This attachment prepared by Carbon TerraVault Holdings, LLC (CTV) is in response to EPA Region 9's request to perform a critical pressure calculation using Method 1 as described in the EPA Class VI Area of Review Guidance.

EPA comment on Attachment B:

> *The approach (i.e., risk-based) used for AoR delineation is not the recommended method given that the storage reservoir system is described as being at hydrostatic pressure (see Section 3.8 page B-7). We assume that this is hydrostatic relative to a relatively fresh water, which would mean that the reservoir is under-pressured with respect to the 20,700 ppm brine in the injection interval. EPA Class VI AoR and Corrective Action Guidance has a clear method (i.e., method 1 on page 39 of the EPA guidance) defining the calculation of critical pressure to delineate the AoR for under-pressured systems. Please update the method.*

Pursuant to our recent technical discussions, EPA requests that CTV calculate the critical pressure front and delineate the area of review (AoR) using Method 1 described in Page 39 of the enclosed EPA Class VI AoR and Corrective Action Guidance (2013). While Method 1 is recommended by EPA's Guidance for under-pressurized injection formations, this does not apply to CTV's proposed injection formation.

In the project area, the base of the underground source of drinking water (USDW) corresponds to a total dissolved solids (TDS) concentration of 8,050 parts per million (ppm). The injection zones, [redacted] have TDS concentrations of 20,700 ppm, 20,700 ppm and 21,100 ppm, respectively. In addition to salinity, the densities and resultant pressure gradients of a column of brine are a function of temperature and depth, as described in the EPA Class VI guidance document. Using the temperature gradient at the CTV VI site location, and empirical correlations for brine density as a function of temperature, this document demonstrates that the resultant expected pressure gradients for [redacted] are 0.435, 0.430 and 0.429 pounds per square inch foot (psi/ft), respectively. Available RFT pressure data in the project area (**Figure 1**) indicate that all injection zone formations are above hydrostatic, with a pressure gradient at 0.439 psi/ft based on a linear fit to available pressure data as shown on **Figure 2.** Demonstrated within this attachment, even using EPA guidance Method 1 (Thornhill et al, 1982) results in a negative critical pressure calculation, which as stated in the guidance document relates to conditions where the injection zone is over-pressured. Because the injection formations are over-pressured, the EPA AoR and Corrective Guidance recommends use of the risk-based AoR delineation approach.

To further illustrate that Methods 1 and 2 are not applicable for the CTV VI site, CTV selected two analysis points based on the structural and thickness variations between [redacted] and the base of the USDW as shown in **Figure 3 through 9**. The calculated critical pressures at Analysis Point 1 and Analysis Point 2 are presented in **Tables 1 through 12**, using both the Nicot (Method 2) and Thornhill (Method 1) methods. These calculations incorporate two sets of density values: (1) a temperature and salinity correlation to calculate density and (2) the Peng-Robinson equation of state referenced in the EPA AoR and Corrective Action Guidance. The resulting critical pressures are either slightly above zero or are negative values, indicating an effectively infinite AoR. Given the above-hydrostatic pressure gradient in the project injection zones and the near-zero or negative critical pressure at both analysis points, CTV contends that the submitted risk-based AoR delineation method is the most appropriate.

Additional detail regarding these calculations is presented in the following sections.

Strategy

For the critical pressure calculations at Analysis Points 1 and 2, all three injection zones were included. Method 2 from the EPA AoR guidance (Nicot) was initially applied, as the pressure gradients in the injection zones exceed hydrostatic conditions. Fluid density was calculated using an empirical correlation based on temperature and salinity. As an alternative, density values interpolated from Figure 3-2 of EPA AoR guidance were also considered. For completeness, Method 1 from the EPA guidance is also discussed, although it is not the applicable approach due to the above-hydrostatic conditions.

[redacted] Critical Pressure Calculation at Analysis Point 1 and Point 2 with Method 2

Input Variables

Equations 3 and 4 in the EPA AoR Guidance (U.S. EPA, 2013) implement Method 2.

$$\Delta P_c = \frac{1}{2} \cdot g \cdot \xi \cdot (z_u - z_i)^2$$

(Equation 3)

where ΔP_c is the critical pressure, g is the acceleration due to gravity, z_u is the elevation of the lowermost USDW, z_i is the elevation of the injection zone, and ξ is a linear coefficient given by:

$$\xi = \frac{\rho_i - \rho_u}{z_u - z_i}$$

(Equation 4)

where ρ_i is the injection zone fluid density and ρ_u is the USDW fluid density.

