Creating a Simplified Model Using Dimensionless Groups for CO_2 Flooding and Storage in Gulf Coast Reservoirs

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Derek Wood

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Outline

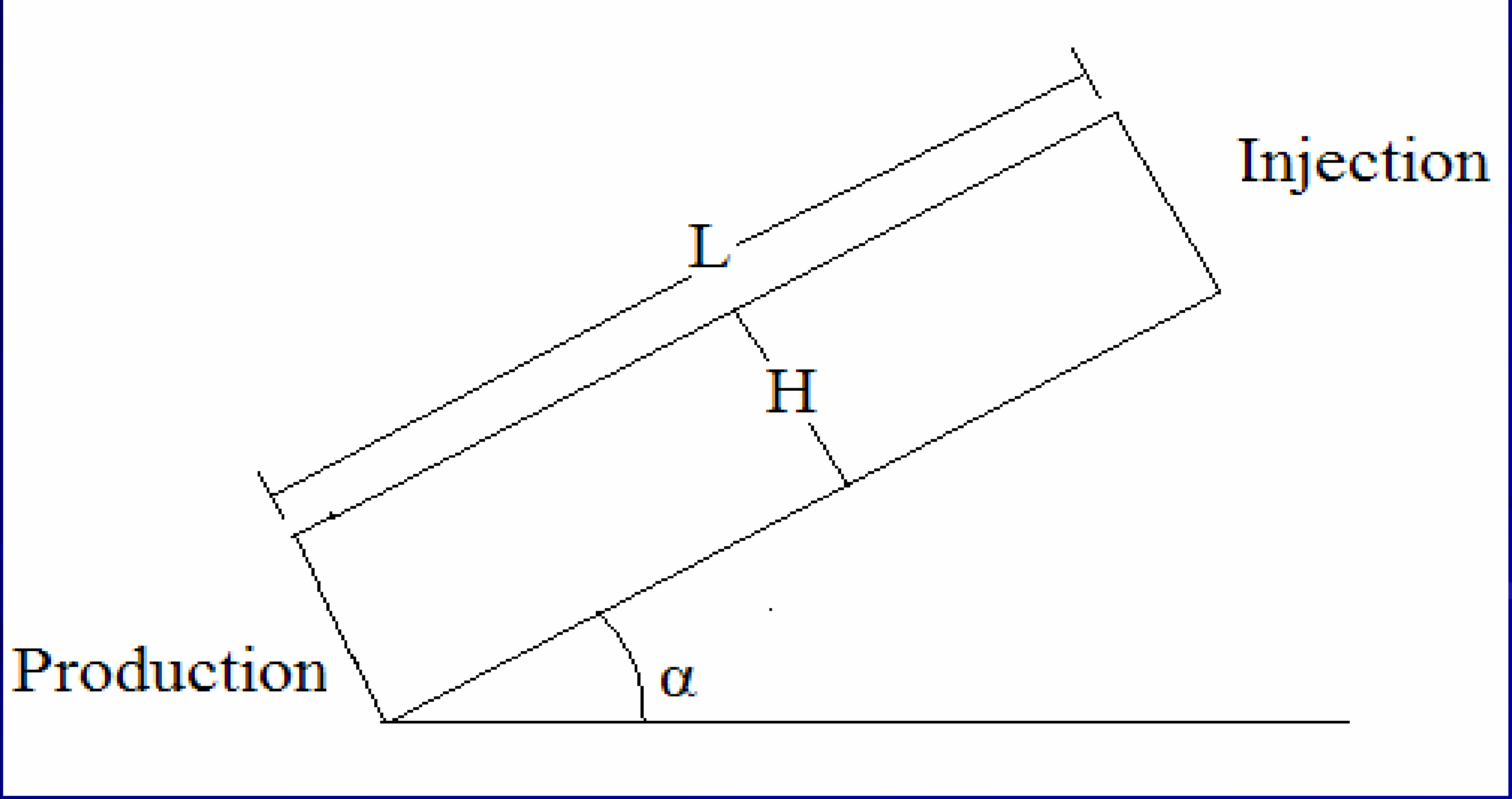
- Background
- Initial approach and results
- New approach and results
- Experimental design and the model

