

Creating a Simplified Model Using Dimensionless Groups for CO₂ Flooding and Storage in Gulf Coast Reservoirs

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Outline

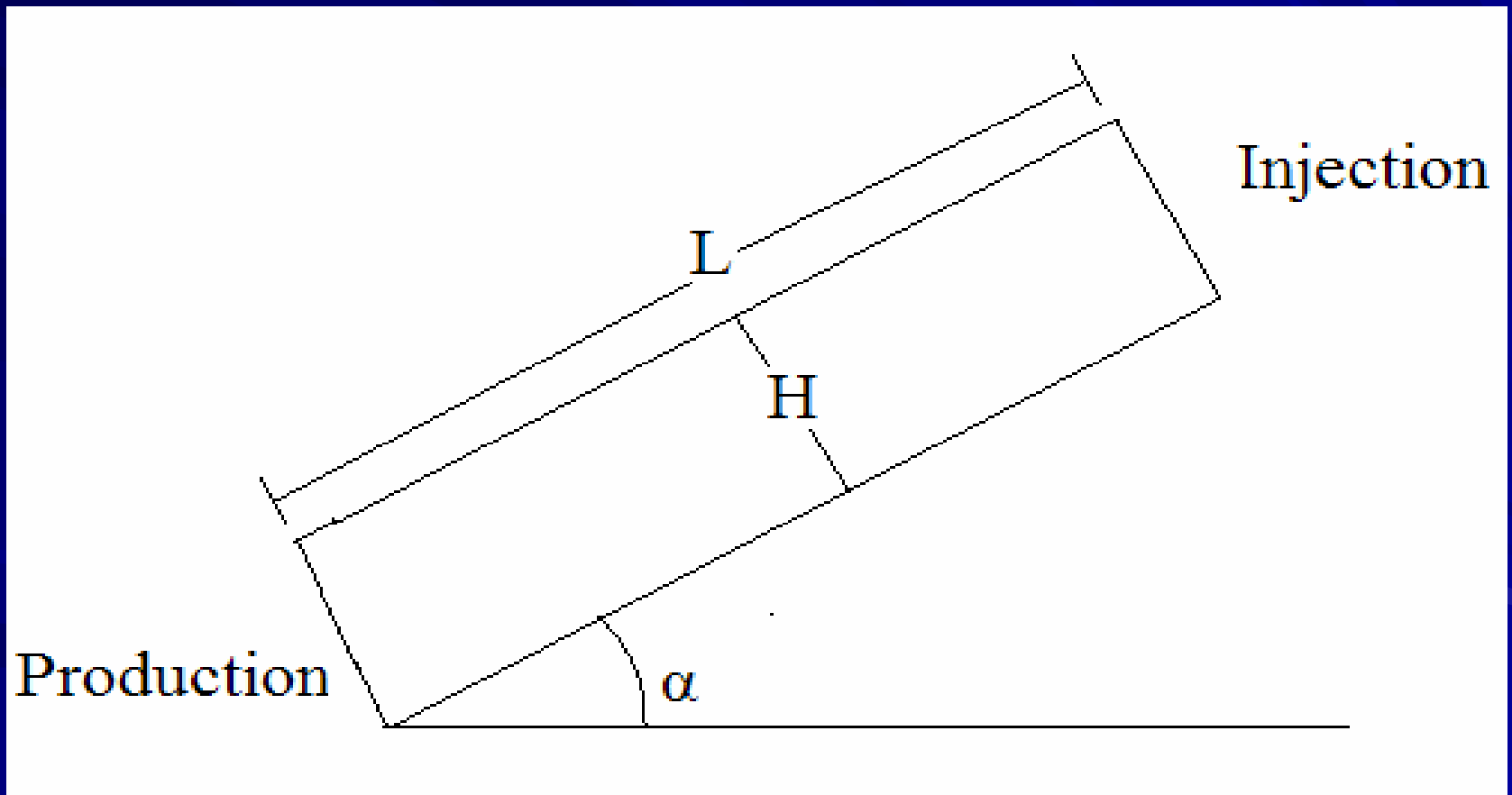
- Background
- Initial approach and results
- New approach and results
- Experimental design and the model

