# Carbon Storage Program Research and Development Needs Workshop Report

## Final Report
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**Prepared By:**

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## Disclaimer

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# List of Acronyms and Abbreviations

| **Acronym/Abbreviation** | **Definition** |
|---|---|
| AOR | Area of Review |
| ARRA | American Recovery and Reinvestment Act |
| BPMs | Best Practice Manuals |
| CCS | Carbon Capture and Storage |
| $CO_2$ | Carbon Dioxide |
| CSLF | Carbon Sequestration Leadership Forum |
| DAS | Distributed Acoustic Sensing |
| DOE | U.S. Department of Energy |
| DTPS | Distributed Thermal Perturbation Sensing |
| DTS | Distributed Temperature Sensing |
| EM | Electromagnetic |
| EOR | Enhanced Oil Recovery |
| EPA | U.S. Environmental Protection Agency |
| FE | Office of Fossil Energy |
| FEPs | Features, Events, and Processes |
| GHG | Greenhouse Gas |
| IEAGHG | International Energy Agency Greenhouse Gas Program |
| IPCC | Intergovernmental Panel on Climate Change |
| MEMS | Micro-Electro-Mechanical Systems |
| MVA | Monitoring, Verification, and Accounting |
| NACAP | North American Carbon Atlas Partnership |
| NETL | National Energy Technology Laboratory |
| ORD | Office of Research and Development |
| R&D | Research and Development |
| RCSPs | Regional Carbon Sequestration Partnerships |
| SDWA | Safe Drinking Water Act |
| Sim-Risk | Simulation and Risk Assessment |
| THMC | Thermal, Hydrologic, Mechanical, and Chemical |
| UIC | Underground Injection Control |
| ZERT | Zero Emissions Research and Technology Center |

# Background

Fossil fuels are considered the most dependable, cost-effective energy source in the world. The availability of these fuels to provide clean, affordable energy is essential for domestic and global prosperity and security well into the 21st century. However, a balance is needed between energy security and increasing concerns over the impacts due to increasing concentrations of greenhouse gases (GHGs) in the atmosphere – particularly carbon dioxide ($CO_2$). At present, roughly one-third of the $CO_2$ emissions in the United States come from power plants. A combined portfolio of carbon management options can be implemented to manage current emission levels while enhancing energy security and building the technologies and knowledge base for export to other countries faced with reducing emissions. The U.S. portfolio includes: (1) use fuels with reduced carbon intensity – renewables, nuclear, and natural gas; (2) adopt more efficient technologies on both the energy demand and supply sides; and (3) use carbon capture and storage (CCS) technology. CCS is a viable emission management option because numerous studies have shown that it can account for up to 55 percent of the emissions mitigation needed to stabilize and ultimately reduce concentrations of $CO_2$.

The U.S. Department of Energy (DOE) launched its CCS Program in 1997 after holding a stakeholders workshop to obtain feedback from the technical and commercial sectors on its draft research plan. Advice was solicited from participants on their perspectives for priorities for the research and development (R&D) program.

CCS continues to be a key element of DOE’s R&D portfolio. Implemented by the National Energy Technology Laboratory (NETL) within DOE’s Office of Fossil Energy (FE), the program is playing a lead role in CCS technology development and has made significant advances in the development of a broad range of effective and economically viable technologies. The DOE program is being implemented through a Carbon Capture Program and Carbon Storage Program within FE.

## Overall Carbon Storage Program Goals and Objectives

The overall objective of the Carbon Storage Program is to develop and advance technologies that will be ready for widespread commercial deployment by 2020. To accomplish widespread deployment, three program goals have been established: (1) develop technologies that will support industries’ ability to predict $CO_2$ storage capacity in geologic formations to within ±30 percent by 2015; (2) develop technologies to demonstrate that 99 percent of injected $CO_2$ remains in the injection zones by 2015; (3) and complete Best Practices Manuals (BPMs) for site selection, characterization, site operations, and closure practices by 2020. Only by accomplishing these goals will CCS technologies be ready for safe, effective commercial deployment both domestically and abroad beginning in 2020 and through the next several decades.

The CCS Program directly supports the Interagency Task Force on CCS. Comprised of 14 Executive Departments and Federal Agencies, the Interagency Task Force on CCS delivered a series of recommendations to President Obama in August 2010 for overcoming the barriers to the widespread, cost-effective deployment of CCS within 10 years (http://www.fossil.energy.gov/programs/sequestration/ccstf/CCSTaskForceReport2010.pdf). The Task Force is co-chaired by DOE and the U.S. Environmental Protection Agency (EPA).

## Carbon Storage Program Structure

Since 1997, DOE's Carbon Sequestration Program has significantly advanced the CCS knowledge base in selected technology areas through a diverse portfolio of applied research projects. The portfolio includes cost-shared, industry-led, technology development projects; university research grants; collaborative work with other national laboratories; and research conducted in-house through NETL's Office of Research and Development (ORD). The Carbon Storage Program is comprised of three principal elements:

***Core R&D –*** The *Core R&D* element involves both applied laboratory- and pilot-scale research focused on developing new technologies and systems for GHG mitigation. *Core R&D* encompasses four technical focus areas for CCS technology and protocol development:

1. Geologic Storage
2. Monitoring, Verification, and Accounting (MVA)
3. Simulation and Risk Assessment
4. $CO_2$ Utilization

***Infrastructure –*** The *Infrastructure R&D* element involves confirmation of $CO_2$ storage approaches through activities such as the seven Regional Carbon Sequestration Partnerships (RCSPs), which are conducting field tests, engaging regional stakeholders, and characterizing opportunities for $CO_2$ storage in their regions. The 19 small-scale and eight large-scale field projects implemented by the RCSPs involve site selection, $CO_2$ injection into different geologic storage formation classes, monitoring, public outreach, and regulatory compliance. Other focus areas within the *Infrastructure R&D* element include other small- and large-scale projects, American Recovery and Reinvestment Act (ARRA)-funded technology transfer centers, and ARRA-funded site characterization projects that focus on characterizing geologic storage formations that offer opportunities for power plants and other industrial facilities to store large volumes of $CO_2$.

***Global Collaborations –*** The United States views international engagement as an important component of our approach to responding to climate change. Accordingly, DOE is partnering with several international organizations, such as the International Energy Agency's Greenhouse Gas Programme (IEAGHG), the Carbon Sequestration Leadership Forum (CSLF), and the North American Carbon Atlas Partnership (NACAP). DOE is also directly engaged in a number of large-scale CCS demonstration projects around the world, spanning five continents.

## Detailed Program Goals and Objectives

***Geological Storage Research Goals –*** Geologic systems are capable of storing $CO_2$ and hydrocarbons for millions of years. DOE is supporting the development of tools and protocols to improve the ability to predict future capacity in closed and open geologic systems within +30 percent, assess and minimize the impacts of $CO_2$ and co-contaminants on geophysical processes, and develop remediation technologies that will prevent or reduce possible releases through existing wellbores and natural pathways. The geologic storage element of the Carbon Storage Program looks to support research that will better our scientific understanding, including:

- Wellbore technologies.
- Remediation technologies.
- Fluid flow.
- Pressure and brine management.
- Geomechanical and geochemical processes.

***Monitoring, Verification and Accounting (MVA) Research Goals –*** The CCS Program is sponsoring the development of technologies and protocols by 2020 that are broadly applicable in different geologic storage classes and have sufficient accuracy to account for greater than 99 percent of all injected $CO_2$. MVA tools will help in the development of one of DOE's goals to quantify storage capacity within ±30 percent accuracy. Research conducted in this focus area includes developing and integrating:

- Atmospheric monitoring technologies.
- Remote sensing and near-surface monitoring technologies.
- Subsurface monitoring technologies in and near the injection zone.
- Design of intelligent monitoring networks and monitoring protocols.

***Goals for Simulation and Risk Assessment –*** As carbon storage capacity increases and projects become commercial beyond 2020, the importance of accurate geologic models and robust risk assessment protocols will become increasingly important to project developers, regulators, and other stakeholders. A major goal of the Carbon Storage Program is to continue improvements to simulation tools and risk assessment protocols through research, including:

- Thermal and hydrologic fate and transport.
- Geochemical simulations.
- Geomechanical simulations.
- Predicting biologic impacts on storage formations.
- Risk assessment and quantification.

***$CO_2$ Utilization Goals –*** Although permanent $CO_2$ storage in geologic formations looks promising as an option for reducing $CO_2$ emissions, this approach may not be viable for all $CO_2$ emitters and could result in minimal economic benefit at significant cost. Therefore, it is highly desirable to develop alternatives that can use captured $CO_2$ or convert it to a useful product, such as a fuel, chemical, or plastic, with revenue from the $CO_2$ use offsetting a portion of the $CO_2$ capture cost.

***New/Additional Carbon Storage Program Drivers –*** In November 2010, EPA finalized requirements for geologic storage of $CO_2$, including the development of a new class of wells, Class VI, under the authority of the Safe Drinking Water Act's (SDWA) Underground Injection Control (UIC) Program. These requirements, also known as the Class VI rule, are designed to protect underground sources of drinking water. The Class VI rule builds on existing UIC Program requirements, with extensive tailored requirements that address $CO_2$ injection for long-term storage to ensure that wells used for geologic storage are appropriately sited, constructed, tested, monitored, and closed. The rule also affords owners or operators the injection depth flexibility to address injection in various geologic settings in the United States in which geologic storage may occur, including very deep formations and oil and gas fields that are transitioned for use as $CO_2$ storage sites.

In a separate, yet complimentary rulemaking under authority of the Clean Air Act, EPA has finalized reporting requirements under the Greenhouse Gas Reporting Program for facilities that inject $CO_2$ underground for geologic storage and all other facilities that inject $CO_2$ underground. Information obtained under the Greenhouse Gas Reporting Program will enable EPA to track the amount of $CO_2$ received by these facilities.

In addition, the utilization of $CO_2$ for enhanced oil recovery (EOR), which results in the storage of $CO_2$ as well as the increased production of oil, has acted as a catalyst for CCS. Approximately 60 million metric tons of $CO_2$ are used each year for EOR.

Like any other basic economic activity, the production of oil via EOR produces direct benefits (e.g., the value of the oil), indirect benefits via other economic activities that support the EOR process (e.g., production of steel pipe for the injection and production wells), and induced economic activity via purchases made using the salaries of employees engaged in these direct and indirect economic activities.

The complementary objective of storing $CO_2$ as cheaply as possible presents the co-optimization problem of getting as much oil out of the ground while leaving as much $CO_2$ behind. Previous work supported by NETL through the GEO-SEQ project has shown that characterization of the reservoir, combined with simulation and active well control, is critical for co-optimizing $CO_2$-EOR.

## R&D Needs Workshop Overview

Since it has been more than 10 years since DOE/NETL has held a stakeholder workshop to seek input on CCS research priorities, DOE and NETL held another $CO_2$ storage workshop, titled "Storage in Saline Formations R&D Workshop," in October 2011.

The purpose of this workshop was to assess the state-of-the-art and identify research needs and highlight new approaches to advance the broad, commercial application of carbon storage. This workshop also focused on the technical aspects of DOE's Carbon Storage Program, while recognizing that technical issues must be addressed within the context of an integrated system of capture, transport, and storage set within a new regulatory framework.

A broad spectrum of approximately 50 researchers from industry, government, national labs, academia, and other research institutions contributed to the success of this workshop. The participants list is found in Appendix I.

The workshop consisted of two segments. Segment I consisted of plenary talks beginning with an overview of the NETL Carbon Storage Program, followed by invited talks summarizing the current status of the key components of storage technology:

- Quantifying and enhancing storage capacity.
- Status of wellbore technologies.
- Status of remediation technologies.
- MVA, both surface and subsurface.
- Simulation and risk assessment (Sim-Risk).

These topics and others are the key components in the NETL Storage Technology Program Plan. The talks also assessed the current technology status in the context of the new EPA and state regulatory requirements for $CO_2$ injection and GHG reporting described previously, as well as what R&D efforts are needed to meet these requirements.

Segment II consisted of parallel, facilitated breakout sections in which research needs/topics were developed and prioritized by the participants. Three breakout sections were conducted, each charged with developing research topics for a different core research area (Geological Storage; MVA; and Sim-Risk) that corresponds to the NETL Storage Technology Program Plan.

The plenary talks provided a basis for discussion in the breakout sessions. In addition, each session was provided with a list of questions that had been developed from the current Technology Plan; the questions are provided in Appendix II. The questions were to be used only to motivate discussion, and were not specifically addressed.

## Workshop Results

## Plenary Session

John Litynski presented an overview of the NETL Storage Program in which he discussed several topics, such as drivers for CCS, technology status, the NETL program overview, and workshop benefits. Drivers for CCS, both internationally and nationally, include:

- The 1997 Kyoto Protocol; various R&D workshops and roadmaps. Of particular relevance is the 1999 U.S. R&D workshop, which resulted in the initial DOE sequestration R&D roadmap.
- The 2005 Intergovernmental Panel on Climate Change (IPCC) Special Report on CCS.
- From 2008 to 2010, the development of climate and CCS-specific legislation in the United States at the Federal and state level, and development of regulations for $CO_2$ storage and emissions accounting.
- The 2010 Presidential Task Force on CCS.

The research pathways being followed to meet the goals and objectives of the current NETL Storage Program were presented, as summarized in the previous section of this report. Also presented were a number of technology challenges, including:

- Prediction of ultimate plume size and time for stabilization; optimization of storage through fluids management.
- Development of MVA approaches for quantification of $CO_2$ and leakage detection.
- Impacts of diversity in depositional environments.
- Offshore storage issues.
- Optimization of storage and enhanced hydrocarbon recovery.

Finally, the presentation cited a major benefit of the workshop as an independent external assessment of R&D needs which would directly influence the future DOE research strategy for geologic storage.

Following the NETL Storage Program overview, there were seven invited talks, which summarized the current status of the key components of storage technology and provided a framework for discussion of R&D gaps and needs. The titles of the talks and respective speakers were:

- Quantifying and Enhancing $CO_2$ Storage Capacity by Charles Gorecki.
- Remediation Technologies by Sally Benson.
- Wellbore Technologies by Dwight Peters.
- Subsurface Monitoring Challenges by Kevin Dodds.
- MVA – Near Surface by Lee Spangler.
- Simulation by Curtis Oldenburg.
- Risk Assessment by Ken Hnottavange-Telleen.

These presentations, along with the program overview, can be found at:

http://www.netl.doe.gov/events/11conferences/carbon_dioxide_storage_and_utilization/index.html.

Charles Gorecki discussed the various factors and assumptions which affect calculation of the $CO_2$ storage capacity of a reservoir, including: hydrologic boundary conditions (i.e., open and closed systems), static vs. dynamic calculations, caprock (shale) permeability, and water extraction. He identified the following research needs:

- Consistent methodology and terminology calculation of storage capacity.
- Understanding the impact of water extraction on storage capacity.
- Understanding the impact and influence of dynamic storage methodologies.
- Need for additional real-world results and real-world data.