The depth of the top of the injection zone [redacted] is highly spatially variable (**Figure 4**), as is the depth of the base of the USDW (**Figure 3**). These depths are used in Equations 3 and 4 as the difference between the base of the USDW and the top of the injection zone. Consequently, we calculated and mapped contours of the differences between the injection zone and USDW depths, as shown on **Figure 7**. We conducted two calculations to illustrate the sensitivity of the calculated critical pressure to the depth difference. These calculations are based on actual well locations within the project area.

The first location is south of the plume where the structure is relatively deeper and the depth difference is relatively smaller (labeled Point 1 on **Figures 3 through 9**). A second calculation was made near the northern border of the plume boundary where the structure is relatively shallower and the TVD difference is relatively larger (labeled Point 2 on **Figures 3 through 9**). Note that the plume boundary shown on these figures is the submitted base case. The depth differences between the injection zone and the USDW used as inputs for the critical pressure calculation are presented in Table 1.

Table 1. Analysis Point 1 and Point 2 TVD Difference Between [redacted] and Base of USDW

Case	$Z_{IZ} - Z_{USDW}$
Analysis Point 1	223 meters (730 feet)
Analysis Point 2	281 meters (922 feet)

The densities of the base of USDW and Injection Zone fluids are functions of temperature, pressure, and fluid composition. For water density, the impact due to pressure is negligible compared to the impact due to temperature and fluid compositions. In our calculation, we approximated fluid composition as a single lumped parameter represented by salinity. An empirical correlation was used to calculate the USDW and injection zone fluid density depending on temperature and salinity (McCutcheon, S.C., Martin, J.L, Barnwell, T.O. Jr. 1993).

As discussed in the **Site Characterization Narrative (Attachment A),** CTV calculated salinities for the lowermost USDW based on the four wells in the general vicinity of the AoR. Petrophysical calculations established a representative estimate of 8,500 ppm TDS for the lowermost USDW. For [redacted] a water sample was available from the [redacted] The measurement of TDS for the sample is 20,700 ppm. The complete water chemistry is shown in **Attachment A Figure 2.8-5**. For [redacted] The measurement of TDS for the sample is 21,100 ppm. The complete water chemistry is shown in Attachment **Figure 2.8-6**. As stated in Sections 2.8.2.3 and 2.8.2.4 of **Attachment A**, there was no complete water geochemistry report for either [redacted] Therefore, it was assumed that these formations have the same salinity as [redacted] (Section 2.8.2.5), which is 20,700 ppm, and is in agreement with [redacted] salinity values for the area reported in Sullivan, 1972.

The EPA AoR and Corrective Action guidance (USEPA, 2013) Figure 3-2 (page 40) presents a method for estimating brine density as a function of depth calculated with the Peng-Robinson equation of state. We used EPA's Figure 3-2, values for the depth of the base of the lowermost USDW and the top of the injection zone at Analysis Points 1 and 2 (as determined from **Figure 3** and **Figure 6**), and the compositional estimates discussed above to estimate the densities of the formation fluids. These estimated densities are presented in **Figure 10**. We made an additional, independent calculation of densities using empirical correlation based on the geothermal and geobaric gradients discussed in **Attachment B Area of Review and Corrective Action Plan** that were used to set the initial conditions for the dynamic model. The density values estimated through the correlation calculations are reasonably consistent with the densities read from Figure 3-2 in the EPA AoR and Corrective Action guidance and are illustrated in **Figure 11**. The fluid densities we obtained as inputs to the critical pressure calculation are shown in **Table 2**.

Table 2. Analysis Point 1 and Point 2 Fluid Density Difference Between [redacted] and USDW

Case	USDW Density	Injection Zone Density	Difference
Analysis Point 1 (interpolated densities)	998 kg/m^3	1,004 kg/m^3	6 kg/m^3
Analysis Point 2 (interpolated densities)	999 kg/m^3	1,006 kg/m^3	7 kg/m^3
Analysis Point 1 (Correlation)	993 kg/m^3	1,000 kg/m^3	7 kg/m^3
Analysis Point 2 (Correlation)	996 kg/m^3	1,002 kg/m^3	6 kg/m^3

Critical Pressure Calculation

We used EPA's Method 2 (Nicot method; Equations 3 and 4) in the EPA AoR and Corrective Action Guidance to calculate critical pressure using the inputs discussed above. The critical pressures we obtained for the various cases are shown in **Table 3**.

