



Semi-Analytical Modelling of the CO₂ Pilot Injection Test in the Leman Field, a depleted SNS gas field

Tim Whittle

Independent Consultant



***Project Poseidon Partners:**

Perenco CCS Subsurface Team:

Wei Cher Feng, Maruro Okamoto, Marta Puig Alenyà

Carbon
Catalyst

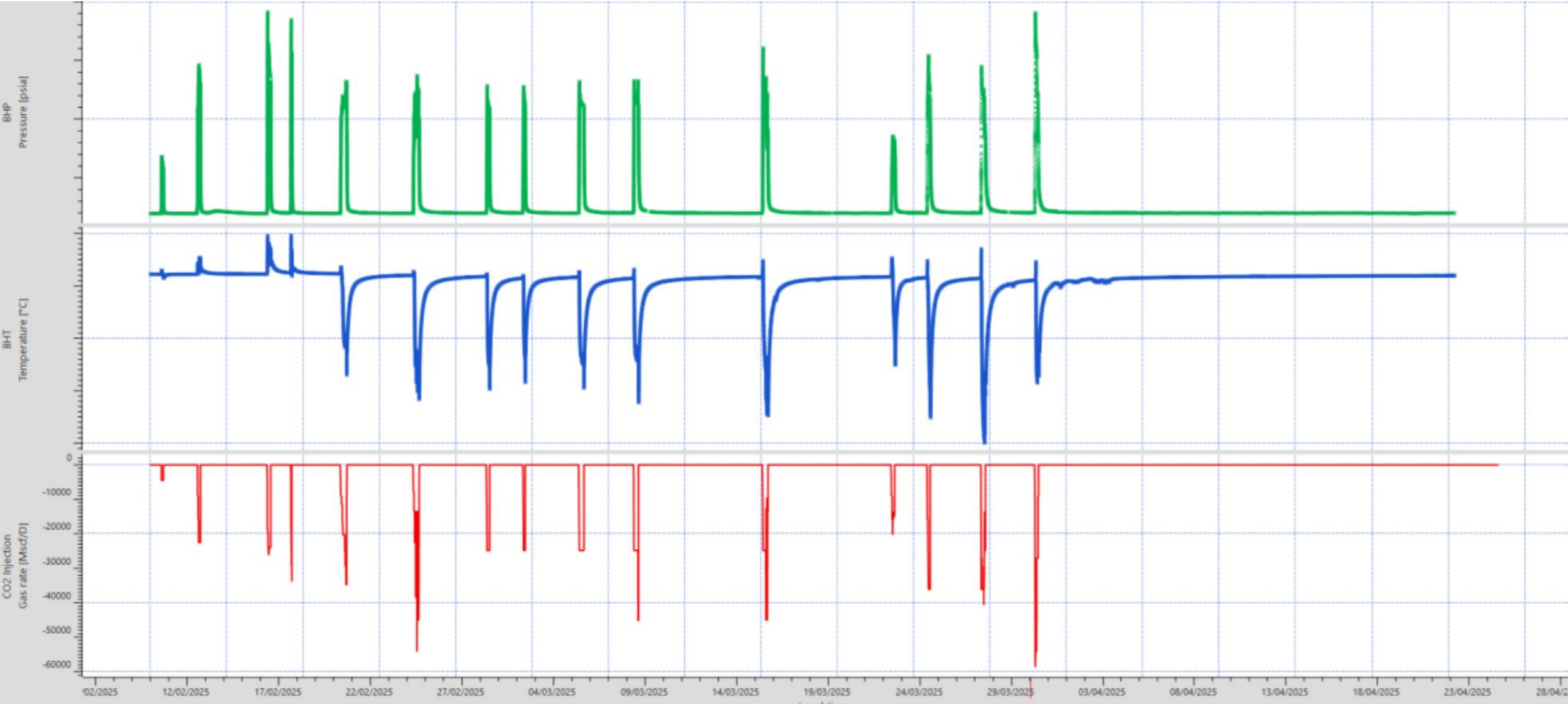
 Harbour
Energy

Outline

- CO₂ Injection Test 2025
- Semi-Analytical Modelling
- Predictions
- Conclusions

