REGION 8
DENVER, CO 80202

March 24, 2026

MEMORANDUM

SUBJECT: EPA Alternative PISC Review and Approval Memorandum for the Front Range Storage Complex Class VI permit– Permit Number CO62455-12770; Weld County, Colorado

FROM: Zac Moore

TO: Administrative Record, CO62455-12770

Summary

Carbon Storage Solutions (CSS), owner and operator of the Front Range Storage Complex, requested an alternative-Post-Injection Site Care (PISC) timeframe of 20 years as a result of modeling outputs validated by EPA in August of 2025. EPA reviewed all parts of the CSS application relevant to the PISC as a part of the technical review. CSS has met the regulatory requirements for an alternative PISC timeframe of 20 years, and EPA concludes that there is substantial evidence that the project will not pose a risk of endangerment to USDWs at the end of the 20-year timeframe as outlined in this memorandum.

Overall Summary of Legal Requirements

The PISC plan is required to be part of a Class VI permit. See generally 40 CFR 146.93. A PISC consists of monitoring requirements that apply to “the period after CO_2 injection ceases—but prior to site closure—during which the owner or operator must continue monitoring to ensure USDW protection from endangerment.” 75 Fed. Reg. 77230, 77266 (December 10, 2010); see also 40 CFR 146.93(a)(1), (b). The “period” is known as the PISC timeframe. See 75 Fed. Reg. at 77266; 40 CFR 146.93(a)(1)(v). The Class VI regulations require the PISC timeframe to be “at least 50 years or for the duration of the alternative timeframe approved by [EPA].” 40 CFR 146.93(b)(1). Under the latter of these options, a permit applicant may submit, and EPA may approve, an alternative timeframe for a PISC “if an owner or operator can demonstrate during the permitting process that an alternative post-injection site care timeframe is appropriate and ensures non-endangerment of USDWs.” 40 CFR 146.93(c); see also 40 CFR 146.93(a)(2)(v). This is often an iterative process where the permit applicant may engage with EPA to meet the data and information requirements in the Class VI regulations.

This permitting process begins with the submission of a demonstration by the permit applicant as part of the permit application. 40 CFR 146.93(c). Under 40 CFR 146.93(c), an alternative PISC timeframe demonstration must consider and document ten elements. 40 CFR 146.93(c)(1). The regulations also outline eight criteria that the information submitted in the demonstration must meet. 40 CFR 146.93(c)(2). Prior to approval, EPA must ensure that the permit applicant's demonstration, comprised of information on each of the ten elements in accordance with the requirements for the eight criteria, meets two standards overall: 1) the demonstration must be based on significant site-specific data and information, including data and information collected in the permit application and the siting criteria; and 2) the demonstration must include substantial evidence to support a conclusion that the project will no longer pose a risk of endangerment to USDWs at the end of the timeframe. 40 CFR 146.93(c). Site-specific data and information collected under these regulatory elements allows EPA to evaluate whether the applicant has demonstrated that the alternative PISC timeframe will not pose a risk of endangerment to USDWs.

EPA may reject a permit applicant's demonstration if any of the information provided indicates a risk of endangerment to a USDW, regardless of support for the alternative timeframe from modeling or any single regulatory requirement. See 40 C.F.R. 146.93(c) (stating that a demonstration must ensure non-endangerment of USDWs). EPA may also provide feedback and accept revisions to the demonstration as necessary. Once satisfied that the demonstration includes all of the required information, EPA may ultimately choose to approve the alternative PISC timeframe if the information provided in the demonstration provides a basis to do so, i.e., if the site-specific data and information indeed demonstrates "that an alternative post-injection site care timeframe is appropriate and ensures non-endangerment of USDWs." 40 CFR 146.93(c). The Agency's approval results in the alternative PISC timeframe's incorporation into the permit. 40 CFR 146.82(a)(17), 146.84(b)(2)(i), 146.93(a). Importantly, the initial PISC timeframe set at permit issuance is based on a projection or estimate and is not final. The initial PISC timeframe must be reconsidered and updated as appropriate prior to injection, during operation, after injection ceases, and at site closure. See 40 CFR 146.82(c)(9) (prior to injection), 146.84(b)(2)(i) (during injection), 146.93(a)(2)(ii) (during injection), 146.93(a)(3) (post injection), 146.93(b)(3) (site closure).

<u>Technical Background Summary of the Ten Elements in the Regulations</u>

As explained in the Legal Requirements Section, an alternative PISC timeframe demonstration must consider and document ten elements. 40 CFR 146.93(c)(1). Overall, those elements must demonstrate that the alternative timeframe ensures non-endangerment of USDWs, i.e., that the project will no longer pose a risk of endangerment to USDWs at the end of the timeframe. Below is a short explanation of each element and how it relates to the PISC timeframe determination.

