Energy Geosciences
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Mechanistic modeling of CO_2 leakage into the water column from off-shore CO_2 wells or pipelines

Curtis M. Oldenburg
Lehua Pan

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Motivation for this work is provided by interest in near-offshore GCS, e.g., in the Gulf Coast region

The Advantages of Offshore CCS in the Gulf of Mexico

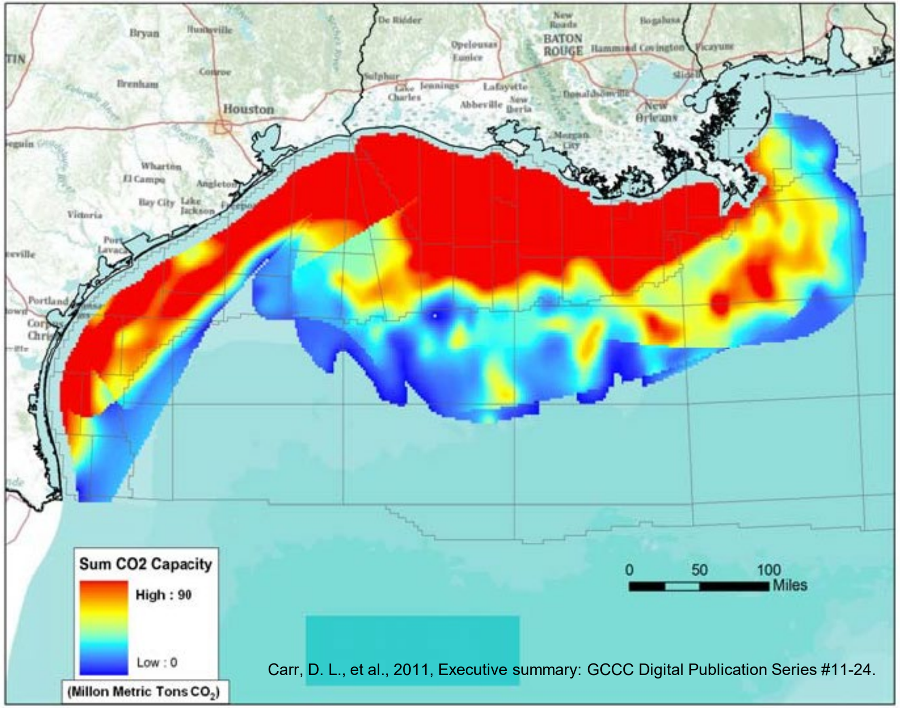
1. One of the most-studied geologic basins in the world
2. High concentration of industrial CO_2-emission sources
3. One of the country's largest volume, lowest risk geology sinks
4. CO_2 industrial sources are close to large offshore sinks
5. Existing CO_2 capture and transportation facilities in place
6. Commercial Enhanced Oil Recovery can offset costs

GoMCarb project
2018-2023
Texas BEG
Gulf Coast Carbon Center
And numerous partners

http://www.beg.utexas.edu/gccc/research/gomcarb

Partnership for carbon capture & offshore geologic storage
GoMCarb

TOTAL Offshore Western GOM = 559 Billion Metric Tons



Carr, D. L., et al., 2011, Executive summary: GCCC Digital Publication Series #11-24.

Main Questions Being Addressed for CO_2 wells:

- **Under what blowout conditions will leaking CO_2 make it to the sea surface (not dissolve in the water column)?**
  - **Water depth, leakage rate, orifice, …**

- **What are the possible blowout flow rates for given reservoir-well conditions?**
  - **Orifice size, reservoir depth, water content, composition, …**

