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Integrated CCS for Kansas (ICKan)

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Research Performance Progress Report (Quarterly)

Submitted to:
The Department of Energy
National Energy Technology Laboratory

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Signature of submitting official:

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INTRODUCTION

A. OBJECTIVES

This *Phase I- Integrated CCS Pre-Feasibility Study* activity under CarbonSAFE will evaluate and develop a plan and strategy to address the challenges and opportunities for commercial-scale Carbon Capture and Storage (CCS) in Kansas, *ICKan (Integrated CCS for Kansas)*. The objectives of *ICKan* include identifying and addressing the major technical and nontechnical challenges of implementing CO_2 capture and transport and establishing secure geologic storage for CO_2 in Kansas. The study will examine three of Kansas' largest CO_2 point sources and corresponding storage sites, each with an estimated 50+ million tons capacity (of saline aquifer storage), and a local transportation network to connect with nearby geologic storage. The project will also provide high level technical sub-basinal evaluation, building on previous characterization of the regional stacked storage complex.

B. SCOPE OF WORK

ACCS Coordination Team will examine three of Kansas' largest CO_2 point sources and corresponding storage sites, each with an estimated 50+ million tons capacity, and a local transportation network to connect with nearby geologic storage. ICKan will evaluate and develop a plan and strategy to address the challenges and opportunities for commercial-scale CCS in Kansas. The *Team* will identify and address the major technical and nontechnical challenges of implementing capture, transportation, and secure geologic storage of CO_2 in Kansas.

The ICKan and CCS Coordination Team will generate information that will allow DOE to make a determination of the proposed storage complex's level of readiness for additional development under Phase II, by establishing and addressing the key challenges in commercial scale capture, transportation, and storage in this investigation.

C. TASKS TO BE PERFORMED

Task 1.0 – Project Management and Planning Integrated CCS for Kansas (ICKan)
This Task includes the necessary activities to ensure coordination and planning of the project with DOE/NETL and other project participants. These activities include, but are not limited to, the monitoring and controlling of project scope, cost, schedule, and risk, and the submission and approval of required National Environmental Policy Act (NEPA) documentation

This Task includes all work elements required to maintain and revise the Project Management Plan, and to manage and report on activities in accordance with the plan.

Subtask 1.1 - Fulfill requirements for National Environmental Policy Act (NEPA) documentation
Phase I shall not involve work in the field, thus the activities shall have no adverse impact on the environment. Potential future activities that could have negative environmental impact in subsequent project phases will be documented in the Phase I reports.

Subtask 1.2 - Conduct a kick-off meeting to set expectations
The PIs shall layout expectations for adherence to scope, schedule, budget, risk management, and overall project plan in an "all-hands" meeting within the first four weeks of project initiation. The PIs shall provide protocols and reporting mechanisms for notice of modifications.

Subtask 1.3 - Conduct regularly scheduled meetings and update tracking

The team shall hold regularly scheduled monthly meetings including all personnel and subcontractors via conference calls or online videoconferences. The PIs shall update scope, tasks, schedule, costs, risks, and distribute to the DOE and the project team. Accountability shall be encouraged by the monthly review sessions. The PIs shall hold full CCS team meetings (including CO_2sources and field operators) quarterly.

Subtask 1.4 - Monitor and control project scope
PIs shall evaluate and analyze monthly reports from all team section leads ensuring compliance with the requirements of DOE.

Subtask 1.5- Monitor and control project schedule
PIs shall closely monitor adherence to the project schedule, facilitated by monthly project team meetings. Schedule tracking and modifications shall be provided to the team on a monthly basis. PI will monitor resources to ensure timely completion of tasks.

Subtask 1.6 - Monitor and control project risk
Project risks and mitigation protocol shall be discussed with the team at the beginning of the project to help limit risks being realized and help recognize patterns that could signal increased risk.

Subtask 1.7 - Finalize the DMP. The DMP and its components shall be finalized by the PI. Information acquired, during the project, will be shared via the NETL-EDX data portal including basic and derived information used to describe and interpret the data and supplementary information to a published document. Information will be protected in accordance with the usage agreements and licenses of those who contribute the data.

Subtask 1.8 - Revisions to the PMP after submission
The PMP shall be updated as needed, including:1) details from the negotiation process through consultation with the Federal Project Officer, 2) revisions in schedule, 3) modifications in the budget, 4) changes in scope and tasks, 5) additions or changes in personnel, and 5) other material changes in the project.

Subtask 1.9 - Develop an integrated strategy/business plan for commercial scale CCS
The PIs shall set goals and timelines in early meetings and the team shall develop and build on strategy that will be documented in a business plan.

Task 2.0 – Establish a Carbon Capture and Storage (CCS) Coordination Team
The PIs shall develop a multidisciplinary team capable of addressing technical and non-technical challenges specific to commercial-scale deployment of the CO_2storage project. The Phase I team will 1) determine if any additional expertise and manpower required for Phase II, 2) recommend individuals, groups or institutions to fill any additional needs that are identified, and 3) assist in the recruitment and gaining formal commitments by key individuals or institutions for Phase II.

Subtask 2.1 - Identify additional CCS team members
Identify additional team members required to evaluate; 1) geologic storage complex, 2) large-scale anthropogenic sources and approaches to capturing CO_2, 3) transportation/delivery systems from source to the geologic complexes and injection into the storage reservoir, 4)costs, economics and financial requirements, 5) legal and political challenges, and 6) public outreach for the Phase II effort. Future needs will also be evaluated and additional team members will be selected if there are additional gaps in technical or non-technical areas that would be advisable to fill.

Subtask 2.2 - Identify additional stakeholders that should be added to the CCS team
The team will identify possible additional stakeholders that could include environmental groups, business

groups, state legislators, state organizations (commerce), rate-payer organizations, land use and land owner groups.

Subtask 2.3 - Recruit and gain commitment of additional CCS team members identified
A comprehensive review of the gap analyses and develop recommendations of additional individuals, groups or institutions which should be filled before proceeding to Phase II. The CCS team shall identify primary and secondary choices, recruit, and gain commitments for possible participation in Phase II.

Subtask 2.4 - Conduct a formal meeting that includes the Phase I team and committed Phase II team members
A one-day working meeting will be conducted to1) review Phase I preliminary results, 2) present draft plans for Phase II, and3) gather input from recruited potential Phase II members. The meeting shall be held at the KGS or a mutually agreed upon alternate site with an option to participate by videoconferencing.

Task 3.0 – Develop a plan to address challenges of a commercial-scale CCS Project
This application presents three candidate sources and identifies three possible geologic complexes suitable for storage. Phase I work shall determine which are most feasible, and shall identify and develop a preliminary plan to address the unique challenges of each source/geologic complex that may be feasible for commercial-scale CCS (50+ million tonnes captured and stored in a saline aquifer). Reliable and tested approaches, such as Road mapping and related activities (Phaal, et al., 2004, Gonzales-Salavar, et al., 2016; IEA, 2013: DOE, 2003) shall be used to identify, select, and establish alternative technical and non-technical options based on sound, transparent analyses including monitoring for adjustment as the assessment matures.

Subtask 3.1 - Identify challenges and develop a plan to address challenges for CO_2 capture from anthropogenic sources
A plan will be developed that addresses CO_2 capture including use of plant configuration, current and anticipated operating conditions, product distribution (e.g. electrical power grid), and regulatory uncertainty.

Subtask 3.2 - Identify challenges and develop a plan to address challenges for CO_2 transportation and injection
A plan will be developed that describes challenges specific to Kansas to deliver $CO_2$to the injection well(s) including addressing regulations, right of way, pipeline configuration, maintenance, safety, and deliverability.

Subtask 3.3 - Identify challenges and develop a plan to address challenges for CO_2 storage in geologic complexes
The KGS shall evaluate candidate geological complexes for technical risks (capacity, seal, faults, seismicity, pressure, existing wellbores), economics (location/distance, injectivity, availability), and legal (pore space rights, liability) and document the results in a plan.

Task 4.0 – Perform a high level technical sub-basinal evaluation using NRAP and related DOE tools
Three candidate sources and two possible storage complexes were identified. Phase I work shall determine which are most feasible, and will identify and develop a plan to address the unique challenges of each storage complex that may be feasible for commercial-scale CCS (50+ Mt captured and stored in a saline aquifer).Each location will be evaluated using NRAP models and the results shall be submitted to DOE.

Subtask 4.1 - Review storage capacity of geologic complexes identified in this proposal and consider alternatives

Three possible sites in two complexes are in various stages of analysis and each appears to meet the50+Mt storage requirement. They shall be further evaluated and a survey of other potential geologic structures will undergo a rigorous site screening and selection process to determine suitability.

Subtask 4.2 - Conduct high-level technical analysis of suitable geologic complexes using NRAP- IAM-CS and other tools for integrated assessment
The KGS shall evaluate candidate storage complexes in terms of capacity, seal, faults, seismicity, pressure, existing wellbores, and injectivity.

Subtask 4.3 - Compare results using NRAP with methods used in prior DOE contracts including regional and sub-basin CO_2 storage
The CCS team shall use the results of the NRAP models obtained in this study with the regional simulation of CO_2 storage in southern Kansas to provide an assessment of risk to this greater area and compare with findings of project DE-FE0002056, including Pleasant Prairie Field and other potentially prospective storage sites (e.g., Eubank, Cutter, and Shuck fields).

Subtask 4.4 - Develop an implementation plan and strategy for commercial-scale, safe and effective CO_2 storage
A technology roadmap or similar methodology shall be used to convey a detailed realistic implementation plan and strategy that shall utilize the experience gained by the KGS in developing a US EPA Class VI permit. The result shall be based on a sound analysis that meets the goals of stakeholders, defines effective action, and is adaptable and open for review and updates as conditions change, e.g., new technology breakthroughs, incentivizing, and market conditions (McDowall, 2012).

Task 5.0 – Perform a high level technical CO_2 source assessment for capture
An assessment of the capture technologies best suited for efficiency, addressing the concerns of the electric utilities and their operating requirements and economic needs will be performed.

Subtask 5.1 - Review current technologies and CO_2 sources of team members and nearby sources using NATCARB, Global CO_2 Storage Portal, and KDM
The CCS team shall develop an organized electronic clearinghouse of vital information pertaining to the project, ranked by suitability, historical usage records, adaptability, scaling, and demonstration of success, and operations and maintenance requirements.

Subtask 5.2 - Determine novel technologies or approaches for CO_2 capture
CO_2 sources shall carefully be evaluated for suitability with new capture technologies. The evaluation will utilize private research including that sponsored by DOE and results of international efforts and projects such as DOE’s Carbon Capture Simulation Initiative (CCSI) to determine the suitability and rational for making decisions to pursue or table the technology.

Subtask 5.3 - Develop an implementation plan and strategy for cost effective and reliable carbon capture
An optimal CCS plan and strategy that best represents the holistic operating environment and requirements of the CO_2 sources will be developed. The team shall develop a means to ensure a mechanism to update and adapt to new disruptive technologies and possibly accommodate them in the design document.

Task 6.0 – Perform a high level technical assessment for CO_2 transportation
The CCS team shall consider best practices in pipeline design to ensure safety, security, and compliance with regulations in force in Kansas and other states were the pipeline may extend.

Subtask 6.1 - Review current technologies for CO_2 transportation
The CCS team shall address the challenges in pipeline transportation and shall catalog and classify the

technologies best suited for use in Kansas.

Subtask 6.2 - Determine novel technologies or approaches for CO_2 transportation
The CCS team shall review the challenges and solutions conveyed by current research and development and using a SWOT analysis determine the suitability and rational for making a decision to pursue or table transportation technologies.

Subtask 6.3 - Develop a plan for cost-efficient and secure transportation infrastructure
The CCS team shall develop an optimal plan and strategy for aCO_2distribution system that aligns with the needs of the proposed CO_2 sources and the storage complex put forth by the team.

Task 7.0 – Technology Transfer

Subtask 7.1 - Maintain website on KGS server to facilitate effective and efficient interaction of the team
The KGS shall create and maintain a web site available to both the members of the CCS team and the public. A non-secured site portion of the site shall be dedicated to apprising the public on the status of the on-going project as well as publishing the acquired data. The format of the public site shall be directed toward both technical and non-technical audiences. The public site will contain all non- confidential reports, public presentations, and papers. All data developed by the project or interpretation of existing data, performed by the project, shall be uploaded to EDX (edx.netl.doe.gov).

Subtask 7.2 - Public presentations
Progress and information gained from the study shall be convey to the public when deemed appropriate to enable an understanding of issues, concerns, and solutions for Integrated CCS in Kansas, *ICKan*. A focused dialog with interested stakeholders shall be sought through informational meetings and workshops that correspond with formal reporting to DOE including intermediate results and the final report. Prior to the final report being released, the CCS team shall invite key stakeholders and interest groups to participate in addressing the general topics of CCS and to comment on the plan and strategy through a conference and workshop in order build public support for taking the next steps in ICKan.

Subtask 7.3 - Publications
The CCS team shall publish methodologies, findings, and recommendations.

D. DELIVERABLES

Reports will be submitted in accordance with the attached "Federal Assistance Reporting Checklist" and the instructions accompanying the checklist.

In addition to the reports specified in the "Federal Assistance Reporting Checklist", the Recipient will provide the following to the DOE Project Officer.

Data Submitted to NETL-EDX
Data generated as a result of this project shall be submitted to NETL for inclusion in the NETL Energy Data eXchange (EDX), https://edx.netl.doe.gov/. The Recipient will work with the DOE Project Officer to assess if there is data that should be submitted to EDX and identify the proper file formats prior to submission. All final data generated by this project shall be submitted to EDX including, but not limited to: 1) datasets and files, 2) metadata, 3) software/tools, and 4) articles developed as part of this project.

