2-D Vertically Integrated Gas
CO₂ Mass per Area (mt/ft²)

Time = 30 yr

Delineating the Horizontal Plume Extent and CO₂ Distribution at Geologic Sequestration Sites

Z. Fred Zhang^{a*}, Signe K. White^a, Mark D. White^a

^aEnergy and Environment Directorate, Pacific Northwest National Laboratory

Richland WA 99352, USA

* Corresponding Author

Hydrology Group

Energy and Environment Directorate

Pacific Northwest National Laboratory

902 Battelle Blvd., Richland, WA 99352, USA

Phone: 1-509-372-4866

Email: fred.zhang@pnnl.gov

Abstract

Geologic carbon sequestration is the process of injecting carbon dioxide captured from an industrial source into the subsurface for long-term storage. An Area of Review (AoR) evaluation is one of the requirements for obtaining a Class VI permit under the Underground Injection Control Program of the U.S. Environmental Protection Agency. The Class VI Rule requires that multi-phase computational modeling be used to delineate the Area of Review, based on the horizontal extent of the separate-phase CO₂ plume. A new approach is presented to quantify the plume extent of CO₂ based on the vertically integrated mass per area (VIMPA). The distribution of CO₂ mass in a horizontal plane is described as VIMPA contour lines. The plume extent can be defined by either a contour line of a pre-defined VIMPA value or a contour line within which a certain percentage of CO₂ mass is contained. The method was demonstrated by a hypothetical injection of CO₂ into a deep saline aquifer. The results indicate that the VIMPA decreases with distance in an exponential manner and hence, most of the injected CO₂ resides in a much smaller area near the injection wells. The VIMPA approach for determining the plume extent applies to all injection scenarios regardless of the spatial variability of the properties of the injection zone and allows for the calculation of the CO₂ plume extent to be standardized for injection permit applications.

Key Words: Area of Review; Carbon Sequestration; Reservoir Simulation

1. Introduction

To reduce the emission of greenhouse gas, carbon dioxide (CO₂) can be captured from an industrial source (e.g., a power plant) and then injected into deep subsurface rock formations such as saline formations, oil and gas reservoirs, or unmineable coal seams for long-term storage. Under the temperature (T) and pressure (P) conditions in a reservoir typically used for carbon storage, CO₂ is usually in the super-critical state. Liquid CO₂ may occur when the temperature is less than the critical temperature and the pressure is greater than the critical pressure. Both super-critical and liquid CO₂ are less dense than aqueous fluids and thus CO₂ in either state will therefore be referred to as the separate-phase CO₂ (sp-CO₂). Consequently, the injected sp-CO₂ will tend to migrate upward due to the buoyancy force in the subsurface environment following the path of least resistance. In this article, CO₂ will refer to the sp-CO₂ especially when used as part of a term (e.g., CO₂ plume) unless otherwise specified (e.g., dissolved CO₂).

There are four primary mechanisms to trap the injected CO₂ within the reservoir. Structural trapping relies on a low-permeability confining zone or an anticlinal structure to prevent the upward migration of the buoyant sp-CO₂. Residual trapping occurs when some of the sp-CO₂ residing in the reservoir in the form of disconnected ganglia becomes immobile, usually during the imbibition process (brine displacing CO₂). Dissolution trapping occurs when CO₂ is dissolved in brine and does not exist as a separate phase. Mineral trapping is the formation of carbonate compounds through reactions between CO₂ and rock minerals in the reservoir. Researchers (e.g., Doughty, 2010; Leetaru et al., 2009; Nilsen et al., 2010; Zhou et al., 2010) have found that, during the injection period, usually only a small fraction of the injected CO₂ is dissolved, and during the post-injection period, more CO₂ is dissolved or immobilized by residual trapping. Usually, mineral trapping becomes important only after a very long period of

time. The majority of the injected CO₂ forms a separate phase CO₂ plume and is immobilized by structural trapping. The CO₂ plume, depending on the geological conditions, may slowly migrate in the up-dip direction. In the absence of a trapping mechanism, it may leak through fractures or abandoned wells thus potentially posing a risk to underground sources of drinking water (USDW).

