Aeon Petroleum Consultants Quarterly Newsletter

Aeon Petroleum Consultants is a professional engineering firm registered in the State of Texas. We specialize in estimating resources and reserves. Our intent on publishing this newsletter is to highlight topics of interest to those involved in estimating, reviewing, or reporting oil and gas resources and reserves.

In this issue, we will discuss the following:

- Aeon Petroleum Consultants website
- CO2 Sequestration
    - Sequestration in an Abandoned Coalbed Methane Reservoir

We hope to make this quarterly newsletter informative and useful. If there are any topics you would like us to discuss in future newsletters, please contact us on our website and let us know.

Aeon Petroleum Consultants Website

The website for Aeon Petroleum Consultants can be found at:

www.aeon-petro.com

The website contains topics and items that should be of interest to those estimating, reviewing or reporting oil and gas resources and reserves. Besides listing the services that Aeon Petroleum Consultants can provide to the oil and gas industry, there are items available for download, software created by Aeon Petroleum Consultants available for download or demo, videos, and resource and reserve guidelines for viewing and download.

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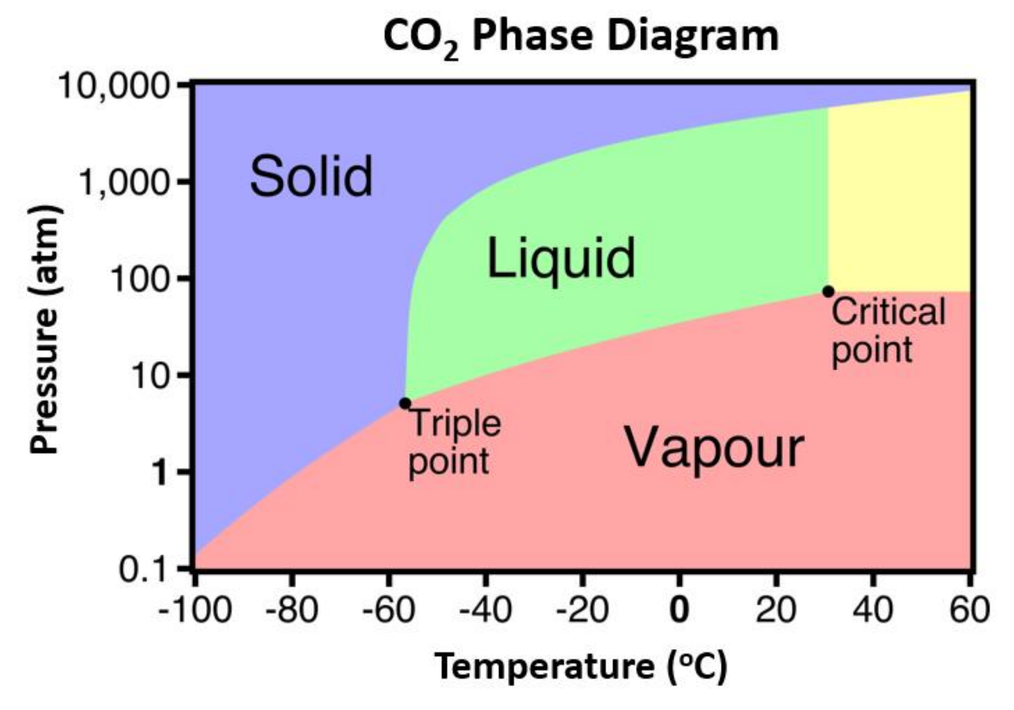
Please feel free to contact us regarding our services, software, or items you would like us to discuss in these newsletters.

CO_2 Sequestration

Of particular interest lately is the idea of injecting CO_2 created from the burning of fossil fuels into underground reservoirs. This is known as sequestration.

At standard conditions, CO_2 is a gas. Occasionally we see CO_2 as a solid (dry ice) that is used in the food industry during transportation and storage. When dry ice changes phase it sublimes from a solid phase to a gas phase. Liquid CO_2 is never present under atmospheric conditions. The phase diagram for CO_2 is shown below:



It should be noted in looking at the diagram that in many sequestration projects, the phase of CO_2 will be in the “yellow” area of the graph. This is the super-critical phase.

