RESERVOIR CHARACTERIZATION PROJECT

Laboratory Assessment of Improved Oil Production from Unconventional Shale Reservoirs

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Outline

- **Background and scope** of study

- **Completed** EOR studies
  - Technical approach (i.e. experimental plan)
  - Laboratory procedures
  - Summary results

- **Planned** EOR research
  - Technical approach
  - Laboratory design
  - Laboratory procedures

Background and Scope of Study

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- **Shale EOR has proven effective with strong results**;[1] however, our understanding of **EOR mechanisms** in unconventional shale reservoirs is still limited.[2]

- Several field tests and numerical modeling have indicated that **gas injection is the most viable EOR method** to produce more oil from liquid-rich tight shale reservoirs; but there are **inconsistencies between laboratory investigations and field trials.**[2]

- The goal of our ongoing research at RCP is to **understand and quantify the fundamentals of gas injection EOR** in shale reservoirs via laboratory experiments.

- Our research will be strengthened by **collaborating with the Lawrence Berkeley National Laboratory (LBNL)** which has appropriate laboratory facilities complementing our research capabilities.

1. *Trent Jacobs, Journal of Petroleum Technology, May 2019*
2. *Ganesh Thakur, Journal of Petroleum Technology, September 2019*

EOR Study at the Berkeley Lab

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- Below are the details of the EOR research[1] conducted at the Berkeley Lab in summer 2019:

  - **Investigated several EOR production strategies** using fine scale, high porosity, **ceramic** and **Teflon** synthetic cores. The cores were used to conduct **huff-and-puff EOR**.

  - Tests were conducted on four different samples with heterogeneous porosity, pore structure, and wettability. Pore size varied from micropores to nanopores. Ceramic samples were **water-wet** and Teflon **oil-wet**.

  - **X-ray CT** was conducted during core flooding of a **fractured ceramic** sample.

  - The **process variables** included gas composition, system pressure (1500 psia) and temperature (150^{o}F), soak and drainage time.

1. *DOE Shale Project ESD00008115, Energy Geosciences Division, LBNL*

EOR Lab Tests Conducted

Method	EOR agent	Porous media	Note
Scoping study (sensitivity and reproducibility)	Supercritical (sc)CO_2	Crushed shale	Niobrara outcrop
	H_2O	Ceramic disk	Weakly anisotropic media
Huff-n-puff (single component gases)	He (helium)	Ceramic disks	Weakly anisotropic media
	N_2	Ceramic disks	Weakly anisotropic media
	CH_4	Ceramic disks	Weakly anisotropic media
	CH_4 [with (sc)CO_2]	Ceramic disks	Weakly anisotropic media
Huff-n-puff (gas mixtures)	CH_4 - CO_2 (changing composition)	Ceramic disks	Weakly anisotropic media
	CH_4 - CO_2 (changing composition)	Ceramic disks + Teflon	Anisotropic media

Synthetic Porous Media

Weakly Anisotropic Media

Ceramic discs[1]
Porosity ~ 45%
Poresize ~ 2.5µm
Perm (horz) ~ 33µD
Perm (vert) < 33µD
Pore volume ~ 87 ml

Anisotropic Media 1

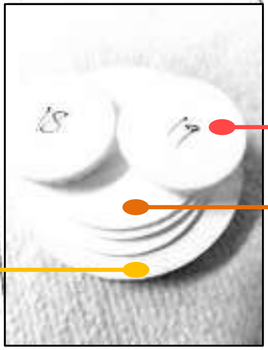
Ceramic/HDPE[2]/PTFE[3]
Porosity ~ 41%
Poresize > 2.5µm
Perm (horz) ~ 40µD
Perm (vert) ~ 15µD
Pore volume ~ 110 ml

Anisotropic Media 2

Ceramic/HDPE/PTFE
Porosity ~ 31%
Poresize ~ 500nm
Perm (horz) ~ 15µD
Perm (vert) ~ 12µD
Pore volume ~ 115 ml

