CO2-EOR Projects
Key Considerations of Design, Implementation and Operation

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Presented by: Craig Walters
Multiple Project Types and Locations
- Miscible Hydrocarbon – Algeria, Alaska
- Miscible CO2 – Texas, Oklahoma, Wyoming

EOR Capabilities
- Analytical tools and process
- Geologic reservoir characterization
- Fluid behavior studies & equation of state (EOS) development
- Compositional reservoir simulation
- Development planning
- Operations experience
- Commercial focus

- Experienced Technical and Operations Personnel
Anadarko’s Wyoming CO2-EOR Assets

- **Fields**
  - Monell
  - Salt Creek
  - Sussex

- **Pipelines**
  - 33 mile, 8”
  - 125 mile, 16”

- **CO₂ Supply**
  - XOM Shute Creek
Salt Creek & Monell EOR Performance

- **Monell, BOPD**
- **Salt Creek, BOPD**
- **Total CO2 Injection, MMCFD**

**September 2008**
- **10,175 BOPD**
- **382 MMCFD CO2 Inj**

Gross Oil Production (BOPD)

Total CO2 Injection (MMCFD)
CO2-EOR: Going from Concept to Reality

- Idea
- Screening
- Project Design
- Approval
- Implementation
- Operation & Surveillance

RED DENOTES A “KEY CONSIDERATION”
**Idea – “I have an oil field…”**

- **Strong oil prices**
  - Drives up equipment & service costs during implementation
  - Delayed production response – ?? years after 1st injection
  - Timing can be critical

- **Everyone’s talking about CO2 flooding**
  - How many of them know HOW to do it?
  - How many of them ARE doing it?

- **Sounds easy – just inject CO2 into my old waterflood**
  - It is NOT easy!!
Screening
Screening CO2-EOR Flood Candidates

✦ Focus on the Basics
  – CO2 Source, Transmission and Cost
  – Basic Field, Reservoir, Rock and Fluid Properties
  – Miscible Process (Immiscible OK, but lower RF)
  – Analogs / Rules of Thumb
  – Field / Site Specific Analyses
  – Scoping Economics

✦ Don’t Overlook the Obvious
  – CO2 supply to the field
  – Focus on fields that were successful waterfloods
  – CO2 will NOT overcome geology
  – Target the big fields first
    • Big fields can support CO2 pipeline infrastructure expansion
    • Scarce human resources with the necessary skill sets
Screening CO2-EOR (cont)

♦ CO2 Source
  - Type – natural or anthropogenic
  - Quality – contaminants impact MMP
  - Quantity – adequate and consistent for the life of project

♦ CO2 Transmission
  - Distance to source or existing pipeline infrastructure
  - Existing infrastructure utilization
    Is there capacity?

♦ CO2 Cost
  - Supplier and transporter will want to cover costs and ROI
  - Expect CO2 cost to be tied to oil price – be mindful of project timing
Screening CO2-EOR (cont)

What data do I need to pull together? (List NOT exhaustive)

General Field Data
- History: discovery, waterflood, other
- Current daily gross production
- Current well count: active, inactive (by type if possible)

Reservoir Data
- Reservoir name
- Lithology & facies type
- Depth, feet
- Field area, acres
- Geologic maps – structure, isopach, volumes
- Average gross and net pay with net-to-gross ratio, feet
- Fluid contact depths – gas/oil, oil/water
- Well spacing, acres
- Waterflood pattern configuration and spacing, acres
- BH Temperature, deg F
- Initial and current BH pressure, psi
- Frac gradient / pressure, psi
- Expected BH CO2 flood operating pressure, psi

Rock and Fluid Properties
- Porosity, %
- Permeability, md
- Dykstra-Parsons coefficient
- Saturations: Swi, Sorw
- Oil gravity and type, deg API
- Initial and current oil FVF, rb/stb
- MMP, psi
- CO2 FVF at operating conditions, rb/mcf
- Relative permeability curves if available

OOIP and Production
- OOIP, MMSTB
- Primary production and RF, MMSTB and % OOIP
- Secondary production and RF
- Total P+S and RF
- S/P ratio

Key Considerations
- Current reservoir pressure compared to expected BH operating pressure
- “Floodable” OOIP (NOT thin, edgy, poor quality)
• Miscible Process? (Immiscible OK, but lower RF)
  – Correlations based on reservoir temp and oil gravity (API)