Sally Benson reviewed remediation options for a variety of potential events which may involve a release of $CO_2$ to the surface. These included: leakage from active or abandoned wells; leakage from the storage reservoir; and unacceptable levels of $CO_2$ in the groundwater, vadose zone, indoor air, and surface waters. Results of recent studies to evaluate $CO_2$ extraction and brine injection strategies for groundwater remediation were summarized. Data on remediation costs were also presented. The following conclusions, including research gaps and needs, were presented:

- Well plugging and abandonment procedures are well known and effective, but can be high-cost.
- Stopping leakage from faults and fractures is more challenging.
    - There is little direct experience.
    - Stopping injection near the leak is the best short-term option.
    - Other ideas need to be developed and tested.
- Remediation of groundwater, vadose zone, and ecosystems is possible.
    - Costs and time are key issues.
    - It is best to avoid the need for remediation through early leak detection and curtailment.

Dwight Peters discussed a number of topics related to design and construction of wellbores, including: purpose of wells (i.e., injection vs. monitoring), integration of data from wells with other monitoring data, well design for injection, types of cement and placement, and regulatory requirements on construction and operation. The effective placement of cement behind casing to form a high-quality seal was highlighted as a key to maintaining well integrity. Cementing is a complex operation. Current technology can yield high-quality results, but close adherence to best practices is essential. Regarding current Class VI regulations, it was noted that the requirement to maintain annular pressure in excess of operating injection pressure raises concerns about:

- Exposure of stage tools to high pressure.
- Damage to the cement isolation capacity.
- Damage to the surrounding formation.

Kevin Dodds discussed monitoring strategies and challenges, and reviewed the current status of a variety of techniques for monitoring the behavior of $CO_2$ in the deep subsurface, with particular focus on plume tracking and leak detection. He discussed data acquisition as well as analysis. Discussed techniques included: seismic methods (including microseismic), electrical (including controlled source electromagnetic and through casing resistivity), gravity, ground surface displacement, and integrated equipment packages. Noted monitoring challenges included:

- Detecting the presence of $CO_2$ far from wells.
- Quantification of containment or leaks.
- Contingency and mitigation.
- Technology and deployment options.
    - Defining cost-effective monitoring systems.
- Equipment robustness.

The following subsurface MVA research suggestions were identified:

- Develop uniform standards for modeling used to design and analyze monitoring measurements.
- For seismic testing: develop long-sweep, low-power buried sources; multiple simultaneous sources; wireless technology.
- Conduct microseismic field tests to better understand locations and mechanisms.
- Explore gravity, electrical, and electromagnetic options; a step change in technology is needed.
    - Electrical: cross-well, borehole to surface.
- Borehole logging – spectral EM measurements for seal properties.
- Specialized slim hole drilling for monitoring.
- Integrated down hole sensor platforms.
    - Robustness, power harvesting, wireless telemetry.
- Sensor development and optical fiber options.
    - Micro-Electro-Mechanical Systems (MEMS) – pressure, temperature, chemical, gyroscope, accelerometers, gravity.
    - Fiber optic sensing technology: Distributed Temperature Sensing (DTS) and Distributed Thermal Perturbation Sensing (DTPS) (temperature perturbations); Distributed Acoustic Sensing (DAS) (pressure sensing).

Lee Spangler addressed the current status of near-surface monitoring technology. He discussed a number of topics, including: purpose of monitoring, available techniques for near-surface applications, current regulations for injection as well as GHG reporting requirements, and results of near-surface monitoring testing carried out under the Zero Emissions Research and Technology Center (ZERT). Key findings from testing include:

- Many near-surface methods are quantitative, but challenges remain.
    - Diurnal, seasonal, and annual variations in ecosystem background flux affect detection limits.

    - Appropriate area integrated, mass balance is a challenge.
- Nearly all methods could detect 0.15 tonnes/day release at the ZERT site.
- Scaling, 6 tonnes/day would be detectable over an area 40 times as large.
- Surface expression was "patchy" – six areas of ~5m radius.
- Natural analogs also seem to have "patchy" surface expression.

Key research issues identified for near-surface MVA were:

- Develop better understanding of realistic leakage mechanisms, rates, and fluxes.
- Use this understanding to develop improved monitoring.

Curtis Oldenburg reviewed the state-of-the-art in simulation R&D from two perspectives: applications and simulation capabilities. Current research activities in applications include: very large-scale simulations (order of $10^7$ grid blocks), improved understanding of trapping mechanisms, reactive transport, pressure rise and dissipation, and inter-comparison studies. Current research activities in capabilities include: thermal, hydrologic, mechanical, and chemical (THMC) coupling; multi-scale and multi-physics modeling; coupled systems (e.g., wellbore, atmosphere); improved grid generation, data input, and post-processing; and fracturing and faulting. R&D needs in the area of applications were identified as:

- Better descriptions/models of system properties.
    - Scaled-up parameters, multi-scale heterogeneity.
    - $P_{cap}$ and $k_r$ dependence on composition, swelling.
    - High-salinity fluid properties.
    - Pure and mixed-gas adsorption.
    - Permeability as a function of grain dissolution/precipitation.
- Better understanding of pressure evolution.
- Better understanding of trapping mechanisms.
- Better methods to interpret field observations and synthesize data for use in simulations, develop integrated conceptual models.
- Protocols for verification, code comparison, and modeling comparison.
- Improved estimation of reservoir parameters and processes through coupled inversion of time-lapse THMC-geophysical datasets.
- Development of best practices, classification of sites, protocols, or guidelines on how to model the different types of sites.
- Conduct a joint validation study using a medium- to large-scale, well-constrained system (e.g., large block, long column).
- Better understanding of heterogeneous fluid distributions and corresponding geophysical properties (e.g., seismic and electrical) is needed.

R&D needs in the area of capabilities were identified as:

- Better gridding and geomodel-to-simulator tools.
- Higher-speed computing for repeated simulations for uncertainty quantification.

- Practical (large enough), fully coupled models (parallelization needs for coupled systems).
- Multi-scale and multi-physics (e.g., flow in pores and wells coupled to reservoir or caprock).
- Ability to model induced seismicity (reactivation of faults) and fracturing with coupling to flow.
- Higher-order schemes in space and time.
- Reduced and simplified models for use by regulators and others.

New R&D directions in simulation were identified as:

- Community-based simulator(s).
- Public domain (non-proprietary) codes.
- Toolbox approach rather than single application.
- Web- and cloud-based simulation.
- More generalization (less specialization).
- Simpler rather than more complex codes.

The last plenary presentation was provided by Ken Hnottavange-Telleen, who discussed concepts, issues, and challenges in developing a risk assessment framework appropriate for CCS. Topics included: features, events, and processes (FEPs); severity and likelihood scales; scenarios; and risk identification. The following research needs were identified:

- Develop semantics tools and linkage utilities for project-specific mining and refining of FEP databases.
- Integration of risk assessment with simulation, operation design, monitoring, and contingency planning activities.
- Catalog, characterize, and set performance criteria for the available risk assessment processes.
- Develop metrics for thoroughness in risk assessment.
- Develop standards for risk assessment "early and often."
- Expand "simulation" to cover entire integrated storage systems, including human and decision factors.

## Breakout Sessions

The breakout sessions developed separate lists of research gaps and needs, where a research gap was loosely defined as a gap in knowledge, and a research need defined as the work to be carried out to fill that gap. The lists of gaps and needs were prioritized through a process of voting by the participants in the breakout sessions. Participants were first asked to identify the top five research gaps. Research needs were then prioritized in a two-step voting process. Beginning with the complete list of research needs, participants first identified the top 10 needs. As part of the initial voting process, participants were asked to specify if a need was a short-, mid-, or long-term research need, where short-term was defined as less than five years, mid-term as five to 10 years, and long-term as greater than 10 years.

After the initial voting, participants were given the opportunity to discuss the results of the voting and to combine ideas before a second vote was taken. In the second vote, each breakout session was asked to identify the top three short-, mid-, and long-term research needs.

Details of the voting process varied slightly among the different groups. After the initial vote to identify the top 10 research needs, the geologic storage group developed a list of all needs receiving five or more votes. Research needs with similar concepts were then consolidated. The consolidated lists contained nine near-term needs, eight mid-term needs, and nine long-term needs. These consolidated lists were used in voting for the top three needs. The MVA group used the top 10 research needs from the first vote as a basis for determining the top three needs. The top 10 short-term list contained one need which was a consolidation of two needs in the original list. In the Sim-Risk session, research needs with similar concepts were consolidated after the initial vote to identify the top 10 needs. The process of consolidation resulted in a reduction in the number of needs from 34 to 25. The consolidated list was used in voting for the top three near-, mid-, and long-term needs.

At the end of the breakout sessions, there was a plenary session in which the results of each breakout group were summarized and presented. These results are presented in the following sections.

***Geological Storage –*** This breakout session had 17 participants, with six representatives from academia, eight from government/private research institutions (including national labs), and three from industry.

The session focused on three sub-topics: storage capacity, wellbore technologies, and remediation. Storage capacity included discussion of the factors affecting the efficient use of the subsurface for storage, as well as the ability to predict how much of the available pore space will actually be utilized in storage projects. The status of technology for construction and operation of wells for injection of $CO_2$, as well as for monitoring, was discussed under the topic of wellbore technologies. The topic of remediation included discussion of potential events which may involve a release of $CO_2$ to the surface for which contingency plans might be needed, as well as the status of technology for remediation of these events.

The group developed a list of 38 research gaps and 46 research needs. The prioritized results are shown in Table 1. This breakout group provided three top research gaps, which resulted from the combination of some top-ranked research gaps which received equal numbers of votes. The results point to the need for further research to assess the leakage vulnerability of natural caprock systems which might also contain fractures and faults, and techniques to remediate such potential events. The importance of wellbore construction in preventing potential $CO_2$ leakage through various types of sealing formations is emphasized in the second gap. Results also highlight the need for further understanding of the impacts of geologic heterogeneity on the distribution of $CO_2$ and accompanying pressure increases, potential brine migration, and induced seismicity.

**Table 1: Geologic Storage Breakout Session Results**

| **High Priority Geologic Storage Research Gaps** |
|---|
| Natural system inability to adequately prevent $CO_2$ from reaching the surface, vulnerabilities, diagnosis, leakage mechanisms. |
| Different caprock behavior – shale salt carbonate/borehole behavior and sealing achieving cement-caprock bond. |
| Impacts of depositional heterogeneity of reservoirs on $CO_2$ distribution and development of models. |
| **High Priority Geologic Storage Near-Term Research Needs** |
| Natural system leakage detection and intervention in the region far from the injection well. |
| Postmortem studies of old wells (accelerated aging protocols and limitations). |
| Storage capacity – pressure effects on seismicity, Area of Review (AOR), other users and resources. |
| **High Priority Geologic Storage Mid-Term Research Needs** |
| Natural system leakage detection and intervention far away from the injection well. |
| Storage capacity – pressure effects on seismicity, AOR, other users and resources. |
| Storage capacity – field measurement of sweep efficiency to validate models. |
| **High Priority Geologic Storage Long-Term Research Needs** |
| Natural system leakage detection and intervention far away from the injection well. |
| Storage capacity – water management related to increased pressure and plume migration – economics and benefits/costs; footprint management. |
| Storage capacity – full-scale injection to stress geologic systems (scale, plume, efficiency). |

Results of the prioritization of research needs emphasized the importance of additional research on natural system and wellbore leakage detection and intervention. This item encompassed a number of more detailed research needs, including: simulations and field verification of methods to stop potential leaks; development of new techniques and materials for sealing leaks in natural systems; research on plume steering and brine extraction; development of cost-effective technologies for detection and diagnosis; and, related to wellbores, development of technology for detection and diagnosis of potential underground blowouts/slow leakage. Natural system and wellbore leakage and intervention appears in the top three research needs for the near-, mid-, and long-term. It is thus seen as a research need requiring immediate attention, but one which will also yield important technology advances over the long term.

Apart from research on leakage, the most important near-term research need related to wellbore technologies was postmortem studies of old wells. The most important near-term research need related to storage capacity focused on pressure effects in the reservoir, and included regional understanding of pressure influence on local storage capacity; far field effects of pressure on other users and resources; study of geomechanical impacts of pressure, including induced seismicity; and water management related to pressure management. This need also appears on the list of mid- and long-term research needs, again reflecting the immediate need and breadth of scope of the research.

In the mid-term, as mentioned above, research on natural system leakage detection and intervention, as well as pressure effects on storage capacity, were given top priority. The third top priority item, also related to storage capacity, was field validation of model predictions of the sweep efficiency of the $CO_2$ plume moving through the reservoir.

Over the long term, "full-scale" injection testing was the third top priority item. Focused on storage capacity, this need involved the concept of tests in which enough $CO_2$ is injected to cause measurable influence of the boundaries of the reservoir containment system on plume movement and pressure changes.

A number of research needs received strong support, though not enough to be prioritized as part of the top three needs. These needs included:

Near-term:

- Improved understanding of the storage capacity of non-clastic reservoirs.
- Improved understanding of the geochemical impacts of $CO_2$ in the reservoir.
- Develop, evaluate, and validate intervention methods for brine migration.

Mid-term:

- Develop technologies to enhance natural containment.
- Develop criteria for determining when remediation activities can be stopped.

Long-term:

- Develop wireless, "smart," permanent monitoring wells.
- Develop methods to monitor and assess effectiveness of leakage intervention and remediation.

***Monitoring, Verification, and Accounting (MVA) –*** This breakout session had 15 participants, with two representatives from academia, eight from government/private research institutions (including national labs), and five from industry.

The participants in this breakout session discussed research gaps and needs for technologies that could be used for MVA in the deep subsurface, near surface, at the surface, and above the surface. In assessing the status of MVA technologies, the participants discussed a number of key topics, including: the Federal regulatory MVA requirements in the EPA Class VI UIC and GHG Reporting rules, remediation and mitigation needs, MVA needs to inform storage optimization, and MVA needs for public outreach. The group identified gaps and needs in several technical areas, such as: well integrity; storage integrity; $CO_2$ plume and pressure monitoring; $CO_2$ leakage (seal, above seal, groundwater, and atmosphere); storage optimization; financial/legal MVA (trespass requirements); biosphere; and long-term data systems.

The group developed a list of 54 research gaps and 50 research needs. The prioritized results are shown in Table 2. The top five research gaps included two related to monitoring of the saturation of $CO_2$ in the subsurface, particularly in the region between wells. Results also pointed to the need for tools to monitor over the long term; conditions in, and near, the wellbore; and cost-effective methods for monitoring the plume, particularly in the region between the wells. Finally, the prioritized needs also included the need for a dedicated test site for development of MVA tools.