Injecting CO_2 into reservoirs is not a new concept. The oil and gas industry has been injecting CO_2 into oil reservoirs for decades to increase recovery of oil. This is especially prevalent in the Permian Basin where gas plants have been built to separate the produced CO_2 and purify it for reinjection. The CO_2

for these projects did not come from fossil fuel burning however, but from natural CO_2 reservoirs like Sheep Mountain, McElmo Dome, and Doe Canyon located in the Rocky Mountains.

For the sequestration of CO_2 from the burning of fossil fuels, there are two types of reservoirs of interest. The first is abandoned oil and gas reservoirs and the second are saltwater aquifers. The choice of which to use depends (or should depend) on the economics of the situation. The items to consider for the choice are as follows:

- Reservoir volume available for CO_2 sequestration
- Volume of CO_2 to be sequestered
- Time over which CO_2 is to be injected
- Distance from source of CO_2 to injection reservoir
- Cost of drilling/completing/working over injection wells
- Operating expenses of injection operations
- Pipeline capital and operating expenses

In the case of abandoned oil and gas reservoirs, CO_2 is stored in the remaining hydrocarbon space in the reservoir (and on the surface of coal in a coalbed methane reservoir) and dissolved in the water saturated area of the reservoir. For aquifers, CO_2 is merely dissolved in the water in the reservoir. Calculations of the potential CO_2 storage must be made on each reservoir of interest to determine their viability for CO_2 storage.

In this newsletter, we are going to show how to calculate the reservoir volume available to CO_2 sequestration for an abandoned coalbed methane (CBM) reservoir. We will calculate the volume of CO_2 that can fill the reservoir at standard conditions. For the purpose of these calculations, we will not consider additional CO_2 that might be sequestered in any remaining water within the reservoir.

CO_2 Sequestration in an Abandoned Coalbed Methane Reservoir

Here are the data for the abandoned gas reservoir:

Depth = 4,500 ft
Initial pressure (P_i) = Sequestration Pressure (P_s) = 2,000 psia = 138 bars
Current pressure (Abandonment pressure P_a) = 200 psia
Reservoir Temperature (T_r) = 105 °F = 565 °R = 40 °C
Gas gravity = 0.7
Reservoir area = 160 acres
Reservoir thickness = 20 feet
Coal density = 1.22 g/cc = 76.1 lb/ft^3
Coal density (dry ash free) = 1.18 g/cc = 73.6 lb/ft^3
Porosity = 2.2%
Cumulative gas production = G_p = 1.8 Bscf