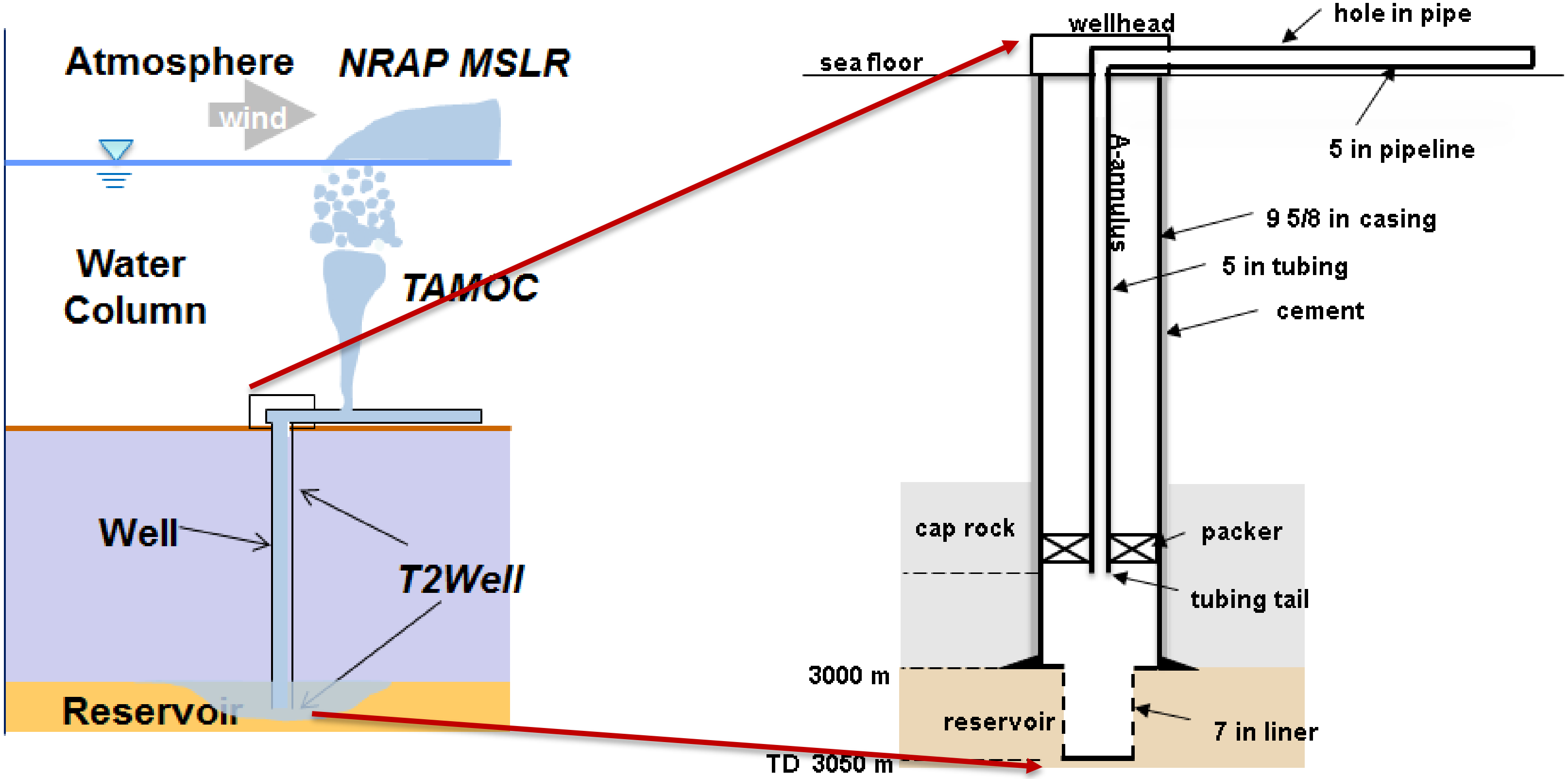
- **If CO_2 is emitted into the atmosphere, what are expected downwind safety distances?**
  - **CO_2 emission rate, wind, …**

Sedco 700 Shallow Gas Blow Out 6 June 2009 11 35am

Nigeria

https://www.youtube.com/watch?v=NJiBS64RVVQ

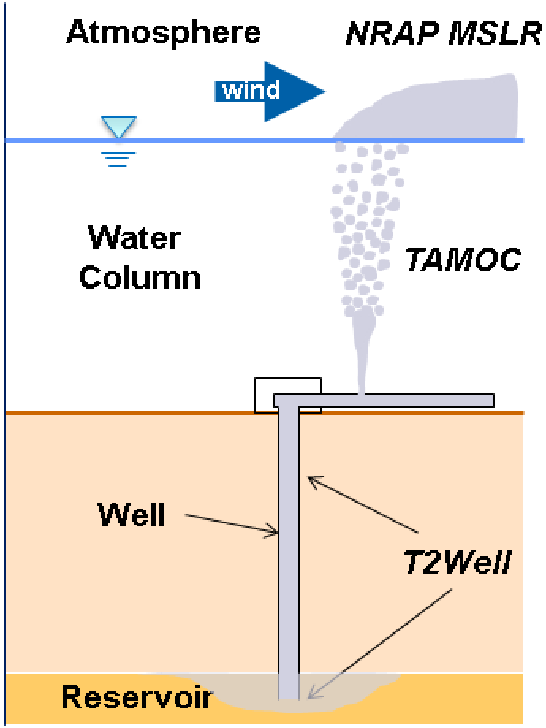
Approach: Simulate offshore CO_2 blowout using T2Well and pass output to TAMOC



