMISSION ESTABLISH JOB TRAINING PROGRAM

Preparing a new generation of welders capable of manufacturing and servicing high-temperature alloy components in advanced coal and natural gas-fueled electric generating stations and other industrial applications.

## CREATING A HIGH-TECH WORKFORCE FOR GOOD PAYING JOBS

DOE/FECM/NETL and the Appalachian Regional Commission (ARC) are partnering through an interagency agreement that established the **Advanced Welding Workforce Initiative (AWWI) job-training program**. The AWWI program will help **create a high-tech workforce** with advanced welding skills to increase the Region's capacity to meet growing demand across a number of industries. Awards were made on the basis of connecting proposals with pressing regional needs, including expanding offerings into economically distressed areas.



Appalachian Regional Commission and NETL Meeting in Morgantown, WV

*Photo taken prior to COVID-19 protocol requirements*

## TRAINING INCLUDES ADVANCED TECHNIQUES IN WELDING, ROBOTICS, AND ADVANCED MANUFACTURING

The program will cover **advanced techniques** in several areas, including the use of **gas tungsten arc welding and technologies** for joining cobalt- and nickel-based superalloys in power plants that operate at extreme temperatures and pressure levels. Other training will focus on **robotics and advanced manufacturing skills** to prepare workers for long careers in growing or emerging industries.



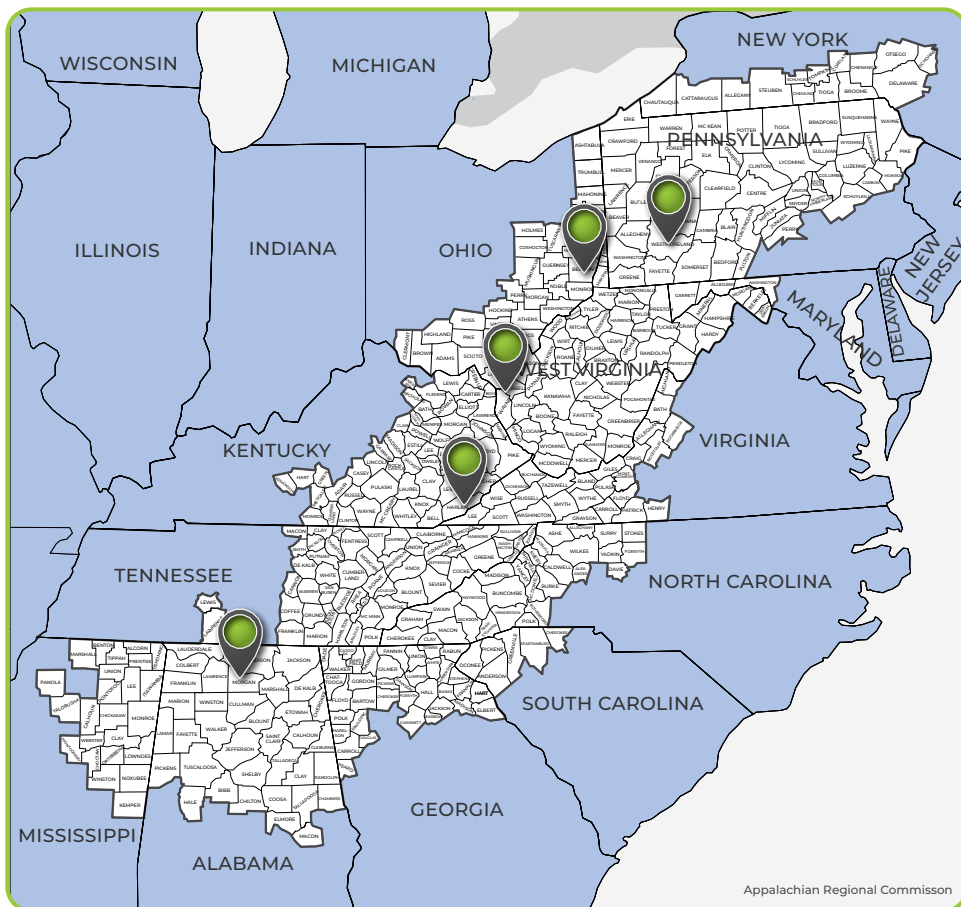
AWWI Program Training for Advanced Technical Workers in Appalachia

*Photo Courtesy of the ARC/AWWI Website <https://www.arc.gov/awwi/>*

## FIVE GRANTS WORTH A TOTAL OF \$1 MILLION WERE AWARDED IN 2021

The agreement is expected to produce a **well-trained workforce for good-paying jobs** that support cleaner coal and gas power plants across Appalachia, a region that stretches from southern New York to northern Mississippi. NETL and ARC awarded five grants in 2021, **totaling \$1 million**, to support training programs.

- Belmont College – St. Clairsville, OH
- Calhoun Community College – Decatur, AL
- Robert C. Byrd Institute at Marshall University – Huntington, WV
- Southeast Kentucky Community and Technical College – Cumberland, KY
- Westmoreland County Community College – Youngwood, PA



### ARC Appalachian Region

Photo Courtesy ARC Website – [www.arc.gov](http://www.arc.gov)

### PARTNER



**Appalachian  
Regional  
Commission**

### PROGRAM NAME

## High Performance Materials Program

### PROJECT BUDGET

FY21 FUNDING



- DOE .....\$750,000
- PERFORMER..... \$250,000

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### FECM RDD&D PRIORITY



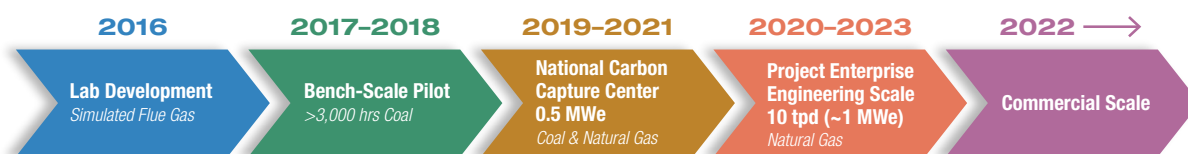
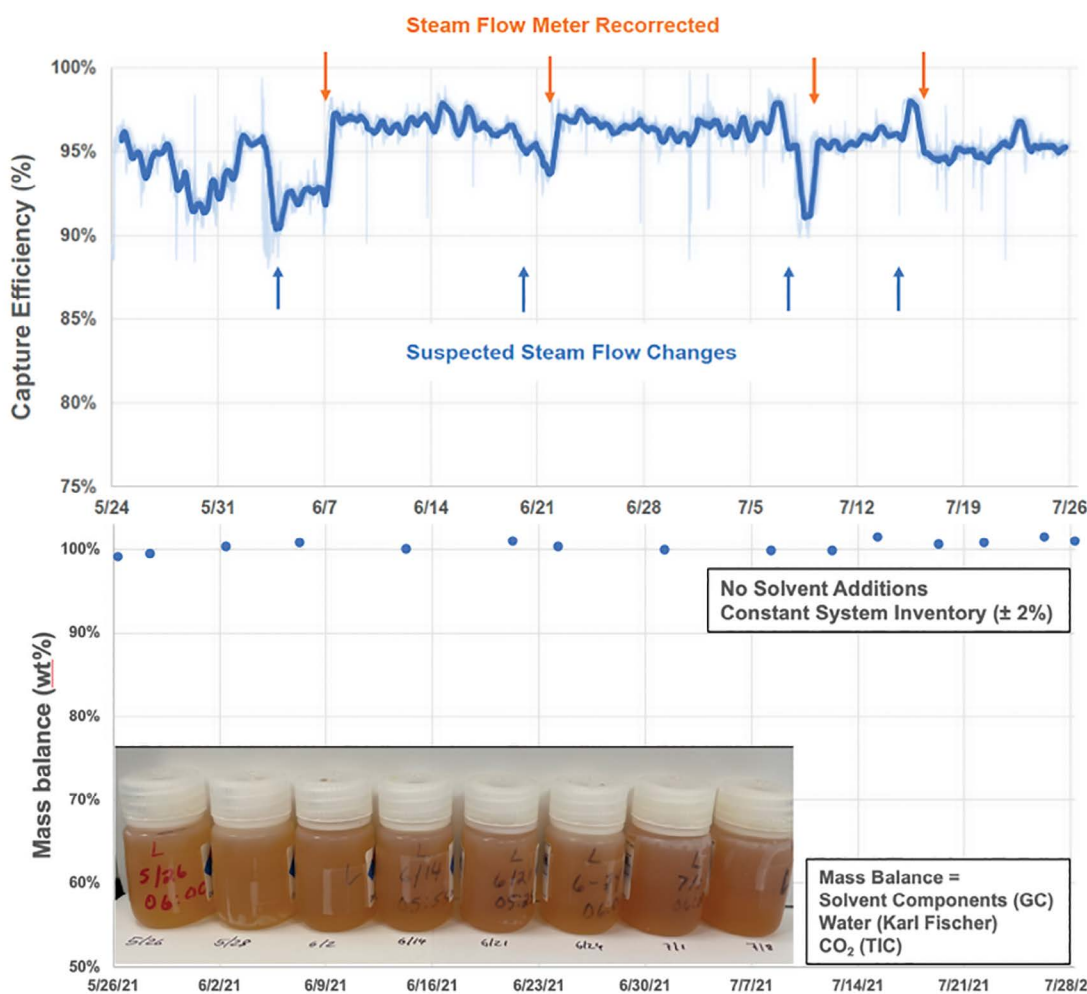
INVEST IN THOUGHTFUL  
TRANSITION STRATEGIES

# SOLVENT ACHIEVES 95% CAPTURE EFFICIENCY ON NATURAL GAS FLUE GAS, PROGRESSES TO FIELD TESTING AT A COMMERCIAL PLANT

Advanced water-lean solvent technology with enhanced CO<sub>2</sub> capture efficiency and increased solvent lifetime.

## SOLVENT PERFORMANCE VALIDATED AT PILOT SCALE

ION Clean Energy, Inc., scaled up a transformational water-lean amine-based solvent technology from bench- to pilot-scale (0.6 MWe) in project "Apollo," validating a reduction in capital and operating costs for the capture of CO<sub>2</sub> from natural gas power plants. Through a comprehensive test campaign at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama, ION's 3<sup>rd</sup> generation solvent, ICE-31, **achieved 95% CO<sub>2</sub> capture and negligible oxidative degradation** during 1,500 hours of steady-state testing in the Pilot Solvent Test Unit with natural gas-fired flue gas. Furthermore, extensive parametric testing led to a close-fitting agreement between the empirical data and the process-simulated results generated in ProTreat®.



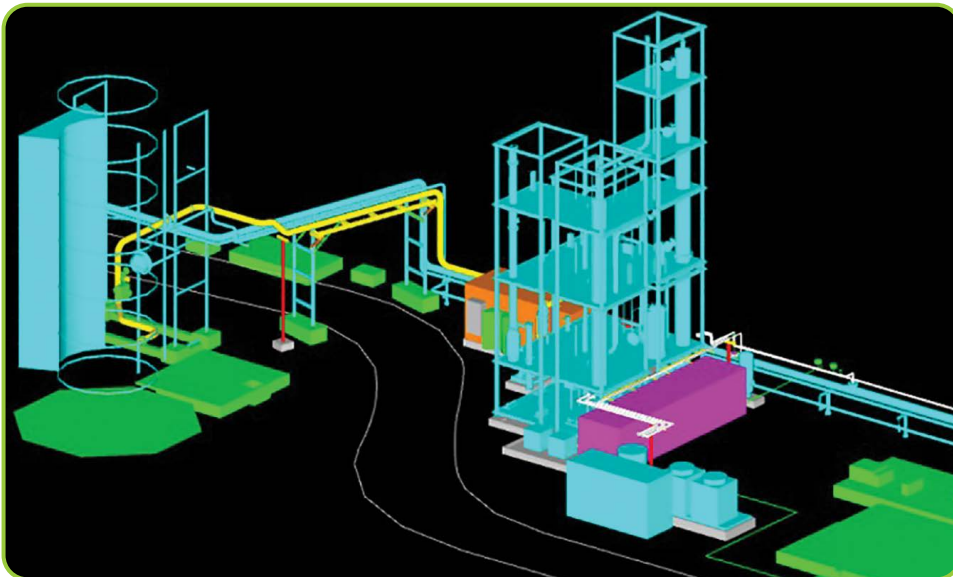
ICE-31 Solvent Development Path

## SOLVENT TECHNOLOGY ADVANCES THROUGH LONG-TERM FIELD TESTING WITH ACTUAL FLUE GAS



Through “Project Enterprise,” ION will field test ICE-31 on a 1 MWe (10 tpd) slipstream of flue gas from Calpine’s Los Medanos Energy Center (LMEC), a commercially dispatched natural gas combined cycle (NGCC) power plant. The kinetic performance and solvent stability of ICE-31 for CO<sub>2</sub> absorption from NGCC flue gas will be validated against baseline test results for ICE-21 (2<sup>nd</sup> generation) and monoethanolamine solvents. ION’s solvent carbon capture technology has potential to be used for **deep decarbonization of NGCC power plants**.

### Modular Pilot System Design for Field Test at LMEC



### PARTNERS



AWARD NUMBER  
**DE-FE0031727**

PROJECT BUDGET  
**\$3.75M**



- DOE ..... \$2,999,998
- PERFORMER.....\$750,000

AWARD NUMBER  
**DE-FE0031950**

PROJECT BUDGET  
**\$16.9M**



- DOE ..... \$13,000,000
- PERFORMER..... \$3,906,839

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### FECM RDD&D PRIORITY



DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE

# PHASE III CARBONSAFE LAUNCHES WITH FIVE PROJECTS TO ADVANCE CARBON STORAGE

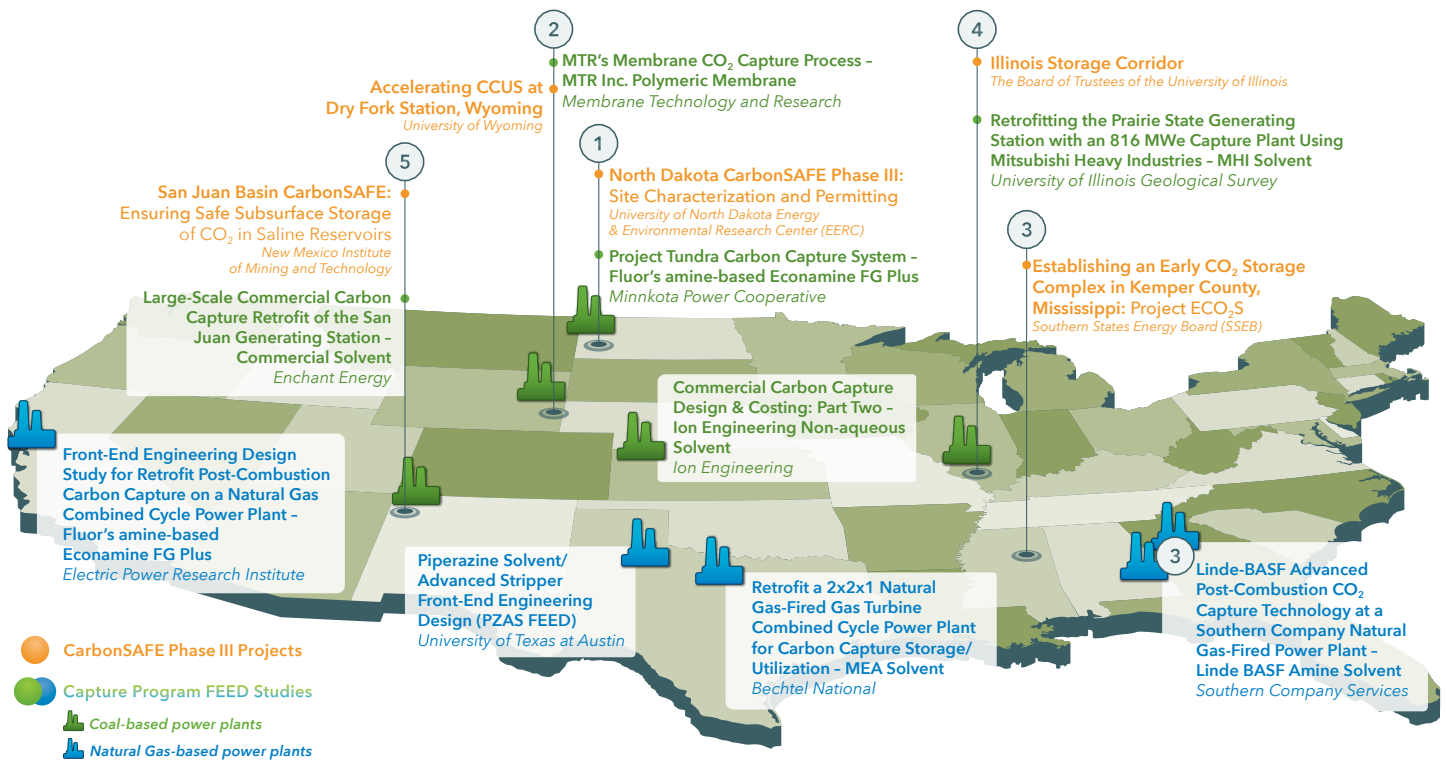
DOE's flagship program demonstrates how to identify, characterize, and permit commercial-scale carbon storage sites.

## ADVANCING TOWARD COMMERCIALIZATION OF CARBON CAPTURE AND STORAGE

The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative addresses key gaps on the critical path toward carbon capture and storage (CCS) deployment. The CarbonSAFE Initiative is taking a phased approach: (I) Integrated CCS Prefeasibility; (II) Storage Complex Feasibility; (III) Site Characterization, Permitting, and Carbon Capture Assessment; and (IV) Injection Site Construction and Obtain Authorization to Inject.

CarbonSAFE Phase III projects commenced in 2020 and include the **acquisition, analysis, and development of information** to fully characterize storage complexes at **six locations across the nation** to demonstrate storage resources for commercial volumes of CO<sub>2</sub>. These projects will provide lessons learned by doing, information on the costs of early mover projects, data on project risks, practice in adhering to regulations, and a basis for public acceptance.

## LINKING STATE-OF-THE-ART STORAGE TECHNOLOGIES AND CAPTURE TECHNOLOGIES WITH INTEGRATED PROJECTS



Five CarbonSAFE Phase III projects are aligned with five front-end engineering and design (FEED) studies awarded by DOE's Carbon Capture Program for carbon capture systems on coal and natural gas power plants. These integrated studies show the ability to **supply 50+ million metric tons of CO<sub>2</sub>** for storage per project and evaluate pipeline routes for transport of the CO<sub>2</sub> to the proposed storage complex.

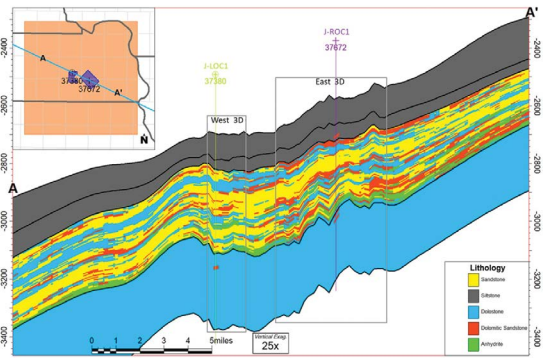
# PHASE III CHARACTERIZATION ACTIVITIES

Phase III projects have **completed the drilling of stratigraphic test wells, conducted surface seismic reflection surveys, and updated sub-surface models** including:

- 3D seismic surveys
- 2D seismic surveys
- Microgravity surveys
- Injection tests
- Core and fluid sampling and analysis
- Geologic and Injection models

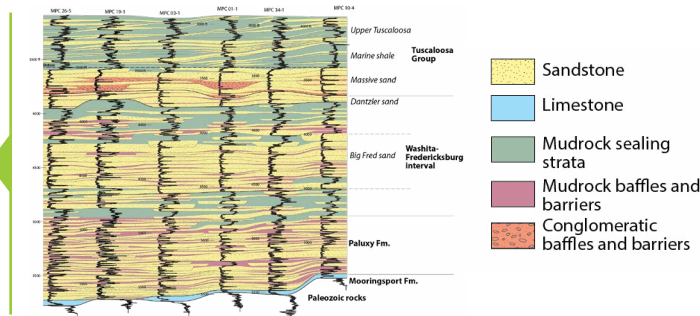
This work is providing the information needed to prepare and submit an Underground Injection Control Class VI construction permit for each proposed injection well at the site(s).

Acquired 25 mi of 2D and 18.7 mi<sup>2</sup> of 3D Seismic Data to Date (North Dakota CarbonSAFE Phase III)



Lithofacies Distribution of Broom Creek Formation (North Dakota CarbonSAFE Phase III)

Stratigraphic Cross Section of Kemper County Carbon Storage Complex

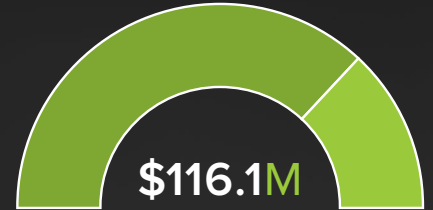


## FUNDING OPPORTUNITY ANNOUNCEMENT #:

# DE-FOA-1999

### PROJECT BUDGET

TOTAL FUNDING



- DOE .....\$85,858,263
- PERFORMER.....\$30,310,878

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**SCOTT QUILLINAN**  
**KIPP CODDINGTON**  
**KENNETH NEMETH**  
**WILLIAM AMPOMAH**

### FECM RDD&D PRIORITIES

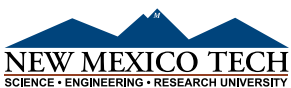


INVEST IN THOUGHTFUL TRANSITION STRATEGIES



DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE

### LEAD PARTNERS



**ILLINOIS**  
Illinois State Geological Survey



**Southern Company**

**UNIVERSITY OF WYOMING**

# FOUR REGIONAL INITIATIVES EXPAND THE CARBON STORAGE INDUSTRY

Setting the stage for reliable storage and transport to meet goals for a net-zero carbon economy.

## FROM STATE TO SITE: ACCELERATING DEPLOYMENT AND INTEGRATION OF COMMERCIAL CARBON CAPTURE, UTILIZATION, AND STORAGE

The Regional Initiatives, as successors of the original Regional Carbon Sequestration Partnerships (RCSPs), offer the opportunity to leverage their established stakeholder networks, long history in best practice development, wealth of data to support further research, and experience in public outreach and education.



## TACKLING CHALLENGES TO PAVE THE WAY FOR CCUS IN THE REGION

### Technical Challenges

- Geologic Characterization
- Storage Performance and Optimization
- MVA Strategies
- Risk Management

### Facilitate Data Collection, Sharing, and Analysis

- Risk Assessment Validation
- Machine Learning
- Focused Collaboration Among State Geologic Surveys

### Evaluate Existing Regional Infrastructure

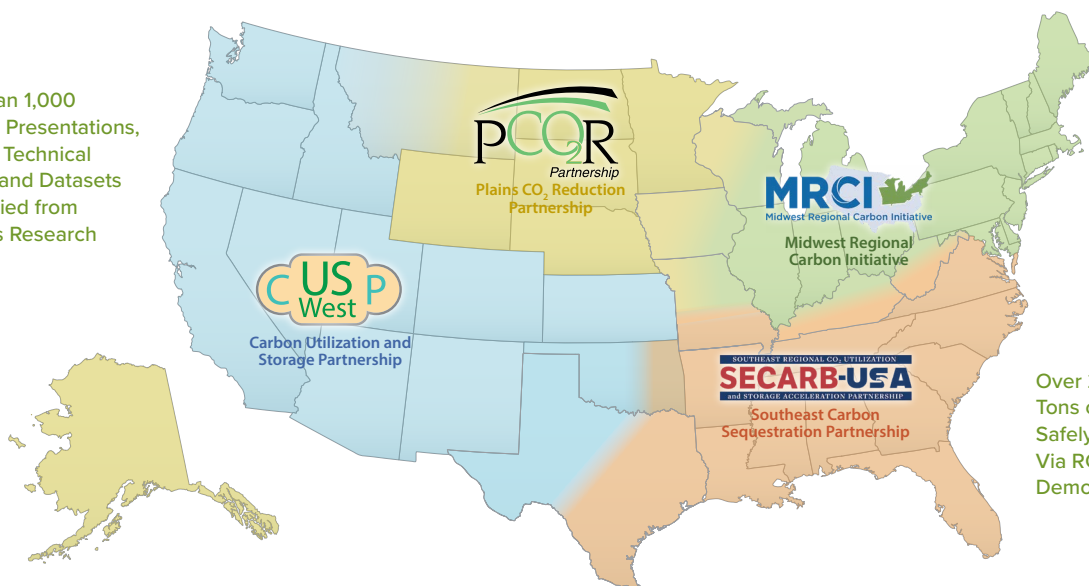
- Techno-Economic Analysis
- Infrastructure Scale-Up Challenges
- Socioeconomic Impacts
- Industry Outreach

### Non-technical Challenges

- Policy and Regulatory Challenges
- Business Models
- Pathways to Commercial Deployment
- Public Outreach

## SEVEN RCSPs TRANSITION TO FOUR REGIONAL INITIATIVES: A SOLID FOUNDATION FOR FUTURE WORK

More than 1,000 Reports, Presentations, Posters, Technical Papers, and Datasets Inventoried from Previous Research



Over 21 Million Metric Tons of CO<sub>2</sub> Have Been Safely and Securely Stored Via RCSPs and Major Demonstration Projects



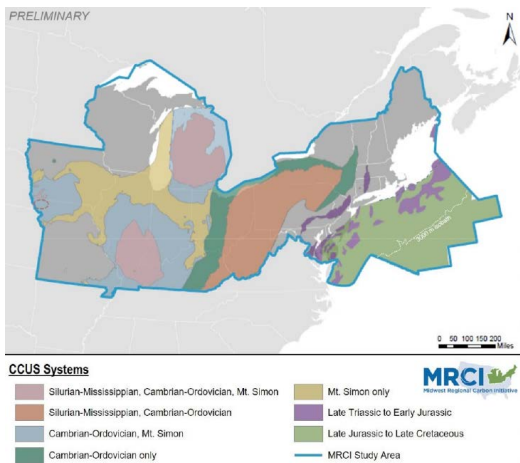
# JUMPSTARTING REGIONAL CCUS THROUGH CONSULTING PRACTICES AND INDUSTRY ENGAGEMENT

Regional Initiatives are supporting the nation's CO<sub>2</sub> storage resource potential and CCUS business cases and opportunities relevant to the regions they represent, as well as nationally. They are providing technical know-how to project developers seeking high-potential storage sites:

- Currently assisting at least 20 (MRCI), 35 (PCOR), and 13 (CUSP) potential large-scale storage projects.
- SECARB-USA has held 51 technical assistance and stakeholder interest meetings in Q2 alone.

