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# Demonstration of plume stability for carbon storage projects

John E. Hunt*, Neil W. Dotzenrod, John A. Templeton, Joshua G. Regorrah, and Kevin C. Connors

*Energy & Environmental Research Center, University of North Dakota 15 North 23rd Street, Stop 9018, Grand Forks, 58202-9018, USA*

**Abstract**

This paper presents an approach for demonstrating carbon dioxide ($CO_2$) plume stability to meet the site closure requirements associated with carbon capture and storage (CCS) policies. CCS is a process in which $CO_2$ is captured and injected underground into a geologic reservoir. During $CO_2$ injection operations, the plume of injected $CO_2$ ($CO_2$ plume) is expected to migrate within the storage reservoir. Operators of $CO_2$ storage sites must demonstrate stability of the $CO_2$ plume and track the migration of the $CO_2$ plume to provide assurance to regulators that the injected $CO_2$ is contained within the injection interval throughout the life of the project. $CO_2$ plume stabilization is defined in this study as follows: the $CO_2$ plume 1) moves minimally and predictably in the storage reservoir such that it will not cross key boundaries and 2) does not pose a threat to human health, underground sources of drinking water, and the environment. Maintaining a postinjection monitoring plan until plume stabilization is demonstrated is crucial for operators of CCS storage sites. Published literature on plume metrics was reviewed to determine which metric or combination of metrics would be most appropriate for the demonstration of $CO_2$ plume stability. A technical approach has been developed to demonstrate $CO_2$ plume stabilization: 1) construct a geologic model, 2) perform numerical simulations, and 3) estimate the rate of change in circumferential area of the $CO_2$ plume with respect to time (dA/dt). Demonstration of the technical approach for plume stabilization is presented using a North Dakota case study. Operators of other prospective storage sites may benefit from using the same approach to inform selection of potential pore space lease and monitoring areas and development of postinjection site care plans that best meet the goals of prospective CCS projects.

*Keywords:* CCS; demonstration; plume stability; plume metrics; policy; postinjection site care; pressure plume; monitoring; site closure

## 1. Introduction

Carbon capture and storage (CCS) is a process in which carbon dioxide ($CO_2$) is captured and injected underground into a geologic reservoir (storage reservoir or injection interval) for permanent storage. Injection wells are used to push $CO_2$ into the target storage reservoir or injection interval at a higher pressure than the native reservoir pressure into available pore space. During $CO_2$ injection operations, the $CO_2$ plume is expected to migrate within the storage reservoir in both vertical and lateral directions. The three-dimensional (3D) extent of injected $CO_2$ in the storage reservoir is referred to as the $CO_2$ plume. Operators of geologic $CO_2$ storage sites within the United States must track the migration of the $CO_2$ plume to provide assurance that the injected $CO_2$ is contained within the injection interval throughout the life of the project. Within the United States, before a storage site is approved by appropriate regulatory agencies (Table 1) for site closure, operators are also required to demonstrate that the $CO_2$ plume has stabilized

* Corresponding author email address: jhunt@undeerc.org

(hereafter plume stability or plume stabilization). The objectives of this study are to provide a unified definition of $CO_2$ plume stability that is compliant across multiple CCS policies and frameworks applicable within the United States and present a technical approach for determining when plume stabilization occurs.

**Nomenclature**

| | |
|---|---|
| 3D | three-dimensional |
| CARB | California Air Resources Board |
| CCS | carbon capture and storage |
| $CO_2$ | carbon dioxide |
| EERC | Energy & Environmental Research Center |
| EPA | U.S. Environmental Protection Agency |
| NDIC | North Dakota Industrial Commission |
| UIC | underground injection control |
| USDW | underground source of drinking water |

### *1.1. CCS Policy Review*

The CCS policies reviewed in this study included the underground injection control (UIC) $CO_2$ injection well (Class VI)-permitting program and Greenhouse Gas Reporting Program Subpart RR requirements as regulated by the U.S. Environmental Protection Agency (EPA) and states with primacy, California 's low-carbon fuel incentive programs, and CCS regulatory frameworks established by the Government of Alberta and European Parliament. Each of the CCS policies was reviewed to identify any guidance or regulatory definition associated with plume stability. Table 1 summarizes the CCS policy review.