Molecular Weight C5+ vs. Oil gravity (Lasater, 1958)

– Is the reservoir deep enough? MMP < frac gradient
Screening CO2-EOR (cont)

- Miscible CO2 Analogs / Rules of Thumb
  - Other CO2 floods – must be similar reservoir and fluids
  - Tertiary Recovery Factor = 12% (8-18%)
  - Tertiary / (Primary + Secondary) = 25% (20-35%)
  - CO2 will NOT overcome geology
Field / Site Specific Analyses

- Streamline simulation (single pattern)
  - Computer software (CO2 Prophet – Texaco software from early 1990’s)
  - Screening tool – falls between empirical correlations and numerical simulation
  - Uses parameters specific to your field – quickly analyze which are key drivers
  - Define initial CO2 slug size and WAG ratio (example 15% and 1:2)
  - Beware relative permeability curves and the “mixing” parameter

- Develop “Dimensionless Curves”
Screening CO2-EOR (cont)

- **Field Development Scale-up**
  - Map out patterns and development schedule by year
    - Timely development with stable CO2 purchase volumes
    - Achievable activity and capital investment levels
  - Identify injection and production streams – oil, water, CO2
  - Identify yearly capital investments – well work, flow & injection lines, facilities

- **Scoping Economics with Sensitivities**
  - Oil price
  - CO2 purchase price
  - OPEX – CO2 handling and recompression become significant, expect double digit lifting cost for life of flood
  - **Does the project make the 1st cut?**
Screening CO2-EOR (cont)

- Ideas for improved economics
  - Target areas of high OOIP for early stage development
  - Increase processing rate – smaller patterns, drier WAG

- Processing rate impact on a single pattern

<table>
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<tr>
<th>HCPVI/Yr</th>
<th>Peak BOPD</th>
<th>Payout, yrs</th>
<th>Life, yrs</th>
<th>NPV10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>21</td>
<td>4.6</td>
<td>21</td>
<td>31%</td>
</tr>
<tr>
<td>8%</td>
<td>17</td>
<td>6.4</td>
<td>26</td>
<td>92%</td>
</tr>
<tr>
<td>5%</td>
<td>11</td>
<td>19.9</td>
<td>42</td>
<td>333%</td>
</tr>
</tbody>
</table>

- CO2 Injected, MCFD
- CO2 Purchased, MCFD
- CO2 Produced, MCFD
- Wt Injected, BWIPD
- Oil Produced, BOPD
Project Design
Project Design

- Reservoir Characterization
- Fluid Characterization
- Operating Parameters
- Pilot Design and Implementation
- Capital Investment Considerations
- Detailed Economics
**Reservoir Characterization (Geo-modeling)**

- Process to quantitatively assign reservoir properties, recognizing geologic information and uncertainty in spatial variability
- Upscaling
- Simulation

**Geology**

Conceptual model, surfaces, facies, sequences, etc.

**Engineering**

Barriers, production data, volumetrics, material balance, interference tests, etc.

**High Resolution Geologic Model**

Integrated model, flow units, uncertainty

**Petrophysics**

Porosity, permeability, log-facies, flow zones, Sw, etc.

**Geophysics**

Major surfaces, faults, attributes, etc.
Fluid Characterization

- Use a reputable lab with recent field samples
- PVT studies
  - Routine oil tests + CO₂ solubility, swelling, viscosity, asphaltene
- MMP determination
  - Rising Bubble Apparatus (RBA)
  - Slim-tube – generally more accurate than RBA
  - Need to consider CO₂ quality and contaminants over time
- Equation of State
  - Develop and test

![Graph showing fractional recovery vs. pressure with data points labeled Lab MMP and Simulation MMP.](image)
**Operating Parameters**
- Pattern type and size
- WAG or continuous injection – water injectivity issues
- Optimum slug size – initial and WAG ½ cycle
- Recycle CO2 – full stream re-injection or NGL recovery
- Operating BHP – consider MMP and frac gradient
- Pumping or flowing producers
- System pressure requirements – injection and production
Project Design (cont)

• Capital Investment Considerations
  – CO2 source / location / transmission
  – Current field operations → proposed operations
  – Existing conditions of wells, facilities, etc.
  – Well work requirements
  – New facilities – gas handling, NGL recovery, etc.