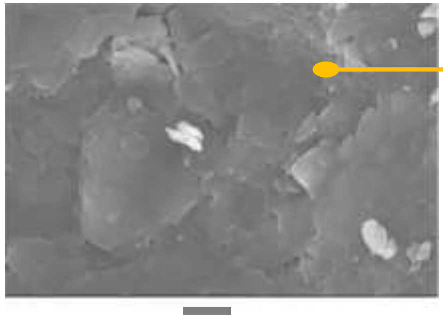
Anisotropic Media 3

Ceramic/HDPE/PTFE
Porosity ~ 32%
Poresize ~ 150nm
Perm (horz) ~ 8µD
Perm (vert) ~ 6µD
Pore volume ~ 105 ml



[1]Ceramic (Al_2O_3)

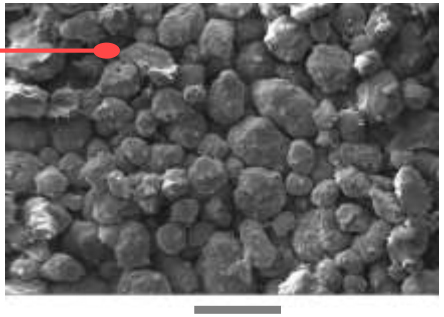
Uniquely porous
Hydrophilic



200 µm

[2]HDPE ($(C_2H_4)_n$)

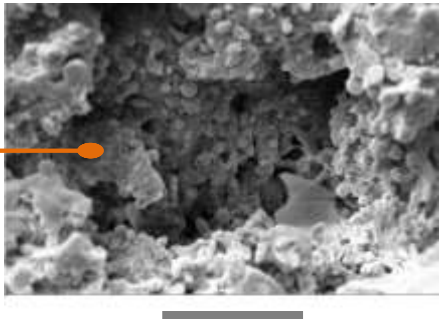
High-density polyethylene
Oleophilic
Porosity ~ 37%
Poresize ~ 10µm
Permeability ~ 120µD



100 µm

[3]PTFE ($(C_2F_4)_n$)

Polytetrafluoroethylene (Teflon)
Oleophilic
Porosity ~ 30%
Poresize ~ 20µm
Permeability ~ 240µD



10 µm

Synthetic Porous Media (Composite Clusters)

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Weakly Anisotropic Media

Anisotropic Media 1

Anisotropic Media 2

Anisotropic Media 3

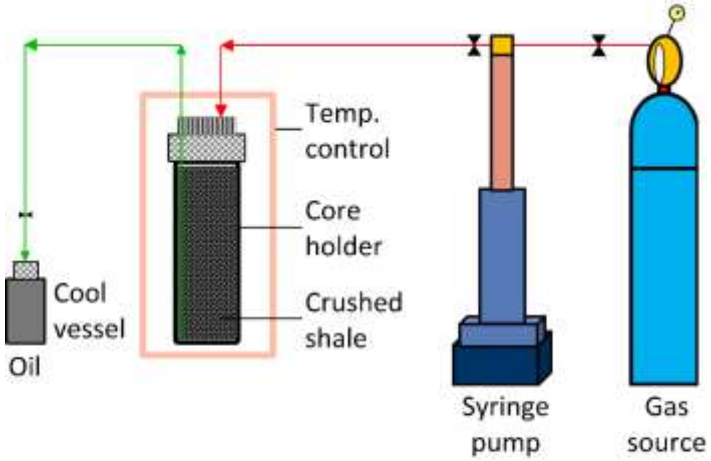
- ***Why synthetic porous media?***
- ***How comparable to shale?***

Porous media clusters	Wettability	Ave. total porosity	Ave. poresize	Ave. horz. permeability	Ave. vert. permeability	Ave. pore volume
Weakly Anisotropic Media	100% water wet	45%	~ 2.5 µm	~ 33 µD	< 33 µD	87 cm^3
Anisotropic Media 1	70%-30% water-oil wet	41%	> 2.5 µm	~ 40 µD	~ 15 µD	110 cm^3
Anisotropic Media 2	70%-30% water-oil wet	31%	~ 500 nm	~ 15 µD	~ 12 µD	115 cm^3
Anisotropic Media 3	70%-30% water-oil wet	32%	~ 150 nm	~ 8 µD	~ 6 µD	105 cm^3

70% inorganic mineral - 30% kerogen

Scoping Studies

Effect of (sc)CO_2 (crushed shale)