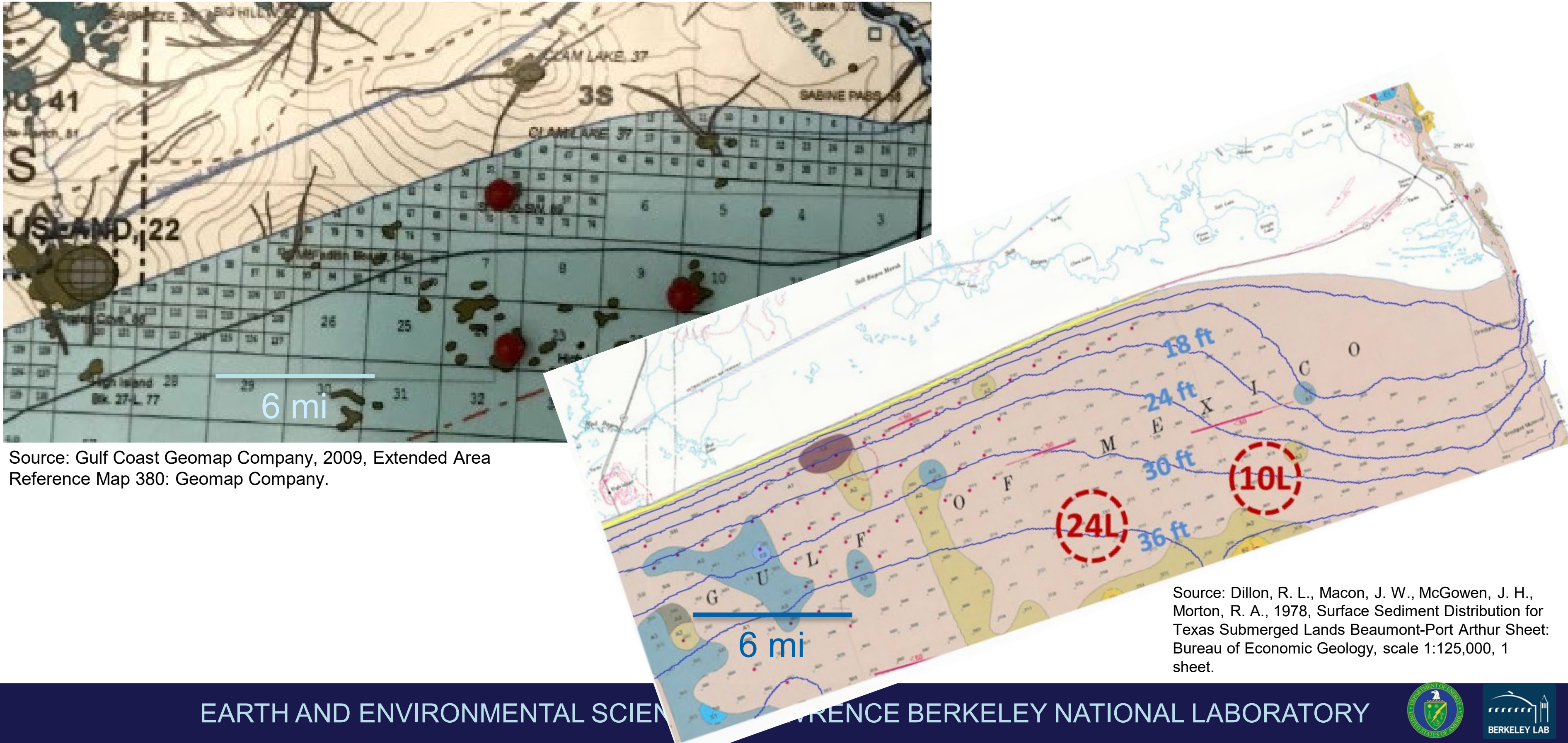
Offshore CO_2 well blowouts are strongly controlled by transport processes in the water column

Relative to ambient air, the water column provides
- **More resistance to flow**
- **Positive buoyancy for CO_2**
- **Vast source of heat to counter cooling caused by decompression**
- **Vast sink for CO_2 dissolution**

Loosely couple two existing models to understand consequences of sub-sea CO_2 leaks and blowouts
- **Reservoir-well flow (T2Well)**
- **Jet and buoyant plume flow in the water column (TAMOC)**



GoMCarb focus is on the High Island 10L and 24L blocks where the water depth is approximately 30-40 ft



Source: Gulf Coast Geomap Company, 2009, Extended Area Reference Map 380: Geomap Company.

Source: Dillon, R. L., Macon, J. W., McGowen, J. H., Morton, R. A., 1978, Surface Sediment Distribution for Texas Submerged Lands Beaumont-Port Arthur Sheet: Bureau of Economic Geology, scale 1:125,000, 1 sheet.