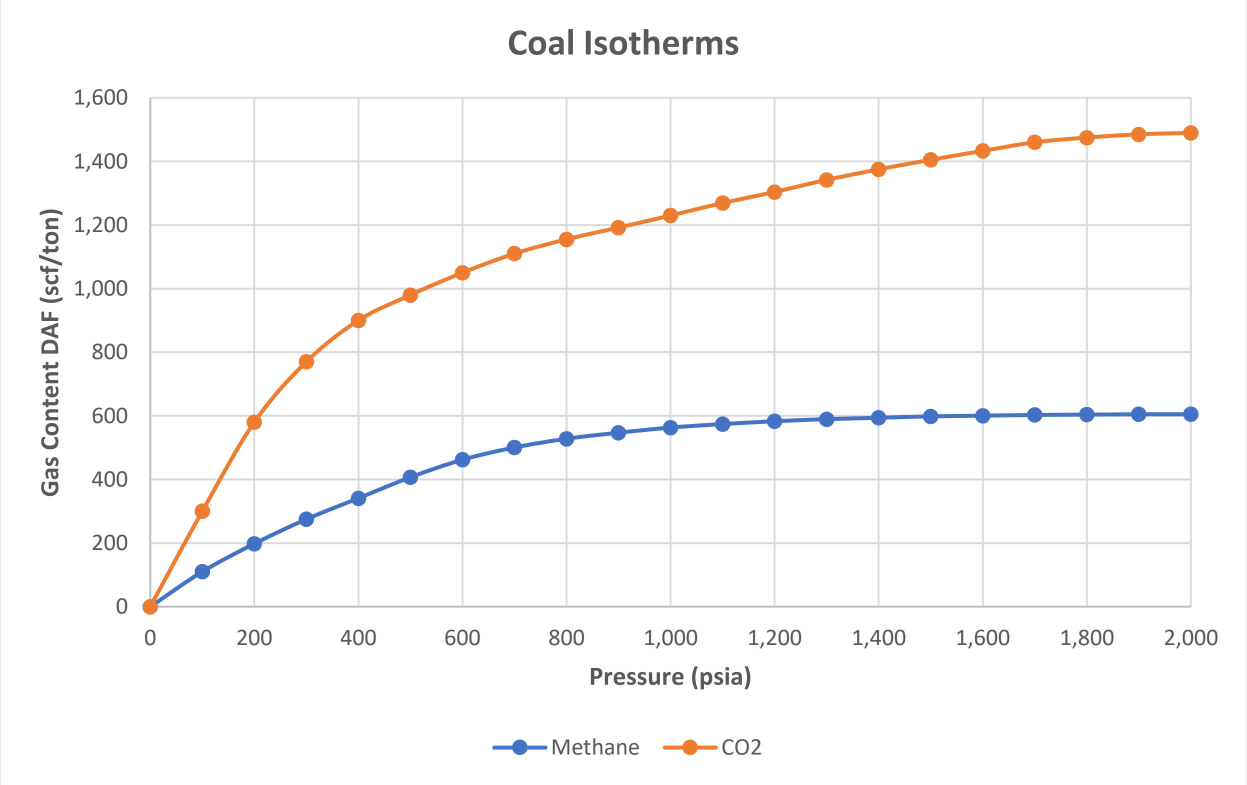
A coalbed methane gas reservoir stores gas on the surface of coal. Initially, most coalbed methane reservoirs have any pore space filled with water. To allow gas to move from the surface of the coal into the pore space and be produced, water must be pumped out of the pore space. Once the water is removed, gas will begin to move from the coal surface into the pore space as the pressure drops.

The volume of gas in a coalbed methane reservoir is dependent on the amount of gas that can be stored on the surface of the coal at initial reservoir pressure. This is known as adsorption. This is determined by taking coal samples and sending them to a lab which measures how much gas can be adsorbed onto the coal at various pressures. All measurements are made at reservoir temperature and are referred to as isotherms. Both methane and CO_2 can be adsorbed onto the surface of coal.

The assumption for sequestration is that CO_2 will be injected into the reservoir until the reservoir pressure is equivalent to the initial pressure. The amount of CO_2 that can be sequestered will be the sum of the CO_2 than can be adsorbed by the coal and the amount that can fill the porosity in the coal.

At the current pressure, there is some residual gas in the reservoir that must be accounted for in the calculations.

Shown below are the isotherms for methane and CO_2 for this particular example. Note that the units of adsorption are standard cubic feet per ton of coal. A ton of coal used in the isotherm is based on the dry (no moisture) ash free weight. This is known as DAF coal. In this case the isotherms were done separately and no isotherms were done with mixtures of methane and CO_2.



The values we are most interested in are the isotherms for methane and CO_2 at the initial and current pressures. These values taken from the above isotherm are:

Initial Methane Isotherm = I_{Mi} = 605 scf/ton

Current Methane Isotherm = I_{Ma} = 198 scf/ton

Initial CO_2 Isotherm = I_{CO2i} = 1,490 scf/ton

Initial CO_2 Isotherm = I_{CO2a} = 580 scf/ton

Step 1: Calculate the tons of coal in the reservoir

$$Tons\ of\ Coal = C_t = 43{,}560 * \frac{h * A * \rho_{cDAF}}{2{,}000} = 43{,}560 * \frac{20 * 160 * 73.6}{2{,}000}$$

$$= 5.13 * 10^6\ tons$$

Step 2: Calculate the tons of coal that actually produced gas

Although we just calculated the total tonnage of coal within the reservoir volume (20 feet and 160 acres), this is not the amount of coal that actually produced gas. To calculate the amount of coal that produced gas, we will use the cumulative gas production and the methane isotherm.

