CO_2 Production and Shut-In Tests at Danielson 33-17 Well

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Findings of CO_2 Production/Shut-In Tests

- Under the shut-in conditions of Danielson 33-17, phase transition from deep liquid CO_2 to shallower gaseous CO_2 occurs at a depth of 2249 feet (685.5 m);

- Under production testing conditions, this phase interface was lowered within one hour to the reservoir level by lowering wellbore pressure to 7 bar;

- The pressure lowering (ΔP) caused significant temperature drop (ΔT) to 2℃ in the wellbore, monitored by bottomhole P/T gauges;

- Significant ΔP in the perforated Zone 5 is expected to produce significant ΔT, which may lead to CO_2 hydrate (or water ice) in the formation near the perforations;

- The radius of the affected reservoir volume is estimated to be less than 1 meter for the CO_2 production over 4.5 days;

- The reservoir volume with hydrate near the perforations might significantly reduce absolute and rel. perm., which was estimated using the following shut-in pressure recovery data.

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  - **CO_2 Flow Rate**
- **Potential Hydrate Formation**
  - **Significant Reduction in Temperature due to JT Cooling**
  - **Potential Hydrate Formation**
  - **Reduction in CO_2 Rel. and Absolute Perm., and Production Rate**
- **Mitigation for CO_2 Production during the Injection Period**
  - **Reduce Pressure Drop by Controlling Q and P at Wellhead**
  - **Inhibitors? Heating?**

1. Danielson 33-17 Well

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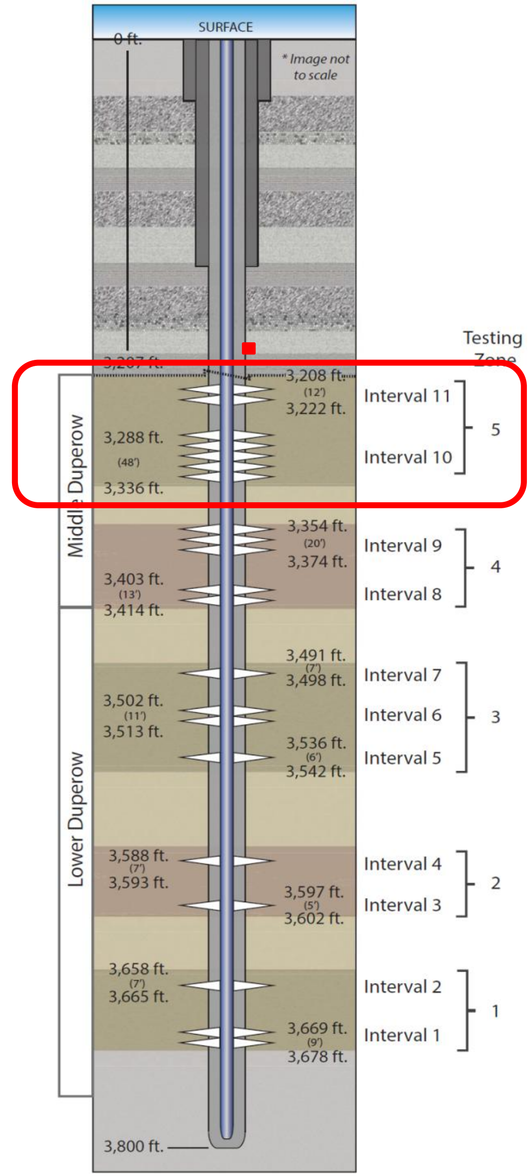
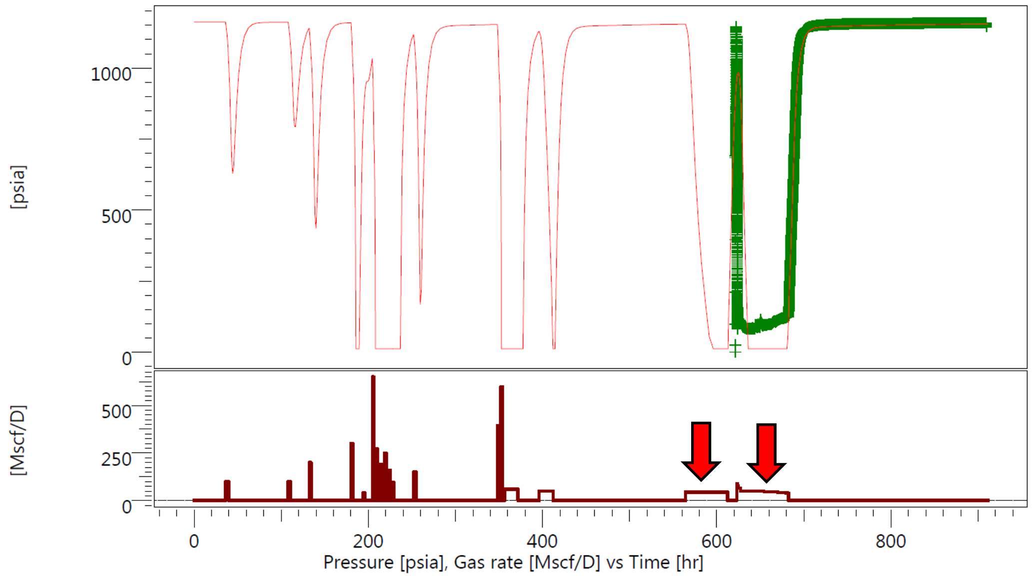
- **Zone 5 of Middle Duperow:**
  - **Interval 11: 3208 – 3222 ft**
  - **Interval 10: 3288 – 3336 ft**

- **Bottomhole P/T Gauges:**
  - **Top Gauge @ 3179 ft**
  - **Lower Gauge @ 3180 ft**

- **Wellhead P/T/Q Monitoring:**
  - **Tubing P/T**
  - **Casing P/T**
  - **Gas T**
  - **CO_2 Flow Rate**
  - **Water Flow Rate**