In a homogeneous reservoir, the CO₂ plume resulting from injection into a vertical well is expected to have a funnel shape with a large amount of CO₂ residing in the reservoir near the overlying confining zone (Figure 1a). The plume at the top of the reservoir has the largest lateral extent. Near the edge of the plume, both the CO₂ saturation and the plume thickness approach zero. In a heterogeneous reservoir of variable thickness, the plume shape is often quite irregular (Figure 1b). In this case, during injection, CO₂ tends to migrate much farther laterally within the higher permeability layers. As a result, the layers with the highest permeability may produce the largest CO₂ footprint.

Figure 1. Schematics illustrating the typical CO₂ plume in (A) a homogeneous reservoir and (B) a heterogeneous reservoir.

The CO₂ plume extent is usually considered to be the maximum distance that CO₂ migrates in the lateral direction, measured at any depth. In both the homogeneous and heterogeneous cases

mentioned above, the plume extent may be biased by the material properties of a small portion of the reservoir; e.g., the top-most layer or the layer with the highest permeability. Furthermore, there can be very large uncertainty in determining the plume boundary using computational modeling because of limited knowledge of the underground CO₂ reservoir.

The leakage of CO₂ and the induced upward movement of brine as a result of geologic carbon sequestration are potential hazards to USDWs. Therefore, the U.S. Environmental Protection Agency (USEPA) requires the Area of Review (AoR) to be estimated using computational models as part of a permit application for a Class VI underground injection control well (USEPA, 2013). The delineation of the AoR requires that the lateral extent of the CO₂ plume and the extent of increased pressure, or pressure front, be determined. The determination of the pressure front has been addressed in USEPA (2013) for different pressure conditions. Birkholzer et al. (2014) proposed the tiered AoR definition in which the projected region of the CO₂ plume extent would have higher regulatory standards than the portion of the AoR lying outside the CO₂ plume, in regards to site characterization, monitoring, and corrective action. However, the method for determining the CO₂ plume size has not been standardized. In this article we focus on the delineation of the sp-CO₂ plume.

A common approach for defining the footprint of the sp-CO₂ plume is to use the maximum radial extent based on CO₂ saturation, S_g (e.g., Doughty, 2010; Leetaru et al., 2009; Nilsen et al., 2010; White and Zhang, 2011; Zhou et al., 2010). Typically, the plume extent is the largest near the uppermost part of the reservoir because of buoyancy. Doughty (2010) and Nilsen et al. (2010) illustrated the CO₂ plume extent as the plan view of the S_g of the top-most model layer. However, exceptions occur when one or more layers of higher permeability exist within the reservoir. For example, Leetaru et al. (2009), Zhou et al. (2010), and White and Zhang (2011)

1 simulated CO₂ migration when CO₂ was injected into a reservoir containing multiple layers,
2 where the most permeable layer was in the lower portion of the reservoir. Their results show that
3 the maximum plume extent at a given time may occur in a permeable layer beneath a less
4 permeable layer. The quantification of the CO₂ plume in a heterogeneous medium is even more
5 challenging because of the very irregular plume edge. In this case, the depth at which the
6 maximum plume extent occurs is strongly dependent on time and the degree of heterogeneity
7 (Doughty et al., 2009; Hermanson, 2014; Olofsson, 2011; Qi, 2008; Sung et al., 2014; White and
8 Zhang, 2011). Generally, the plume extent cannot be determined by the CO₂ saturation in an
9 individual layer or at a given depth. The plume extent may only be determined by the projection
10 of the three-dimensional (3-D) distribution of CO₂ saturation onto the horizontal plane. Because
11 of the complexity of the CO₂ distribution, the algorithm for the projection is not straightforward.
12 In addition, when using the S_g -based approach to determine plume extent several issues can
13 arise:

- 14 • In a stratified medium, the CO₂ transport in the most permeable layers can strongly bias
15 the plume extent. Furthermore, it is not appropriate to just vertically average S_g , because
16 the reservoir properties (e.g., porosity, thickness) and conditions (e.g., P , T) vary
17 spatially.
- 18 • In a heterogeneous medium, determining the plume extent can be cumbersome because
19 of the strong irregularity of the plume shape.
- 20 • Defining the plume extent without quantifying the mass distribution within the plume can
21 be misleading because most of the CO₂ mass typically resides in a region much smaller
22 than that bounded by the contour line corresponding to $S_g = 0$.