**Table 2: MVA Breakout Session Results**

| **High Priority MVA Research Gaps** |
|---|
| Saturation quantification. |
| Permanent (long-term) wellbore monitoring tools. |
| Cost effectiveness of $CO_2$ plume monitoring methods. |
| Need for a dedicated MVA test site. |
| Developing a way to detect low $CO_2$ saturations. |
| **High Priority MVA Near-Term Research Needs** |
| Improved high resolution saturation measurement tools. |
| Need to determine geomechanical effects on fault systems and seals. |
| Real-time monitoring systems for identification of leaks. |
| Long-term installation of robust high-resolution monitoring systems. |
| **High Priority MVA Mid-Term Research Needs** |
| Special purpose, slim hole, low-cost monitoring wells. |
| Long-term installation of robust high-resolution monitoring systems. |
| Understanding relationship of pressure front, brine front, and plume front. |
| **High Priority MVA Long-Term Research Needs** |
| Advanced large area MVA systems for near surface and atmosphere. |
| Real-time monitoring systems for identification and characterization of leaks. |
| Permanently installed well monitoring system. |

Prioritization of the research needs emphasized the importance of developing tools for improving the resolution of measurements and for long-term monitoring. Development of high resolution, long-term monitoring systems was identified as a need in both the near- and mid-term. Over the long term, such systems should be developed for permanent installation in wells. Monitoring systems to provide identification of leaks was identified as a high priority in both the near- and mid-term. Improvements in monitoring systems needed to achieve long-term (i.e., 50 years, as required by EPA regulations), reliable, cost-effective monitoring during the post-injection phases of projects should begin now, and will continue to be required over the long term. Some improvements in measurement resolution can be made in the near term, but further improvements will take longer. The benefits of increased resolution are considered to be significant enough to warrant long-term research support. In the near-term, one of the specific targets for improving measurement resolution was the measurement of $CO_2$ saturation, particularly in the region between wells.

Storage integrity and leak detection were addressed through near-term research needs on geomechanical effects on fault systems and seals, as was development of real-time monitoring systems for leak identification.

In the mid-term, in addition to high resolution, long-term monitoring systems, top priority was given to research focused on development of special purpose, slim hole, low-cost monitoring wells for monitoring storage integrity and development of methods to distinguish between the $CO_2$ plume front, the displaced brine front, and the pressure front.

Over the long term, in addition to leak detection and permanently installed well monitoring systems, the development of advanced systems for near-surface and atmospheric monitoring was identified as the top priority. In particular, the MVA group stressed the development of new, advanced systems which are capable of monitoring the very large surface footprint associated with commercial storage projects.

A number of research needs received strong support, though not enough to be prioritized as part of the top three needs. These needs included:

Near-term:

- Improved understanding of the exposure of cement and other well materials to long-term contact with $CO_2$.
- Use of natural gas storage fields as analogues for study of natural system leakage systems.
- Use $CO_2$-EOR fields for optimizing monitoring methods.
- Integration of MVA with reservoir characterization, risk assessment, and reservoir modeling.
- Advanced seismic resolution of faults.

Mid-term:

- Development of wireless, “smart” injection wells.
- Development of new techniques to identify deterioration of cement and casing.
- Integration of geophysical measurements for saturation measurement.
- Improved data on electrical properties of rocks.
- Measurement and field testing of potential $CO_2$ flow paths in surrounding formations.

Long-term:

- Use of nanotechnology as tracers to measure fault reactivation.
- Automated data analysis for advanced pattern recognition (e.g., neural networks).

***Simulation and Risk Analysis* –** This breakout session was attended by 14 participants, with two representatives from academia, 10 from government/private research institutions (including national labs), and two from industry.

This group focused on research gaps and needs in the interrelated areas of simulation and risk analysis. Simulation refers to the computer models used to model/predict the various physical processes associated with geologic storage, and is a key component of risk analyses. The process of risk assessment helps focus simulation on the most important processes and informs the bounds and details of those simulations. This group first broke into sub-groups to develop separate lists of gaps and needs for simulation and risk analysis. They then combined the two lists into one before prioritizing gaps and needs.

The group developed a list of 44 research gaps and 34 research needs. The prioritized results are shown in Table 3. The group identified five top research gaps, which resulted from the combination of several of the gaps identified in the original list. Results point to the need for improved simulation codes to model: geomechanical processes in general and, specifically, induced seismicity; geologic heterogeneity, including compartmentalization and fractures; and leakage processes, including fault flow. The value of the output of simulation and risk analysis is heavily dependent upon the quality of the input, which describes the physical system to be modeled. Research gaps related to input data included: uncertainty and sensitivity analysis approaches; confidence in modeling complex, coupled, long-term systems; constraining models with limited data; characterization of geologic heterogeneity; and knowledge of sealing processes and properties, particularly for shales.

**Table 3: Simulation and Risk Assessment Breakout Session Results**

| **High Priority Simulation and Risk Analysis Research Gaps** |
|---|
| Geomechanical process simulation; simulating induced seismicity. |
| Constraining models with very limited data; confidence in modeling complex, coupled, long-term systems; uncertainty analysis; sensitivity analysis approaches. |
| Need better simulation technology for leakage and seal-related processes, especially fault flow processes. |
| Characterizing and simulating heterogeneity and/or compartmentalization and/or fractures. |
| Need to understand sealing processes and properties and capacity of caprock; an especially important gap is the paucity of data on shale characteristics. |
| **High Priority Simulation and Risk Analysis Near-Term Research Needs** |
| Measuring and determining model parameters; up-scaling of THMC parameters; measurement at field-scale; $CO_2$-groundwater-rock interactions. |
| Coupled THMC simulations (induced seismicity, understand/characterize how geomechanical process effect well bores/caprocks/fault and fracture). |
| Comprehensive analysis of existing relevant data from oil and gas/EOR operations to develop probabilities/distributions of scenarios/impacts. |
| **High Priority Simulation and Risk Analysis Mid-Term Research Needs** |
| Comprehensive analysis of existing relevant data from oil and gas/EOR operations to develop probabilities/distributions of scenarios/impacts. |
| Measuring and determining model parameters; up-scaling of THMC parameters; measurement at field-scale; $CO_2$-groundwater-rock interactions. |
| Coupled THMC simulations (induced seismicity, understand/characterize how geomechanical process effect well bores/caprocks/fault and fracture). |
| **High Priority Simulation and Risk Analysis Long-Term Research Needs** |
| Coupled THMC simulations (induced seismicity, understand/characterize how geomechanical process effect well bores/caprocks/fault and fracture). |
| Post-audit of past projects for risk assessment approach validation. |
| Measuring and determining model parameters; up-scaling of THMC parameters; measurement at field-scale; $CO_2$-groundwater-rock interactions. |

The group combined several research needs from the original list in order to obtain the top research needs in simulation and risk analysis. The research needs focus on particular activities needed to address the research gaps in simulation codes and input data for those codes. These activities are long-term efforts, with benefits expected in the near-, mid-, and long term. The top priority research activity in the area of code improvement was coupled (THMC codes), with a focus on simulation of induced seismicity, and geomechanical processes associated with wellbores, seals, and faults and fractures. The group discussed benefits of development of increasingly sophisticated, complex, coupled codes, as well as the benefits of development of more easily useable, simplified models.

A second high-priority research need, focused on reducing uncertainty in input data for simulation codes, was the determination and measurement of input parameters. Included in this research area were: development of new approaches to upscale THMC parameters, field-scale measurement of parameters, and $CO_2$-groundwater-rock chemical interactions.

The third high-priority research need, focused on reduction of uncertainty in risk analyses, was the comprehensive analysis of existing oil/gas/EOR operations as analogues to $CO_2$ storage operations. The objective of this research would be to develop probabilities of adverse impacts, and inform the development of event scenarios and impacts in $CO_2$ storage operations. In the long term, this activity would expand to include post-audit of past $CO_2$ injection projects.

A number of research needs received strong support, though not enough to be prioritized as part of the top three needs. These needs included:

Near-term:
- Development of improved methods for uncertainty quantification.
- Improved quantification and characterization of leakage impacts ($CO_2$ and brine).
- Development of simplified models.

Mid-term:
- Systematic comparison of risk assessment approaches.
- Improved understanding of storage in shale, including fracturing, sorption, injectivity, and enhanced recovery of methane.
- Improved understanding of impact of geomechanical processes on wellbores, caprocks, faults, and fractures.
- Develop Total System Simulators for risk assessment.

Long-term:
- Improved understanding of the baseline state of stress, dynamic changes in stress, and impacts on reservoir properties.
- Development of methods for integration of risk assessment with MVA.

## Discussion

Although each breakout session was focused on a specific geologic storage technology area, two common themes emerged from the discussions which highlight general issues requiring additional research. Further research related to leakage, particularly via wellbores and faults/fractures, was one common theme. Development of methods, approaches, or tools to predict, detect, monitor, quantify, or mitigate leakage were given high priority in all three breakout sessions. A second common theme was geomechanics, including induced seismicity. The geologic storage group highlighted the need to develop methods for regional pressure and stress management. The MVA group prioritized research on detection, characterization, and monitoring of faults and fluid pressures in the reservoir, and the simulation and risk analysis group prioritized the improved geomechanics simulation capabilities.

**Comparison of the research focus areas in the current program plan with the research needs identified in the workshop shows that most of the high-priority items identified by the workshop were already contained in the program plan. Thus, the workshop provides a strong endorsement of the current program, while providing justification for focus on certain research areas**. In addition, high-priority research needs defined by the breakout sessions were consistent with, and generally inclusive of, those noted by the plenary speakers.

**Identification of research ideas not currently in the program is another benefit of the workshop. New ideas which were identified as high-priority needs included:**

- **Postmortem studies of old wells.**
- **Full-scale injection to stress geologic systems (scale, plume, efficiency).**
- **Special purpose, slim hole, low-cost monitoring wells.**
- **Post-audit of past projects for risk assessment approach validation.**

Some other ideas, from both the plenary presentations and the breakout sessions which did not make the high-priority list, are worthy of note due to their novelty and potential impact. Noteworthy additional ideas from the plenary session include:

- Possibility of a “step change” in technology from integration of non-seismic monitoring methods.
- Implementation of MEMS sensor technologies in monitoring systems.
- Need to better understand realistic leakage mechanisms, rates, and fluxes as a basis for development of surface and above-surface monitoring techniques.
- Need for “practical” coupled simulators and “simple” models.
- Development of semantics tools and linkage utilities for project-specific mining and refining of FEPs.
- Development of metrics for thoroughness in risk assessment.

Noteworthy additional ideas from the breakout sessions include:

- Need for improved understanding of storage capacity in non-clastic reservoirs.
- Development of success criteria for remediation – how to decide when remediation is sufficient.
- Development of methods to monitor the effectiveness of remediation activities.
- Utilization of gas storage and $CO_2$-EOR projects as analogues in development of MVA methods and approaches.
- Improved techniques for assessing cement and casing degradation.

## Conclusions

Consistent with Administration and Congressional priorities, CCS continues to be a key element of DOE's R&D portfolio. Implemented by NETL within DOE's FE, the program is playing a lead role in CCS technology development and has made significant advances in the development of a broad range of effective and economically viable technologies. The Carbon Storage Program is comprised of three principal elements: Core R&D, Infrastructure, and Global Collaborations. The Core R&D Area consists of projects to develop solutions for geologic storage technologies, monitoring, simulation, risk assessment, and utilization of $CO_2$. DOE and NETL held a $CO_2$ storage workshop, titled "Storage in Saline Formations R&D Workshop," in October 2011 in order to assess the state-of-the-art, and identify research needs in the Core R&D technology areas. The participants in this workshop developed lists of numerous research needs and then selected the top three near-, mid-, and long-term research needs in each of three technology areas (Geologic Storage, MVA, and Sim-Risk). Two common research themes emerged from the breakout sessions: development of methods, approaches, or tools to predict, detect, monitor, quantify, or mitigate potential $CO_2$ leakage; and development of methods and tools to predict, monitor, and manage geomechanical processes associated with storage. Some new, novel research ideas also emerged. Overall, however, most of the high-priority items identified by the workshop were already contained in the program plan. Thus, the workshop provides a strong endorsement of the current program, while also providing justification for focus on certain existing and new research areas.

# Appendix I: List of Participants

**Table AI- 1: List of Participants**

| List of Participants | | |
|---|---|---|
| **Count** | **Name** | **Affiliation** |
| 1 | Roger Aines | Lawrence Livermore National Laboratory |
| 2 | Stefan Bachu | Alberta Innovates - Technology Futures |
| 3 | Diana H. Bacon | Pacific Northwest National Laboratory |
| 4 | Ludmilla Basava-Reddi | IEAGHG |
| 5 | Sally Benson | Stanford University |
| 6 | Alain Bonnevile | Pacific Northwest National Laboratory |
| 7 | David Borns | Sandia National Laboratories |
| 8 | Tom Brouns | Pacific Northwest National Laboratory |
| 9 | Elizabeth Burton | Lawrence Berkeley National Laboratory |
| 10 | Al Cunningham | Montana State University |
| 11 | Thomas Daley | Lawrence Berkeley National Laboratory |
| 12 | Kevin Dodds | BP Alternative Energy |
| 13 | Mark de Figueiredo | U.S. EPA |
| 14 | Robert J. Finley | Illinois State Geological Survey |
| 15 | Michael Frish | Physical Sciences, Inc. |
| 16 | Ellen Gilliland | VA Center for Coal & Energy Research |
| 17 | Charlie Gorecki | Energy & Environmental Research Center |
| 18 | Neeraj Gupta | Battelle |
| 19 | John Harju | Energy & Environmental Research Center |
| 20 | Ken Hnottavange-Telleen | Schlumberger Carbon Services |
| 21 | Jinesh Jain | URS Corporation |
| 22 | Zunsheng Jiao | University of Wyoming Carbon Management |
| 23 | Michael Karmis | VA Center for Coal & Energy Research |
| 24 | Dan Kieke | Chevron |
| 25 | George Koperna | Advanced Resources International, Inc. |
| 26 | Vello Kuuskraa | Advanced Resources International |
| 27 | Brian McPherson | Southwest Regional Partnership |
| 28 | Srikanta Mishra | Battelle Memorial Institute |

| | | |
|---|---|---|
| 29 | Shahab Mohaghegh | West Virginia University |
| 30 | Curtis Oldenburg | Lawrence Berkeley National Laboratory |
| 31 | Bjorn Paulsson | Paulsson, Inc. |
| 32 | Rajesh J. Pawar | Los Alamos National Laboratory |
| 33 | Dwight Peters | Schlumberger Carbon Services |
| 34 | David Richey | Utah State University |
| 35 | Dave Riestenberg | Advanced Resources International |
| 36 | Ben Roth | VA Center for Coal & Energy Research |
| 37 | Jim Rutledge | LANL |
| 38 | John A Rupp | Indiana Geological Survey |
| 39 | Jim Sorensen | Energy & Environmental Research Center |
| 39 | Lee Spangler | MSU Energy Research Institute |
| 40 | Rob Trautz | EPRI |
| 41 | Paul Williams | Baker Hughes |
| 42 | Richard Winschel | CONSOL Energy, Inc. |
| 43 | Yu-Shu Wu | Colorado School of Mines |

# Appendix II: Breakout Session Discussion Questions

## Simulation and Risk Assessment

- Are computational models sufficient to predict the behavior of $CO_2$ in the subsurface? During operations? For the long term?
- Do computational models adequately represent important physical processes? Hydrologic? Mechanical? Chemical? Biological? Coupling between processes?
- Are computational models sufficient to predict the behavior of $CO_2$ in all depositional environments? In fractured rock? Coal? Shale? Basalt? Oil and gas reservoirs?
- Are additional small and/or large scale field tests needed to validate computational models?
- Are current simulators and risk analysis/risk assessment approaches cost effective? Are there opportunities for significant cost reductions?
- Are there improvements to simulators and/or risk analysis/risk assessment approaches which would enable improved storage performance?
- Are computational models sufficient to support MVA?
- Are computational models sufficient to support risk analysis?
- Are currently available risk analysis/risk assessment methods sufficient for CCS?
- Do risk assessment methods quantify risks sufficiently?
- Are additional small and/or large scale field tests needed to validate risk analysis/risk assessment methods?