The study identified two key elements in each policy relative to plume stability. The first key element is a demonstration of a near-stationary position of the $CO_2$ plume. The second key element is a focus on containment of the injected $CO_2$ to protect human health and the environment. While the language in each policy may be worded differently the unifying message behind these policies is focused on protecting human health and the environment. For example, EPA focuses on nonendangerment to underground sources of drinking water (USDWs), as the rule is under the Safe Water Drinking Act. Other policies, such as those from California, the European Parliament, and the Government of Alberta focus more broadly on eliminating risk of leakage from the injection interval. Wyoming is perhaps the most prescriptive and adds a note about the need for demonstrating plume stability with monitoring data. In North Dakota, the risk is discussed in terms of the plume being unlikely to cross a project's permit boundary (e.g., pore space lease area).

Additionally, it is worth noting that in the United States, EPA guidance for postinjection site care (PISC) and site closure [4] states: "If plume migration rates are extremely slow, and/or if a demonstration can be made that no conduits for fluid movement/leakage pathways exist in the direction(s) of plume migration within long timeframes (e.g., hundreds to thousands of years) until the plume reaches a potential receptor, USDW endangerment potential may be determined to be low."

### *1.2. Unified Definition of Plume Stability*

Based on review of the regulations stated above and previous review of plume stabilization metrics [1], this study defines plume stability as follows: the $CO_2$ plume 1) moves minimally and predictably in the storage reservoir such that it will not cross key boundaries and 2) does not pose a threat to human health, USDWs, and the environment.

Table 1. Summary of plume stability rules and guidance from CCS policies.

| Regulatory Body | Policy | Reference | Guidance/Rule |
|---|---|---|---|
| EPA | Title 40 Code of Federal Regulations | § 146.93(b) | "The owner or operator shall monitor the site following the cessation of injection to show the position of the carbon dioxide plume and pressure front and demonstrate that USDWs are not being endangered." |
| North Dakota | North Dakota Century Code | § 38-22-17(5)(d) | Show that the injected $CO_2$ plume "has become stable," or that the plume is "essentially stationary or, if it is migrating or may migrate, that any migration will be unlikely to cross the storage reservoir boundary." |
| Wyoming | Wyoming Code of Regulations | § 24-2(hh) | Show that the injected $CO_2$ plume "essentially no longer expands vertically or horizontally and poses no threat to USDWs, human health, safety, or the environment, as demonstrated by a minimum of three consecutive years of monitoring data." |
| Louisiana | Louisiana Administrative Code | 43:XVII, Chapter 36, § 3633.A.2 | "The owner or operator shall monitor the site following the cessation of injection to show the position of the carbon dioxide plume and pressure front and demonstrate that USDWs are not being endangered." |
| California | Low Carbon Fuel Standard CCS Protocol | Chapter A Section (2)(a)(85) | Show that the injected $CO_2$ plume's "migration and pressure changes are small and predictable, such that the measured rate of plume migration has a high certainty of no $CO_2$ leakage over a 100-year period." |
| Government of Alberta | CCS Statutes Amendment Act of 2010 | § 14-9.120(3)(f) | Show that the injected $CO_2$ plume is "behaving in a stable and predictable manner, with no significant risk of future leakage." |
| European Parliament | European Union Directive 2009/31/EC | Chapter 1, Article 18(2) | Demonstrate "conformity of the actual behavior of the injected $CO_2$ plume with the modeled behavior, the absence of detectable leakage, and that the storage site is evolving toward a situation of long-term stability." |

Maintaining a postinjection monitoring plan until plume stabilization is demonstrated is crucial for potential CCS storage site operators. While not required by all CCS policies, a best practice to demonstrate plume stability should incorporate monitoring data to show conformance with predictions from numerical simulations and be compliant with CCS policy. Some CCS policies (e.g., California's CCS Protocol) also recommend using risk assessment to show how the risk profile of $CO_2$ plume migration has decreased as part of the final demonstration. Commercial-ready methods available for tracking $CO_2$ plumes include time-lapse seismic or electromagnetic surveys and pulsed-neutron logging.

## 2. Technical Approach

The University of North Dakota Energy & Environmental Research Center (EERC) has established a technical approach for determination of $CO_2$ stabilization. This method has been used to develop technical exhibits demonstrating plume stability for several North Dakota UIC Class VI permit applications. To date, several permit applications using this method have been approved by the North Dakota Industrial Commission (NDIC) Department of Mineral Resources which has been granted primacy authority for the regulation of Class VI wells in North Dakota.