Background - Models

- CO₂ Prophet – too simple
- CO₂ Predictive Model – too complex
- KinderMorgan Spreadsheet – too rigid
- Dimensionless group scaling – just right

Background - Reservoir

GEM Simulator – 2D model



Background - Scaling

■ Scaling

- Geometrically and petrophysically similar reservoirs should behave similarly
- Uses dimensionless groups to compare different reservoirs

■ Commonly think of dimensionful properties

- Permeability (mD), length (ft), etc

■ Dimensionless groups strategically combine properties so that units cancel

- i.e. L/H (ft/ft = dimensionless)

Background - Scaling

- Dimensionless groups allow comparison
 - Reservoirs with equal group values should behave similarly
- Two different reservoirs
 - 1. Length = 1000 ft
Height = 100 ft
 - 2. Length = 2000 ft
Height = 200 ft
- $L/H = 10$ in both cases

Background – Scaling

- Must determine minimum number of groups needed to describe the problem
 - Use dimensional analysis as initial basis for group generation
 - Use experience/intuition to postulate other groups
 - Eliminate unnecessary and statistically insignificant groups

Initial Approach and Results

- Dimensional analysis (Shook et al.)
 - Water flood case
 - Use basic petroleum equations
 - Normalize into dimensionless equations
 - Extract groups
- Used groups from water flood case
 - Aspect ratio (R_L), dip angle group (N_α), mobility ratios (M^o), buoyancy number (N_g), capillary number (N_{Pc})

Initial Groups

- Aspect ratio (R_L) – measures vertical communication/mixing of fluids
- Dip angle group (N_α) – purely geometric, affects CO_2 /oil interface angle
- Mobility ratios (M^o) – ratio of viscous forces of CO_2 /water to oil
- Buoyancy number (N_g) – ratio of gravity to viscous forces
- Capillary number (N_{Pc}) – ratio of capillary to viscous forces