The well blowout is simulated using T2Well for the coupled reservoir-well flow

T2Well models three-phase flow in the reservoir and in the well for this problem

- **Three-phase Darcy's law for flow in the reservoir**
- **Drift-flux model for flow in the well pipe**
- **Friction in the well is a function of roughness and flow rate (Re)**
- **Continuous range of flow regimes depending on phase saturations and Re**
- **Equation of state for CO_2-brine mixtures was used here**
- **Salinity, pressure, temperature effects on density and solubility**

https://tough.lbl.gov/licensing-download/tough-related-codes-licensing-download/

Pan, L. and Oldenburg, C.M., 2014. T2Well—an integrated wellbore–reservoir simulator. Computers & Geosciences, 65, pp.46-55.

Approach to simulating CO_2 rise in the water column: TAMOC (integral model for gas jets and bubble plumes by Scott Socolofsky, Texas A&M)

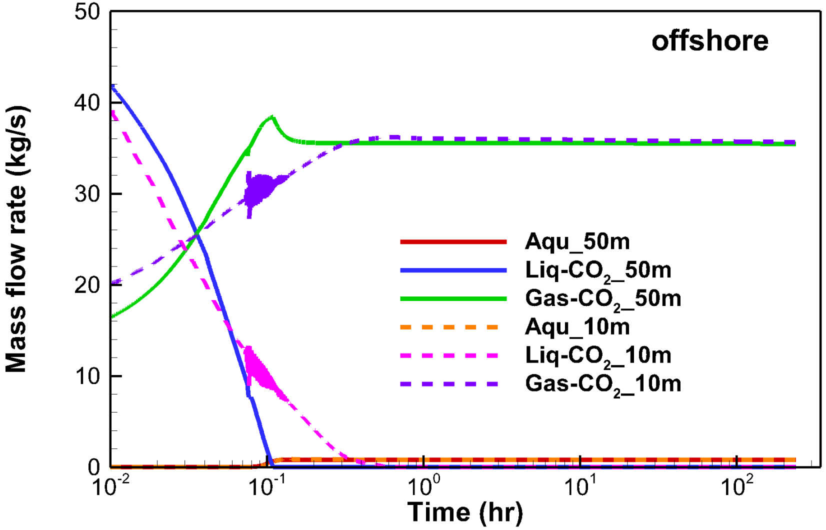
TAMOC models complex physical processes using an integral approach:

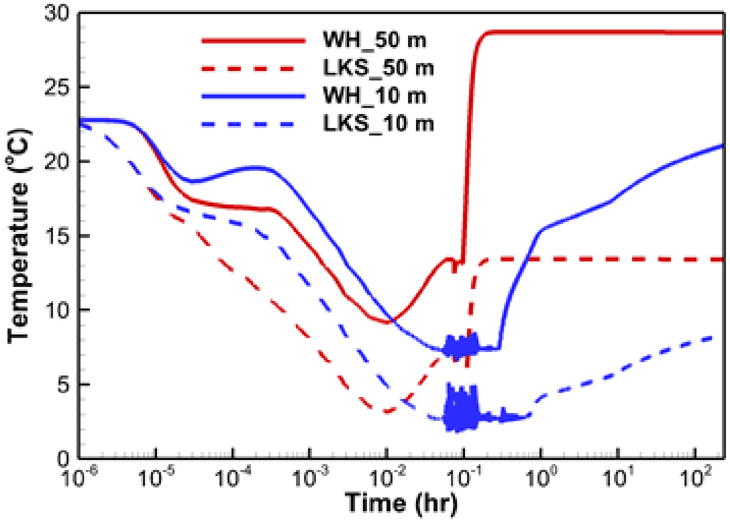
- **Jet flow of gas into water column**
- **Transition from jet flow to bubbly flow**
- **Top-hat velocity profiles with fluid entrainment**
- **Buoyant bubble rise w/ dynamics based on bubble-size distribution**
- **Equations of state for multiple gases and gas mixtures**
- **Crossflow of seawater**
- **Stratification of seawater**
- **Salinity, pressure, temperature effects on density and solubility**

https://www.marine.usf.edu/c-image/component/k2/texas-a-m-oilspill-calculator-tamoc-modeling-suite-for-subsea-spills

Dissanayake, A. L., Gros, J., and Socolofsky, S. A. (2018). "Integral models for bubble, droplet, and multiphase plume dynamics in stratification and crossflow." Environ Fluid Mech, 18(5), 1167-1202.