• Detailed Economic Analysis
  – Sensitivities to oil price, CO2 cost, project delays, performance variations, OPEX, HCPVI
  – What are the key drivers and risks?
Project Design (cont)

- **Pilot Design**
  - What are the critical unknowns – is a pilot necessary?
  - Pilot design driven by what you need to learn – clearly define the objectives
  - Scale appropriately – multiple patterns

- **Pilot Implementation**
  - CO2 availability – pipeline or truck?
  - Wellbore utilization – existing or new?
  - Over-communicate with all team members
  - Involve regulatory agencies early
  - Be prepared to capture the pilot data when you need it

- **Don’t go “poor-boy”**
Approval
Approvals

- Internal – multi-year project sanctioning
- Partners
- Mineral interest owners – unitization
- Regulatory agencies – Federal and State

- BLM
  - Project Proposal / Plan of Development – provide detailed overview of the project to BLM for evaluation if an Environment Assessment (EA) or Environmental Impact Statement (EIS) is required – 3 months
    - EA preparation and approval – 6-12 months
    - EIS preparation and approval – 2-5 years
    - Right-of-way and sundry requirements – 1-4 months
  - Wildlife stipulations – impact operations and scheduling
Approvals (cont)

- **WOGCC**
  - Approval of injection fluid for Class II wells (CO2, Water, gas, etc.) – 60 days
  - Approval of wells for Class II injection (new drill, reactivation, recompletion), including notification of surface owners within a ½ mile radius – 75 days
  - Determine maximum surface injection pressures – 30 days after technical information is gathered (step rate tests, frac gradients, temp/tracer logs)
  - Mechanical integrity testing – upon well completion and then every 5 years

- **WYDEQ**
  - Air Quality Permits (compressors, dehy, tank battery, etc.) – 4-6 months
Implementation
Implementation

- Project Execution Plan
- Planning and Scheduling
- Contracting and Procurement Strategy
- Facilities
- NGL Recovery
- Compression
- Infrastructure
- Electrical System
- Well Work
- Surface Control and Measurement
Implementation (cont)

- **Project Execution Plan**
  - Identifies high level goals and objectives
  - Defines roles and responsibilities
  - Identifies manpower requirements – internal and external
  - States major assumptions and risks to successful execution

- **Planning and Scheduling**
  - Map the process with all stakeholders – avoid “Uh-Ohs”
  - Identify work breakdown structure
  - Include contractors in the scheduling process for accountability
  - Key to success – planning, planning and more planning
Implementation (cont)

- **Contracting and Procurement Strategy**
  - Proper assessment of manpower requirements is critical
  - Level load contractors to avoid excess mob and demob
    - Minimize labor turnover
    - Increased efficiency with consistent workforce
  - Supply chain management – **plan for long lead items**

- **Facilities**
  - CO2 is corrosive when wet – **operating conditions and temperatures are key**
  - Fluid composition – CO2, hydrogen sulfide, oxygen, water
  - Plan for corrosion – materials, metallurgy, dehydration, chemical inhibition, monitoring
  - Stainless or carbon steel, fiberglass, polyethylene liners
Implementation (cont)

- Recent Inflationary Pressures

![Graph showing recent inflationary pressures with data from the U.S. Bureau of Labor Statistics. The graph includes various price indices such as Consumer Price Index, #2 Diesel Fuel Price Index, Copper & Copper Products Price Index, Steel Pipe and Tube Price Index, Oil Field Equipment Price Index, and Stainless Steel Index. The data spans from December 2007 to December 2008, with percentage increases marked at various points.]

Data Source: U.S. Bureau of Labor Statistics
Implementation (cont)
Implementation (cont)

- **NGL Recovery from Produced CO2**
  - Full stream re-injection or NGL recovery?
  - Why? – $ and MMP increases with decreasing CO2 mole %
  - Increases electrical consumption and compression needs

- **Compression**
  - Field pressure and volume requirements dictate HP needs
  - Configure dehydration to minimize stainless steel needs
  - Electric or gas – fuel gas availability vs. electricity cost
  - Only need compression to reach “super-critical” conditions – use lower cost H-pumps to get to higher system pressure
  - Station design should facilitate future expansion
  - Cooling capability matched to ambient conditions
Implementation (cont)

- **Flow and Injection Infrastructure**
  - Optimize for cost efficiency and operational control
  - Hub & Spoke or Trunk & Lateral
  - Provide for accurate well testing capability