First element: the results of the computational modeling performed for the Area of Review (AoR) as required by 40 CFR 146.93(c)(1)(i). The AoR is "the region surrounding the geologic sequestration project where USDWs may be endangered by the injection activity." 40 CFR

146.84(a). For Class VI wells, the AoR is determined using advanced computational modeling to predict development of the injected CO_2 and area of elevated pressure underground. The injected fluid is sometimes referred to as the CO_2 plume once it is underground. Permit applicants must perform computational modeling to determine the size of the AoR. More specifically, computational modeling, as well as site characterization (element #4 below) and monitoring and operational data, are used to predict the migration of the CO_2 plume until the plume movement reaches its maximum and ceases (element #3 below) and until the pressure differentials (element #2 below) sufficient to cause movement of fluids into USDWs are no longer present. 40 CFR 146.84(c)(1). The regulation contains strict requirements for computational modeling. See 40 CFR 146.84(c)(1)(i)-(iii). The model relies upon "significant site-specific data and information" from the other regulatory elements in 40 CFR 146.93(c), which, among other things, ensure that the model accounts for conditions present in the geology as inputs, outputs, variables, and assumptions. 40 CFR 146.93(c). The PISC timeframe should extend at minimum to the point in time that the model shows the migration of the CO_2 plume underground will cease and the elevated pressure will dissipate. At this point, the injected CO_2 will continue to remain in the injection zone long term, ensuring non-endangerment of USDWs.

Second element: the predicted timeframe for pressure declines within the injection zone as required by 40 CFR 146.93(c)(1)(ii). Pressure ripples out both vertically and horizontally from the point of injection and dissipates or declines both over time and distance from the injection well. An understanding of the rise and decline of underground pressure in the geology around the injection well is important for many reasons. It helps predict the underground movement of the CO_2 plume (element #3 below). It is also important to understand because fluid movement outside of the rock formations can occur and thus pose a risk of endangerment to USDWs when pressure gets too high. See Proposed Class VI Rule, 73 Fed. Reg. 43492, 43519 (July 26, 2008) (explaining that "[a] record of the pressures in the injection formation can help the owner or operator determine that the injected fluid does not pose endangerment to USDWs."). The predicted pressure decline is relevant to determining an alternate PISC timeframe because the PISC timeframe should extend at minimum to the point in time that the model shows the migration of the CO_2 plume underground will cease and the elevated pressure will dissipate. As stated above, at this point, the injected CO_2 will continue to remain in the injection zone long term, ensuring non-endangerment of USDWs.

Third element: the predicted rate of CO_2 plume migration within the injection zone as required by 40 CFR 146.93(c)(1)(iii). The CO_2 plume refers to the injected CO_2 in the subsurface, which can migrate during the injection period and even after injection ceases due to residual pressure (element #2 above). An understanding of the migration of injection zone is important for many reasons including that CO_2 outside of the confining zone (element #7 below) could pose a risk to USDWs (element #10). The PISC timeframe should extend at minimum to the point in time that the model shows the migration of the CO_2 plume underground will cease and the elevated pressure will dissipate. As stated above, at this point, the injected CO_2 will continue to remain in the injection zone long term, ensuring non-endangerment of USDWs.

Fourth element: a description of the site-specific processes that would result in CO_2 trapping as required by 40 CFR 146.93(c)(1)(iv). CO_2 trapping occurs when CO_2 is injected into the subsurface for capture and storage. See 75 Fed. Reg. at 77232 (defining trapping). Injected CO_2 accumulates, i.e., becomes trapped in one area or another due to variations in rock structure and properties. Depending on the phase and rate of the trapping, it can appropriately prevent migration of the CO_2 plume. Trapping can be concerning when it is uneven and excessive and occurs next to a fault or conduit because it may allow for unintended fluid movement. (see elements #7-#8 below).

The site-specific processes that will result in trapping are both physical and geochemical. The physical characteristics are often the low permeability of the confining rock formations, which are often made of shale and dolomite, and the related pore spaces. They also include physical characteristics of the injection zone, that are often comprised of rocks like sandstone or siltstone that are of higher permeability with ample pore space. These physical properties affect structural and immobile capillary trapping. The former refers to a geological barrier that prevents fluid movement. The latter refers to residual CO_2 that is left behind in the pore spaces of a rock formation as the CO_2 gains buoyancy and migrates to other available pore spaces.

The geochemical characteristics are the properties of the rock formations in the injection zone that will allow for dissolution, which can result in the dissolved phase of trapping (see element #5 below) and mineralization, which can result in the mineral phase of trapping (see element #5 below). Dissolution refers to when CO_2 goes from gaseous to aqueous (liquid-like) phase and eventually becomes a part of the rock formation due to the presence of salty water (brine). Mineralization refers to when elements in the injection zone chemically react with CO_2 to create a new element (primarily clay).

The PISC timeframe should extend at minimum to the point in time that the model shows the migration of the CO_2 plume underground will cease and the movement of the CO_2 plume is affected by trapping. In addition, trapping must be considered to confirm that the injected fluid will not move in unintended ways and will remain in the injection zone long term, thus ensuring non-endangerment of USDWs.

Fifth element: the predicted rate of CO_2 trapping in the immobile capillary phase, dissolved phase, and/or mineral phase as required by 40 CFR 146.93(c)(1)(v). EPA considers trapping to help determine how CO_2 will be confined in the subsurface. In other words, the modeling of the plume migration (element #1) may not be accurate if it does not account for the potential for trapping. Immobile capillary phase, dissolved phase, and/or mineral phase are all types of trapping. The model (element #1 above) includes predicted rates of CO_2 plume migration that account for trapping in the immobile capillary phase, dissolved phase, and the mineral phase. Thus, modeling results should confirm that trapping will occur at appropriate locations and points in time and uneven excess trapping of CO_2 will not occur within the predicted rates for the immobile capillary phase, dissolved phase, or mineral phase, or that if uneven excess trapping is predicted to occur, that it will not result in unintended fluid movement. As stated above, the PISC timeframe should extend at minimum to the point in time that the model shows the migration of the CO_2 plume underground will cease and the movement of the CO_2 plume is affected by trapping. In addition, trapping must be considered to confirm that the injected fluid will not move in unintended ways and will remain in the injection zone long term, thus ensuring non-endangerment of USDWs.