Other key deliverable include:

- Task 1.0–Project Management Plan
- Task 1.10 – Technical report on *Integrated Strategy For Commercial-Scale CCS Project*
- Task 2.0 – Commitment letters from fully formed *CCS Coordination Team*
- Task 3.0 – Technical report on *Plan to Address Challenges of the Commercial-Scale CCS Project*
- Task 4.0 – Technical report on *High-Level Sub-Basinal Evaluations*
- Task 5.0 – Technical report on *High-Level CO_2 Source Assessment for Capture*
- Task 6.0 – Technical report on *High-Level Assessment for CO_2 Transportation*
- Initial Business Plan that describes the selected source, capture technology, transportation route, and injection site(s), in a saline aquifer, with anticipated surface and subsurface infrastructure requirements. Additionally, a data gap analysis should be performed and include a discussion on the missing data and how the identified data gaps will be filled. There should be a discussion on non-technical issues such as outreach, political aspects of the project, legal requirements such as pore space ownership, permitting requirements, and the ownership of the CO_2/liability throughout the process of capturing, transportation and injection. An economic analysis should be performed that includes anticipated costs for filling in data gaps, anticipated capital expenditures, construction costs, and future system operational expenditures for the proposed CCS system. There should be a list of anticipated sources of funding and strategies to pay for the installation and the operation of the CCS system. The business plan should also have discussions on how the costs of oil will affect the financing of the project and at what price point will it be economically feasible.

E. BRIEFINGS/TECHNICAL PRESENTATIONS

The Recipient shall prepare detailed briefings for presentation to the Project Officer at a location(s) to be designated by the Project Officer, which may include the Project Officer's facility located in Pittsburgh, PA or Morgantown, WV. The Recipient shall make a presentation to the NETL Project Officer/Manager at a project kick-off meeting held within ninety (90) days of the project start date. At a minimum, annual briefings shall also be given by the Recipient to explain the plans, progress, and results of the technical effort and a final project briefing prior to the close of the project shall also be given.

The Recipient shall also provide monthly E-mail updates on the status of the project to the FPM.

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Accomplishments

Task 1.0 – Project Management and Planning Integrated CCS for Kansas

Subtask 1.1 - Fulfill requirements for National Environmental Policy Act documentation

Completed in Q1.

Subtask 1.2 - Conduct a kick-off meeting to set expectations

Completed in Q1.

Subtask 1.3 - Conduct regularly scheduled meetings and update tracking

KGS Team Meetings:
Team meetings were held monthly. Topics focused primarily on technical updates for identifying geologic sites and planning as well as follow-up on for the All Hands wrapu-up meeting held on July 26th.

Full Team Meeting:
The All-Hands wrap-up meeting was held on 07/26/2018. A summary of the meeting and key details are below:

On July 26, 2018 the Kansas Geological Survey (KGS) and the State CO_2 EOR Deployment Workgroup (State Workgroup) hosted its second Carbon Capture and Utilization in Kansas conference. The meeting was held in the Beren Conference Center in the recently opened Earth Energy & Environment Center at the University of Kansas.

Nearly seventy individuals with wide-ranging interests and from different industry sectors participated in the one-day conference, including representatives from CO_2 sources (coal power and ethanol plants), geologic sites (oil and gas industry—four largest oil producers in Kansas and largest CO_2-EOR company in the U.S.), regulatory and public policy, governmental officials and scientists and researchers involved in two U.S. DOE-funded Phase 1 CarbonSAFE projects. Kansas government dignitaries included Andrew Wiens, Chief Policy Office for Governor Colyer, State representatives Tom Sloan and Mark Schreiber, and Commissioner Dwight Keen. On the regulatory and agency side, representatives from EPA Region 7, Kansas Department of Health and Environment, Kansas Corporation Commission, and the U.S. Department of Energy participated.

Four main meeting objectives were accomplished through ten presentations, topical breakout sessions followed by an all-group discussion.

- Report on DOE-funded Integrated Carbon Capture Utilization and Storage (CCUS) for Kansas (Phase I) and plans for Phase II.
- Discuss regional and national CCUS initiatives, anticipated activities related to 45Q, and the State CO_2-EOR Deployment Work Group.
- Identify economic opportunities from an industry perspective in Kansas and the region.
- Networking for a collaborative carbon capture and EOR initiative in Kansas and surrounding states.

Brad Crabtree provided an update on the recent and future efforts by the State Workgroup and the Carbon Capture Coalition (formerly the National Enhanced Oil Recovery Institute – NEORI). The State Workgroup is an organization managed by Great Plains Institute, a partner in the ICKan project. It is comprised of state officials from 14, mostly central U.S. states, along with private sector stakeholders and experts seeking to accelerate the deployment of carbon capture from power plants and industrial facilities and increase the use of anthropogenic CO_2 in enhanced oil recovery, while safely and permanently storing the CO_2 underground in the process. Crabtree recapped the passage of the FUTURES Act expanding and extending 45Q tax credits for CO_2 EOR and storage, in which the State Workgroup and NEORI were instrumental, and outline additional legislative initiatives that could help facilitate wide-spread deployment USE IT Act and the Carbon Utilization Act.

A highlight of the meeting were presentations by both White Energy (CEO Greg Thompson) and Occidental Petroleum (Al Collins, Senior Director Regulatory Affairs and Charlene Russell, VP Low Carbon Ventures). They discussed their recently announced CCUS partnership. CO_2 from two White Energy Texas Panhandle ethanol plants will be captured, compressed and pipelined to OXY's Permian Basin oil fields for EOR and concurrent storage.

CarbonSAFE projects reviewed

Four presentations provided an update and results of the Kansas Geological Survey managed CarbonSAFE Phase 1 ICKan project and an introduction to the Phase 2 project in which the KGS will participate:

- Overview of ICKan: Integrated Carbon Capture and Storage in Kansas – Eugene Holubnyak, Kansas Geological Survey
- Known Unknowns: Legal, Regulatory and Public Policy Issues with CCS and CCUS and Possible Solutions – Joe Schremmer, Depew Gillen Rathbun & McInteer, LC
- Economics for CO_2 Capture, Compression and Transportation in the Mid-Continent – Martin Dubois, Improved Hydrocarbon Recovery, LLC
- Integrated Midcontinent Stacked Carbon Storage Hub - Andrew Duguid, Battelle

Industry perspective

Industry point of views from three sectors, oil and gas, ethanol, and midstream, were presented by Dana Wreath (Berexco LLC), Scott McDonald (Archer Daniels Midland) and Keith Tracy (CornerPost CO_2 LLC).

Breakout sessions and all-group discussions

Much of the afternoon session was devoted to lively discussions in breakout sessions defined by topic followed by an all-group discussion that concluded with an informal plan for future engagement by the stakeholders in CCUS for Kansas and the region. There were three breakout groups covering 1) CO_2 Sources, Capture and Transportation, 2) Geologic Sites for EOR and Saline Storage, and 3) Legal/Regulatory/Public Policy. The groups discussed challenges and possible solutions specific to the group and identified issues that cross-cut with other sectors. The all-group discussions that followed focused on topics that impact all stakeholders and sectors: 1) Understanding 45Q, 2) Feasibility for largescale infrastructure project in the Midcontinent, 3) Aggregation of CO_2 from relatively small, disparate sources, Class VI wells. Please see the Summary of Discussions documents for details (www.kgs.ku.edu/PRS/ICKan).

Figure 1. Andrew Wiens, Chief Policy Officer for Kansas Governor Jeff Colyer gives welcoming remarks during the morning session. Wiens commented that the first official letter Governor Colyer signed after being sworn in to office was in support of Phase II of the ongoing KGS CO_2 project. Governor Colyer was unable to attend due to a busy campaign season.

Figure 2. Eugene Holubnyak, Kansas Geological Survey and Co-PI, gives an overview of the KGS CarbonSAFE Phase 1 study: Integrated Carbon Capture and Storage in Kansas (ICKan).

Figure 3. Dana Wreath, Vice President at Berexco, LLC. gives his view on strategies and considerations for operators to enter into the CCUS market and reviewed Berexco's CO_2 EOR pilot project. Berexco has been a valuable and long-time partner in KGS CO_2 research.

Other:
The KGS team became better acquainted with Battelle and other Phase II participants. Ongoing Phase I work was prepared to transition into Phase II strategies.

KGS, IHR, and Linde representatives made a site visit to the Holcomb power plant on July 27th 2018. Discussions focused on capture, economics, and the potential for CCUS commercialization in the near-term.

Subtask 1.4 - Monitor and control project scope

The KGS held regular monthly and bimonthly meetings with the team to discuss the status of deliverables and evaluate tasks. Participants provided a brief overview of their work and discussed synthesis for the Final Report.

Subtask 1.5 - Monitor and control project schedule

The project schedule was reviewed during monthly and bimonthly meetings with the team.

Subtask 1.6 - Monitor and control project risk

Risks were evaluated in an ongoing basis within normal workflow. Larger concerns were presented in team meetings where in-depth discussions could be held. Many of these risks were evaluated during the All-Hands meeting in July as well as follow up discussions with regulatory and industry partners.

Subtask 1.7 - Finalize the DMP.

Completed in Q3.

Subtask 1.8 - Revisions to the PMP after submission

Nothing to report.

Subtask 1.9 - Develop an integrated strategy/business plan for commercial scale CCS

This topic was discussed in extensively during the All-Team meeting and follow up meetings.

Task 2.0 – Establish a Carbon Capture and Storage (CCS) Coordination Team

The Integrated CCUS for Kansas and Nebraska Integrated Carbon Capture and Storage Pre-Feasibility Study, led by Energy & Environmental Research Center, Phase I projects joined Battelle Memorial Institute's Integrated Mid-Continent Carbon Stacked Storage Hub (DE-FE0029264), in a single CarbonSAFE Phase II proposal. Possible gaps in the CCS coordination team for the combined project were identified in a December 5, 2017 meeting of the three projects in held in Lincoln, Nebraska, and in subsequent conference calls. ICKan secured additional industry partners and stakeholder as well as commitments from key Phase I partners.

Subtask 2.1 - Identify additional CCS team members

Completed in Q3-Q4.

Subtask 2.2 - Identify additional stakeholders that should be added to the CCS team

Completed in Q3.

Subtask 2.3 - Recruit and gain commitment of additional CCS team members identified

Completed in Q3.

Subtask 2.4 - Conduct a formal meeting that includes the Phase I team and committed Phase II team members

A full ICKan project meeting was held on July 26th that included all ICKan Phase I participants as well as newly recruited industry partners and stakeholders.

Significant activities and accomplishments in the reporting period for Task 2 include the following:

- Awarded Phase II funding for project titled Integrated Midcontinent Stacked Carbon Storage Hub, announced on May 24, 2018. DOE Funding: $9,637,962; Non-DOE Funding: $3,701,000; Total Value: $13,338,962. This project combines three Phase I projects led by the KGS, Battelle and EERC. Battelle is the lead on the Storage Hub project. This project was introduced at the July 26th meeting.

Goals and objectives for the next Quarter:

All data and findings will be synthesized into the Final Report which will be submitted by December 2018.

Products for Task 2.0:

No physical products for Q6.

Task 3.0 – Develop a plan to address challenges of a commercial-scale CCS Project

Subtask 3.1 - Identify challenges and develop a plan to address challenges for CO2 capture from anthropogenic sources

A plan will be developed that addresses CO_2 capture, including use of plant configuration, current and anticipated operating conditions, product distribution (e.g. electrical power grid), and regulatory uncertainty.

The ICKan proposal presented three candidate sources for CO_2 capture. The objective of Phase I work is to determine which are most feasible, and to identify and develop a preliminary plan to address the unique challenges of each source that may be feasible for commercial-scale CCS (50+ million tonnes captured and stored in a saline aquifer). Although no time frame was defined by FOA15824 for the processing of 50 million tonnes, the ICKan project set 2.5 million tonnes/year over a 20-year period as a target.

Summary of Activities:
Linde has performed a preliminary design and economic analysis to determine the feasibility of implementing carbon capture at the Sunflower Electric Power Corporation-Holcomb Station. The summary and details of this assessment have been discussed with the Sunflower Electric Power Corporation team members.

Significant Results/Key Outcomes:
Results of implementing carbon capture at the identified facilities will be described in the Final Technical Report.

Goals and objectives for the next Quarter:
Capture cost estimates will be completed and the team will integrate the costs for capture into the integrated project economics for the Final Technical Report.

Products for Subtask 3.1:
A preliminary design and economic anlaysis report for the Sunflower Plant will be included in the Final Technical Report.

Subtask 3.2 - Identify challenges and develop a plan to address challenges for CO_2 transportation and injection (non-technical)

Subtask 3.3 - Identify challenges and develop a plan to address challenges for CO_2 storage in geologic complexes (non-technical)

Note - The SOPO combined technical and non-technical aspects of the Phase I project in Task 3, in particular Subtasks 3.2 and 3.3. To simplify for reporting and for the reader, the technical and non-technical are discussed separately. Furthermore, the non-technical subject matter pertaining to Subtasks 3.2 and 3.3 have considerable overlap and will be combined for this and future reports.

<u>Subtasks 3.2 and 3.3 Non-Technical Section:</u>

Overview
The ICKan Legal, Regulatory and Public Policy team (LRPP), is comprised of attorneys from Depew Gillen

Rathbun & McInteer (DGRM), public policy experts from Great Plains Institute and the Kansas Geological Survey outreach manager. In this quarter LRPP continued their dialogues with State and Federal regulators and agencies, worked towards a better understanding of Class VI wells, and developed a preliminary plan to address business and contractual requirements to address technical and financial risks.

Significant activities and accomplishments in the reporting period for Subtasks 3.2 and 3.3 include the following:

1. Continued discussions with the Kansas Corporation Commission.
2. Communicated with stakeholders for support of the ICKan all team meeting and CCUS in Kansas conference.

Goals and objectives for the next Quarter (non-technical)**:**

- Compile summary of results of non-technical part of Subtasks 3.2 and 3.3 in the Final Technical Report.

Products for Subtasks 3.2 and 3.3 (non-technical)**:**

- Summary of the CCUS in Kansas forum as presented under Task 1.

Subtasks 3.2 and 3.3 Technical Section:

Subtask 3.2 - Identify challenges and develop a plan to address challenges for CO2 transportation and injection *(Technical)*

The likely mode of transportation for large-scale CCS is via pipelines. Because of the long history (40+ years) of CO2 transportation, and even a longer history of transporting high pressure natural gas, there are no significant technical challenges to transporting CO2 via pipelines. Non-technical challenges are covered separately.

Summary of significant activities:
None to report.

Significant Results/Key Outcomes:
None to report.

Goals and objectives for the next Quarter:
None to report.

Subtask 3.3- Identify challenges and develop a plan to address challenges for CO2 storage in geologic complexes *(Technical)*

Summary of significant activities:
None to report.

Significant Results/Key Outcomes:
None to report.

Goals and objectives for the next Quarter:
None to report.