## Monitoring, Verification, and Accounting

- Is current monitoring technology sufficient to meet EPA MVA requirements for Class VI and GHG reporting?
- Is technology sufficient to monitor pressure and plume migration?
- Is technology sufficient to monitor for leaks? In wells? In the subsurface? At the surface?
- Is technology sufficient to monitor for induced seismicity?
- Is technology sufficient for all depositional environments, including those containing oil and gas?
- Is technology sufficient to establish baselines? In the subsurface? At the surface?
- Are additional small and/or large scale field tests needed to validate MVA technologies?
- Is technology sufficient for post-injection monitoring?
- Is current technology sufficiently cost-effective? Are there opportunities for significant cost reductions?
- Are there opportunities for MVA advances which would enable improved storage performance?

## Geologic Storage Technologies

- Is understanding of plume migration sufficient to manage injection operations in all depositional environments, including those containing oil and gas? Are field tests needed?
- Is understanding of plume migration sufficient to determine storage capacity? Are there opportunities to significantly improve storage performance?
- Is understanding of brine migration sufficient for its management at project scale? At basin scale? In all depositional environments? Are field tests needed?
- Are current brine management methods sufficient and cost-effective? Are there significant opportunities to reduce costs?
- Is understanding of caprock sealing capacity sufficient in all depositional environments?
- Is the understanding of geochemical reactions between $CO_2$ and brine, casing and cement, reservoir and caprocks, and fracture and fault infilling materials sufficient? Are there opportunities to improve storage performance? Are field tests needed?
- Are the potential impacts of co-contaminants on injection and storage understood sufficiently - are field tests needed?
- Is the understanding of impacts of reservoir pressure increases (due to $CO_2$ injection) sufficient?
- Is understanding of induced seismicity sufficient for its management? Are field tests needed?
- Is current drilling and completions technology sufficient to meet EPA requirements for Class VI?
- Is current drilling technology sufficient for all depositional environments? Are there opportunities for significant cost reductions?
- Is cement technology sufficient, and cost-effective?
- Are current remediation technologies sufficient and cost-effective? Are there opportunities for significant cost reductions?
- Is technology sufficient to remediated $CO_2$ leaks?
- Is technology sufficient to remediate brine intrusion?
- Is field demonstration of remediation technologies required?

# Appendix III: Simulation and Risk Assessment Breakout Session Results

The following tables contain the results from the Simulation and Risk Assessment Breakout Session. Table AIII-1 shows the prioritized list of research gaps obtained from the first stage of voting in which each person was allotted 5 votes. The number of votes cast for each research gap is shown in the right-hand column.

**Table AIII-1: Simulation and Risk Assessment Research Gaps (Full List)**

| Type | Research Gaps | Votes |
|---|---|---|
| Simulation | Simulating $CO_2$ +/- Brine Leakage | 5 |
| Simulation | Simulating Induced Seismicity | 5 |
| Simulation | Characterizing and Simulating Heterogeneity and/or Compartmentalization and/or Fractures | 5 |
| Risk Analysis | Geomechanical Process Simulation | 5 |
| Simulation | Constraining Models With Very Limited Data | 4 |
| Simulation | Sealing Processes, Properties and Capacity of Caprock | 3 |
| Simulation | Ability to Simulate Reactive Geochemistry | 3 |
| Simulation | Simplified Models (Efficient Tools) to Compare Against Full Simulation | 3 |
| Risk Analysis | Inability to Predict Induced Micro-Seismicity | 3 |
| Risk Analysis | Extension of Current Knowledge/Data to Longer Time, Longer Scale | 3 |
| Risk Analysis | Alternative Approaches for Modeling that Help Run Large Number of Calculations | 3 |
| Risk Analysis | Approaches for the Total System Simulations | 3 |
| Risk Analysis | Data on Shale Characteristics | 3 |
| Simulation | Knowledge of Saturation-Dependence of Seismic Velocity for Simulating Geophysical Processes | 2 |
| Simulation | Improve Multi-Physics Models | 2 |
| Simulation | Confidence in Modeling Complex, Coupled, Long-Term Systems | 2 |
| Simulation | Improve Computational Efficiency | 2 |
| Risk Analysis | Lack of Consensus on Metrics | 2 |
| Risk Analysis | Lack of Relative Permeability Data | 2 |

| | | |
|---|---|---|
| Risk Analysis | Data for Model and Approach Validation | 2 |
| Risk Analysis | Approaches of Value of Data to Reduce Risk and Quantify Uncertainty | 2 |
| Risk Analysis | What is the $CO_2$ Detection Threshold at Different Depths? | 2 |
| Risk Analysis | Knowledge/Data Mining/Interpretation of $CO_2$/EOR Oil and Gas Projects | 2 |
| Risk Analysis | Validated Models for Multi-Phase Flow and Coupled Processes in Fast Paths | 2 |
| Simulation | Simulating Biological Impacts of GCS | 1 |
| Simulation | Ability to Conveniently Vary Conceptual Model | 1 |
| Simulation | Confidence in Veracity of Equation Solutions | 1 |
| Simulation | Consensus in Simulation Approaches, Methods | 1 |
| Simulation | Lack of Communication and Learning from Hydrocarbon Community | 1 |
| Risk Analysis | Improve Uncertainty Analysis Approaches | 1 |
| Risk Analysis | Improve Sensitivity Analysis Approaches | 1 |
| Risk Analysis | Existence of Past Project Data/Results | 1 |
| Risk Analysis | Models for Human Behavior in the Context of Actions and Impacts on CCS Projects | 1 |
| Risk Analysis | Risk Assessment of Monitoring Integration Strategies | 1 |
| Simulation | Initial Conditions for a Natural System that has Equilibrated Over Millions of Years | 0 |
| Simulation | Lack of Regional Upscale Data | 0 |
| Simulation | Ability to Upscale Lab Data to Reservoir Scale | 0 |
| Risk Analysis | Scope/Approach for Risk Assessment | 0 |
| Risk Analysis | Maps of Baseline In-situ State of Stress | 0 |
| Risk Analysis | Method for Post-Audit of Risk Assessment | 0 |
| Risk Analysis | Capillary/Interfacial Data | 0 |
| Risk Analysis | Data on Rock Mechanical Properties | 0 |
| Risk Analysis | Develop Databases Governing to Kinetic/Equilibrium Geochemical/Processes | 0 |
| Risk Analysis | Understanding Effects of Bio-Geochemical Process on Reservoir Characteristics | 0 |

Tables AIII-2 to AIII-4 show the prioritized list of near-, mid-, and long-term research needs obtained from the first stage of voting in which each person was allotted 10 votes. The number of votes cast for each research need is shown in the right-hand columns.

**Table AIII-2: Simulation and Risk Assessment Short-Term Needs (<5 yrs) Full List Vote 1**

| Type | Short-Term Research Needs (< 5 Years) | Votes |
|---|---|---|
| Risk Analysis | Comprehensive Analysis of Existing Relevant Data from Oil and Gas/EOR Operations to Develop Probabilities/Distributions of Failures/Scenarios/Impacts | 8 |
| Simulation | Definition/Measurement of Model Parameters | 7 |
| Risk Analysis | Incorporate Coupled THMC Simulations | 7 |
| Risk Analysis | Understand/Characterize How Geomechanical Process Effects Well Bores/Caprocks/Faults and Fractures | 7 |
| Simulation | Upscaling of Geochemical Parameters and Laboratory Parameters | 6 |
| Risk Analysis | Impact of Leakage ($CO_2$ + Brine)- Identify Characteristics and Quantification | 6 |
| Simulation | Characterizing, Parameterizing, and Modeling Heterogeneity | 5 |
| Simulation | Develop Fit-for-purpose Simplified Models | 5 |
| Risk Analysis | Develop New Approaches for Simulation that are Driven by Data for Better UQ (Uncertainty Quantification) | 5 |
| Risk Analysis | Data for risk assessment approach validation | 5 |
| Simulation | Validation of numerical models | 4 |
| Simulation | UQ Arising from Multiple Sources | 4 |
| Simulation | $CO_2$ Groundwater Reaction with Metals, Reversibility | 4 |
| Risk Analysis | Post-Audit of Past Projects for Risk Assessment Approach Validation | 4 |
| Simulation | Transient Data as Constraints on Models | 3 |
| Simulation | Brine Intrusion Into Groundwater | 3 |
| Risk Analysis | Comparison of Risk Assessment Approaches and Value Added Going from Qualitative to Quantitative | 3 |
| Risk Analysis | Define Comprehensive Framework of Risk Assessment Metrics | 3 |
| Risk Analysis | Comprehensive Analysis of Existing Microseismic Data | 3 |
| Risk Analysis | Map Baseline In-situ State of Stress | 3 |

| | | |
|---|---|---|
| Risk Analysis | Simulation of Induced Seismicity | 3 |
| Risk Analysis | Better Approaches for UQ That Will Induce Sampling?/Model Abstractions/Integrations | 3 |
| Risk Analysis | Approaches for Better Risk Assessment and Monitoring Integration Risk Management | 3 |
| Simulation | Accurate Modeling of High Pressures in Reservoir and Surrounding Formations | 2 |
| Simulation | Accurate Modeling of Phase Changes in Reservoir | 2 |
| Simulation | Storage in Shale: Fracturing, Sorption, Injectivity, Enhanced $CH_4$ Recovery (EGR) | 2 |
| Risk Analysis | Biological Processes and Their Impacts on Reservoir Properties Through Simulation/Lab/Field Experiments | 2 |
| Risk Analysis | Develop Performance Criteria for Thoroughness of Risk Assessment Metrics | 2 |
| Simulation | Capability for Long-Term $CO_2$/EOR Simulators | 1 |
| Simulation | HM (Hydro-Mechanical): Different Scales, Discrete Features, Dynamic Feedback, Discretion Needs Vary by Type of Code | 1 |
| Risk Analysis | Community Risk Assessment System Analysis Model with all Relevant Stakeholders | 1 |
| Risk Analysis | Approaches for Total System Simulations for Risk Assessment | 1 |
| Simulation | Incorporate Effects of Deformation | 0 |
| Simulation | Incorporate Permeability Anisotropy in Models | 0 |

**Table AIII-3: Simulation and Risk Assessment Mid-Term Needs (5-10 yrs) Full List Vote 1**

| Type | Mid-Term Research Needs (5-10 Years) | Votes |
|---|---|---|
| Risk Analysis | Approaches for Total System Simulations for Risk Assessment | 7 |
| Simulation | Upscaling of Geochemical Parameters and Laboratory Parameters | 6 |
| Risk Analysis | Define Comprehensive Framework of Risk Assessment Metrics | 6 |
| Risk Analysis | Develop New Approaches for Simulation that are Driven by Data for Better UQ | 6 |
| Simulation | Validation of Numerical Models | 5 |
| Risk Analysis | Better Approaches for UQ That Will Induce Sampling/Model Abstractions/Integrations | 5 |
| Risk Analysis | Data for Risk Assessment Approach Validation | 5 |
| Risk Analysis | Understand/Characterize How Geomechanical Process Effects Well Bores/Caprocks/Faults and Fractures | 5 |
| Simulation | Definition/Measurement of Model Parameters | 4 |
| Simulation | UQ Arising from Multiple Sources | 4 |
| Simulation | Develop Fit-for-purpose Simplified Models | 4 |
| Risk Analysis | Comprehensive Analysis of Existing Relevant Data from Oil and Gas/EOR Operations to Develop Probabilities/Distributions of Failures/Scenarios/Impacts | 4 |
| Risk Analysis | Post-Audit of Past Projects for Risk Assessment Approach Validation | 4 |
| Simulation | Characterizing, Parameterizing, and Modeling Heterogeneity | 3 |
| Simulation | Accurate Modeling of High Pressures in Reservoir and Surrounding Formations | 3 |
| Simulation | Transient Data as Constraints on Models | 3 |
| Simulation | Incorporate Permeability Anisotropy in Models | 3 |
| Risk Analysis | Incorporate Coupled THMC Simulations | 3 |
| Risk Analysis | Comprehensive Analysis of Existing Microseismic Data | 3 |
| Risk Analysis | Develop Performance Criteria for Thoroughness of Risk Assessment Metrics | 3 |
| Risk Analysis | Simulation of Induced Seismicity | 3 |
| Risk Analysis | Approaches for Better Risk Assessment and Monitoring Integration Risk Management | 3 |
| Simulation | Accurate Modeling of Phase Changes in Reservoir | 2 |
| Simulation | Incorporate Effects of Deformation | 2 |
| Simulation | HM: Different Scales, Discrete Features, Dynamic Feedback, Discretion Needs Vary by Type of Code | 2 |
| Simulation | Storage in Shale: Fracturing, Sorption, Injectivity, Enhanced $CH_4$ Recovery (EGR) | 2 |

| | | |
|---|---|---|
| Risk Analysis | Biological Processes and Their Impacts on Reservoir Properties Through Simulation/Lab/Field Experiments | 2 |
| Risk Analysis | Map Baseline In-situ State of Stress | 2 |
| Risk Analysis | Community Risk Assessment System Analysis Model with All Relevant Stakeholders | 2 |
| Simulation | Capability for Long-Term $CO_2$/EOR Simulators | 1 |
| Simulation | Brine Intrusion into Groundwater | 1 |
| Simulation | $CO_2$ Groundwater reaction with metals, Reversibility | 1 |
| Risk Analysis | Comparison of Risk Assessment Approaches and Value Added Going from Qualitative to Quantitative | 1 |
| Risk Analysis | Impact of Leakage ($CO_2$ + Brine) Identify Characteristics and Quantification | 1 |