Sixth element: the research used to verify the information required in 40 CFR 146.93(c)(1)(iv) and (v) (elements #4 and #5 above). The permit applicant should provide references to the research conducted and the sources and studies used to verify the information that went into the trapping analysis and model scenarios discussed in elements #4 and #5 above. Permit applicants may also perform testing on a test hole to establish site-specific geochemical, petrological, and geological characteristics. As stated above, the PISC timeframe should extend at minimum to the point in time that the model shows the migration of the CO_2 plume underground will cease and the movement of the CO_2 plume is affected by trapping. In addition, trapping must be considered to confirm that the injected fluid will not move in unintended ways and will remain in the injection zone long term, thus ensuring non-endangerment of USDWs. If the research verifying the trapping information is flawed or inaccurate, then the trapping analysis may be unreliable.

Seventh element: a characterization of the confining zone, including a demonstration that it is free of transmissive faults, fractures, and micro-factures and of appropriate thickness, permeability and integrity as required by 40 CFR 146.93(c)(1)(vii). A characterization of the confining zone is relevant to determining an alternative PISC timeframe because it affects the computational modeling results (element #1 above) in at least two ways. First, the model must account for the characteristics of the confining zones because CO_2 moves differently in different rock formations. See EPA, UIC Program Class VI Area of Review Evaluation and Corrective Action Guidance, at 31 (May 2013) ("Class VI AoR Guidance"). Because the model is meant to predict the extent of the CO_2 plume, it needs to account for how the CO_2 will migrate in the rock formations present in the confining zone. See 40 C.F.R. 146.84(c)(1)(iii). Second, the model must include the characteristics of the confining zone because the goal of the modeling is to determine the full plume at its maximum extent and confirm that the plume will remain contained at that extent long term. The proposed Class VI Rule explains, "[t]he confining system [element #7] should be of sufficient regional thickness and lateral extent to contain the entire CO_2 plume [element #3] and associated pressure front [element #2] under the confining system following the plume's maximum lateral expansion [as modeled]." 73 Fed. Reg. at 43505. In addition, a characterization of the confining zone must be considered to confirm that the injected fluid will not move beyond the confining zone and will remain in the injection zone long term, thus ensuring non-endangerment of USDWs.

Eighth element: the presence of potential conduits for fluid movement as required by 40 CFR 146.93(c)(1)(viii). EPA evaluates the presence of potential conduits to determine whether there are any pathways that could allow the CO_2 plume to migrate in an unintended way and endanger USDWs. Conduits for fluid movement typically occur in three scenarios. First, faults in the rock formations can create potential conduits for fluid movement. 73 Fed. Reg. at 43505. Second, wells that penetrate the confining zone can create conduits for fluid movement. 73 Fed.

Reg. at 43515. The first two of these scenarios are addressed in element #7 above and element #9 below.

Under the third scenario, injection and monitoring wells associated with the project are intended to allow conduits for fluid movement by their design. 73 Fed. Reg. 43503. Fluid movement is necessary during the operating life of the wells (i.e., the wells act as conduits for the intentional act of injecting CO_2 and monitoring wells to oversee such injection). See EPA, UIC Program Class VI Well Plugging, Post-Injection Site Care, Site Closure Guidance, at xi (2016) ("Class VI PISC Guidance") (definition of well plugging). So, while there is a potential conduit for fluid movement in the third scenario, the intentional fluid movement during the operating life of the wells is not a risk to USDWs. Unintended fluid movement during operation is mitigated by the proper well construction and operating parameters in concert with the approved Testing and Monitoring Plan. See 40 CFR 146.86; 146.88. Unintended fluid movement can also occur through the wells when operation ceases. To address the concern of unintended fluid movement post-injection, wells are plugged, meaning that the conduits are closed. See Class VI PISC Guidance at ii ("After injection ceases at a Class VI GS project, the injection well must be plugged to ensure that the well does not become a conduit for fluid movement into USDWs."). The permit applicant is required to submit a Plugging and Abandonment Plan to address these potential conduits.

The PISC timeframe should extend at minimum to the point in time that the model shows the migration of the CO_2 plume underground will cease and the movement of the CO_2 plume is unaffected by the presence of conduits. In addition, fluid conduits must be considered to confirm that the injected fluid will not move in unintended ways and will remain in the injection zone long term, thus ensuring non-endangerment of USDWs.