Task 4.0 – Perform a high level technical sub-basinal evaluation using NRAP and related DOE tools

Subtask 4.1 - Review storage capacity of geologic complexes identified in this proposal and consider alternatives

In the proposal we identified three possible sites in two complexes that were in various stages of analysis and each appeared to meet the 50+Mt storage requirement. Post award, they were to be evaluated further and a survey of other potential geologic structures were to be screened and evaluated for suitability.

Overview:

Two geologic complexes identified in the initial proposal as potential sites for storing >50 million tonnes (Mt) are the Pleasant Prairie field geologic site, considered the primary storage site, and the Davis Ranch and John Creek fields, in the Forest City Basin (FCB) storage complex, considered a secondary site. Preliminary capacity evaluation for the FCB indicated it not capable of storing >50Mt CO2 (Q1 ICKan report). In the process of evaluating the Pleasant Prairie site, four separate geologic structures were identified as each having potential for storing 50Mt. The four structures, aligned on the same regional geologic structure, are similar in size, have >100 ft of closure, and similar geologic histories. The four potential sites, Rupp, Patterson, Lakin and Pleasant Prairie are in what we have named North Hugoton Storage Complex (NHSC) [Figure 1]. CO2 injection simulation studies are now complete for the Lakin (reported in Q2 ICKan report) and the four structures in Figure 1, Pleasant Prairie, Lakin, Patterson, and Rupp. The Patterson site has been determined to be the primary site for a Phase II storage site and the other three sites in the NHSC will be considered alternative sites. Preliminary reports for the Lakin and Patterson sites were provided in prior quarterly reports. This report covers the Pleasant Prairie site and, to a lesser extent, the Rupp site.

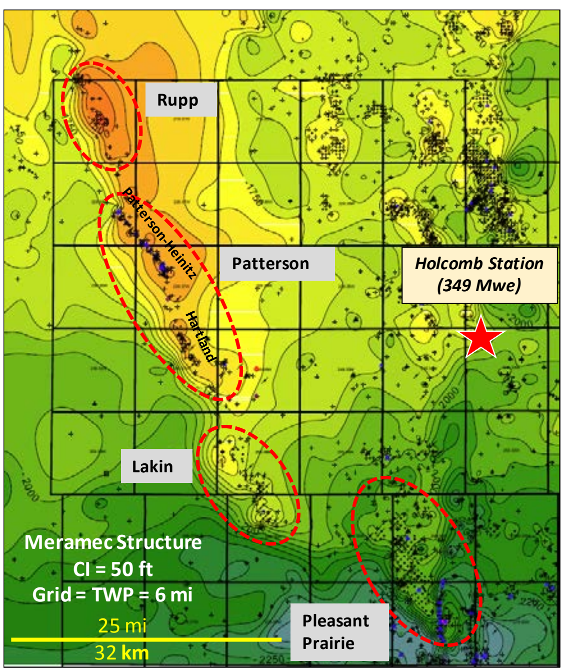

Figure 4. Location of four plausible storage sites within the North Hugoton Storage Complex. Map is the structure on the top of the Meramec (Mississippian). Patterson is the primary site and the others are alternative sites.

Pleasant Prairie Fault Mapping

Methods

The first step for evaluating the Pleasant Prairie 3D seismic volume was to map key horizons. The first horizon of importance was the basement followed by the Arbuckle and Mississippian. These surfaces were key in evaluating the reservoir and seal. Once these horizons were mapped across the seismic volume the next step was to determine and map the possible faults present within the volume. There were about 10 major structures within our horizons of focus. The major structures that went from the basement through or to the Meramec ranged from around 8,000-16,000ft in length. Three major structures started in the basement and penetrated the Meramec as shown in Figure 6.

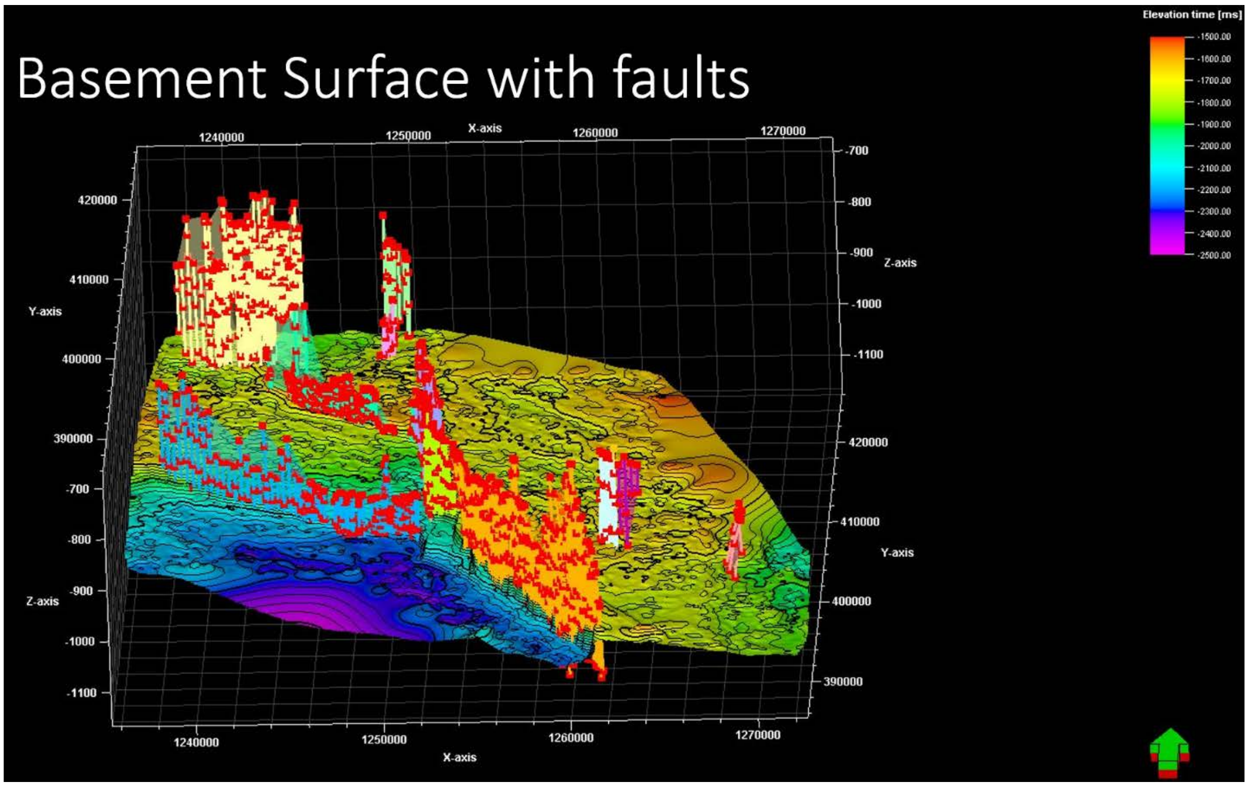

Figure 5. Snapshot of the modeled basement surface with 10 identified features.

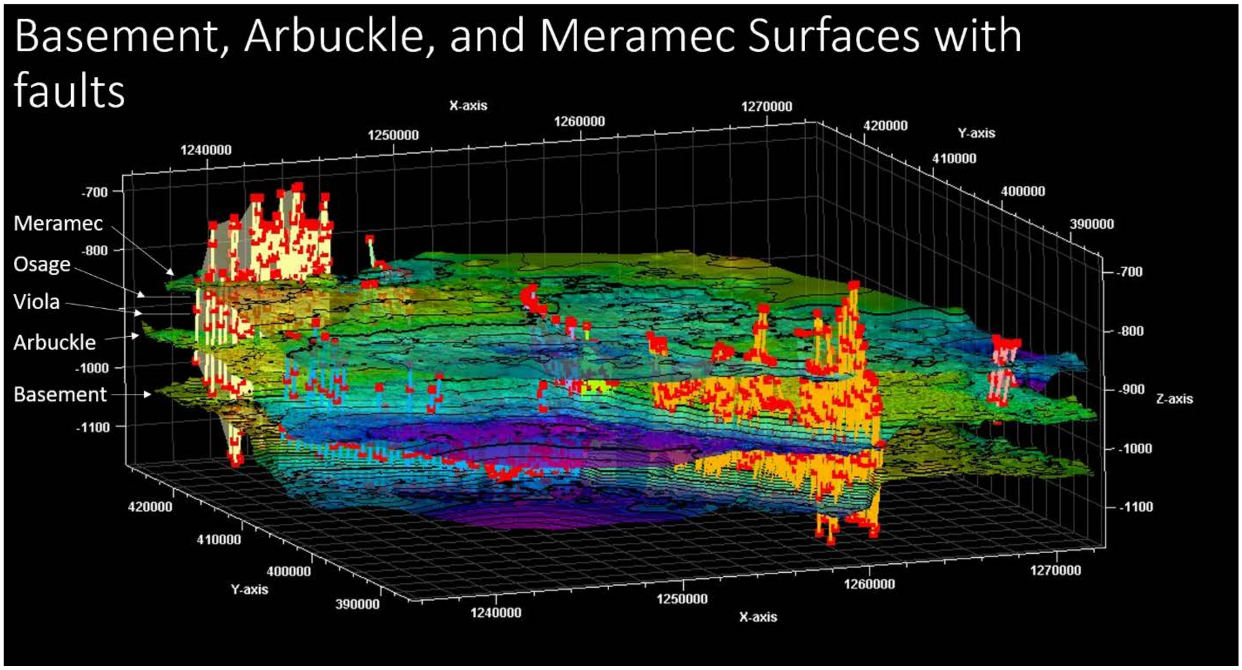

Figure 6. View showing the location and approximate depth of the 10 identified features in relation to the basement, Arbuckle, and Meramec surfaces included in the model.

These large structures that penetrate the Meramec, introduce possible risk within the reservoir that would require further analysis to assess this risk better.

Summary of significant activities:

- The Rupp technical summary was compiled but was unable to be completed at the time the Q6 report was submitted. It will be added to the Final Technical Report.
- 10 faults were identified and modeled at the Pleasant Prairie Site.

Significant Results/Key Outcomes:

- Rupp site results will be included in the Final Technical Report.
- Larger faults identified at the Pleasant Prairie site could introduce possible risks and require further analysis.

Goals and objectives for the next Quarter:

- The primary goal for the following quarter is to integrate final technical reports for all geologic sites modeled into the Final Technical Report.

Products for Subtask 4.1:

- Technical report for the Rupp site to be included in the Final Technical Report.

Subtask 4.2 - Conduct high-level technical analysis of suitable geologic complexes using NRAP- IAM-CS and other tools for integrated assessment

The KGS shall evaluate candidate storage complexes in terms of capacity, seal, faults, seismicity, pressure, existing wellbores, and injectivity.

Summary of significant activities:
All Technical analysis is complete and will be integrated into the Final Technical Report.

Significant Results/Key Outcomes:
Significant results will be included in the Final Technical Report for the Rupp site.

Goals and objectives for the next Quarter:

- Finalize the technical report for the Rupp geological site and integrate into the Final Technical Report.
- Integrate the high-level technical evaluation reports for the Patterson, Lakin, Rupp, and Pleasant Prairie sites.
- Complete technical risk assessments for the Patterson site.
- Finalize and submit the Final Technical Report

Products for Subtask 4.2:

- Summary technical report for the Pleasant prairie site (capacity, injectivity, seals) presented in the body of this report.
- Rupp site preliminary injection and storage capacity documented through simulations.

Subtask 4.3 - Compare results using NRAP with methods used in prior DOE contracts including regional and sub-basin CO_2 storage

Significant accomplishments:
Results using the NRAP tools are presented in the report titled, "Assessing CO_2 injection risks using NRAP (National Risk Assessment Partnership) Tools" included in Appendix A. Three sample figures from the report are provided below.

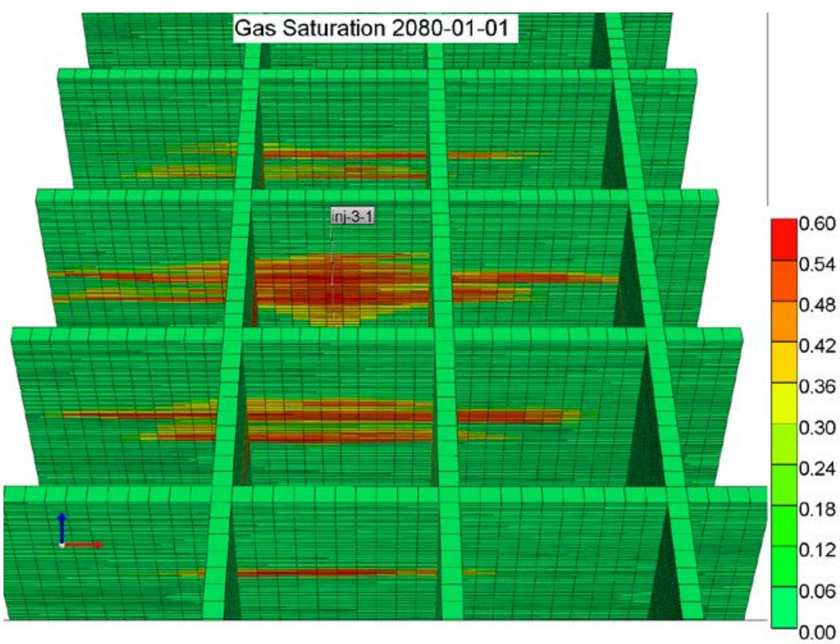

Figure 7: Projected grid blocks from corner point to the Cartesian grid. CO_2 plume in the Osage formation after 60 years (30 years of injection) is shown.