In this paper, we propose an approach to determine the horizontal plume extent based on the vertically integrated mass of CO₂ per area (VIMPA) of ground surface. The advantages of this approach are that: 1) it prevents the potential bias from an individual layer with high permeability; 2) the method relates the plume size with the mass distribution of the CO₂ contained within the plume and hence can provide the plume extent corresponding to the percent of mass; and 3) it allows for the comparison of plumes at different sequestration sites. The VIMPA approach was used in the CO₂ injection control permit application for FutureGen 2.0 Morgan County, IL, Class VI Wells (FutureGen Alliance, 2013) and was accepted by the USEPA. The VIMPA approach will be demonstrated with a hypothetical scenario having two injection wells.

2. Methods

Generally, most of the CO₂ injected into a geological sequestration site exists as a separate phase, assuming appropriate reservoir pressure and temperature, while a small fraction of the injected CO₂ dissolves in the aqueous phase. Often, before the actual injection begins, numerical simulations are conducted to estimate the plume extent. This involves discretization in time and space, and solving for variables such as pressure and CO₂ saturation for each cell in the domain at every time step. To define the CO₂ plume extent, the vertically integrated mass of CO₂ per area is calculated as follows:

$$VIMPA_{i,j} = \frac{1}{A_{i,j}} \sum_k M_{i,j,k} \quad (1)$$

where: M = the total CO₂ mass in a cell

A = the horizontal cross-sectional area of a column of cells

i and j = cell indices in the horizontal directions

k = cell index in the vertical direction.

The VIMPA may be calculated for the separate-phase CO₂, the dissolved CO₂, or the total of the two for the entire vertical depth or for a specific layer or layers (e.g., the reservoir or caprock). The VIMPA of CO₂ distributes nonuniformly in the horizontal plane. Generally, the VIMPA is larger near the injection well and decreases gradually away from the well. For a given time, the VIMPA can be shown as contours in a horizontal plane. It is noted that the accuracy of the CO₂ plume extent using the VIMPA approach depends on the accuracy of the numerical simulation results, which are subject to uncertainties because of the limited knowledge of model inputs and any limitations of the numerical model used.

Intuitively, one may choose a contour line that corresponds to VIMPA = 0 to define the plume boundary. However, although it indeed indicates the maximum plume extent, this line may suffer from very large numerical uncertainty because a very small number (e.g., 10^{-14} depending on the configuration of the computer system that executes the simulation) may be considered as nonzero in the numerical calculations. Hence, the plume that contains all of the CO₂ mass can appear to be very large and uncertain, while most of the CO₂ mass may in fact reside in a much smaller sub-region of that area.

Two different methods may be used to define the plume boundary. The first method is to use a pre-defined cut-off value of VIMPA [e.g., 0.01 metric ton/m² (MT/m²)]. This method may be more relevant for purchasing subsurface pore space for storing CO₂ regardless of the reservoir thickness and depth. While this approach is easy to apply, it is difficult to define a defensible cut-off value. In some cases, the plume boundary cannot be defined when no VIMPA values are

larger than the specified cut-off value. This may happen when the injected total CO₂ mass is very small and/or CO₂ migrates predominately laterally within a thin but very permeable layer.

The second method is to define the plume boundary based on the percent of CO₂ mass in the domain. Different percentages, e.g., 100%, 99%, or 95%, of the total mass may be used to define the plume boundary. This method can better quantify the whereabouts of the injected CO₂. Note that a plume defined by a constant cut-off value of VIMPA may not always contain the same percent of CO₂ mass. Vice versa, the VIMPA value that defines the boundary of the plume containing a certain percentage of injected CO₂ may vary with time, among simulation scenarios, and from site to site.