Initial Approach and Results

$$R_L = \frac{L}{H} \sqrt{\frac{k_z}{k_x}}$$

$$N_\alpha = \frac{L}{H} \tan \alpha$$

$$M^o = \frac{k_{rw}^o * \mu_o}{k_{ro}^o * \mu_w}$$

$$M^o = \frac{k_{rg}^o * \mu_o}{k_{ro}^o * \mu_g}$$

$$N_g^o = \frac{k_x \lambda_{r2}^o \Delta \rho g \cos \alpha}{u_T} \frac{H}{L}$$

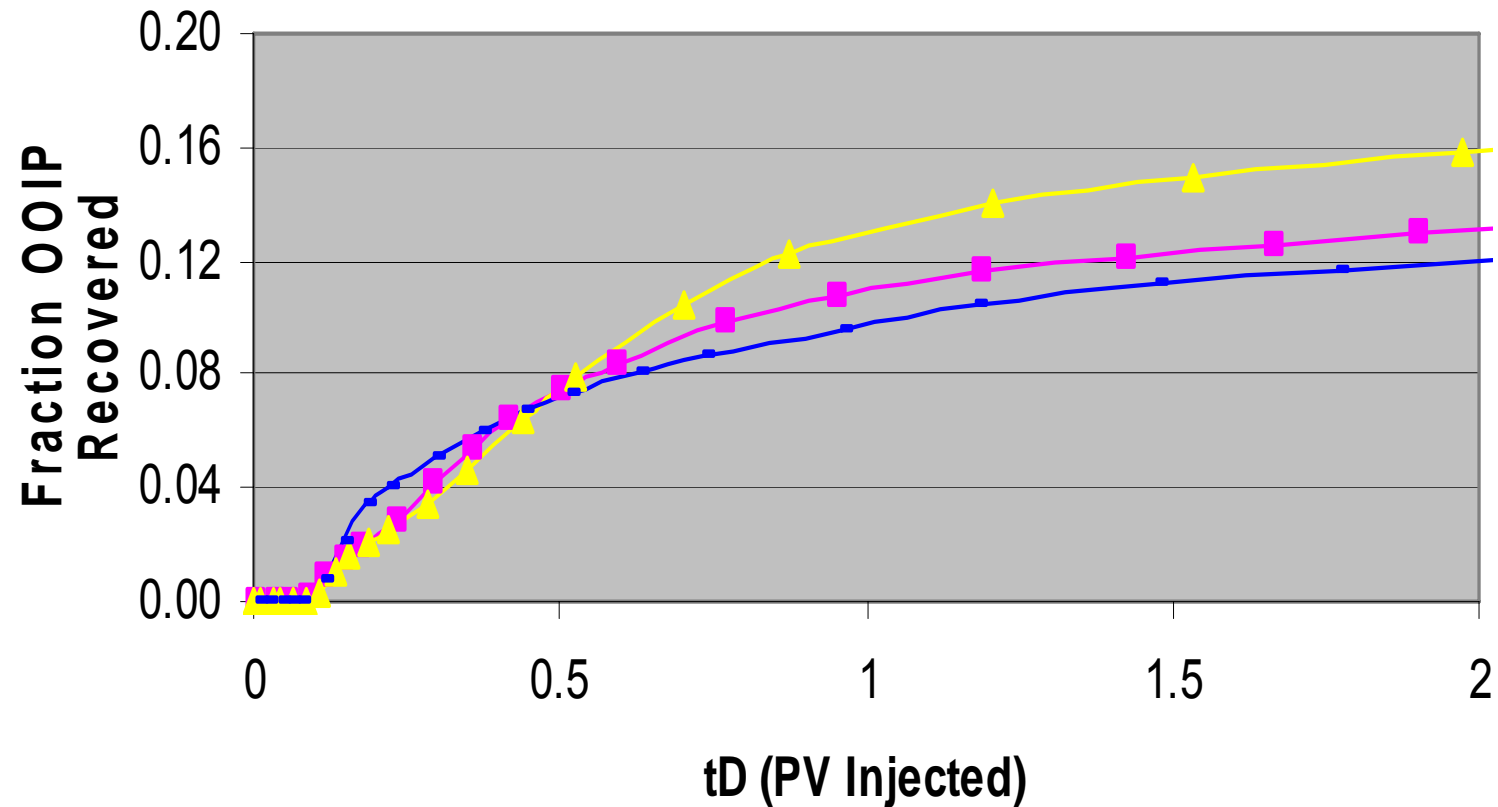
$$N_{P_c} = \frac{\lambda_{r2}^o \sigma}{L u_T} \sqrt{\phi k_x}$$

Dimensionless Time

$$t_D = \frac{qt}{LWH\phi} = \frac{V_{inj}}{V_p}$$

Initial Approach and Results

Results with Initial Groups



New Approach

- Needed new groups to describe problem
- Change from constant injection rate to constant injection and production pressures (P_{inj} and P_p , $\Delta P = P_{inj} - P_p$)
- Dimensional analysis reveals new form of buoyancy number, capillary number discarded

New Groups

$$R_L = \frac{L}{H} \sqrt{\frac{k_z}{k_x}}$$

$$N_\alpha = \frac{L}{H} \tan \alpha$$

$$M^o = \frac{k_{rw}^o * \mu_o}{k_{ro}^o * \mu_w}$$

$$\boxed{M}^o = \frac{k_{rg}^o * \mu_o}{k_{ro}^o * \mu_g}$$

$$N_g^o = \frac{H \Delta \rho g \cos \alpha}{\Delta P}$$

New Approach

- New pressure groups postulated based on the minimum miscibility pressure
 - Minimum miscibility pressure (MMP) is a function of temperature and fluid properties
 - Governs degree of miscibility between CO₂ and oil
- Initial conditions and rock properties contribute final groups