CO_2 Production Tests



(SLB, 2015)

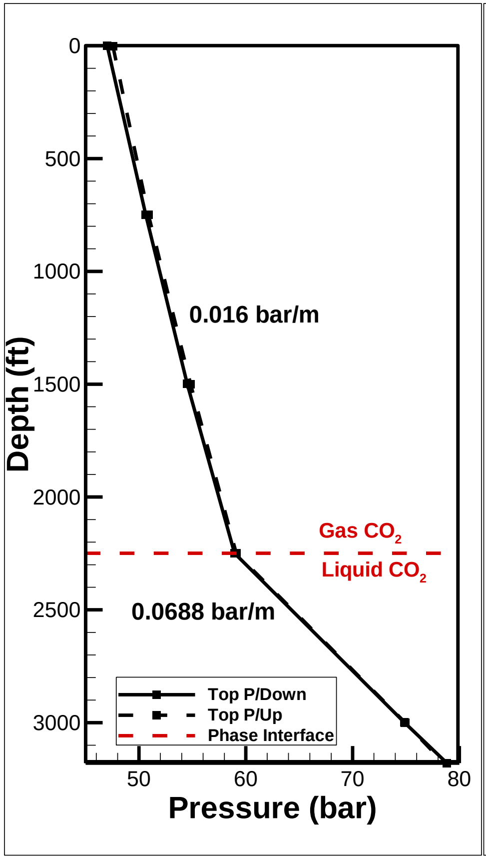
5-Dec	100 MSCF	2 Hours
6-Dec	200	1
	40	1.5
8-Dec	300	1
	40	1
9-Dec	650	1
	270	1
	190	1
	250	1
	160	1
	95	1
11-Dec	150	3
15-Dec	394	1
	597	1.75
	60	16
17-Dec	50	16
24-Dec	45	48

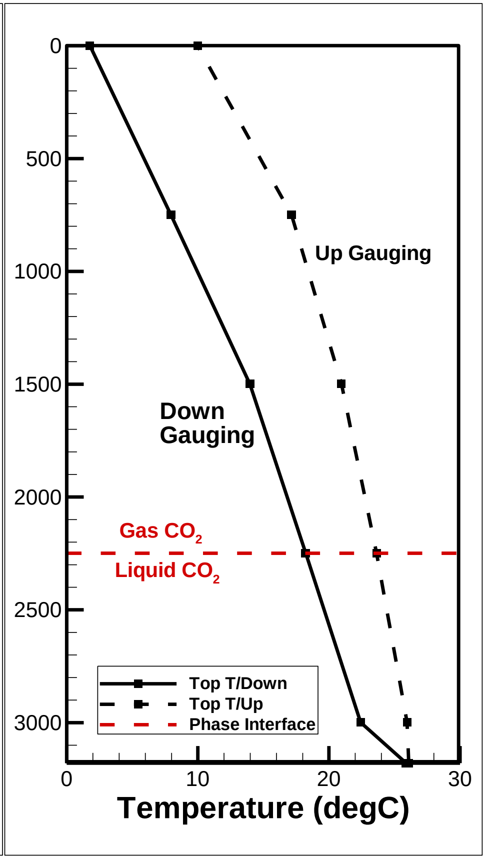
(Kirksey, 2015)

- **14 production tests of 1-3 hours from Dec 5 to 15, 2014;**
- **2 production tests of 16 hours on Dec 15 and 17;**
- **1 production test of 2 days on Dec 24, 2014;**
- **1 production (2.5 days) test on Dec 26 – 28, 2014, followed by a shut-in test of 10 days.**
- **How were these tests conducted? Vent, i.e., open the well and let CO_2 freely flow out of the well? What is wellhead pressure control for flow rate?**
- **Interplay between different tests for the wellbore and reservoir? Cumulative effects?**