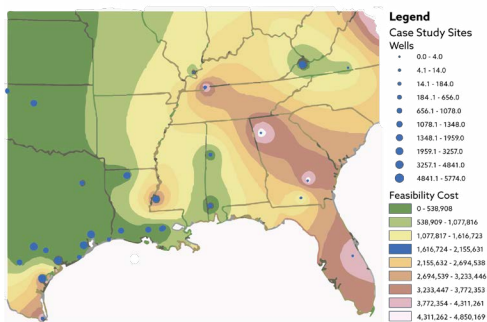
## LAYING THE CORNERSTONES OF STORAGE HUBS

Regional Initiatives are providing information needed to fill the cost and performance knowledge gaps for launching the carbon storage industry by 2025 and beyond.



MRCI Completed a Preliminary Assessment of Geologic Provinces and Basins in the Northeast; Preeminent Geologic Locations Were Identified

Regional Distribution of the Feasibility Investment Gate Costs



SECARB-USA is Working Alongside Southern Company, and Others, to Identify Potential Storage Hub Sites in the Southeast

## FUNDING OPPORTUNITY ANNOUNCEMENT #: DE-FOA-2000

### PROJECT BUDGET

TOTAL FUNDING



- DOE\* .....\$48,314,554
- PERFORMER.....\$ 19,894,463

\*CUSP and SECARB-USA are each scheduled to receive an additional ~\$5 million DOE funds in early FY22

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### FECM RDD&D PRIORITIES

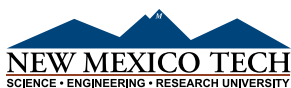


DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE



INVEST IN THOUGHTFUL TRANSITION STRATEGIES

### LEAD PARTNERS



# MAJOR MILESTONES ACHIEVED TOWARD COMPLETING FULL-SCALE ADVANCED ULTRASUPERCRITICAL COMPONENT DEMONSTRATIONS

Demonstrating commercial readiness by testing fullscale versions of key AUSC power plant components.

## PUSHING BOUNDARIES ON TEMPERATURE AND PRESSURE

AUSC materials were developed to operate at high pressures and temperatures to meet global electricity demand, reduce overall emissions, and increase efficiency in coal-fired power plants. AUSC power plants are 25% more efficient than average power plants, and 10% more efficient than state-of-the-art power plants.

## BUILDING POWER PLANTS OF THE FUTURE

### The ComTest project advanced AUSC technology by:

Expanding a qualified domestic supply chain to manufacture nickel superalloy components for AUSC power plants.

Validating that AUSC components can be designed and built for reliable operation under both steady-state and varying load operating conditions for the 30-year design life of an AUSC boiler.

Developing fabrication, installation, and repair methods for cast and forged nickel superalloy AUSC components and sub-assemblies.

## HIGHLIGHTING THE UNIQUE CAPABILITY OF BUILDING AUSC COMPONENTS

### PHASE I: COMPLETE

Completed front-end engineering design and detailed engineering. Began developing a domestic supply chain for AUSC nickel superalloy components and determined that operational testing of an AUSC steam turbine and AUSC superheater was not required.

### PHASE II: COMPLETE

Fabricated the key components and sub-assemblies of an AUSC boiler, steam turbine, and steam piping system at sizes equivalent to an 800-MWe power plant. Fabrication of AUSC boiler components began in FY2019. Production of these components demonstrated the capability of U.S. manufacturers to produce AUSC power plant parts.



# TESTING AUSC COMPONENTS FOR FULL-SCALE COMMERCIAL USE

## Key Successes

- The world's largest triple melted H282 nickel superalloy ingot (28,410 pounds and 34-inch diameter x 8.83 feet length) was successfully produced and forged into a steam turbine rotor shaft.
- The world's largest Inconel 740H nickel superalloy pipe (22-inch outer diameter x 3.7-inch wall thickness x 14 feet length) was successfully fabricated from an Inconel 740H ingot.
- The world's largest triple melted Inconel 740 nickel superalloy ingot (37,539 lbs) was successfully produced and will be used to make a large wye pipe fitting by forging and machining fabrication processes.
- The world's largest H282 casting was made of a 1/2 section of an AUSC steam turbine nozzle carrier case.
- A complete section of an AUSC boiler superheater/reheater assembly was fabricated and field erected to demonstrate tube and pipe production, tube bending, thin and thick wall welding, and machining for the nickel superalloys and advanced austenitic steel alloy that would be used in an AUSC boiler.

Actual H282 Casting Produced by the Project



AWARD NUMBER  
**DE-FE0025064**

## PROJECT BUDGET

FY20 FUNDING



- DOE .....\$20,186,577
- PERFORMER ..... \$7,149,245

## CONTACTS

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## FECM RDD&D PRIORITY



INVEST IN THOUGHTFUL  
TRANSITION STRATEGIES

## PARTNERS



# NICKEL SUPERALLOY APPROVED FOR USE IN BOILERS AND PRESSURE VESSELS

NETL and ORNL addressed materials issues in qualifying and deploying a nickel-based alloy for use in an advanced ultrasupercritical coal-fired boiler.

## AMERICAN SOCIETY OF MECHANICAL ENGINEERS APPROVES NETL-SPONSORED ALLOY

Approved for use in boilers, fired heaters, and pressure vessels up to 875 °C

NETL partnered with Oak Ridge National Laboratory and Haynes International to address materials issues relevant to qualifying and deploying a nickel-based alloy for a new application in an advanced ultrasupercritical (AUSC) coal-fired boiler.

The project deployed the **Haynes282 (H282)** alloy for application in power plant components such as superheaters, reheaters, and steam delivery pipes by completing base metal and cross-weld creep and tensile testing needed for acceptance by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code.

The Haynes International's H282 alloy, a gamma prime precipitate-strengthened nickel superalloy, was approved by the ASME for use in boilers, fired heaters, and pressure vessels up to 875 °C. This temperature rating covers the maximum anticipated operating conditions of AUSC steam and indirect-fired supercritical CO<sub>2</sub> power generation cycles, which is needed to reduce CO<sub>2</sub> emissions and increase power plant operating efficiency.

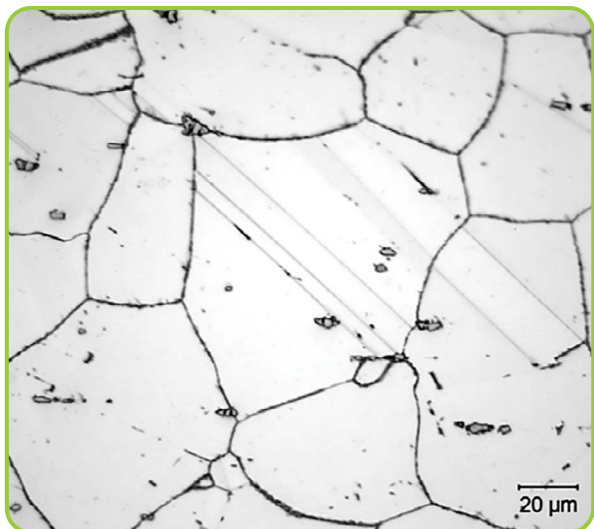


Haynes 282 Boiler Tubing



Haynes 282 Boiler Tube Assembly

**ONLY THE SECOND SUCH SUPERALLOY APPROVED FOR USE IN BOILERS AND PRESSURE VESSELS**



Alloy Microstructure in Age Hardened Condition



Haynes 282 Test Specimens

**AWARD NUMBERS**  
**DE-FEAA117**  
**DE-FE0025064**

**PROJECT BUDGET**

FY21 FUNDING



● DOE ..... \$820,000

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**FECM RDD&D PRIORITY**



INVEST IN THOUGHTFUL  
 TRANSITION STRATEGIES

**PARTNERS**



# MAJOR MILESTONES ACHIEVED IN SUPERCRITICAL CARBON DIOXIDE POWER CYCLES

New  $s\text{CO}_2$  power cycle pilot plant will prove critical capabilities of a novel technology for more efficient power generation at lower cost, making the United States a leader in domestic and global power generation.

## PATH TO LOWER-COST DOMESTIC AND GLOBAL POWER GENERATION

**Supercritical carbon dioxide ( $s\text{CO}_2$ ) power cycles** offer potential for power generation with increased efficiency, lower cost of electricity, reduced customer costs, and reduced water consumption.

**S T E P**

**SUPERCritical  
TRANSFORMATIONAL  
ELECTRIC  
POWER**

## PROVING A NOVEL POWER CYCLE USING A RECONFIGURABLE, FLEXIBLE STEP PILOT PLANT TEST FACILITY



The **STEP pilot plant** will demonstrate a fully integrated, functional, electricity-generating power plant using  **$s\text{CO}_2$  technology**. This plant aims to show component performance and cycle operability over a range of operating conditions, as well as show progress toward a **lower cost of electricity**.

## REDUCING BARRIERS AND RISKS TO COMMERCIALIZATION

### U.S. Leading the Way on a Cutting-Edge Power Cycle Technology

DOE's investment in  $s\text{CO}_2$  power cycle technology through the 10 MWe  $s\text{CO}_2$  power cycle pilot plant enables the U.S. to lead in developing and commercializing  $s\text{CO}_2$  power cycle deployment for both domestic and global power generation.



# LARGEST INDIRECT-FIRED sCO<sub>2</sub> POWER CYCLE TEST FACILITY IN THE WORLD

## KEY PROCESS EQUIPMENT FABRICATED AND DELIVERED TO THE FACILITY IN FY21



Distributed Control System



Turbine



Main and Bypass Compressors



Primary Heater



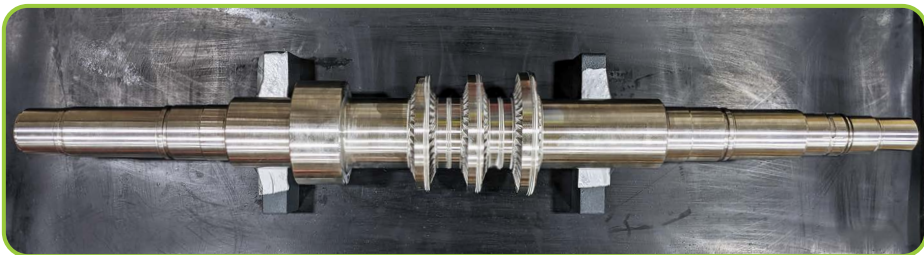
Cooling Tower System



Turbine Skid and Bypass Compressor



Main Compressor



Turbine Rotor



- Primary heater included a hot section fabricated using IN 740H.
- Major accomplishment for this relatively new high-temperature nickel alloy.
- IN 740H fabrication and use is essential for the successful commercialization of sCO<sub>2</sub> power cycles.
- Installed at facility and inspected.

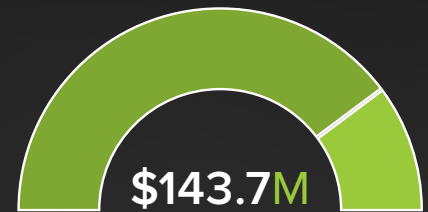
### PROGRESSING TOWARD SIMPLE CYCLE PLANT COMMISSIONING

#### PARTNERS



AWARD NUMBER  
**DE-FE0028979**

#### PROJECT BUDGET



- DOE .....\$114,967,589
- PERFORMER.....\$28,741,945

#### CONTACTS

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#### FECM RDD&D PRIORITIES



INVEST IN THOUGHTFUL  
TRANSITION STRATEGIES



ADDRESS THE ENERGY  
WATER NEXUS

# ADVANCED MANUFACTURING TO ENABLE 65% OR GREATER GAS TURBINE EFFICIENCY

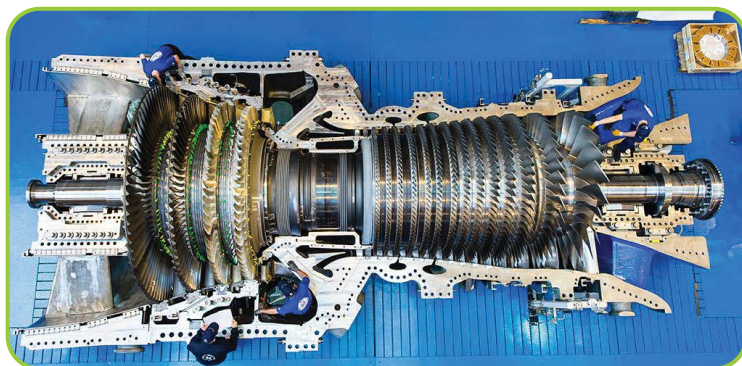
Nozzle/Airfoil fabrication that supports a combined cycle efficiency of 65% at 3,100°F turbine inlet temperature.

## COMBINING ADVANCED MANUFACTURING AND INNOVATIVE TURBOMACHINERY COMPONENTS TO ENABLE HIGHER EFFICIENCIES IN GAS TURBINES

Combined cycle efficiency of 65% at 3,100°F turbine inlet temperature

### Improved Efficiency Benefits

- Lower fuel requirement
- Lower capital expenditure
- Lower cost of electricity for the customer
- Lower emissions



## HIGH-TEMPERATURE CERAMIC MATRIX COMPOSITE NOZZLES: INNOVATIVE TURBOMACHINERY COMPONENT CONTRIBUTING TOWARD DOE GOAL FOR ADVANCED GAS TURBINE EFFICIENCY

CMC component development activity facilitates high firing temperatures and improved performance through enhanced designs and concepts, better sealing, reduced leakage, leveraging advanced manufacturing processes to facilitate high performing turbomachinery, and revolutionary component architecture that will improve gas turbine performance.

## IDENTIFY THE DESIGN CHANGES AND MANUFACTURING PROCESSES NEEDED TO MAKE A SUCCESSFUL CMC NOZZLE

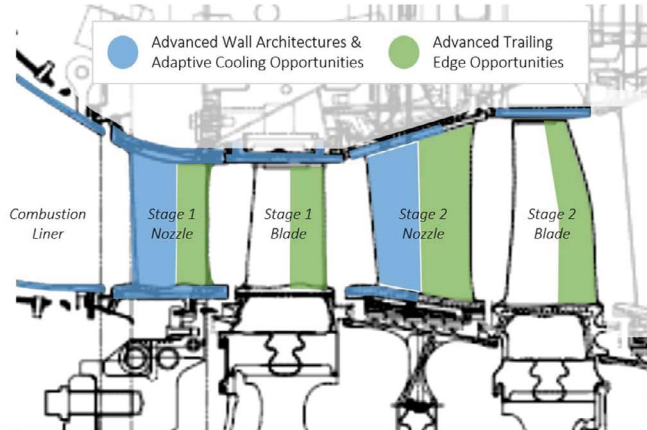
- CMC nozzles fabricated.
- Completed the instrumentation definition of the CMC nozzle for engine installation.
- All flow tests for CMC nozzle parts to study CMC benefits have been completed.





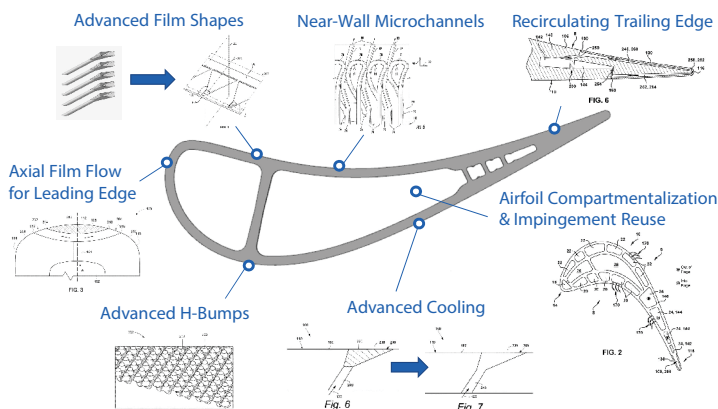
# LEVERAGING STATE-OF-THE-ART ADDITIVE MANUFACTURING TO DEVELOP NOVEL AND INNOVATIVE TURBINE HOT SECTION COMPONENT ARCHITECTURES

- Airfoil and end wall architectures provide cooling flow reduction while maintaining the component durability and robustness expected of today's gas turbines.



## NOZZLE DESIGN PHILOSOPHY

- Raise the combustion temperature to increase engine output and performance.
- Manage cooling to increase performance and component lifetime.



**THE FIRST DIRECT METHOD LASER MELTING PRINT OF THE ADVANCED AIRFOIL CONCEPT WITH DOWN-SELECTED WALL ARCHITECTURE HAS BEEN COMPLETED.**

### PARTNERS



AWARD NUMBER  
**DE-FE0024006**

PROJECT BUDGET



**\$9.66M**

- DOE .....\$6,564,478
- PERFORMER.....\$3,097,624

AWARD NUMBER  
**DE-FE0031611**

PROJECT BUDGET



**\$9.24M**

- DOE .....\$6,491,957
- PERFORMER.....\$2,751,676

### CONTACTS

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FECM RDD&D PRIORITY



INVEST IN THOUGHTFUL  
TRANSITION STRATEGIES

# NATIONAL CARBON CAPTURE CENTER ACHIEVES MAJOR MILESTONE WITH FIRST FIRE OF NATURAL GAS TESTING SYSTEM

The NCCC's new natural gas infrastructure paves the way for testing of carbon capture technologies using actual natural gas-derived flue gas.

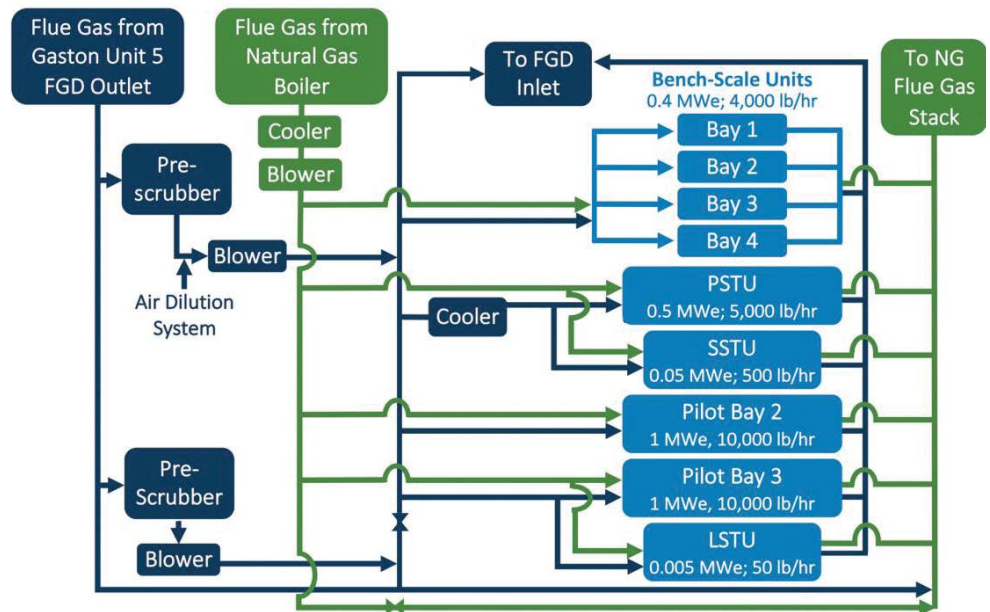
## NCCC INTRODUCES NATURAL GAS FLUE GAS CARBON CAPTURE TESTING

Southern Company Services began operating a new natural gas-fired (NG-fired) boiler at the National Carbon Capture Center (NCCC) in early 2021 in a project sponsored by NETL.

The Carbon Capture Program, which develops and optimizes carbon dioxide (CO<sub>2</sub>) capture technology for industrial, coal, natural gas sources, and negative emissions technologies, supported the expansion of technology testing capabilities at the NCCC.

This milestone is significant because it expands the NCCC's ability to evaluate carbon capture technologies for natural gas power plants, which generated ~1.6 Gigatons of CO<sub>2</sub> in the U.S. in 2020. First fire of the new system occurred in December 2020 with shakedown testing in January and February 2021.

The NG-fired boiler system, which was available for testing starting in March 2021, offers significant advantages for carbon capture technology developers to demonstrate and scale up technologies, including expanded testing windows and more flexibility.



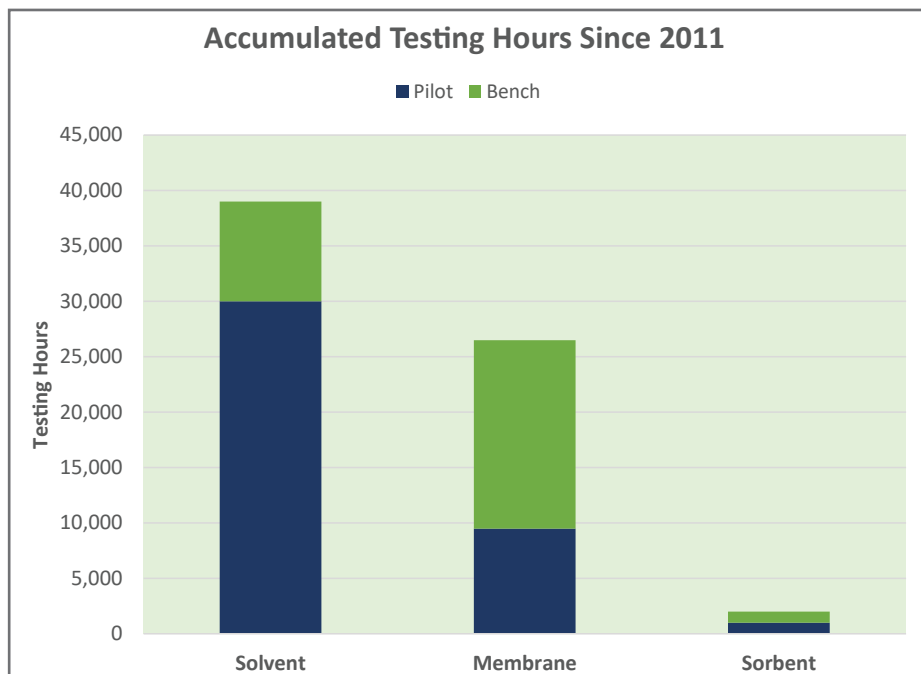
NCCC Test Bays Configuration



NCCC at Alabama Power's Plant Gaston in Wilsonville, Alabama

# A DECADE OF IMPACT ON CARBON CAPTURE R&D

The NCCC is a world-class facility that works with innovators throughout the world to accelerate the development of technologies to reduce greenhouse gas emissions from fossil-based power plants, and to promote carbon utilization and direct air capture solutions.



Source: NCCC/Southern Company, August 2021

Commissioned in 2011, the NCCC completed a decade of testing in 2021, which has had a dramatic impact on carbon capture R&D. The NCCC has collected more than 68,000 hours of performance data on 46 technologies from 33 government, university, and research organizations from seven countries during that period. Eight of the technologies tested have been scaled-up to 10+ MW.

On the basis of pilot testing and development, the center has already reduced the projected cost of carbon capture from fossil-based power generation by approximately 40%.

AWARD NUMBER  
**FE0022596**

## PROJECT BUDGET



- DOE ..... \$253,385,107
- PERFORMER..... \$94,596,277

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## PARTNERS



## FECM RDD&D PRIORITY



DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE

# NEW SEDIMENTARY UNIT IN THE ILLINOIS BASIN NAMED

New data obtained from MGSC establishes the Argenta Sandstone as a new formation.