Additional Groups

$$P_{injD} = P_{inj} / MMP \qquad P_{pD} = P_p / MMP$$

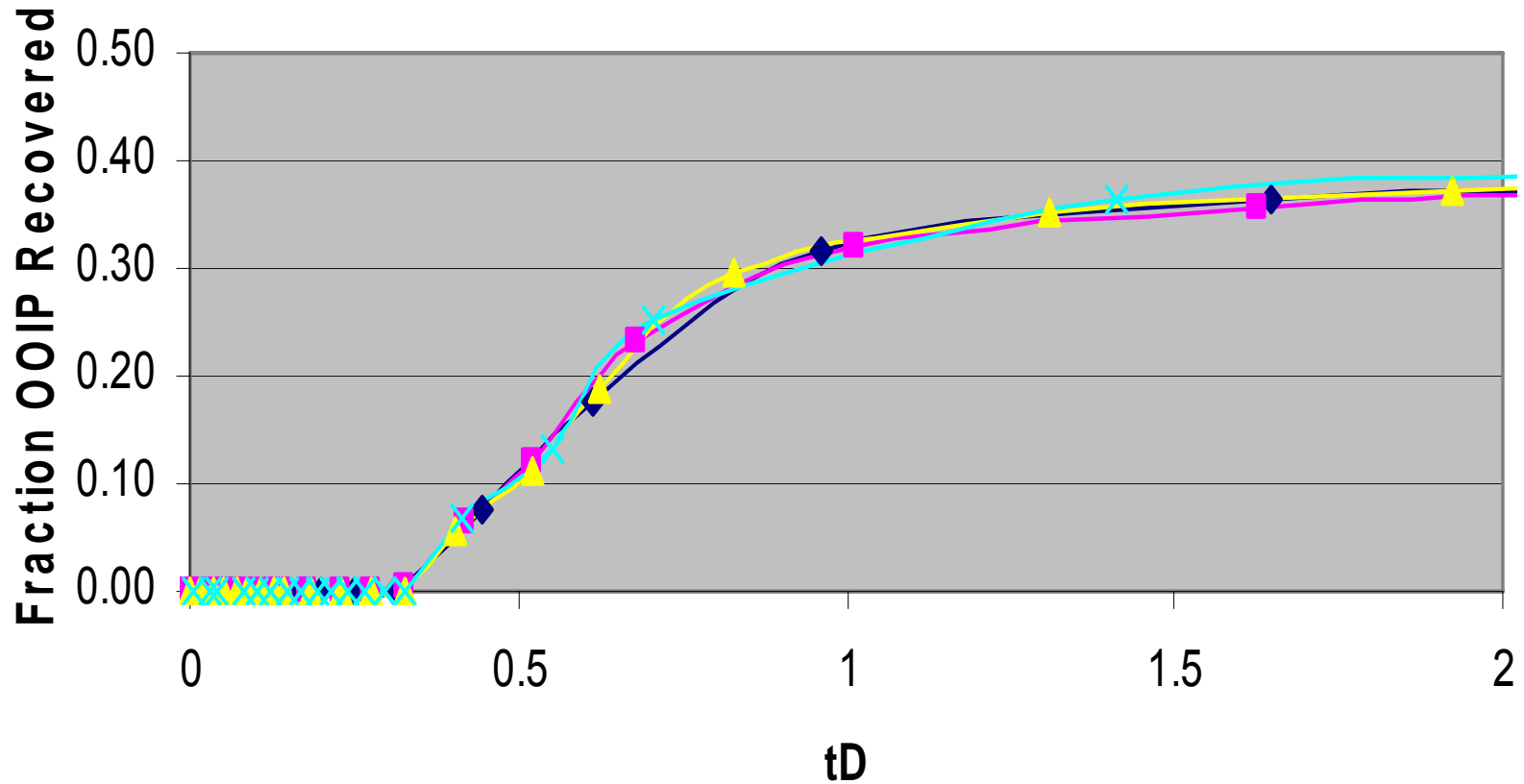
$$S_{oi}$$

$$S_{orw}$$

$$S_{org}$$

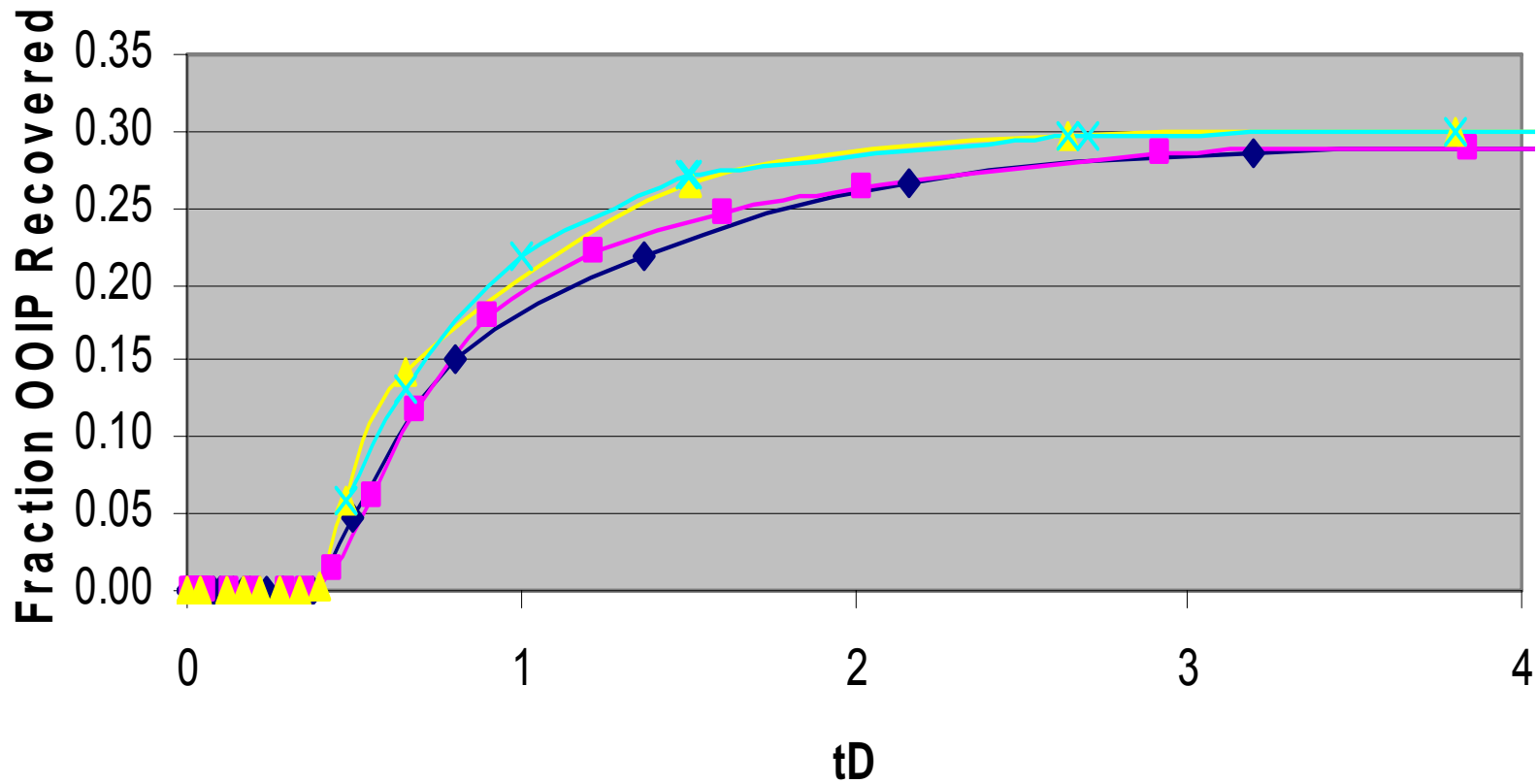
Results – Group Values Set 1

Results with New Groups



Results – Group Values Set 2

Results with New Groups



Experimental Design

- Box-Behnken experimental design
 - Determine high, low and average group values
 - Run GEM simulations at different combinations of group values
 - For 10 factors, 161 GEM simulations required
- Fit oil recovery from each run to exponential equation