A total of 426 MSCF CO_2

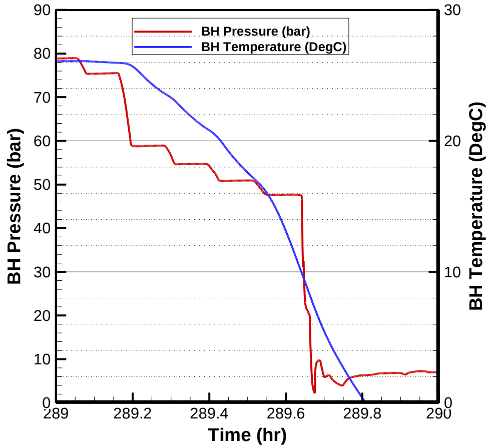
2. Shut-In P/T Profiles



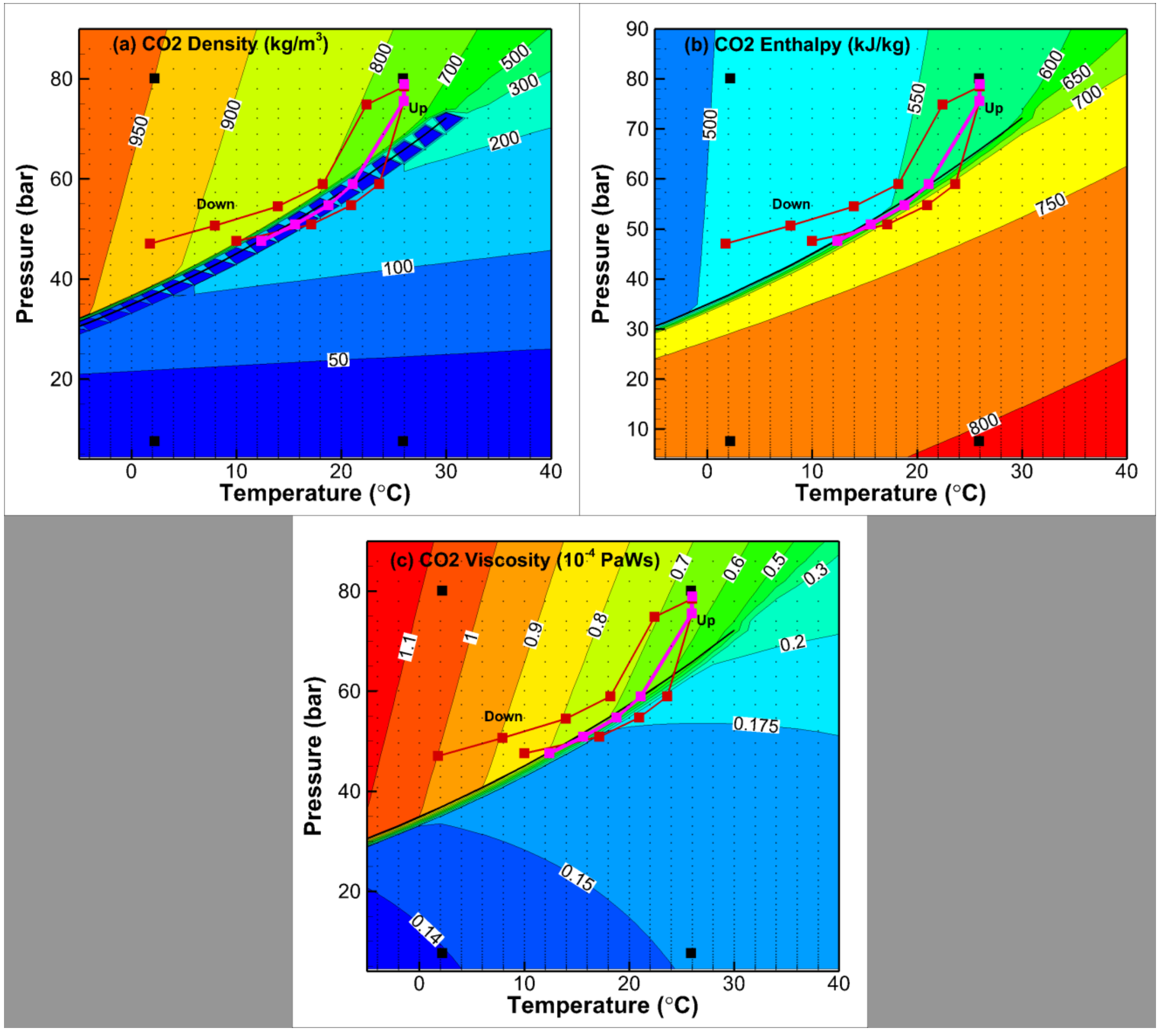


- Data 1 (Down) was acquired 9 – 11 am, Dec 26, 2014 before the production test on Dec 26 – 28;
- Data 2 (Up) was acquired 10:04 – 10:39 am, Jan 7, 2015;
- Pressure profiles in both datasets show **phase transition** from liquid in the deep to gaseous CO_2 in the shallower segment of the well;
- Pressure data are at equilibrium at each depth; **while temperature are not equilibrated**.

Top Gauge	@11am, 12/26/14	@10 am, 01/07/15
BH P	1144 psi (78.8 bar)	1147 psi (79.0 bar)
BH T	78.6 ℉ (25.9 ℃)	78.89 (26.1 ℃)
WH P	682.4 psi (47.0 bar)	690.9 psi (47.6 bar)
WH T	35.2 (1.8 ℃) ?	50.0 (10 ℃)