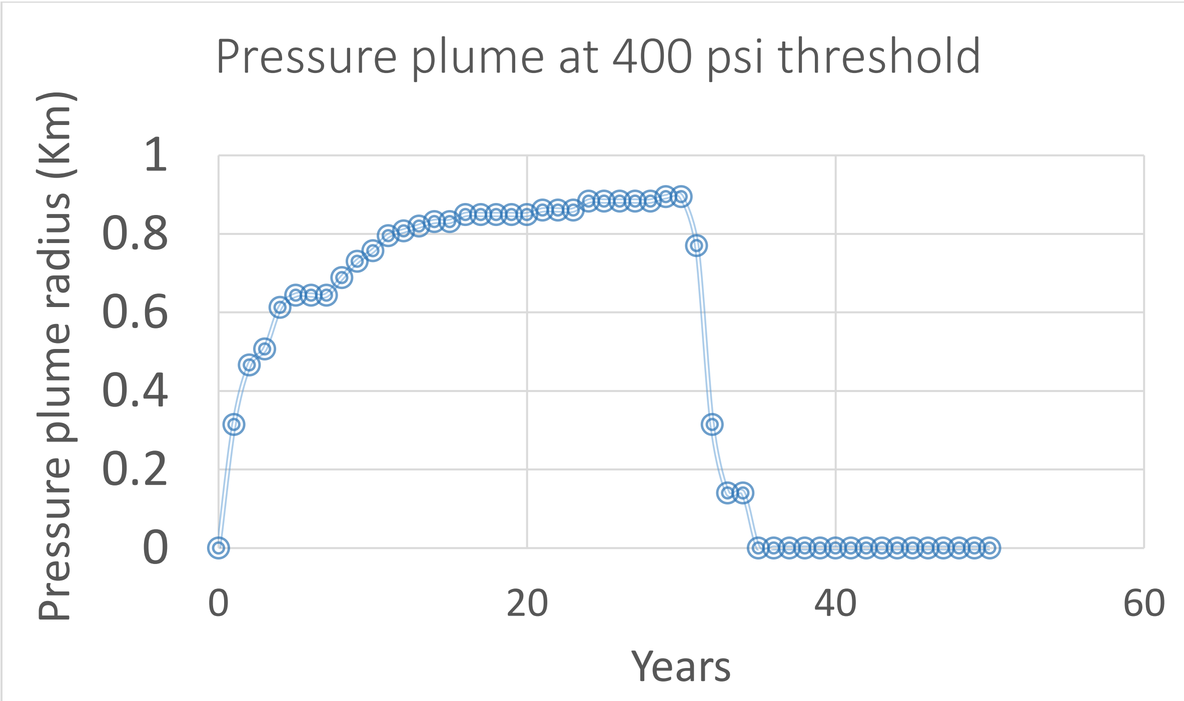

Figure 8: Pressure plume evolution in the Arbuckle. Injection stops after 30 years and within ~5 years the overpressure plume dissipates in the Arbuckle formation.

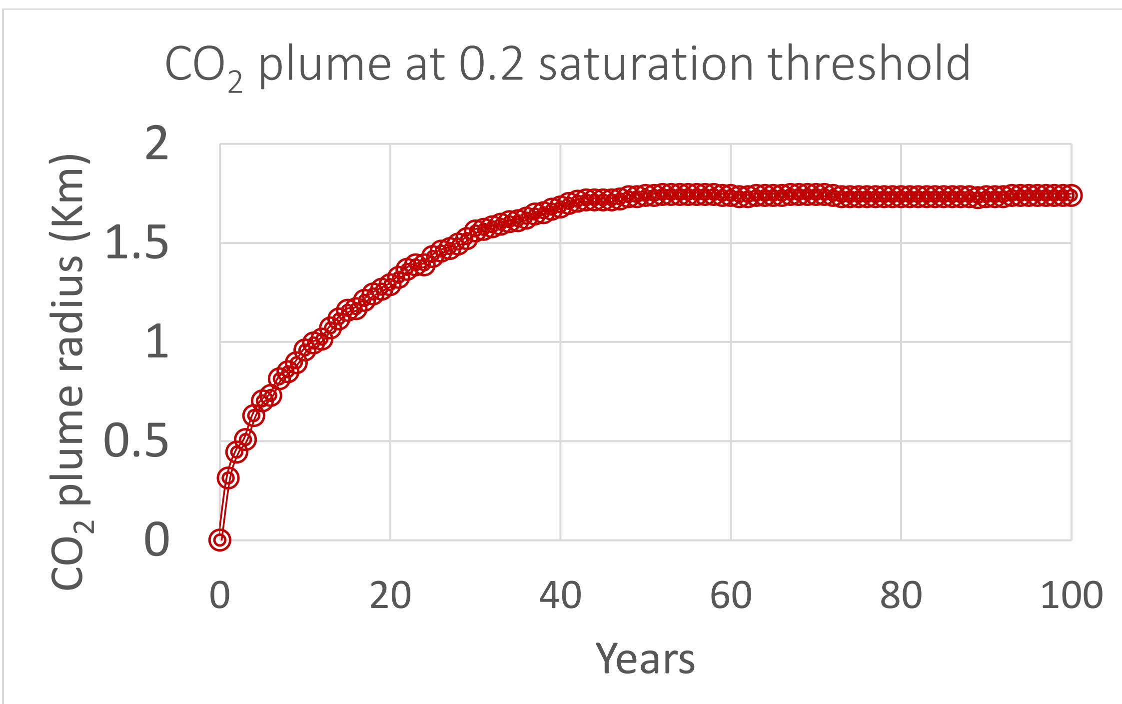

Figure 9: CO_2 plume evolution at 0.2 saturation threshold in the Arbuckle formation. The plume growth decreases after injection period (30 years) and its growth stops after another ~15 years at ~1.75 km distance from the well.

Task 5.0 – Perform a high level technical CO2 source assessment for capture

An assessment of the capture technologies best suited for efficiency, addressing the concerns of the electric utilities and their operating requirements and economic needs will be performed.

Subtask 5.1- Review current technologies and CO_2 sources of team members and nearby sources using NATCARB, Global CO_2 Storage Portal, and KDM

The CCS team shall develop an organized electronic clearinghouse of vital information pertaining to the project, ranked by suitability, historical usage records, adaptability, scaling, and demonstration of success, and operations and maintenance requirements.

Summary of Activities: Completed in Q1

Significant Results/Key Outcomes: Completed in Q1

Subtask 5.2- Determine novel technologies or approaches for CO_2 capture

Goals and Objectives: CO_2 sources shall carefully be evaluated for suitability with new capture technologies. The evaluation will utilize private research including that sponsored by DOE and results of international efforts and projects such as DOE's Carbon Capture Simulation Initiative (CCSI) to determine the suitability and rational for making decisions to pursue or table the technology.

Summary of Activities: Completed in Q2.

Significant Results/Key Outcomes: Completed in Q2.

Subtask 5.3- Develop an implementation plan and strategy for cost effective and reliable carbon capture

Goals and Objectives: An optimal CCS plan and strategy that best represents the holistic operating environment and requirements of the CO_2 sources will be developed. The team shall develop a means to ensure a mechanism to update and adapt to new disruptive technologies and possibly accommodate them in the design document.

Summary of Activities: Completed in Q2

Significant Results/Key Outcomes: Completed in Q2

Goals and objectives for the next Quarter:
The team will consolidate data and preliminary reports into a comprehensive final report.

Products for Subtask 5: None to report.

Task 6.0 – Perform a high level technical assessment for CO2 transportation

Subtask 6.1 - Review current technologies for CO_2 transportation

Nothing to report. Work is essentially complete.

Subtask 6.2- Determine novel technologies or approaches for CO_2 transportation

Nothing to report. Work is essentially complete.

Subtask 6.3 - Develop a plan for cost-efficient and secure transportation infrastructure

Overview:
Understanding the economics of transporting CO2 from anthropogenic sources in the most optimal manner is a key component of the ICKan project. In December, 2017, three Phase I pre-feasibility projects agreed to combine efforts for a single, Phase II proposal with Battelle as the lead. The combined project involves the ICKan Project (KGS, FE0029474), and two others, Nebraska Integrated Carbon Capture and Storage Pre-Feasibility Study (Energy and Environmental Research Center, **FE0029186**), and the Midcontinent Stacked Carbon Storage Hub Project (Battelle, **FE0029264**). In the current quarter, several possible source-geologic site scenarios for the combined Phase II project were evaluated.

Summary of significant activities:

Nothing to report. Work is essentially complete.

Significant Results/Key Outcomes:

Nothing to report. Work is essentially complete.

Products for Subtask 6.3:

None to report. Work is essentially complete.

Goals and objectives for the next Quarter:

The team will consolidate data and preliminary reports into the Final Technical Report.

Task 7.0 – Technology Transfer

Efforts continued on developing a CO_2 –ready catalog for potential CO_2 –EOR sites. Five different counties were identified as possible candidates and analyzed in the Kansas Geological Survey Database. All available field information was provided to the team to begin developing an inventory and refining the dataset. The project web page provided direct access to the wells in the study areas. The web page URL is http://www.kgs.ku.edu/PRS/ICKan/Summary/.

Subtask 7.1- Maintain website on KGS server to facilitate effective and efficient interaction of the team

The ICKan Project Well Data Summary Web Page provides a publicly available database for users to view and download data collected from the ICKan project. This paged is updated on a regular basis and maintained by KGS staff.

Subtask 7.2 - Public presentations

Presentations were given at the annual DOE Carbon Storage Review Meeting in August at Pittsburgh, PA, KIOGA conference in Wichita, KS in August, and the Kansas Geological Survey Field Conference in August.

Updates posted to the ICKan project page (http://www.kgs.ku.edu/PRS/ICKan/presentations.html).

Subtask 7.3 - Publications

Publications are posted to the ICKan project page.

Appendix A

Assessing CO_2 injection risks using NRAP (National Risk Assessment Partnership) Tools

Reservoir Evaluation (REV) tool: REV tool from NRAP (King, 2016a) is used to assess CO_2 injection into the Osage, Viola and Arbuckle formations at the Patterson Field. REV tool uses other simulator's results and visualizes several important metrics for studying the response of the formation to carbon storage. These metrics include CO_2 plume size and pressure plume size. Obtaining these metrics are useful for determining the post injection fate of the carbon dioxide such as the post shut-in decay rate of pressure, plume growth rate in a long-term period as well as maximum pressure increase at the shut-in time.

The input of the REV tool are the pressure and saturations for all grid-blocks as time-series obtained from reservoir simulation models. The tool has a defined threshold for pressure and saturation and calculates the differential pressure and CO_2 plume size in all grid blocks and maps it into a 2D horizontal surface to visualize the area of plume and its evolution through time. The saturation threshold defines the extent of the CO_2 plume and is set to 0.2 in the current study while the pressure threshold defines the extent of overpressure front, depends on factors such as wellbore pressure and is set to 400 psi as deemed appropriate for the study. Other parameters in the tool such as depth of the storage reservoir or brine density are the same as values used in the reservoir simulation model.

The REV tool was not able to process the corner point grids. We created an equivalent regular-rectangular Cartesian grid for our corner point gridding of the Patterson area (Figure 1). The REV metrics for assessing CO_2 injection into the Arbuckle and Osage formations are shown in Figures 2-4. The REV tool version 2018 is used in this study.

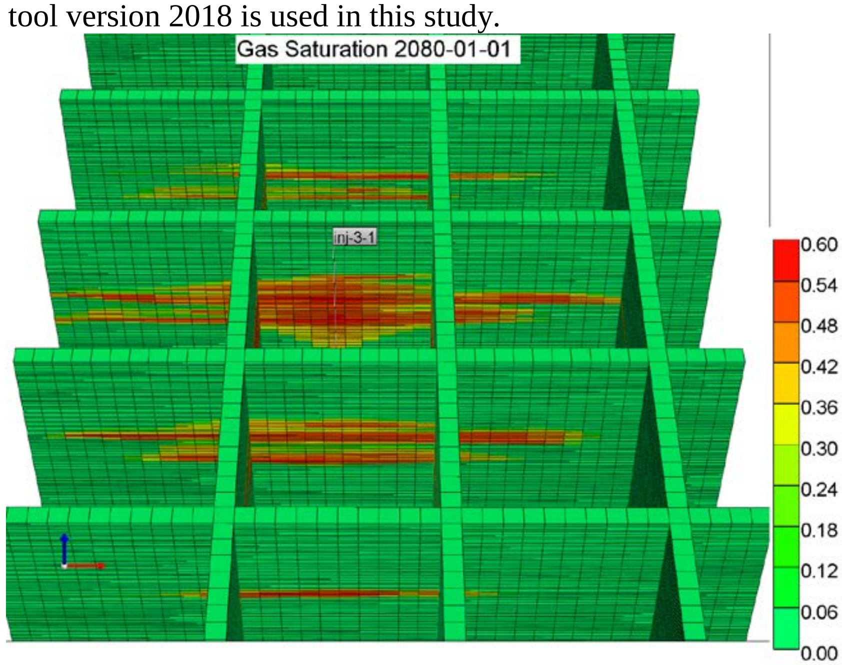

Figure 1: Projected grid blocks from corner point to the Cartesian grid. CO_2 plume in the Osage formation after 60 years (30 years of injection) is shown.

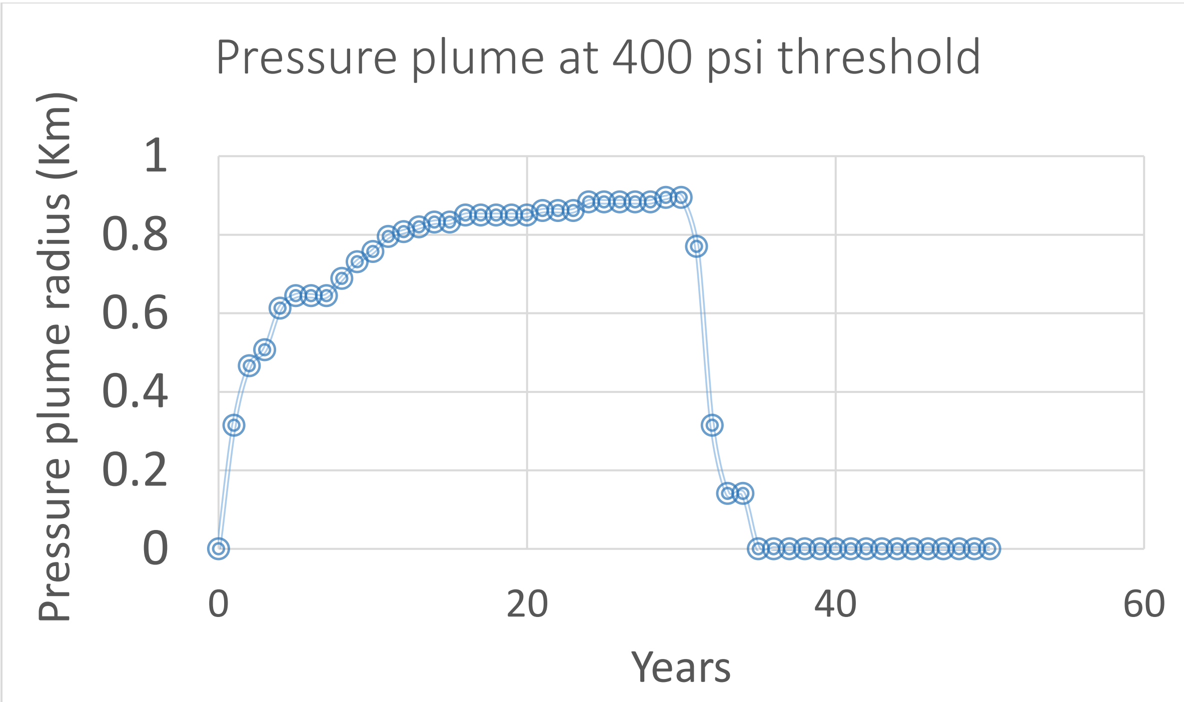

Figure 2: Pressure plume evolution in the Arbuckle. Injection stops after 30 years and within ~5 years the overpressure plume dissipates in the Arbuckle formation.