**Table AIII-4: Simulation and Risk Assessment Long-Term Needs (>10 yrs) Full List Vote 1**

| Type | Long-Term Research Needs (> 10 Years) | Votes |
|---|---|---|
| Risk Analysis | Incorporate Coupled THMC Simulations | 8 |
| Simulation | Storage in Shale: Fracturing, Sorption, Injectivity, Enhanced $CH_4$ Recovery (EGR) | 6 |
| Risk Analysis | Define Comprehensive Framework of Risk Assessment Metrics | 6 |
| Risk Analysis | Data for Risk Assessment Approach Validation | 6 |
| Simulation | Characterizing, Parameterizing, and Modeling Heterogeneity | 5 |
| Risk Analysis | Map Baseline In-situ State of Stress | 5 |
| Risk Analysis | Simulation of Induced Seismicity | 5 |
| Risk Analysis | Develop New Approaches for Simulation that are Driven by Data for Better UQ | 5 |
| Risk Analysis | Post-Audit of Past Projects for Risk Assessment Approach Validation | 5 |
| Risk Analysis | Approaches for Total System Simulations for Risk Assessment | 5 |
| Simulation | Definition/Measurement of Model Parameters | 4 |
| Simulation | Incorporate Effects of Deformation | 4 |
| Simulation | UQ Arising from Multiple Sources | 4 |
| Risk Analysis | Understand/Characterize How Geomechanical Process Effects Well Bores/Caprocks/Faults and Fractures | 4 |
| Simulation | Accurate Modeling of High Pressures in Reservoir and Surrounding Formations | 3 |
| Simulation | Accurate Modeling of Phase Changes in Reservoir | 3 |
| Simulation | Transient Data as Constraints on Models | 3 |

| | | |
|---|---|---|
| Simulation | Incorporate Permeability Anisotropy in Models | 3 |
| Risk Analysis | Comprehensive Analysis of Existing Relevant Data from Oil and Gas/EOR Operations to Develop Probabilities/Distributions of Failures/Scenarios/Impacts | 3 |
| Risk Analysis | Approaches for Better Risk Assessment and Monitoring Integration Risk Management | 3 |
| Simulation | Upscaling of Geochemical Parameters and Laboratory Parameters | 2 |
| Simulation | Validation of Numerical Models | 2 |
| Simulation | Capability for Long-Term $CO_2$/EOR Simulators | 2 |
| Simulation | $CO_2$ Groundwater Reaction with Metals, Reversibility | 2 |
| Simulation | HM: Different Scales, Discrete Features, Dynamic Feedback, Discretion Needs Vary by Type of Code | 2 |
| Risk Analysis | Biological Processes and Their Impacts on Reservoir Properties Through Simulation/Lab/Field Experiments | 2 |
| Risk Analysis | Better Approaches for UQ That Will Induce Sampling /Model Abstractions/Integrations | 2 |
| Risk Analysis | Comparison of Risk Assessment Approaches and Value Added Going from Qualitative to Quantitative | 1 |
| Risk Analysis | Impact of Leakage ($CO_2$ + Brine) Identify Characteristics and Quantification | 1 |
| Risk Analysis | Comprehensive Analysis of Existing Microseismic Data | 1 |
| Risk Analysis | Develop Performance Criteria for Thoroughness of Risk Assessment Metrics | 1 |
| Risk Analysis | Community Risk Assessment System Analysis Model with All Relevant Stakeholders | 1 |
| Simulation | Brine Intrusion into Groundwater | 0 |
| Simulation | Develop Fit-for-purpose Simplified Models | 0 |

Table AIII-5 shows the prioritized list of research gaps obtained from the second stage of voting in which each person was allotted 5 votes. Some ideas from the initial list of research gaps were combined together before the second stage vote was taken. The number of votes cast for each research gap is shown in the right-hand column.

**Table AIII-5: Simulation and Risk Assessment Research Gaps Vote 2**

| Research Gaps | Votes |
|---|---|
| Geomechanical Process Simulation; Simulating Induced Seismicity | 10 |
| Constraining Models With Very Limited Data; Confidence in Modeling Complex, Coupled, Long-Term Systems; Uncertainty Analysis; Sensitivity Analysis Approaches | 9 |
| Need Better Simulation Technology for Leakage and Sealage Processes; Fault Flow Processes | 8 |
| Characterizing and Simulating Heterogeneity and/or Compartmentalization and/or Fractures | 6 |
| Sealing Processes and Properties and Capacity of Caprock; Data on Shale Characteristics | 5 |
| Lack of Existing Information/Data, Especially Lack of Multiphase, Geochemical, and Geomechanical Data at All Scales; Develop Databases Governing to Kinetic/Equilibrium Geochemical/Processes | 4 |
| Ability to Simulate Reactive Geochemistry | 3 |
| Approaches for Total System Simulations | 3 |
| Simplified Models (Efficient Tools) to Compare Against Full Simulation; Alternative Approaches for Modeling that Help Run Large Number of Calculations | 2 |
| Improve Computational Efficiency | 2 |
| Lack of Consensus on Metrics | 2 |
| Knowledge/Data Mining/Interpretation of $CO_2$/EOR Oil and Gas Projects | 2 |
| Extension of Current Knowledge/Data to Longer Time, Longer Scale | 1 |
| Approaches of Value of Data to Reduce Risk and Quantify Uncertainty | 1 |
| Simulating Biological Impacts of GCS | 1 |
| Lack of Communication and Learning from Hydrocarbon Community | 1 |
| Knowledge of Saturation-Dependence of Seismic Velocity for Simulating Geophysical Processes | 0 |
| Improve Multi-Physics Models | 0 |
| What is the $CO_2$ Detection Threshold at Different Depths | 0 |

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|---|---|
| Validated Models for Multi-Phase Flow and Coupled Processes in Fast Paths | 0 |
| Ability to Conveniently Vary Conceptual Model | 0 |
| Confidence in Veracity of Equation Solutions | 0 |
| Consensus in Simulation Approaches, Methods | 0 |
| Models for Human Behavior in the Context of Actions and Impacts on CCS Projects | 0 |
| Risk Assessment of Monitoring Integration Strategies | 0 |
| Initial Conditions for a Natural System that Has Equilibrated Over Millions of Years | 0 |
| Way to Judge Thoroughness of Risk Assessment | 0 |
| Method for Post-Audit of Risk Assessment | 0 |
| Understanding Effects of Bio-Geochemical Process on Reservoir Characteristics | 0 |

Tables AIII-6 to AIII-8 show the prioritized list of near-, mid-, and long-term research needs obtained from the second stage of voting in which each person was allotted 3 votes. Some ideas from the initial list of research needs were combined together before the second stage of voting. The number of votes cast for each research gap is shown in the right-hand column.

**Table AIII-6: Simulation and Risk Assessment Short-Term Needs (<5 yrs) Vote 2**

| Short-Term Research Needs (< 5 Years) | Votes |
|---|---|
| Measuring and Determining Model Parameters; Upscaling of THMC Parameters; Measurement at Field-Scale; $CO_2$ Groundwater Reaction with Metals, Reversibility | 7 |
| Coupled THMC Simulations (Induced Seismicity, Understand/Characterize How Geomechanical Process Effects Well Bores/Caprocks/Faults and Fractures) | 6 |
| Comprehensive Analysis of Existing Relevant Data from Oil and Gas/EOR Operations to Develop Probabilities/Distributions of Failures/Scenarios/Impacts | 5 |
| UQ Arising from Multiple Sources; Better Approaches for UQ that Will Induce Sampling /Model Abstractions/Integrations | 4 |
| Develop Fit-for-purpose Simplified Models | 3 |
| Impact of Leakage ($CO_2$ + Brine) Identify Characteristics and Quantification | 2 |
| Develop New Approaches for Simulations that are Driven by Data for Better UQ | 1 |
| Simulation and Risk Assessment Approach Validation | 1 |
| Post-Audit of Past Projects for Risk Assessment Approach Validation | 1 |
| Comparison of Risk Assessment Approaches and Value Added Going from Qualitative to Quantitative | 1 |
| Define Comprehensive Framework of Risk Assessment Metrics | 1 |
| Approaches for Better Risk Assessment and Integration with Monitoring | 1 |
| Gas Exsolution and its Effects on Sealing Capacity | 1 |
| Develop Performance Criteria for Thoroughness of Risk Assessment | 1 |
| Approaches for Better Risk Assessment and Integration with Monitoring | 1 |
| Transient Data as Constraints on Models | 0 |
| Brine Intrusion Into Groundwater | 0 |
| Comprehensive Analysis of Existing Microseismic Data | 0 |

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|---|---|
| Map Baseline State of Stress; Dynamic Changes on the Stress State of the Reservoir and Its Effect on Reservoir Properties | 0 |
| Storage in Shale: Fracturing, Sorption, Injectivity, Enhanced $CH_4$ Recovery (EGR) | 0 |
| Biological Processes and Their Impacts on Reservoir Properties Through Simulation/Lab/Field Experiments | 0 |
| Capability for Long-Term $CO_2$/EOR Simulators | 0 |
| HM: Different Scales, Discrete Features, Dynamic Feedback, Discretion Needs Vary by Type of Code | 0 |
| Community Risk Assessment System Analysis Model with All Relevant Stakeholders | 0 |
| Understand/Characterize How Geomechanical Process Effects Well Bores/Caprocks/Faults and Fractures | 0 |

**Table AIII-7: Simulation and Risk Assessment Mid-Term Needs (5-10 yrs) Vote 2**

| Mid-Term Research Needs (5-10 Years) | Votes |
|---|---|
| Comprehensive Analysis of Existing Relevant Data from Oil and Gas/EOR Operations to Develop Probabilities/Distributions of Failures/Scenarios/Impacts | 4 |
| Measuring and Determining Model Parameters; Upscaling of THMC Parameters; Measurement at Field-Scale; $CO_2$ Groundwater Reaction with Metals, Reversibility | 3 |
| Coupled THMC Simulations (Induced Seismicity, Understand/Characterize How Geomechanical Process Effects Well Bores/Caprocks/Faults and Fractures) | 3 |
| Simulation and Risk Assessment Approach Validation | 3 |
| Post-Audit of Past Projects for Risk Assessment Approach Validation | 3 |
| Develop New Approaches for Simulation that are Driven by Data for Better UQ | 2 |
| UQ Arising from Multiple Sources; Better Approaches for UQ that Will Induce Sampling/Model Abstractions/Integrations | 2 |
| Comparison of Risk Assessment Approaches and Value Added Going from Qualitative to Quantitative | 2 |
| Storage in Shale: Fracturing, Sorption, Injectivity, Enhanced $CH_4$ Recovery (EGR) | 2 |
| Understand/Characterize How Geomechanical Process Effects Well Bores/Caprocks/Faults and Fractures | 2 |
| Approaches for the Total System Simulations for Risk Assessment | 2 |
| Impact of Leakage ($CO_2$ + Brine) Identify Characteristics and Quantification | 1 |
| Develop Fit-for-purpose Simplified Models | 1 |
| Transient Data as Constraints on Models | 1 |
| Brine Intrusion Into Groundwater | 1 |

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|---|---|
| Define Comprehensive Framework of Risk Assessment Metrics | 1 |
| Comprehensive Analysis of Existing Microseismic Data | 1 |
| Map Baseline State of Stress; Dynamic Changes on the Stress State of the Reservoir and Its Effect on Reservoir Properties | 1 |
| HM: Different Scales, Discrete Features, Dynamic Feedback, Discretion Needs Vary by Type of Code | 1 |
| Approaches for Better Risk Assessment and Integration with Monitoring | 0 |
| Gas Exsolution and Its Effects on Sealing Capacity | 0 |
| Biological Processes and Their Impacts on Reservoir Properties Through Simulation/Lab/Field Experiments | 0 |
| Develop Performance Criteria for Thoroughness of Risk Assessment | 0 |
| Capability for Long-Term $CO_2$/EOR Simulators | 0 |
| Community Risk Assessment System Analysis Model with All Relevant Stakeholders | 0 |

**Table AIII-8: Simulation and Risk Assessment Long-Term Needs (>10 yrs) Vote 2**

| Long-Term Research Needs (> 10 Years) | Votes |
|---|---|
| Coupled THMC Simulations (Induced Seismicity, Understand/Characterize How Geomechanical Process Effects Well Bores/Caprocks/Faults and Fractures) | 4 |
| Post-Audit of Past Projects for Risk Assessment Approach Validation | 4 |
| Measuring and Determining Model Parameters; Upscaling of THMC Parameters; Measurement at Field-Scale; $CO_2$ Groundwater Reaction with Metals, Reversibility | 3 |
| Develop New Approaches for Simulation that are Driven by Data for Better UQ | 3 |
| Simulation and Risk Assessment Approach Validation | 3 |
| Approaches for the Total System Simulations for Risk Assessment | 3 |
| Comprehensive Analysis of Existing Relevant Data from Oil and Gas/EOR Operations to Develop Probabilities/Distributions of Failures/Scenarios/Impacts | 2 |
| Impact of Leakage ($CO_2$ + Brine) Identify Characteristics and Quantification | 2 |
| Develop Fit-for-purpose Simplified Models | 2 |
| Map Baseline State of Stress; Dynamic Changes on the Stress State of the Reservoir and Its Effect on Reservoir Properties | 2 |
| Approaches for Better Risk Assessment and Integration with Monitoring | 2 |
| UQ Arising from Multiple Sources; Better Approaches for UQ that Will Induce Sampling /Model Abstractions/Integrations | 1 |

| | |
|---|---|
| Comparison of Risk Assessment Approaches and Value Added Going from Qualitative to Quantitative | 1 |
| Storage in Shale: Fracturing, Sorption, Injectivity, Enhanced $CH_4$ Recovery (EGR) | 1 |
| Develop Performance Criteria for Thoroughness of Risk Assessment | 1 |
| Capability for Long-Term $CO_2$/EOR Simulators | 1 |
| Community Risk Assessment System Analysis Model with All Relevant Stakeholders | 1 |
| Transient Data as Constraints on Models | 0 |
| Brine Intrusion Into Groundwater | 0 |
| Define Comprehensive Framework of Risk Assessment Metrics | 0 |
| Comprehensive Analysis of Existing Microseismic Data | 0 |
| Gas Exsolution and Its Effects on Sealing Capacity | 0 |
| Biological Processes and Their Impacts on Reservoir Properties Through Simulation/Lab/Field Experiments | 0 |
| HM: Different Scales, Discrete Features, Dynamic Feedback, Discretion Needs Vary by Type of Code | 0 |
| Understand/Characterize How Geomechanical Process Effects Well Bores/Caprocks/Faults and Fractures | 0 |

# Appendix IV: Monitoring, Verification, and Accounting Breakout Session Results

The following tables contain the results from the MVA Breakout Session. Table AIV-1 shows the prioritized list of research gaps obtained from the first stage of voting in which each person was allotted 5 votes. This breakout session voted only once on research gaps. The number of votes cast for each research gap is shown in the right-hand column.