Ninth element: A description of the well construction and an assessment of the quality of plugs of all abandoned wells within the AoR required by 40 CFR 146.93(c)(1)(ix). See also 40 CFR 146.86 (Class VI well construction requirements). Unplugged or improperly plugged wells can act as fluid conduits that might endanger USDWs. See Class VI PISC Guidance at 1. Under 40 CFR 146.82(a)(4), a permit application must include "[a] tabulation of all wells within the area of review which penetrate the injection or confining zone. Such data must include a description of each well's type, construction, date drilled, location, depth, record of plugging and/or completion, and any additional information the Director may require." In addition, 40 C.F.R. 146.84(c)(2) requires permit applicants to "identify all penetrations, including active and abandoned wells and underground mines, in the area of review that may penetrate the confining zone(s). Provide a description of each well's type, construction, date drilled, location, depth, record of plugging and/or completion, and any additional information the Director may require." The PISC timeframe should extend at minimum to the point in time that the model shows the migration of the CO_2 plume underground will cease and the movement of the CO_2 plume is unaffected by the presence of penetrations (such as abandoned wells) that could serve as fluid conduits. In addition, the condition of abandoned wells must be considered to confirm that the injected fluid will not move in unintended ways and will remain in the injection zone long term, thus ensuring non-endangerment of USDWs.

Tenth element: the distance between the injection zone and the nearest USDWs as required by 40 CFR 146.93(c)(1)(x). Among other things, an understanding of the distance from the injection zone to the nearest USDW is necessary to determine (and avoid reaching) the amount of pressure required for the injected CO_2 to travel through rock formations to reach a USDW (calculated as the pressure differential).

Summary of the Eight Criteria in the Regulations

As explained in the Legal Requirements Section, the information submitted as part of an alternative PISC timeframe demonstration must meet eight criteria. 40 CFR 146.93(c)(2). These criteria help ensure the accuracy of the data and information underlying the ten elements so that EPA can rely upon the information provided for the ten elements.

1. Tests are accurate, reproducible, and meet quality assurance standards
2. Use of appropriate or EPA-certified test protocols
3. Predictive models are tailored to site conditions
4. Calibration of predictive models
5. Account for uncertainty
6. Use reasonably conservative values and assumptions
7. Must have quality assurance and quality control plan
8. Any additional criteria EPA requires

Factual Background

In Carbon Storage Solutions, LLC's Class VI permit application submitted to EPA in May of 2024, the injection period was 12 years and the alternative PISC timeframe was 20 years. The primary basis for this proposal was CSS's computational model which indicated that the injection zone pressure would decline to near pre-injection levels in 20 years after injection ceases (G. Post-Injection Site Care Plan (May 2024)).

Analysis of CSS' Alternative PISC Timeframe Demonstration

This Analysis is organized into four parts. Part I confirms that CSS's alternative PISC timeframe demonstration considers and documents the ten required regulatory elements. Part II concludes that CSS's demonstration is based on significant site-specific data and information, including data and information collected in the permit application and the siting criteria. Part III finds that the information submitted in CSS's demonstration meets the eight quality-control regulatory criteria. Part IV determines that CSS's demonstration includes substantial evidence to support a conclusion that the project will no longer pose a risk of endangerment to USDWs at the end of the proposed 20-year timeframe.

Part I: Ten Elements

CSS's alternative PISC timeframe demonstration must consider and document the ten elements of 40 CFR 146.93(c)(1). Overall, those elements must demonstrate that the alternative timeframe of 20 years ensures non-endangerment of USDWs, i.e., that the project will no longer pose a risk of endangerment to USDWs at the end of 20 years post-injection. Below is a discussion of the information that CSS considered, documented, and submitted to EPA and in turn, that EPA reviewed regarding each element.

Element #1: the results of the computational modeling performed for the Area of Review (AoR) as required by 40 CFR 146.93(c)(1)(i).

The results of the computational model demonstrate that the injection zone pressure will return to a less than 1% difference than pre-injection levels within 20 years post-injection. The model incorporated site-specific data from the Front Range 1-1 well. Gathering geologic information at the project site allowed the model to account for local heterogeneity, proposed operating conditions, and migration pathways. There is no evidence that there are natural or artificial migration pathways for the CO_2, as explained in Elements #8 and #9. The model showed that the expansion of the plume will plateau in the model by that time as well. EPA has verified that computational modeling demonstrates that the injectate will stabilize and injection zone pressures will decrease soon after injection ends. The model included trapping rates that supported the plume migration results. A sensitivity analysis was also performed to model various site-specific porosity and permeability scenarios using data from the characterization of local geology, further justifying the 20-year PISC timeframe (PBI_G._PISC and Site Closure Plan, 2024). EPA agrees with the model's inputs, outputs, variables, and assumptions.

Element #2: the predicted timeframe for pressure decline within the injection zone as required by 40 CFR 146.93(c)(1)(ii).

After the injection period of 12 years, pressure in the injection zone falls rapidly. Twenty (20) years after injection ceases, modeling predicts the pressure in the injection zone will decrease to pre-injection levels. That is, the pressure differential is expected to be less than or equal to 1% (PBI_G._PISC and Site Closure Plan, 2024,a at Figure B.3-5. (2024)).

Element #3: the predicted rate of CO2 plume migration within the injection zone as required by 40 CFR 146.93(c)(1)(iii).

The CO_2 plume as predicted by the model is largely static at 12 years post-injection and beyond this time (PBI_G._PISC and Site Closure Plan, 2024, at Figures B.4-3). Ten (10) years in the post injection site care period the rate of plume expansion is minimal at 0.01 mi^2/yr, which is a 98% reduction from plume expansion rate during operation. A sensitivity analysis was also performed to model various porosity and permeability scenarios that could affect CO_2 migration. This indicates that the plume migration will plateau within the 20-year post-injection period.