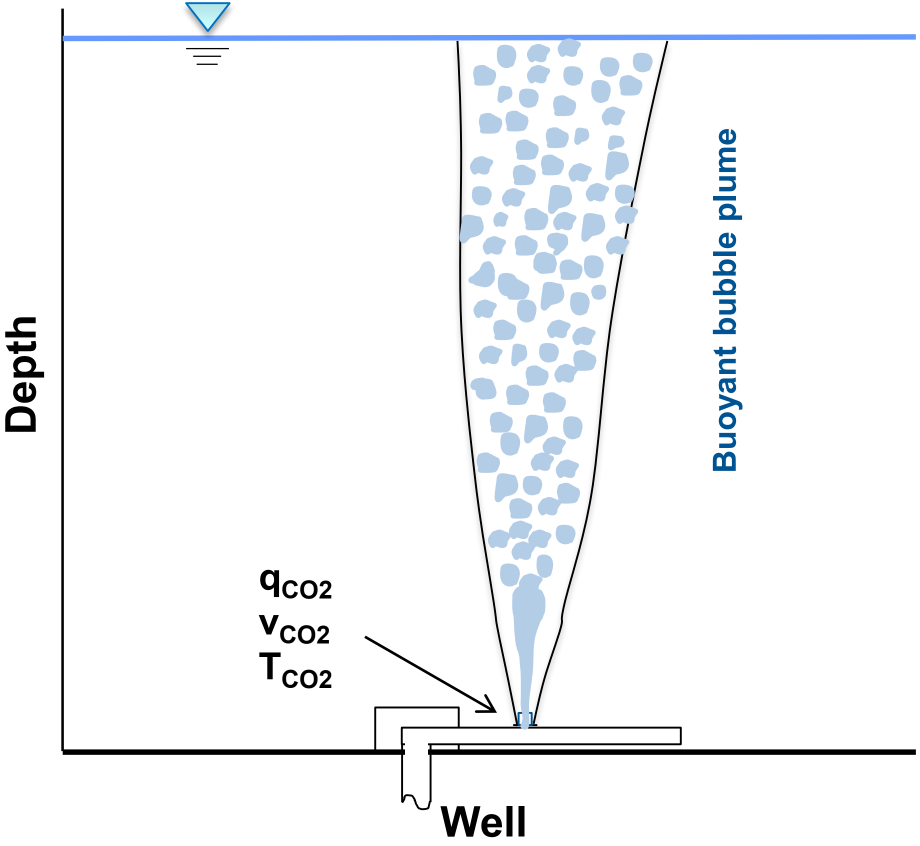
Results: T2Well Flow and Temperature at the Seafloor for CO_2 Blowout in the 50 m and 10 m Depth Cases





Aqu = aqueous phase; Liq-CO_2 = liquid CO_2 phase; Gas-CO_2 = gaseous or supercritical CO_2
WH = wellhead; LKS = leakage source (hole in pipe)

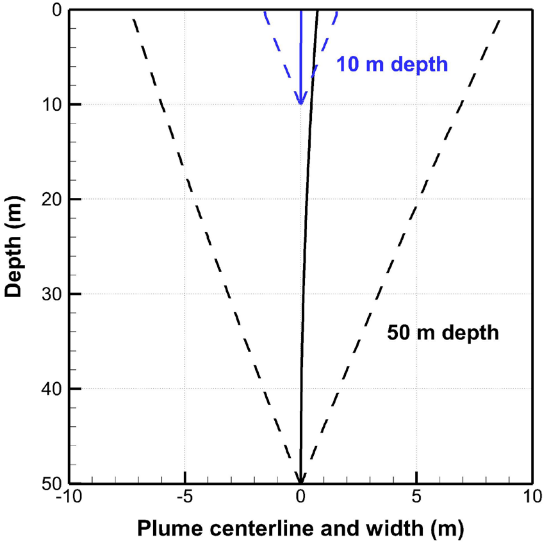
TAMOC Modeling of the Buoyant CO_2 Bubble Plume