Exponential Fit

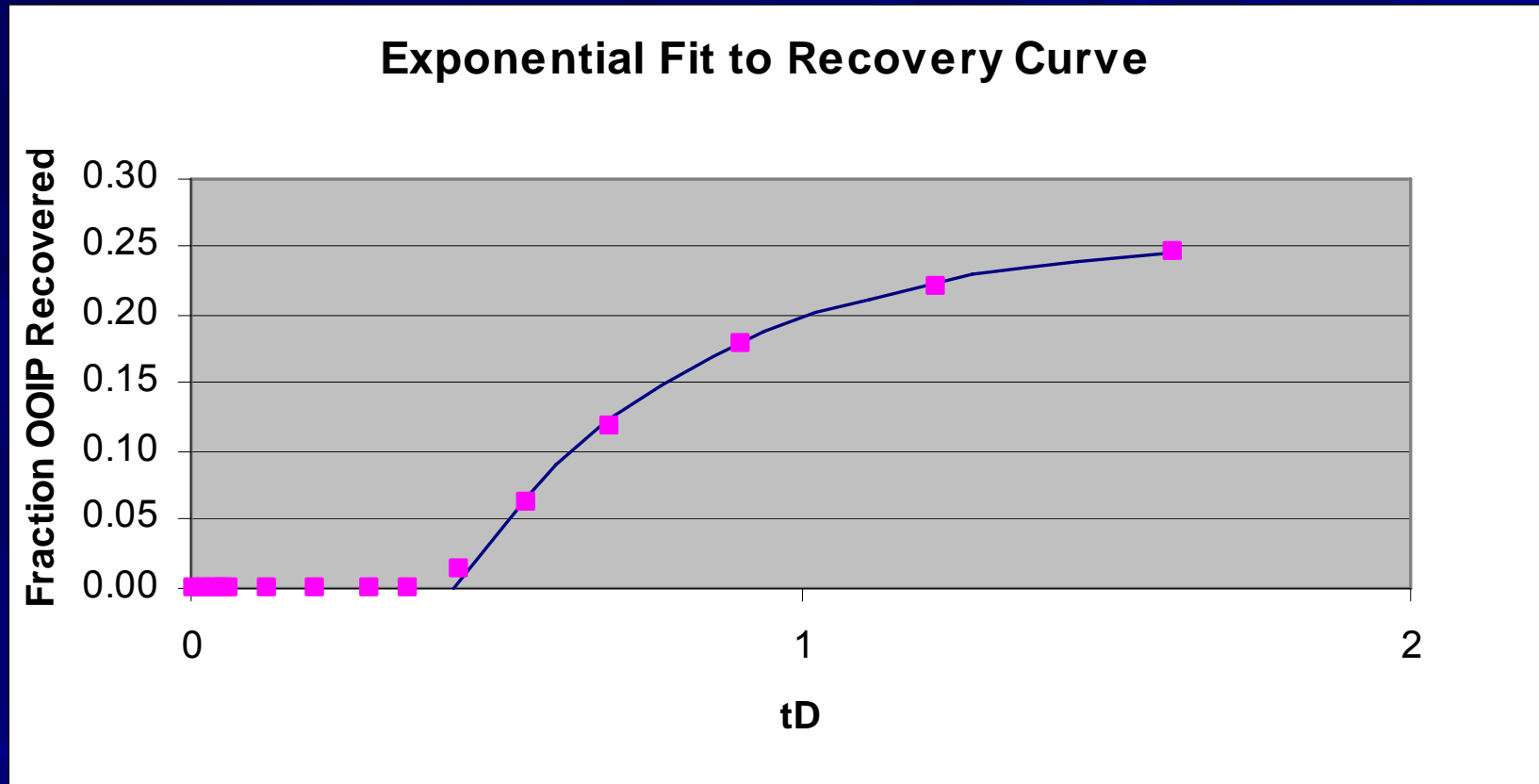
$$(\text{Fraction OOIP}) = A (1 - \text{EXP}(-B (t_D - t_D^o)))$$