Element #4: a description of the site-specific processes that would result in CO2 trapping as required by 40 CFR 146.93(c)(1)(iv).

Trapping reduces CO_2 migration and was assessed as a part of the computational model. The computational model used site-specific data and information collected in the permit application under 40 CFR 146.82(a)(6) to account for trapping. The site-specific processes that will result in trapping are both physical and geochemical and they are documented in the Site Characterization, AoR and Corrective Action portions of the application. (PBI_A.1_SiteCharacterization and PBI_B Area of Review and Corrective Action. 2024)

The physical processes that result in trapping are the properties of the rock formations, such as permeability and porosity, and how they impact the ability of the fluid to flow or migrate through the rock formations. The model shows that these processes will result in two types of trappings, stratigraphic trapping and immobile capillary phase trapping.

The low permeability and very limited pore spaces in the Upper Satanka (Blaine and Opeche Members) confining layer, which is composed of shale, siltstone, sandstone, anhydrite and minor dolomite in the formation, results in stratigraphic trapping.

Carbon Storage Solutions (CSS) demonstrated immobility (capillary) trapping through reservoir simulations that explicitly represent hysteresis in capillary pressure and relative permeability and include facies-specific capillary entry pressures. CSS calibrated these functions to core and log data and implemented them in a heterogeneous geologic model of the Lyons Formation. Injection and post-injection imbibition were simulated to capture snap-off and ganglion formation behind the advancing CO_2 plume, with outputs tracking residual CO_2 saturation, mobile saturation, plume footprint, and pressure response over time.

The modeling shows that a substantial fraction of injected CO_2 becomes residually immobilized within the swept zone shortly after injection ceases, with local capillary contrasts further impeding upward migration. Results are robust across sensitivities to injection rate, wettability, interfacial tension, and heterogeneity, and they indicate plume stabilization, and declining mobile-phase relative permeability. Together, these lines of evidence substantiate capillary trapping as a durable containment mechanism for the project.

Element #5: the predicted rate of CO2 trapping in the immobile capillary phase, dissolved phase, and/or mineral phase as required by 40 CFR 146.93(c)(1)(v).

CSS provided comprehensive evidence to support that injected carbon dioxide remains trapped and immobile, ensuring the protection of Underground Sources of Drinking Water (USDWs).

To substantiate this claim, CSS utilized computational modeling to predict the stabilization of the CO_2 plume and pressure field within the requested 20-year PISC timeframe. This model incorporates site-specific data obtained during pre-operational testing and considers hydrodynamic, residual, and solubility-trapping processes. Although mineralization is too slow to affect the timeframe, these trapping mechanisms are crucial for demonstrating CO_2 immobility.

The "Area of Review and Corrective Action Plan" further reinforces these findings through sensitivity analyses on the impact of permeability, affected by natural fractures within the injection zone. The permeability study is essential due to its influence on the areal extent of the CO_2 plume. CSS predicts rapid pressure decay post-injection, reaching the minimum threshold pressure by Year 13, and ensuring insufficient pressure to drive fluids into USDWs.

Additionally, the confining zones are characterized by their impermeability, with no transmissive faults or fractures, offering further assurance of CO_2 containment. Predicted stabilization of both pressure and plume by Year 32, representing 12 years of injection and 20 years post-injection, supports the alternate PISC timeframe, demonstrating compliance with regulatory requirements.

Together, these documents provide a robust narrative that demonstrates CSS's commitment to ensuring the injected CO_2 remains trapped and immobile, thus safeguarding USDWs and aligning with 40 CFR 146.93(c)(1)(v).

Element #6: the research used to verify the information required in 40 CFR 146.93(c)(1)(iv) and (v) (elements #4 and #5 above).

The equations and models used to verify the trapping information come from reputable scientific literature and are industry standards that have been validated over time. CSS summarized many of these sources, reproduced below:

- Duan and Sun (2003) developed a thermodynamic model for the solubility of CO_2 in pure water and aqueous solutions.
- Razipechikolaee et al., 2013 shows the CMG solubility model using Henry's law is in good agreement with the Duan and Sun model under different pressure and temperature conditions.
- The amount of CO_2 residually trapped in the aquifer due to relative permeability hysteresis is determined by the Land Model (Land, 1968).
- Linear Land's equation is used in the simulator for modeling hysteresis in relative permeability (CMG-GEM,2022, Land, 1968).
- The input parameters that control the amount of trapped gas are the relative permeability curves to estimate Land model's parameters depending on CO_2 saturation at each time step (relative permeability curve provided in Section 2.1.4 Constitutive Relationships and Other Rock Properties) of the Area of Review and Corrective Action Plan, and maximum residual gas saturation.
- As mentioned, one of the parameters that controls the amount of trapped gas by relative permeability hysteresis is the maximum residual gas saturation, which is a function of the formation pore structure (Raziperchikolaee et al., 2013).

Furthermore, all equations and models have been verified and validated by EPA. Additionally, data will be collected from the injection and monitoring wells before, during, and after operations to verify the computational models (PBI_G._PISC and Site Closure Plan, 2024).

Element #7: a characterization of the confining zone, including a demonstration that it is free of transmissive faults, fractures, and micro-factures and of appropriate thickness, permeability and integrity as required by 40 CFR 146.93(c)(1)(vii).