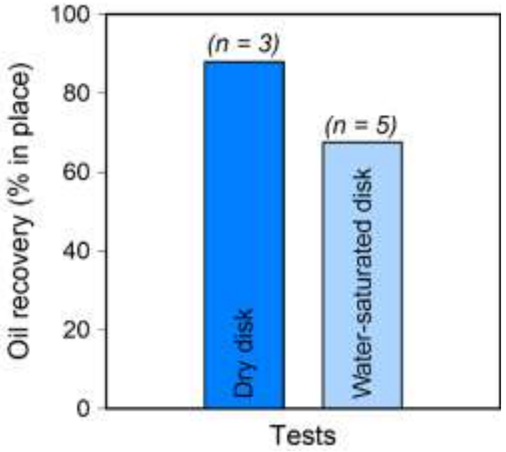


Schematic of experimental apparatus

Crushed Niobrara shale

Effect of water displacement (ceramic disk)

Oil droplets on ceramic disk



- **(sc)CO_2** was injected into **crushed Niobrara** shale at 140°F and 1300 psia.
- **Very small mass of oil** was recovered.
- **Poorly characterized sample**; not ideal testing method.

- Oil was displaced from ceramic discs by **water** at room temperature and pressure.
- **Oil spontaneously effused** from the ceramic sample as water was imbibed.
- **Average oil recovery was 88%** for a dry sample and **66%** for a water-wet sample.

Huff-n-Puff EOR Lab Setup (Berkeley Lab)

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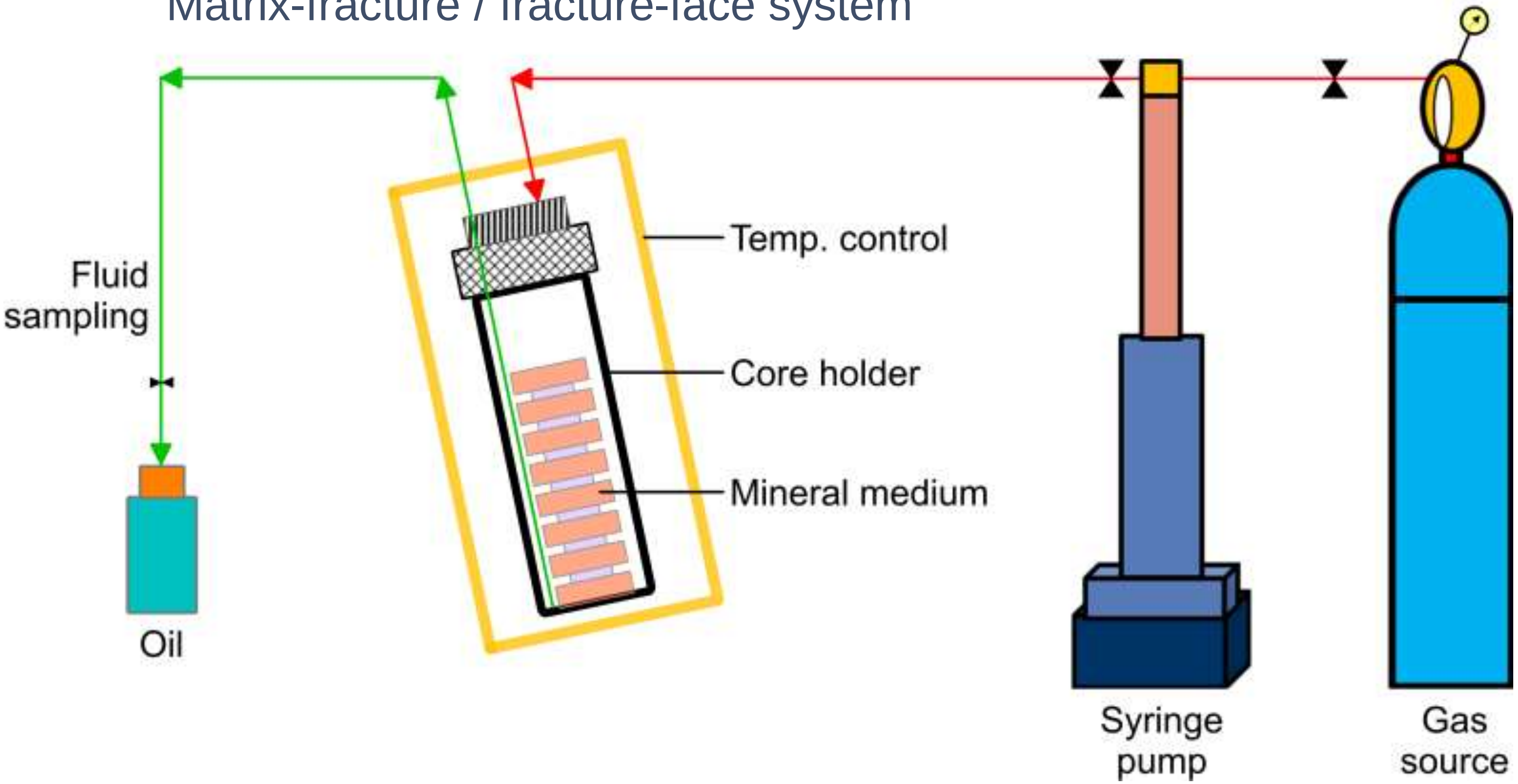
1	Sample preconditioning with water vapor
2	Sample pressure-saturate with dodecane[1] (1500 psia)
3	Gas-driven drainage of excess dodecane (1500 psia)
4	Soak with gas/gas-mixture of choice (140°F, 1500 psia)
5	Produce dodecane by depress. (1500 psia - vent)
6	Change test variables and repeat the process