The technical approach has three essential steps: 1) construct a geologic model, 2) perform numerical simulations, and 3) apply the appropriate plume metric to estimate when the injected $CO_2$ plume stabilizes.

Published literature on plume metrics was reviewed to determine which metric or combination of metrics would be most appropriate for the demonstration of $CO_2$ plume stability. Ultimately, estimation of the $CO_2$ plume's dA/dt [2], or the rate of change in circumferential area of the $CO_2$ plume with respect to time, was selected. Other metrics discussed in literature include but are not limited to risk profile assessments, tracking lateral mobility of the $CO_2$ plume's effective centroid, and characterizing trapping mechanisms (e.g., mineralization, hydrodynamics, and dissolution) [1]. The dA/dt metric was selected above others primarily because tracking the $CO_2$ plume (as required under CCS policy) in terms of a rate of areal change is ideal for history-matching time-lapse geophysics-based monitoring results with predictions from numerical simulations.

This section includes an example of this technical approach for plume stabilization using a North Dakota case study. The case study assumes more than 1 million tonnes of $CO_2$ injection annually for 20 years with a single injection well into a regionally extensive and flat-lying aeolian sandstone and saline aquifer in the Williston Basin of North Dakota.

## *2.1. Geologic Model*

The geologic model, constructed in SLB's Petrel software, considered the injection interval and associated confining zones, as depicted in Fig. 1. The Broom Creek Formation is the target injection interval and is dominated by aeolian sandstone and associated dolostone and anhydrite deposits. The Opeche, Minnekahta, Spearfish, and Piper Formations comprise the upper confining zone and consist primarily of siltstone. The Amsden Formation is the lower confining zone and consists primarily of dolostone. Data for constructing the geologic model were obtained from core, well logs, and seismic data.

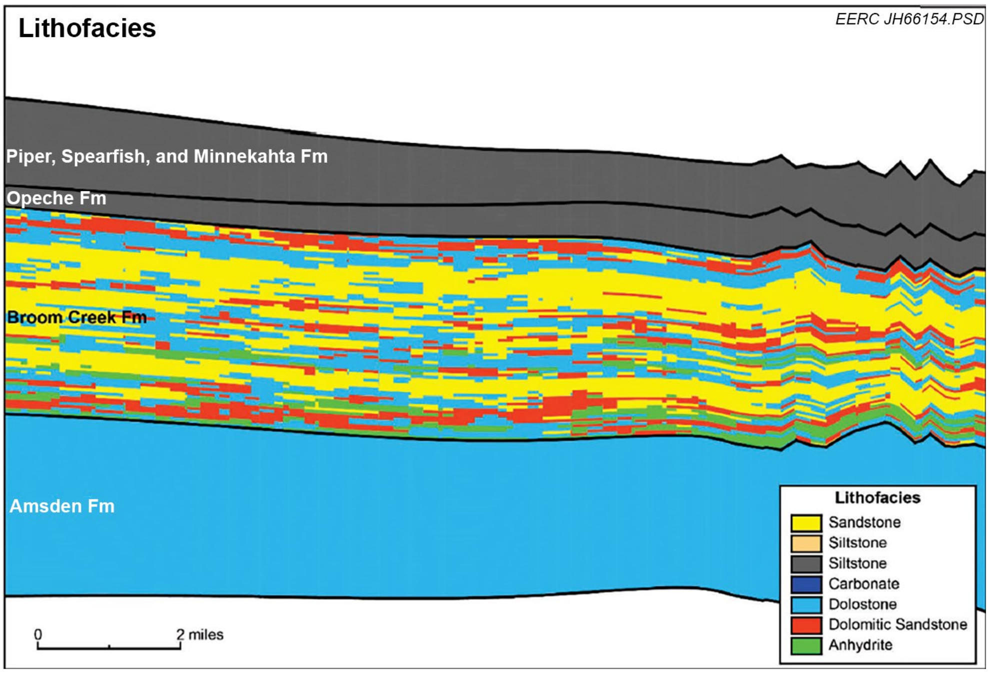


Fig. 1. Cross section of geologic model constructed, depicting the distribution of lithofacies [1]. 35× vertical exaggeration shown.