CSS's assessment of the confining zone demonstrates its robustness in several key aspects. Geophysical surveys and detailed subsurface mapping confirm the absence of transmissive faults and fractures that could compromise the containment integrity (PBI_A.I_SiteCharacterization,2024). This ensures that the zone acts as an effective barrier, preventing CO_2 leakage and protecting USDWs.

Furthermore, the confining zone has been evaluated for its physical properties, showing adequate thickness and low permeability (PBI_A.I_SiteCharacterization,2024). These characteristics are crucial, as they contribute to the zone's ability to impede fluid movement, thereby enhancing the trapping mechanisms for CO_2. The low permeability of the zone ensures that even in the event of elevated pressures within the injection zone, there is minimal risk of migration beyond the designated boundaries.

The structural integrity of the confining zone has been validated through comprehensive geological studies, confirming that it can withstand the pressures associated with CO_2 injection without compromising stability (PBI_A.I_SiteCharacterization,2024). This integrity is vital for maintaining the long-term effectiveness of the storage site.

Through these detailed evaluations, CSS has demonstrated that the criterion set out in 40 CFR 146.93(c)(1)(vii) has been met, ensuring that the confining zone is suitable to contain the injected CO_2. This demonstration aligns with regulatory standards designed to protect environmental and public health. For more information on the characterization of the confining zone, see the Fact Sheet at regulations.gov, docket # EPA-R8-OW-2026-1915

Element #8: the presence of potential conduits for fluid movement as required by 40 CFR 146.93(c)(1)(viii).

Vertical migration of injectate is restricted due to the absence of geological conduits within the AoR. There are no wells that penetrate the upper confining zone within the AoR (PBI_AoR and Corrective Action, 2024). Only the injection well and the deep monitoring well will penetrate the confining zone within the modeling plume extent (PBI_G._PISC and Site Closure Plan, 2024).

Element #9: A description of the well construction and an assessment of the quality of plugs of all abandoned wells within the AoR required by 40 CFR 146.93(c)(1)(ix). See also 40 CFR 146.86 (Class VI well construction requirements).

The injection and monitoring wells are constructed with industry standard steel, corrosion-resistant materials to ensure that the well will be constructed in a sustainable manner for both the injection period and PISC timeframe and that mechanical integrity is maintained throughout the life of the project (PBI_A.II_WellConstructionDetails, 2024). The draft permit also requires that the wells will be properly plugged with cement compatible with Class VI projects (PBI_F._InjWellPluggingPlan, 2024).

Element #10: the distance between the injection zone and the nearest USDWs as required by 40 CFR 146.93(c)(1)(x).

At the project site, the nearest USDW above the injection zone is the Entrada Formation, which is greater than 600 ft above the Lyons Formation. The Ingleside Formation is greater than 200 below the base of the injection zone. This project requires an injection depth waiver, for more information please refer to the Injection Depth Waiver Report.

Part II: Significant site-specific Information

CSS's alternative PISC demonstration is based on significant site-specific data and information, including data and information collected in the permit application and the siting criteria. 40 CFR 146.93(c) (PBI_A.I_SiteCharacterization, 2024).

CSS has collected a wealth of site-specific data to ensure the Front Range Storage Complex's suitability for CO_2 sequestration. The comprehensive data collection process covers various aspects of the project's geologic and hydrologic characteristics.

Most importantly, Carbon Storage Solutions (CSS) drilled the FR 1-1 and FR 2-1 wells as part of their comprehensive site characterization efforts for the Front Range Storage Complex. These wells provided valuable data through sidewall cores and routine core analyses, offering insights into the subsurface geological formations. CSS conducted detailed logging during drilling, capturing crucial information on the depth, thickness, and mineralogical composition of the rock layers encountered. The analysis of sidewall cores allowed CSS to assess porosity, permeability, and capillary pressure, contributing to a better understanding of the injection and confining zones. These efforts ensure precise mapping of geological features and confirm the site's suitability for CO_2 sequestration, reinforcing CSS's commitment to thorough and responsible data collection.

Extensive geophysical surveys and subsurface mapping were conducted to evaluate the regional geology, hydrogeology, and local geologic structure using geologic and topographic maps, as well as cross-sections. This analysis included detailed descriptions of all rock layers from the basement to the surface, providing a robust framework for understanding the site's stratigraphy and its role in aquifer systems.

Data from well logs and regional literature contributed to creating structural cross-sections and isopach maps, providing insights into the depth, thickness, mineralogy, porosity, permeability, capillary pressure, lithology, and facies changes of the injection and confining zones. These assessments confirm the presence and continuity of the sequestration interval and confining units across the site.

Site-specific geochemical data were collected from groundwater in the shallow alluvial and Cretaceous drinking water sources, as well as deeper formation fluids. Samples from the Lyons Sandstone, the primary injection interval, revealed a geochemical system dominated by sodium chloride.

Additionally, soil gas probes installed at the site monitored CO_2 concentrations in the vadose zone, providing crucial information on naturally occurring subsurface CO_2 sources. CO_2 efflux measurements further characterized the site's geochemical profile.

Overall, the significant amount of site-specific data collected serves as a foundational basis for ensuring the project's safety and efficacy, as it helps to ensure accuracy of the information and greater confidence in the modeling.