## CHARACTERIZATION INCREASES THE UNDERSTANDING OF THE MOUNT SIMON AND PRE-MOUNT SIMON

### The Illinois Basin – Decatur Project Site

In 2007, the Midwest Geological Sequestration Consortium (MGSC)—one of seven of DOE's Regional Carbon Sequestration Partnerships—began site characterization of the Illinois Basin storage complex at the Decatur project site.

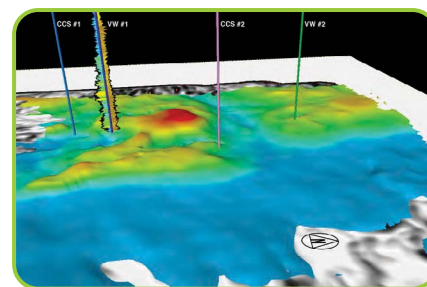
The goals of the site characterization were to:

- Demonstrate CO<sub>2</sub> injectivity.
- Establish storage capacity.
- Validate efficiency of the reservoir.
- Verify the integrity of the seals.
- Implement pre-injection characterization.
- Perform injection process monitoring.
- Execute post-injection monitoring.



## IMPROVED DEEP SUBSURFACE DATA OF THE ILLINOIS BASIN

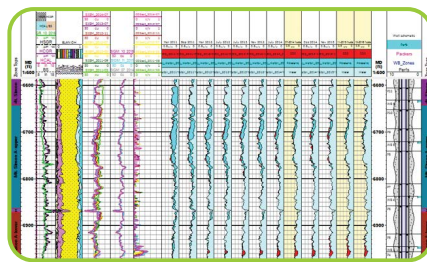
- Data obtained by drilling and logging characterization wells.
- Cores obtained from multiple geologic formations.
- Regional structure and isopach maps.
- Regional Geophysical data.
- 2D and 3D surface seismic data.
- Microseismic data.
- Full wireline well log suites.
- Baseline pressure and temperature measurements.



Visualization of Mount Simon Sandstone Using 3D Seismic Reflection



Mount Simon Sandstone Core Recovered from CCS1



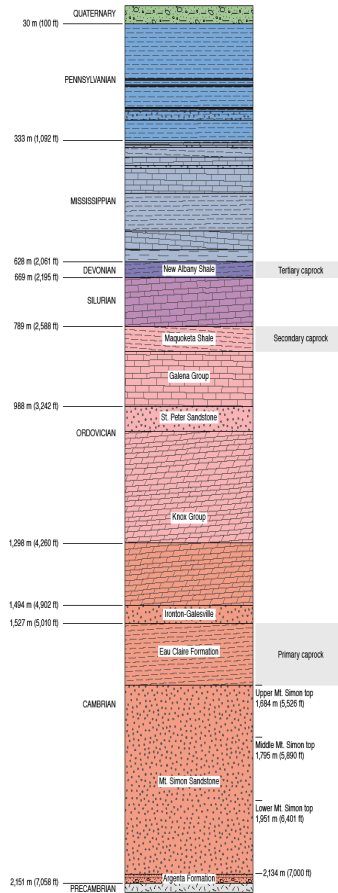
Pulsed Neutron Logging at VW1 Well



3D VSP Pattern

# NEW DATA SEPARATES THE ARGENTA FROM THE MOUNT SIMON

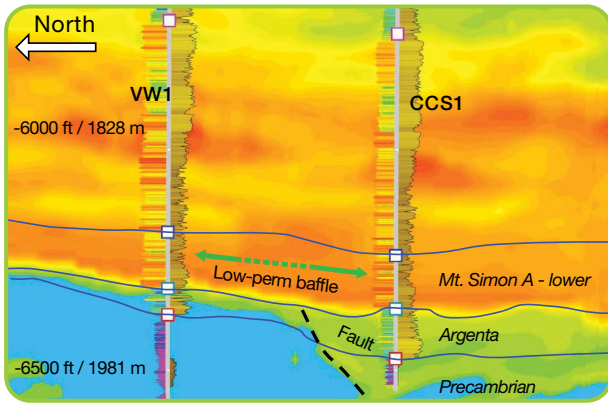
The Argenta Sandstone was previously identified as part of the Mount Simon Formation. New core and geophysical log data obtained by MGSC clearly establish the petrophysical and sedimentological distinctness required by the North American Stratigraphic Code for recognition of a new formation.



# ARGENTA FORMATION PROVIDES NEW INSIGHT INTO CARBON STORAGE

Impacts of characterizing the Argenta:

- New input for storage capacity estimates for the Mount Simon, which has been identified as the region's prime reservoir for commercial-scale CO<sub>2</sub> storage.
- Influence on the extent to which induced seismicity may occur in the basement rock below the Mount Simon during and after CO<sub>2</sub> injection.
- Improved understanding of the Mount Simon and Pre-Mount Simon depositional systems and structural settings.



Visualization of Cross Section Using Reflection of Seismic Porosity Inversion

Generalized Geologic Column

AWARD NUMBER  
**DE-FC26-05NT42588**

## PROJECT BUDGET

TOTAL FUNDING



- DOE ..... \$112,719,485
- PERFORMER..... \$30,241,458

## CONTACTS

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**DR. SALLIE GREENBERG**

## FECM RDD&D PRIORITY



DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE

## PARTNERS



# SUCCESSFUL DEMONSTRATION OF INNOVATIVE “SENSOR RING” FOR LONG-TERM WIRELESS MONITORING IN THE SUBSURFACE

Developing next-generation sensors to accurately monitor deep subsurface operations.

## SUBSURFACE SENSOR DESIGN TO TRACK CO<sub>2</sub> IN STORAGE FORMATIONS

### Sensor Design Completed

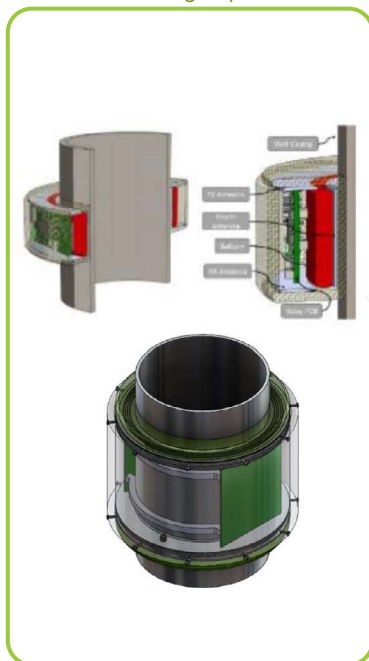
Downhole sensing system is designed to measure temperature as the primary indicator of CO<sub>2</sub> away from the borehole. Key technologies being developed:

- Central data collection and transmitter
- Wireless charging
- Energy harvesting
- Data relay system to surface
- Encapsulation
- Retrievable wireless battery charging

Encapsulation



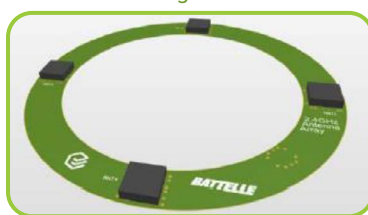
Sensor Ring Depiction



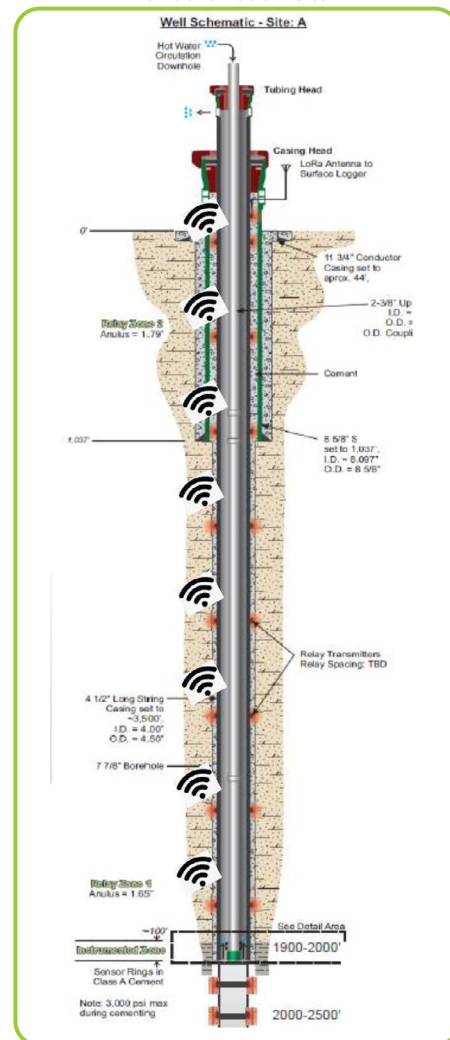
Sensor Operating and Control System



Sensor Ring Fabrication



Well Schematic – Site A



## ONGOING WORK FOR MONITORING, VERIFICATION, ACCOUNTING:

- Fabrication of the sensor rings, relay rings, and centralizers has begun. A total of 100 sensor rings/relays will be constructed for field testing in two wells.
- Finalized arrangements for field testing the sensor system in two oil wells in Guernsey County, Ohio. Field testing is planned for November 2021.

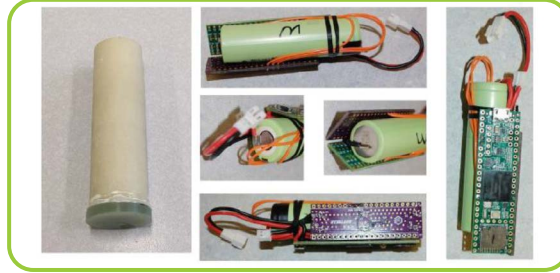
# SUCCESSFUL SENSOR SYSTEM OPERATION

## Lab-Scale Testing

Sensor prototype was exposed to supercritical CO<sub>2</sub> in a pressure test cell at high temperatures and pressures for 24 hours.

Resin housing protected electronics and showed no corrosion.

Visual Inspection of Sensor Prototype After Exposure Testing



## Bench-Scale Testing

Data relay ring communication testing was completed in a series of test pipes with lengths of 3 to 120 feet.

Results demonstrated signal communication through cemented pipe greater than 120 feet.

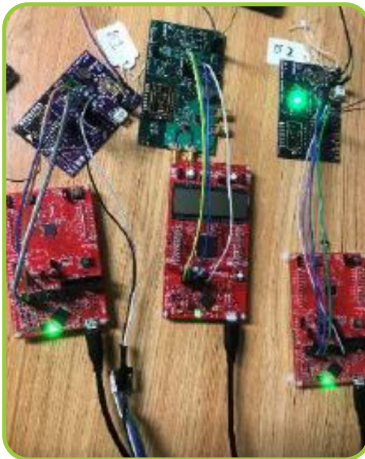
3- to 120-ft-Long Pipe-in-Pipe Set Up



## Functional Testing

A series of tests confirmed operation of temperature sensors, wireless charging, sonic energy harvesting, data handling, and surface logging.

Temperature Sensor Data Handling

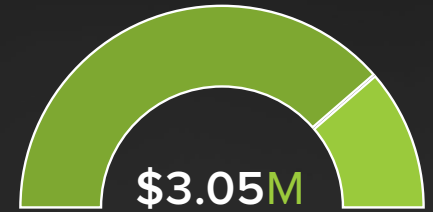


Sonic Harvesting and Wireless Charging



AWARD NUMBER  
**DE-FE0031850**

PROJECT BUDGET  
TOTAL PROJECT BUDGET



- DOE .....\$2,374,747
- PERFORMER..... \$677,000

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## FECM RDD&D PRIORITIES



**DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE**



**INVEST IN THOUGHTFUL TRANSITION STRATEGIES**

## PARTNERS



# NETL-SPONSORED CO<sub>2</sub>-TO-CONCRETE TECHNOLOGY WINS \$7.5 MILLION GRAND PRIZE

A scalable process for upcycling CO<sub>2</sub> and coal combustion residues into construction products.

## UCLA WINS RIGOROUS NRG CANADA'S OIL SANDS INNOVATION ALLIANCE CARBON XPRIZE GLOBAL COMPETITION

- In part through an NETL-sponsored project, CarbonBuilt Inc., a University of California-Los Angeles (UCLA) spin-off, won a \$7.5 million grand prize in the NRG Canada's Oil Sands Innovation Alliance (COSIA) Carbon XPRIZE Global Competition for their process that locked away and incorporated CO<sub>2</sub> from the emissions of power plants and industrial facilities into marketable, industrial-strength concrete.
- The NRG COSIA competition was a six-year global competition that began in 2015 and awarded innovators with breakthrough technologies for creating the most valuable product with the most CO<sub>2</sub> incorporated.



## PRIZE-WINNING PROCESS SUCCESSFULLY INCORPORATED CO<sub>2</sub> FROM FLUE GAS INTO CONCRETE WITHOUT UPSTREAM CO<sub>2</sub> CAPTURE

### Demonstration at Pilot Scale

- The CO<sub>2</sub>-to-concrete process was field tested at the Integrated Test Center in Gillette, Wyoming and the National Carbon Capture Center in Wilsonville, Alabama.
- Testing was successful with coal and natural gas flue gas without upfront CO<sub>2</sub> capture.
- Approximately 15,000 blocks were carbonated (Over 4 tonnes of CO<sub>2</sub> stored).
- Achieved in excess of 75% CO<sub>2</sub> utilization efficiency.
- CO<sub>2</sub> concrete product complied with industry standard specifications.



Wilsonville, Alabama



## CARBON REMOVAL PURCHASE AGREEMENT SECURED

### 1st Commercial Project

- Stripe, a financial services company, will pay CarbonBuilt \$250,000 to sequester nearly 1,000 metric tons of CO<sub>2</sub>.
- The agreement will partially offset the cost of the first-of-a-kind commercial Reversa™ process that stores about 0.75 pounds of CO<sub>2</sub> in each concrete block.

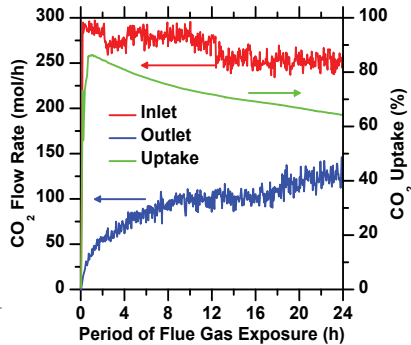
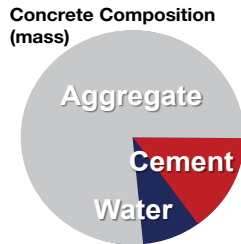




# THE PROBLEM WITH CONVENTIONAL CONCRETE

## CO<sub>2</sub> Emissions

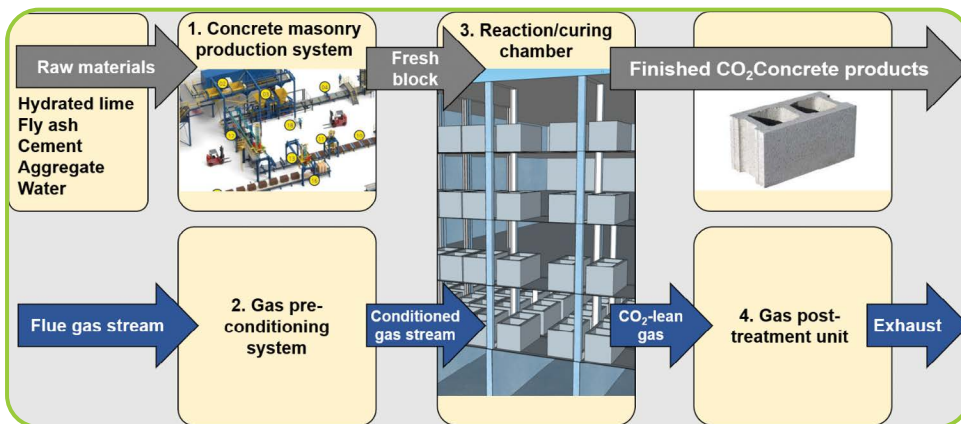
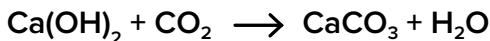
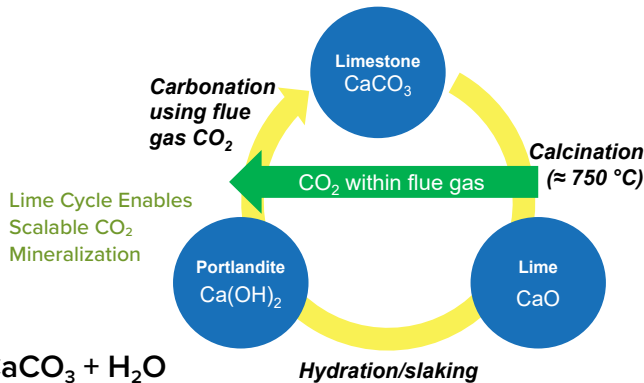
- 10% of global CO<sub>2</sub> emissions are due to cement production.
- ~0.9 tons of CO<sub>2</sub> emitted per ton of cement.
- ~4 billion tons of cement produced per year.
- Most emissions due to calcination.



# PROCESS OBJECTIVE AND CONCEPT

## Upcycle industrial wastes and CO<sub>2</sub>

- Produce low-carbon CO<sub>2</sub> concrete products from coal combustion residues, flue gas CO<sub>2</sub>, and low-grade waste heat.



AWARD NUMBER  
**DE-FE0031718**

## PROJECT BUDGET



- DOE .....\$1,800,000
- PERFORMER.....\$460,265

## CONTACTS

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## FECM RDD&D PRIORITY



LOW-CARBON INDUSTRIAL  
SUPPLY CHAINS

## PARTNERS



**Susteon**

**UCLA**

**Samueli**  
Chemical & Biomolecular Engineering

# PILOT-SCALE PLANTS TO RECOVER RARE EARTHS AND CRITICAL MINERALS FROM COAL AND COAL REFUSE

Extracting valuable rare earth element concentrates from coal and coal refuse.

## PILOT RECOVERY PLANTS COMMISSIONED IN KENTUCKY AND NORTH DAKOTA

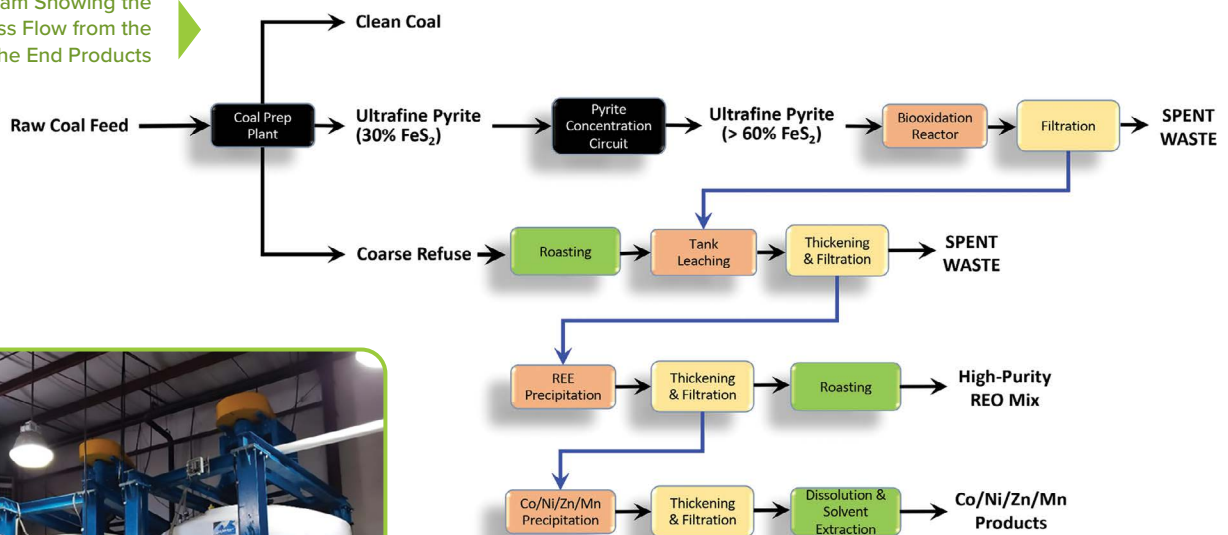
Rare earth elements (REE) and critical minerals (CM) are essential materials used in a broad range of technologies that are significant to domestic and national security, energy, and daily consumer products.

Two projects have made significant progress toward piloting technologies aimed at recovering REE and CM from coal and its refuse. The University of Kentucky (UK) installed and commissioned a pilot-scale plant near Providence, KY, while the University of North Dakota (UND) has begun to operate a pilot-scale plant in Grand Forks, ND.

## UK PILOT PLANT EXPECTS MIXED RARE EARTH OXIDE PURITY OF GREATER THAN 90%

The UK plant will recover mixed rare earth oxides with an expected purity of greater than 90%, which could be refined in a future project to produce individual rare earths and rare earth metals. The pilot plant will also recover cobalt, manganese and, possibly, other critical minerals from coal refuse.

Block Diagram Showing the Generalized Process Flow from the Feed Source to the End Products



Three 3000-Gallon Bioreactors Used to Produce Two Gallons/Minute of Sulfuric Acid from Coal Pyrite at a Strength of Approximately 0.5M (One Bioreactor is a Feed Preparation Tank While the Remaining Two are Production Units Equipped with Denver Sub-Aeration Units Driven by 30 HP Motors and 8 Tons of Chilling Capacity)

# UND PILOT PLANT TO PRODUCE MIXED RARE EARTH OXIDES WITH A PURITY GREATER THAN 75%

The UND Institute for Energy Studies is initiating operation of a pilot-scale, novel technology for REE recovery from North Dakota lignite coal and related feedstocks.

North Dakota lignite coal has been discovered with REE levels as high as anything ever reported previously for U.S. coals. In lignite coal, the REE are weakly bound as organic complexes, rather than in mineral forms that are typical of higher-rank coals.

UND is using a mild acid to leach valuable materials from the source, including mixed rare earth oxides with a purity greater than 75% and critical minerals such as germanium and gallium. UND plans to separate the mixed rare earth oxides into individual rare earth compounds.



UND Coal and Mineral-Rich Tailings Filter Presses, with the Liquid Processing Tanks Featured in the Background



UND Coal Washing Systems Associated with the Coal Filter Presses

## PARTNERS



AWARD NUMBER  
**DE-FE0031827**

PROJECT BUDGET  
**\$6.25M**

- DOE .....\$5,000,000
- PERFORMER.....\$1,250,000

AWARD NUMBER  
**DE-FE0031835**

PROJECT BUDGET  
**\$6.5M**

- DOE .....\$4,989,255
- PERFORMER.....\$1,519,300

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**RICK HONAKER (DE-FE0031827)**

**NOLAN THEAKER (DE-FE0031835)**

## FECM RDD&D PRIORITY



ADVANCE CRITICAL MINERALS,  
RARE EARTH ELEMENTS (REE),  
AND MINE REMEDIATION

# COMPREHENSIVE FIELD CAMPAIGN WILL LEAD TO IMPROVED DECISION MAKING ON EMISSIONS REDUCTIONS FROM OIL AND NATURAL GAS WELLS

NETL supports collection and evaluation of representative, defensible, and repeatable emissions data.

## MAJORITY OF WELLS IN THE US ARE MARGINAL PRODUCERS

### What is a Marginal Well?

Marginal wells are defined as producing less than 15 barrels of oil equivalent (BOE) per day of combined oil and natural gas.

There are more than 1.1 million oil and natural gas wells in the U.S., of which approximately 770,000 (~70%) are considered “marginal” in terms of their profitability or low production.

### Production Considerations

Marginal wells can remain in operation while releasing emissions even when commodity prices and production rates fall below set thresholds due to federal and state tax credits.

### Production Considerations

Quantifying and delineating emissions from marginal wells is the first step toward implementing sound policies and regulations designed to reduce the environmental impact caused by methane emissions.

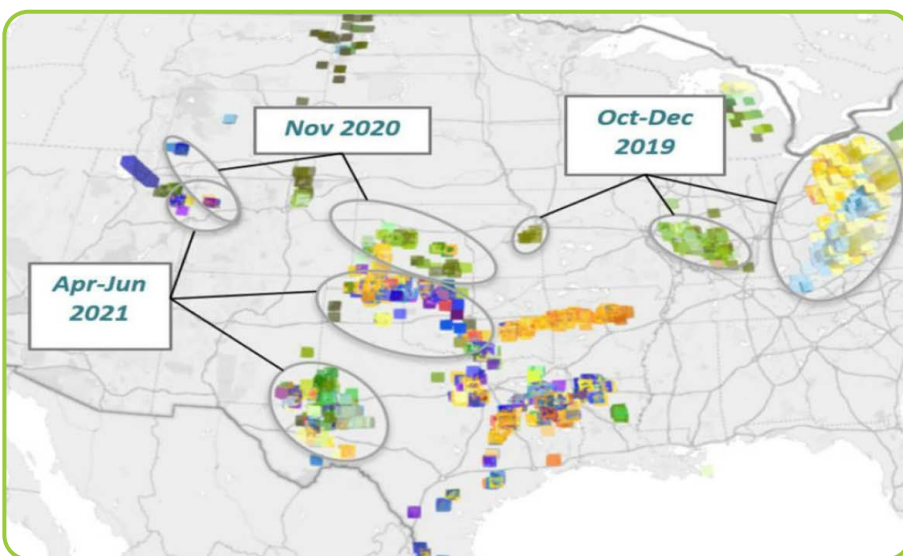


Emissions Were Identified Using an Optical Gas Imaging (OGI) Camera and Quantified, Where Possible, Using a Bacharach Hi-Flow Sampler (BHFS)

## REGIONAL FIELD CAMPAIGN WITH STRATEGIC SITE SELECTION

### Representative Field Sites

- All regional field campaigns were conducted between October 2019 and June 2021. Field campaigns were designed to prioritize locations with dense populations of marginal well sites.
- Data were collected across seven U.S. oil and gas producing basins.
- 589 well sites visited in coordination with 15 participating host operators.
- 524 wells exhibited marginal well behavior.
- Characterized sites with equipment and operations ranging from 2 to 79 years old.