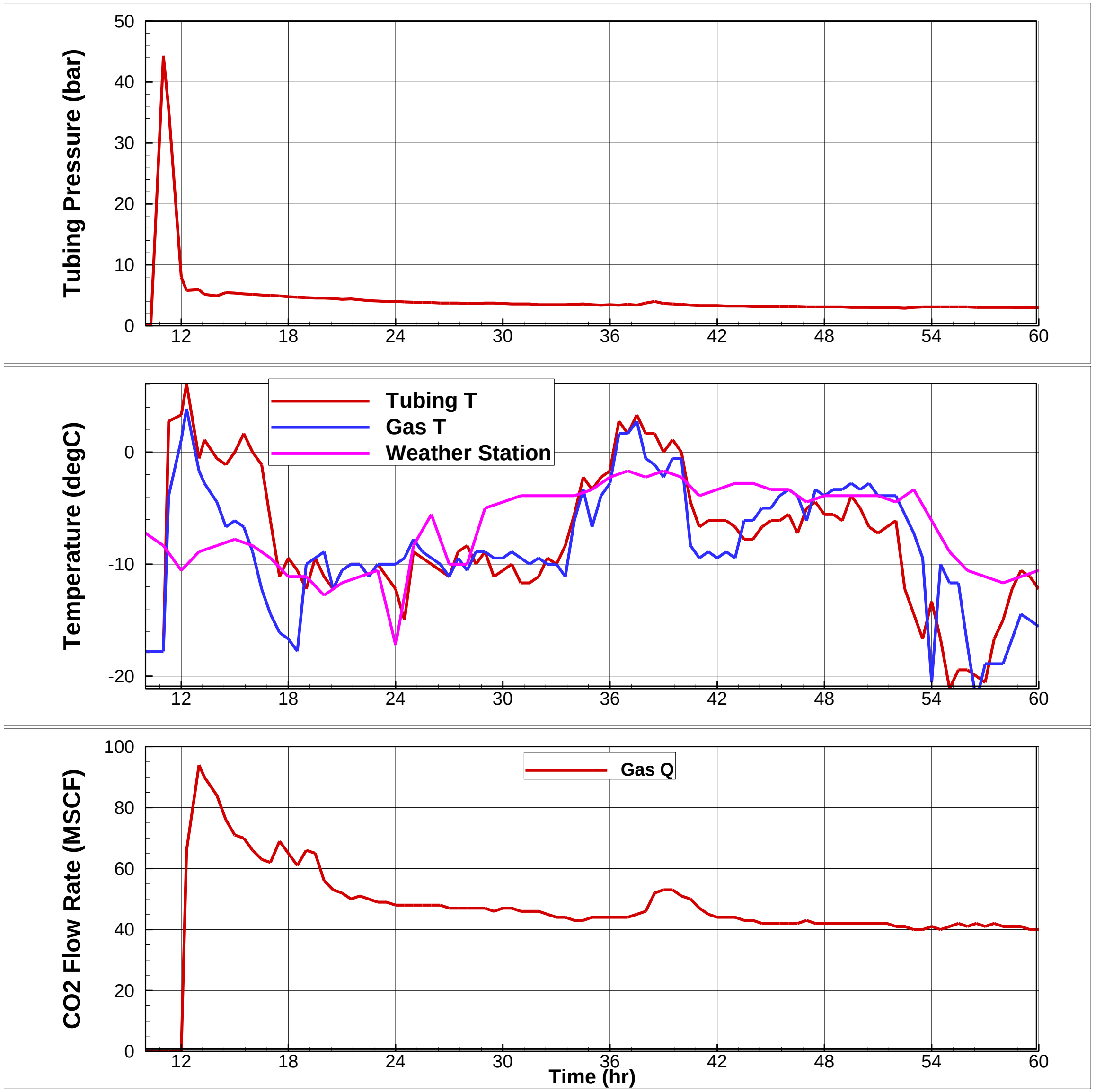


Wellbore Phase Diagram



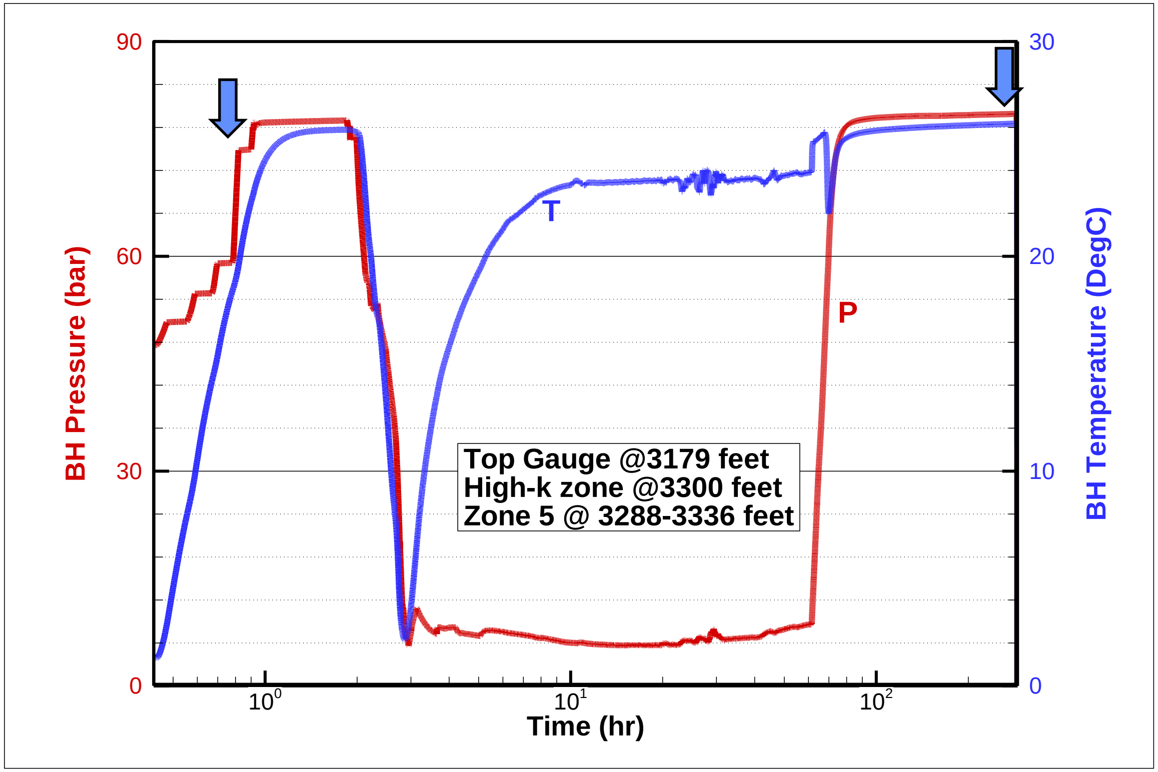
- Shut-in on Jan 7, 2015
- Shut-in on Dec 26, 2014
- T profiles are corrected using pressure profile data to assure the transition between liquid and gas CO_2;
- First 3 depths in liquid CO_2
  - 2249 ft (transition)
  - 2999 ft
  - 3179 ft
- Last 3 depths in gas CO_2
  - Ground Surface
  - 749 ft
  - 1499 ft

3. Production Test: Wellhead P/T/Q



- **Wellhead pressure dropped from 643 to 43 psi, or 44.3 to 3.0 bar;**
- **CO_2 flow rate reduced from 94 to 40 MSCFD;**
- **Wellhead and gas T may be affected mainly by the weather T, rather than the subsurface T?**