- **Electrical System**
  - Load projections
  - Optimize cost based on voltage purchase rate schedules
  - Optimize distribution grid
Well Work

- Well mechanical integrity critical to maintaining proper isolation of the target zone
- Requires special cement blends, tools, tubulars, kill fluids

Surface Control and Measurement

- Evaluate system for pressure drops that could cause freezing issues due to CO2 expansion – choke placement, slip-stream
- Accurate measurement & well testing is critical – bad data can lead to bad decisions
- Effective allocation methods
- Mass flow meters for custody transfer
- Other meter types – wedge, V-cone, turbine
Operations & Surveillance
Operation

- Project Execution Plan
  - Details the yardsticks with which to measure performance, and the surveillance program to measure the yardsticks
  - “Plan the work, work the plan”
  
  **BUT be prepared to make changes**
  The plan is not etched in stone

- Operational Issues
  - Artificial lift – ESP, rod, other
  - Scaling, corrosion
  - Well interventions w/ 1.0 psi/ft grad
  - Temperature issues
    - Pressure drops & freezing – slip stream
    - Difficulty in separation
    - Recycle compression – “hot” CO2 less dense, impacts injectivity – heat exchanger
  - Many others – no 2 floods are the same
**Surveillance**

- **Waterflood vs. CO2 flood**
  - Water: plentiful, cheap, favorable mobility
  - CO2: scarce, expensive, unfavorable mobility
  - Smaller CO2 RF / oil target leaves less margin for error

- **Surveillance Program – Vital to Success**
  - Goal is to optimize the performance and value of the project
    - Maximize processing rate
    - Optimize WAG – dry as possible
    - Maximize sweep efficiency – areal and vertical
  - Establish a dedicated surveillance team
  - Pattern surveillance / analysis
**Surveillance (cont)**

- **Surveillance Team**
  - Guides all aspects of flood operations and defines operating parameters
  - Engineers, geologists, field foreman, technicians, operators
  - Frequent communication is critical
  - Set slug sizes, WAG ratios, schedules, IWR, balances patterns
  - Monitors bottom-hole pressure and automation settings
  - Maintain Pres > MMP & Pinj < frac gradient
    - Bottom-hole pressures (dedicated monitoring wells) & step-rate tests
  - Evaluates performance and CO2 utilization
  - Recommends pattern re-configuration, stimulations, infill drilling
Pattern Surveillance Data Requirements
- Measure and account for all injected and produced fluids and pressures
- Average Reservoir Conditions – BH temp and pressure
- Formation Volume Factors – Oil, CO2 and water
- Reservoir volumes – PV and/or HCPV
- Pattern allocation factors – injector centered patterns
  - Subjective process: use geometric initially, modifying over time based on streamline simulation or field observation

Pattern Analysis – Plots with both Time and HCPVI on the X-axis
- Surface Rate and Pressure Data – typical prod & inj plot
- Cumulative HCPVI, CO2 + water
- Cumulative HCPVP, CO2 + water + oil + HC gas
- Injection / Withdrawal ratio (monthly and cumulative)
- Cumulative CO2 Injected, % of HCPV
- Cumulative Oil Produced, % of OOIP
- Gross and Net CO2 Utilization, MCF / BO (standard conditions)
- Gas-Liquids Ratio (GLR), CO2 / (Oil + Water) (standard conditions)
What to Look For

- Actual vs Forecast performance – how are we doing
- Pattern maturity and balancing – when to WAG
- Maintain injection-withdrawal ratio > 1.0
- Processing rate differences – understand why, think about the parameters involved with HCPV and Q

Goal: Optimize NPV without jeopardizing recovery
Summary
CO2-EOR Projects – Keys to Success

1. Identify the “right” field – can’t change Mother Nature
2. Put the time in upfront to avoid headaches later
   - Visit other CO2 floods
   - Pilot test? If so, define size, scope and objectives
   - Where necessary, get early involvement from regulatory agencies
3. Design & implementation – understand the big knobs
   - Accelerate oil response
   - Phased implementation – continual learning & improvement
4. On-going surveillance is vital
5. Right #’s of right people in the right jobs
6. Open communication by ALL involved parties
7. Planning, planning and more planning
8. Maintain commercial focus: Drive for Economic success – not just technical success
Thank you!