General Locations and Times of Regional Field Campaigns

# DIRECT EMISSIONS MEASUREMENTS IN THE FIELD

## Field Campaigns Have Been Completed

No emissions were detected at approximately 55% of visited natural gas production sites and approximately 60% of visited oil production sites.

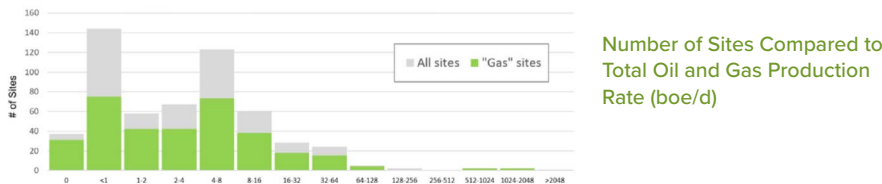
Approximately 90% of the cumulative emissions detected in the combined field campaigns are attributable to 13% of visited sites for both natural gas and oil production.

Approximately 90% of observed methane emissions were less than 23 standard cubic feet per hour (scfh) and 95% of observed methane emissions were less than 45 scfh.

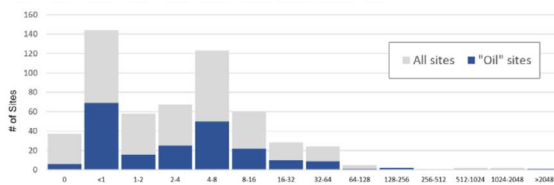
Study wide, the top 10% of emitting sources contributed 90% of total methane emissions observed.

The ten largest observed sources, each emitting between 100 and 780 scfh of methane, accounted for 2% of total measured emissions.

### Study-wide Distribution of Site Oil and Gas Production (preliminary results)



Total Combined Oil and Gas Production of Visited Field Study Sites, as Reported by Host Operators



# EMISSIONS ANALYSIS AND RESULTS

## Overall Emissions Quantification

A large percentage of overall emissions are released from few locations.

- 65% of natural gas well sites had no measurable emissions.
- 75% of oil well sites had no measurable emissions.

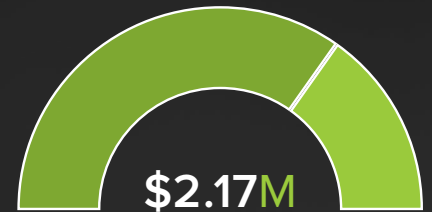
## PARTNERS



AWARD NUMBER  
**FE-0031702**

## PROJECT BUDGET

FY20 FUNDING



- DOE ..... \$1,496,987
- PERFORMER..... \$682,500

## CONTACTS

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**RICHARD L. BOWERS**

## FECM RDD&D PRIORITY



REDUCE METHANE EMISSIONS

# PIPELINE SURFACE TREATMENT TO IMPROVE U.S. ENERGY PIPELINE RELIABILITY PROVED EFFECTIVE

A non-toxic, water-and-oil repellent nanocomposite material increases surface protection and reduces corrosion and pressure drop in oil and gas pipelines.

## DRAGX™ PROVIDES RAPID AND IMMEDIATE DECARBONIZATION IMPACTS

An NETL-led public-private research effort with Oceanit Laboratories Inc. was able to reduce the occurrence of low-rate, hard to detect natural gas leaks within the approximately 320,000 miles of existing gathering and transmission pipelines in the United States.

The solution is an ultra-thin, “omniphobic” surface treatment to achieve the following with minimal surface preparation:

- Reduce internal friction.
- Protect against corrosion.
- Limit the chance of deposition within these pipelines.

Through this research effort, DragX™ was field tested and approved by several major industry partners. **Widespread use of DragX™ could be a game-changer for industry in terms of improving the resiliency and longevity of natural gas pipeline infrastructure and drastically reducing methane emissions.**



Image of Water Droplet on Untreated Pipeline (Left) vs. DragX™ Treated Pipeline (Right).

## A BROAD RANGE OF APPLICATIONS

The scalable application process for DragX™ (≤ 10 mile length, up to 36” in diameter) does not require costly trenching and replacement and has proved to be highly adaptable for almost any type of enclosed line. Examples below include application of DragX™ to lines with “un-piggable 90° bends,” coiled tubing, casing pipeline, and bypass valves under a wide range of pressures, temperatures, and gas compositions.



Test Applications of DragX™ Completed During This Effort Working With Different Industry Partners: (A) 8,000+ Feet of Casing Pipe, (B) 1,000+ Feet of Transport Pipe, (C) 10,000+ Feet of Coiled Tubing, (D) 1,000+ Feet of Wastewater Feed

## DRAGX™ ECONOMIC AND ENVIRONMENTAL BENEFITS

Treated pipe sections deployed in the Alaska assets of Eni S.p.A., along with follow-up studies:

- Showed total prevention of microbially-induced corrosion (MIC), eliminating pitting and wall loss,
- Determined that the DragX™ treated pipe surface was 36 times better at preventing material loss compared to untreated pipe attacked by MIC, and
- Found reduced bacterial adhesion by over 90%



Typical Mic Damage to Spool (Left) vs. Dragx™ Treated Spool After Six Months (Right)

Estimates taken from field demonstrations show that **surface roughness and the associated pressure drop due to friction is lowered by approximately 15% after DragX™ treatment.** Different studies estimate that a single compressor station can generate in excess of 33,000 Mcf of methane per year; with approximately 1,700 total stations, **even a 10% reduction in fuel usage would result in carbon savings of over 33M tons per year,** equivalent to carbon sequestered by approximately 40 million acres of U.S. forests in one year or CO<sub>2</sub> emissions from roughly eight coal power plants.

## A PUBLIC-PRIVATE PARTNERSHIP MODEL FOR RAPID DEPLOYMENT OF FUTURE ENERGY TRANSITION TECHNOLOGIES

With the aid of DOE and NETL, **Oceanit's DragX™ surface treatment has been developed from a benchtop technology into a turnkey commercial solution that has been vetted for adoption by multiple industry operators.**

The unique combination of flexible application and highly chemically resistant material also allows the technology to be a part of a future energy transition away from traditional resources, such as part of a composite coating solution to retrofitting existing pipeline infrastructure for future blended natural gas or pure hydrogen transport. Its demonstrated compatibility in sour gas conditions also makes it an intriguing option to protect existing CO<sub>2</sub> storage from corrosion and leaks.

### PARTNERS



AWARD NUMBER  
**DE-FE-0029069**

### PROJECT BUDGET

FY21 FUNDING



- DOE ..... \$1,950,00
- PERFORMER..... \$487,500

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**MATTHEW NAKATSUKA**

### FECM RDD&D PRIORITY



REDUCE METHANE EMISSIONS

# HEAT TRANSFER ENHANCEMENT TECHNOLOGY FOR POWER PLANTS DEMONSTRATED AT COMMERCIAL SCALE

Interphase Materials has scaled and commercialized the THERMOPHASE heat transfer enhancement technology.

## A MORE EFFICIENT HEAT THERMAL TREATMENT

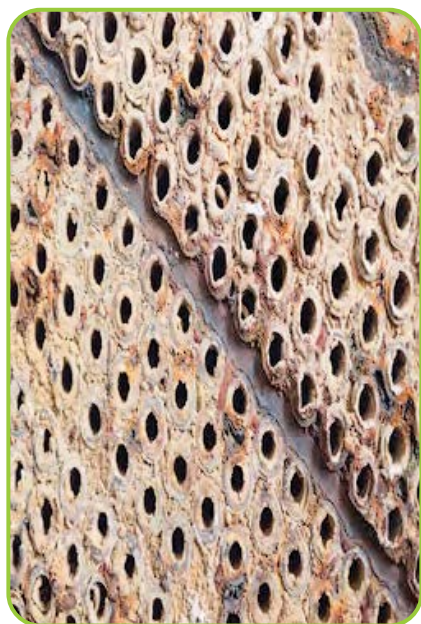
In July 2021, Interphase Materials conducted a second pilot application at the Longview Power Plant to determine potential improvements to condenser efficiency and continuous-feed water treatment reduction.

Next, Interphase Materials demonstrated the NETL-supported thermal treatment technology (THERMOPHASE) at commercial scale. THERMOPHASE is a biocide-free **surface treatment** designed to **keep heat transfer surfaces clean** from organic and biological fouling.

## ANTI-BIOFOULING AND HEAT TRANSFER ENHANCEMENT

Pilot-scale testing in rigs at Longview Power Plant in Madsville, West Virginia, has previously shown that the thermal treatment technology could inhibit biofouling (microbiologically induced corrosion) and scale buildup as well as improve the baseline heat transfer efficiency of cooling.

For the second application, the condenser back pressure has been on average 5.01% lower (-0.108 inches Hg). A back pressure reduction of this magnitude is estimated to reduce the heat rate of a power plant by 0.23%. As an example, a 770 MW coal plant with an average heat rate of 10,300 BTU/kW/hr would equate to \$255,000 in fuel savings alone and a reduction of approximately 14,000 tons of CO<sub>2</sub>.



Examples of Cleaned and Fouled Condenser Surfaces



## INTERPHASE COMPLETES SECOND TEST OF THERMOPHASE CONDENSER TREATMENT

When used as a finishing step to existing cleaning and water treatment protocols, the technology promotes additional cleanliness to enhance heat transfer leading to **lower fuel usage and less emissions per kW/hr generated.**



THERMOPHASE Used in Testing at Longview Power Plant

Initial results indicate a modest decrease in back pressure, which will be further analyzed.

## THERMOPHASE BENEFITS

“This stuff really works” – Power Plant Manager

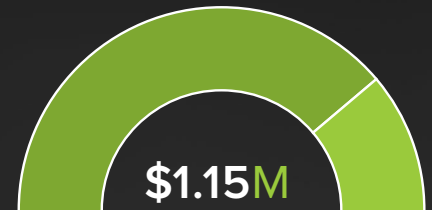
- Reduces build-up of inorganic and biological fouling.
- Enhances heat transfer to reduce energy and water use.
- Reduces water treatment costs and chemical volumes.
- Helps meet EPA Clean Water Act requirements.
- Maintains surface cleanliness and improves cleanability of surfaces.
- Enables less frequent cleanings and reduces maintenance costs
- Boosts efficiency and fights fouling.
- Increases hardware life cycles.

## PARTNERS



AWARD NUMBER  
**DE-FE-0031561**

## PROJECT BUDGET



- DOE .....\$895,521
- PERFORMER.....\$258,352

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PRINCIPAL INVESTIGATOR  
**DR. NOAH SNYDER**

## FECM RDD&D PRIORITIES



INVEST IN THOUGHTFUL  
TRANSITION STRATEGIES



ADDRESS THE ENERGY  
WATER NEXUS

# TWO LARGE-SCALE CAPTURE PILOTS PROCEED TO DETAILED DESIGN AND CONSTRUCTION

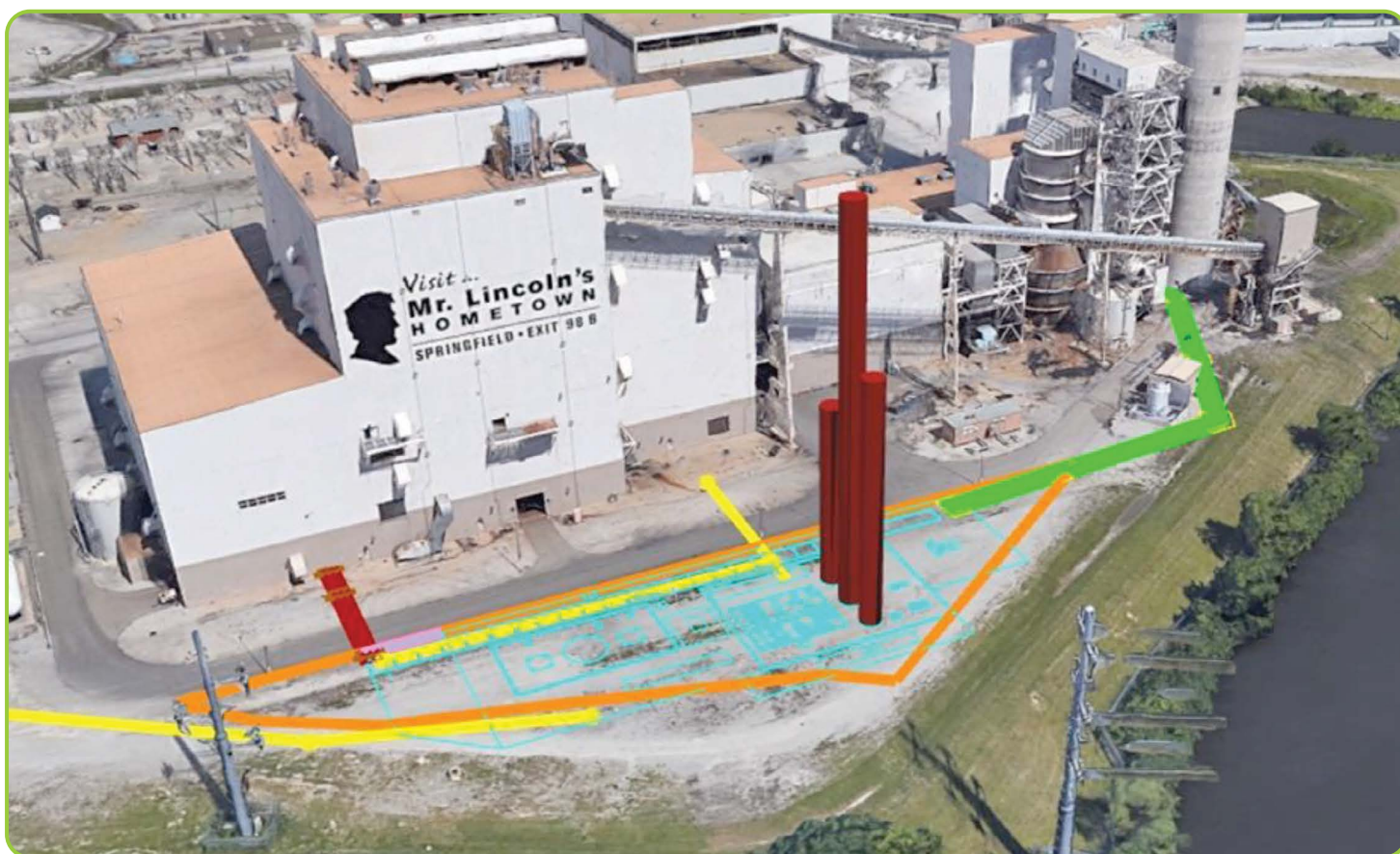
Large pilot testing of advanced carbon capture systems at actual sites will provide a detailed understanding of carbon capture costs in a commercial application.

Two advanced carbon dioxide (CO<sub>2</sub>) capture technologies will be tested at large-scale pilot facilities using nominal 10-MWe exhaust slipstreams from existing power plants.

## 10-MWE TESTING OF LINDE-BASF OASE® BLUE SOLVENT SYSTEM AT DALLMAN POWER PLANT IN SPRINGFIELD, IL

The University of Illinois has partnered with Linde Engineering, BASF Corporation, and Affiliated Construction Services to build and operate a 10-MWe advanced amine-based post-combustion CO<sub>2</sub> capture (PCC) system at the coal-fired City Water, Light and Power (CWLP) Dallman Unit 4 in Springfield, IL.

The PCC system is **designed for >90% CO<sub>2</sub> capture [~200 tonnes of CO<sub>2</sub> per day (TPD)] with 50% turndown capacity** and includes a patented water wash process to reduce OASE® blue solvent loss and aerosol emissions, a unique two-phase, plate-and-frame reboiler design to improve load-following capabilities, stripper interstage heating, and high-pressure stripper operation (3.4 bar).

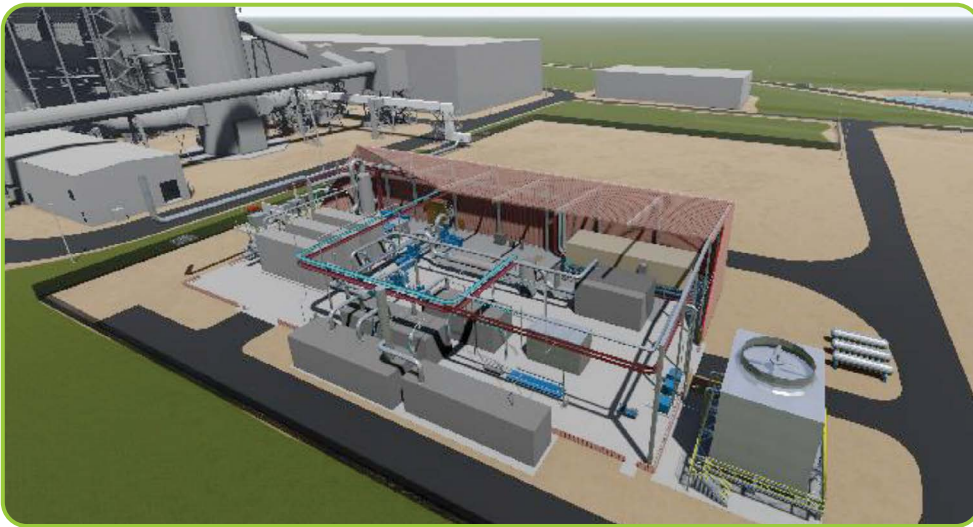


CWLP Dallman Plant with Rendering of Capture Unit

# 10-MWE TESTING OF MTR GEN-2 POLARIS MEMBRANE SYSTEM AT THE WYOMING INTEGRATED TEST CENTER IN GILLETTE

Membrane Technology and Research (MTR) has partnered with Sargent & Lundy, Trimeric, and Graycor to construct and operate a **two-stage membrane process designed for 70% CO<sub>2</sub> capture** from a 10-MWe coal-fired slipstream (~150 TPD) at the Wyoming Integrated Test Center in Gillette, WY.

The MTR process will feature high-permeance (>1,500 GPU) Gen-2 Polaris™ membranes in planar membrane modules designed for low pressure drop (4X reduction from earlier spiral-wound modules) followed by CO<sub>2</sub> liquefaction to evaluate product purification (>99%) and compression to 2,234 psia (154 bara).



## PRIMING TECHNOLOGY FOR COMMERCIAL DEPLOYMENT

The two five-year projects will complete construction in 2023 for operation in the 2024–2025 time frame and will prime the CO<sub>2</sub> capture technologies for commercial deployment while also providing critical data and knowledge collection that can be applied to other power and industrial CO<sub>2</sub> emitting facilities.

AWARD NUMBER  
**DE-FE0031581**  
(U of Illinois)

### PROJECT BUDGET

**\$71.8M**

- DOE .....\$50,862,896
- PERFORMER.....\$20,942,223

AWARD NUMBER  
**DE-FE0031587**  
(MTR)

### PROJECT BUDGET

**\$72.2M**

- DOE .....\$55,698,626
- PERFORMER.....\$16,470,049

### CONTACTS

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PRINCIPAL INVESTIGATORS

**KEVIN O'BRIEN (U. of Illinois)**

**RICHARD BAKER (MTR Co-PI)**

**BRICE FREEMAN (MTR Co-PI)**

### FECM RDD&D PRIORITY



DEMONSTRATE AND  
DEPLOY POINT-SOURCE  
CARBON CAPTURE

#### PARTNERS



THE LINDE GROUP



Sargent & Lundy



# CONVERSION OF CARBON-BASED MATERIALS INTO EXCEEDINGLY HIGH-QUALITY GRAPHENE

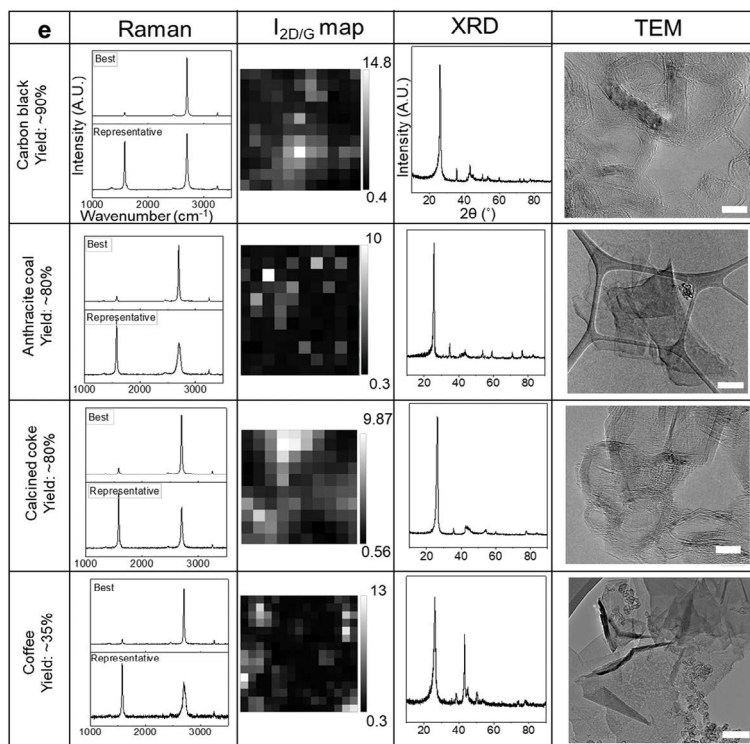
Producing high-value solid products from domestic U.S. carbon ore.

## ADVANCED CONVERSION PROCESS RAPIDLY PRODUCES LOW-COST, HIGH-QUALITY GRAPHENE

Researchers at Rice University have used an advanced conversion process called flash Joule heating (FJH) to rapidly produce low-cost, high-value graphene from coal using scalable next-generation technology and advanced manufacturing methods.

The FJH process is an energy-efficient method that can convert almost any carbon-based precursor into quantities of graphene in less than a second. The FJH process has a >90% processing yield with ~100% excellent quality graphene.

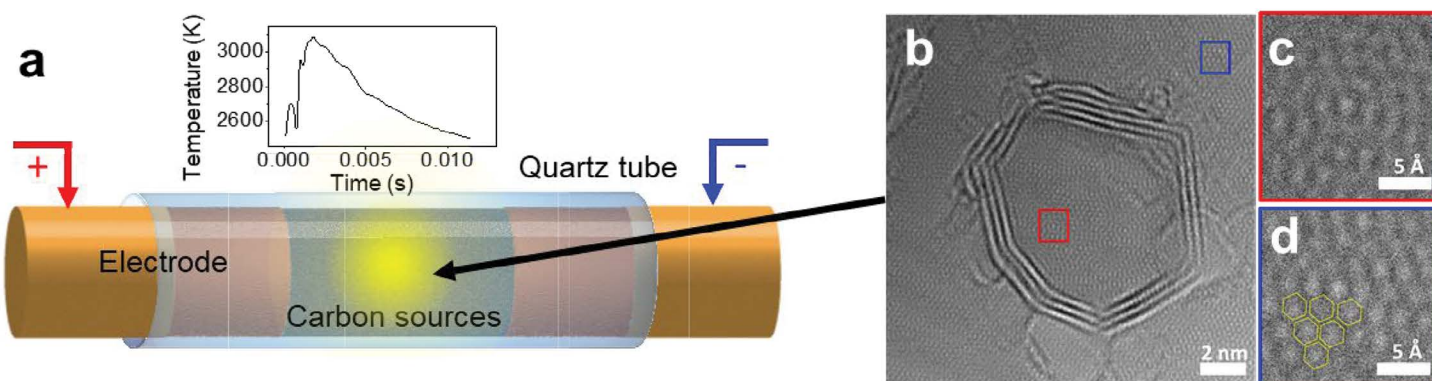
Carbon Sources to Graphene with Characterization Data (Scalebars 5,200, 5,100 nm Top to Bottom)



## FJH IS AN ADVANCED MATERIALS SYNTHESIS TECHNIQUE

FJH is an innovative approach to graphene production that does not require chemicals, water, or purification steps. FJH uses a controlled amount of electricity, in this case referred to as a flash, to add thermal energy (measured in Joules) to the carbon material. The carbon is heated by this energy, which converts it into the desired form.

Electrical energy is stored in large capacitors and is discharged through the carbon-based material, which heats it to approximately 2,700 °C (4,892 °F). This controlled heating converts the carbon material into graphene flakes.