In the following sections of this paper, we will use the second method to demonstrate delineation of the horizontal CO₂ plume extent. To distinguish from the maximum plume extent containing 100% CO₂ mass, the plume extent that contains less than 100% of the CO₂ mass is referred to as the effective plume extent. For brevity, the percentage will be included as a subscript of the variables VIMPA and A. For example, the VIMPA contour line within which 99% of the CO₂ mass resides is expressed as VIMPA₉₉ and the corresponding area is expressed as A₉₉.

To determine a specific percent of CO₂ mass, e.g., VIMPA₉₉, Eq. 1 can be used iteratively by varying the VIMPA values until an appropriate value is found. We used Tecplot360 (Tecplot, Inc., Bellevue, WA, USA) to calculate the total mass by blanking the cells with VIMPA being less than a given value. Then the plume extent, A₉₉ can be determined by integrating the area within VIMPA₉₉. One may calculate the VIMPA and A of a CO₂ plume that contains any percentage of CO₂ mass. In this paper, 100%, 99%, and 95% will be used.

3. Demonstration

To demonstrate this concept, a hypothetical scenario of pure CO₂ injection into a saline reservoir was simulated using the Subsurface Transport Over Multiple Phases (STOMP-CO₂) simulator (White et al., 2015). Thirty million metric tons (MMT) of CO₂ was injected at a rate of 1 MMT/yr into a 850-ft thick saline reservoir ranging between the depth of 4050 ft (1234.4 m) and 4900 ft (1493.5 m) over a period of 30 years. The salt concentration is 130 g/L and the temperature is 110 °F (43.33 °C) at the bottom of the reservoir. The temperature increases with depth by a gradient of 0.01 °F/ft (0.0182 °C/m). Two injection wells, screened between 4600 ft (1402.1 m) and 4900 ft (1493.5 m), were separated by 0.5 miles (804.7 m). It was assumed that the reservoir contains three layers: the Upper Mount Simon (MS) layer, the Lower MS layer, and an underlying Arkosic layer. The physical properties of the three layers are listed in Table 1.

Table 1. Geological structure and properties

Geologic al units	Depth (m)	k _h , k _v (mD)	Porosity (-)	Entry Pressure (m)	Pore-Size distribution parameter, λ (-)	Residual Aqueous Saturation (-)	Residual Gas Saturation (-)
Upper MS	1234.4-1235.9	37.1, 3.71	0.096	1.1	0.564	0.081	0.2
Lower MS	1235.9 – 1440.2	213, 21.3	0.123	0.853	0.564	0.081	0.2
Arkosic	1440.2 – 1493.5	417.1, 41.71	0.171	0.245	0.564	0.081	0.2

Because of the symmetry of the flow in the easting (x) and northing (y) directions, flow in $\frac{1}{4}$ of the domain was simulated. The simulation domain is about 50 miles (80467.2 m) in the horizontal direction and was discretized with variable grid spacing (Δx , Δy , and Δz). The minimum values for Δx and Δy were 15 ft (4.6 m), near the injection well location and increased by a factor of 1.3 moving away from the well. The minimum value for Δz was 5 ft (1.5 m) near

the overlying seal and the maximum value was 25 ft (7.6 m) away from the seal. The number of nodes in the x , y , and z directions were 46, 33, and 43, respectively. A no flow condition was applied to the top, the bottom, and the two symmetric lateral boundaries, while a constant head condition was applied to the other two lateral boundaries.

STOMP-CO₂ provides an option for the user to request the vertically integrated mass as an output variable either for the gas (scCO₂) phase, the dissolved phase, or the total mass in all phases. For orthogonal grids where all cells in a particular vertical column have the same cross-sectional area, the vertically integrated mass per area can be requested. STOMP-CO₂ then sums and reports the CO₂ mass of the requested phase for all grid cells in a vertical column of the domain. All cells in the same vertical column will report the same summed mass in the output file, allowing the user to select one layer of the model for plotting.