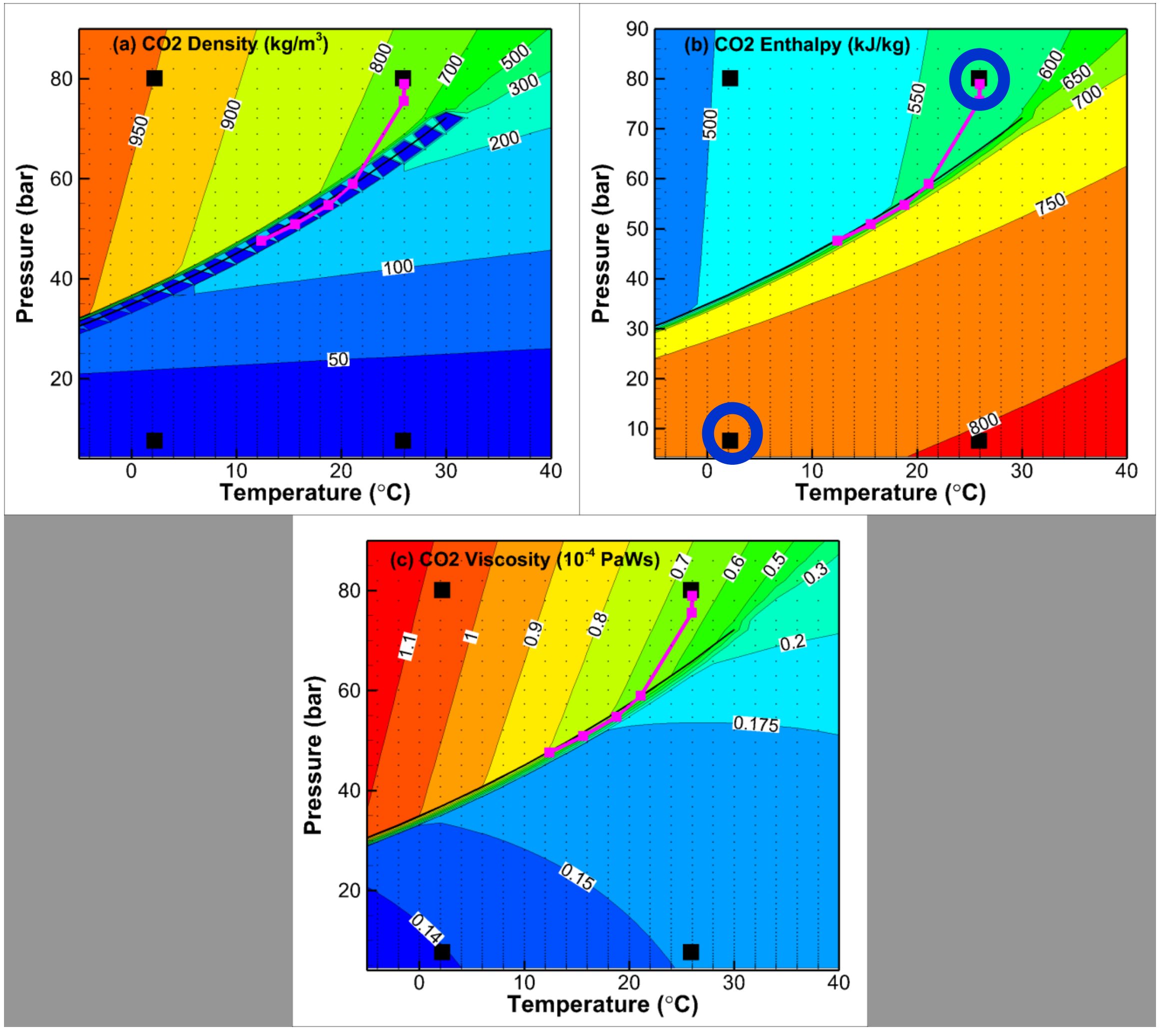
Production Test: BH P/T



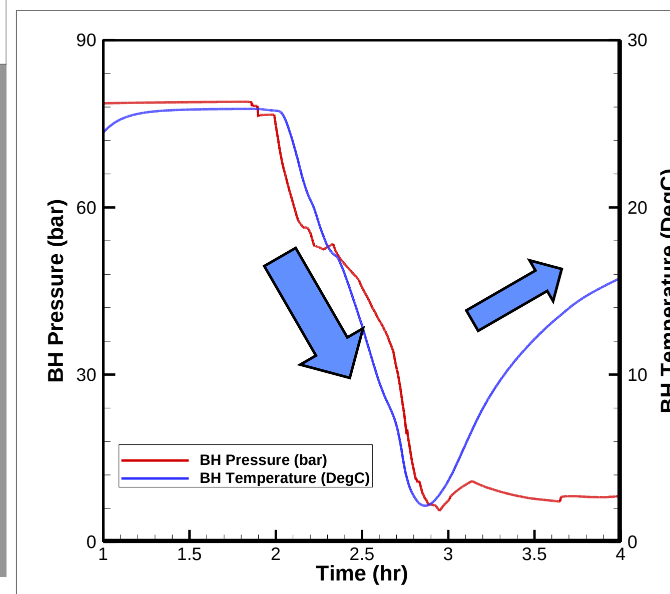
- Temperature was not equilibrated at each depth, thus the T profiles cannot be used directly;
- Pressure was at equilibrium for each depth.

- Downhole gauge is located at depth of 3180 feet, ~100 feet above Zone 5 of the Middle Duperow;
- Pressure dropped from 1145 to 85 psi, or from 78.8 to 5.9 bar;
- The large ΔP resulted in ΔT = 78.6 – 35.8 ºF, showing a significant JT cooling effect
- Minimum T = 35.8 ºF (2.2 ºC), showing potential hydrate formation in the reservoir.

Joule-Thomson Cooling in Wellbore



- ❖ **Production Conditions @BH Gauges**
  - ➢ **P: 1145 to 110.6 psi (78.9 to 7.6 bar);**
  - ➢ **T: 78.61 to 35.88 ℉ (25.9 to 2.2℃);**
  - ➢ **Enthalpy: 569.3 to 781.6 kJ/kg**