**Table AIV-1: MVA Research Gaps (Full List)**

| Type | MVA Gaps | Votes |
|---|---|---|
| STORAGE INTEGRITY | Improve Saturation Quantification | 10 |
| WELL INTEGRITY | Permanent (long term) wellbore monitoring tools | 5 |
| $CO_2$ PLUME AND PRESSURE MONITORING | Cost effectiveness of $CO_2$ plume monitoring methods | 4 |
| $CO_2$ PLUME AND PRESSURE MONITORING | Lack of a dedicated MVA test site | 4 |
| STORAGE INTEGRITY | Detecting low $CO_2$ saturations | 3 |
| $CO_2$ PLUME AND PRESSURE MONITORING | Remote pressure/monitoring plume | 3 |
| LEAKAGES | Wide area tools / techniques | 3 |
| REMEDIATION/MITIGATION | Rapid response system adapted to specific site needs | 3 |
| STORAGE OPTIMIZATION | Laboratory petrophysical characterization of $CO_2$/brine mixtures | 3 |
| WELL INTEGRITY | Method to Assess Cement Integrity | 2 |
| WELL INTEGRITY | MIT Protocols needed | 2 |
| STORAGE INTEGRITY | Improved Seismic Interpretation | 2 |
| STORAGE INTEGRITY | Geomechanical Modeling | 2 |
| STORAGE INTEGRITY | Optimize MVA goals/tools | 2 |
| STORAGE INTEGRITY | Understand Pressure Signal (compression vs. leak) | 2 |

| | | |
|---|---|---|
| LEAKAGES | What does a leak look like? | 2 |
| LEAKAGES | Determination of Atmospheric baselines | 2 |
| LEAKAGES | Cost effective suites that are quantitative | 2 |
| LEAKAGES | Unique signals of $CO_2$ leakage | 2 |
| STORAGE OPTIMIZATION | Zone by zone monitoring and injection | 2 |
| WELL INTEGRITY | Method to Assess Casing Integrity | 1 |
| WELL INTEGRITY | Standardization over Long Term | 1 |
| STORAGE INTEGRITY | Monitoring Well costs | 1 |
| STORAGE INTEGRITY | Couple Characterization with monitoring | 1 |
| STORAGE INTEGRITY | Utilize nanoparticles and other tracers | 1 |
| $CO_2$ PLUME AND PRESSURE MONITORING | Coupling modeling and MVA needs | 1 |
| $CO_2$ PLUME AND PRESSURE MONITORING | Relationship between pressure and plume | 1 |
| $CO_2$ PLUME AND PRESSURE MONITORING | Seismic for large scale Projects | 1 |
| LEAKAGES | Scale of leakage and impacts | 1 |
| REMEDIATION/MITIGATION | Early warning detection system | 1 |
| REMEDIATION/MITIGATION | High frequency MVA and analysis within leak to guide remediation | 1 |
| REMEDIATION/MITIGATION | Utilize shallow wells for deep monitoring | 1 |
| STORAGE OPTIMIZATION | Permanent monitoring systems | 1 |
| FINANCIAL/LEGAL GAPS | Trespassing of mineral rights | 1 |
| BIOSPHERE | New monitoring tools | 1 |
| WELL INTEGRITY | Length of time of seq. projects | 0 |
| STORAGE INTEGRITY | Structural Interpretation | 0 |
| $CO_2$ PLUME AND PRESSURE MONITORING | Saturation (plume edge detection) | 0 |
| $CO_2$ PLUME AND PRESSURE MONITORING | Miscibility at plume edge | 0 |

| | | |
|---|---|---|
| LEAKAGES | Poor utilization of natural analogs | 0 |
| LEAKAGES | Couple monitoring and risk assessment | 0 |
| LEAKAGES | Cost / reliability of surface $CO_2$ MVA tools | 0 |
| LEAKAGES | $CO_2$ migration through shales / confining zones | 0 |
| REMEDIATION/MITIGATION | Precise ID of leakage | 0 |
| REMEDIATION/MITIGATION | Monitoring to determine efficacy (signal vs. saturation) of remediation | 0 |
| REMEDIATION/MITIGATION | Leakage Scenarios (i.e. different leakage types) | 0 |
| REMEDIATION/MITIGATION | Sufficient Geomechanical Models | 0 |
| STORAGE OPTIMIZATION | Plume interaction | 0 |
| FINANCIAL/LEGAL GAPS | Economic valuation of leakage risk | 0 |
| FINANCIAL/LEGAL GAPS | Monitoring for due diligence | 0 |
| FINANCIAL/LEGAL GAPS | Long term cost estimates | 0 |
| FINANCIAL/LEGAL GAPS | Caprock as a resource in the future | 0 |
| BIOSPHERE | Characterization of effects | 0 |
| BIOSPHERE | Bioengineered Barriers | 0 |

Tables AIV-2 to AIV-4 show the prioritized list of near-, mid-, and long-term research needs obtained from the first stage of voting in which each person was allotted 10 votes. The number of votes cast for each research need is shown in the right-hand column.

**Table AIV-2: MVA Short-Term Needs (<5 yrs) Full List Vote 1**

| Type | Short-Term Needs (<5 YRS) | Votes |
|---|---|---|
| $CO_2$ PLUME AND PRESSURE | Improved high resolution saturation measurement tools -near and far from well bore<br>-Borehole gravity/seismic<br>-GM Methods<br>-Coupling of elastic and electrical data<br>-Application of integrated tools | 8 |
| STORAGE INTEGRITY | Geomechanical effects on fault systems and seal | 7 |
| STORAGE INTEGRITY | Integration of reservoir characterization and MVA | 7 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Coupling of MVA, risk assessment and reservoir modeling | 7 |
| FINANCIAL/LEGAL (Trespass requirements) | Use natural gas storage fields for analogs | 7 |
| STORAGE INTEGRITY | Advanced seismic resolution of faults | 6 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | In-depth studies of natural gas storage leakage systems (with adjustments for special properties of $CO_2$) | 6 |
| REMEDIATION/MITIGATION | Real time monitoring systems for identification and characterization of leaks | 6 |
| STORAGE OPTIMIZATION | Optimizing and monitoring $CO_2$ storage in an oil field | 6 |
| WELL INTEGRITY | Understanding the exposure of cement and other well materials to long term contact with $CO_2$ | 5 |
| STORAGE INTEGRITY | Long Term installation of robust high resolution monitoring systems | 5 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Guidelines for establishing baseline for groundwater and soil monitoring | 5 |
| $CO_2$ LEAKAGE (seal, above | Advanced large area MVA systems for near surface and atmosphere | 5 |

| | | |
|---|---|---|
| seal, ground water, atm) | -LIDAR<br>-Eddy Covariance<br>-Automated data collection<br>-Models | |
| WELL INTEGRITY | Technologies for early detection of deterioration over the long term:<br>-cement (alternative to MIT)<br>-Casing (feedback system using electrical signals) | 4 |
| $CO_2$ PLUME AND PRESSURE | Understanding relationship of pressure front, brine front, and plume front | 4 |
| $CO_2$ PLUME AND PRESSURE | Higher Resolution (appropriate) use of seismic for tracking pressure and $CO_2$ plume | 4 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Defining optimal cost effective suite of MVA systems and tools<br>-within seal<br>-above zone<br>-groundwater<br>-atmosphere | 4 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Independent diagnostic technologies to determine if leakage is occurring without having adequate baseline data | 4 |
| STORAGE OPTIMIZATION | "Smart" $CO_2$ injection wells for zonal isolation, feedback systems, and wireless systems | 4 |
| STORAGE OPTIMIZATION | Permanently installed well monitoring system | 4 |
| STORAGE INTEGRITY | Special purpose, slim hole, low cost monitoring wells | 3 |
| $CO_2$ PLUME AND PRESSURE | More robust data bank on electrical properties of rocks | 3 |
| $CO_2$ PLUME AND PRESSURE | Integrated field test of plume and pressure tracking<br>-MVA test site | 3 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Measurement and field test of $CO_2$ flow paths (full stack of reservoir rocks) | 3 |
| REMEDIATION/MITIGATION | Adaptation of interference testing for existence of above zone leaks (pressure network) | 3 |
| REMEDIATION/MITIGATION | Below weathered zone horizontal monitoring wells (500 ft below ground surface) | 3 |
| STORAGE INTEGRITY | Need for field test of pressure and raw compression effects to identify leakage | 2 |

| | | |
|---|---|---|
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Establish impacts for alternative scales of leakage (alt. volumes of leakage) | 2 |
| REMEDIATION/MITIGATION | Customize MVA to leakage type and volume | 2 |
| STORAGE OPTIMIZATION | Detailed characterization of reservoir (electrical properties, clay content, etc) for designing monitoring system | 2 |
| STORAGE OPTIMIZATION | Using reservoir architecture to optimize $CO_2$ storage (feedback systems) | 2 |
| STORAGE OPTIMIZATION | Need for field testing of MVA equipment at multiple sites (including safety) | 2 |
| LONG TERM DATA SYSTEMS | Data collection management for 50 yrs of MVA | 2 |
| STORAGE INTEGRITY | Use of nanotechnology as tracers to measure fault reactivation | 1 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Models for temporal changes in baseline data | 1 |
| REMEDIATION/MITIGATION | High resolution testing of secondary reservoirs or caprocks to identify leaks | 1 |
| REMEDIATION/MITIGATION | Optimize MVA systems to adapt to existing leak in order to quantify leak, locate leak, and inform mitigation | 1 |
| REMEDIATION/MITIGATION | Pre-established geomechanical model to describe stress fields and leakage conduits | 1 |
| REMEDIATION/MITIGATION | Automated data analysis for advanced pattern recognition (EG neural networks) | 1 |
| STORAGE OPTIMIZATION | Multi well $CO_2$ field configuration for optimization of commercial storage | 1 |
| FINANCIAL/LEGAL (Trespass requirements) | Minimal requirements for due diligence | 1 |
| IMPACT ON BIOSPHERE | Tools for baseline and time lapse monitoring interpretation | 1 |
| LONG TERM DATA SYSTEMS | Analysis techniques enabled by 50 yrs of data | 1 |
| $CO_2$ PLUME AND PRESSURE | High Resolution tiltmeters, especially for low permeability reservoirs | 0 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Improved interpretation capacity for soil gas surveys | 0 |
| REMEDIATION/MITIGATION | MVA for seal integrity and flow ($CO_2$ saturation in seal) | 0 |
| FINANCIAL/LEGAL (Trespass requirements) | Multi resource area baselines | 0 |
| FINANCIAL/LEGAL (Trespass requirements) | Economic valuation of risk | 0 |

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|---|---|---|
| FINANCIAL/LEGAL (Trespass requirements) | conducting long term monitoring post injection audits | 0 |
| FINANCIAL/LEGAL (Trespass requirements) | Long term remediation/mitigation costs | 0 |

**Table AIV-3: MVA Mid-Term Needs (5-10 yrs) Full List Vote 1**

| Type | Mid-Term Needs (5-10 YRS) | Votes |
|---|---|---|
| STORAGE OPTIMIZATION | "Smart" $CO_2$ injection wells for zonal isolation, feedback systems, and wireless systems | 9 |
| WELL INTEGRITY | Technologies for early detection of deterioration for the long term:<br>-cement (alternative to MIT)<br>-Casing (feedback system using electrical signals) | 8 |
| $CO_2$ PLUME AND PRESSURE | Improved high resolution saturation measurement tools -near and far from well bore<br>-Borehole gravity/seismic<br>-GM Methods<br>-Coupling of elastical and electrical data<br>-Application of integrated tools | 8 |
| STORAGE INTEGRITY | Integration of reservoir characterization and MVA | 6 |
| STORAGE INTEGRITY | Special purpose, slim hole, low cost monitoring wells | 6 |
| STORAGE INTEGRITY | Long Term installation of robust high resolution monitoring systems | 5 |
| $CO_2$ PLUME AND PRESSURE | More robust data bank on electrical properties of rocks | 5 |
| $CO_2$ PLUME AND PRESSURE | Integrated field test of plume and pressure tracking<br>-MVA test site | 5 |
| $CO_2$ PLUME AND PRESSURE | Understanding relationship of pressure front, brine front, and plume front | 5 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Measurement and field test of $CO_2$ flow paths (full stack of reservoir rocks) | 5 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Coupling of MVA, risk assessment and reservoir modeling | 5 |

| | | |
|---|---|---|
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Defining optimal cost effective suite of MVA systems and tools<br>-within seal<br>-above zone<br>-groundwater<br>-atmosphere | 5 |
| REMEDIATION/MITIGATION | MVA for seal integrity and flow ($CO_2$ saturation in seal) | 5 |
| STORAGE OPTIMIZATION | Permanently installed well monitoring system | 5 |
| STORAGE INTEGRITY | Advanced seismic resolution of faults | 4 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | In-depth studies of natural gas storage leakage systems (with adjustments for special properties of $CO_2$) | 4 |
| WELL INTEGRITY | Understanding the exposure of cement and other well materials to long term contact with $CO_2$ | 4 |
| STORAGE INTEGRITY | Geomechanical effects on fault systems and seals | 3 |
| $CO_2$ PLUME AND PRESSURE | Higher Resolution (appropriate) use of seismic for tracking pressure and $CO_2$ plume | 3 |
| REMEDIATION/MITIGATION | High resolution testing of secondary reservoirs or caprocks to identify leaks | 3 |
| REMEDIATION/MITIGATION | Real time monitoring systems for identification and characterization of leaks | 3 |
| REMEDIATION/MITIGATION | Pre-established geomechanical model to describe stress fields and leakage conduits | 3 |
| REMEDIATION/MITIGATION | Below weathered zone horizontal monitoring wells (500 ft below ground surface) | 3 |
| STORAGE OPTIMIZATION | Detailed characterization of reservoir (electrical properties, clay content, etc) for designing monitoring system | 3 |
| STORAGE OPTIMIZATION | Optimizing and monitoring $CO_2$ storage in an oil field | 3 |
| STORAGE OPTIMIZATION | Need for field testing of MVA equipment at multiple sites (including safety) | 3 |
| STORAGE INTEGRITY | Use of nanotechnology as tracers to measure fault reactivation | 2 |
| STORAGE INTEGRITY | Need for field test of pressure and raw compression effects to identify leakage | 2 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Independent diagnostic technologies to determine if leakage is occurring without baseline | 2 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Advanced large area MVA systems for near surface and atmosphere<br>-LIDAR<br>-Eddy Covariance | 2 |