Matrix-fracture / fracture-face system



[1] n-Dodecane ($C_{12}H_{26}$)
Liquid, intermediate alkane hydrocarbon
Boiling point = 420°F

Primary Oil Recovery from Composite Clusters

Weakly Anisotropic Media

Ceramic
100% water-wetting
Porosity ~ 45%
Pore size ~ 2.5μm

Anisotropic Media 1

Ceramic/HDPE/PTFE
70%:30% water-oil wetting
Porosity ~ 41%
Pore size > 2.5μm

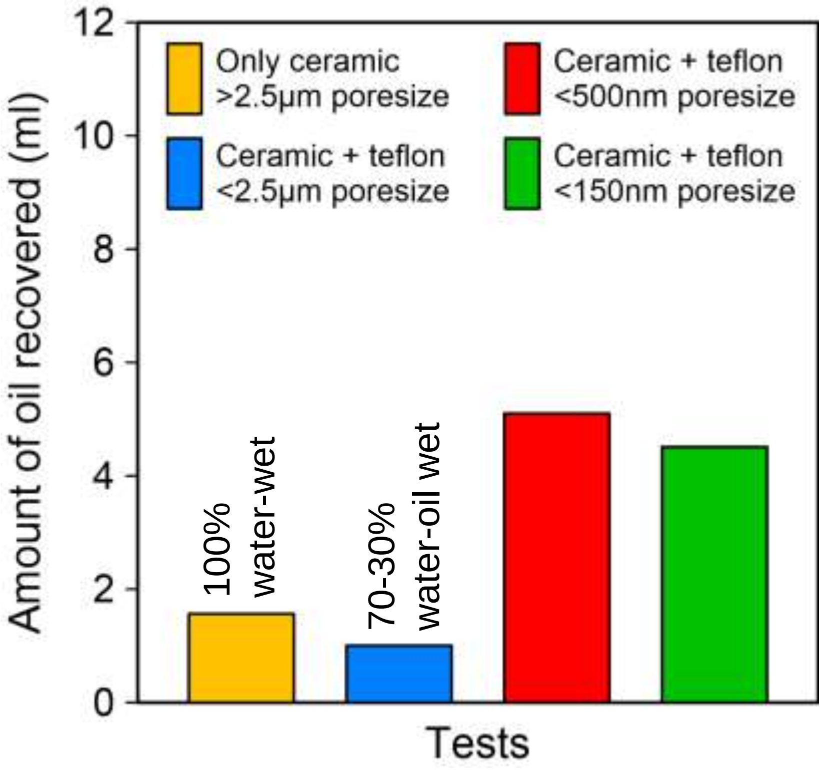
Anisotropic Media 2

Ceramic/HDPE/PTFE
70%:30% water-oil wetting
Porosity ~ 31%
Pore size ~ 500nm