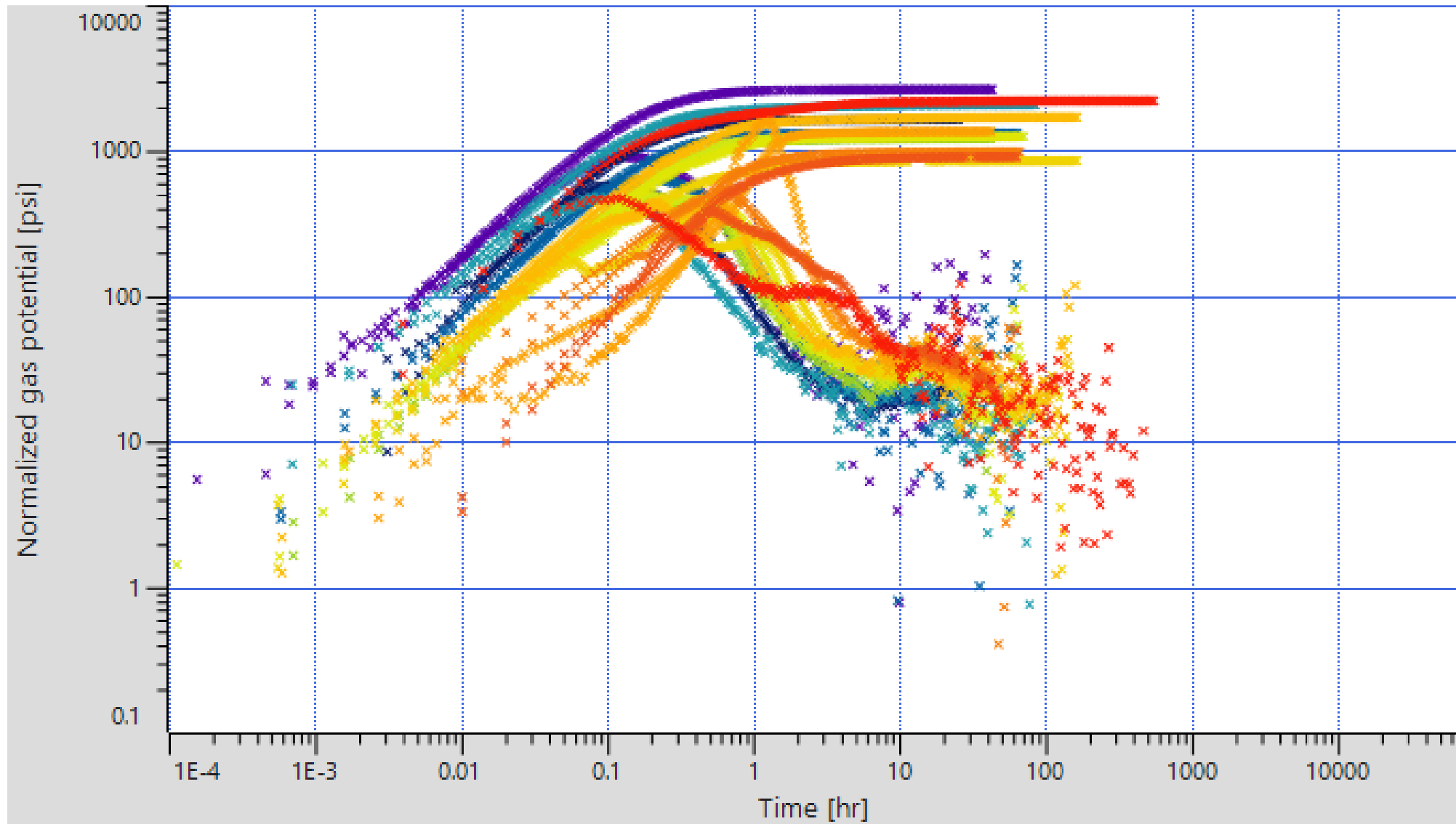
CO₂ Injection Test 2025: Overview

Injection rates varied between 4.5 Mscf/d and 58.7 MMscf/d for a minimum of 1 and a maximum of 9 hours duration. The falloffs lasted between 25 and 600 hrs. Bottom hole temperatures measured at the gauge varied between a maximum of 60 and a minimum of 20 degrees Centigrade.



CO₂ Injection Test 2025: Relatively Consistent KH

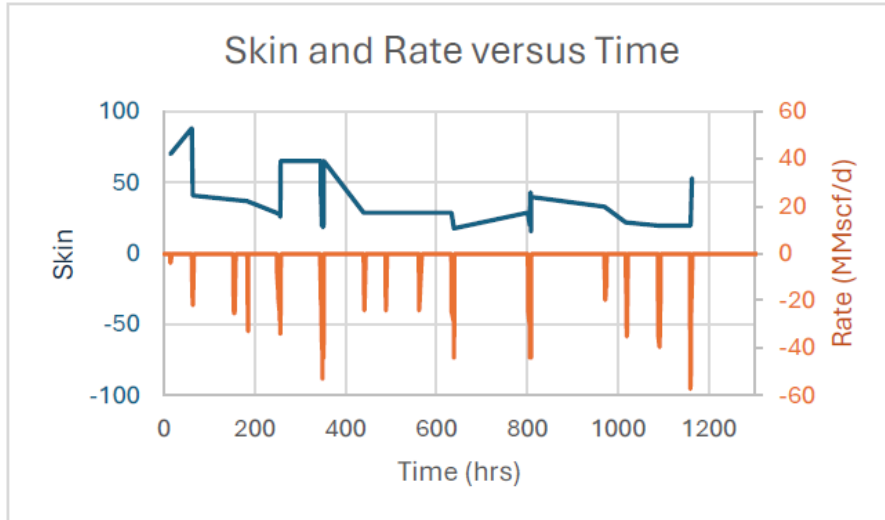
Rate normalized log-log Plot of Pressure Change and Derivative for all fall offs shows relatively consistent kh and variable injectivity (high and changing skin)



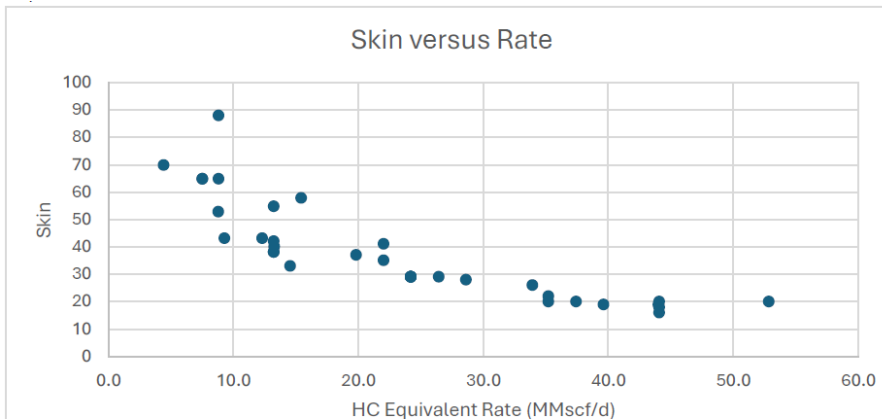
CO₂ Injection Test 2025: Variable Skin?

Injectivity is changing during the test which can be modelled with a variable skin model.

The skin varied between +16 and +88



Inverse skin versus rate correlation...



Observations so far:

- KH remains reasonably consistent
- Skin appears highly variable
- Injectivity improves with rate
- Conventional interpretation becomes problematic

Behaviour suggests dynamic near-well effects rather than reservoir-scale permeability variation?

The key question became whether evolving CO₂ thermophysical properties and thermal effects could produce the observed injectivity response?

→ Semi-Analytical Model as a solution?