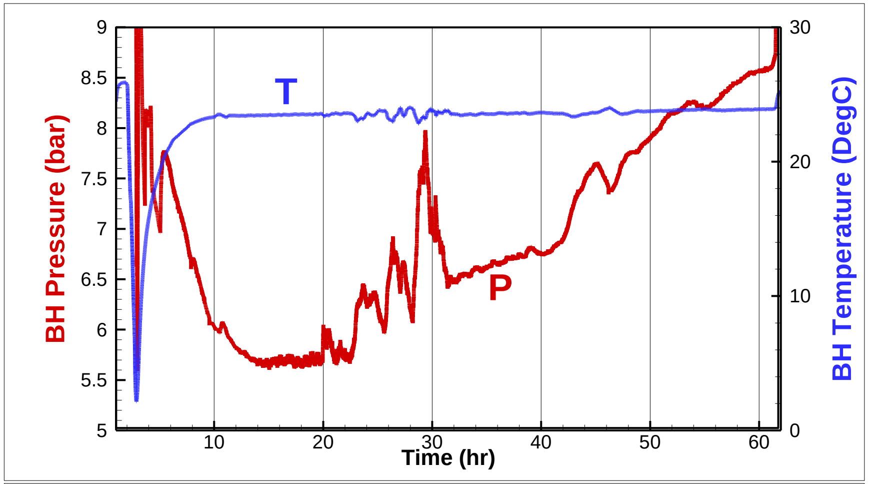
4. JT Cooling in Reservoir and Hydrate Formation ?

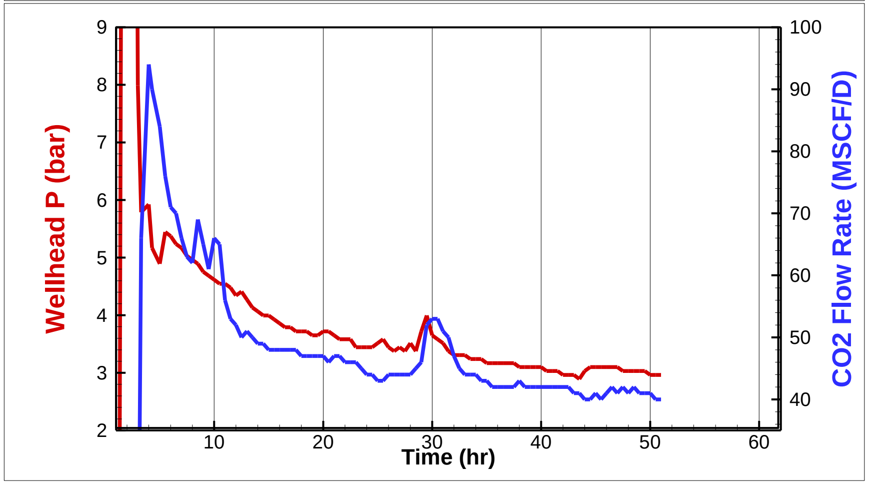
- **Reservoir Conditions**
  - **Pressure @ 1145 (78.9 bar);**
  - **Temperature @ 78.61 ℉ (25.9 ℃);**
  - **Enthalpy: 569.3 kJ/kg**

- **Wellbore Conditions @ Zone 5**
  - **Pressure @ 110.6 psi (7.6 bar);**
  - **Temperature @ 35.88 ℉ (2.2 ℃);**
  - **Enthalpy: 781.6 kJ/kg**

- **CO_2 Flow Mass for Two Vents**
  - **45.84 + 44 + 10.3 = 100.14 MSCF**
  - **1 MSCF = 28.3 m^3 * 1.98 kg/m^3 = 56.1 kg**
  - **CO_2 total mass = 5617.8 kg**
  - **CO_2 mass in previous production = 5049 kg;**

- **Heat Released to have 0 ℃**
  - **= -(780-570) kJ/kg*(5618+5049) kg**
  - **= -2,240,000 kJ**





Cooling-Affected Reservoir Volume/Radius

- **Specific Heat**
  - **Dolostone rock: 0.92 kJ/kg/K**
  - **Water: 4.186 kJ/kg/K**
  - **Porosity = 6%**

- **Dolomite density = 2.84 x 10^3 kg/m^3**

- **ΔT = 26℃ for 0℃ for hydrate formation;**

- **Affected Volume/Radius:**
  - **Heat/(density*Sh*ΔT) = 2,240,000 kJ/(2.84*1000*0.92*26) = 33.0 m^3**
  - **Zone 5 Thickness = 48 feet = 14.6 m**
  - **Radius = 0.85 m**

5MPa.

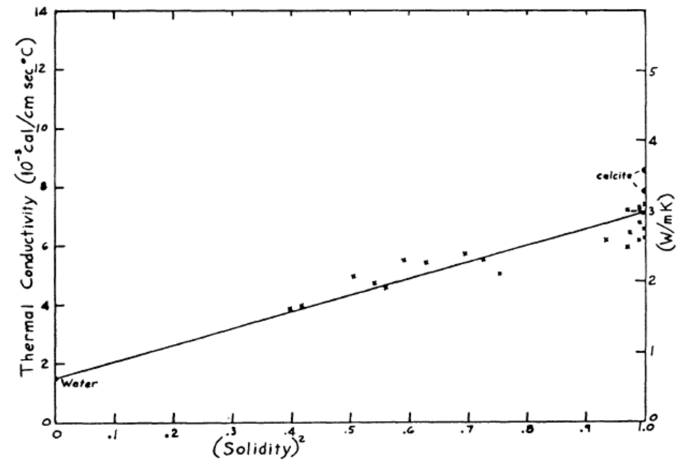


FIGURE 6. Thermal conductivity of limestone with water in the pores, showing variation with solidity, at 300 K, 5MPa.