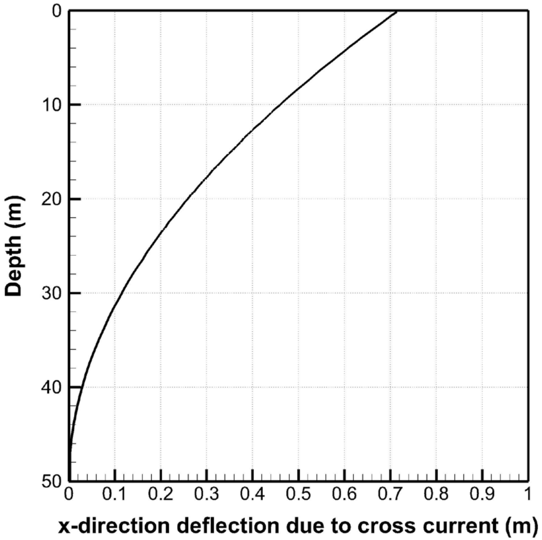


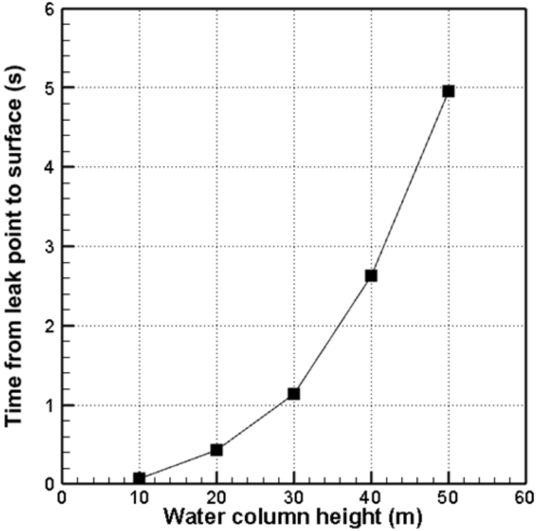
Main inputs to TAMOC:

- CO_2 mass flow rate from T2Well
- CO_2 temperature from T2Well
- Diameter of hole (orifice)
- Depth of water column
- Depth of release point
- Temperature and salinity of seawater
- Crossflow velocity of seawater
- Bubble size distribution

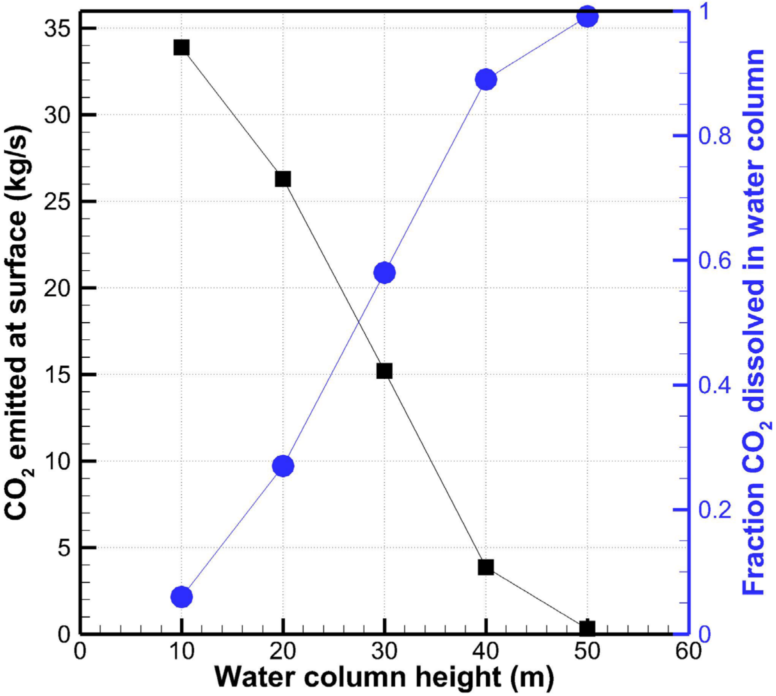
Results: TAMOC-simulated plume in 50 m case spreads to diameter of 15 m and is deflected 0.7 m by cross flow of 0.15 m/s







CO_2 blowout plume is almost entirely attenuated by seawater column if 50 m deep



Conclusions

- Offshore sites are being considered for GCS in the Texas Gulf Coast
- There is a need to understand risks of CO_2 blowouts at offshore sites
- Offshore CO_2 blowouts will behave differently from onshore blowouts because of the strong effects of the water column
- We loosely coupled two models for simulations of this system:
  - T2Well (reservoir and well or pipeline)
  - TAMOC (water column)
- Results for large blowout (~1 Mtonne/yr) show
  - Median bubble size diameter is estimated to be 0.5 mm
  - 99% of the CO_2 is dissolved in the seawater for a blowout at 50 m depth
  - 94% of the CO_2 is emitted at the sea surface for a blowout at 10 m depth
- TAMOC results can be rationalized independently by estimates of
  - Mass transfer rate from median-size bubble
  - Seawater entrainment rate needed to dissolve leaked CO_2
- The results agree qualitatively with model results from another group using totally different methods

Further Research Directions

- Expand range of seafloor conditions (e.g., temperature, depth)
- Expand range of blowout/leakage flow rates and reservoir conditions
- Examine effects of ocean currents (cross flow)
- Sensitivity analysis of input parameters

Further investigate

- Effects of decompression, e.g., formation of liquid CO_2 and hydrates
- Multicomponent effects in reservoir and well
- Multicomponent absorption effects in the water column
- Multicomponent ebullition
- Impurity effects on bubble mass transfer, surface tension
- Atmospheric dispersion following sea-surface emission

Acknowledgments

We thank Scott Socolofsky (Texas A&M) and Jonas Gros (GEOMAR Helmholtz Centre for Ocean Research Kiel) for help with using TAMOC, and Margaret Murakami, Tip Meckel, Ramon Trevino, and Susan Hovorka (Texas BEG) for assisting with characterization of the near-offshore region in the Gulf of Mexico.