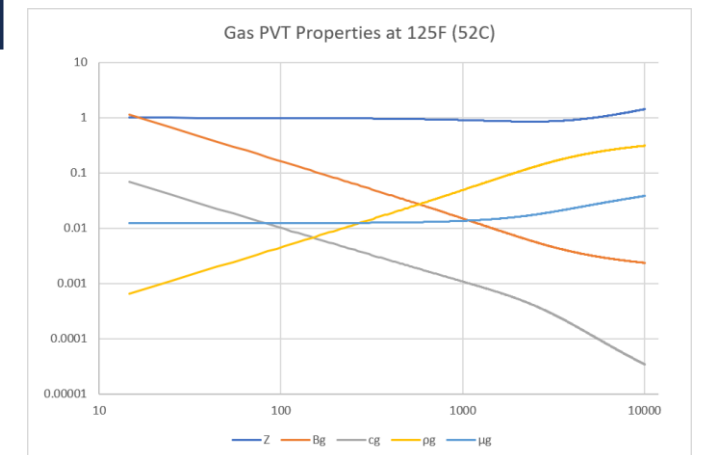
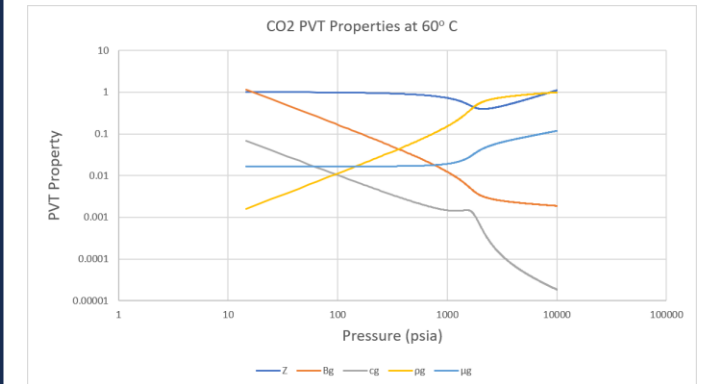
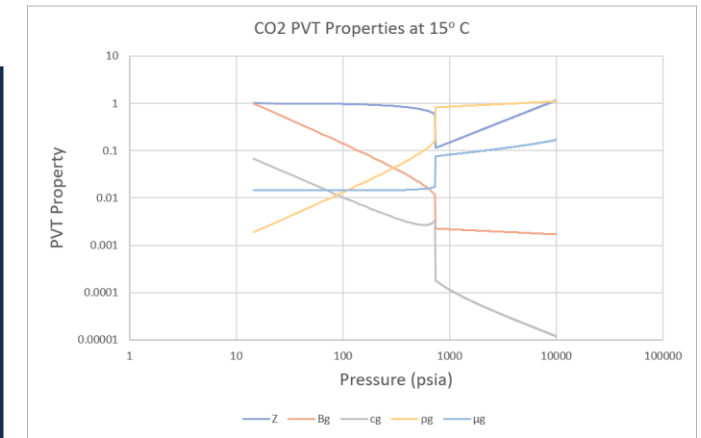
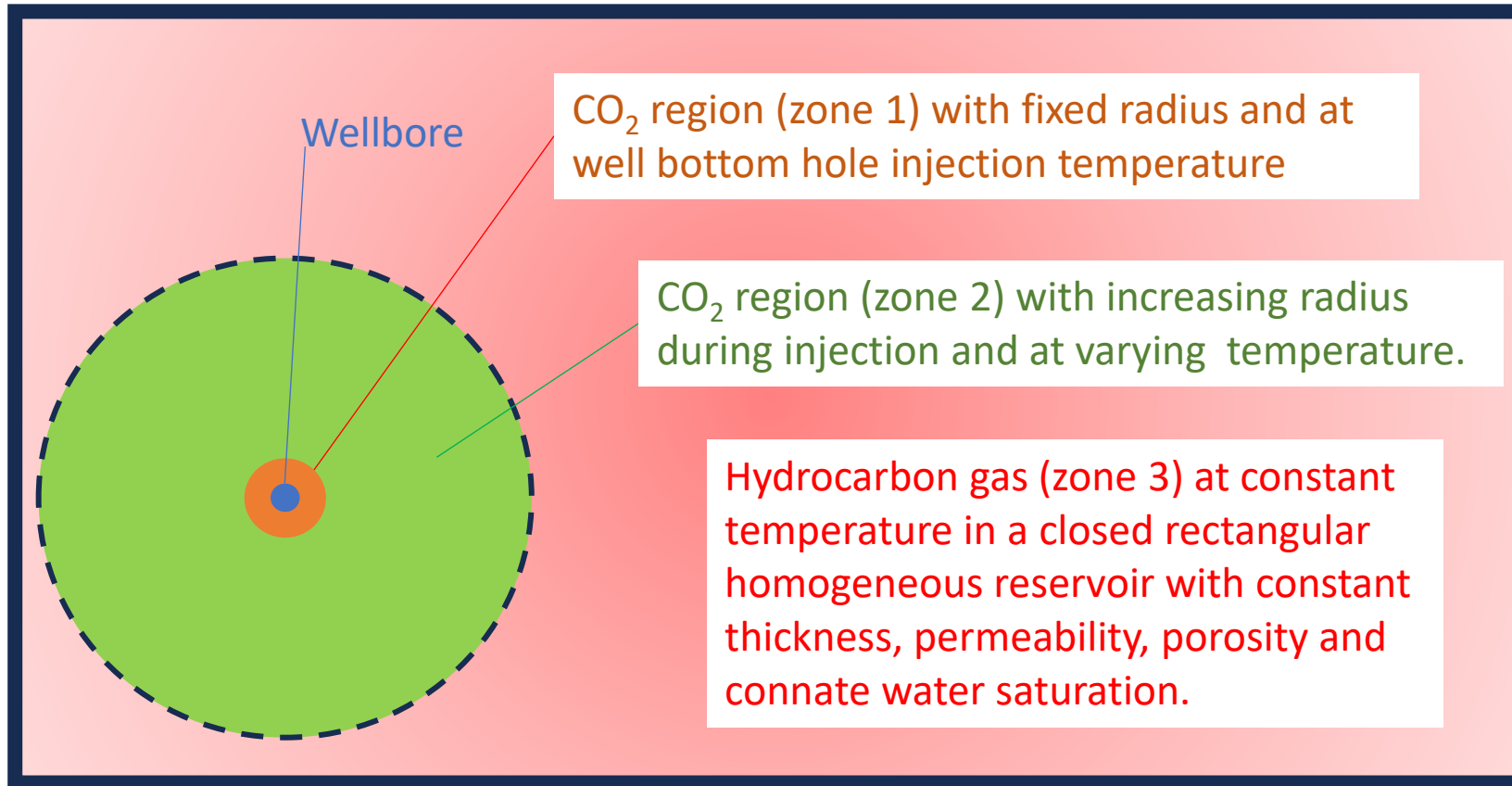
Analytical model

- Constant skin
- Misses observed behaviour

Semi-analytical model

- Captures pressure evolution
- Captures thermal effects
- Reduces need for arbitrary skin changes

Semi-Analytical Model: Three Zone Radial Composite Model Physical Concept



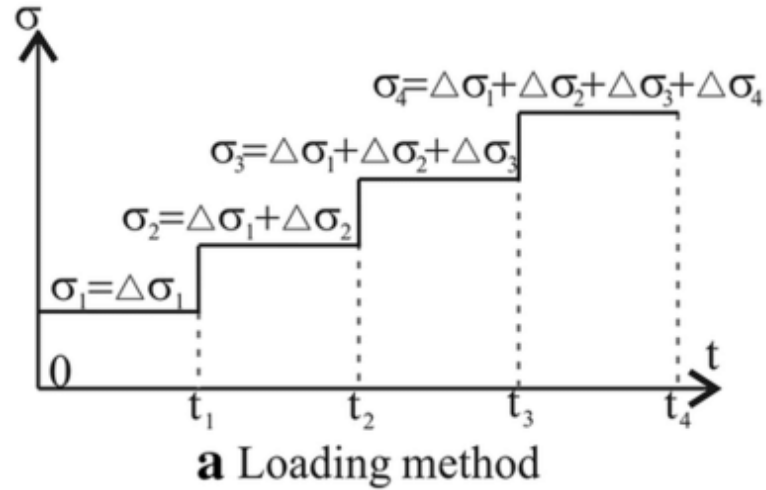
Physical Concept:

- Temperature-dependent CO₂ PVT properties
- Expanding invasion radius
- Material balance preservation
- Reservoir boundaries
- Transient pressure response

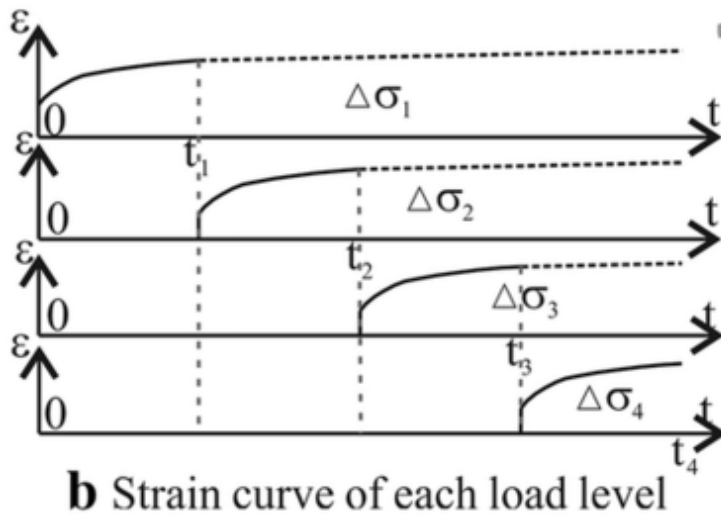
Semi-Analytical Model: Three Zone Radial Composite Model Mathematical Concept

Principle of superposition

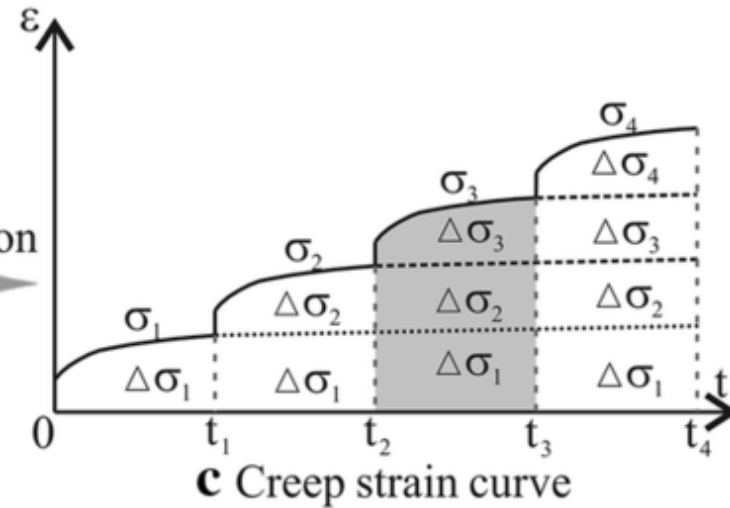
“Rate”



“Pressure”



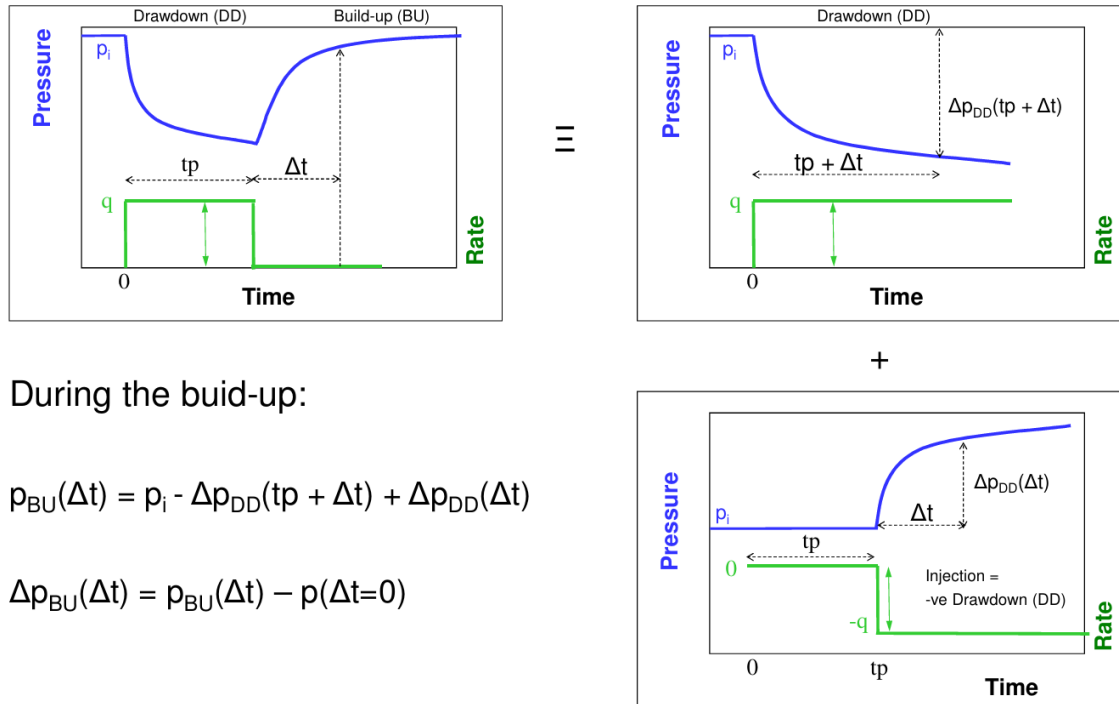
Superposition



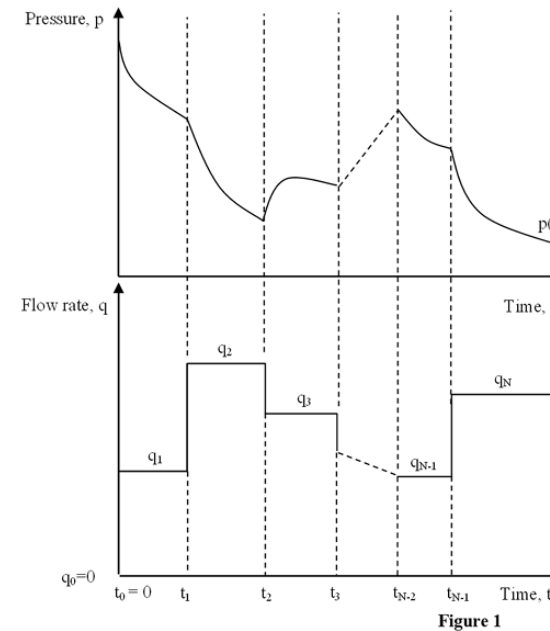
“Pressure”