| | | |
|---|---|---|
| | -Automated data collection<br>-Models | |
| REMEDIATION/MITIGATION | Customize MVA to leakage type and volume | 2 |
| REMEDIATION/MITIGATION | Optimize MVA systems to adapt to existing leak in order to quantify leak, locate leak, and inform mitigation | 2 |
| REMEDIATION/MITIGATION | Automated data analysis for advanced pattern recognition (EG neural networks) | 2 |
| LONG TERM DATA SYSTEMS | Data collection management for 50 yrs of MVA | 2 |
| LONG TERM DATA SYSTEMS | Analysis techniques enabled by 50 yrs of data | 2 |
| $CO_2$ PLUME AND PRESSURE | High Resolution tiltmeters, especially for low permeability reservoirs | 1 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Guidelines for establishing baseline for groundwater and soil monitoring | 1 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Improved interpretation capacity for soil gas surveys | 1 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Models for temporal changes in baseline data | 1 |
| REMEDIATION/MITIGATION | Adaptation of interference testing for existence of above zone leaks (pressure network) | 1 |
| STORAGE OPTIMIZATION | Multi well $CO_2$ field configuration for optimization of commercial storage | 1 |
| STORAGE OPTIMIZATION | Using reservoir architecture to optimize $CO_2$ storage (feedback systems) | 1 |
| FINANCIAL/LEGAL (Trespass requirements) | Economic valuation of risk | 1 |
| FINANCIAL/LEGAL (Trespass requirements) | conducting long term monitoring post injection audits | 1 |
| FINANCIAL/LEGAL (Trespass requirements) | Use natural gas storage fields for analogs | 1 |
| IMPACT ON BIOSPHERE | Tools for baseline and time lapse monitoring interpretation | 1 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Establish impacts for alternative scales of leakage (alt. volumes of leakage) | 0 |
| FINANCIAL/LEGAL (Trespass | Multi resource area baselines | 0 |

| | | |
|---|---|---|
| requirements) | | |
| FINANCIAL/LEGAL (Trespass requirements) | Minimum requirements for due diligence | 0 |
| FINANCIAL/LEGAL (Trespass requirements) | Long term remediation/mitigation costs | 0 |

**Table AIV-4: MVA Long-Term Needs (>10 yrs) Full List Vote 1**

| Type | Long-Term Needs (>10 YRS) | Votes |
|---|---|---|
| STORAGE INTEGRITY | Use of nanotechnology as tracers to measure fault reactivation | 9 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Advanced large area MVA systems for near surface and atmosphere<br>-LIDAR<br>-Eddy Covariance<br>-Automated data collection<br>-Models | 8 |
| REMEDIATION/MITIGATION | Real time monitoring systems for identification and characterization of leaks | 8 |
| STORAGE INTEGRITY | Integration of reservoir characterization and MVA | 7 |
| REMEDIATION/MITIGATION | Automated data analysis for advanced pattern recognition (EG neural networks) | 7 |
| STORAGE OPTIMIZATION | Permanently installed well monitoring system | 7 |
| STORAGE INTEGRITY | Long Term installation of robust high resolution monitoring systems | 6 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Defining optimum cost effective suite of MVA systems and tools<br>-within seal<br>-above zone<br>-groundwater<br>-atmosphere | 6 |
| WELL INTEGRITY | Technologies for early detection of deterioration for the long term:<br>-cement (alternative to MIT)<br>-Casing (feedback system using electrical signals) | 5 |
| $CO_2$ LEAKAGE (seal, above | Measurement and field test of $CO_2$ flow paths (full stack of reservoir rocks) | 5 |

| | | |
|---|---|---|
| seal, ground water, atm) | | |
| FINANCIAL/LEGAL (Trespass requirements) | conducting long term monitoring post injection audits | 5 |
| $CO_2$ PLUME AND PRESSURE | Improved high resolution saturation measurement tools -near and far from well bore<br>-Borehole gravity/seismic<br>-GM Methods<br>-Coupling of elastical and electrical data<br>-Application of integrated tools | 4 |
| REMEDIATION/MITIGATION | Optimize MVA systems to adapt to existing leak in order to quantify leak, locate leak, and inform mitigation | 4 |
| REMEDIATION/MITIGATION | Pre-established geomechanical model to describe stress fields and leakage conduits | 4 |
| IMPACT ON BIOSPHERE | Tools for baseline and time lapse monitoring interpretation | 4 |
| LONG TERM DATA SYSTEMS | Data collection management for 50 yrs of MVA | 4 |
| LONG TERM DATA SYSTEMS | Analysis techniques enabled by 50 yrs of data | 4 |
| WELL INTEGRITY | Understanding the exposure of cement and other well materials to long term contact with $CO_2$ | 4 |
| STORAGE INTEGRITY | Advanced seismic resolution of faults | 3 |
| STORAGE INTEGRITY | Special purpose, slim hole, low cost monitoring wells | 3 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Independent diagnostic technologies to determine if leakage is occurring without baseline | 3 |
| REMEDIATION/MITIGATION | MVA for seal integrity and flow ($CO_2$ saturation in seal) | 3 |
| REMEDIATION/MITIGATION | Customize MVA to leakage type and volume | 3 |
| STORAGE OPTIMIZATION | "Smart" $CO_2$ injection wells for zonal isolation, feedback systems, and wireless systems | 3 |
| STORAGE OPTIMIZATION | Detailed characterization of reservoir (electrical properties, clay content, etc) for designing monitoring system | 3 |
| STORAGE OPTIMIZATION | Optimizing and monitoring $CO_2$ storage in an oil field | 3 |
| STORAGE OPTIMIZATION | Need for field testing of MVA equipment at multiple sites (including safety) | 3 |
| FINANCIAL/LEGAL (Trespass | Multi resource areas baselines | 3 |

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|---|---|---|
| requirements) | | |
| $CO_2$ PLUME AND PRESSURE | High Resolution tiltmeters, especially for low permeability reservoirs | 2 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Establish impacts for alternative scales of leakage (alt. volumes of leakage) | 2 |
| REMEDIATION/MITIGATION | Below weathered zone horizontal monitoring wells (500 ft below ground surface) | 2 |
| STORAGE OPTIMIZATION | Multi well $CO_2$ field configuration for optimization of commercial storage | 2 |
| FINANCIAL/LEGAL (Trespass requirements) | Economic valuation of risk | 2 |
| STORAGE INTEGRITY | Geomechanical effects on fault systems and seals | 1 |
| STORAGE INTEGRITY | Need for field test of pressure and raw compression effects to identify leakage | 1 |
| $CO_2$ PLUME AND PRESSURE | More robust data bank on electrical properties of rocks | 1 |
| $CO_2$ PLUME AND PRESSURE | Integrated field test of plume and pressure tracking<br>-MVA test site | 1 |
| $CO_2$ PLUME AND PRESSURE | Higher Resolution (appropriate) use of seismic for tracking pressure and $CO_2$ plume | 1 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | In-depth studies of natural gas storage leakage systems (with adjustments for special properties of $CO_2$) | 1 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Models for temporal changes in baseline data | 1 |
| REMEDIATION/MITIGATION | High resolution testing of secondary reservoirs or caprocks to identify leaks | 1 |
| FINANCIAL/LEGAL (Trespass requirements) | Use natural gas storage fields for analogs | 1 |
| $CO_2$ PLUME AND PRESSURE | Understanding relationship of pressure front, brine front, and plume front | 0 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Coupling of MVA, risk assessment and reservoir modeling | 0 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Guidelines for establishing baseline for groundwater and soil monitoring | 0 |
| $CO_2$ LEAKAGE (seal, above seal, ground water, atm) | Improved interpretation capacity for soil gas surveys | 0 |
| REMEDIATION/MITIGATION | Adaptation of interference testing for existence of above zone leaks (pressure | 0 |

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| | network) | |
| STORAGE OPTIMIZATION | Using reservoir architecture to optimize $CO_2$ storage (feedback systems) | 0 |
| FINANCIAL/LEGAL (Trespass requirements) | Minimal requirements for due diligence | 0 |
| FINANCIAL/LEGAL (Trespass requirements) | Long term remediation/mitigation costs | 0 |

Tables AIV-5 to AIV-7 show the prioritized list of research needs obtained from the second stage of voting in which each person was allotted 3 votes. The second stage vote used a list of the top 10 research needs, which was derived from those needs which had received 5 or more votes in the first stage vote. The number of votes cast for each research need is shown in the right-hand column.

**Table AIV-5: MVA Short-Term Needs (<5 yrs) Vote 2**

| **Top 10 Short-Term Needs (<5 YRS)** | **Votes** |
|---|---|
| Improved high resolution saturation measurement tools -near and far from well bore (Borehole gravity/seismic, GM Methods, Coupling of elastical and electrical data, Application of integrated tools) | 10 |
| Geomechanical effects on fault systems and seal | 5 |
| Real time monitoring systems for identification and characterization of leaks | 5 |
| Long Term installation of robust high resolution monitoring systems | 5 |
| Use natural gas storage fields for analogs / In-depth studies of natural gas storage leakage systems (with adjustments for special properties of $CO_2$) | 4 |
| Optimizing and monitoring $CO_2$ storage in an oil field | 4 |
| Understanding the exposure of cement and other well materials to long term contact with $CO_2$ | 4 |
| Integration of reservoir characterization and MVA | 3 |
| Advanced seismic resolution of faults | 3 |
| Coupling of MVA, risk assessment and reservoir modeling | 2 |

**Table AIV-6: MVA Mid-Term Needs (5-10 yrs) Vote 2**

| Top 10 Mid-Term Needs (5-10 YRS) | Votes |
|---|---|
| Special purpose, slim hole, low cost monitoring wells | 10 |
| Long Term installation of robust high resolution monitoring systems | 8 |
| Understanding relationship of pressure front, brine front, and plume front | 5 |
| Improved high resolution saturation measurement tools -near and far from well bore (Borehole gravity/seismic, GM Methods, Coupling of elasticity? and electrical data, Application of integrated tools) | 4 |
| Integration of reservoir characterization and MVA | 4 |
| Measurement and field test of $CO_2$ flow paths (full stack of reservoir rocks) | 4 |
| "Smart" $CO_2$ injection wells for zonal isolation, feedback systems, and wireless systems | 3 |
| Technologies for early detection of deterioration for the long term:<br>-cement (alternative to MIT)<br>-Casing (feedback system using electrical signals) | 3 |
| More robust data bank on electrical properties of rocks | 3 |
| Integrated field test of plume and pressure tracking<br>-MVA test site | 1 |

**Table AIV-7: MVA Long-Term Needs (>10 yrs) Vote 2**

| Top 10 Long-Term Needs (>10 YRS) | Votes |
|---|---|
| Advanced large area MVA systems for near surface and atmosphere (LIDAR, Eddy Covariance, Automated data collection, Models) | 10 |
| Real time monitoring systems for identification and characterization of leaks | 7 |
| Permanently installed well monitoring system | 7 |
| Long Term installation of robust high resolution monitoring systems | 6 |
| Use of nanotechnology as tracers to measure fault reactivation | 4 |
| Automated data analysis for advanced pattern recognition (EG neural networks) | 3 |
| Technologies for early detection of deterioration for the long term (cement-alternative to MIT, Casing-feedback system using electrical signals) | 3 |
| Integration of reservoir characterization and MVA | 2 |
| Measurement and field test of $CO_2$ flow paths (full stack of reservoir rocks) | 2 |
| Defining optimal cost effective suite of MVA systems and tools (within seal, above zone, groundwater, atmosphere) | 1 |

# Appendix V: Geologic Storage Technologies Breakout Session Results

The following tables contain the results from the Geologic Storage Breakout Session. Table AV-1 shows the prioritized list of research gaps obtained from voting in which each person was allotted 5 votes. This breakout session voted only once on research gaps. The number of votes cast for each research gap is shown in the right-hand column.

**Table AV-1: Geologic Storage Research Gaps (Full List)**

| Research Gaps | Votes |
|---|---|
| natural system failures (faults, fractures, caprock) - don't know where vulnerabilities are/where intervention can occur, diagnosis to leaking mechanism | 6 |
| natural system failures (faults, fractures, caprock) - lack of techniques to reliably seal leaks (delivery materials) | 6 |
| different caprock behavior - shale salt carbonate/ borehole behavior and sealing achieving cement-caprock bond | 5 |
| $CO_2$ - how big a leak needs intervention | 5 |
| $CO_2$ - what are manifestations of leaks in the natural contaminated system and remote from injection well | 5 |
| non - $CO_2$ intervention (induced seismicity, pressure building, brine migration, land surface deformation) - how much injection reduction is needed to reduce induced seismic events | 5 |
| Long-term fate/behavior of well materials | 4 |
| non - $CO_2$ intervention (induced seismicity, pressure building, brine migration, land surface deformation) - what measures short of stopping a project can be used to remedy non-$CO_2$ issues | 4 |
| natural system failures (faults, fractures, caprock) - effectiveness of stopping injection on leakage reduction | 4 |
| develop slimhole/microhole drilling technology for monitoring | 3 |
| what metallurgy is really necessary | 3 |
| self-healing of wells - precipitation, mechanical deformation of cement and caprock, migration of fines | 2 |
| smart wells that communicate without wires "forever" (monitoring for outside annulus leaks) | 2 |
| well technology to control flow/conformance (e.g. perforations that can be opened/closed) | 2 |
| improve cement emplacement or understanding implications of cement inadequacy | 2 |
| wellbore failure - non injection wells - how do you know you have a problem (underground blowouts, slow leakage) | 2 |

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|---|---|
| wellbore failure - non injection wells - effective sealing technologies under relevant conditions and time frames | 2 |
| $CO_2$ - how do you evaluate the effectiveness of intervention mechanisms | 2 |
| effect of pressure buildup on storage capacity | 2 |
| what is the fluid environment/exposure to well materials | 1 |
| develop self healing cements - gels, biofilms, expansive cement, etc | 1 |
| $CO_2$ - effectiveness of natural attenuation for leak remediation e.g. self sealing | 1 |
| non - $CO_2$ intervention (induced seismicity, pressure building, brine migration, land surface deformation) – pre-injection characterization measures to avoid non$CO_2$ impacts | 1 |
| natural system failures (faults, fractures, caprock) - effectiveness of venting $CO_2$/brine to stop leaks | 1 |
| natural system failures (faults, fractures, caprock) - overpressure brine able leak to reverse gradient | 1 |
| understanding of geochemical effects on storage | 1 |
| sweep efficiency of $CO_2$ | 1 |
| impacts of depositional heterogeneity of reservoirs on $CO_2$ distribution and development of models that accommodate such | 1 |
| alternative cement formulations that are more compatible with $CO_2$-brine | 0 |
| perforation design for optimal $CO_2$ sweep | 0 |
| prevention of micro annuli w cement formulations | 0 |
| developing logging tools for proving integrity | 0 |
| understanding processes (MIT, data acquisition) on well integrity and on log interpretation | 0 |
| develop well technology to allow coupled monitoring and observation methods | 0 |
| develop models and experiments to understand how multiphase fluids migrate through external annulus | 0 |
| developing $CO_2$ - specific fracking methods (use $CO_2$ for fracking fluid) | 0 |
| remediation - grow/ecosystem, accessible for remediation, $CO_2$ brine | 0 |
| wellbore failure - non injection wells - post remedy success evaluation | 0 |

Tables AV-2 to AV-4 show the prioritized list of near-, mid-, and long-term research needs obtained from the first stage of voting in which each person was allotted 10 votes. The number of votes cast for each research need is shown in the right-hand column.