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Properties of the well and surface pipeline

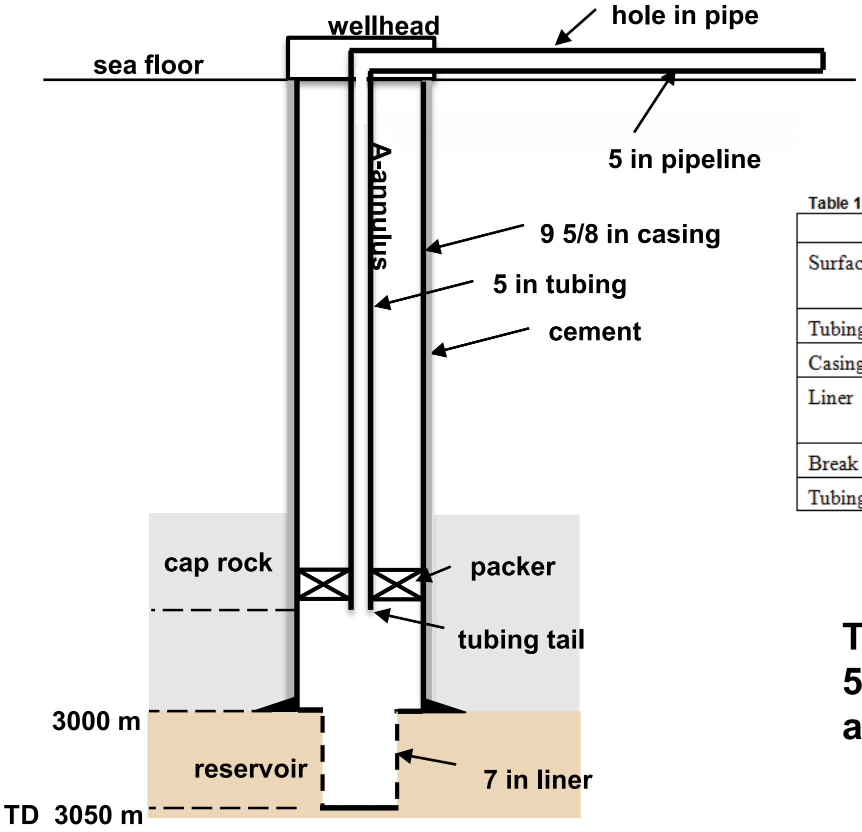
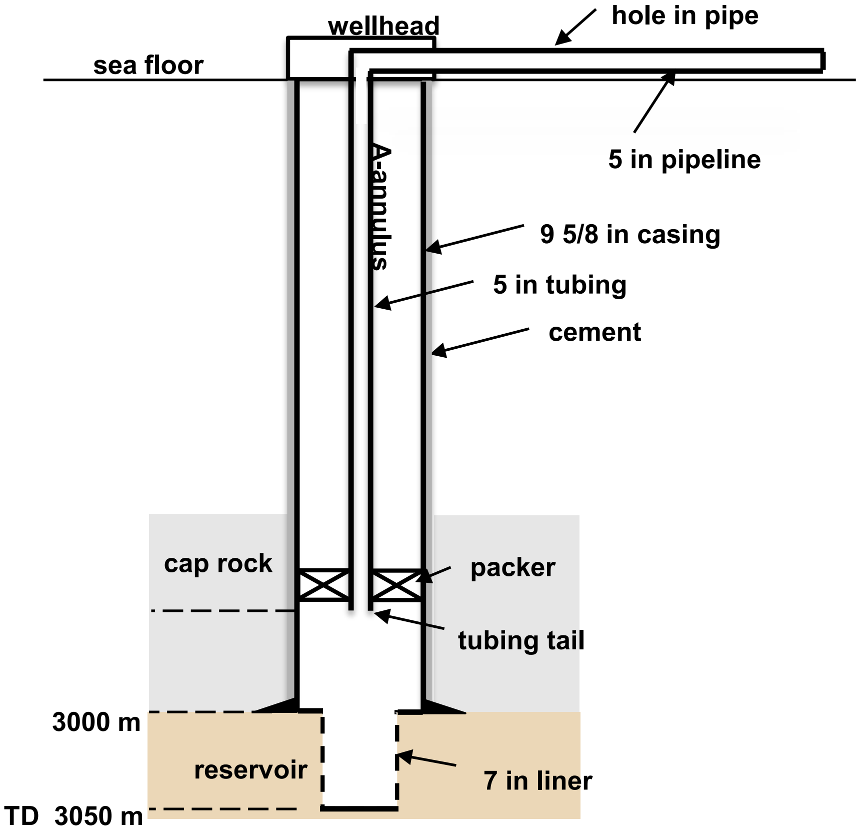