Part III: Eight Criteria

As explained in the Legal Requirements Section, the information submitted as part of CSS' alternative PISC timeframe demonstration must meet eight criteria. 40 CFR 146.93(c)(2). The information supporting the 20-year PISC timeframe meets all eight criteria:

1. Tests are accurate, reproducible, and meet quality assurance standards

Analyses and tests used to support the alternative PISC demonstration are accurate, reproducible, and performed in accordance with established quality assurance standards. Physical and chemical properties of the geologic units at the site were measured using industry standard methods. Analyses of the geologic units are reproducible and were able to be tested for accuracy. Properties of the injection zone and confining layers were obtained from measurements of sidewall cores, multiple well log types, and reservior formation tests. Well log data collected by CSS included gamma ray, resistivity, porosity, elemental neutron, X-ray diffraction (XRD), and X-ray fluorescence (XRF) logs. The results of each individual log were compared against other logs to check for accuracy. Interpreted properties of the geologic units from well logs could be checked against core samples in the lab. Permeability values of the injection zone and confining zones were calculated from measured porosity values using porosity-permeability transform function, and these values were consistent with direct lab measurements of permeability from core samples. Relative permeability curves measured from samples in the lab were also found to be consistent with permeability curves obtained from analysis of core samples regionally. (PBI_A.I_SiteCharacterization, 2024).

The modeling of the predicted CO_2 plume is reproducible, as the values for the input parameters, details on the modeling software, and equations used within the model were provided by CSS in the application. It is possible to re-run the predictive model using these data. During the sensitivity analysis of the model, CSS ran test cases of the model with differing input parameters and static earth model (SEM) realizations. Equations used to calculate model parameter values are also reproducible. These equations include calculations of permeability based on porosity and maximum injection pressure based on fracture pressure gradient and depth.

2. Use of appropriate or EPA-certified test protocols

CSS used a SEM created in Schlumberger Petrel modeling software, which was used as a framework for dynamic reservoir modeling (DRM) in Eclipse and CO2STORE to model the injection of CO_2. The methods used in computational modeling of the injected CO_2 plume demonstrate that the geologic, chemical, and physical properties of the site are appropriate.

3. Predictive models are tailored to site conditions and composition of the CO_2 stream

The predictive model used to determine the future extent of the CO_2 plume over time is tailored to site conditions. CSS collected site specific data on the geology from the Front Range 1-1 and Front Range 2-1 wells to generate inputs for the computational model. Sidewall cores (SWC), fluid samples, and well logs (e.g., elemental neutron, gamma ray, resistivity, and porosity logs) were obtained from this well to characterize the geology at the proposed injection well site. Core samples and well logs obtained from the Front Range 1-1 well were used to determine the lithology of geologic units (injection and confining zones) into different environments of deposition. Quad Combo logging was used to calculate the petrophysics characteristics of the injection and confining zones. Porosity was determined from density porosity logging and verified with SWC samples. Special core analysis, Mercury Intrusion Capillary Pressure (MICP), is a high-pressure technique that forces mercury into rock pores to determine pore-throat size distribution, porosity, and estimate permeability. Permeability values for rock units were calculated from porosity values using porosity-permeability transform functions and compared against permeability values measured in the lab.

Values directly measured or calculated from the Front Range 1-1 stratigraphic test well were input into the predictive model. Classification of the rock column into different environments of deposition along with distributions of porosity and permeability were used to model porosity and permeability in the injection and confining zones. Other parameters used in the model based on values from the Front Range 1-1 include compressibility, capillary pressure, formation brine geochemistry, temperature at depth, pore pressure gradient, and fracture gradient.

The model is also tailored to the composition of the CO_2 stream. The anticipated physical properties of the CO_2 stream and the anticipated composition of the CO_2 stream are included. The fluid properties of the injected CO_2 stream were modeled using the anticipated physical properties of the CO_2 stream, such as temperature and pressure (PBI_B._AoR-CA-Plan, 2024).

4. Calibration of predictive models

The predictive models CSS used were calibrated. To calibrate a predictive model, output probabilities are adjusted to better align with the actual observed outcomes by using a separate validation dataset, typically through methods like histogram binning, Platt scaling (logistic regression), or isotonic regression, where a new function is fitted to the model's predictions to correct for any systematic biases in probability estimations, ultimately creating a calibration curve that closely follows the diagonal line representing perfect calibration; this is often visualized through a calibration plot where the x-axis shows the predicted probabilities and the y-axis shows the actual event rate within probability bins.

The methods used in computational modeling of the injected CO_2 plume and used in measuring the geologic, chemical, and physical properties of the site are appropriate and the calibration is certified.

5. Use reasonably conservative values and assumptions

The model used to predict the plume of injected CO_2 incorporated reasonably conservative values and assumptions. The maximum annual injection rate and maximum surface and bottom hole injection pressures were used in the computational model. As these are the maximum values possible during operation of the well, actual injection rate and pressure will be less than or equal to the modeled values, which produced a conservative model output. High and low estimates for porosity and permeability parameters were used in multiple runs of the model as part of the sensitivity analysis.