Semi-Analytical Model: Three Zone Radial Composite Model Mathematical Concept

Superposition in Time For a single flow and shut-in



Superposition in Time: Multi-rate



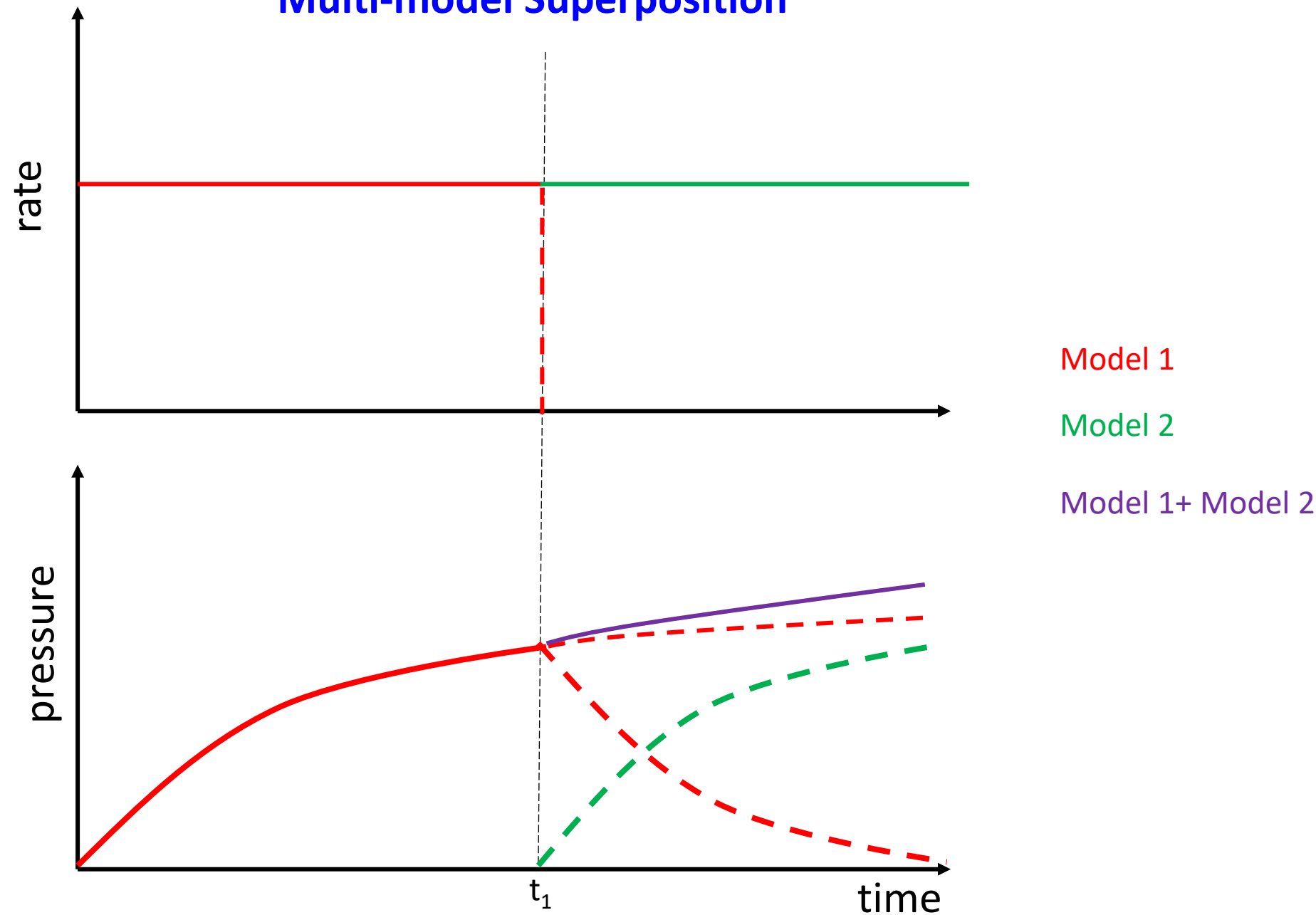
$$p(t) = p_i - \sum_{i=1}^N \Delta p_{DD}[(q_i - q_{i-1}), (t - t_{i-1})]$$

Which can be re-written in the following equation where $p_D(t_D)$ is the constant rate dimensionless pressure response at dimensionless time, t_D .

$$p(t) = p_i - \frac{B\mu}{a_1 kh} \left\{ \sum_{i=1}^N (q_i - q_{i-1}) p_D([t - t_{i-1}]_D) \right\}$$

Semi-Analytical Model: Three Zone Radial Composite Model Mathematical Concept

Multi-model Superposition



Semi-Analytical Model in a Nutshell

Calculate PVT



Update mobility



Update diffusivity



Compute analytical solution



Preserve volumes



Superpose next timestep

The semi-analytical model uses the principle of superposition in time to simulate a changing model versus time (SPE-209628, 2022). It does this by simultaneously simulating the shut-in of the previous model with the flowing of the next model.

The model is a well in a three-zone radial composite reservoir bounded on four sides with either no-flow, constant pressure or infinite boundaries.

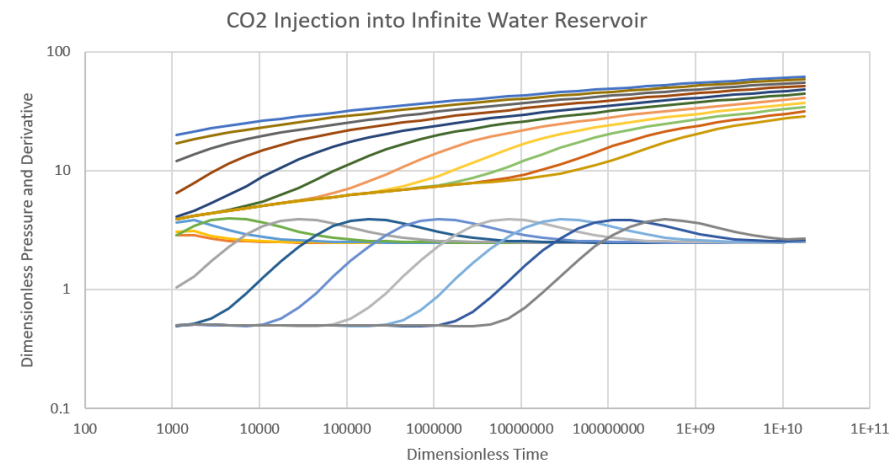
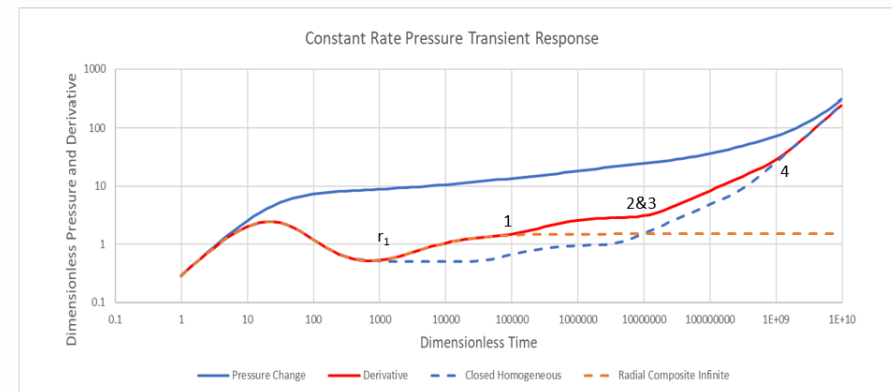
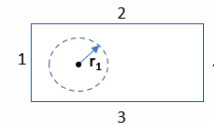
- The inner two radial zones contain the injected CO_2 , and the outer radius of the second zone expands with time as injection proceeds.
- The radius of the first inner zone remains fixed and is assumed to be at the same temperature as the injected CO_2 .
- Beyond this radius, the temperature is assumed to be some average of the temperature in the reservoir and the temperature at the well.
- The third zone contains the reservoir hydrocarbon fluid at a constant average reservoir temperature.