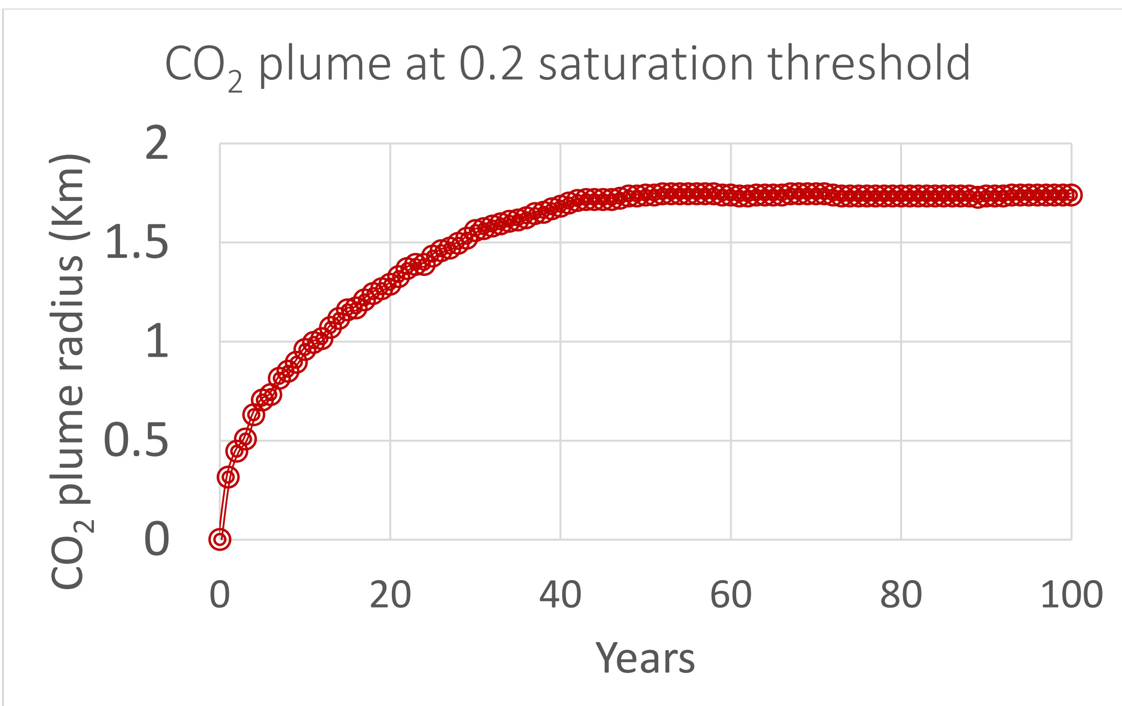

Figure 3: CO_2 plume evolution at 0.2 saturation threshold in the Arbuckle formation. The plume growth decreases after injection period (30 years) and its growth stops after another ~15 years at ~1.75 km distance from the well.

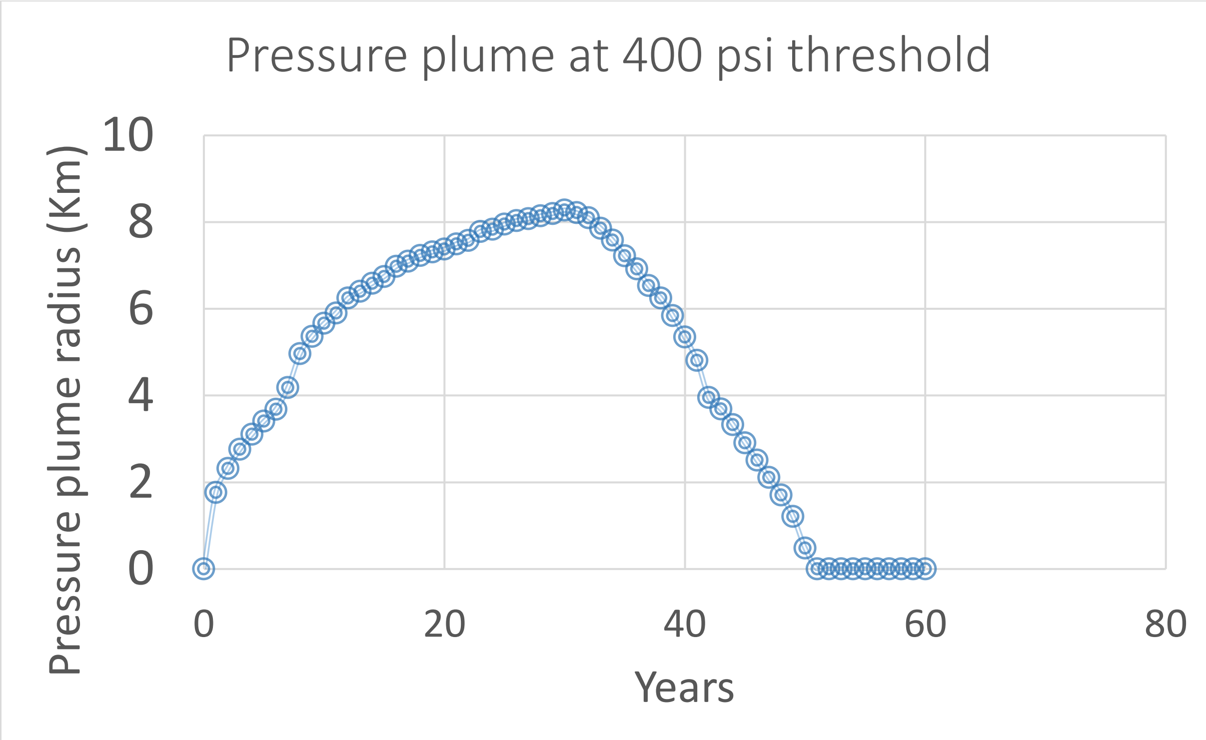

Figure 4: Pressure plume evolution at 400 psi threshold in Osage formation. The overpressure plume dissipates in the formation and disappears 20 years after shut-in (30 years).

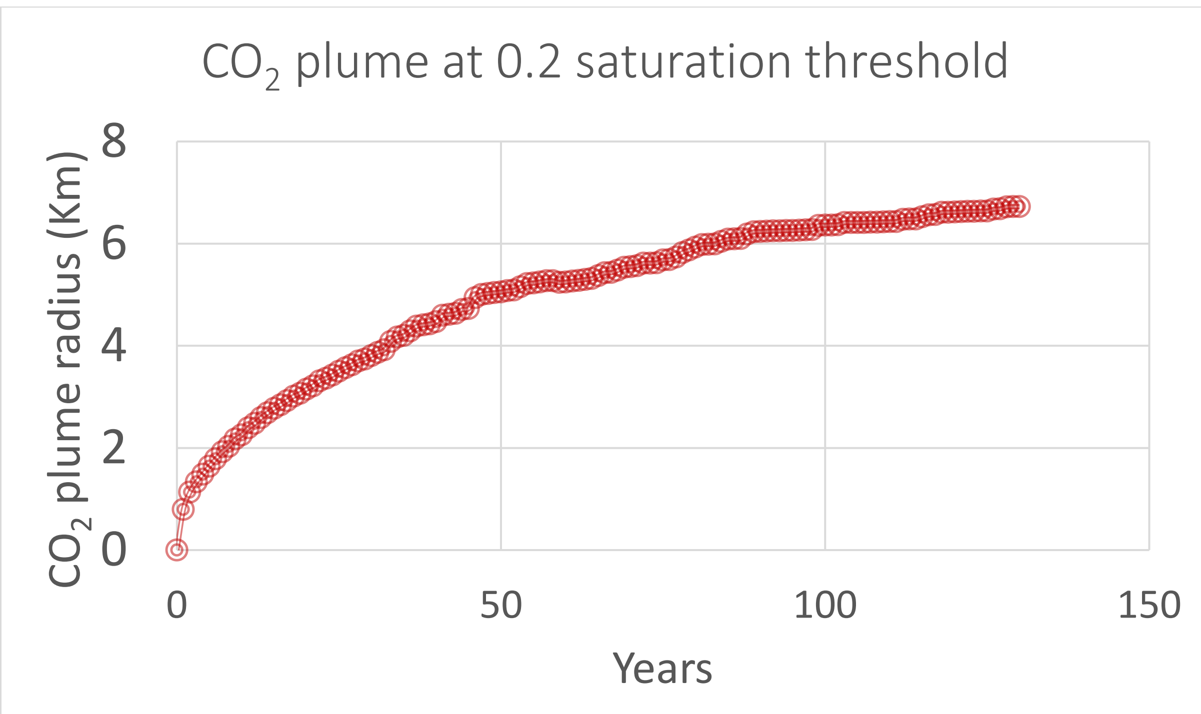

Figure 5: CO_2 plume evolution at 0.2 saturation threshold in Osage formation. The CO_2 plume reaches a distance of ~4 km from then injection stops (30 years) and its slower rate growth reaches 6 km after ~90 years.

NSealR (NRAP Seal Barrier Reduced-Order Model) tool: NSealR offers a one-dimensional model for analyzing two-phase flow of supercritical CO_2 through brine-saturated rock (Lindner, 2016). This toolkit uses 1-D Darcy equation to describe the flow and leakage of CO_2 through the seal (i.e. low permeability rock) and uses two-phase (CO_2-brine) relative permeability models.
We use NSealR to quantify and assess the leakage risk of injected CO_2 into the Arbuckle, Osage and Viola groups in the Patterson field. Simpson shale, Kinderhook and Spergen-Meramec are the caprock barriers for the Arbuckle, Viola and Osage, respectively. The main barrier is the thick, non-permeable limestone, Meramec-Spergen, overlying the Osage. Additionally, the Morrow shale, the seal of Kansas petroleum reservoirs, acts as the ultimate barrier. The properties of the seals used in the NSealR are summarized in Tables 1-2. Morrow shale properties are based on the S1537 and S1461 samples presented by (Krushin, 1997).

Table 1: Range of properties of the caprock seals

Caprock seal $\boldsymbol{Min - Max}$	Formation top (ft)	Elevation Depth (ft)	Thickness (ft)	Porosity	Horizontal Permeability (md)
Morrow-Chester shale	4,750	1,300-1,968	44.6-282.5	0.0141-0.18	0.0117-3.926
Morrow shale	4,750	1,300-1,968	40-70	1e-10-0.03	5.13e-11-0.001
Meramec limestone	4,900	1,435-2,028	0-225.4	1e-10-0.1	1e-10-0.6832
Lower Meramec	4,965	1,500-2,111	28.6-126.8	1e-10-0.12	1e-10-0.9315
Spergen limestone	5,100	1,578-2,235	82.63-124.8	1e-10-0.16	1e-10-76.061
Kinderhook limestone	5,475	1,900-2,646	102.5-168.8	1e-10-0.2	0.0021-5.45
Simpson shale	5,775	2,170-2,853	19.9-35.57	0.0334-0.14	0.1-69.11

Table 2: μ_x and σ_x for the properties of the caprock seals

Caprock seal	Porosity $\boldsymbol{\mu_x, \sigma_x}$	Horizontal Permeability (md) $\boldsymbol{\mu_x, \sigma_x}$
Morrow-Chester shale	0.0458, 0.0231	0.269, 0.4357
Morrow shale	0.022, 0.010	5.1e-6, 0.001
Meramec limestone	0.0249, 0.0201	0.0677, 0.122
Lower Meramec	0.0260, 0.0182	0.0739, 0.1321
Spergen limestone	0.0265, 0.0180	0.7696, 4.3102
Kinderhook limestone	0.0587, 0.0319	0.5784, 0.7846
Simpson shale	0.0682, 0.0201	2.0850, 2.4329

The vertical permeability is assumed to be 0.1 of the horizontal permeability. The maximum and minimum values for the vertical permeability are assumed to come from a log-normal distribution. We use NSealR's default relative permeability and capillary pressure model for caprock. At a reference depth of 5260 ft, the reference brine pressure is 1,650 psi and the reference temperature is 140 °F. The salinity is assumed to be 100 g/l. The affected seal area (i.e. maximum plume area) is calculated using CMG GEM to have an average diameter of 2.9 mile (4.6 km), when approximately 8 Mt CO_2 injected per well into the Osage (storage zone below Meramec). 50 realization are sampled using Monte Carlo method. The seal assessment results for the Morrow shale and Meramec limestone, the topmost seal barriers, are shown in Figures 6-9.