Background - Models

- CO_2 Prophet – too simple
- CO_2 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

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

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

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

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

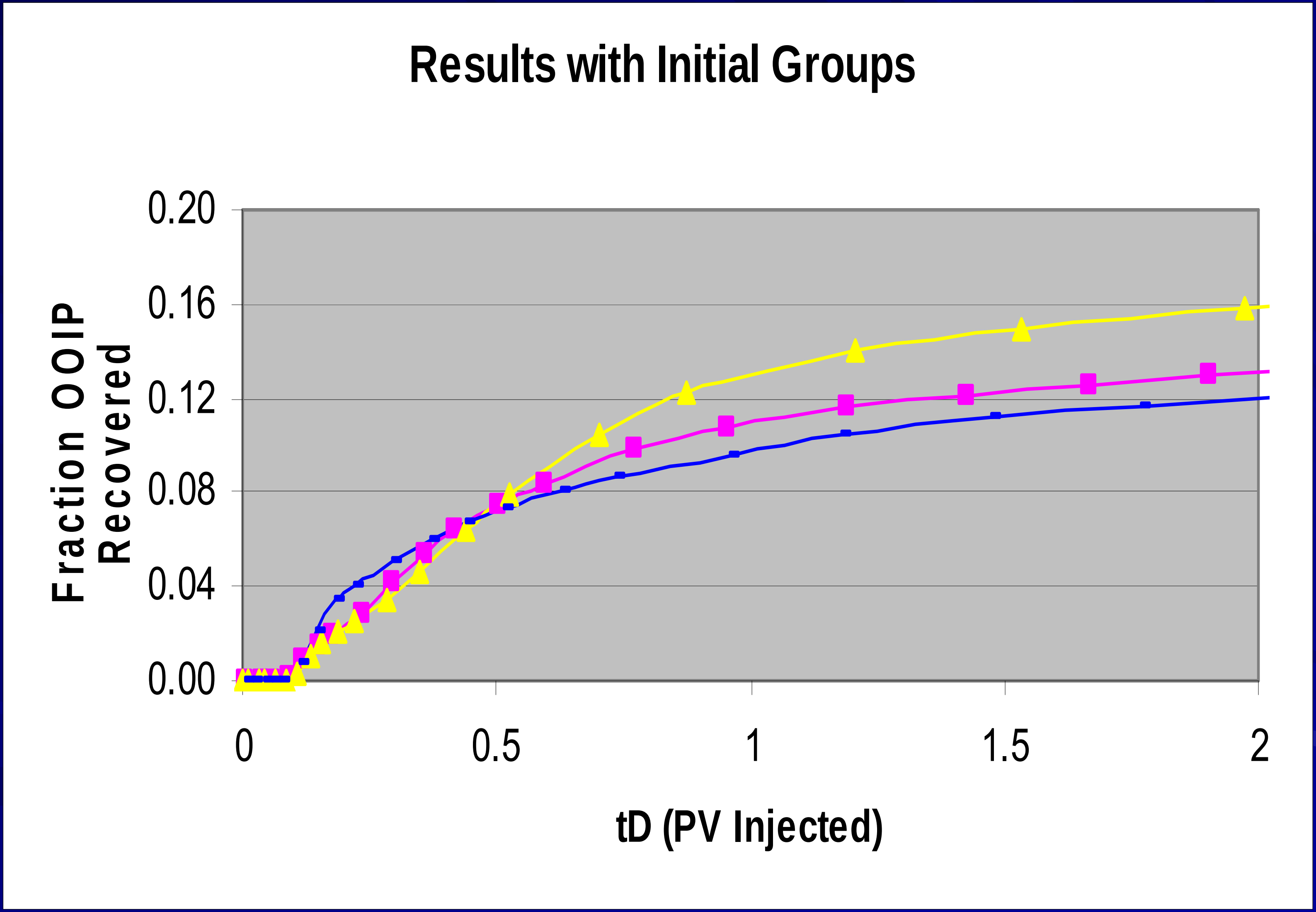
$$N_g^o = \frac{k_x \lambda_{r2}^o \Delta\rho g \cos\alpha}{u_T}\frac{H}{L}$$