The geologic model is approximately 23 square miles (37 square kilometers), with a grid cell size of 1000 feet (305 meters) in both the x and y directions. Layer thickness varies from 5 to 7 feet (1.5 to 2 meters). The model also assumes no-flow boundaries for both the upper and lower confining zones.

*2.2. Numerical Simulations*

Multiphase fluid flow numerical simulations were performed in Computer Modelling Group's GEM software. Site-specific data were used to constrain the fluid flow parameters such as porosity and permeability. The injection scenario assumed 77 million tonnes of $CO_2$ stored in the Broom Creek Formation in 20 years and a 50-year postinjection period. The scenario assumed two injection wells. The 50-year postinjection simulation period was chosen based on the EPA ruling provided under Title 40 Code of Federal Regulations § 146.93.

Gas saturation, representing the free-phase $CO_2$ plume present in the injection interval, was selected as the simulation output and was run in at least 5-year time steps over the 70-year period. A 5-year time step was used to correspond with CCS policy which requires operators to regularly review the permit. Numerical simulation results produced gas saturation values for each cell from 0 to 100% (minus any irreducible water content). A 5% gas saturation cutoff was applied [3] to approximate the limit of seismic resolution in good-porosity (20% to 30%) reservoir rock. Maps were generated for each time step by using the 5% cutoff within a single cell to define the edge of the $CO_2$ plume, as the example illustrates in Fig. 2.

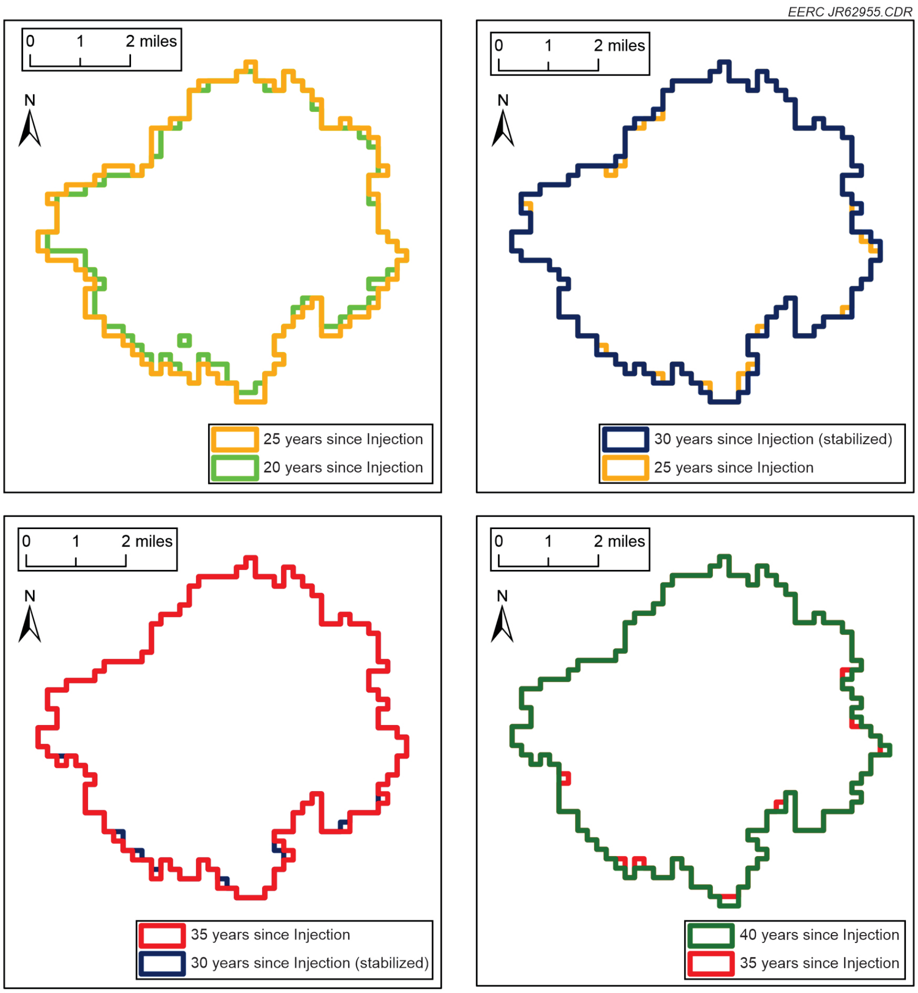


Fig. 2. Maps generated for Years 20 through 40 since $CO_2$ injection began [1]. Each of the four blocks has two maps represented to illustrate the change in $CO_2$ plume area for each 5-year time step.

