Objective: Building tools and improving the science base to address key questions related to environmental impacts from potential release of CO$_2$ or brine from the storage reservoir, and potential ground-motion impacts due to injection of CO$_2$. 
NRAP Phase I Accomplishments

Assessing environmental risk and quantifying uncertainties in risk performance at CO₂ storage sites

• Generated the first publicly available quantitative, site-specific risk profiles for a complete CO₂ storage system

• Created the first comprehensive risk model for induced seismicity

• Characterized the behavior of key risk metrics associated with pressure and plume sizes for a wide variety of reservoir conditions

• Developed a toolset used to address leakage impacts and ground motion from underground storage of CO₂

• Developed and applied a novel approach for using reduced-order modeling to quantify uncertainty in subsurface systems

• Identified no-impact thresholds for groundwater quality

• Reduced uncertainty in understanding leakage pathways through experimental studies
NRAP Phase I Products

Virtual Special Issue of *International Journal of Greenhouse Gas Control* with 54 articles considering aspects of:

- Reservoir response and plume evolution.
- Fluid migration through leakage pathways.
- Groundwater impacts.
- Atmospheric leakage.
- System integrated assessment.
- Strategic monitoring.
- Ground motion/induced seismicity.

Using Science-Based Prediction to Probe Reservoir Behavior

NRAP Tools Available at: www.edx.netl.doe.gov/nrap
NRAP Phase II Technical Focus

Managing environmental risk and reducing uncertainties in risk performance at CO$_2$ storage sites

• Containment assurance
• Induced seismicity risk
• Strategic monitoring for better system design
• Applying and validating risk assessment tools and methodologies using synthetic and field data
Developing robust, science-based workflows and software tools to:

- **predict** containment effectiveness and leakage risk
- **evaluate** the effectiveness of leakage risk monitoring, management, and mitigation.

- **NRAP OpenIAM now in Beta testing.**
- **Workflows release target August 2019.**
Next-generation Integrated Assessment Model (NRAP-OpenIAM)

Combined ensemble and statistical visualization of system model output

Graphic representation of system model parameter/output correlations

Building confidence in GCS Conformance using robust decision analysis

Building confidence in PISC by plume stability analysis

Constraining system model output and reducing uncertainty by model updating using MCMC

Evaluating the uncertainty of plume stability through ensemble analysis

- Plume mobility
- Plume spreading

Volume of aquifer above TDS threshold (m³)

Time (years)

Pearson correlation

Conformance (Robustness)

Plume mobility

Plume spreading

2D map of plume

Uₚₐᵣᵢₙ

Uᵢₚₒᵣₜₜ

Prior

Posterior

Density

Log₁₀ brine leakage rate (kg/s)

Log₁₀ brine leakage rate (kg/s)

CDF
Developing practical tools to assess and manage induced seismicity risk at carbon storage sites and identify site characteristics and operational approaches to lower seismic risk.

- Probabilistic seismic risk forecasting tool generated.
- State of Stress tool available.
Induced Seismicity Risk Tool Catalog

State-of-Stress Assessment Tool

Joint probability for $\sigma_H$ and $\sigma_H$

Probability of activating critically-oriented fault

Short Term Seismic Forecasting (STSF) Tool

Probabilistic Seismic Risk Assessment Tool

Ground motion functions

- Empirical GMPEs
- Empirical Green's Fns
- Analytical Green's Fns
- Numerical modeling

Risk Curves
Developing insights, methods, and tools to understand the ability of monitoring technologies to detect system behavior, in the context of uncertainties in system features, events, and processes.

- Version 2 monitoring design tool DREAM (beta) released.
- DREAM v2 ERT module Beta released
- Considers both remote and point source monitoring parameters
- More flexible user input including compatibility with NRAP-OpenIAM output

Risk-Based Monitoring Network Design

Probability of detection using monitoring response

Proposed monitoring well locations

Two-stage monitoring design solution

Toward an adaptive monitoring design for leakage risk – Closing the loop of monitoring and modeling

Yu-Mei Yang,*, Robert M. Dilmore, Grant S. Bronnibil, Mitchell J. Small
Validation and Use of Risk Assessment Tools and Methodologies

Enabling the adoption of NRAP tools and methods for large-field demonstration projects and validating the tools and the science-based risk assessment approach.