The cumulative gas production is the difference between the initial and current isotherms multiplied by the tons of coal from which the gas was produced. Therefore, we can calculate the tons of coal that produced the gas as:

$$Coal\ Produced = C_P = \frac{G_p}{I_{Mi} - I_{Ma}} = \frac{1.8 * 10^9}{605 - 198} = 4.4 * 10^6\ tons$$

Since the isotherms use DAF coal in their calculations, this tonnage is DAF coal. The tonnage of coal in the ground contains moisture and ash and its tonnage is calculated as:

$$Coal\ Produced\ in\ Ground = C_{Pg} = C_P * \frac{Coal\ Density}{DAF\ Coal\ Density} = 4.4 * 10^6 * \frac{76.1}{73.6}$$

$$= 4.55 * 10^6\ tons$$

The volume of coal that produced gas is calculated as:

$$Coal\ Volume\ of\ Production = V_{Pg} = \frac{2{,}000 * C_{Pg}}{Coal\ Density} = \frac{2{,}000 * 4.55 * 10^6}{76.1}$$

$$= 119.6 * 10^6\ ft^3$$

The reason we cannot use the entire tonnage and volume of coal in the spacing unit is because not all of the coal produced gas. Remember, water had to be removed prior to production and the water may not have been removed from the entire spacing unit. In that case, the area of coal with water in the pore space could not produce gas and cannot contain any residual gas. These tonnages and volumes will be used in future calculations to determine sequestration volumes.

Step 3: Calculate the reservoir pore volume

$$Pore\ Volume = PV = V_{Pg} * \emptyset = 119.6 * 10^6 * 0.022 = 2.6 * 10^6\ ft^3$$

Step 4: Calculate the residual gas in the pore volume

The z-factor at 200 psia and 105 °F is $z_a = 0.971$

$$Gas\ Expansion\ Factor = Eg_{ca} = 35.3 * \frac{P_a}{T_f * z_a} = 35.3 * \frac{200}{(565) * (0.971)}$$
$$= 12.9\ scf/ft^3$$

$$Residual\ Gas\ Volume = G_r = PV * Eg_a = 2.6 * 10^6 * 12.9 = 33.5\ MMscf$$

We will assume that this gas will not be re-adsorbed onto the coal as CO_2 is sequestered in the reservoir, but that it will take up some of the pore space as pressure is increased. The next step will calculate the volume of pore space that this residual gas will occupy.

Step 5: Calculate the pore volume that the residual gas will occupy at sequestration pressure

The z-factor at 2,000 psia and 105 °F is $z_i = 0.743$

$$Gas\ Expansion\ Factor = Eg_i = 35.3 * \frac{P_i}{T_f * z_i} = 35.3 * \frac{2{,}000}{(565) * (0.743)}$$

$$= 168.2\ scf/ft^3$$

$$Residual\ Gas\ Volume\ at\ Sequestration\ Pressure = V_{ri} = \frac{G_r}{Eg_i} = \frac{33.5 * 10^6}{168.2}$$

$$= 199 * 10^3\ ft^3$$

Step 6: Calculate the amount of CO_2 that can be sequestered on the surface of the coal

We will assume that at the current pressure of 200 psia, the coal surface has adsorbed methane and will not adsorb CO_2 until the pressure is increased. Although it is possible that some CO_2 could be adsorbed at 200 psia, we are going to assume that CO_2 can only be adsorbed between the pressures of 200 and 2,000 psia. The calculation is as follows:

$$Sequestration\ Absorbed\ Volume = SV = C_P * (I_{CO2i} - I_{CO2a})$$

$$= 4.4 * 10^6 * (1{,}490 - 680) = 3.56\ Bscf$$

Step 7: Calculate CO2 densities at standard conditions and sequestration conditions

The density of CO_2 at standard conditions is $\rho_{scCO2} = 0.115\ lb/scf$

The density of CO_2 at sequestration conditions (initial reservoir conditions) is found on a chart as shown on the following page. This chart is from *Improved Oil Recovery* by the Interstate Oil Compact Commission, 1983.