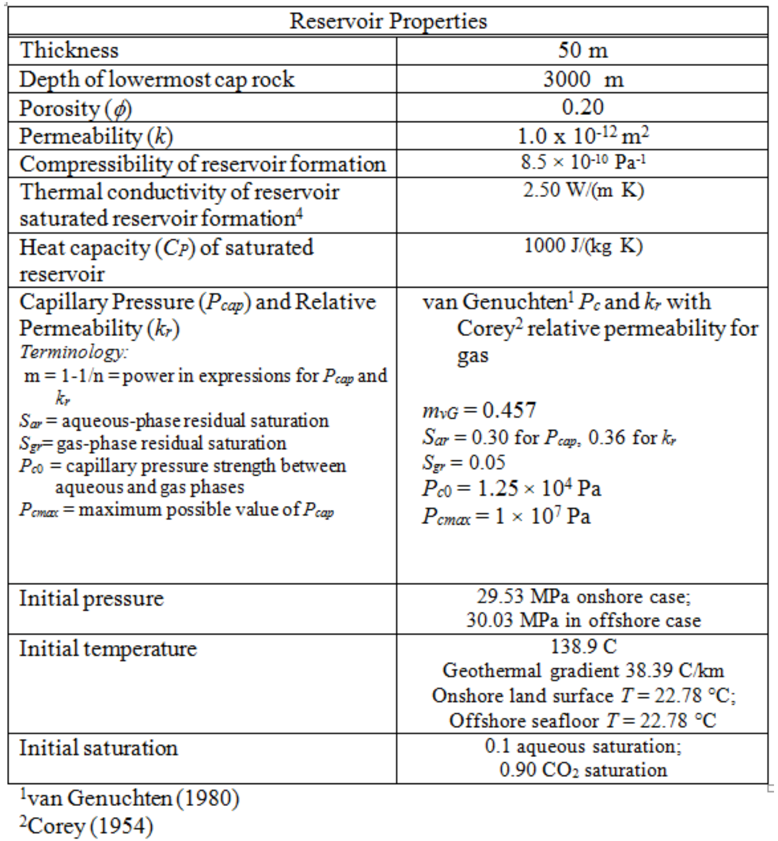
Table 1.Well component dimensions.

Model element	Value
Surface pipe	ID = 0.10556 m (5 inch tubing), horizontal, with hole located 10 m away from the wellhead
Tubing	ID = 0.10556 m (5 inch tubing), vertical, (0-2900 m)
Casing	ID = 0.2205 m (9 5/8 inch casing, 0 – 3000 m, simulated 2900-3000 m)
Liner	ID = 0.15037 (7 inch liner, 3000-3050 m from surface or seafloor, perforated)
Break in pipe (hole in pipe)	Effective ID = 0.0508 m (2 in) (10 m away from the center of well)
Tubing and pipeline wall roughness	45.72×10^{-6} m

The only difference in the two cases is that the 50 m water column causes additional pressure at the hole relative to the 10 m case.

The well is coupled to the reservoir in T2Well





Reservoir Properties	
Thickness	50 m
Depth of lowermost cap rock	3000 m
Porosity (ϕ)	0.20
Permeability (k)	1.0 x 10^{-12} m^2
Compressibility of reservoir formation	8.5 × 10^{-10} Pa^{-1}
Thermal conductivity of reservoir saturated reservoir formation[4]	2.50 W/(m K)
Heat capacity (C_P) of saturated reservoir	1000 J/(kg K)
Capillary Pressure (P_{cap}) and Relative Permeability (k_r) *Terminology:* m = 1-1/n = power in expressions for P_{cap} and k_r S_{ar} = aqueous-phase residual saturation S_{gr}= gas-phase residual saturation P_{c0} = capillary pressure strength between aqueous and gas phases P_{cmax} = maximum possible value of P_{cap}	van Genuchten[1] P_c and k_r with Corey[2] relative permeability for gas $m_{vG} = 0.457$ S_{ar} = 0.30 for P_{cap}, 0.36 for k_r S_{gr} = 0.05 $P_{c0} = 1.25 \times 10^4$ Pa $P_{cmax} = 1 \times 10^7$ Pa
Initial pressure	29.53 MPa onshore case; 30.03 MPa in offshore case
Initial temperature	138.9 C Geothermal gradient 38.39 C/km Onshore land surface T = 22.78 °C; Offshore seafloor T = 22.78 °C
Initial saturation	0.1 aqueous saturation; 0.90 CO_2 saturation

[1] van Genuchten (1980)

[2] Corey (1954)