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

Dimensionless Time

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

Initial Approach and Results



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

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

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

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

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

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

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 CO_2 and oil
- Initial conditions and rock properties contribute final groups

Additional Groups

$$P_{injD} = P_{inj} / MMP$$

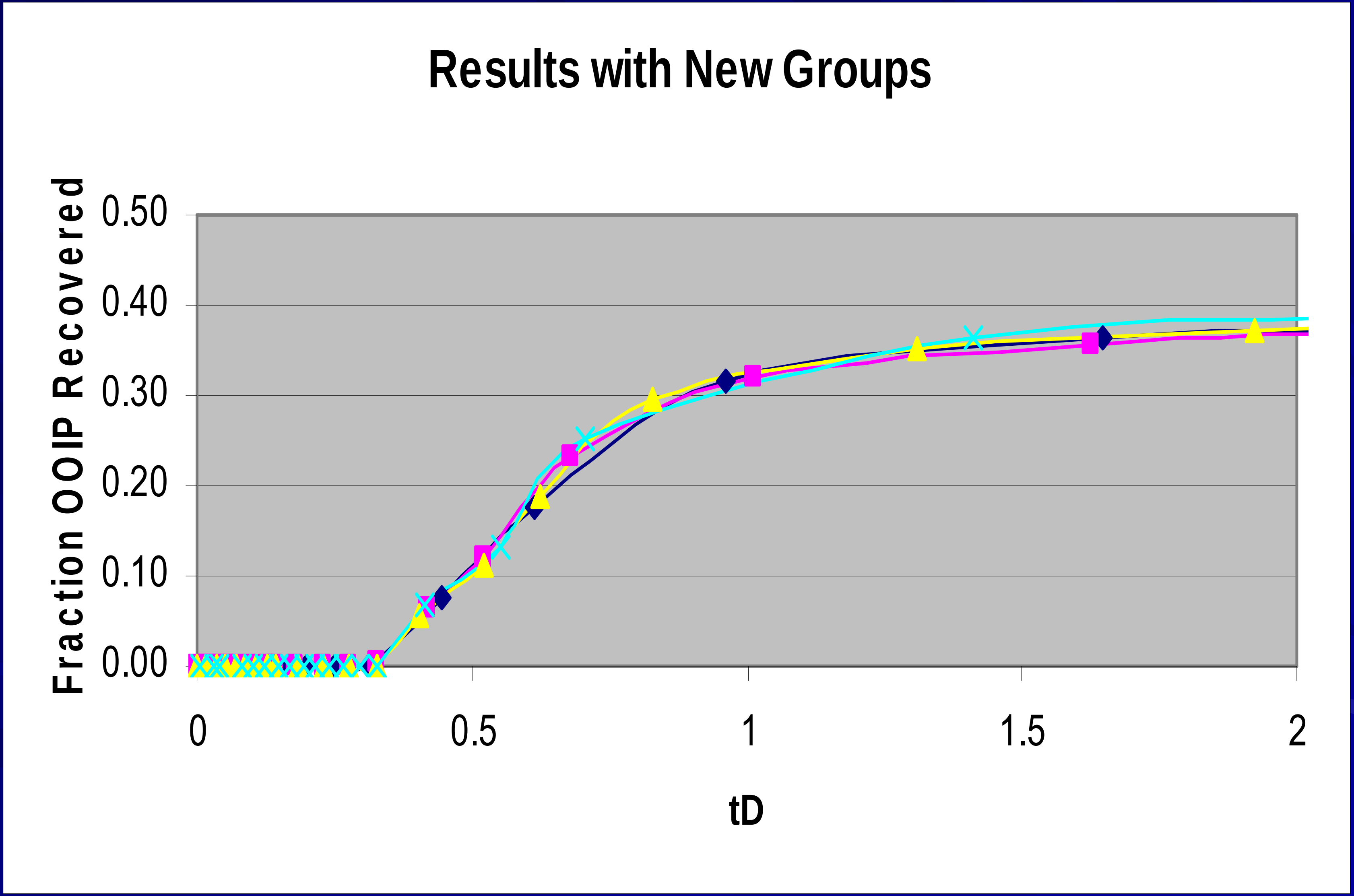