At each time step, the model calculates the PVT properties of each zone according to its temperature and pressure, assigns the mobility and diffusivity accordingly and then calculates analytically the pressure response.

Material balance is preserved and at the end of each time step, the model continues to calculate the pressure response as if the well was shut in. For the next time step, the model is updated with the new properties etc.

Closed Radial Composite Reservoir

- Using Superposition...



Model Validation: Semi-Analytical Model History Match Comparison with Analytical model (constant skin)

Snapshots of the history match removed as per request from client

Analytical model

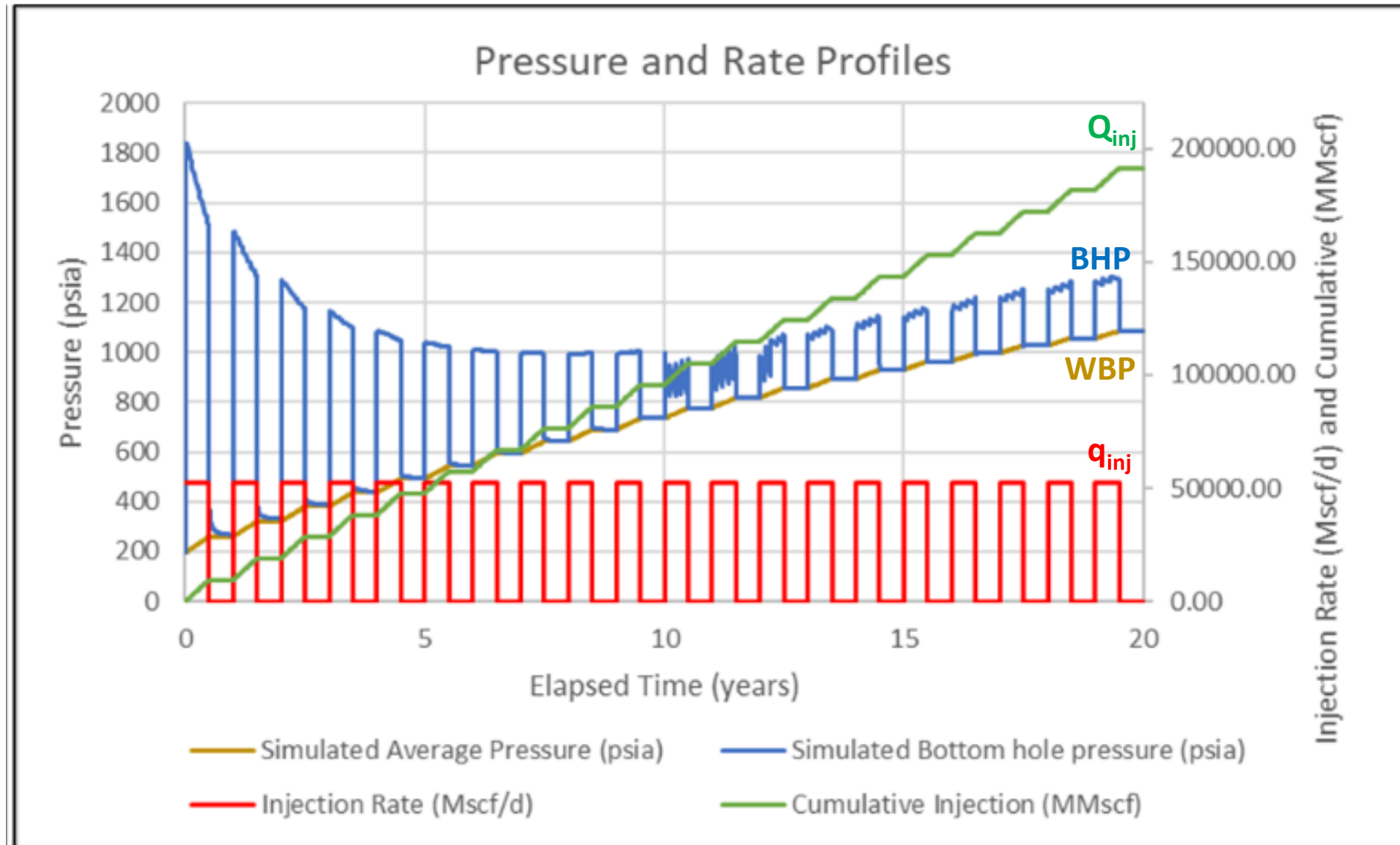
- Constant skin
- Misses observed behaviour

Semi-analytical model

- Captures pressure evolution
- Captures thermal effects
- Reduces need for arbitrary skin changes