Table 3. [redacted] Analysis Point 1 and Point 2 Critical Pressure Summary with Method 2

Case	Delta P (critical)
Analysis Point 1 (interpolated densities)	6,942 Pa (1.0 psi)
Analysis Point 2 (interpolated densities)	8,502 Pa (1.2 psi)
Analysis Point 1 (Correlation densities)	7,641 Pa (1.1 psi)
Analysis Point 2 (Correlation densities)	8,267 Pa (1.2 psi)

Pa = Pascals
psi = Pounds per square inch

[redacted] Critical Pressure Calculation at Analysis Point 1 and Point 2 with Method 1

Method 1 in the EPA AoR and Corrective Action Guidance (USEPA, 2013) is based on Equation 2:

$$\Delta P_{if} = P_u + \rho_i g \cdot (z_u - z_i) - P_i \qquad \text{(Equation 2)}$$

where ΔP_{if} is the critical pressure, P_u is the initial pressure in the USDW, and P_i is the initial pressure in the injection zone.

We used Equations 2 to calculate critical pressure using the inputs discussed above as given in **Tables 1 and 2**. The critical pressures we obtained for the various cases are all negative as given in **Table 4.** As stated in the EPA AoR and Corrective Action Guidance, a negative value indicates that the injection zone is over-pressured; therefore, the method is not applicable.

Table 4. Claimed as PBI Analysis Point 1 and Point 2 Critical Pressure Summary With Method 1

Case	Delta P (critical)
Analysis Point 1 (interpolated densities)	-195,338 Pa (-28.3 psi)
Analysis Point 2 (interpolated densities)	-162,200 Pa (-23.52 psi)
Analysis Point 1 (Correlation densities)	-203,830 Pa (-29.56 psi)
Analysis Point 2 (Correlation densities)	-172,258 Pa (-24.98 psi)

Pa = Pascals
psi = Pounds per square inch

Claimed as PBI Critical Pressure Calculation at Analysis Point 1 and Analysis Point 2 with Method 1 and Method 2

Claimed as PBI Critical Pressure Calculation at Analysis Point 1 and Point 2 with Method 2

For the Claimed as PBI injection zone, the TVD difference between injection zone and USDW is shown in **Table 5**. The fluid densities at the two analysis points are based on empirical correlation and EPA AoR and Corrective Action guidance Figure 3-2, and were used as inputs to the critical pressure calculation (**Table 6**)**.** We used Equations 3 and 4 to calculate critical pressure with Method 2 (Nicot) using the inputs discussed above. The critical pressures we obtained for the various cases are negative as shown in **Table 7**, indicating that the method is not applicable**.**

Table 5. Analysis Point 1 and Point 2 TVD Difference Between Claimed as PBI to Base of USDW

Case	$Z_{IZ} - Z_{USDW}$
Analysis Point 1	1275 meters (4,182 feet)
Analysis Point 2	1306 meters (4,284 feet)

Table 6. Analysis Point 1 and Point 2 Fluid Density Difference Between Claimed as PBI and USDW

Case	USDW Density	Injection Zone Density	Difference
Analysis Point 1 (interpolated densities)	998 kg/m^3	991 kg/m^3	-7 kg/m^3
Analysis Point 2 (interpolated densities)	999 kg/m^3	994 kg/m^3	-6 kg/m^3
Analysis Point 1 (Correlation)	993 kg/m^3	988 kg/m^3	-5 kg/m^3
Analysis Point 2 (Correlation)	996 kg/m^3	991 kg/m^3	-5 kg/m^3

Table 7. [redacted] Analysis Point 1 and Analysis Point 2 Critical Pressure Summary with Method 2

Case	Delta P (critical)
Analysis Point 1 (interpolated densities)	-43,140 Pa (-6.3 psi)
Analysis Point 2 (interpolated densities)	-36,760 Pa (-5.3 psi)
Analysis Point 1 (Correlation densities)	-31,261 Pa (-4.5 psi)
Analysis Point 2 (Correlation densities)	-32,021 Pa (-4.6 psi)

[redacted] Critical Pressure Calculation at Analysis Point 1 and Point 2 with Method 1

We used Equations 2 to calculate critical pressure with Method 1 using the inputs discussed above and shown in **Tables 5 and 6**. The critical pressures we obtained for the various cases are negative as shown in **Table 8**, indicating that the method is not applicable.

Table 8. [redacted] Analysis Point 1 and Analysis Point 2 Critical Pressure Summary with Method 1

Case	Delta P (critical)
Analysis Point 1 (interpolated densities)	-447,693 Pa (-64.9 psi)
Analysis Point 2 (interpolated densities)	-381,352 Pa (-55.3 psi)
Analysis Point 1 (Correlation densities)	-480,579 Pa (-69.7 psi)
Analysis Point 2 (Correlation densities)	-416,447 Pa (-60.4 psi)

[redacted] Critical Pressure Calculation at Analysis Point 1 and Analysis Point 2 with Method 2

For [redacted] injection zone, the depth difference between injection zone and USDW is shown at **Table 9**. The fluid densities at the two analysis points are based on empirical correlation and EPA AoR and Corrective Action guidance Figure 3-2, and were used as inputs to the critical pressure calculation (**Table 10**)**.** We used Equations 3 and 4 to calculate critical pressure with Method 2 using the inputs discussed above. The critical pressures we obtained for the various cases are negative as shown in **Table 11**, indicating that the method is not applicable.