$$P_{pD} = P_p / MMP$$

$$S_{oi}$$

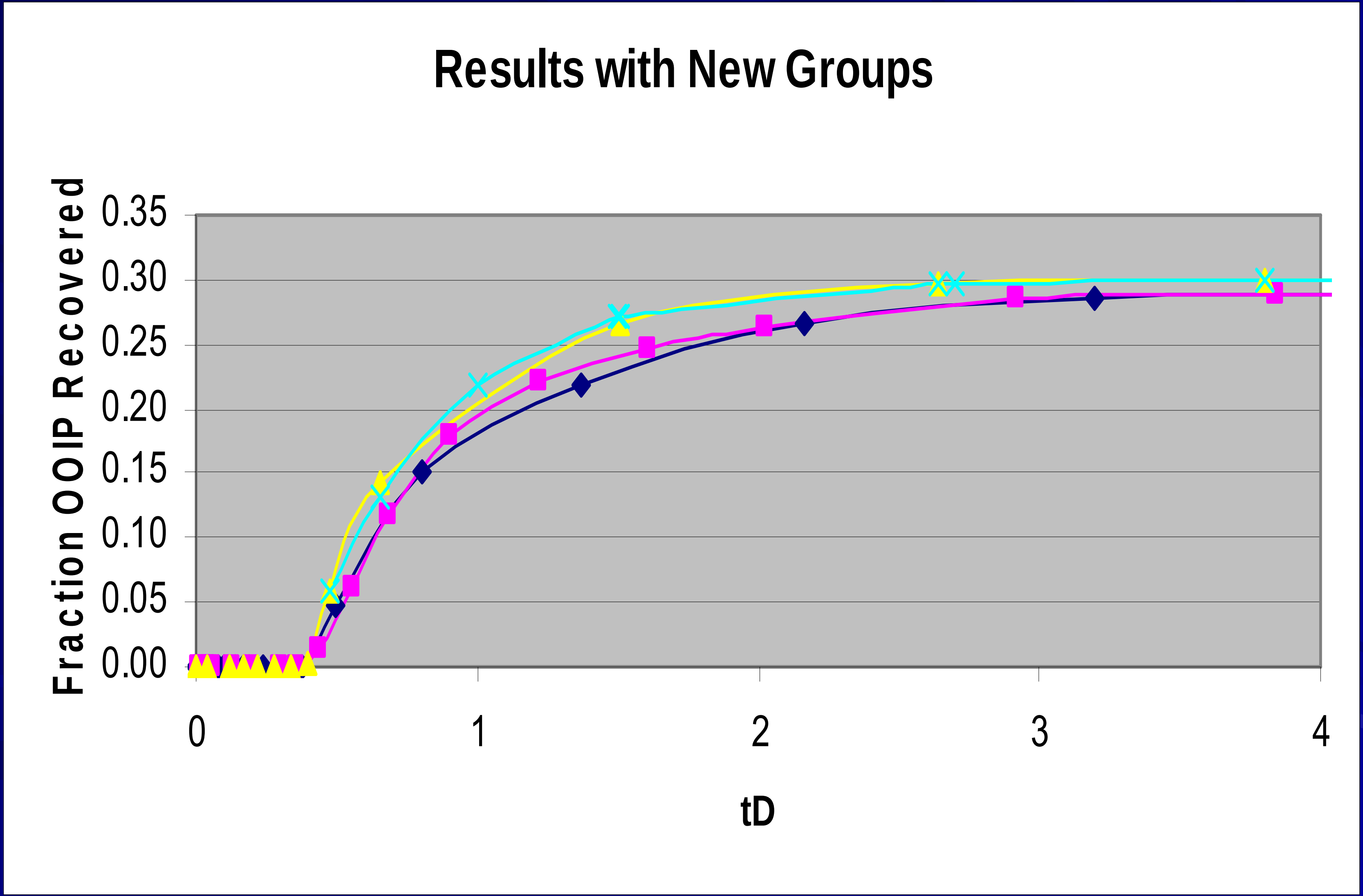
$$S_{orw}$$

$$S_{org}$$

Results – Group Values Set 1



Results – Group Values Set 2



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

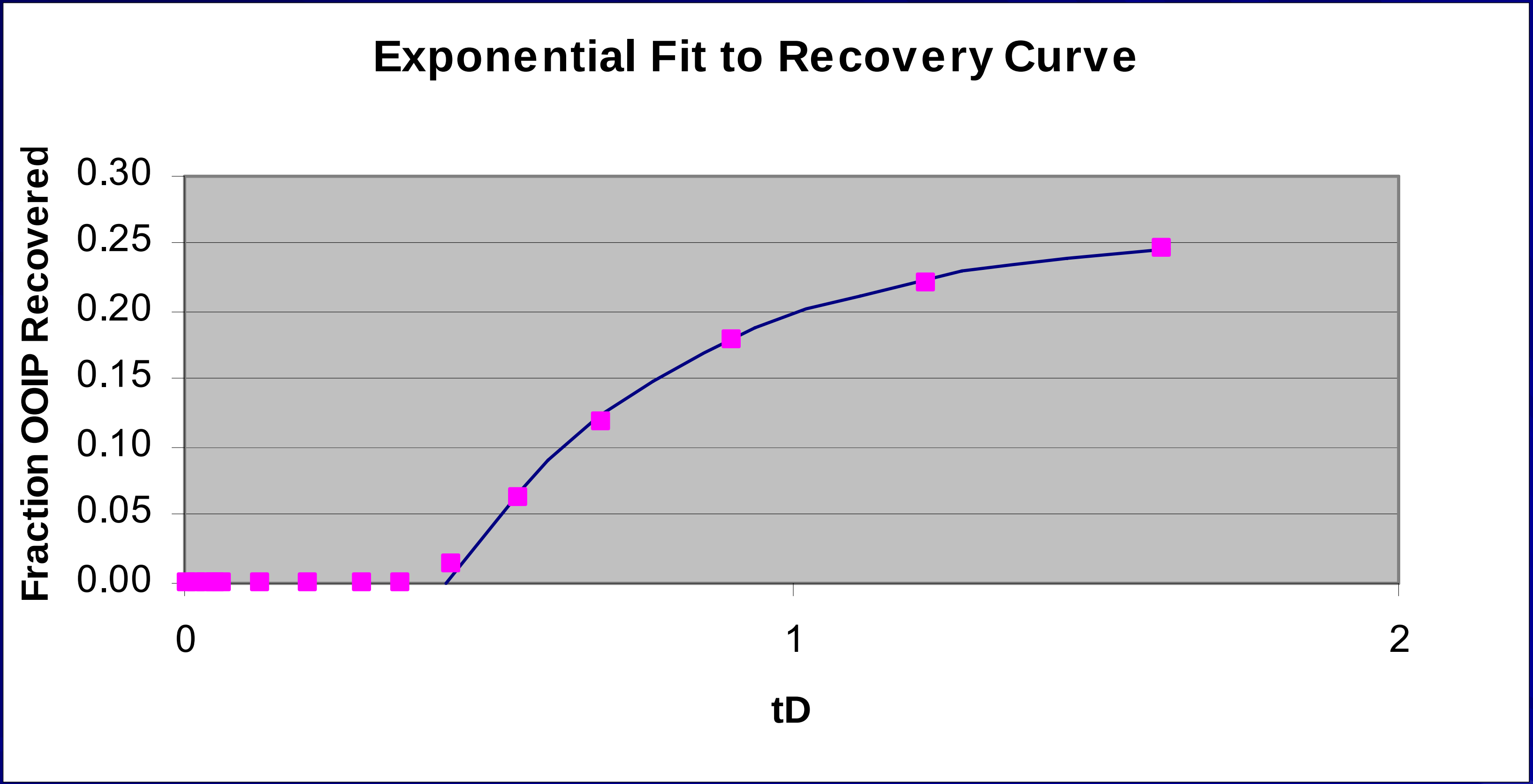
$$(\text{Fraction OOIP}) = A\,(1 - \text{EXP}(-B\,(t_D - t_D^o))$$