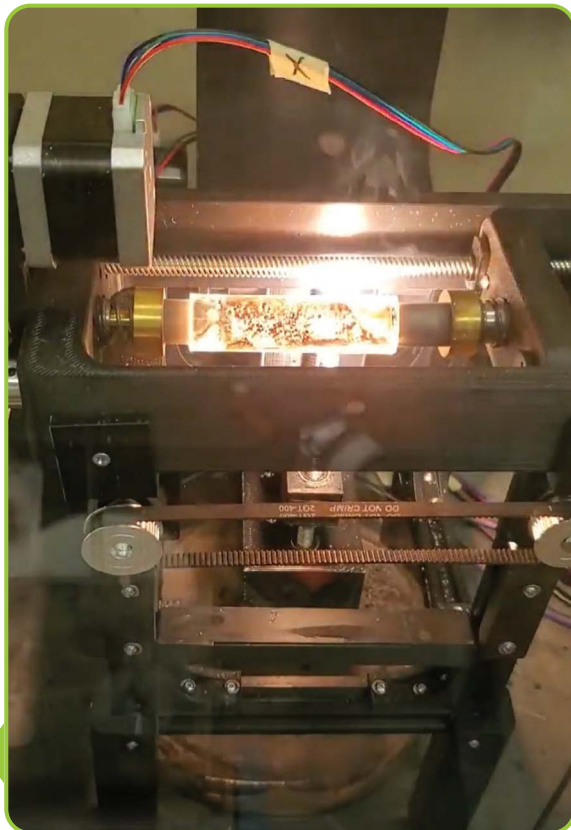


Carbon Materials are Converted Efficiently Into High-Quality Turbostratic Graphene

## CARBON-BASED PRECURSORS CONVERTED TO GRAPHENE IN LESS THAN A SECOND

Using an automated FJH process, the Rice research team met the key project milestone of producing a total of 1 kilogram (kg) of graphene in less than one day (two hours).

The process is being further developed at a spin-off company, Universal Matter. Scaling of the process is aimed at achieving 1 ton per day graphene production in 2022 with the promise of much greater growth in the future.



Automation of FJH Graphene Process

## GRAPHENE BENEFITS A WIDE VARIETY OF APPLICATIONS

Due to being composed of a single layer of carbon atoms tightly bound in a honeycomb-like pattern, graphene has incredible mechanical and electrical properties (e.g., tensile strength over 200 times greater than structural steel, and electrical conductivity greater than copper). Graphene shows promise in a wide variety of applications including composite building materials (such as cement, concrete, and plastics), automotive and aerospace parts, batteries and supercapacitors for energy storage, or as an electrical conductor.

### PARTNERS



RICE UNIVERSITY



UNIVERSAL  
MATTER

ADVANCED MATERIALS

AWARD NUMBER  
**DE-FE0031794**

### PROJECT BUDGET



- DOE .....\$750,000
- PERFORMER.....\$187,500

### CONTACTS

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PRINCIPAL INVESTIGATOR  
**DR. JAMES TOUR**

### FECM RDD&D PRIORITY



ADVANCE CRITICAL MINERALS,  
RARE EARTH ELEMENTS (REE),  
AND MINE REMEDIATION

# NETL'S MICROWAVE CATALYSTS PRODUCE CARBON NEUTRAL HYDROGEN FROM CAPTURED CARBON DIOXIDE AND WASTE METHANE

NETL has scaled novel microwave catalysts from atomic-level design to pre-pilot scale demonstration and kilogram-scale synthesis.

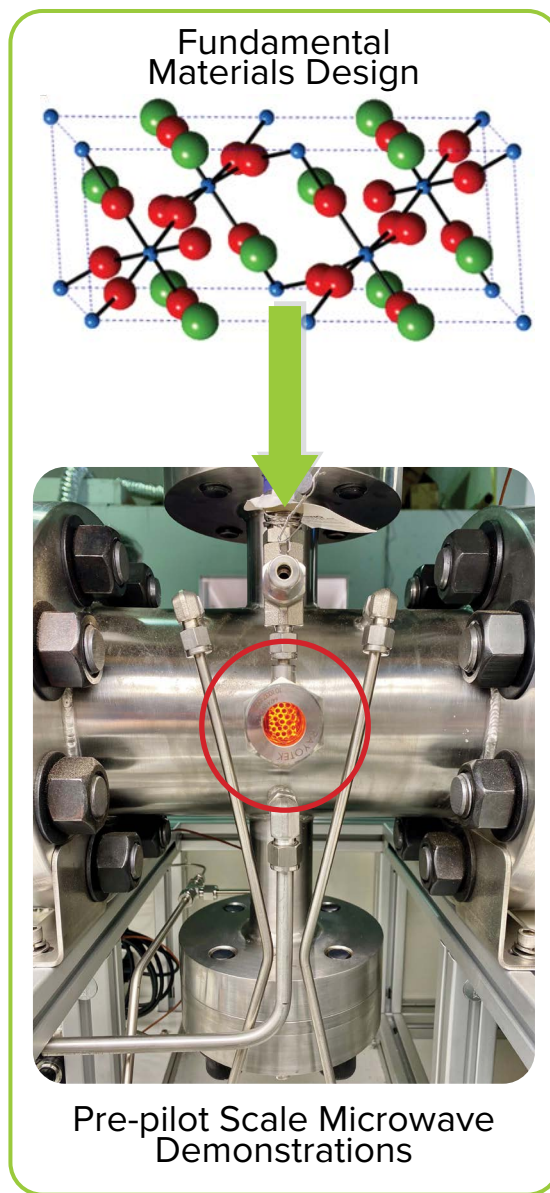
## NETL'S MICROWAVE CATALYSTS DEMONSTRATE RECORD-BREAKING EFFICIENCY

**NETL's microwave catalysts demonstrate twice the energy efficiency** of electrochemical CO<sub>2</sub> conversion technologies and **exceed the DOE's 2020 goal for electrochemical H<sub>2</sub> production** (<44 kWh/kg H<sub>2</sub>).

NETL is applying a unique set of tools in a multidisciplinary approach to microwave technology development. Combining extensive material development capabilities, state-of-the-art microwave reactor facilities, and advanced computation resources, research teams collaborated to understand how microwaves interact with fossil fuels at the molecular level, in bench-scale experiments, and simulations of larger scale operations.

## BENEFITS OF MICROWAVE-ASSISTED CATALYTIC PROCESSES

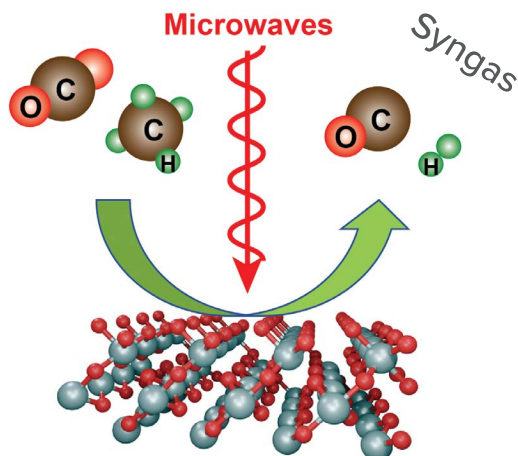
- Rapid, selective heating with microwaves provides process intensification by reducing reactor size and downstream separation units.
- May be used to mitigate process upsets allowing for continued operations for processes requiring long restart times.
- Flexibility and tunability of microwave fields allow system to respond to variations in feed rate and composition, as well as to intermittent periods of reduced resource availability.
- Microwave systems can operate using excess, carbon-neutral electricity, making the technology comparable to state-of-the-art electrochemical technologies.



## MICROWAVE TECHNOLOGY CAN HASTEN TECHNOLOGY COMMERCIALIZATION

Microwave energy is uniquely suited for modular applications due to the process intensification it provides through rapid, selective heating of a reacting system. Modular systems provide an opportunity to hasten the advance of technologies to commercialization by allowing the scale of a process to be increased with additional, smaller units, rather than by increasing the size of the system.

## NETL MICROWAVE CATALYSTS CONVERT CAPTURED CO<sub>2</sub> AND WASTE METHANE INTO H<sub>2</sub> AND CO (SYNGAS)



## SYNGAS AS FEEDSTOCK TO MAKE A MULTITUDE OF VALUE-ADDED CHEMICAL PRODUCTS



## U.S. PATENTS PENDING AND INDUSTRIAL PARTNERS ENGAGEMENT IS UNDERWAY

NETL has filed patents and authored many peer-reviewed publications demonstrating proof-of-concept of this technology.



AWARD NUMBER  
**FWP-1022426**

### PROJECT BUDGET

FY21 - 22 FUNDING



● DOE .....\$598,234

### CONTACTS

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PRINCIPAL INVESTIGATOR  
**DOUGLAS KAUFFMAN**

### FECM RDD&D PRIORITIES



LOW-CARBON INDUSTRIAL  
SUPPLY CHAINS



ACCELERATE CARBON-NEUTRAL  
HYDROGEN (H<sub>2</sub>)



REDUCE METHANE EMISSIONS

# NETL INVENTS NOVEL THIN FILM COMPOSITE MEMBRANE FOR POST-COMBUSTION CO<sub>2</sub> CAPTURE

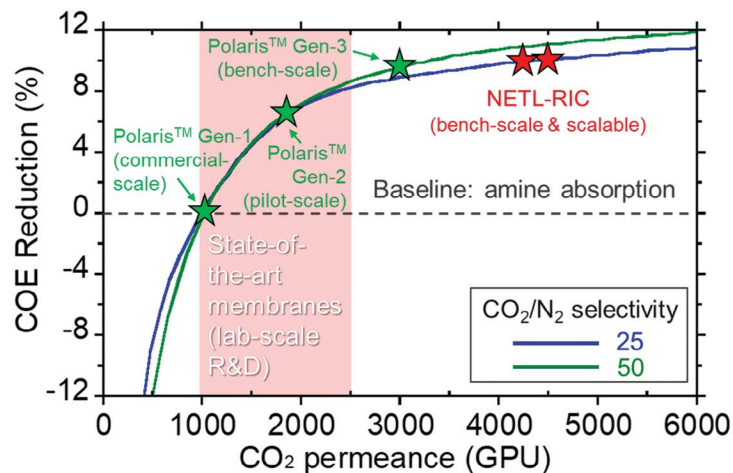
Superior membrane support plus a superior polymer blend material result in NETL's high-performance membrane.

## NEW POLYMERIC MEMBRANES OUTPERFORM COMMERCIAL MEMBRANES

Membranes with extremely high permeance are needed to make membrane technology economically viable.

NETL's answer is a thin film composite membrane for post-combustion carbon capture. It has a demonstrated CO<sub>2</sub> permeance of > 4200 Gas Permeance Units (GPU) and CO<sub>2</sub>/N<sub>2</sub> selectivity of >30 under lab conditions, **far outperforming any commercially available polymer membranes.**

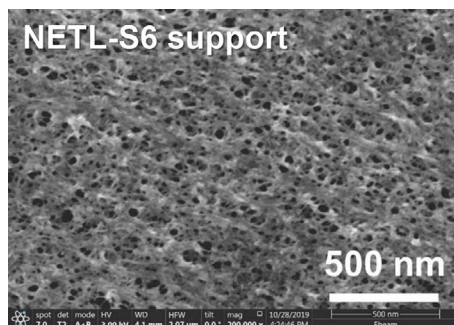
The membrane is a new high-permeance polymer support overlaid with an ultra-thin selective layer of a novel rubbery polymer blend.



Cost of Electricity (COE) Cost Analysis Performed by NETL-RIC for Coal Flue Gas Decarbonization Using Membranes vs. Commercial Amine Absorption

## MEMBRANE SUPPORT DEVELOPMENT

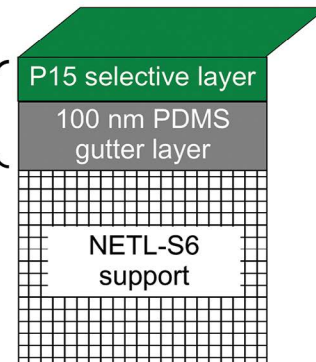
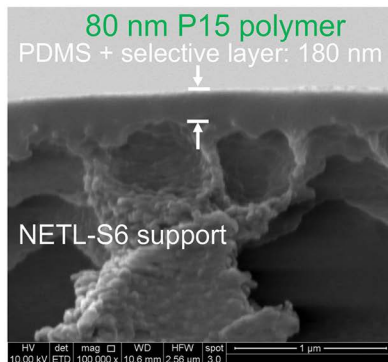
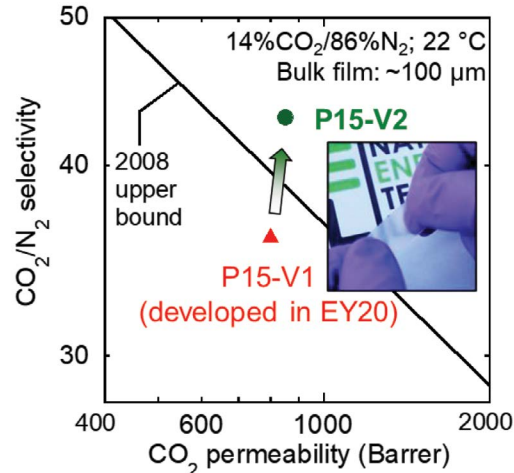
The novel and scalable nanoporous support provides much greater CO<sub>2</sub> permeance (260,000 GPU), surface porosity, and physicochemical stability than commercial polymer porous supports.



## SELECTIVE LAYER MATERIAL AND THIN-FILM DEVELOPMENT

NETL P15 rubbery polymer blends have excellent CO<sub>2</sub>/N<sub>2</sub> separation performance and anti-aging properties.

The CO<sub>2</sub>/N<sub>2</sub> separation performance of sub-200 nm thin film composite membranes exceeds that of state-of-the-art membranes.





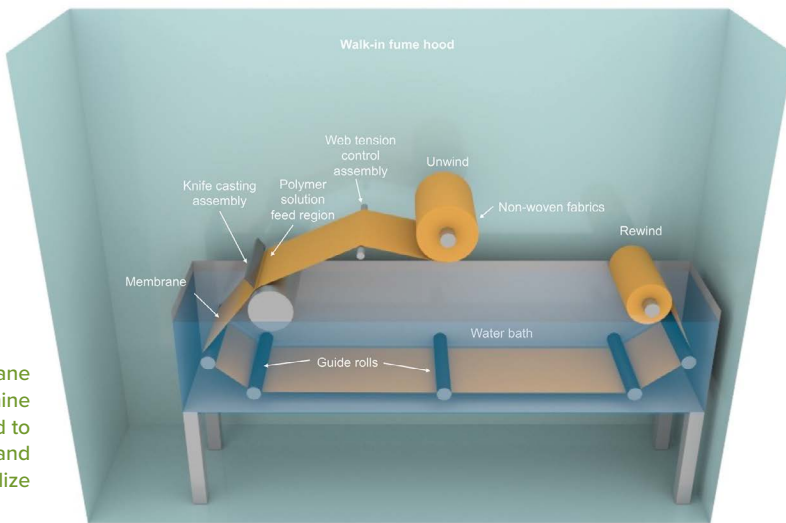
# PATENTING AND SCALE-UP DEMONSTRATIONS

## Path to Commercialization

NETL has submitted a non-provisional U.S. patent application for the membrane support, and another is being prepared for the selective material. The membrane support and selective material both have **high commercial potentials**. NETL has been working to **scale up the membrane for small module demonstrations in different industrial flue gas point sources** like coal-fired power plants, steel mills, and cement plants. NETL plans to establish collaborations with a commercial membrane manufacturer to further scale up and then mature this technology.



NETL's Membrane Test Unit at NCCC for Coal Flue Gas Decarbonization (Operational)



Roll-to-Roll Membrane Fabrication Machine Envisioned to Help Scale Up and Commercialize

AWARD NUMBER  
**FWP-1022402**

## PROJECT BUDGET

EY21 FUNDING



- DOE .....\$279,000
- PERFORMER..... \$110,000

## CONTACTS

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PRINCIPAL INVESTIGATORS  
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**LINGXIANG ZHU**

## FECM RDD&D PRIORITY



DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE

## PARTNERS



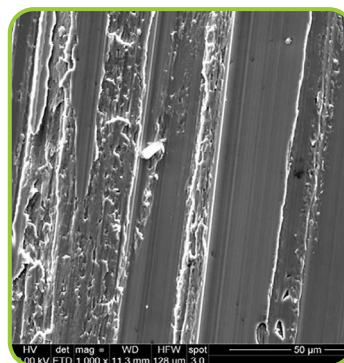
# NETL FILES PATENT FOR HYDROPHOBIC CARBON CAPTURE SOLVENT THAT REDUCES CORROSION OF STEEL TO LOWEST REPORTED LEVELS

New hydrophobic solvent CASSH-1 shows potential for extending equipment lifetime for pre-combustion carbon capture processes.

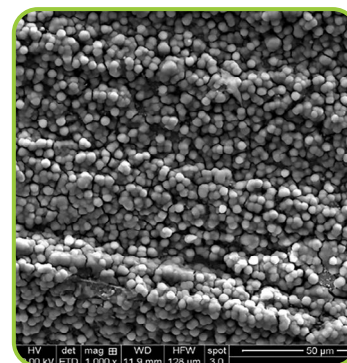
## NON-CORROSIVE SOLVENT CAN LOWER CARBON CAPTURE COSTS

Extending the lifetime of process equipment can decrease capital expenses

- Pre-combustion carbon capture processes rely on solvents that can capture carbon dioxide (CO<sub>2</sub>) at high capacity and selectivity over hydrogen in the presence of water.
- Solvents with hydrophilic properties tend to corrode both stainless and carbon steel, which are common equipment materials for absorbers.
- Rapid corrosion can result in equipment replacement and higher operating costs, driving the need to develop high-performance, non-corrosive solvents for carbon capture, including CASSH-1.



Carbon Steel Surface Before Exposure to Corrosive Solvent



Carbon Steel Surface After Exposure to Corrosive Solvent

## RIGOROUS EXPERIMENTAL TESTING OF CORROSION RATES



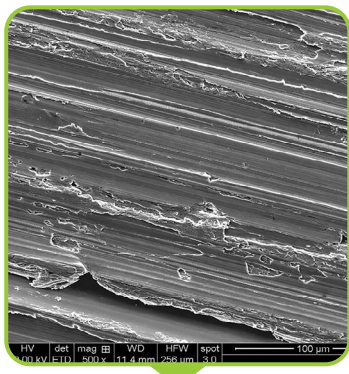
Cross-section of steels, solvents, and operating conditions investigated

- NETL/RIC research facilities are used to synthesize and test hydrophobic solvents in specialized Parr reactors.
- Corrosion rates of both carbon and stainless steel exposed to eight different solvents and aqueous solutions were measured under a range of temperatures, pressures, and gas compositions.
- The amount of corrosion is determined by measuring both the formation of nodules on the steel surface and the concentration of free metal ions released into the solvent.
- Long-term experimental testing, spanning one-to-four weeks, gives results that more accurately represent the projected performance of the solvents.

Parr Reactors (Top) are Used to House Steel Samples in Solvents for a Period of Time (A Low Corrosion Rate Results in a Clear Solvent [Bottom Left], While a High Corrosion Rate Imparts a Yellow Hue to the Solvent [Bottom Right])

# NETL-DEVELOPED SOLVENT SHOWS UNPRECEDENTED CORROSION RESISTANCE

CASSH-1 shows notable capture performance.



Steel Surface After Exposure to Non-Corrosive Cassh-1 Solvent

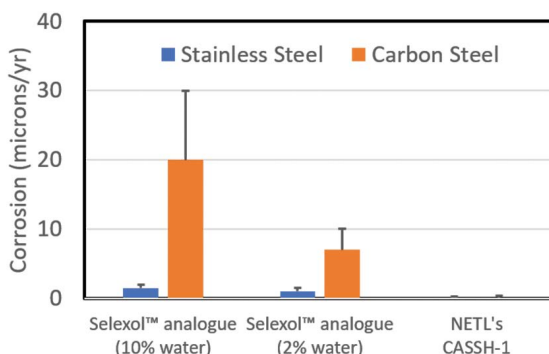
- Computational simulations (with OLI Studio Software) for predicting corrosion rate and water and CO<sub>2</sub> uptake were used to downselect promising candidates.
- Testing of solvent capture properties showed that CASSH-1 outperforms commercially available solvents in terms of corrosion rates, vapor pressure, and absorption kinetics.
- Simulations were validated by corrosion testing of the **hydrophobic solvent, which caused no measurable corrosion with either carbon or stainless steel.**

## HIGH POTENTIAL FOR IMPLEMENTATION OF SOLVENT WITH NEAR-ZERO STEEL CORROSION

This novel solvent can benefit capture processes even when used with cheaper carbon steel.

The hydrophobic CASSH-1 solvent demonstrates superior performance, with uptake capacities comparable to hydrophilic Selexol™ and similar selectivities for CO<sub>2</sub>.

These results show a promising technology ideal for long-lasting compatibility with absorber equipment.



Corrosion Test Results Demonstrated a Notable Decrease in Corrosion Rates Compared to a Benchmark Capture Solvent

AWARD NUMBER  
**FWP-1022402**

PROJECT BUDGET

EY20 + EY21 FUNDING



● DOE ..... \$386,000

### CONTACTS

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TECHNICAL PORTFOLIO LEAD  
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PRINCIPAL INVESTIGATOR  
**NICHOLAS SIEFERT**

FECM RDD&D PRIORITY



DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE

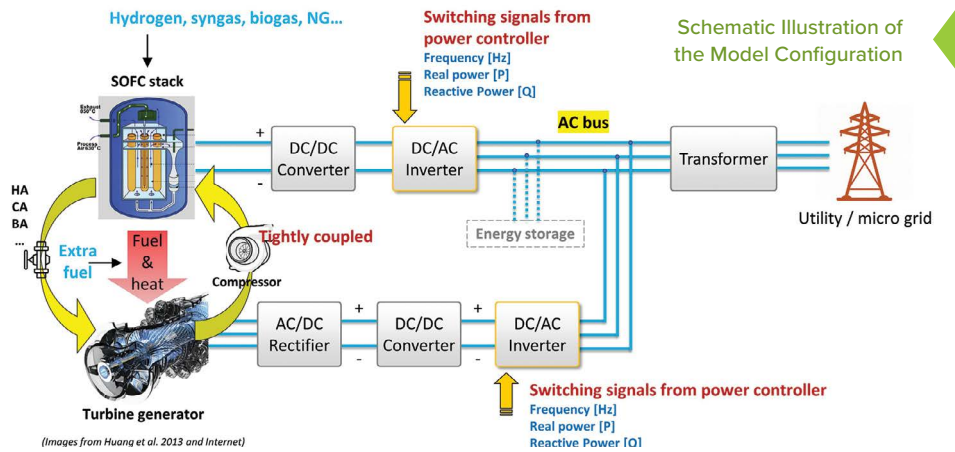
### PARTNERS



# RAPID LOAD TRANSITIONS FOR A SOLID OXIDE FUEL CELL GAS TURBINE HYBRID POWER SYSTEM SUCCESSFULLY DEMONSTRATED

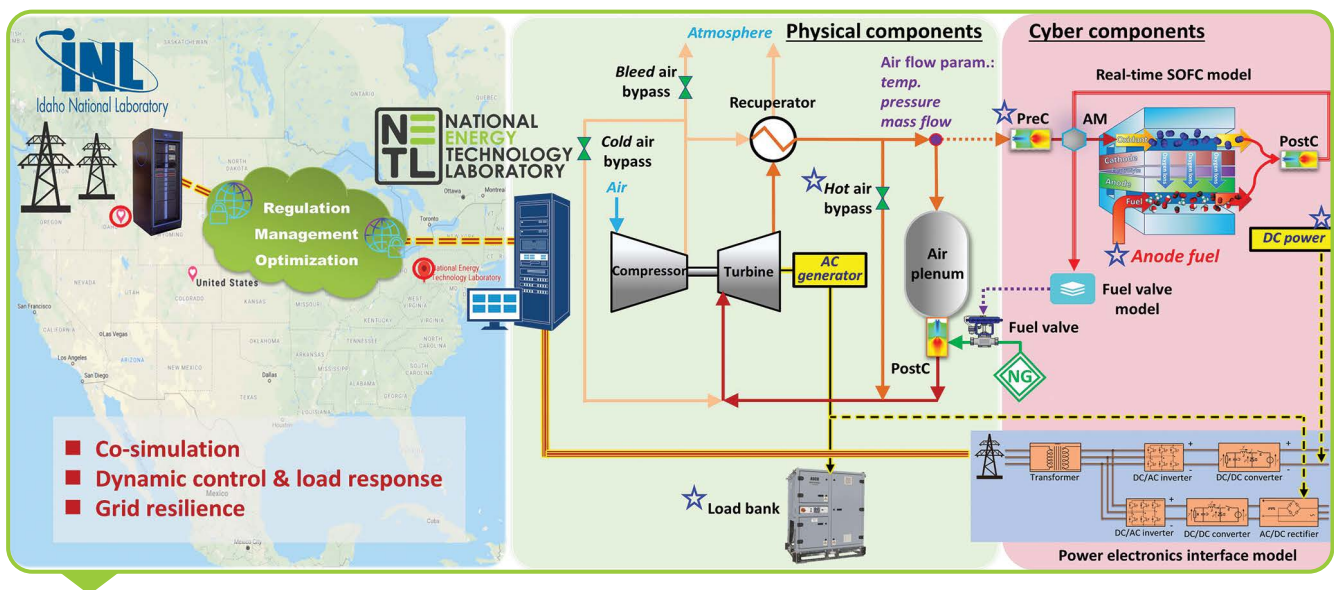
Rapid load changes enable higher levels of variable renewable power on the nation's electric grid.