6. Account for uncertainty

In conformance with 40 CFR 146.93(c)(2)(vi), CSS conducted a sensitivity study on the impact of permeability on the areal extent of the Year 32 plume, representing 12 years of injection and 20 years post-injection, to support the requested 20-year alternate PISC timeframe. Permeability was selected as the independent variable since it is believed to have significant uncertainty due to the unpredictable impact of natural fractures within the injection zone; all other reservoir properties were held constant at their Base Case values. Three cases were established:

- Low Permeability: This case utilizes the matrix permeability without any credit for natural fractures in the injection zone. Permeability ranges from 0.1 to 14.8 mD.
- Base Case: This case utilizes a 30% credit for natural fractures in the injection zone as discussed in Section B.2.4. Permeability ranges from 0.1 to 19.3 mD.
- High Permeability: This case utilizes a 100% credit for natural fractures in the injection zone. Permeability ranges from 0.2 to 29.7 mD.

The areal extent of the Year 32 plume was selected as the dependent variable since it is a proxy for the areal extent of the AoR. Figure B.3-6 summarizes results from the sensitivity analysis. All three cases show the same general shape for the areal extent of the Year 32 plume. The plume for Low Permeability Case is the smallest, while plumes for the Base Case and High Permeability Case are essentially identical. The results demonstrate that permeability is potentially a useful calibration variable for history matching activities associated with future injectivity testing and field data from the injection period; however, the results also indicate the plume size predicted by the computational model becomes insensitive to permeability when the natural fracture credit exceeds 30%.

Case	Year 32 Plume	
	Areal Extent, mi²	Change vs. Base Case
Low Permeability (No Credit for Natural Fractures)	4.03	-36.7%
Base Case (30% Credit for Natural Fractures)	6.37	-
High Permeability (100% Credit for Natural Fractures)	6.27	-1.6%

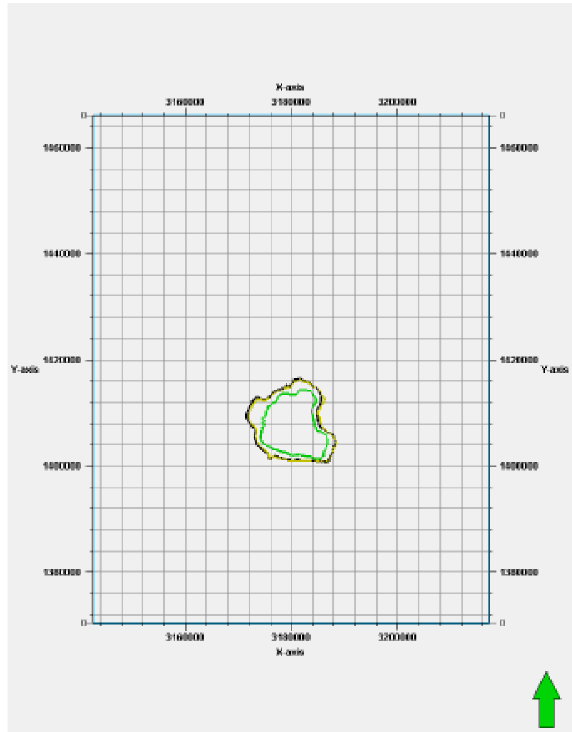

Figure 1. Sensitivity analysis for Front Range 1-1 AoR delineation.

7. Must have quality assurance and quality control plan

The permit application has a quality assurance and quality control plan. The quality assurance and quality control plan is contained within PBI_E.I_QASP_202405.

8. Any additional criteria EPA requires

EPA does not require any additional criteria for this project.

<u>Part IV: No Risk of Endangerment Conclusion</u>

CSS's alternative PISC demonstration was based on significant site-specific data and information provided via the application documents, submissions in response to EPA's Requests for Additional Information, technical discussions with the applicant, and siting criteria, as required by 40 CFR 146.93(c). CSS's alternative PISC timeframe demonstration includes substantial evidence to support the conclusion that the project will not pose a risk of endangerment to USDWs at the end of the 20-year timeframe.

To summarize from the ten elements above, the key ways in which the site-specific data and information in the demonstration supports a 20-year alternative PISC timeframe and addressed risk to USDWs are as follows: the computational modeling (element 1) demonstrated that the CO_2 plume (element 2) will stabilize by year 13 of the PISC timeframe and that the pressure front (element 3) will dissipate to native levels by year 20 of the PISC timeframe. The modeling shows that the site-specific processes that will occur in the Lyons Formation injection zone will result in appropriate trapping of the injected CO_2 to ensure uniform capture, storage, and movement of the CO_2 (elements 4-6). The predicted rates of the various trapping phases demonstrate that 99% trapping will be complete by year 20 of the PISC timeframe. There is significant separation (approximately 600 feet) between the top of the injection zone (Lyons) and the bottom of the lowest/nearest USDW (Entrada) (element 10), including the Lykins confining layer located in between, which is of appropriate thickness, permeability, and integrity to prevent vertical migration of the CO_2 plume at year 20 post-injection and beyond (element 7) and is free of fractures and faults (element 7) that could provide a pathway for fluid movement into a USDW (element 8). There are no wells in the AoR except wells associated with this project (element 9). The construction of the injection well (Front Range 1-1) will ensure CO_2 injection occurs only at depth within the Lyons Formation injection zone (element 9). Together, all these elements demonstrate that the CSS project will not pose a risk of endangerment to USDWs after the 20-year PISC timeframe.

Based on the substantial evidence contained in the draft permit administrative record, including the alternative PISC demonstration, EPA concludes that CSS has demonstrated that the well will no longer pose a risk of endangerment to USDWs at the end of the 20-year alternative PISC timeframe.