4. Results

Based on the numerical simulation results, we first present the migration of the injected CO₂ and the CO₂ plume extent based on S_g at varying times as indicated by the 3-D CO₂ distribution. Then we present the two-dimensional (2-D) distribution of the VIMPA of CO₂ in the horizontal plane and the resulting plume extent determined using the VIMPA approach.

4.1. CO₂ Saturation Distribution and Saturation-Based Plume Extent

Snapshots of the CO₂ distribution expressed as CO₂ saturation at different times are shown in Figure 2. Because CO₂ is less dense than brine, it tends to move upward (Figure 2a at 1 yr). When the CO₂ front reaches the interface between the Lower MS and Upper MS units, it does not enter into the less permeable Upper MS layer until the pressure becomes high enough to overcome the entry pressure of that layer. The difference between the rock properties of the two

1 layers causes the accumulation of CO₂ below this interface and results in a stronger lateral
2 migration (Figure 2b at 5 yr and Figure 2c at 10 yr). As more CO₂ is injected into the reservoir,
3 some of the CO₂ already in the system reaches the top of the reservoir (Figure 2c at 10 yr), which
4 is capped by an impermeable seal. Then the CO₂ migrates laterally, below the seal (Figure 2d 20
5 yr and Figure 2e at 30 yr). The hypothetical injection ends after 30 years. From that time on, the
6 injected CO₂ continues to migrate upward and laterally, forming a CO₂ zone of relatively high
7 CO₂ saturation beneath the impermeable seal (Figure 2f at 80 yr). As seen in Figure 2, the largest
8 lateral spreading of CO₂ is at the interface between the Lower MS and Arkosic formations at 1
9 year, between the Upper MS and Lower MS from 5 to 30 years, and at a very thin layer at the top
10 of the Upper MS at 80 years.

11 The progression of the plume extents determined using CO₂ cut-off saturations of zero and
12 0.02 are shown in Figure 3. The overall plume extent was controlled by the local plume extent at
13 the interface between the Lower MS and Upper MS before 40 years and at the top of the Upper
14 MS after 40 years (Figure 3). Comparison of Figure 3a and Figure 3b indicates that an increase
15 in the cut-off saturation values from 0 (Figure 3a) to 0.02 (Figure 3b) reduces the calculated
16 plume extent. However, only the CO₂ saturation in the layer with the largest plume extent
17 matters in determining the plume size, while the CO₂ saturation in the other layers has no impact
18 on the calculated plume size. This suggests that a rock layer having either relatively large
19 permeability or residing beneath an impermeable layer determines the estimated plume extent.

Figure 2. Snapshots of the simulated super-critical CO₂ distribution expressed as CO₂ saturation at different times. The vertical scale is 3 times exaggerated. The injection rate was 0.5 MMT/yr for each of the two wells, which are 2500-ft (762-m) apart. Injection ceased at year 30.

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Figure 3. The horizontal plume area at the interface between the Lower MS and Upper MS, at the top of the Upper MS, and the overall plume area. (a) The cut-off CO_2 saturation was set to zero and (b) the cut-off CO_2 saturation was set to 0.02. The numbers in the plots show the plume area at 80 years.

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4.2. Vertically Integrated Mass Per Area of CO_2 and VIMPA-Based Plume

Extent

Figure 4 demonstrates the VIMPA distribution in the horizontal plane at 30 years (the time at which CO_2 injection ceased), and at year 80 (50 years post-injection). As expected, the VIMPA is very high near the injection wells [1.2 MT/ft^2 (12.9 MT/m^2) at 30 years and 0.55 MT/ft^2 (5.9 MT/m^2) at 80 years] and gradually decreases to zero in an exponential manner as the distance from the injection location increases. This indicates that most of the CO_2 mass resides in a very small region around the injection wells. The contour line corresponding to $\text{VIMPA} = 0$ defines the maximum plume extent $A^{\max}$, within which 100% of the CO_2 mass $M^{\max}$ resides. The

- 1 irregular boundaries of the plumes are due to the coarsened horizontal discretization of the
- 2 simulation grid away from the injection location.