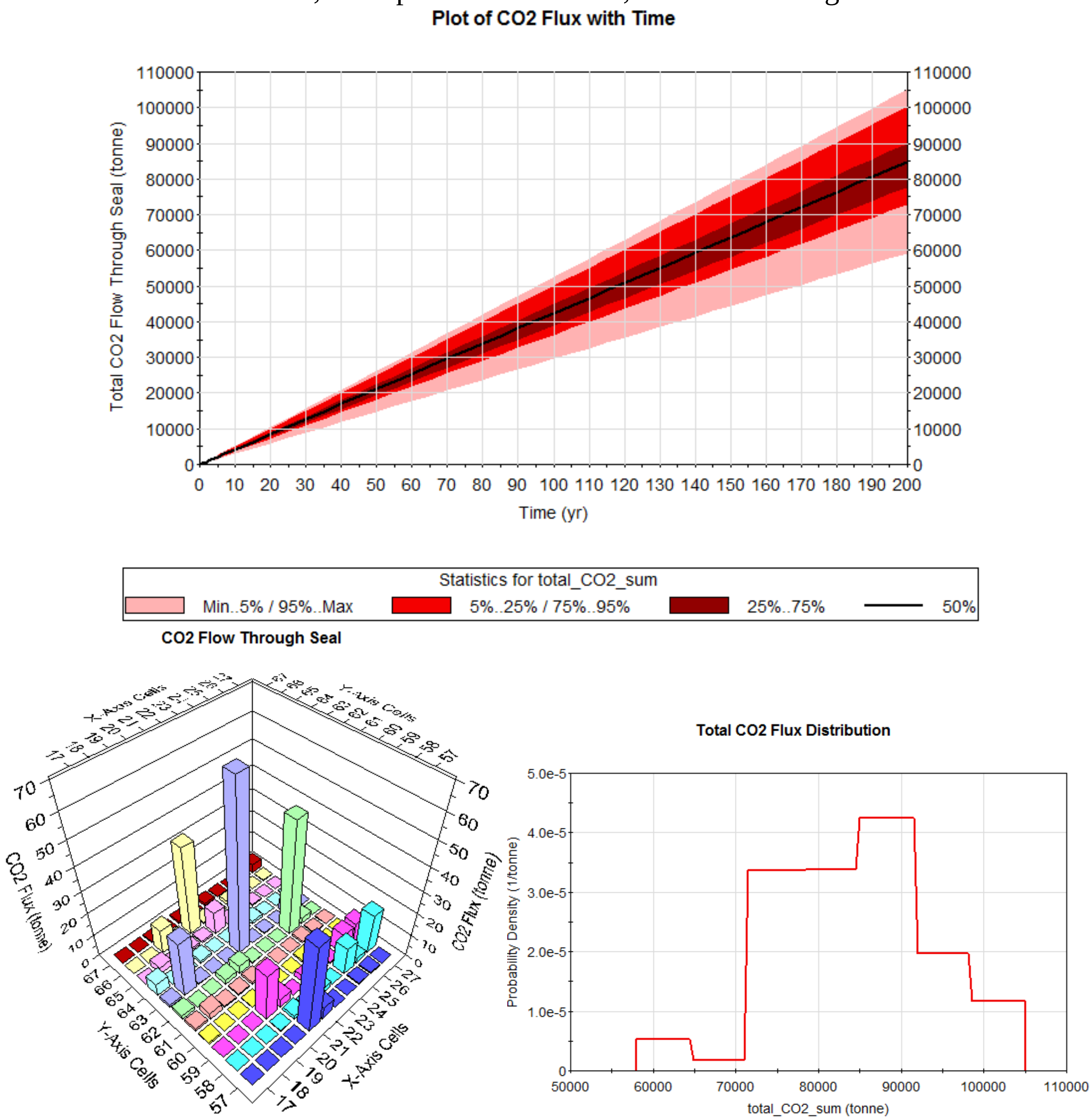

Figure 6: CO_2 flux through the Morrow shale. The top figure shows total CO_2 leakage and its corresponding probability versus time. The bottom right figure shows one realization for the CO_2 leakage rate assuming the entire seal is divided into 100 × 100 grid blocks. The bottom left figure shows the probability distribution for total CO_2 leakage.

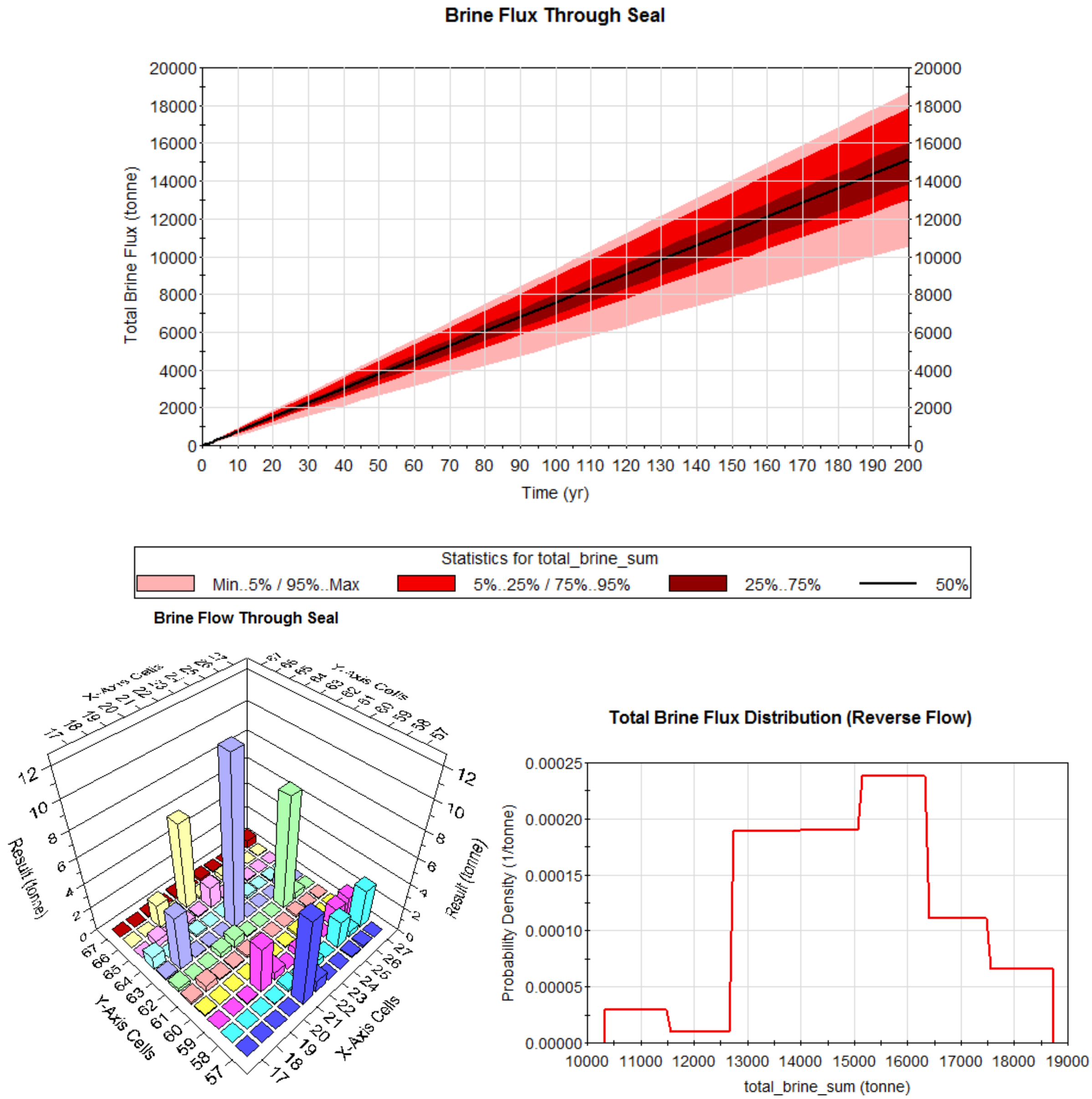

Figure 7: Brine flux through the Morrow shale. The top figure shows total brine leakage and its corresponding probability versus time. The bottom right figure shows one realization for the brine leakage rate assuming the entire seal is divided into 100×100 grid blocks. The bottom left figure shows the probability distribution for total brine leakage.

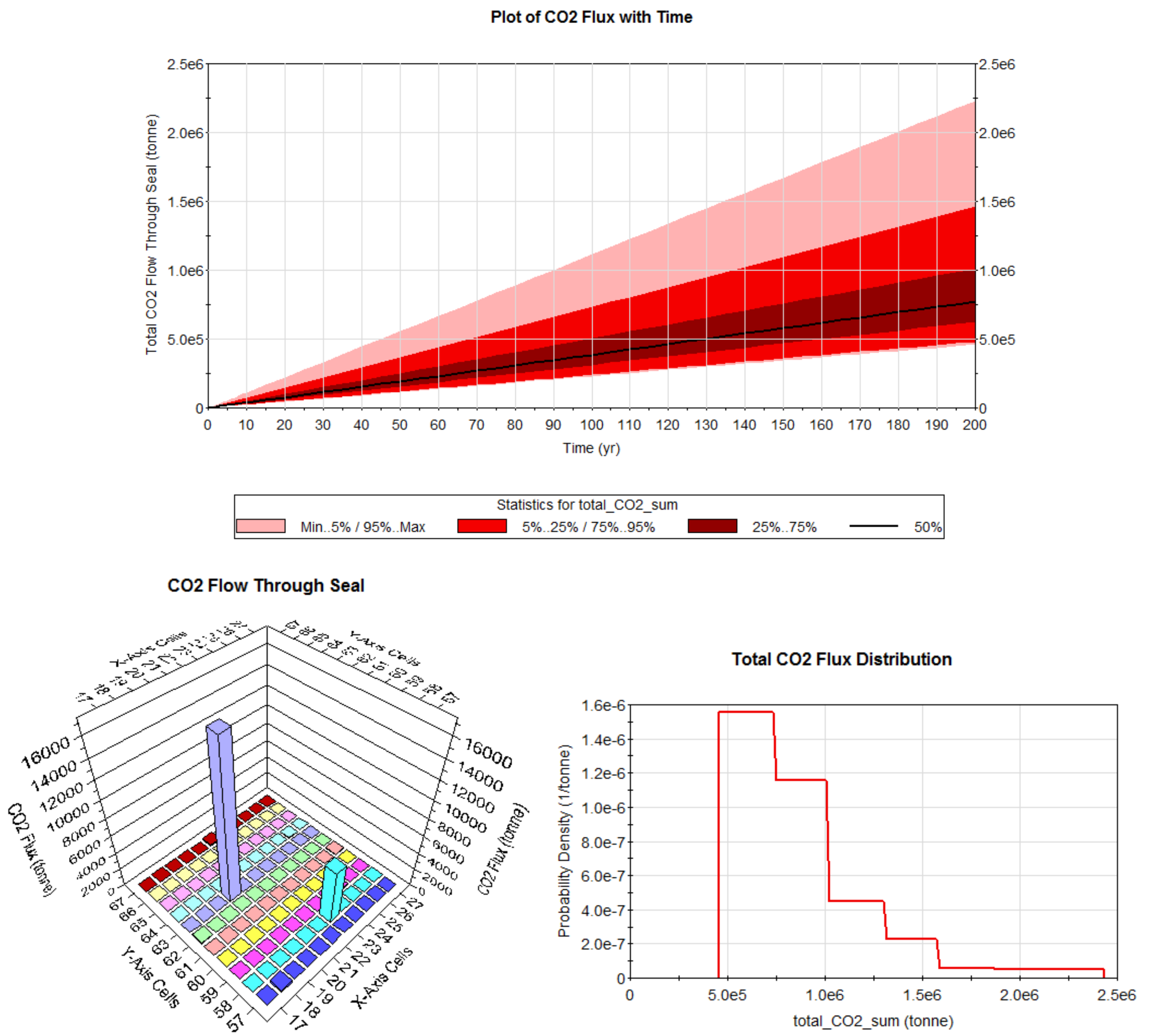

Figure 8: CO_2 flux through the Meramec limestone. The top figure shows total CO_2 leakage and its corresponding probability versus time. The bottom right figure shows one realization for the leakage rate assuming the entire seal is divided into 100 × 100 grid blocks. The bottom left figure shows the probability distribution for total CO_2 leakage.

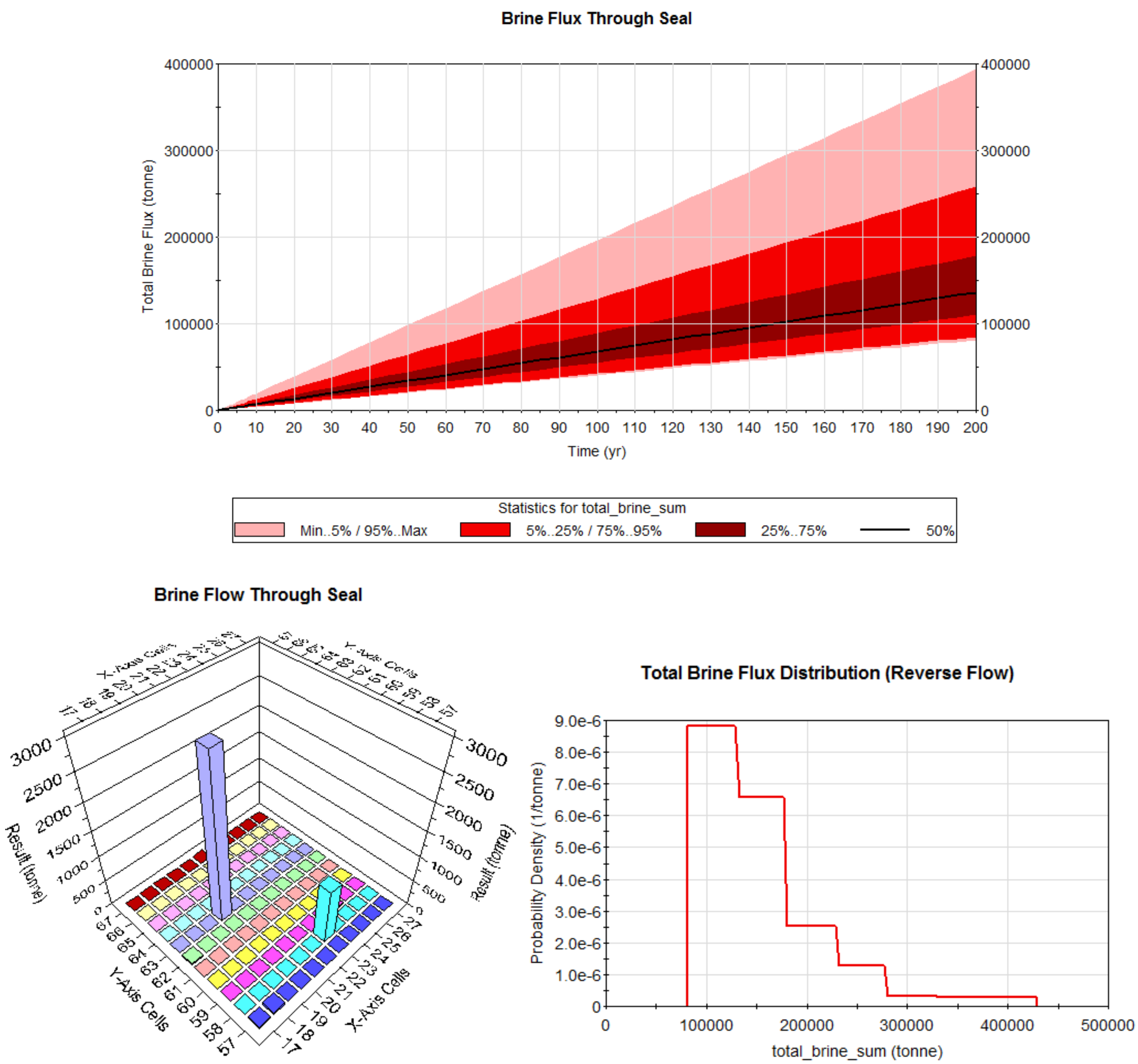

Figure 9: Brine flux through the Meramec limestone. The top figure shows total brine leakage and its corresponding probability versus time. The bottom right figure shows one realization for the leakage rate assuming the entire seal is divided into 100 × 100 grid blocks. The bottom left figure shows the probability distribution for total brine leakage.