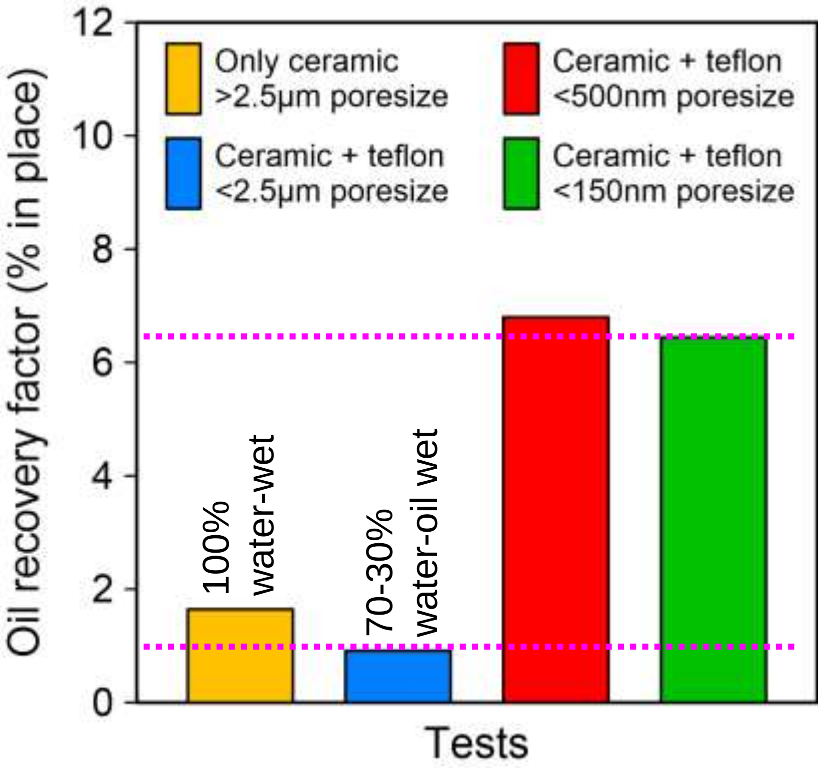
Anisotropic Media 3

Ceramic/HDPE/PTFE
70%:30% water-oil wetting
Porosity ~ 32%
Pore size ~ 150nm

Oil recovery amount



Oil percent recovery



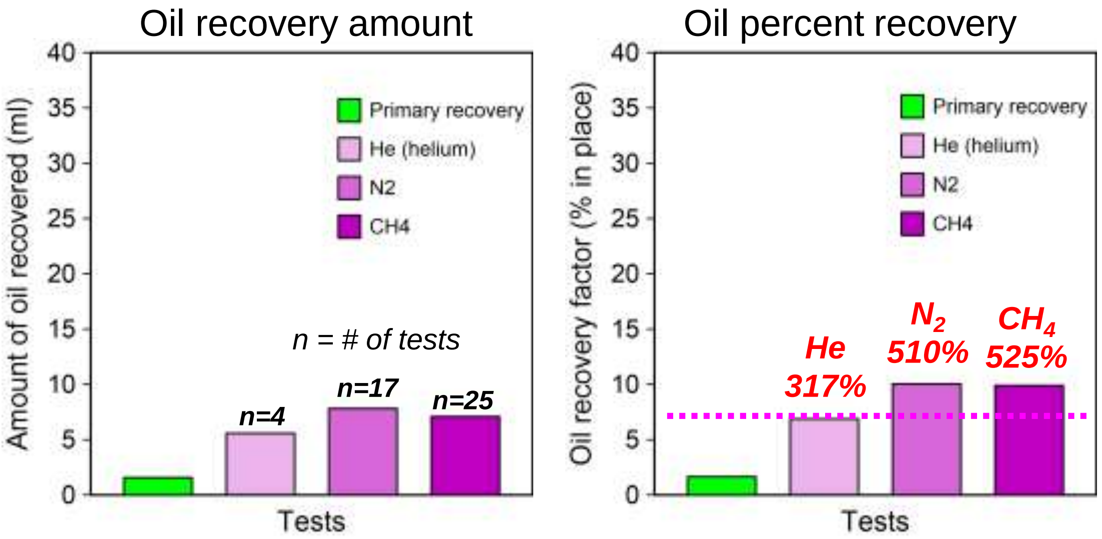
Key observations:

- Porous media **mineralogy and wettability exhibited large effect** on oil production.
- **Smaller poresize** samples produced more oil than the larger poresize samples.
- Sample **total porosity** *less intensely* affecting the oil production.