Figure 4. The distribution of super-critical CO₂ in the horizontal plane as the mass per area at years 30 and 80. The injection rate was 0.5 MMT/yr for each of the two wells, which are 2500-ft (762-m) apart. Injection ceased at year 30.

- 3
- 4 Within a VIMPA contour line with a value larger than zero, the area becomes smaller and
- 5 contains a portion of the CO₂ mass. Figure 5 shows the area $F_A(\%)$ and CO₂ mass $F_M(\%)$ relative
- 6 to their maximum values and their variation with VIMPA. Both $F_A(\%)$ and $F_M(\%)$ decrease from
- 7 100% to zero as VIMPA increases from 0 to a certain maximum value, i.e., about 1.2 MT/ft²
- 8 (12.9 MT/m²) at 30 years. However, the $F_A(\%)$ line decreases much faster than the $F_M(\%)$ line at
- 9 low VIMPA values [roughly for VIMPA < 0.1 MT/ft² (1.1 MT/m²)]. For example, when VIMPA
- 10 = 0.09 MT/ft² (0.97 MT/m²), the relative plume area is reduced to 55% of the maximum, while
- 11 the relative mass is reduced to only 95% of the maximum (Figure 5). When VIMPA = 0.34
- 12 MT/ft² (3.7 MT/m²), the relative plume area is reduced to 18% of the maximum while the

1 relative mass is reduced to 50% of the maximum. This indicates that 95% of the CO₂ resides
2 within the inner 55% of the plume area and about half of the CO₂ mass resides in the inner 18%
3 of the plume area. There are several implications from these results. There is very little CO₂ mass
4 in a considerable portion of the plume area near the edge evident by the very low CO₂ VIMPA.
5 In reality, the CO₂ at very low saturation tends to be relatively easily immobilized by residual
6 trapping or dissolution. Hence, to better describe the plume extent, the plume area containing a
7 certain percent of CO₂ mass may be used instead of the CO₂ saturation. In a spatially
8 heterogeneous system, the plume shape is often very irregular and plume growth may be slowed
9 in one place and sped up in another. The temporal change shown in VIMPA plots such as those
10 in Figure 4 can potentially show where the speeding-up and slowing-down happen.

Figure 5. The variation of the relative CO₂ mass and plume area with VIMPA at 30 years. The CO₂ mass and plume area are expressed relative to their corresponding maximum values.

We calculated the boundaries of the plume containing 100%, 99% and 95% CO₂ mass (Figure 6). Each of the plots in Figure 6 contains multiple lines, denoting the plume boundaries at year 1 through year 80 at one year intervals, showing the progression of the plume boundary. A larger distance between adjacent lines means a fast expansion of the CO₂ plume. Roughly, the line spacing becomes smaller after the cessation of CO₂ injection at year 30. However, the plume continues to grow as CO₂ migrates upward and/or laterally. The plume that contains 100% mass (Figure 6a) is the largest but has irregular boundaries, which are artifacts of the variable gridding used in the numerical simulation. The plumes that contain 99% (Figure 6b) and 95% (Figure 6c) are much smaller and their boundaries are much smoother.

Despite the small difference in CO₂ mass contained, the plume areas (Figure 7) differ substantially. For example, at 80 yr, the plume areas that contain 100%, 99%, and 95% CO₂ are 23.5, 16.8, and 12.8 km², respectively. The plumes containing 99% and 95% of the CO₂ mass are, respectively, 71% and 55% of the area containing 100% mass. This indicates that the plume size may vary considerably if different VIMPA criteria are used.

Figure 6. The extent of super-critical CO₂ plume containing (A) 100%, (B) 99%, and (C) 95% of CO₂ mass. Each plot is composed of multiple lines, denoting the plume boundaries at years 1 through 80 at one year intervals. The inner-most line corresponds to year 1 and the out-most line corresponds to year 80. The lines at years 1, 5, 30, and 80 are shown in red. The injection rate was 0.5 MMT/yr for each of the two wells, which are 2500-ft (762-m) apart. Injection ceased at year 30.