• **Tools used in >15 planned or existing projects**
  – 7 CarbonSAFE projects; CaMi, IBDP, Farnsworth, OK water injection, ITRI, and more

CaMI Field Test Site

FutureGen 2.0 Risk-Based AOR
Using a risk-based approach to justify closure at a GCS site

Purpose: To provide a technical basis for a cost-effective and safe closure of GCS projects, using a risk-based approach as opposed to a default monitoring period.

Key Learnings:
• Monitoring during injection yields a better understanding of reservoir performance and builds confidence in safe, long-term storage.
• Drivers for leakage decrease once injection stops.
• PISC period can be reduced for many storage reservoir systems.
Thanks!

www.edx.netl.doe.gov/nrap
NRAP@netl.doe.gov
Additional Workflows

Risk assessment use cases

Monitoring design use cases

Conformance evaluation use cases
  Initial risk assessment

Updated risk assessment

- Monitoring Data
# State-of-Stress Assessment Tool (SoSAT)

## Input data available
- Pore pressure
- Overburden density

## Joint probability for $\sigma_H$ and $\sigma_h$

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<thead>
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<th>$\sigma_H$ (MPa)</th>
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## Probability of activating critically-oriented fault

- Regional stress indicators
- Geodetic data

## Local measurement of $\sigma_h$

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Probabilistic Seismic Risk Assessment Tool (RiskCat)

Carbon Storage Program

MISSION
Ensure Permanence – Protect Environment – Facilitate Awareness – Improve Storage Efficiency – Commercial-Readiness by 2030

Program Approach & Technical Accomplishments

<table>
<thead>
<tr>
<th>ADVANCED STORAGE</th>
<th>STORAGE INFRASTRUCTURE</th>
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<tr>
<td>Monitoring, Verification, and Accounting</td>
<td>Onshore and Offshore Characterization, Brine Extraction Storage Tests (BEST), and CarbonSAFE</td>
</tr>
<tr>
<td>Geologic Storage, Simulation, and Risk Assessment</td>
<td>Regional Carbon Sequestration Partnership Initiative</td>
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Risk and Integration Tools

For more information, please visit the Carbon Storage Program web page at: https://www.netl.doe.gov/coal/carbon-storage

– NETL – Industry – Universities – National Labs –
Using Science-Based Prediction to Probe Reservoir Behavior and the Reservoir Evaluation and Visualization (REV) tool

- **Size of CO₂ plume injection**
  - Rate of growth for early phase
  - Rate of growth for long-term phase
  - Plume radius at end of injection

- **Size of pressure plume**
  - Maximum size of plume
  - Various pressure thresholds, relevant
    - Brine rise
    - Fault-slip criteria

- **Pressure at a location**
  - Maximum pressure increase

---

**Size of CO₂ Plume**

- $m_1$: growth rate for early phase
- $m_2$: growth rate for long-term phase
- $R_i$: plume size (radius) at end of injection

**Size of Pressure Plume**

- $R_{\text{max}}$: maximum size of plume
  - for a specific pressure increase

**Pressure at a Location**

- $\Delta P_{\text{max}}$: maximum pressure increase
- $t_{0.5}$: time for pressure to decay to 0.5$\Delta P_{\text{max}}$
Demirkanli, Bacon, White, Risk-based Area of Review (AoR) Determination for a Deep-Saline Carbon Storage Site Using National Risk Assessment Partnership’s Open-Source Integrated Assessment Model (NRAP-IAM-CS v2)." submitted to IJGGC

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Harp, D., Ohishi, T., Chu, S., Chen, S., Pawar, R. Development of quantitative metrics of plume migration at geologic CO₂ storage sites. submitted to Greenhouse Gas Science


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