NETL CO_2 –SCREEN

The US-DOE methodology known as NETL CO_2-SCREEN (Goodman, Sanguinito, & Levine, 2016) is used for estimating CO_2 storage potential in Patterson area. The methodology is general and could be applied globally, however we refine the required data using the currently available information for the Patterson area. Patterson area is an open system (no impermeable boundary) with closures to vertically constrain and trap the injected CO_2 within the injected area. Thus the percentage of pore space that can be filled with CO_2 primarily depends on storage efficiencies and is independent of bottom hole pressure. The Patterson field has an approximated are of 50 mile^2 (129.5 km^2) with three potential injection formation Osage (limestone), Viola (Dolomite) and Arbuckle (Dolomite). Table 3 summarizes geological properties of each formation as needed by CO_2-SCREEN.

Table 3: Properties of the Patterson area

Grid #	Area* (km^2)	Gross Thickness* (m)		Total Porosity* (%)		Pressure† (MPa)		Temperature† (°C)	
	Mean	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
1	129.5	45.72	0	12.3	6.4	11.38	0	53.89	0
2	129.5	54.86	0	7.5	2.5	11.51	0	55.56	0
3	129.5	173.7	0	5.4	3.7	11.72	0	58.33	0

The storage efficiency of the saline formations (G_{CO2}) is calculated by:

$$G_{CO2} = A_t h_{gross} \phi_{tot} \rho_{CO_2} E_{saline}$$

in which pore space ($A_t h_{gross} \phi_{tot}$) obtained using Table 3 parameters is multiplied by $\rho_{CO_2}$to convert to CO_2 mass in the reservoir and the multiplied by storage efficiency factor for saline formations (E_{saline}) defined as:

$$E_{saline} = E_A E_h E_\phi E_v E_d$$

In which E_A is the net-to-total area, E_h is the fraction of total thickness that meets minimum permeability and porosity requirements, E_ϕ is the fraction of interconnected porosity, E_v is the volumetric displacement efficiency defining the volume that can be contacted by CO_2 plume and E_d is the microscopic displacement efficiency describing the fraction of water in water-filled pore volume that can be displaced by contacting CO_2. Table 4 summarizes the efficiency values based on Goodman et al., 2011. The E_A *and* E_h values are chosen higher that the global recommended values considering that the Osage, Viola and Arbuckle formations in the Patterson area have good net-to-total area and net-to-gross thickness. These values can be refined as more data become available.

Table 4: Storage efficiencies for the Patterson area

Grid #	Lithology and Depositional Environment	E_A		E_h		E_ϕ		E_v		E_d	
		P_{10}	P_{90}	P_{10}	P_{90}	P_{10}	P_{90}	P_{10}	P_{90}	P_{10}	P_{90}
1	Limestone: Unspecified	0.6	0.9	0.85	0.95	0.64	0.75	0.27	0.42	0.33	0.57
2	Dolomite: Unspecified	0.6	0.9	0.75	0.85	0.53	0.71	0.57	0.64	0.26	0.43
3	Dolomite: Unspecified	0.6	0.9	0.35	0.65	0.53	0.71	0.57	0.64	0.26	0.43

Table 5 summarizes injection capacity of each formation and the probability results the calculated storage efficiency factors (i.e. $p(E_{saline})$) assuming one grid block for each formation. The injection capacity of the Arbuckle and Osage are high because the former has high thickness and the latter has higher porosity and is limestone. Table 6 shows total CO_2 capacity for the Patterson area. Results of Tables 5-6 are summarized in Figures 10-11.

Table 5: Calculated storage efficiency factors for each formation

Grid	P_{10} (Mt)	P_{50} (Mt)	P_{90} (Mt)	Lithology and Depositional Environment	Saline Efficiency (%)		
					P_{10}	P_{50}	P_{90}
1	9.940	21.244	44.767	User Specified	4.54	7.21	10.57
2	9.887	17.570	30.728	User Specified	5.18	7.73	10.87
3	7.892	20.415	50.436	User Specified	2.79	4.72	7.32

Table 6: Calculated storage for the Patterson area.

	P_{10}	P_{50}	P_{90}	
Summed CO_2 Total	27.72	59.23	125.93	Mt
Average CO_2 per Grid	9.24	19.74	41.98	Mt

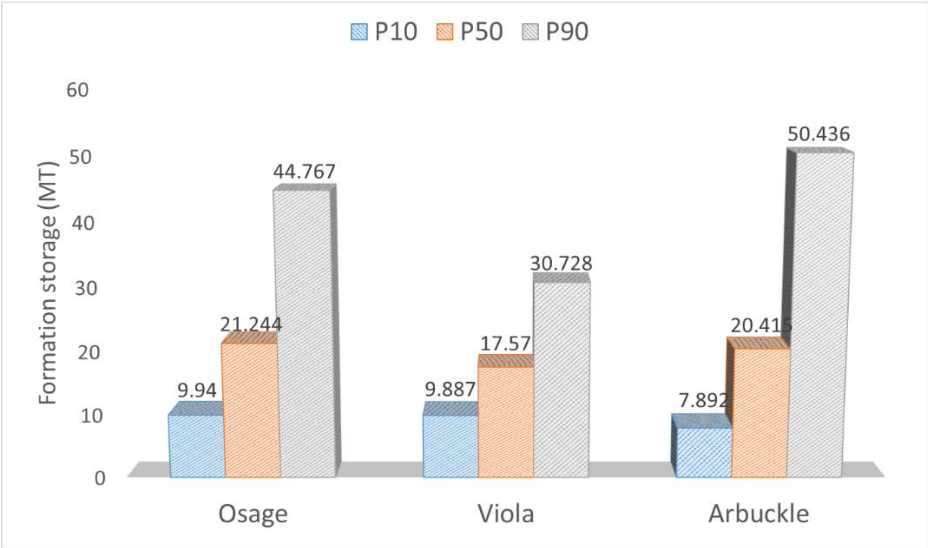

Figure 10: Formation capacity for the formations in the Patterson area

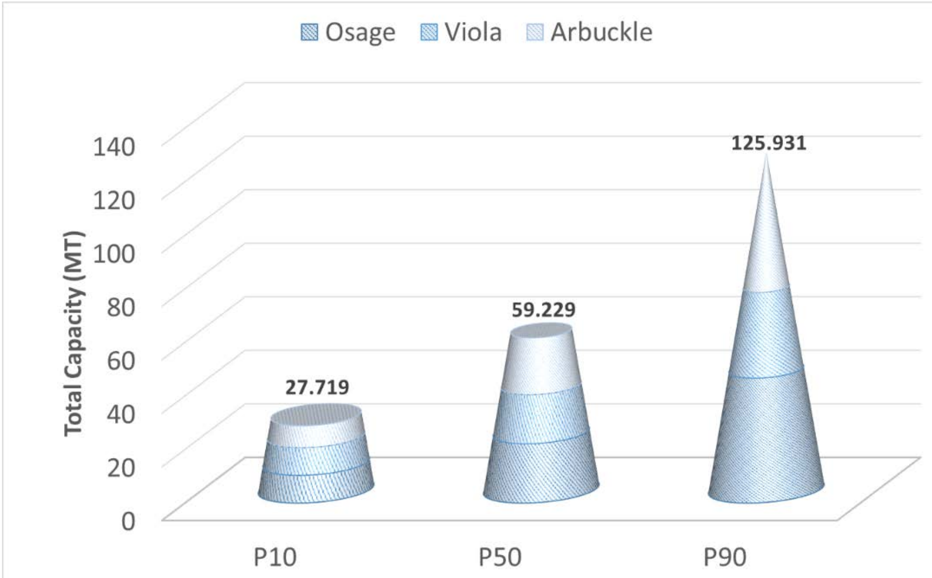

Figure 11: Maximum storage for the Patterson area

RROM-GEN tool (Reservoir Reduced Order Model Generator)

The RROM-GEN (King, 2016b) uses interpolation to reduce the simulation model dimension into 100×100 grid blocks representation in the horizontal direction and outputs the file in a format readable by Integrated Assessment Model (IAM) tool. The RROM-GEN also extracts a single layer for representing the reservoir-seal boundary. Figure 12 shows the reduced order model generated for the Paterson area. RROM-GEN version 2018 was obtained from the Author for this study.

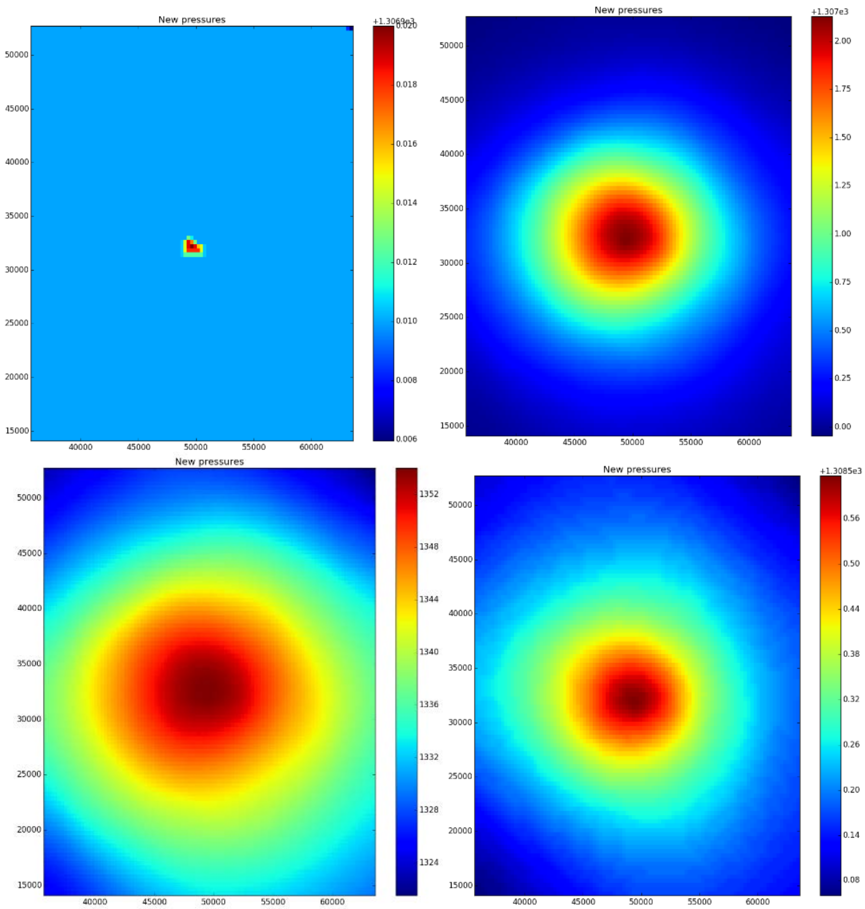

Figure 12: Pressure plume after 31 days, 1 year, 30 years and 100 years. RROM-GEN is used to reduce the CMG-GEM model to 100×100 grid blocks. The Integrated Assessment Model (IAM) tool requires the reduced order model generated by RROM-GEM as input.

NRAP-IAM-CS

The NRAP Integrated Assessment Model (IAM) for Carbon Storage (CS) tool (Philip Stauffer, Shaoping Chu, Cameron Tauxe, 2016) accounts for key geological parameters to model long-term leakage behavior to the groundwater aquifer or atmosphere through the legacy wellbores and caprock. The tool quantifies the uncertainty and probability of leakage using Monte Carlo approach. The tool is used to model leakage from the Osage formation in the Patterson field given the range of properties in Tables 7-8.

Table 7: Osage formation properties

Storage zone $\boldsymbol{Min - Max}$	Formation top (ft)	Elevation depth (ft)	Thickness (ft)	Porosity	Horizontal Permeability (md)
Osage	5,310	1,767-2,520	129.3-155.98	0.0229-0.3118	0.0876-184.3813

Table 8: Osage formation properties

Storage zone $\boldsymbol{\mu_x, \sigma_x}$	Porosity	Horizontal Permeability (md)
Osage	0.1124, 0.0645	18.4587, 29.535

The Patterson field is assumed as a rectangle having an area of 50 square mile (129.5 km^2) with a 3/1 aspect ratio and the injection well located in the middle of the reservoir. The legacy wells are cemented and their density in the Patterson area is ~2.5 to 3 wells/km^2. The cement permeability is assumed to FutureGen low rate wells distribution in the tool among three other options available (based on Alberta wells, based on Gulf of Mexico wells, High rate FutureGen wells) because Kansas wells are not overpressured and their flow rates are low (Carey, 2017). The groundwater aquifer and atmosphere properties are set to the tool's default here and will be refined as more data becomes available. The default properties of the groundwater aquifer and atmosphere are summarized in Tables 9-10. Figures 13-14 shows the CO_2 and brine leakage through all legacy wells to the groundwater aquifer respectively and Figure 15 shows CO_2 leakage to atmosphere. Figure 16 shows the importance of various factors contributing to the leakage indicating that the Legacy wellbores and their cement permeability pose the highest leakage risk among other factors such as reservoir permeability, reservoir porosity or caprock permeability.