Figure 7. The area of the super-critical CO₂ plume vs. time. The numbers in the plots show the plume area at 80 years. The dotted vertical line shows the cessation time (30 years) of CO₂ injection.

5. Discussion

Maximum plume extent. It is of interest to know the difference between the plume extent based on the CO₂ saturation and that based on VIMPA. Comparison of Figure 3a and Figure 7 indicates that the plume extents based on the zero gas saturation and zero VIMPA are the same. This is in agreement with the definition of VIMPA. Hence, both methods can be used to determine the maximum plume extent no matter how small the amount of CO₂. When the saturation-based approach is used, the extent of CO₂ in different rock layers varies and the maximum extent may be in any one of them and can change with time. The CO₂ plume in a heterogeneous media generally is very irregular (Doughty and Pruess, 2001; Olofsson, 2011). In

these cases, the rock layers may not be laterally continuous and therefore, the largest extent of the CO₂ plume cannot be determined from any one layer. Consequently, determining the plume extent can be cumbersome if the saturation-based approach is used. The VIMPA approach converts the 3-D distribution of CO₂ into a 2-D distribution by summing up all the CO₂ mass in the vertical direction. Hence, the determination of the maximum CO₂ extent using the VIMPA approach is applicable regardless of the heterogeneity of the reservoir.

Effective CO₂ plume extent. The plume extent that contains less than some percentage (e.g. 100%, 99% or 95%) of CO₂ mass does not correspond to a certain cut-off saturation. The reason for this is that a given CO₂ saturation equates to a different volume of CO₂ for formations with different porosity. For example, a saturation of 0.02 in a 1-m³ rock is equivalent to 1.92×10⁻³ m³ of CO₂ in the upper Mount Simon, 2.46×10⁻³ m³ of CO₂ in the lower Mount Simon, and 3.422×10⁻³ m³ of CO₂ in the Arkosic formation. Considering that the volume of CO₂ is dependent on both *P* and *T*, the same volume of CO₂ does not equate to the same amount of mass at all places in the reservoir even if the porosity is the same because the *P* and *T* vary throughout the domain. Thus, the choice of any cut-off saturation does not have a statistical meaning for expressing the relative quantity of CO₂. Furthermore, it is possible that the CO₂ in very thin but very permeable layers can move very far laterally while the local CO₂ saturation can remain high (Sundal et al., 2013). When CO₂ migration is predominantly in one layer, the saturation-based approach tends to over-predict the effective CO₂ plume extent. The VIMPA approach can provide statistically meaningful effective plume extents that are independent of formation porosity, pressure and temperature.

Monitoring system design. Another important aspect of the VIMPA approach is that it quantifies the geographic distribution of CO₂ mass below the ground surface at a given time

(Figure 4). Further integration of VIMPA over the area will yield the total CO₂ mass within the plume. Moreover, the VIMPA distribution for zones of interest, e.g., the injection zone and the confining zone, may be calculated. This information can be useful for management of the injected CO₂. Knowing the predicted distribution of CO₂ mass in the reservoir and caprock can help in identifying areas of greater risk. Additionally, the VIMPA distribution can be used in the design of a monitoring system so that sensors are placed in locations with a higher probability of CO₂ detection.

Threshold for geophysical monitoring. Surface geophysical methods (e.g., seismic) are often used for monitoring the migration of CO₂. When the CO₂ mass per area is lower than the detect threshold of the method, the CO₂ cannot be detected. The VIMPA may be used as a criterion for demonstrating the conformance between the simulated and monitored plume behavior with the consideration of detectability of the monitoring technology used.

CO₂ immobilization. The VIMPA concept can also be applied to the dissolved, trapped, or mineralized CO₂ to quantify the distribution of CO₂ immobilization. This knowledge may be useful for risk analysis and assessment.