t_D^o – breakthrough time for oil recovery

A – ultimate recovery

B – rate of approach to ultimate recovery

Example Exponential Fit



$$t_D^o = 0.43$$

$$A = 0.26$$

$$B = 2.5$$

Response Surface Models

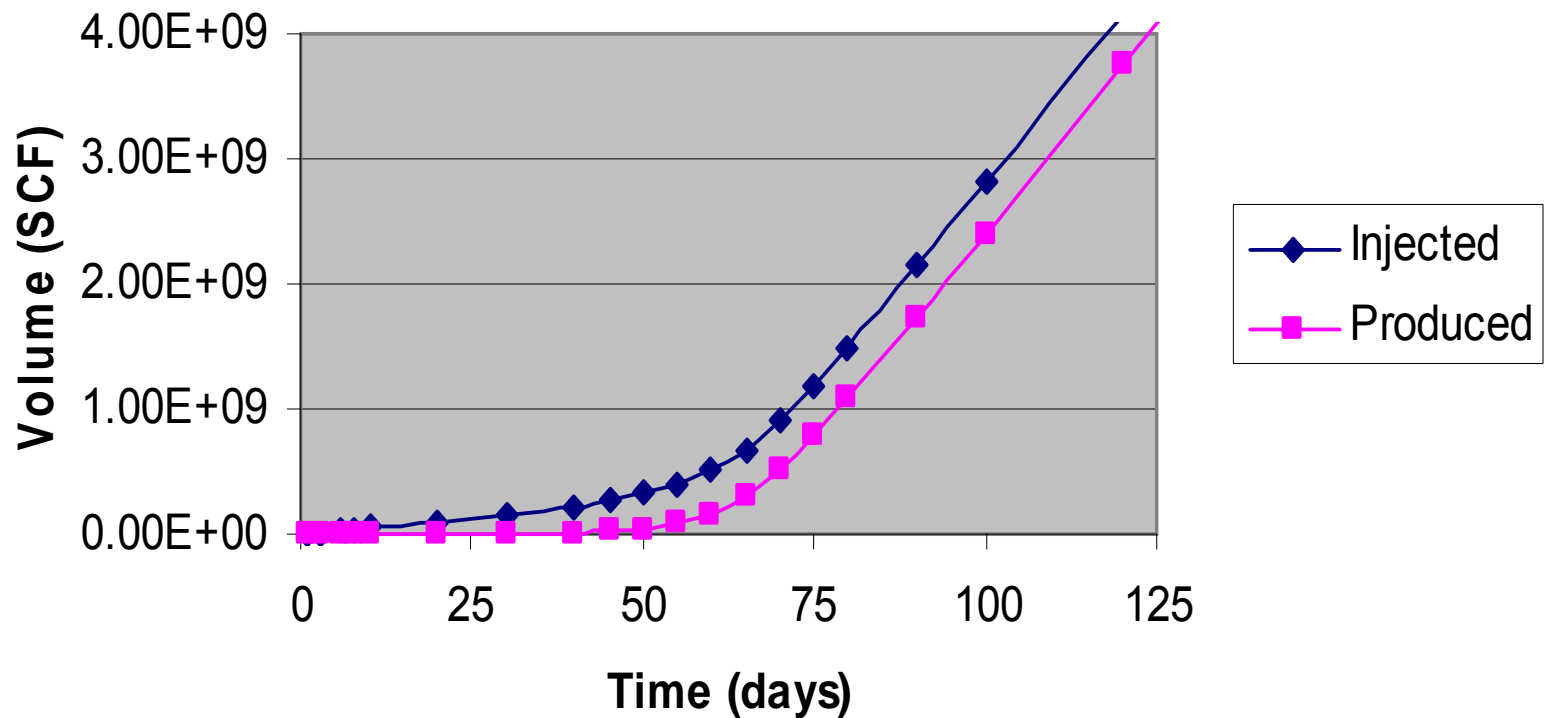
- Must model t_D^0 , A, and B
- Develop 2nd order response surfaces with quadratic, linear, and interaction terms

$$\begin{aligned} \text{Value} = & c_1x_1^2 + c_2x_2^2 + \dots + c_{10}x_{10}^2 + \\ & c_{11}x_1 + c_{12}x_2 + \dots + c_{20}x_{10} + \\ & c_{21}x_1x_2 + c_{22}x_1x_3 + \dots + c_{65}x_9x_{10} \end{aligned}$$

c_i – coefficients x_i - groups

CO₂ Storage

CO₂ Injection and Production



CO₂ Storage

- Time independent after breakthrough - volume injected before breakthrough is volume stored
- 0.3 – 0.4 PV stored in miscible floods
- Economics determined by oil recovery

Application

- Model can be applied to candidate Gulf Coast reservoirs in BEG database
- Potential for use by small and big operators alike to quickly identify best reservoirs

Summary - Accomplishments

- Identified necessary groups to fully describe CO₂ flooding problem
- Identified exponential fit as acceptable model of oil recovery

Summary - Future

- Use Box-Behnken experimental design to fit data to exponential curves
- Apply to candidate reservoirs in BEG database