t_D^o – breakthrough time for oil recovery

A – ultimate recovery

B – rate of approach to ultimate recovery

Example Exponential Fit



$t_D^o = 0.43$ $A = 0.26$ $B = 2.5$

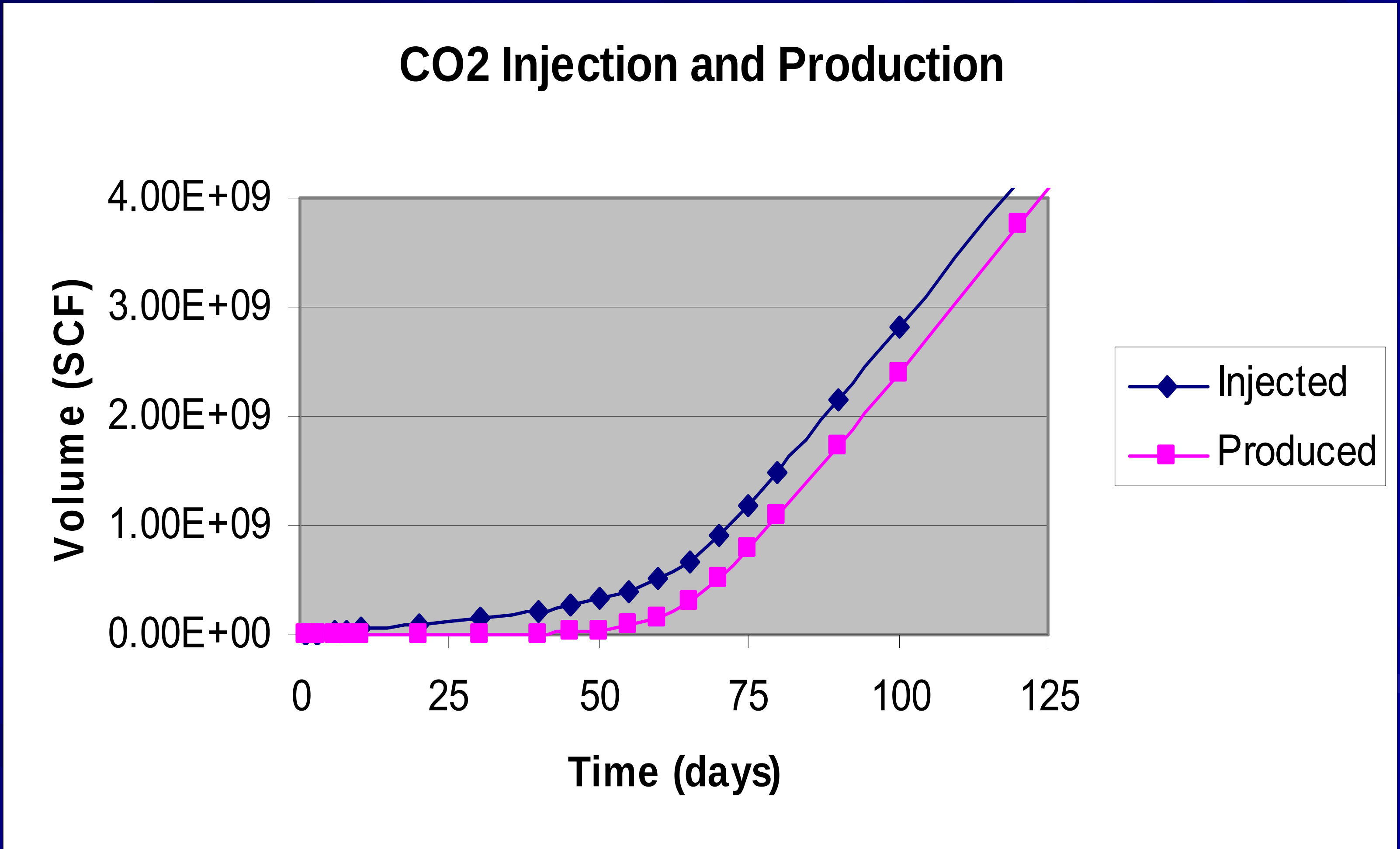
Response Surface Models

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

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

c_i – coefficients x_i - groups

CO_2 Storage



CO2 Injection and Production
Volume (SCF)
4.00E+09
3.00E+09
2.00E+09
1.00E+09
0.00E+00
0
25
50
75
100
125
Time (days)
Injected
Produced

CO_2 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 CO_2 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