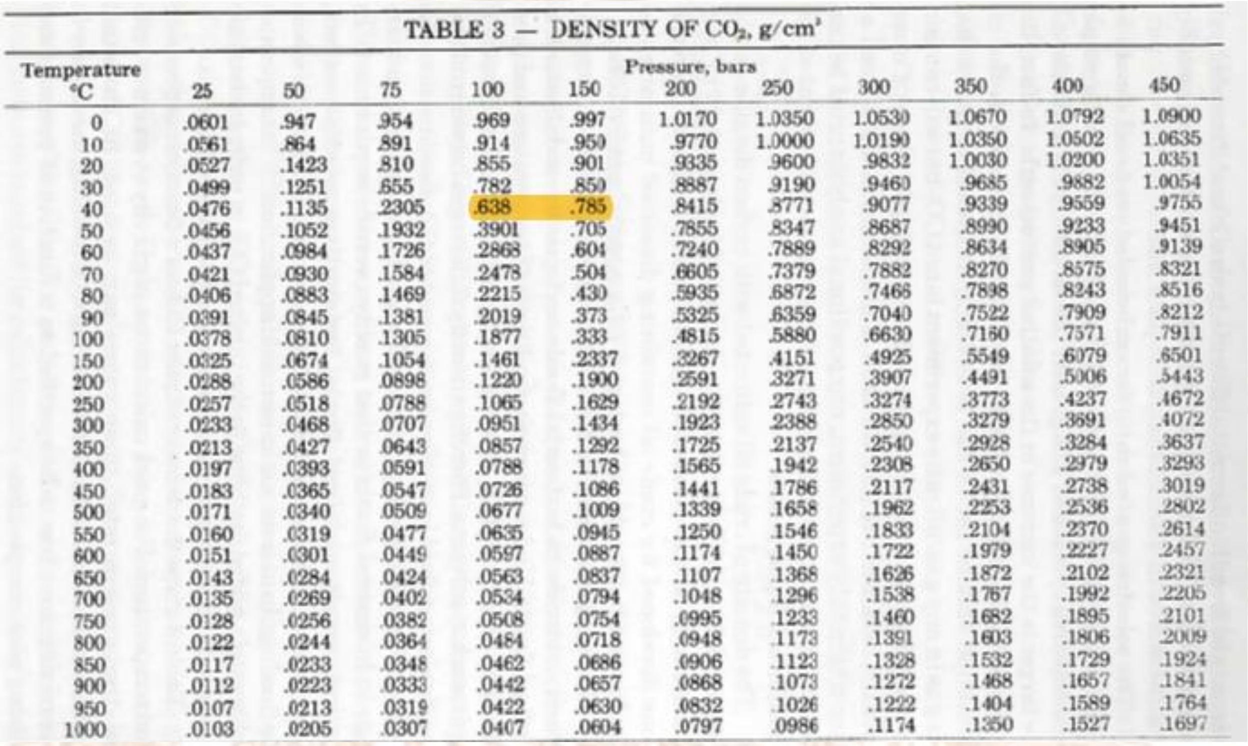


TABLE 3 — DENSITY OF CO$_2$, g/cm^3

Temperature °C	Pressure, bars										
	25	50	75	100	150	200	250	300	350	400	450
0	.0601	.947	.954	.969	.997	1.0170	1.0350	1.0530	1.0670	1.0792	1.0900
10	.0561	.864	.891	.914	.950	.9770	1.0000	1.0190	1.0350	1.0502	1.0635
20	.0527	.1423	.810	.855	.901	.9335	.9600	.9832	1.0030	1.0200	1.0351
30	.0499	.1251	.655	.782	.850	.8887	.9190	.9460	.9685	.9882	1.0054
40	.0476	.1135	.2305	.638	.785	.8415	.8771	.9077	.9339	.9559	.9755
50	.0456	.1052	.1932	.3901	.705	.7855	.8347	.8687	.8990	.9233	.9451
60	.0437	.0984	.1726	.2868	.604	.7240	.7889	.8292	.8634	.8905	.9139
70	.0421	.0930	.1584	.2478	.504	.6605	.7379	.7882	.8270	.8575	.8321
80	.0406	.0883	.1469	.2215	.430	.5935	.6872	.7466	.7898	.8243	.8516
90	.0391	.0845	.1381	.2019	.373	.5325	.6359	.7040	.7522	.7909	.8212
100	.0378	.0810	.1305	.1877	.333	.4815	.5880	.6630	.7160	.7571	.7911
150	.0325	.0674	.1054	.1461	.2337	.3267	.4151	.4925	.5549	.6079	.6501
200	.0288	.0586	.0898	.1220	.1900	.2591	.3271	.3907	.4491	.5006	.5443
250	.0257	.0518	.0788	.1065	.1629	.2192	.2743	.3274	.3773	.4237	.4672
300	.0233	.0468	.0707	.0951	.1434	.1923	.2388	.2850	.3279	.3691	.4072
350	.0213	.0427	.0643	.0857	.1292	.1725	.2137	.2540	.2928	.3284	.3637
400	.0197	.0393	.0591	.0788	.1178	.1565	.1942	.2308	.2650	.2979	.3293
450	.0183	.0365	.0547	.0726	.1086	.1441	.1786	.2117	.2431	.2738	.3019
500	.0171	.0340	.0509	.0677	.1009	.1339	.1658	.1962	.2253	.2536	.2802
550	.0160	.0319	.0477	.0635	.0945	.1250	.1546	.1833	.2104	.2370	.2614
600	.0151	.0301	.0449	.0597	.0887	.1174	.1450	.1722	.1979	.2227	.2457
650	.0143	.0284	.0424	.0563	.0837	.1107	.1368	.1626	.1872	.2102	.2321
700	.0135	.0269	.0402	.0534	.0794	.1048	.1296	.1538	.1767	.1992	.2205
750	.0128	.0256	.0382	.0508	.0754	.0995	.1233	.1460	.1682	.1895	.2101