## HYBRID ENERGY SYSTEMS HAVE THE POTENTIAL TO ADEPTLY RESPOND TO A FAST-CHANGING ELECTRIC GRID



NETL successfully demonstrated that a **50% load change for a solid oxide fuel cell (SOFC) - gas turbine (GT) hybrid power system in less than 10 seconds is possible without violating operability constraints.** This rapid transition was accomplished by controlling cathode inlet air flow and temperature to manage temperature gradients in the SOFC.

These results demonstrate that **SOFC-GT integrated energy systems can provide the fast-ramping characteristics essential to accommodate higher levels of variable renewable power** necessary for carbon mitigation while maintaining grid resilience and reliability.

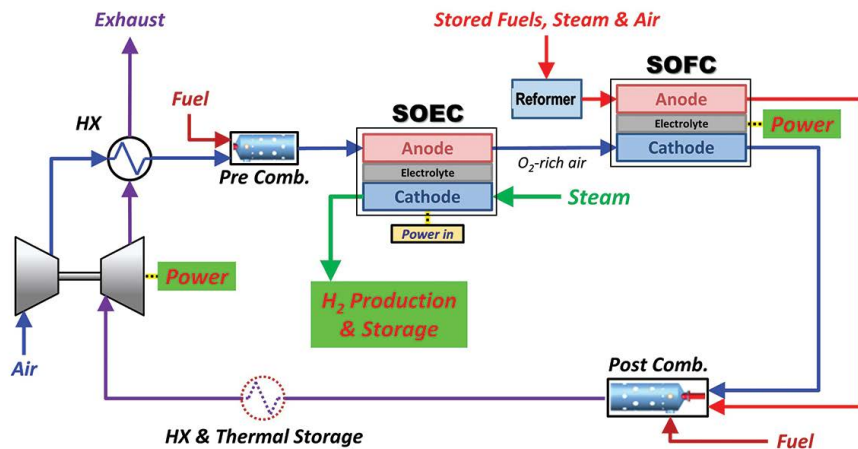


Schematic Illustration of the Cyber-Physical Testbed (Hyper) at NETL (The Hyper Facility has been Linked to a Grid Simulation Capability at Idaho National Laboratory to Investigate the Grid Response of Hybrid Energy Systems)

# SYNERGISTIC APPLICATION OF ADVANCED SOFC TECHNOLOGY

Managing an electric grid comprising an increasing share of variable renewable energy presents new challenges to maintaining resilience and affordable electricity.

A hybrid solid oxide system for the efficient and cost-effective production of hydrogen and electricity is proposed. A cyber-physical approach, which uses a combination of real hardware and models to simulate a complex system, is implemented to preserve both fidelity and flexibility throughout the exploration and design process. The project is expected to provide the basis for accelerated development to catalyze the transition to net-zero carbon power generation.



Fuel Cell Technology Integrated with the Grid

**SOFCs exhibit great potential in rapid load transitions and grid demand responses to accommodate an evolving, dynamic electric grid.**

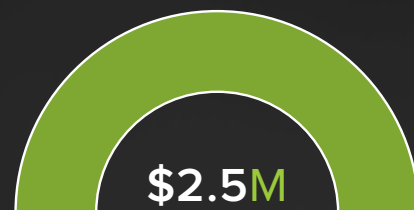
However, several challenges to broad deployment of these technologies remain, which are primarily related to automatic dynamic controls, cell degradation, and maintenance costs.

Pairing SOFCs with other power equipment has the potential to **dramatically improve both cell lifetime and power system efficiency and reduce energy costs.** Demonstrating rapid load transition capability is key to the success of this novel strategy.

AWARD NUMBER  
**FWP-1022460**

PROJECT BUDGET

FY21 FUNDING



● DOE .....\$2,500,000

## CONTACTS

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**SAMUEL BAYHAM**

## FECM RDD&D PRIORITIES



ACCELERATE CARBON-NEUTRAL HYDROGEN (H<sub>2</sub>)



INVEST IN THOUGHTFUL TRANSITION STRATEGIES

# COMPUTATIONAL SIMULATION IDENTIFIES SOLID OXIDE FUEL CELL IMPROVEMENT OPPORTUNITY

Solid oxide fuel cells enable the generation of efficient, low-cost electricity.

## ELECTRODE IMPROVEMENTS INCREASE SOLID OXIDE FUEL CELL (SOFC) LIFETIME

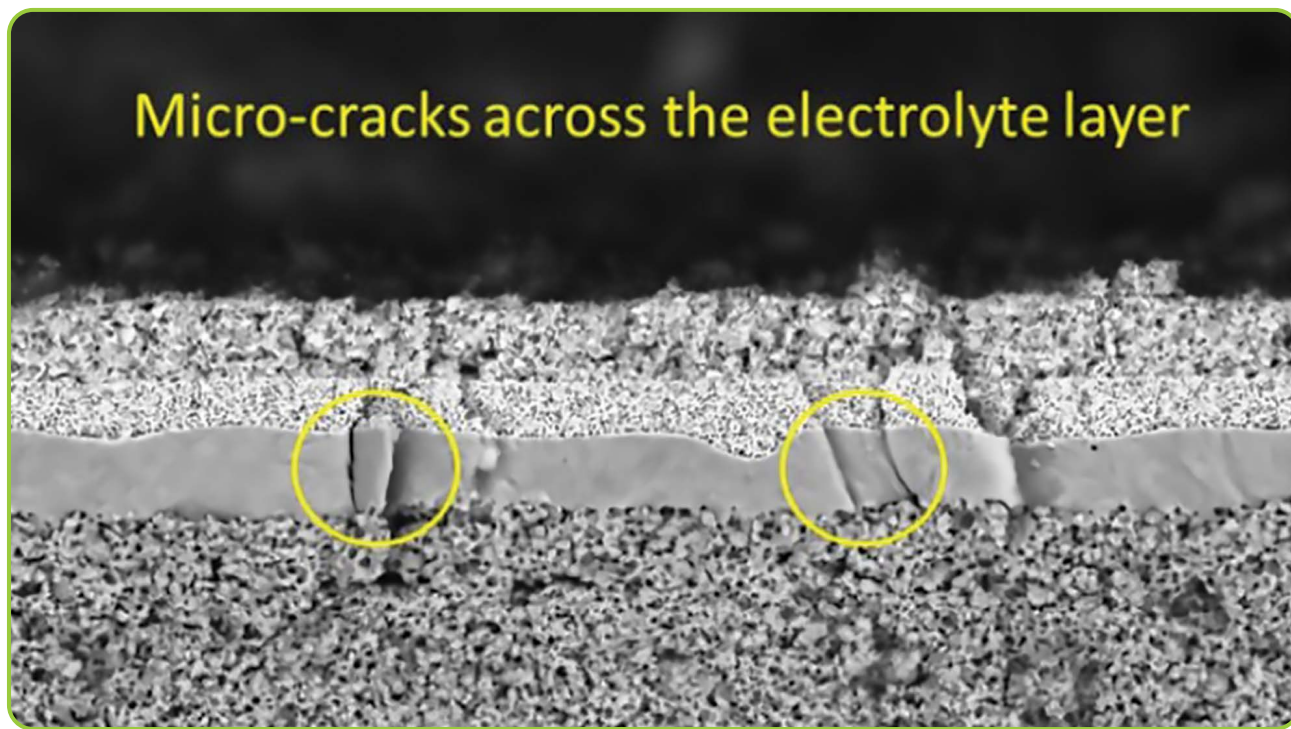
### Favorable Economics Enhance SOFC Commercialization

The NETL SOFC research team used computational simulations to show that functionally graded electrodes can be purposely engineered to reduce temperature gradients and current density gradients in planar SOFCs.

Reducing temperature and current density gradients in SOFCs is an important finding that can be implemented in fuel cell fabrication to lower fuel cell degradation rates, increase the lifetime of SOFCs, and enable the commercialization of SOFC technologies through favorable economics.

Mitigating SOFC degradation helps to determine operability requirements and to develop integration and control strategies to achieve the flexibility and resilience that SOFCs must meet to be fully compatible with an evolving power grid.

## COMPUTATIONAL SIMULATIONS REDUCE SOFC ELECTRODE DEFECTS



Scanning Electron Microscope Image Showing Micro-Cracks Through the Electrolyte Layer Resulting From Cell Performance

## TEMPERATURE GRADIENTS REDUCED BY APPROXIMATELY 30%

Achieved Through Re-Engineering the Cell Electrode Structure

**SOFCs exhibit characteristics that are more compatible with an evolving, dynamic electric grid than with conventional resources such as coal boilers or gas turbines.** However, several challenges to their broad deployment remain, primarily related to cell degradation and maintenance costs.

NETL simulations show temperature and current density gradients—and therefore **cell degradation—can be reduced by altering cell porosity and the ratio of nickel (Ni)/yttria stabilized zirconia (YSZ)** in regions where high gradients occur.

Computational results show **temperature gradients were reduced by approximately 30% for strategic Ni/YSZ ratio distributions** in the hydrogen electrode of a cell operating in fuel cell mode.

### PARTNERS

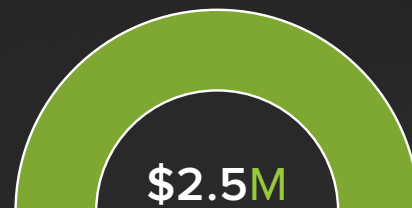


**WISCONSIN**  
UNIVERSITY OF WISCONSIN-MADISON

AWARD NUMBER  
**FWP-1022460**

### PROJECT BUDGET

FY21 FUNDING



● DOE .....\$2,500,000

### CONTACTS

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**SAMUEL BAYHAM**

### FECM RDD&D PRIORITIES



ACCELERATE CARBON-NEUTRAL HYDROGEN (H<sub>2</sub>)



INVEST IN THOUGHTFUL TRANSITION STRATEGIES

# NETL TESTING HIGHLIGHTS NEED FOR NEW ALLOYS IN ADVANCED POWER GENERATION

NETL utilizes its extensive alloy development and manufacturing capabilities to improve alloys and processes that enable advanced energy systems and advanced technologies.

## INTEGRATED STRESS AND CORROSION TESTING SHOWS NEED FOR MORE CORROSION-RESISTANT MATERIALS

**NETL's Advanced Alloy Development portfolio is developing affordable, durable, cost-effective, heat-resistant alloys** to improve the existing fleet of fossil energy (FE) power plants, and enabling advanced FE systems, such as advanced ultra-supercritical Rankine and supercritical carbon dioxide (sCO<sub>2</sub>) power cycles.

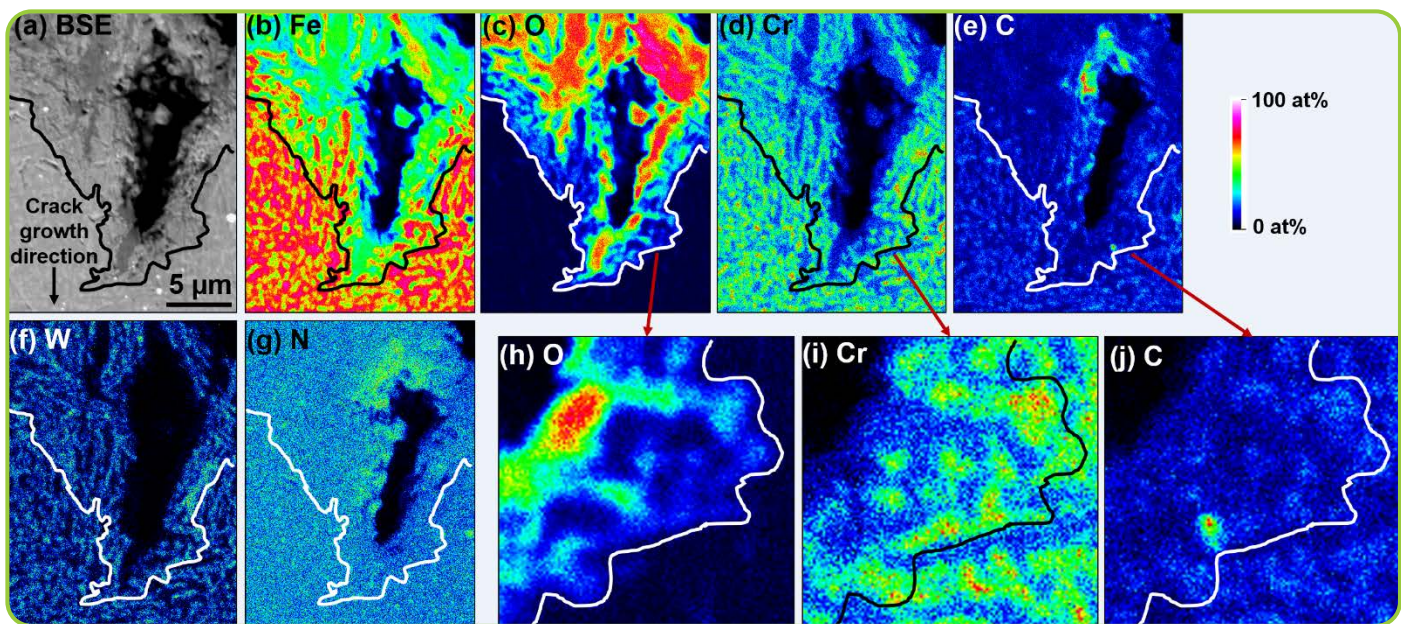
**NETL researchers have determined the combined effects of stress and corrosion for an important class of steel (9Cr martensitic steel) in high-temperature CO<sub>2</sub>.**

The steel was simultaneously exposed to large stresses and a flowing CO<sub>2</sub> gas in an environmental creep frame to closely simulate the harsh conditions expected in future sCO<sub>2</sub> power cycles. As part of the project, NETL led a collaboration with Oregon State University and Pacific Northwest National Laboratory, which employed specialized analytical techniques to reveal precisely how an alloy degrades by reaction with oxygen and carbon in hot CO<sub>2</sub>.

**The results revealed that the steel was severely degraded by CO<sub>2</sub>,** where the combined effects of stress, oxidation, and carburization led to environmentally assisted cracking and premature failure.

**This information is critical for informing material selection for sCO<sub>2</sub> power cycles** and indicates that more corrosion-resistant materials will be needed for the high-temperature portions of these systems.

Quantitative Microprobe Analysis of a Crack Tip Near the Fracture Surface for a Specimen Exposed to CO<sub>2</sub>



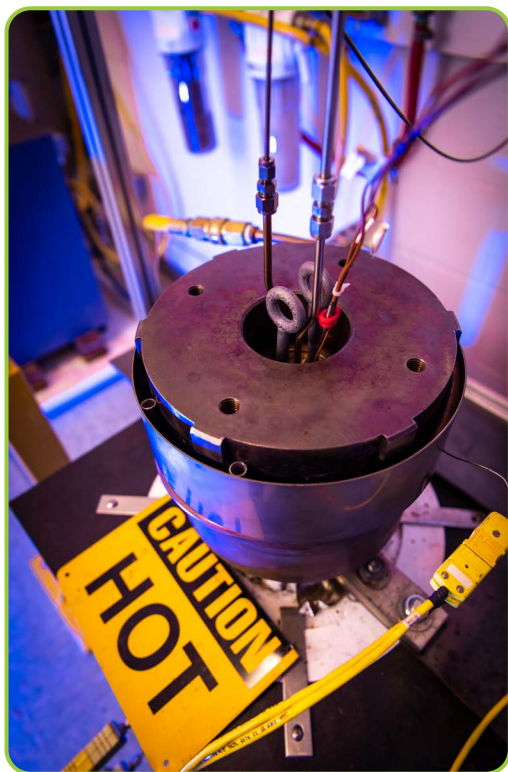


# REMOVING BARRIERS TO ADVANCED POWER GENERATION

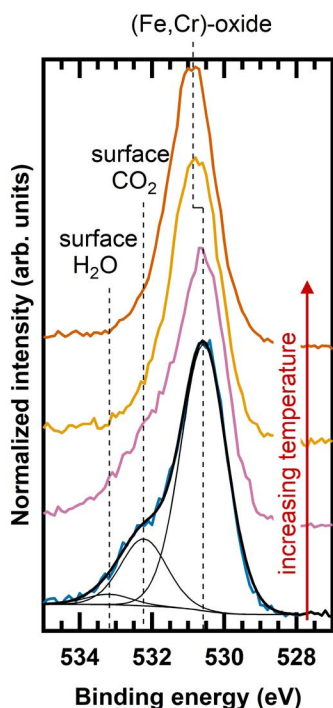
Energy trends are changing, which means the nation's energy infrastructure must change too, including the designs of transformational power technologies like ultra-supercritical steam plants and power systems.

To operate efficiently at the required higher temperatures and pressures, power plants of the future will need new affordable alloys that can deliver both superior corrosion and creep resistance.

The knowledge generated from this accomplishment reduces the materials barrier to successful commercialization of high-efficiency sCO<sub>2</sub> power cycles for nuclear, concentrated solar, and fossil-based power generation.



The Autoclave Reactor Is Used to Test Alloys in Flowing sCO<sub>2</sub> at Extremely High Temperatures and Pressures to Closely Simulate sCO<sub>2</sub> Power Cycle Environments



Ambient Pressure X-Ray Photoelectron Spectroscopy Was Used to Reveal Important Details of Alloy Degradation in Hot CO<sub>2</sub> by Analyzing the Reacting Alloy Surface in Situ

AWARD NUMBER  
**FWP-1022406**

## PROJECT BUDGET

FY21 FUNDING



● DOE .....\$3,200,000

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## FECM RDD&D PRIORITY



DEMONSTRATE AND  
DEPLOY POINT-SOURCE  
CARBON CAPTURE

# MULTIPHASE MODELING ACCELERATES DESIGN OF GASIFICATION PLANTS

Enabling future plants for conversion of multi-feedstocks into high-value hydrogen and other products.

## SIMULATION OF MIXED FEEDSTOCK GASIFIER

### NETL MFIX (Multiphase Flow with Interphase Exchanges) Capabilities Leveraged

NETL researchers used MFIX simulations to **model operating conditions in a gasifier** located at the University of Alaska, using a mixture of coal and biomass as a feedstock. The international collaboration with Italy's Sotacarbo Sustainable Research Centre **provides design and validation data required for future gasifier systems** using multi-material feedstock, helping to tailor future systems to site-specific needs.



Sotacarbo Pilot-Scale Moving Bed Gasifier

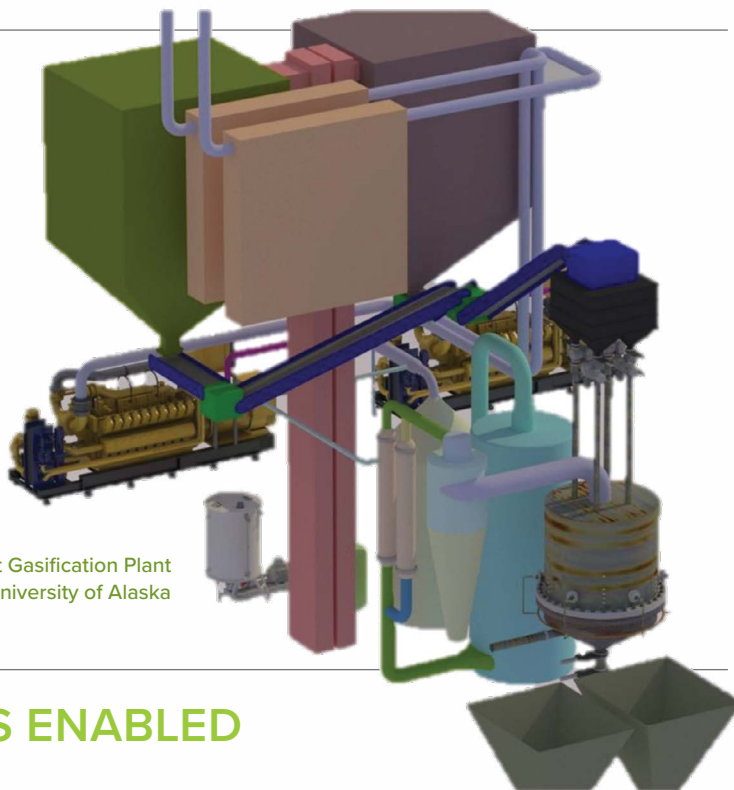


## ESTABLISHED PROTOTYPE VIABILITY FOR PLANT APPLICATION

### 22MW<sub>th</sub> prototype: candidate gasifier for Net-Zero Carbon and Hydrogen

Modeling results have demonstrated that gasifier syngas **closely matches plant engineering and design study requirements** for the University of Alaska gasification plant system. Transient behavior analysis showed that the gasifier responds well to load changes with syngas output **responding quickly, and with stable syngas composition**.

Concept Gasification Plant at University of Alaska



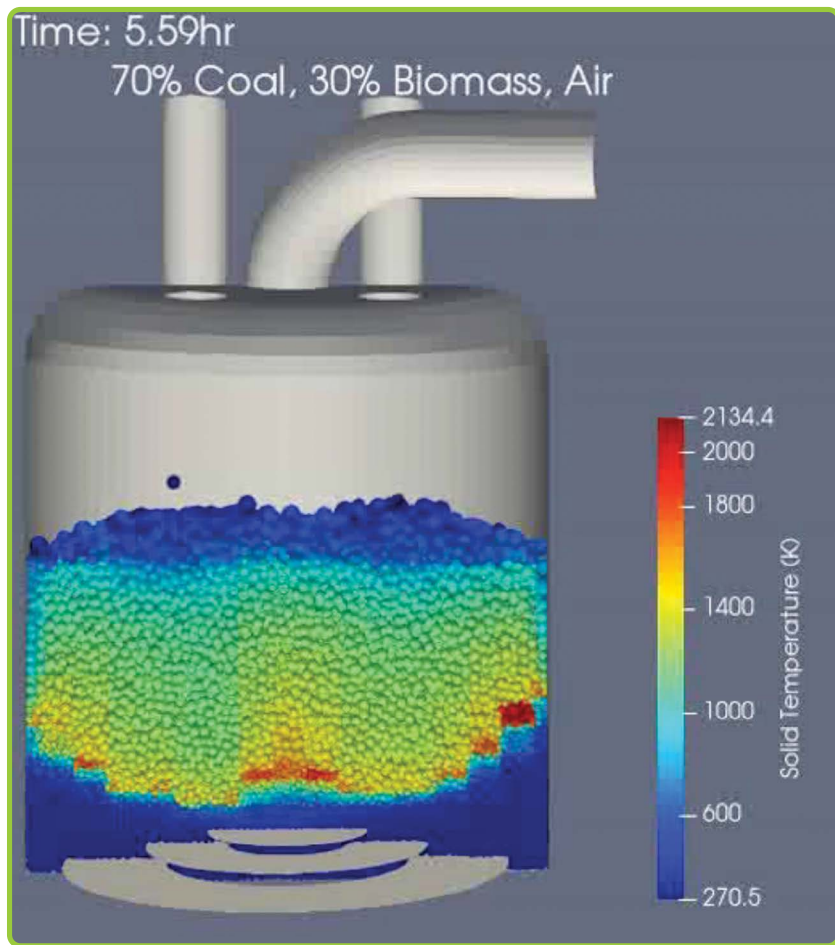
## SITE/SYSTEM-SPECIFIC DESIGNS ENABLED

### Customization to Isolated Communities

Gasification systems tailored to the resources and needs of isolated communities could enable **utilization of multi-feedstock mixtures** of biomass, waste coal, municipal solid waste, and plastic waste **to produce hydrogen, chemicals, electricity, and heat** as needed at the site or locale.

# PROTOTYPE DESIGN INVESTIGATED NET-ZERO CARBON, BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS), AND H<sub>2</sub> PRODUCTION

MFiX simulations have provided an understanding of the effects and challenges of **increasing biomass proportions in gasifiers** and showed gasifier adaptability to increasing oxygen enrichment with steam and carbon dioxide diluents. These findings provide **invaluable insight into gasifier behavior**, setting the stage for deployment of gasification systems with net-zero carbon emissions capability.



Gasifier Simulations with Mixed Coal-Biomass Feed

## PARTNERS



Hamilton Maurer International, Inc.