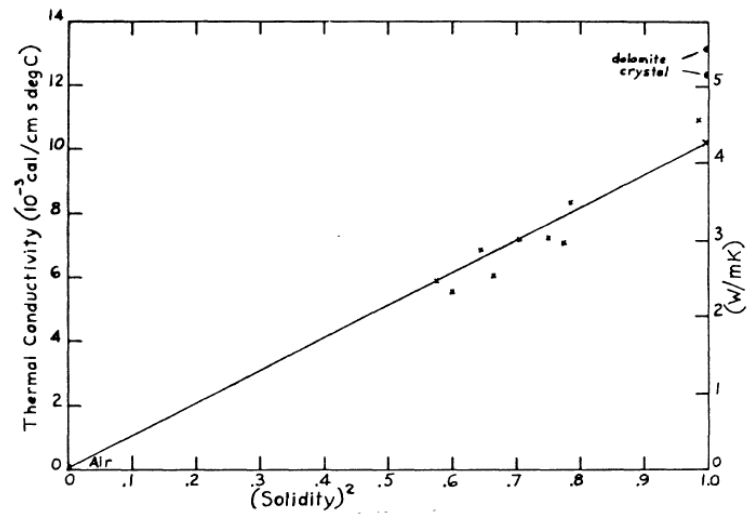
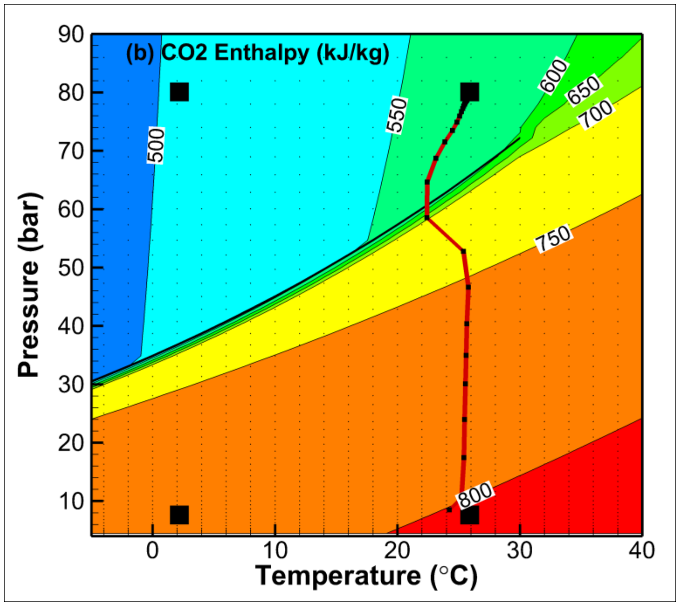
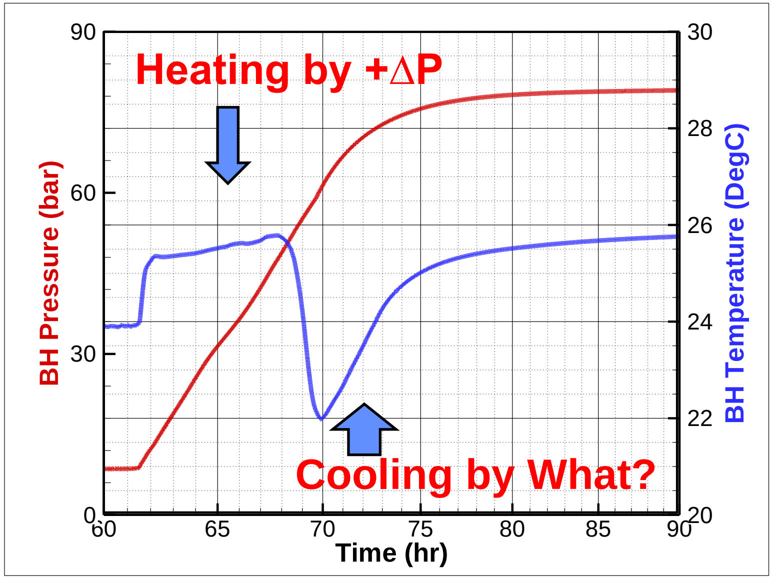


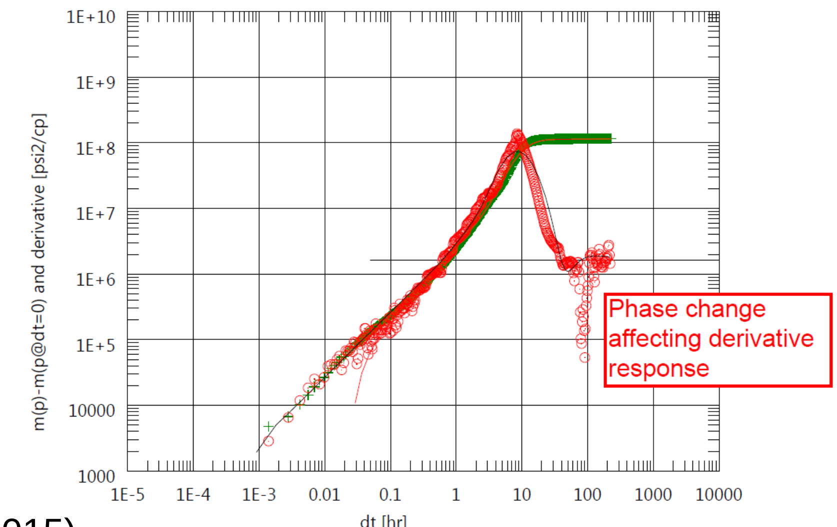
FIGURE 7. Thermal conductivity of dolostone with air in the pores, showing variation with solidity, at 300 K, 5MPa.

Evidence of Hydrate Formation?

- Temperature at gauges @ 3180 ft increased by positive ΔP, and then decreased by up-moving of cooler CO_2 in the reservoir;