*2.3. Plume Stability Results and Discussion*

Determination of when the plume stabilizes for this case study was identified by plotting dA/dt and picking the point at which dA/dt slows significantly and approaches a horizontal asymptote ($t_{critical}$), as shown in Fig. 3. In this case, $t_{critical}$ occurs in Year 10 of postinjection (or Year 30 since injection began), where dA/dt slows to approximately 0.1 square miles (0.25 square kilometers) annually.

The storage reservoir boundary (pore space lease area) is not shown in Fig. 2, but the results from this case study show the $CO_2$ plume will stay within the boundary selected by the operator. Operators of other prospective storage sites may use this same approach to inform selection of the pore space lease and monitoring areas that best meet the goals of the carbon storage project to ensure the regulatory definition of plume stability is met. Determining plume stability as part of the initial permitting process may also help inform postinjection monitoring activities and timing and derive total cost as an input into the financial assurance needed to permit the project.

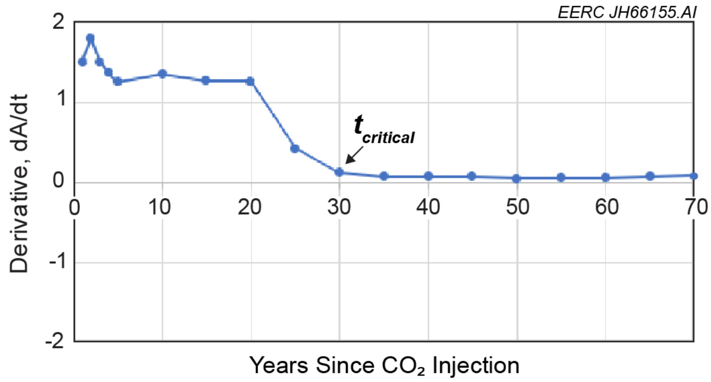


Fig. 3. Plot of dA/dt over the 70-year simulation period, illustrating the occurrence of where the derivative slows significantly and reaches a horizontal asymptote ($t_{critical}$) [1].

## 3. Conclusions

Conclusions from this study are summarized below:

- Many CCS regulatory policies and frameworks require the demonstration of plume stability for the duration of injection and postinjection phases of a carbon storage project.
- The EERC has developed a technical approach to define and demonstrate plume stability for potential CCS projects, which has been successfully used within permitting applications in the state of North Dakota.
- Plume stability means the injected $CO_2$ plume moves minimally and predictably such that key boundaries are not crossed and human health and the environment are protected.
- To demonstrate plume stability, the proposed technical approach includes the following: 1) construct a geologic model, 2) perform numerical simulations, and 3) estimate the rate of change in circumferential area of the $CO_2$ plume with respect to time (dA/dt).
- While not required by all CCS policies, a best practice to demonstrate plume stability should incorporate monitoring data to show conformance with predictions from the methodology presented and to compare results.
- Operators of carbon storage projects benefit from determining the stabilized plume during the permitting process to help guide development of the PISC plan.

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## References

[1] Regorrah JG, Hunt JE, Templeton JA, Dotzenrod NW, Azzolina NA, Dalkhaa C, Peck WD, Livers-Douglas AJ, Connors KC. A quantitative approach for demonstrating plume stabilization under CCS policy frameworks. Plains $CO_2$ Reduction (PCOR) Partnership White Paper, 2023-EERC-05-03.

[2] Harp D, Onishi T, Chu S, Chen B, Pawar R. Development of quantitative metrics of plume migration at geologic $CO_2$ storage sites. Greenh Gas Sci Technol 2019; 9:687–702. doi: 10.1002/ghg.

[3] Roach LAN, White DJ, Roberts B. Assessment of 4D seismic repeatability and $CO_2$ detection limits using a sparse land array at the Aquistore $CO_2$ storage site. Geophysics 2014; 80:WA1-WA13. doi: 0.1190/GEO2014-0201.1.

[4] U.S. Environmental Protection Agency, 2016, Underground Injection Control (UIC) Program Class VI well plugging, post-injection site care, and site closure guidance; https://www.epa.gov/sites/default/files/2016-12/documents/uic_program_class_vi_well_plugging_post-injection_site_care_and_site_closure_guidance.pdf (accessed November 2024).