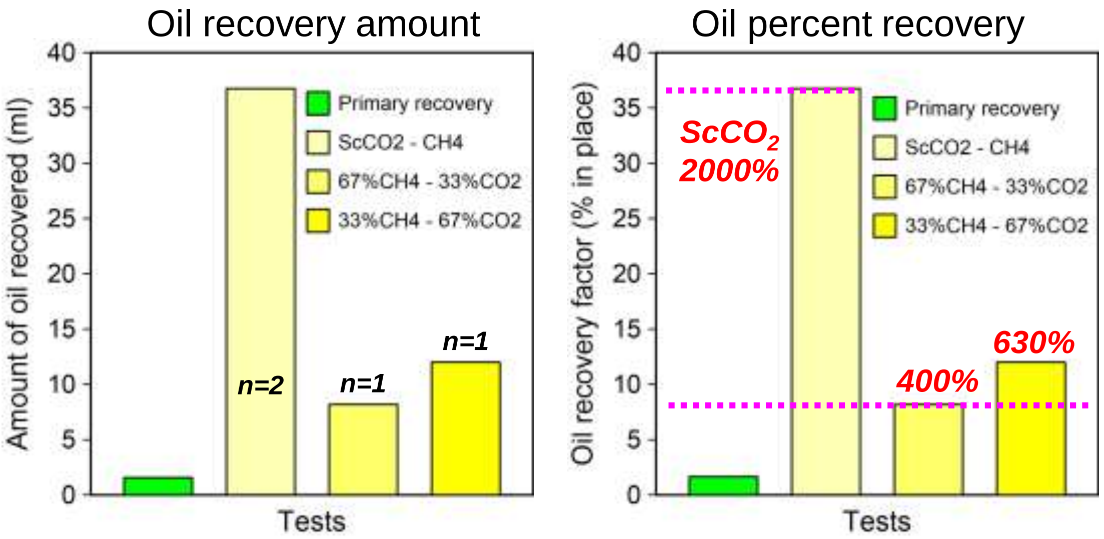
EOR in Ceramic Disks

Weakly Anisotropic Media
Layered, homogeneous ceramic disks
100% water-wetting
Porosity ~ 45%
Pore size ~ 2.5μm

EOR efficiency of single component gas



EOR efficiency of (sc)CO_2-CH_4/gas-mixtures



Key observations:

- **Helium performed poorly**; appeared not to be promising, and eliminated from further consideration.
- Both **N_2 and CH_4 outperformed He**.

Key observations:

- **(sc)CO_2** significantly increased oil recovery.
- Gas mixtures with **higher CO_2 concentrations** increased oil recovery.