Comparison of Observed Data to the Predicted VIMPA. The actual VIMPA of a CO₂ sequestration site can be determined based on the monitored profiles of CO₂ saturation, temperature, and pressure at monitoring wells at given times along with the distribution of rock porosity. It may also be estimated using a surface geophysical method such as seismic survey. For example, Ivanova et al. (2012) demonstrated that an estimate of the total amount of CO₂ visible in seismic data can be made using the petrophysical measurements on core samples and geophysical logging of CO₂ saturation levels. Comparison of the monitored and predicted VIMPA can be used for model calibration and provide confidence in the AoR defined for the

project of CO₂ injection. Additionally, using mass balance instead of CO₂ saturation for plume tracking provides regulators with a better tool for determining potential impacts to the environment.

6. Summary

A simple method to quantify the extent of the CO₂ plume is presented based on calculating the vertically integrated mass per area. The VIMPA method considers all the CO₂ within the simulation domain rather than just that residing in a certain layer. Hence, the methodology for determining the plume extent applies to all injection scenarios regardless of the spatial variability of the properties. The choice of the cut-off VIMPA value has a statistical meaning regarding the CO₂ mass, while the choice of a saturation cut-off value is often arbitrary. This allows the user to choose certain meaningful VIMPA values, e.g., corresponding to the percentage of CO₂ mass encompassed within the corresponding contour line. The VIMPA can be applied to different zones such as the injection zone or confining zone (or any zones of interest) to understand the distribution of CO₂ mass. These VIMPA values can be useful for guiding monitoring system design. The calculation of VIMPA is based on the CO₂ mass and is independent of the system conditions such as pressure and temperature. Additionally, the VIMPA values across different depths are additive. Hence, the CO₂ mass balance can be easily determined. The VIMPA approach can be applied to the different phases or states of CO₂ to determine the distribution of the immobile CO₂ (i.e., dissolved CO₂ and entrapped CO₂) and mobile CO₂. The VIMPA approach allows the calculation of the CO₂ plume extent to be standardized for injection permit applications.

Based on the VIMPA distribution in the horizontal plane, the CO₂ plume is a zone co-inhabited by both CO₂ and brine rather than a zone of only CO₂. Generally there is a much higher fraction of CO₂ in the area near the injection well than there is farther away. In the demonstration presented in this paper, 95% of the CO₂ mass resides in the central 55% of the plume area. Hence, use of the maximum plume size may not be appropriate because of the small amount of CO₂ in the region near the plume edge.

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List of figures

Figure 1. Schematics illustrating the typical CO₂ plume in (A) a homogeneous reservoir and (B) a heterogeneous reservoir.

Figure 2. Snapshots of the simulated super-critical CO₂ distribution expressed as CO₂ saturation at different times. The vertical scale is 3 times exaggerated. The injection rate was 0.5 MMT/yr for each of the two wells, which are 2500-ft (762-m) apart. Injection ceased at year 30.

Figure 3. The horizontal plume area at the interface between the Lower MS and Upper MS, at the top of the Upper MS, and the overall plume area. (a) The cut-off CO₂ saturation was set to zero and (b) the cut-off CO₂ saturation was set to 0.02. The numbers in the plots show the plume area at 80 years.

Figure 4. The distribution of super-critical CO₂ in the horizontal plane as the mass per area at years 30 and 80. The injection rate was 0.5 MMT/yr for each of the two wells, which are 2500-ft (762-m) apart. Injection ceased at year 30.

Figure 5. The variation of the relative CO₂ mass and plume area with VIMPA at 30 years. The CO₂ mass and plume area are expressed relative to their corresponding maximum values.

Figure 6. The extent of super-critical CO₂ plume containing (A) 100%, (B) 99%, and (C) 95% of CO₂ mass. Each plot is composed of multiple lines, denoting the plume boundaries at years 1 through 80 at one year intervals. The inner-most line corresponds to year 1 and the out-most line corresponds to year 80. The lines at years 1, 5, 30, and 80 are shown in red. The injection rate was 0.5 MMT/yr for each of the two wells, which are 2500-ft (762-m) apart. Injection ceased at year 30.

Figure 7. The area of the super-critical CO₂ plume vs. time. The numbers in the plots show the plume area at 80 years.