AWARD NUMBER  
**FWP-1022405**

## PROJECT BUDGET

FY21 FUNDING



● DOE .....\$753,000

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## FECM RDD&D PRIORITY



ACCELERATE CARBON-NEUTRAL HYDROGEN (H<sub>2</sub>)

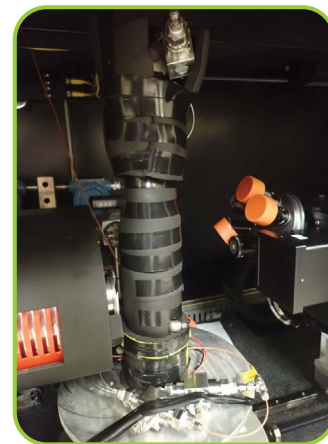
# PRESSURE-CORE ANALYSIS SYSTEM PROVES EFFECTIVE IN FIRST USE ON NATURAL HYDRATE SAMPLES FROM GULF OF MEXICO

NETL'S PCXT provides high-resolution 3D imaging and pore-scale analysis of hydrate field samples while maintaining natural, in-situ reservoir conditions.

## PRESSURE-CORE CHARACTERIZATION AND X-RAY VISUALIZATION TOOLS

Successful application of Pressure Core X-Ray Tool (PCXT) system on pressure cores retrieved from the Gulf of Mexico demonstrated:

- PCXT instrument suite can manipulate hydrate-bearing pressure cores and drill out subsamples while maintaining natural reservoir pressures.
- Specialized modules can measure core-scale and pore-scale physical properties while maintaining in-situ reservoir pressures.
- X-RAY CT scanning instrument creates high-resolution 3D core-scale and pore-scale images while preserving sample integrity.



PCXT Micro-CT Scanning Assembly



PCXT Sample Cutter and Manipulator



PCXT Chamber for Sub-Sampling and Transfer to Micro-CT

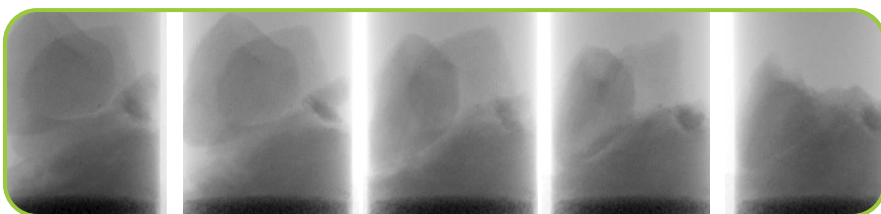


Adaptor for Micro-CT Chamber

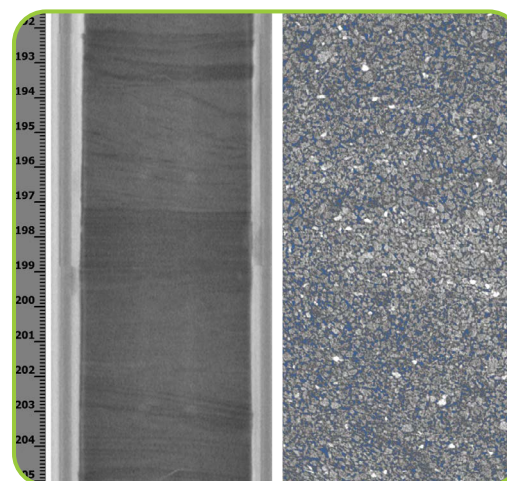
## PRESSURE CORES FROM NATURAL HYDRATE RESERVOIRS ARE DIFFICULT TO PRESERVE

Yet they provide the only direct samples of hydrate reservoirs

- Natural samples are delicate and degrade rapidly.
- Samples must be maintained at in-situ reservoir pressure and temperature to preserve natural structure.
- PCXT is the first tool capable of subsampling and imaging without destroying hydrate material or altering sample structure.



Left to Right: Progressive Degradation of Hydrate Subsamples Over 24-Hr Period, Showing Collapse of Internal Structure In Conventional Systems

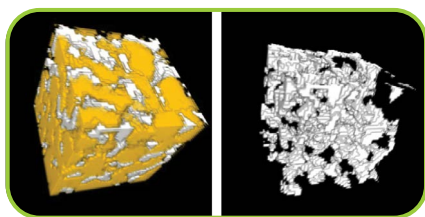
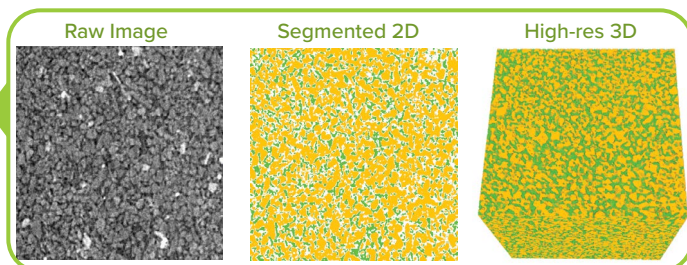


Pressure Core From Gulf of Mexico Showing Core-Scale Structure of Raw Sample (at Left) and High-Resolution X-Ray Ct Image of Completely Intact Pore-Scale Sediment/Hydrate Structure (at Right)

## PCXT MAINTAINS SAMPLE INTEGRITY AND ALLOWS PORE-SCALE VISUALIZATION

- PCXT system now proven on pressure-core samples retrieved from Gulf of Mexico.
- First-ever observation and visualization of pore-scale structure of hydrate crystal framework in natural samples.
- Image processing of pore-scale structure reveals mechanical grain support among hydrate crystals in 3D.

PCXT Image Processing Sequence: Green Is Hydrate and Yellow Is Sand



3D Cutout of Hydrate-Bearing Core (at Left) and 3D Skeletal Framework of Hydrate Crystals With Sand Removed (Right)

## LINKING PORE-SCALE AND CORE-SCALE MEASUREMENTS

- PCXT bridges the gap between core-scale and pore-scale observations.
- All imaging occurs at in-situ reservoir pressures.
- Subsampling occurs without destruction of hydrate-sediment structure.
- Results projected to reservoir scale to inform hydrate reservoir characterization and modeling efforts.



PCXT Anisotropic Permeability Chamber Measures Permeability in X, Y, and Z Directions

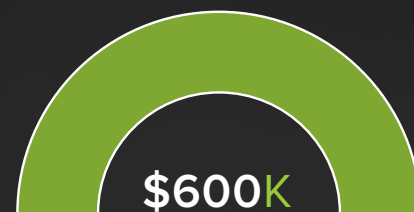
PCXT Triaxial Stress Chamber Measures Mechanical Strength at Core Scale



AWARD NUMBER  
**FWP-1022410**

PROJECT BUDGET

FY21 FUNDING



● DOE ..... \$600,000

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FECM RDD&D PRIORITY



INVEST IN THOUGHTFUL  
TRANSITION STRATEGIES

### PARTNERS



**Rensselaer**



# UNDERSTANDING CARBON STORAGE IN SHALES AFTER FLUID FRACTURING INJECTION, A POTENTIAL CARBON MANAGEMENT RESOURCE

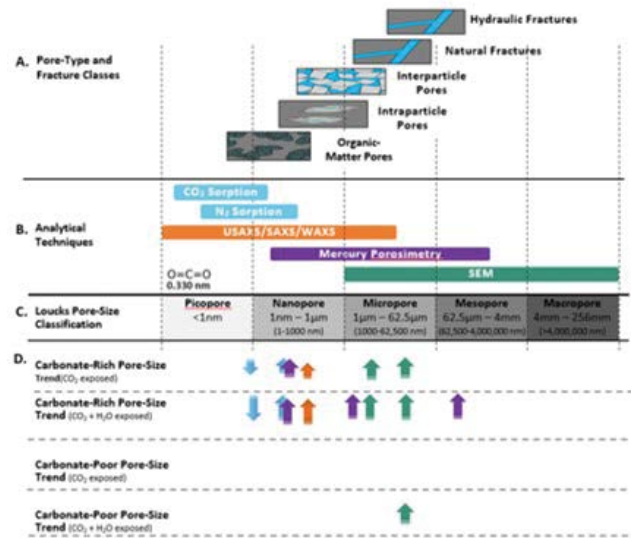
Carbon storage advanced research and development.

## EXPLORING WAYS TO PERMANENTLY STORE CO<sub>2</sub> IN SHALE AFTER OIL RECOVERY

NETL Research and Innovation Center researchers have shown that shales reacted with hydraulic fracturing fluid, followed by CO<sub>2</sub>, undergo carbonate dissolution and barite, gypsum, and carbonate precipitation under in-situ conditions.

**These changes lead to etching and pitting of the shale that increases micro-porosity, potentially increasing the ability of the shale to store CO<sub>2</sub>.**

Understanding the impact on CO<sub>2</sub> transport into the matrix is critical to understanding the potential of CO<sub>2</sub> storage in depleted shale reservoirs.



## ANALYSIS OF RESULTS SHOW SHALE COMPOSITION HAS A MAJOR EFFECT ON CO<sub>2</sub>-SHALE INTERACTIONS AND IMPACTS THE ABILITY TO STORE CO<sub>2</sub>

### Synthetically aged (30 days in synthetic fracturing fluid) and non-aged shale:

#### Non-Aged

- Pores decrease with CO<sub>2</sub> exposure.
- Pores increase with CO<sub>2</sub> + H<sub>2</sub>O exposure.

#### Carbonate content in shales:

##### Carbonate rich:

- Micro-scale porosity increases with CO<sub>2</sub> and CO<sub>2</sub>/H<sub>2</sub>O.
- Nano-scale porosity decreases with CO<sub>2</sub> and CO<sub>2</sub>/H<sub>2</sub>O.

##### Reactivity of CO<sub>2</sub> and impact on permeability:

- CO<sub>2</sub> did not promote significant reactivity with the shale if water was not present.
- Porosity and permeability increased in core shale samples after exposure to CO<sub>2</sub>-saturated-fluid due to dissolution of carbonate (no new or altered flow paths created; increased microporosity).
- Exposure to CO<sub>2</sub> and CO<sub>2</sub>-saturated-fluid did not alter the mechanical properties of the shale samples.
- No trend that could tie CO<sub>2</sub> or fluid reactivity to physical or chemical properties of the shale formations at the basin scale was observed.

#### Aged

- Pores decrease with CO<sub>2</sub> exposure and CO<sub>2</sub> + H<sub>2</sub>O exposure.

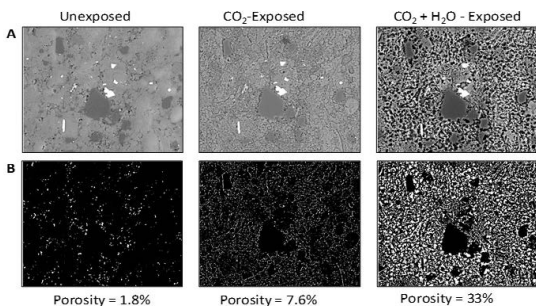
##### Carbonate poor:

- Increase in micro fracture abundance and size for both conditions.

# REACTIVITY OF CO<sub>2</sub> WITH UTICA, MARCELLUS, EAGLE FORD, AND BARNETT SHALES AND THE IMPACT ON PERMEABILITY

Researchers examined samples from three shale basins across the U.S. (Utica and Marcellus Shales in the Appalachian Basin, Barnett Shale in the Bend Arch-Ft. Worth Basin, and Eagle Ford in the Western Gulf Basin). Images below show conditions prior to exposure, after exposure to pressurized CO<sub>2</sub>, and after exposure to pressurized CO<sub>2</sub> (14 days) and water (14 days).

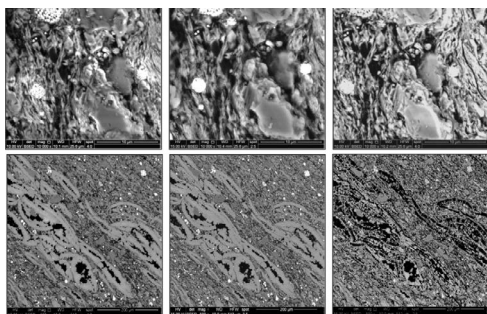
## Utica Shale



- Etching and pitting from CO<sub>2</sub> exposure.
- Increase in dissolution and porosity with exposure to CO<sub>2</sub> and H<sub>2</sub>O.

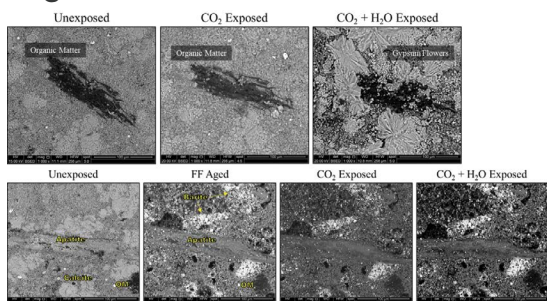
B: modified above image where porosity is white and solid space is black.

## Marcellus Shale



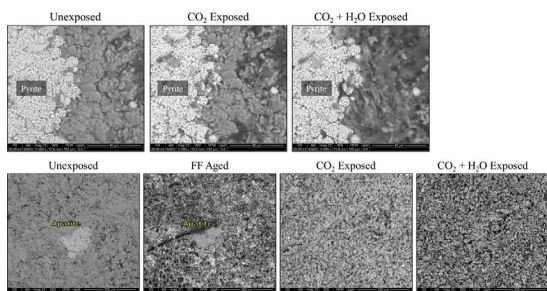
- Top: silicate rich shale, no etching and pitting.
- Bottom: gray carbonate veins are dissolved, causing etching and pitting.

## Eagle Ford Shale



- Top: organic matter reacts in CO<sub>2</sub> and H<sub>2</sub>O, precipitates gypsum/ dissolves carbonate.
- Bottom: hydraulic fracturing fluids etch and pit, precipitate barite.

## Barnett Shale



- Carbonate dissolution observed.
- No formation of gypsum (organic matter did not contain sulphur).

AWARD NUMBER  
**FWP-1022403**

## PROJECT BUDGET

TOTAL FUNDING



● DOE ..... \$948,000

## CONTACTS

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## FECM RDD&D PRIORITIES



DEMONSTRATE AND  
DEPLOY POINT-SOURCE  
CARBON CAPTURE



INVEST IN THOUGHTFUL  
TRANSITION STRATEGIES

# THE NATIONAL RISK ASSESSMENT PARTNERSHIP RECOMMENDS RISK REDUCTION AND MANAGEMENT PRACTICES FOR CARBON STORAGE SITES

Draft reports on recommended practices for risk-based decision support at geologic carbon storage sites released.

NRAP TRANSLATES RESEARCH COMPUTATIONAL TOOLS AND RECOMMENDED PRACTICES INTO INSIGHTS FOR MANAGING GEOLOGIC CARBON STORAGE RISK



## INSIGHTS

Yielding insights into risk management that support program goals to accelerate the safe and effective **commercial-scale deployment** of Carbon Capture and Storage.

## RECOMMENDED PRACTICES

- Developed two draft **recommended practices reports related to risk management for potential leakage and induced seismicity risks**.
- Released these reports for a period of public comment.

## TOOLS

- Developed and **publicly-released a toolset** for geologic storage risk quantification and monitoring design.
- Hosted at a recent **NRAP tools workshop**.

## RESEARCH

Research highlighted in an NRAP Virtual Special Issue of the *International Journal of Greenhouse Gas Control*.



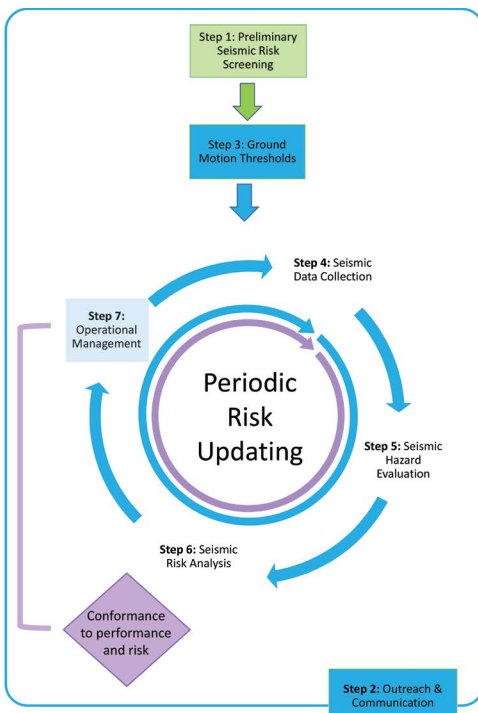
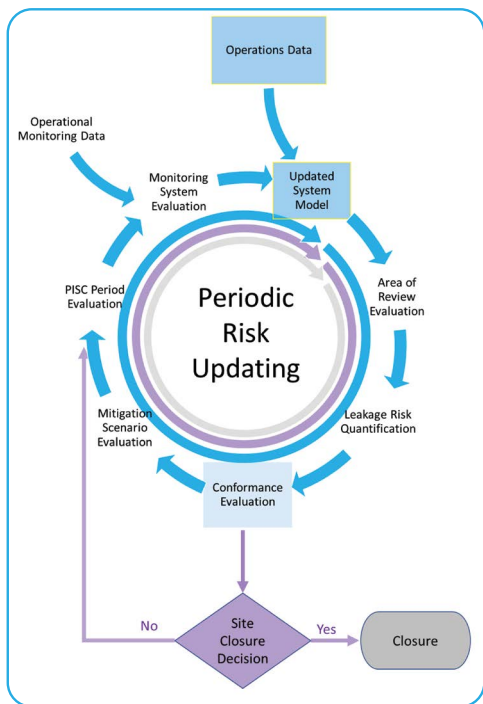
# ESTABLISHED WORK FLOWS TO ASSESS AND MANAGE RISKS AT GEOLOGIC CARBON STORAGE SITES FOR:

## CONTAINMENT ASSURANCE AND LEAKAGE RISK –

including aspects of site characterization, risk-based area of review determination, monitoring design, and site closure.

## POTENTIAL INDUCED SEISMICITY –

including aspects of seismic hazard evaluation, risk analysis, and support for operational management decisions.



Recommended practices for both containment assurance and induced seismicity risk management involve periodically updating the risk assessment during the operations and post-operations project phases. The periodic risk updates, based on operational and monitoring data, are used to ensure conformance and progress toward successful site closure.

AWARD NUMBER  
**FWP-1022407**

## PROJECT BUDGET

EY21 FUNDING



- DOE .....\$1,215,000
- PERFORMER.....\$3,560,000

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## FECM RDD&D PRIORITY



DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE

## PARTNERS



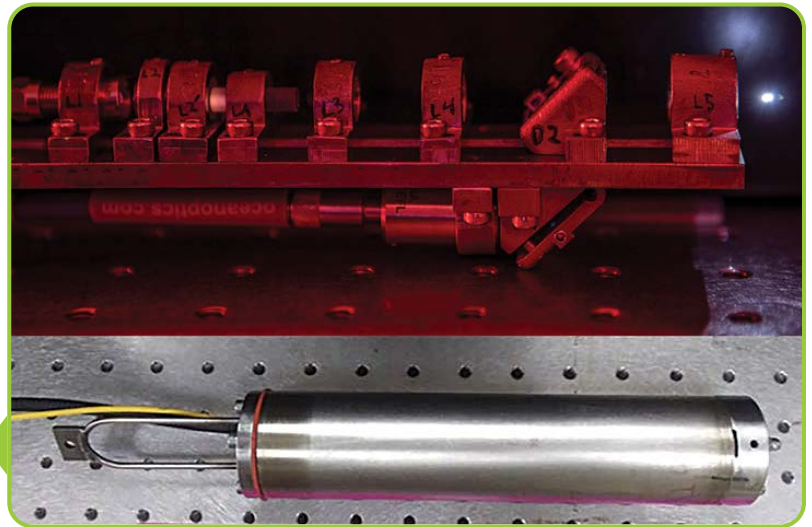
# NETL-DEVELOPED ADVANCED LASER-BASED TECHNOLOGY SUCCESSFULLY DEMONSTRATED

Advanced Sensors and Controls research supports chemical measurements in subterranean waters and brines relevant to carbon storage or legacy waste cleanup.

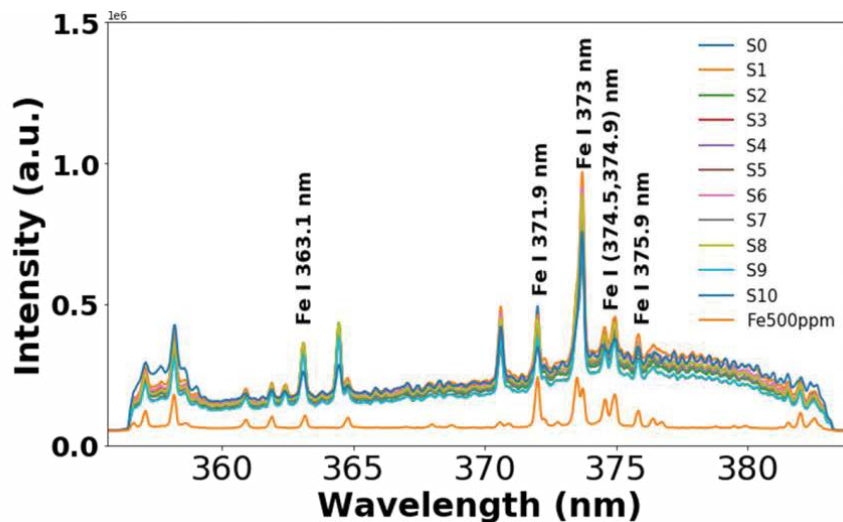
## ADVANCED LASER-BASED TECHNOLOGY ENABLES RAPID, PRECISE SUBSURFACE MONITORING

NETL researchers completed field testing of a subterranean laser induced breakdown spectroscopy (LIBS) system. The sensor enables efficient and reliable field analysis without removing samples from the well, which saves time and reduces cost. Applications include carbon storage, process monitoring, rare earth element detection, and environmental monitoring.

The LIBS Probe Features Simplified Construction, Reducing the Cost of the Laser Head and Maximizing the Amount and Quality of Light Returned for Analysis



The complete downhole LIBS prototype sensor system was successfully deployed in a test well at the NETL-MGN site at 27-ft well depth (15 ft water depth). Measurements were performed on 14 days over a 20-day period. Results demonstrate the full system works in the target environment without serious complication, which raises the technology readiness level to 5: Lab/bench scale, similar system validation in relevant environment.



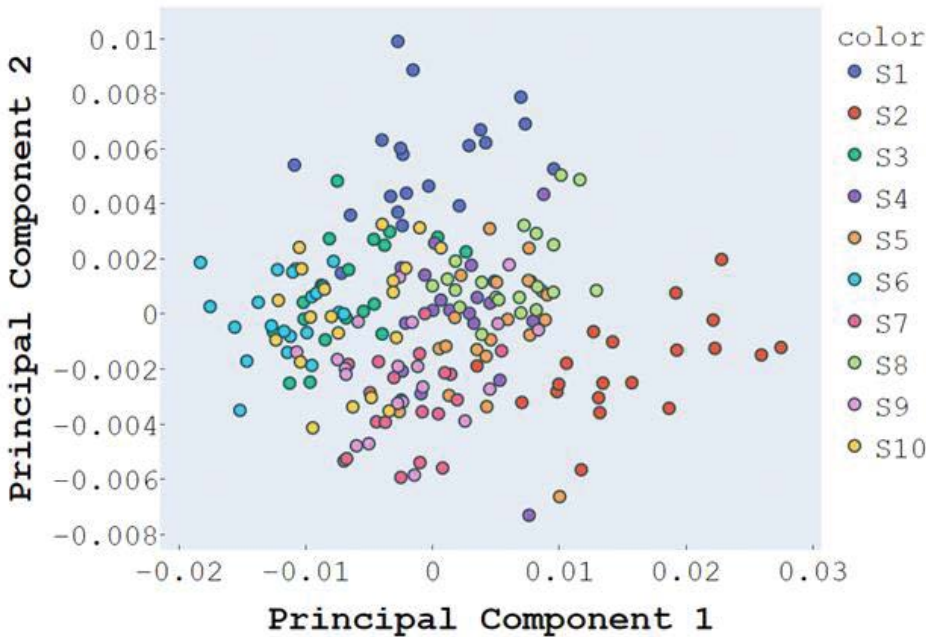
Samples	Water samples collected on
S0	19-Dec-19
S1	29-Sep-20
S2	30-Sep-20
S3	1-Oct-20
S4	2-Oct-20
S5	3-Oct-20
S6	4-Oct-20
S7	5-Oct-20
S8	6-Oct-20
S9	7-Oct-20
S10	8-Oct-20
Fe	500 PPM Fe

All samples contained 10% HNO<sub>3</sub>

Averaged LIBS Spectra from NETL-Morgantown B19 Water Samples and 500 ppm Fe Calibration Sample

## LIQUID SAMPLES SHOWED STRONG EMISSION LINES OF IRON IN LIBS SPECTRA

These results provided working experience with actual field water samples from water leaching of ash and insight into the sensitivity of the measurement approach to iron concentration with the submersible probe and water jet system.