EOR in Composite Clusters

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Anisotropic Media 1

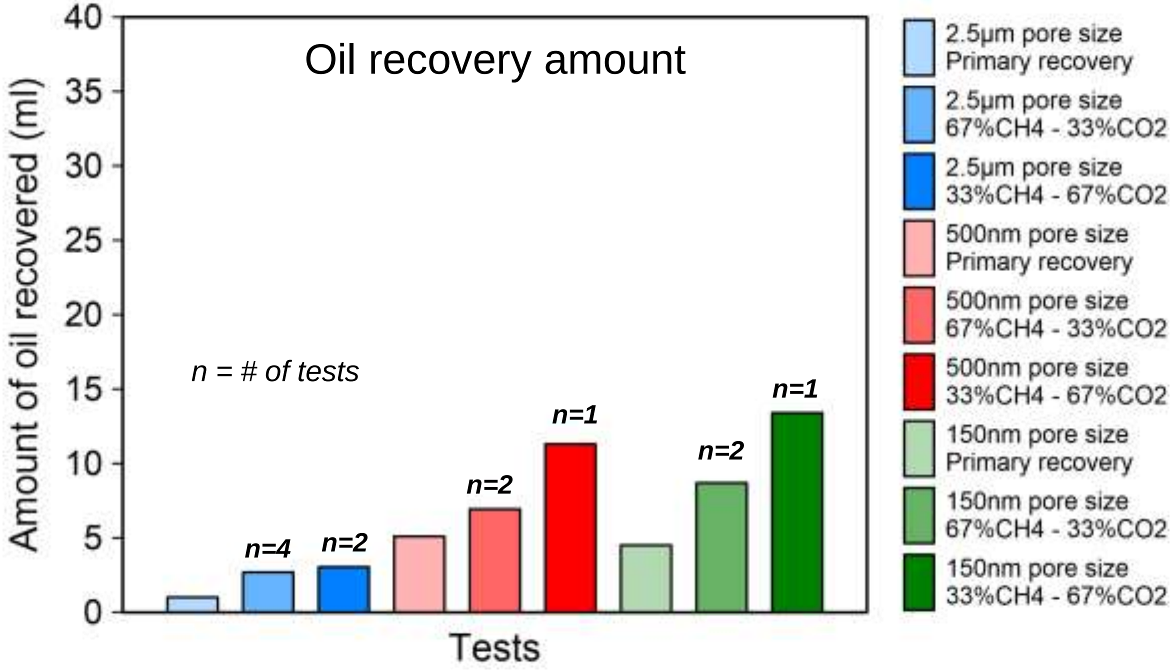
Ceramic/HDPE/PTFE
70%:30% water-oil wetting
Porosity ~ 41%
Pore size > 2.5µm

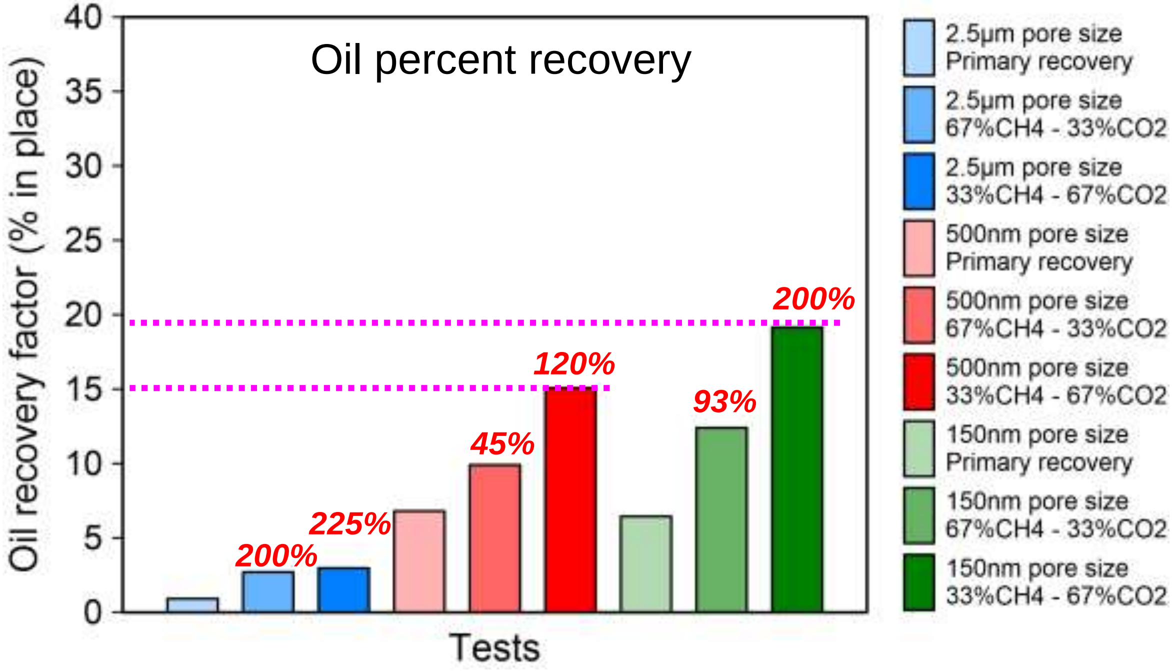
Anisotropic Media 2

Ceramic/HDPE/PTFE
70%:30% water-oil wetting
Porosity ~ 31%
Pore size ~ 500nm

Anisotropic Media 3

Ceramic/HDPE/PTFE
70%:30% water-oil wetting
Porosity ~ 32%
Pore size ~ 150nm





Key observation: 150-500 nanometer poresize samples produced more oil compared to the **2.5 micrometer** samples.