Table 9. Analysis Point 1 and Analysis Point 2 TVD Difference Between [redacted] and Base of USDW

Case	$Z_{IZ} - Z_{USDW}$
Analysis Point 1	1,591 meters (5220 feet)
Analysis Point 2	1,727 meters (5667 feet)

Table 10. Analysis Point 1 and Analysis Point 2 Fluid Density Difference Between [redacted] and USDW

Case	USDW Density	Injection Zone Density	Difference
Analysis Point 1 (interpolated densities)	998 kg/m^3	986 kg/m^3	-12 kg/m^3
Analysis Point 2 (interpolated densities)	999 kg/m^3	988 kg/m^3	-12 kg/m^3
Analysis Point 1 (Correlation)	993 kg/m^3	984 kg/m^3	-9 kg/m^3
Analysis Point 2 (Correlation)	996 kg/m^3	985 kg/m^3	-11 kg/m^3

Table 11. [redacted] Analysis Point 1 and Analysis Point 2 Critical Pressure Summary with Method 2

Case	Delta P (critical)
Analysis Point 1 (interpolated densities)	-90,755 Pa (-13.2 psi)
Analysis Point 2 (interpolated densities)	-100,401 Pa (-14.6 psi)
Analysis Point 1 (Correlation densities)	-70,232 Pa (-10.2 psi)
Analysis Point 2 (Correlation densities)	-93,199 Pa (-13.5 psi)

[redacted] Calculation at Analysis Point 1 and Point 2 with Method 1

We used Equations 2 to calculate critical pressure with Method 1 using the inputs discussed above (**Tables 9 and 10**). The critical pressures we obtained for the various cases are negative as shown in **Table 12**, indicating the method is not applicable.

Table 12. [redacted] Analysis Point 1 and Analysis Point 2 Critical Pressure Summary with Method 1

Case	Delta P (critical)
Analysis Point 1 (interpolated densities)	-588,675 Pa (-85.4 psi)
Analysis Point 2 (interpolated densities)	-561,566 Pa (-81.5 psi)
Analysis Point 1 (Correlation densities)	-618,328 Pa (-89.7 psi)
Analysis Point 2 (Correlation densities)	-606,132 Pa (-87.9 psi)

Discussion

In summary, [redacted] injection zones critical pressure calculated using Method 1 in the EPA AoR and Corrective Action guidance are large negative values, indicating that the injection zone(s) are over-pressured relative to the base of the USDW. For this reason, the simple calculations presented in the EPA Guidance (Methods 1 and 2) are not applicable. The AoR for the CTV VI project, when calculated using either Method 2 (Nicot) or Method 1, is essentially infinite. This creates a fundamentally flawed result whereby no AoR or model boundary is sufficiently large.

For these reasons, the submitted risk-based AoR delineation method is the most appropriate method.

References

Claimed as PBI [redacted]

[redacted]

[redacted]

Claimed as PBI

[redacted]

Figure 1. Wells with pressure data.

Claimed as PBI [redacted]

Figure 2. **Injection Zones of** Claimed as PBI [redacted] **Pressure Profile and Data.**

Claimed as PBI

[redacted]

Figure 3. USDW structure (TVD).

Claimed as PBI [redacted]

Figure 4. Claimed as PBI [redacted] **structure (TVD).**

Claimed as PBI

Figure 5. Claimed as PBI structure (TVD).

Claimed as PBI

[redacted]

Figure 6. Claimed as PBI [redacted] **structure (TVD).**

Claimed as PBI [redacted]

Figure 7. Thickness between base of USDW and Claimed as PBI [redacted]

Claimed as PBI [redacted]

Figure 8. Thickness between base of USDW and Claimed as PBI [redacted]

Claimed as PBI [redacted]

Figure 9. Thickness between base of USDW and Claimed as PBI [redacted]

Claimed as PBI [redacted]

Figure 10. Analysis Point 1 and Point 2 Fluid Density from EPA AoR and Corrective Action Guidance Figure 3-2 Interpolated at USDW, Claimed as PBI [redacted]

Claimed as PBI [redacted]

Figure 11. Analysis Point 1 and Point 2 Fluid Density from Empirical Correlation Depending on Temperature and Salinity at USDW, Claimed as PBI [redacted]