Table 9: Shallow aquifer properties

Depth	100 m (below mean sea-level)
Pressure	1 MPA
Temperature	20.25 $°C$
Permeability	$1.148 \times 10^{-12}\ m^2$
Porosity	0.2

Table 10: Atmosphere properties

Wind speed at 10 m above land surface	1 m/s
Ambient temperature	20 $°C$
Ambient pressure	1 atm
Leaked Gas Temperature	20 $°C$
Threshold concentration	0.002
Number of Checking points	7

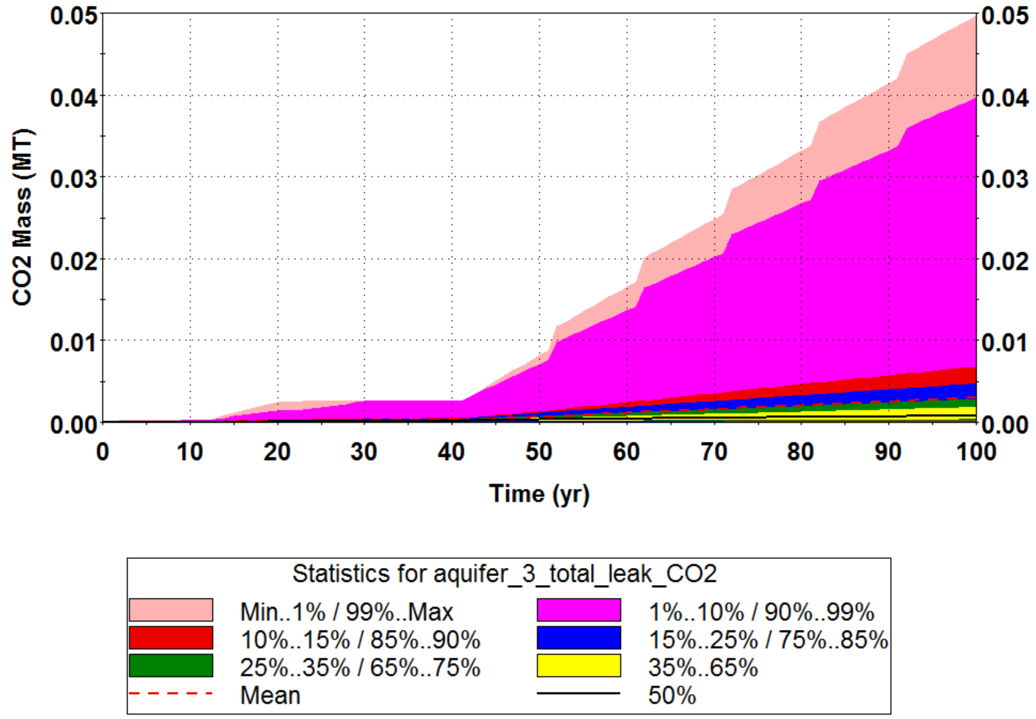

Figure 13: The probability of total CO_2 leakage to groundwater aquifer through the legacy wellbores.

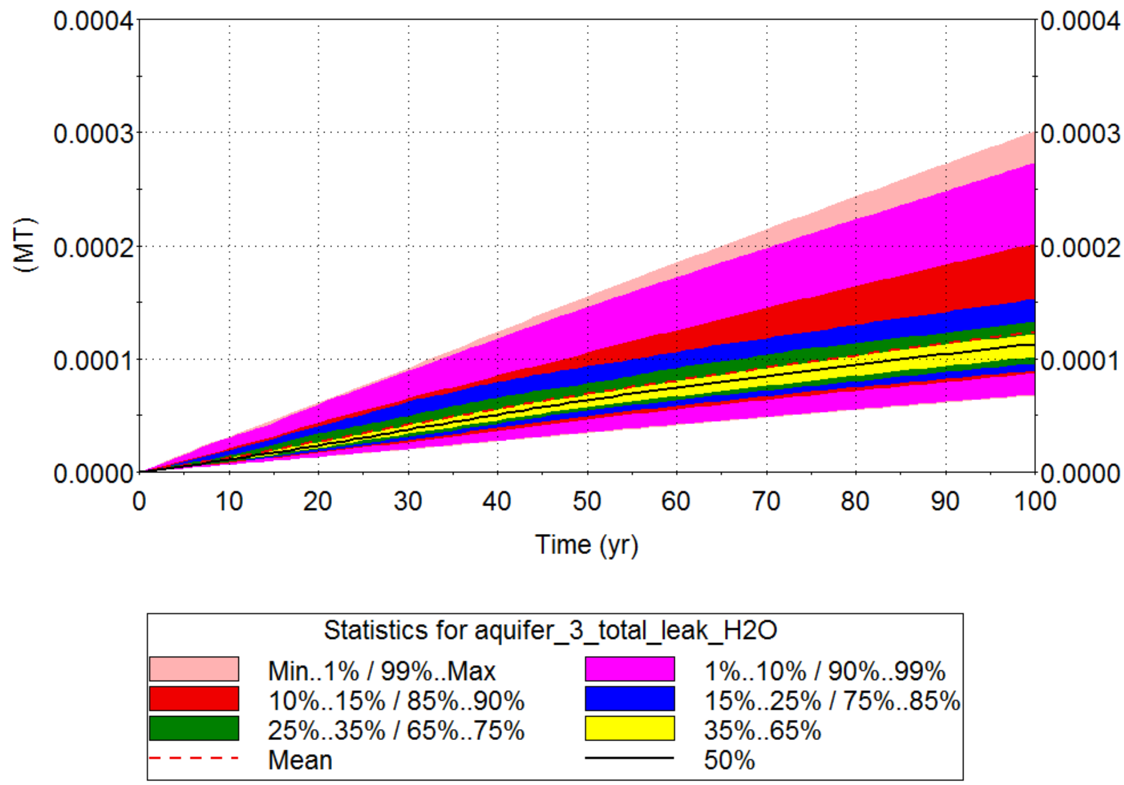

Figure 14: The probability of total brine leakage to groundwater aquifers through the legacy wellbores.

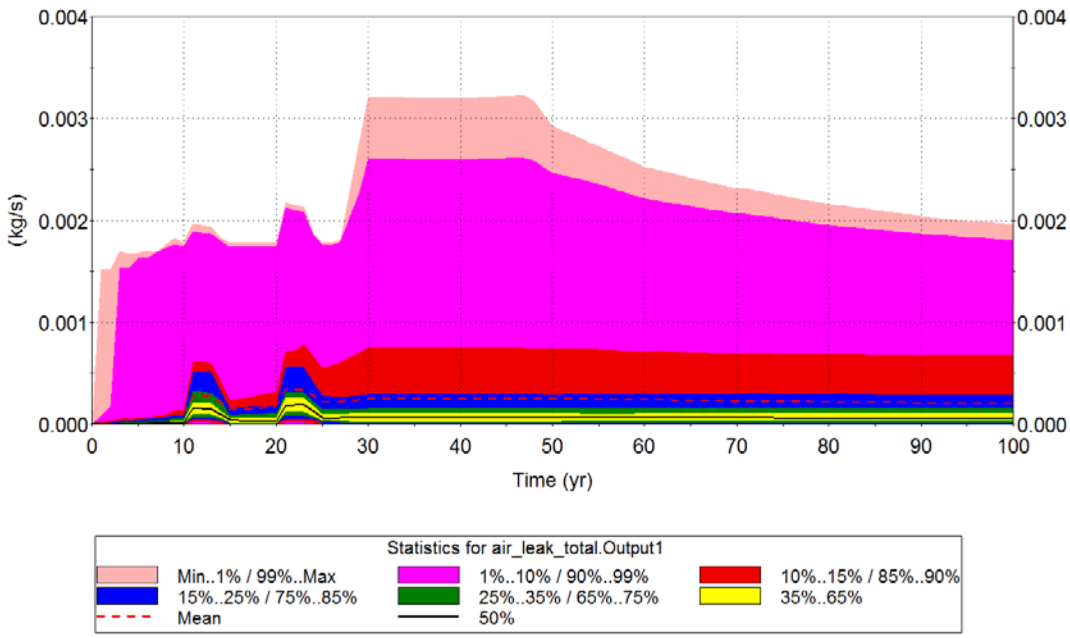

Figure 15: The probability of CO_2 leakage to atmosphere (in kg/s) through legacy wellbores.

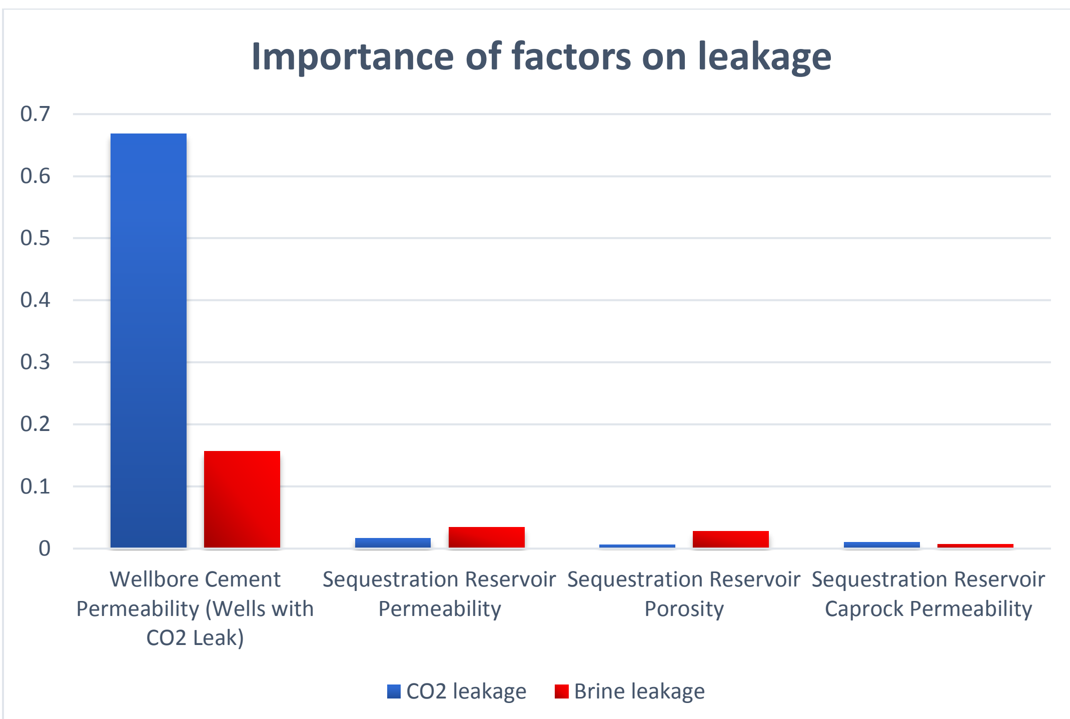

Figure 16: Importance of different factors on CO_2 and brine leakage. Legacy wellbores and their cement permeability pose the highest leakage risk.

WLAT (Well Leakage Analysis Tool)

WLAT tool is useful for evaluating the leakage through the injection well or legacy wells (Huerta, N. J.; Vasylkivska, 2016). The tool has options for a thief zone and a shallow aquifer to calculate the leakage to each of these zones and to the atmosphere. The critical data for the tool are the wellbore diameter, cement permeability, thief zone and shallow aquifer properties (i.e. permeability and depth). The tool also requires pressure and saturation at the leak point (i.e. wellbore) over time inferred from the numerical simulation in the format of separate time series. The well can be cemented, multi-segmented or open (in case of legacy wells). An effective wellbore permeability (k_{eff}) of 1e-4 md, Osage depth of 5,310 ft and pressure and saturation profile at bottom of CO_2 injector (Figure 17) and tool's default properties for the shallow aquifer and atmosphere are used for calculating the leakage rates (Figure 18). NOTE: IAM-CS results are more reasonable for cemented wellbores. Currently the cemented wellbore model in WLAT is giving an error and open wellbore model with very small permeability (1e-4 md) is used here.

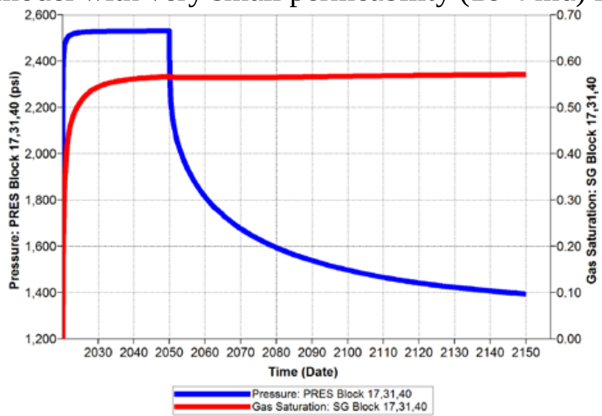

Figure 17: Pressure and saturation profile at the CO_2 injection well.

References

Carey, W. (2017). Probability Distributions for Effective Permeability of Potentially Leaking Wells at CO 2 Sequestration Sites, (April). Retrieved from http://www.netl.doe.gov/research/on-site-research/publications/featured-technical-

Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., … Guthrie, G. (2011). U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. *International Journal of Greenhouse Gas Control*, *5*(4), 952–965. https://doi.org/10.1016/j.ijggc.2011.03.010

Goodman, A., Sanguinito, S., & Levine, J. S. (2016). Prospective CO 2 saline resource estimation methodology: Refinement of existing US-DOE-NETL methods based on data availability. *International Journal of Greenhouse Gas Control*, *54*, 242–249. https://doi.org/10.1016/j.ijggc.2016.09.009

Huerta, N. J.; Vasylkivska, V. S. (2016). Well Leakage Analysis Tool (WLAT) User's Manual,

(November).
King, S. (2016a). Reservoir Evaluation and Visualization (REV) Tool User’s Manual, Version: 2016.
King, S. (2016b). Reservoir Reduced-Order Model – Generator (RROM-Gen) Tool User’s Manual, Version: 2016.11-1.2, (November).
Krushin, J. T. (1997). Seal Capacity of Nonsmectite Shale. *Seals, Traps, and the Petroleum System*, (67), 31–47. Retrieved from http://search.datapages.com/data/specpubs/mem67/ch03/ch03.htm
Lindner, E. N. (2016). NRAP Seal Barrier Reduced-Order Model (NSealR) Tool User’s Manual, Version: 2016.11-14.1, (November).
Philip Stauffer, Shaoping Chu, Cameron Tauxe, R. P. L. (2016). NRAP Integrated Assessment Model-Carbon Storage (NRAP-IAM-CS) Tool User ’ s Manual , Version : 2016 . 04-1 . 1.