Each Data Point in the Plot Represents One Libs Spectral Data Point of a Corresponding Sample, and Each Sample Has 20 Such Spectra

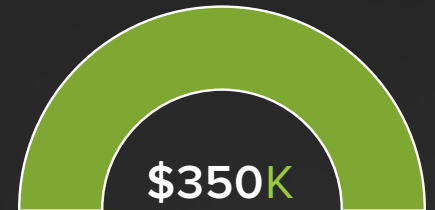
Creating new monitoring systems that yield quick and effective information, even under harsh conditions in the field, builds on NETL's mission to drive innovation and deliver solutions for an environmentally sustainable and prosperous energy future.

AWARD NUMBER  
**FWP-1022427**

**Task 71**

### PROJECT BUDGET

FY21 FUNDING



● DOE ..... \$350,000

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### FECM RDD&D PRIORITIES



DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE



ADVANCE CRITICAL MINERALS, RARE EARTH ELEMENTS (REE), AND MINE REMEDIATION



ADDRESS THE ENERGY WATER NEXUS

# WORLD-LEADING RESOURCE FOR CARBON STORAGE DATA

Visit [edx.netl.doe.gov](https://edx.netl.doe.gov) to explore carbon storage resources



## NETL'S ENERGY DATA EXCHANGE™ (EDX™) HAS CURATED ONE OF THE WORLD'S LARGEST COLLECTIONS OF OPEN-SOURCE CARBON STORAGE DATA RESOURCES

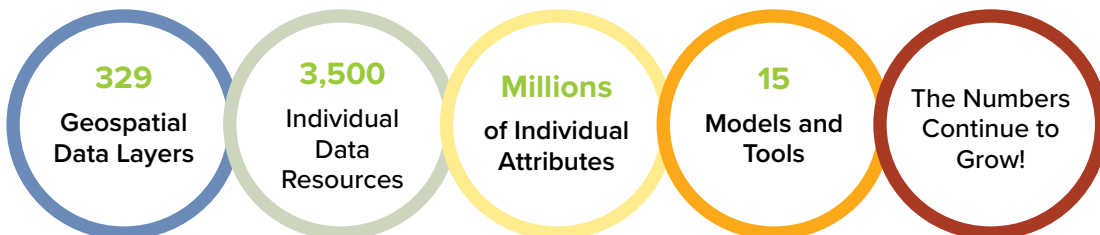
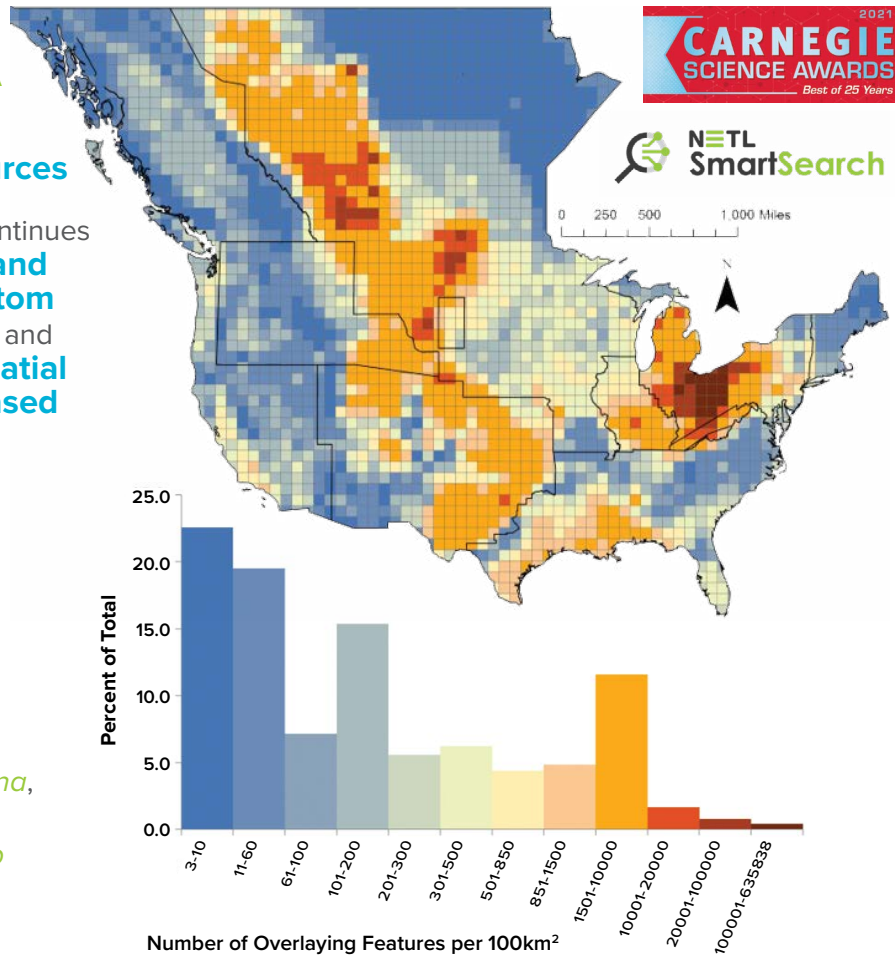
NETL systematically compiled and curated one of the **world's largest collections of open-source datasets, models, and tools for geologic carbon storage (CS) systems** utilizing award-winning deep learning and customized natural language processing (NLP) informed algorithms.

### DIVERSE OPEN-SOURCE CARBON STORAGE DATA COLLECTION

**EDX contains over 3,500 data resources** from the FECM Carbon Storage Program's partnerships and research projects. Data continues to grow as **new assets are submitted and currently includes more than 15 custom models and tools** and million of features and attributes. The collection consists of **geospatial data, well logs, seismic data, text-based resources, tools, models, and data catalogs that include both surface and subsurface geology.**

#### EDX Data Sources Include:

- National Carbon Sequestration Database (*NATCARB*).
- The Regional Carbon Sequestration Partnership (*RCSP*) data.
- Field projects, including *FutureGen 2.0*, the *Illinois Basin Decatur Project*, *Kimberlina*, and the *Appalachian Basin*.
- *The National Risk Assessment Partnership* data, models, and tools.
- *CarbonSAFE* field project data.
- Other open-source authoritative resources from the world-wide web (*SmartSearch*).



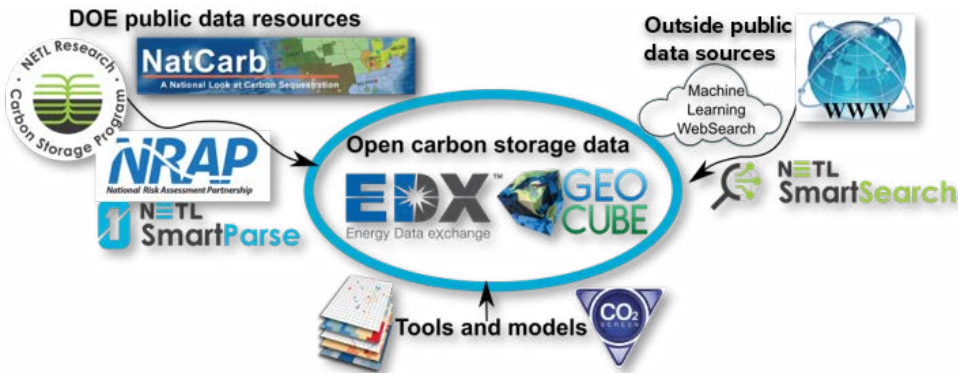
**VISIT THE OPEN CARBON STORAGE DATA COLLECTION:**

## ENSURING ACCESS TO CRITICAL DATASETS

Supporting DOE FECM's Carbon Storage Program by:

- Systematically curating NETL/FECM-funded research products.
- Using data science methods to improve access, discoverability, and reuse of these data resources using the *EDX platform* and the geospatial data mapping module, *GeoCube*.

The application of these EDX-driven artificial intelligence, machine learning, and NLP capabilities has **helped discover, label, and integrate additional carbon storage data resources while ensuring enduring access to the resources in the future.**



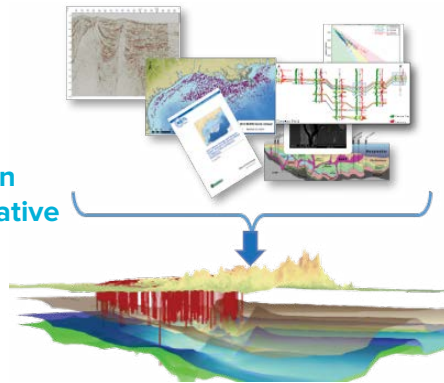
## CATALYZING THE CARBON STORAGE ECONOMY

Applications Using EDX's CS Data Volume to Support Net-Zero Carbon Emissions Goals:

- Site Screening
- Reservoir Modeling
- CCS Risk Modeling
- Storage Estimation

### Data Users

- State Geologic Surveys
- CarbonSAFE Projects
- Industry Groups (e.g., EPRI)
- Science-informed Machine Learning for Accelerating Real-Time Decisions in Subsurface Applications (SMART) Initiative
- National Risk Assessment Partnership
- Advancing ML/NLP Research



AWARD NUMBER  
**FWP-1022456**

### EDX STATISTICS



**17 EDX Groups** curating collections of carbon storage data

**100+TB of CS data** uploaded to EDX in last 12 months

**2,847 Registered** EDX Users

**2,161,826** total EDX downloads

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### FECM RDD&D PRIORITIES



**ADVANCE CARBON DIOXIDE REMOVAL AND LOW-CARBON SUPPLY CHAINS**



**DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE**



**INCREASE EFFICIENT USE OF BIG DATA AND ARTIFICIAL INTELLIGENCE**



**INVEST IN THOUGHTFUL TRANSITION STRATEGIES**



**LOW-CARBON INDUSTRIAL SUPPLY CHAINS**

### PARTNERS

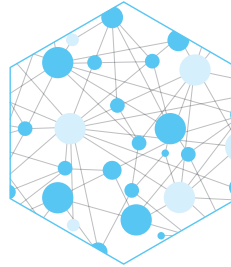


# IDAES LEADING DEVELOPMENT OF INTEGRATED ENERGY SYSTEMS OF THE FUTURE

Enabling integration of carbon management and green hydrogen into the future energy mix.

The Institute for the Design of Advanced Energy Systems (IDAES) Integrated Platform **accelerates cost-effective technology deployment needed to support critical DOE missions.**

IDAES enables the design and optimization of complex, interacting technologies and systems by providing **rigorous modeling** capabilities to **increase efficiency, lower costs, improve sustainability, and reduce uncertainty** of power generation and electricity distribution.



# IDAES

Institute for the Design of Advanced Energy Systems

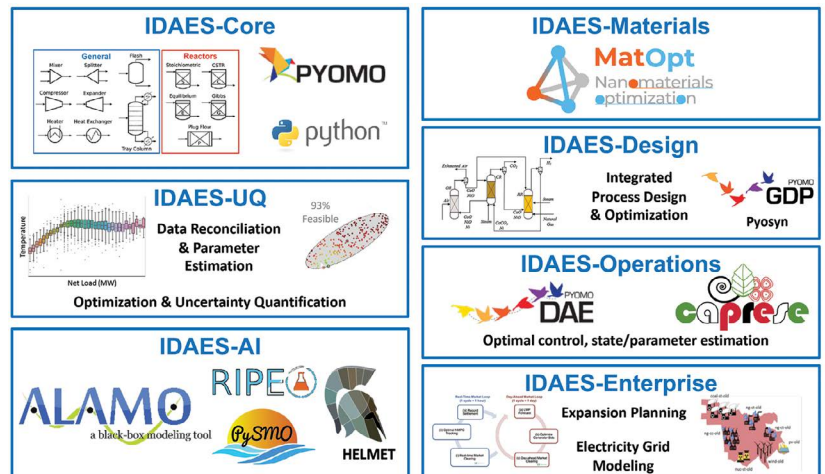
## NEXT-GENERATION COMPUTATIONAL FRAMEWORK

IDAES builds on fundamental advances in algorithms and computing technology to address a critical capability gap in process modeling tools.

The IDAES Integrated Platform includes tools for the **large-scale optimization** of **complex dynamic systems, machine learning, and uncertainty quantification.**

IDAES was the winner of a prestigious **2020 R&D 100 award.**

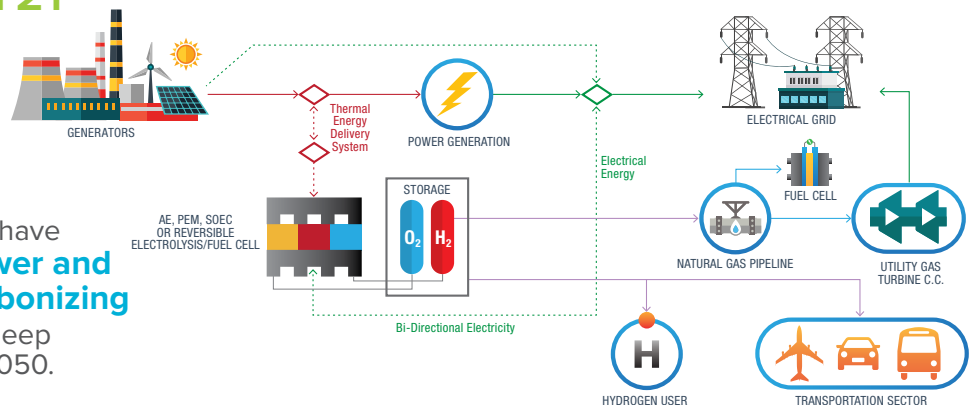
## The IDAES Integrated Platform



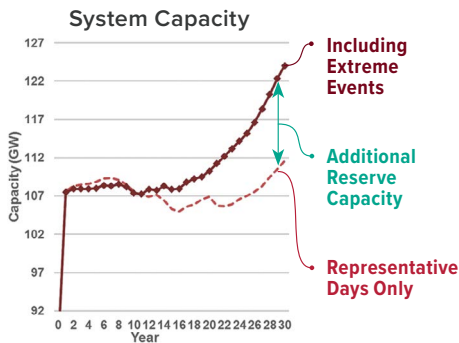
## MODELING THE ENERGY SYSTEMS OF THE FUTURE IN FY21

### Integrated Energy Systems

The IDAES platform is being applied to explore how tightly coupled **integrated energy systems** that have the flexibility to **produce both power and hydrogen** can help facilitate **decarbonizing the power sector by 2035** and deep decarbonization of the economy by 2050.



# PLANNING FOR EXTREME EVENTS



Traditional expansion planning could **fail to include sufficient reserve capacity** for extreme events. Inclusion of extreme events in the expansion planning models **ensures sufficient reserves** are available.

# REDUCING TECHNICAL RISK

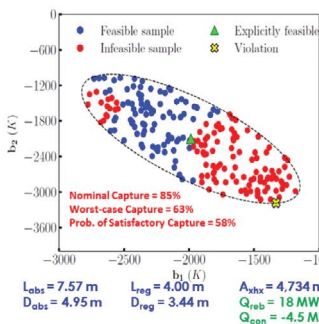
Uncertainty is inherent in process designs:

- Operational uncertainty
- Economic uncertainty
- Epistemic uncertainty

IDAES is applying state-of-the-art, **robust optimization tools** that enable **performance guarantees** despite uncertainty.

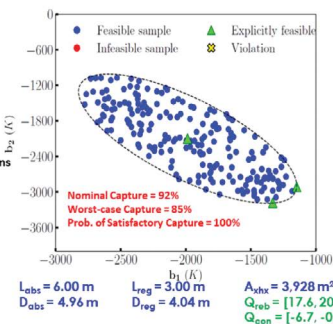
## Deterministic Solution

Cost: \$7.25 MM/yr  
Second-stage Cost: \$5.19 MM/yr



## Robust Solution

Cost: \$10.90 MM/yr  
Expected Second-stage Cost: \$5.51 MM/yr



**DETERMINISTIC DESIGN** fails to meet CO<sub>2</sub> capture performance requirement with a 33% probability.

**ROBUST DESIGN** guarantees CO<sub>2</sub> capture in all scenarios; cost increase is kept to the minimum necessary to achieve this.

**ROBUSTNESS ACHIEVED** utilizes smaller equipment overall, putting more emphasis on reboiler and condenser duty control.

# ONGOING DEVELOPMENT

IDAES had **four software releases** during FY21. Key new features include:

- **Dynamic Energy Systems** model library
- **Uncertainty Quantification** toolbox
- **Model Diagnostics and Troubleshooting** toolbox

## PARTNERS

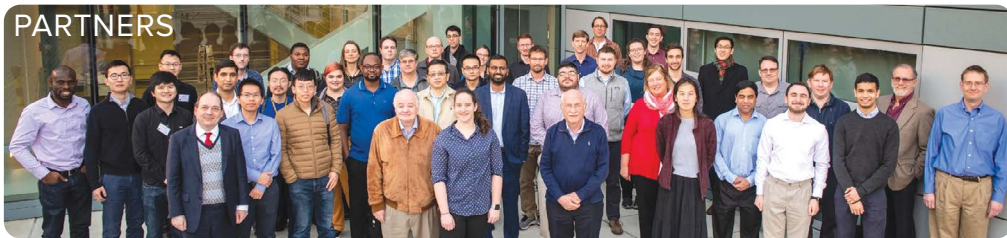


Photo taken prior to COVID-19 protocol requirements



## AWARD NUMBERS

FWP-1022423, FWP-1022476,  
FWP-1022460, FWP-1022461

## PROJECT BUDGET

FY21 FUNDING



- DOE ..... \$2,574,000
- PERFORMERS ..... \$4,503,000

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**NICK SAHINIDIS**

## FECM RDD&D PRIORITIES



**DEMONSTRATE AND DEPLOY POINT-SOURCE CARBON CAPTURE**



**ACCELERATE CARBON-NEUTRAL HYDROGEN (H<sub>2</sub>)**



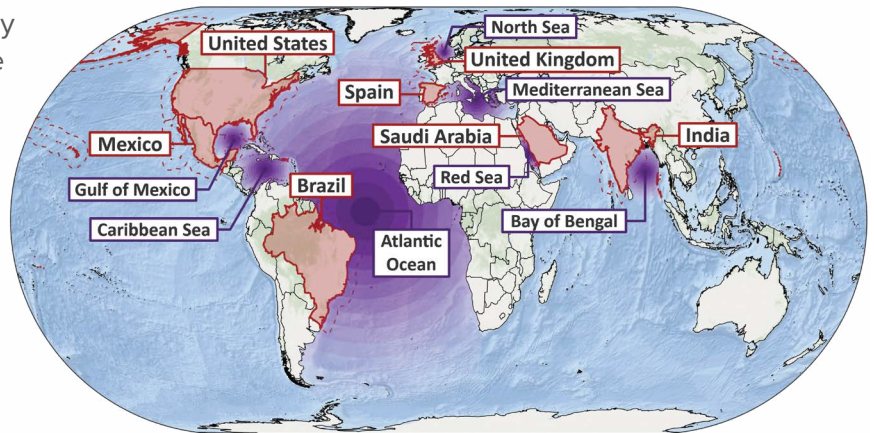
**INCREASE EFFICIENT USE OF BIG DATA AND ARTIFICIAL INTELLIGENCE**

# NETL'S AWARD-WINNING CLIMATE AND RISK FORECASTING MODEL GARNERS INTERNATIONAL ADOPTION



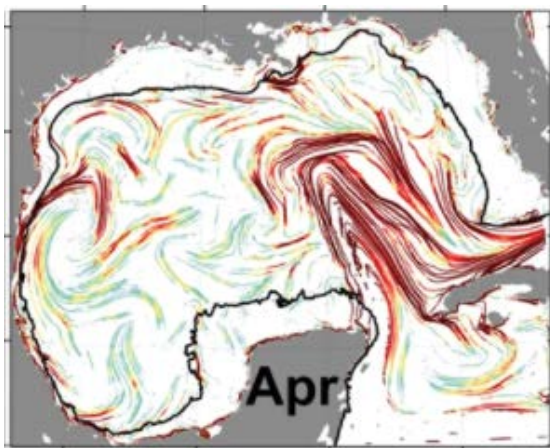
## CLIMATOLOGICAL AND INSTANTANEOUS ISOLATION AND ATTRACTION MODEL (CIAM) APPLIED TO INTERNATIONAL WATERS FOR TRANSPORT MODELING

Since its release in 2018, simulations using NETL's CIAM, a metocean model, have been used by teams worldwide to aid in the rapid and more accurate forecasting of ocean-current pathways. These forecasts have proven *beneficial* and *innovative* for a variety of applications beyond their energy-environment origins within *NETL's Offshore Spill Prevention Research Portfolio*. To date, CIAM has been **applied by ten external research groups to international offshore regions** to address the topics highlighted in the infographic below.



CIAM IS USED TO UNDERSTAND AND ANTICIPATE TRANSPORTATION OF:	Oil Spills	Derelict Vessels	Sediment	Marine Larvae	Search & Rescue Ops
	Red Tides	Sargassum	Flotsam	Climate-Change Induced Pathway Shifts	Current-Induced Stress Regions

## IDENTIFYING PREDOMINANT METOCEAN TRANSPORT FOR RISK ASSESSMENT



A CiAM Output for Conditions in April in the Gulf of Mexico Shows Areas of Strong Attraction (Red Lines) and Isolation (White Areas)

Using advanced mathematical and oceanographic theoretical developments, CIAM **efficiently extracts ocean current and wind pathways as well as transport behavior from large datasets**. This information:

- Improves the understanding of transport within areas under review.
- Is used to extract the main patterns from large data sets.
- Provides general and accurate guidelines for scientists and policymakers to understand a complex system.

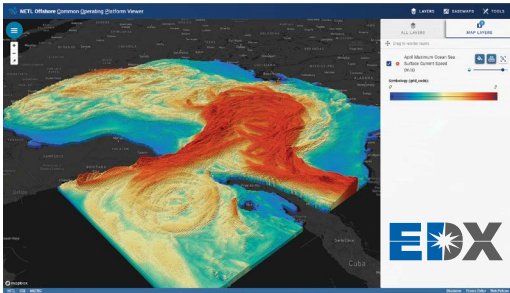
CIAM results from a Gulf of Mexico application were published in the prestigious journal, *Nature Scientific Reports*.



# CLIMATE MODELING FOR IMPROVED OFFSHORE SPILL PREVENTION

## Comprehensive Environmental Hazard Assessment

CIAM, a component of NETL's award-winning *Offshore Risk Modeling Suite (ORM)*, is being **integrated into multiple software and online tools**, including NETL's *Common Operating Platform*, making it accessible for integrated analyses. As a component of the ORM, CIAM offers users the ability to:



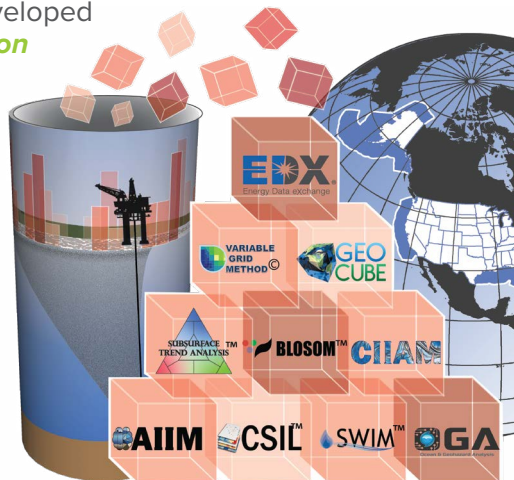
- Improve their understanding of conditions that may lead to oil spills or endanger safe operations.
- Inform socially and environmentally prudent development.
- Forecast pathways adapted to changing conditions and more extreme weather events.

The ORM suite:

- Provides a *comprehensive framework for future predictions, analyses, visualizations for oil spill prevention, and better-informed offshore operations.*
- Offers tools and models that can be used *individually or synergistically*, allowing **flexibility to evaluate an area or item of interest within the context of the full offshore system.**

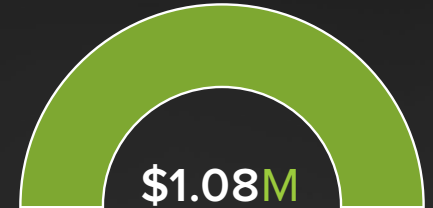
The ORM suite is a group of tools developed under NETL's *Offshore Spill Prevention Research Portfolio*, which encompasses projects that focus on innovative solutions to solve challenges associated with:

- Oil spill prevention
- Hazard prediction
- Geohazard and subsurface uncertainty reduction
- Infrastructure integrity and optimization for new and existing infrastructure systems



AWARD NUMBER  
**FWP-1022409**

PROJECT BUDGET  
TASK 6



● DOE .....\$1,080,000

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**KELLY ROSE**

## FECM RDD&D PRIORITIES



INVEST IN THOUGHTFUL  
TRANSITION STRATEGIES

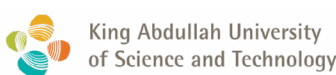


INCREASE EFFICIENT USE  
OF BIG DATA AND ARTIFICIAL  
INTELLIGENCE



REDUCE METHANE EMISSIONS

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626 Cochrans Mill Road  
P.O. Box 10940  
**Pittsburgh, PA** 15236  
412-386-4687

Program staff are also located in  
**Houston, TX** and **Anchorage, AK**

**CUSTOMER SERVICE**  
1-800-553-7681

**[www.NETL.DOE.gov](http://www.NETL.DOE.gov)**