**Table AV-2: Geologic Storage Short-Term Needs (<5 yrs) Full List Vote 1**

| Short-Term Needs | Votes |
|---|---|
| post mortem studies of old wells (accelerated aging protocols and limitations | 8 |
| natural system failures (faults, fractures, caprock) - simulations and field verification of methods to stop leaks | 8 |
| Storage capacity - far field effects for pressure on geomechanics or other users and resources | 7 |
| natural system failures (faults, fractures, caprock) - identify, discover new techniques and materials for sealing leaks | 6 |
| non - $CO_2$ intervention (induced seismicity, pressure building, brine migration, land surface deformation) - research on plume steering, brine extraction, rate reduction to develop better understanding and approach | 6 |
| natural system failures (faults, fractures, caprock) - cost effective technology for detection and diagnosis | 6 |
| Storage capacity - capacity of nonclastic reservoirs | 6 |
| Storage capacity - what is the largest pressure that can buildup over the regional scale that will not result in increased seismicity | 5 |
| develop models and experiments to understand how multiphase fluids migrate through external annulus | 5 |
| wellbore failure - non injection wells - technology for detection and diagnosis of underground blowouts/slow leakage | 5 |
| Testing and monitoring techniques for $CO_2$ leakage intervention mechanisms | 5 |
| non - $CO_2$ intervention (induced seismicity, pressure building, brine migration, land surface deformation) - simulation (HMCT) of plume steering, brine extraction, rate reduction | 5 |
| Storage capacity - define common terminology | 5 |
| Storage capacity -regional understanding of pressure influence on local storage capacity | 5 |
| Storage capacity - water management related to pressure and plume - economics and benefits/costs footprint management | 5 |
| Storage capacity - systematic evaluation of heterogeneity on sweep efficiencies and plume footprint | 5 |
| Storage capacity - what are the geochemical impacts of $CO_2$ on the reservoir | 4 |
| invent and test cements that expand/bond/swell | 4 |
| effect of $CO_2$ on steel | 4 |

| | |
|---|---|
| Storage capacity - full-scale injection to stress geologic system (scale, plume, efficiency) | 3 |
| after leaks stop - what degree of remediation is needed - how long will it take | 3 |
| wellbore failure - non injection wells - tested, effective, and proven (under relevant conditions) material and delivery for sealing | 3 |
| wellbore failure - non injection wells - technologies to evaluate the effectiveness of sealing operations | 3 |
| Storage capacity - field measurement of sweep efficiency to validate models | 3 |
| Storage capacity - geomechanics of fault failure | 3 |
| Storage capacity - change in sweep efficiency with scale | 3 |
| Storage capacity - optimization of sweep efficiency | 3 |
| Storage capacity - scarcity of offshore and onshore data for capacity estimates | 3 |
| Storage capacity - scaling up from local to regional stresses | 3 |
| Storage capacity - funding of full field monitoring associated with large scale injection (regional pressure management and stress relationships) | 2 |
| apply sensors to determine fluid movement | 2 |
| effective methods for groundwater, vadose zone, ecosystems | 2 |
| wellbore failure - non injection wells - P&A wells - intervention/remediation technologies | 2 |
| Storage capacity - reservoir geomechanical field test of fault/failure geomechanics | 1 |
| field studies to examine those features | 1 |
| create and use field experiments | 1 |
| develop self healing cements (gels, biofilms, expansive cement | 1 |
| Storage capacity - is there a technology available to prevent natural system failure | 1 |
| Storage capacity - technologies that enhance natural containment | 0 |
| need to test emplacement methods to test long-term survival | 0 |
| computational field and experiments to develop technology | 0 |
| apply mineral coring (how to seal) | 0 |
| use $CO_2$ for fracking fluid | 0 |
| smart wells that communicate without wires "forever" | 0 |
| Storage capacity - technologies that can improve containment/injection operations | 0 |

**Table AV-3: Geologic Storage Mid-Term Needs (5-10 yrs) Full List Vote 1**

| Mid-Term Needs | Votes |
|---|---|
| Storage capacity - funding of full field monitoring associated with large scale injection (regional pressure management and stress relationships) | 7 |
| wellbore failure - non injection wells - technology for detection and diagnosis of underground blowouts/slow leakage | 6 |
| natural system failures (faults, fractures, caprock) - cost effective technology for detection and diagnosis | 6 |
| Storage capacity - field measurement of sweep efficiency to validate models | 6 |
| Storage capacity - what is the largest p that can buildup over regional scale that will not result in increased seismicity | 6 |
| post mortem studies of old wells (accelerated aging protocols and limitations | 5 |
| after leaks stop - what degree of remediation is needed - how long will it take | 5 |
| wellbore failure - non injection wells - tested, effective, and proven (under relevant conditions) material and delivery for sealing | 5 |
| non - $CO_2$ intervention (induced seismicity, pressure building, brine migration, land surface deformation) - research on plume steering, brine extraction, rate reduction to develop better understanding and approach | 5 |
| Storage capacity -regional understanding of pressure influence on local storage capacity | 5 |
| Storage capacity - scarcity of offshore and onshore data for capacity estimates | 5 |
| Storage capacity - full-scale injection to stress geologic system (scale, plume, efficiency) | 5 |
| Storage capacity - technologies that enhance natural containment | 5 |
| apply sensors to determine fluid movement | 4 |
| natural system failures (faults, fractures, caprock) - simulations and field verification of methods to stop leaks | 4 |
| Storage capacity - technologies that can improve containment | 4 |
| invent and test cements that expand/bond/swell | 3 |
| use $CO_2$ for fracking fluid | 3 |
| develop self healing cements (gels, biofilms, expansive cement | 3 |
| wellbore failure - non injection wells - technologies to evaluate the effectiveness of sealing operations | 3 |
| Testing and monitoring techniques for $CO_2$ leakage intervention mechanisms | 3 |
| non - $CO_2$ intervention (induced seismicity, pressure building, brine migration, land surface deformation) - simulation (HMCT) of plume steering, brine extraction, rate reduction | 3 |
| natural system failures (faults, fractures, caprock) - identify, discover new techniques and materials for sealing leaks | 3 |

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|---|---|
| Storage capacity - geomechanics of fault failure | 3 |
| Storage capacity - technologies that can improve injection operations | 3 |
| Storage capacity - is there a technology available to prevent natural system failure | 3 |
| Storage capacity - capacity of nonclastic reservoirs | 3 |
| Storage capacity - systematic evaluation of heterogeneity on sweep efficiencies and plume footprint | 3 |
| Storage capacity - reservoir geomechanical field test of fault/failure geomechanics | 3 |
| apply mineral coring (how to seal) | 2 |
| create and use field experiments | 2 |
| effect of $CO_2$ on steel | 2 |
| develop models and experiments to understand how multiphase fluids migrate through external annulus | 2 |
| smart wells that communicate without wires "forever" | 2 |
| wellbore failure - non injection wells - P&A wells - intervention/remediation technologies | 2 |
| Storage capacity - far field effects for pressure on geomechanics or other users and resources | 2 |
| Storage capacity - water management related to pressure and plume - economics and benefits/costs footprint management | 2 |
| Storage capacity - optimization of sweep efficiency | 2 |
| Storage capacity - scaling up from local LOT to regional stresses | 2 |
| Storage capacity - what are the geochemical impacts of $CO_2$ on reservoir | 2 |
| need to test emplacement methods test long-term survival | 1 |
| computational field and experiments to develop technology | 1 |
| effective methods for groundwater, vadose zone, ecosystems | 1 |
| Storage capacity - change in sweep efficiency w scale | 1 |
| field studies to examine those features | 0 |
| Storage capacity - define common terminology | 0 |

**Table AV-4: Geologic Storage Long-Term Needs (>10 yrs) Full List Vote 1**

| Long-Term Needs | Votes |
|---|---|
| smart wells that communicate without wires "forever" | 7 |
| natural system failures (faults, fractures, caprock) - simulations and field verification of methods to stop leaks | 7 |
| Storage capacity - water management related to pressure and plume - economics and benefits/costs footprint management | 7 |
| Storage capacity - full-scale injection to stress geologic system (scale, plume, efficiency) | 7 |
| wellbore failure - non injection wells - technology for detection and diagnosis of underground blowouts/slow leakage | 6 |
| natural system failures (faults, fractures, caprock) - cost effective technology for detection and diagnosis | 6 |
| natural system failures (faults, fractures, caprock) - identify, discover new techniques and materials for sealing leaks | 6 |
| use $CO_2$ for fracking fluid | 5 |
| after leaks stop - what degree of remediation is needed - how long will it take | 5 |
| Testing and monitoring techniques for $CO_2$ leakage intervention mechanisms | 5 |
| Storage capacity - scarcity of offshore and onshore data for capacity estimates | 5 |
| Storage capacity - technologies that enhance natural containment | 5 |
| wellbore failure - non injection wells - technologies to evaluate the effectiveness of sealing operations | 4 |
| non - $CO_2$ intervention (induced seismicity, pressure building, brine migration, land surface deformation) - simulation (HMCT) of plume steering, brine extraction, rate reduction | 4 |
| Storage capacity - funding of full field monitoring associated with large scale injection (regional pressure management and stress relationships) | 4 |
| post mortem studies of old wells (accelerated aging protocols and limitations | 3 |
| need to test emplacement methods test long-term survival | 3 |
| effective methods for groundwater, vadose zone, ecosystems | 3 |
| non - $CO_2$ intervention (induced seismicity, pressure building, brine migration, land surface deformation) - research on plume steering, brine extraction, rate reduction to develop better understanding and approach | 3 |
| Storage capacity -regional understanding of pressure influence on local storage capacity | 3 |
| Storage capacity - far field effects for pressure on geomechanics on other users and resources | 3 |
| Storage capacity - field measurement of sweep efficiency to validate models | 3 |
| Storage capacity - systematic evaluation of heterogeneity on sweep efficiencies and plume footprint | 3 |

| | |
|---|---|
| Storage capacity - change in sweep efficiency w scale | 3 |
| Storage capacity - scaling up from local LOT to regional stresses | 3 |
| Storage capacity - reservoir geomechanical field test of fault/failure geomechanics | 3 |
| Storage capacity - what are the geochemical impacts of $CO_2$ on reservoir | 3 |
| computational field and experiments to develop technology | 2 |
| invent and test cements that expand/bond/swell | 2 |
| develop self healing cements (gels, biofilms, expansive cement | 2 |
| wellbore failure - non injection wells - tested, effective, and proven (under relevant conditions) material and delivery for sealing | 2 |
| Storage capacity - technologies that can improve containment | 2 |
| Storage capacity - technologies that can improve injection operations | 2 |
| Storage capacity - optimization of sweep efficiency | 2 |
| Storage capacity - what is the largest p that can buildup over regional scale that will not result seismicity | 2 |
| apply sensors to determine fluid movement | 1 |
| field studies to examine those features | 1 |
| apply mineral coring (how to seal) | 1 |
| create and use field experiments | 1 |
| wellbore failure - non injection wells - P&A wells - intervention/remediation technologies | 1 |
| Storage capacity - geomechanics of fault failure | 1 |
| Storage capacity - is there a technology available to prevent natural system failure | 1 |
| Storage capacity - capacity of nonclastic reservoirs | 1 |
| effect of $CO_2$ on steel | 0 |
| develop models and experiments to understand how multiphase fluids migrate through external annulus | 0 |
| Storage capacity - define common terminology | 0 |

Tables AV-5 to AV-7 show the prioritized list of research needs obtained from the second stage of voting in which each person was allotted 3 votes. The second stage vote used a list of the top 8 research needs, which was derived from those needs which had received 5 or more votes in the first stage vote. The number of votes cast for each research need is shown in the right-hand column.

**Table AV-5: Geologic Storage Short-Term Needs (<5 yrs) Vote 2**

| Short-Term Needs | Votes |
|---|---|
| natural system leakage detection and intervention away from the injection well | 13 |
| storage capacity - press effects on seismicity, AOR, other users and resources | 10 |
| sweep efficiency of all rocks | 6* |
| post mortem studies of old wells (accelerated aging protocols and limitations) | 5* |
| storage capacity of nonclastic reservoirs | 4 |
| intervention methods evaluation and validation | 4 |
| develop models and experiments to understand how multiphase fluids migrate through external annulus | 1 |
| storage capacity common terminology | 0 |

**After voting there was lengthy discussion and the group ultimately reversed the priority of these two needs.*

**Table AV-6: Geologic Storage Mid-Term Needs (5-10 yrs) Vote 2**

| Mid-Term Needs | Votes |
|---|---|
| storage capacity - pressure effects on seismicity, AOR, other users and resources | 11 |
| natural system leakage detection and intervention away from the injection well | 9 |
| Storage capacity - field measurement of sweep efficiency to validate models | 9 |
| Storage capacity - scarcity of offshore and onshore data for capacity estimates | 7 |
| after leaks stop - what degree of remediation is needed - how long will it take | 5 |
| Storage capacity - technologies that enhance natural containment | 5 |
| post mortem studies of old wells (accelerated aging protocols and limitations | 2 |
| intervention methods evaluation and validation for non-$CO_2$ (brine) | 0 |

**Table AV-7: Geologic Storage Long-Term Needs (>10 yrs) Vote 2**

| Long-Term Needs | Votes |
|---|---|
| Storage capacity - full-scale injection to stress geologic system (scale, plume, efficiency) | 12 |
| Storage capacity - water management related to pressure and plume - economics and benefits/costs footprint management | 10 |
| natural system leakage detection and intervention away from the injection well | 9 |
| after leaks stop - what degree of remediation is needed - how long will it take | 6 |
| smart wells that communicate without wires "forever" | 4 |
| Storage capacity - scarcity of offshore and onshore data for capacity estimates | 3 |
| Testing and monitoring techniques for $CO_2$ leakage intervention mechanisms | 2 |
| Storage capacity - technologies that enhance natural containment | 2 |
| use $CO_2$ for fracking fluid | 0 |