Semi-Analytical Model Predictions

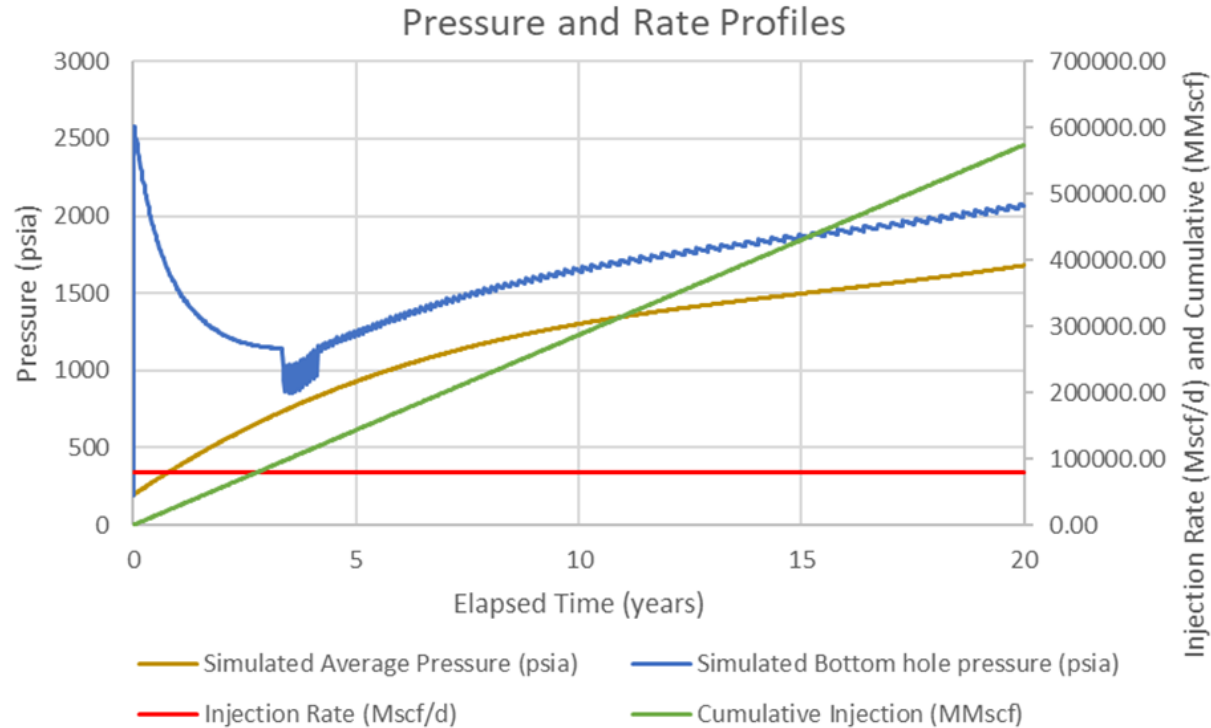
Scenario 1: 1.0 Mtpa (52.4MMscf/D) for 6 months, then shut-in for 6 months. Repeat x 20



Semi-Analytical Model Prediction & Sensitivity

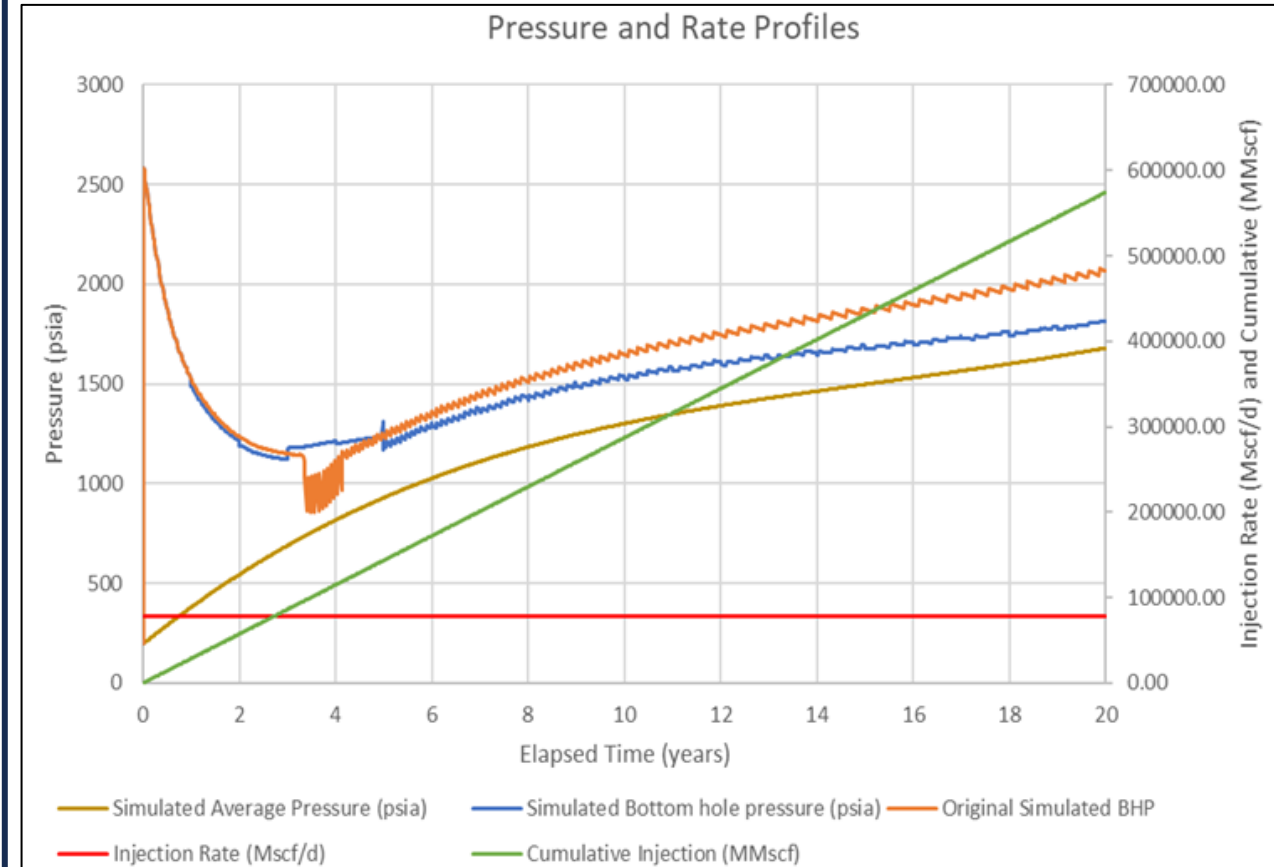
Scenario 2:

1.5Mtpa (78.6MMscf/D) continuously for 20 years



Scenario 2 Sensitivity:

Injection Temperature Increased + Reducing Skin

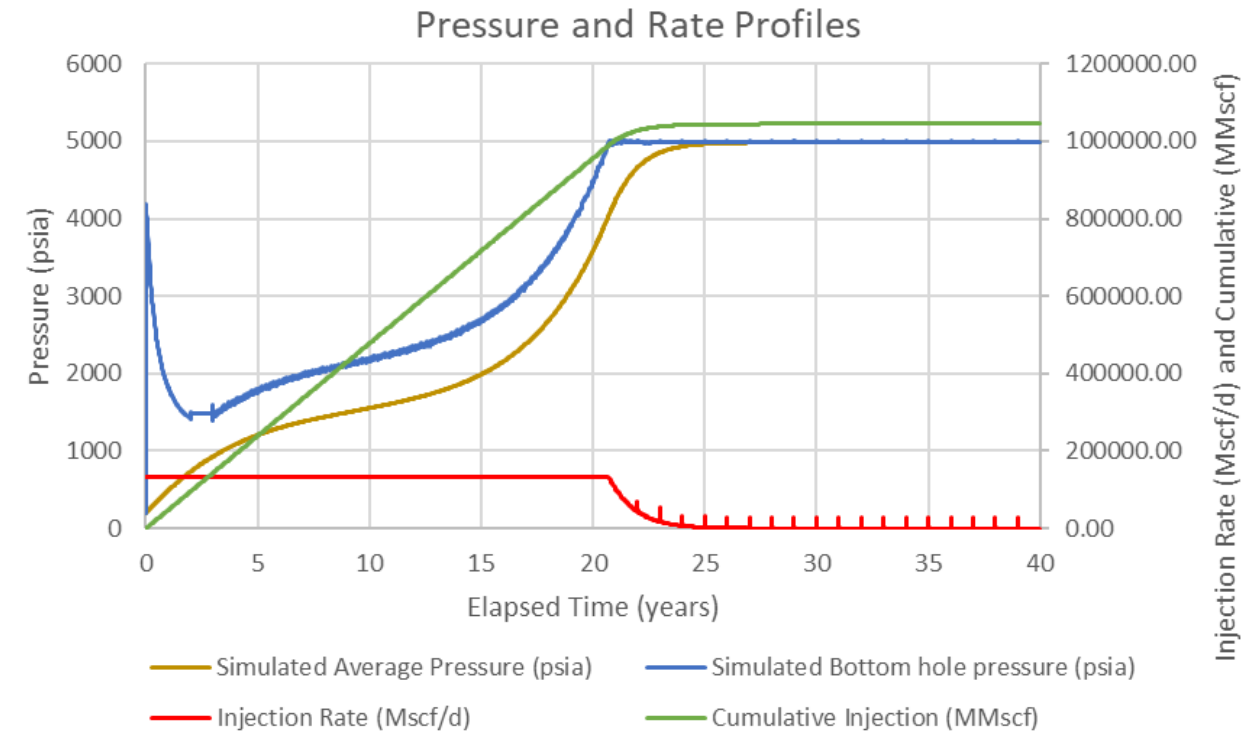


For Scenario 2, an increasing BHT and reducing skin factor over time is modelled. The reducing skin causes a lowering of the injection pressure whilst maintaining the same constant rate.

Semi-Analytical Model Prediction & Sensitivity

Scenario 3:

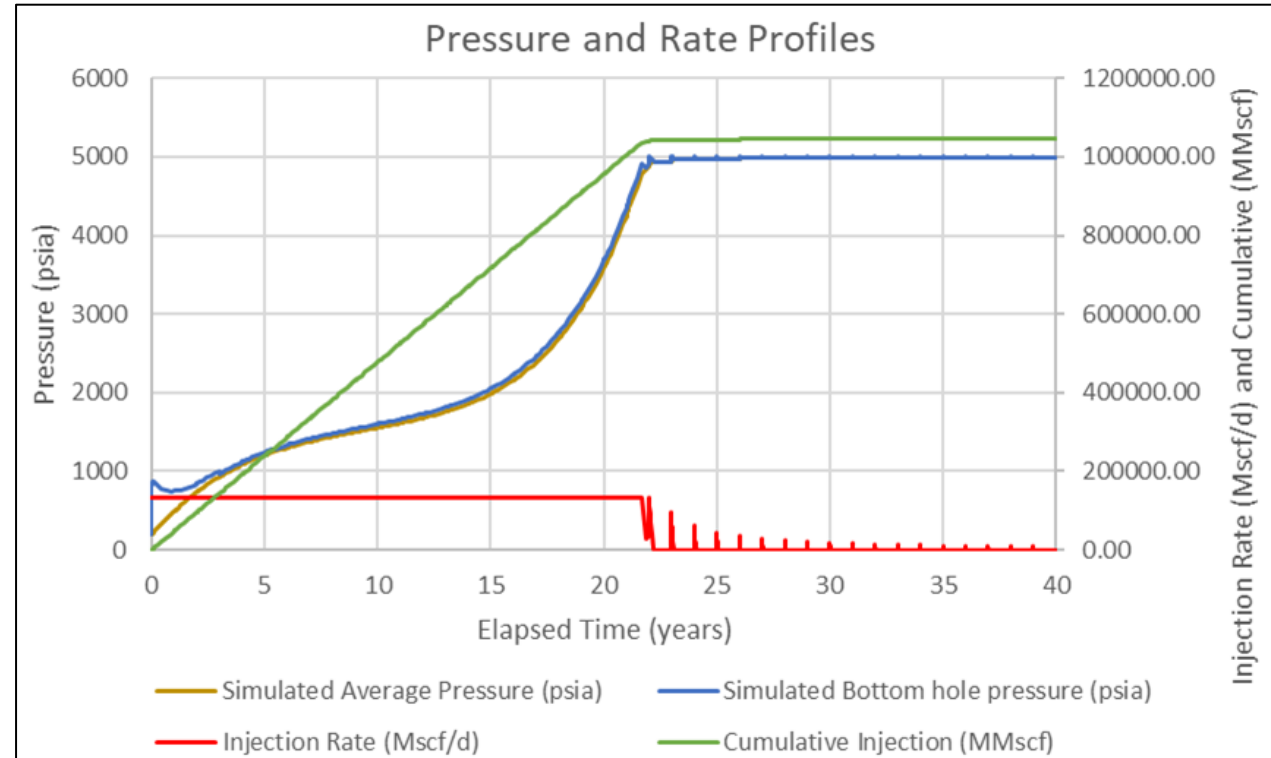
2.5Mtpa (130.9MMscf/D) continuously for 40 years



- Extended 40 years of injection demonstrate rate constraint as the maximum injection pressure (5000psia) is reached
- Injection rates declines quickly to zero consequently

Scenario 2 Sensitivity:

Skin reduced to zero



- Zero skin damage vs previous case which assumed high skin (+54)
- Injection pressure is lower & rate remains on plateau for additional year before reaching maximum injection pressure
- Apart from reduction in pressure which may reduce the facility power consumption, the impact of reducing skin is not significant.

Conclusions

- The CO₂ pilot exhibited lower injectivity than expected from historical gas deliverability
- Pressure-transient analysis indicates relatively stable KH but highly variable apparent skin
- A temperature-dependent semi-analytical radial-composite model reproduces the observed behaviour and matches numerical simulation
- The semi-analytical model in a simple to use spreadsheet application provides a rapid screening tool for CCS injection design and operational optimisation