800	.0122	.0244	.0364	.0484	.0718	.0948	.1173	.1391	.1603	.1806	.2009
850	.0117	.0233	.0348	.0462	.0686	.0906	.1123	.1328	.1532	.1729	.1924
900	.0112	.0223	.0333	.0442	.0657	.0868	.1073	.1272	.1468	.1657	.1841
950	.0107	.0213	.0319	.0422	.0630	.0832	.1026	.1222	.1404	.1589	.1764
1000	.0103	.0205	.0307	.0407	.0604	.0797	.0986	.1174	.1350	.1527	.1697

At interpolating between 100 and 150 bars at 40 °C (105 °F), at 138 bars (initial pressure of 2,000 psia) we get

$$\rho_{iCO2} = 0.744\,\frac{g}{cc} = 46.4\ lb/ft^3$$

Step 8: Calculate the amount of CO₂ that can be sequestered in the pore space

$$Pounds\ of\ CO_2 = (PV - V_{ri}) * \rho_{iCO2} = (2.6 * 10^6 - 199 * 10^3) * 46.4 = 111.4 * 10^6\ lbs$$

Step 9: Calculate volume of CO₂ at standard conditions to fill the pore space

$$Volume\ of\ Pore\ Space\ CO_2 = \frac{Pounds\ of\ CO_2}{\rho_{scCO2}} = \frac{111.4 * 10^6}{0.115} = 0.97\ Bscf$$

Step 10: Calculate the total amount of CO_2 that can be sequestered

$$Sequestered\ Volume\ of\ CO_2 = Absorbed + Pore\ Space = 3.56 + 0.97 = \mathbf{4.53\ Bscf}$$

Step 11: Calculate tons of CO_2 sequestered

$$Tons\ of\ CO_2\ Sequestered = \frac{Sequestered\ Volume * \rho_{scCO2}}{2{,}000}$$

$$= \frac{4.53 * 10^9 * 0.115}{2{,}000} = \mathbf{260{,}475\ tons}$$

As can be seen, an estimate of CO_2 sequestration in an abandoned coalbed methane reservoir requires quite a bit of additional work than that of an abandoned gas reservoir or aquifer.

An important thing to notice is that the sequestered CO_2 volume (at standard conditions) is almost two and a half times the original methane production. This is due to two things; coal has a higher adsorption capacity for CO_2 than for methane, and the original pore space that was initially filled with water is now available for the storage of CO_2. In this case, the pore space accounts for about 21% of the sequestration volume.