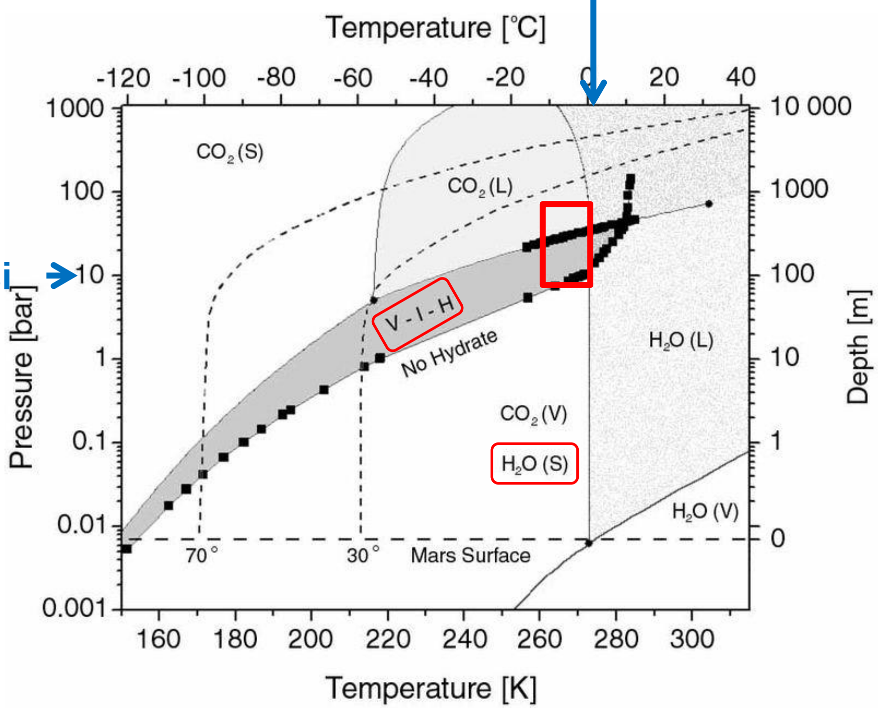
- Changes of pressure derivative around 80 hours were attributed to phase change in wellbore and reservoir by SLB

(SLB, 2015)

Hydrate Formation: Stability Diagram

36 F = 2.2 C

145 psi



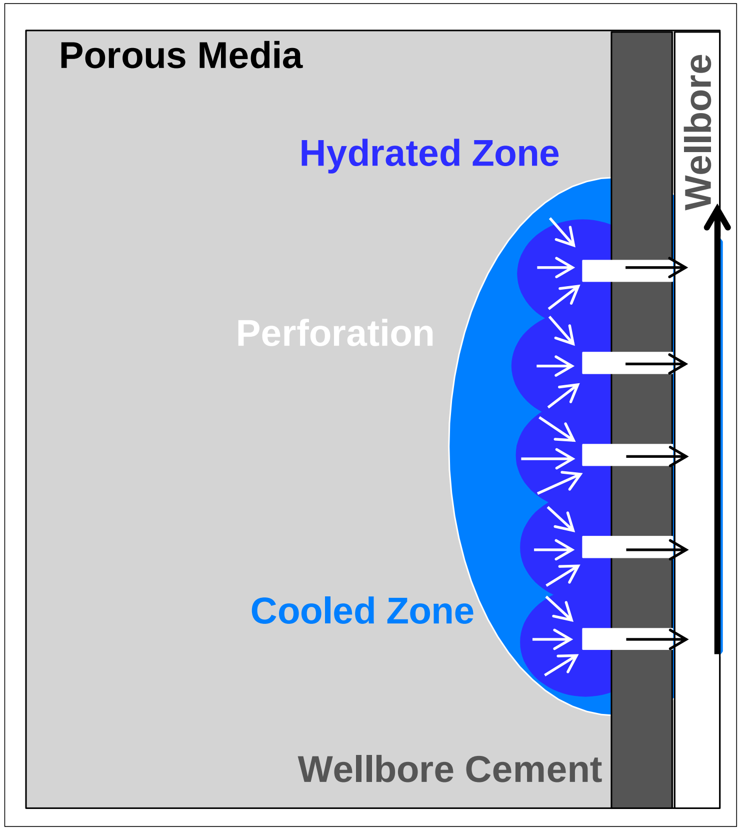
CO_2-hydrate has 5.75-7.67 moles H_2O per mole CO_2

Anderson, Graydon K. "Enthalpy of dissociation and hydration number of carbon dioxide hydrate from the Clapeyron equation." *The Journal of Chemical Thermodynamics* 35.7 (2003): 1171-1183.

CO_2 hydrate phase diagram. The black squares show experimental data (after Sloan, 1998 and references therein). The lines of the CO_2 phase boundaries are calculated according to the Intern. thermodyn. tables (1976). The H_2O phase boundaries are only guides to the eye. The abbreviations are as follows: L - liquid, V - vapor, S - solid, I - water ice, H - hydrate.

Hydrate Formation: Conceptual Model

- Liquid CO_2, water, and oil co-exist in the perforated Zone 5 of Middle Duperow, with water saturation: 0-34% and oil saturation: 0-4.4%;
- No water production was observed;
- CO_2 liquid flashing to vapor <u>and</u> JT cooling during flow test could have cooled the formation just outboard of perforations in the formation where the ΔP is large;
- Hydrate could have formed here, plugging pores and reducing permeability;
- Six moles of water for every mole of CO_2 would consume all the water;
- Outside of CO_2-hydrate stability zone, H_2O ice also could have formed.



5. Conclusions

- Under the shut-in conditions of Danielson 33-17, phase transition from deep liquid CO_2 to shallower gaseous CO_2 occurs at a depth of 2249 feet (685.5 m);
- Under production testing conditions, this phase interface was lowered within one hour to the reservoir level by lowering wellbore pressure to 7 bar;
- The pressure lowering (ΔP) caused significant temperature drop (ΔT) to 2 ℃ in the wellbore, monitored by bottomhole P/T gauges;
- Significant ΔP in the perforated Zone 5 is expected to produce significant ΔT, which may lead to CO_2 hydrate (or water ice) in the formation near the perforations;
- The radius of the affected reservoir volume is estimated to be less than 1 meter for the CO_2 production over 4.5 days;
- The reservoir volume with hydrate/ice near the perforations might significantly reduce absolute and rel. perm., which was estimated using the following shut-in pressure recovery data;
- More significant effect with enlarged affected reservoir volume and radius is expected for high-rate production over four years of the CO_2 injection phase;
- Mitigation measures may include reducing pressure drop by controlling Q and P at wellhead and use of some inhibitors and heating (?)