Key observation: gas mixtures with **higher CO_2 concentrations** increased oil recovery, and have potential for further study and development.

Planned EOR Research on Shale Cores (Berkeley Lab)

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- The earlier EOR tests in composite **synthetic** cores at **LBNL** have established that **N_2, CH_4 and CO_2 have potential for EOR applications.**

- Require **additional tests** to fill in data-gap and confirm results.

- **In the new tests** I will conduct EOR experiments using **wet gas** and **CO_2 injection** in **shale** cores at expected reservoir pressure and temperature.

Planned EOR Study – Phase I Lab Experiments

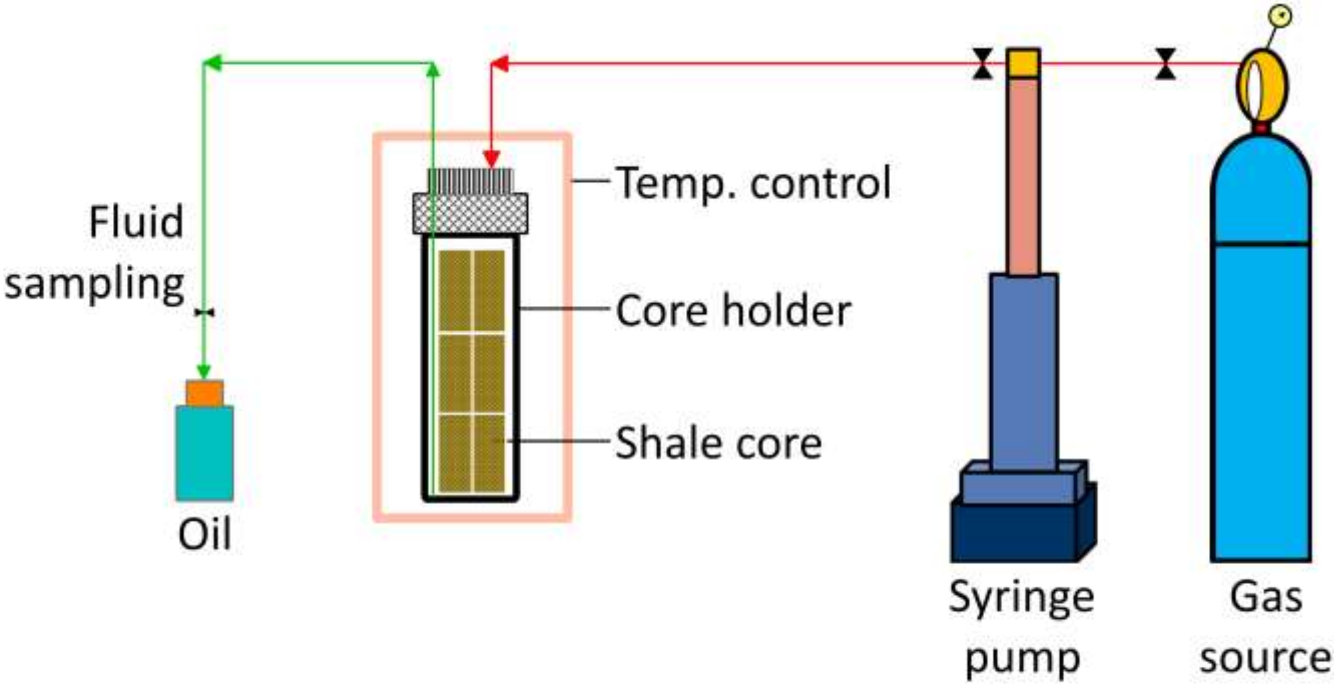
- **Huff-n-puff** (**fracture-face**) **EOR experiments** in shale cores:

  1) Using a mixture of C_1-C_5 to displace n-C_{12} in 2 x 7-inch <u>unfractured long cores</u> at 200°F and 2000 to 2500 psia.

  2) Repeating same experiment in <u>fractured long cores</u>.

  3) Repeat above experiments using CO_2.

<u>Experimental apparatus schematic for Phase I</u>



Planned EOR Study – Phase II Lab Experiments

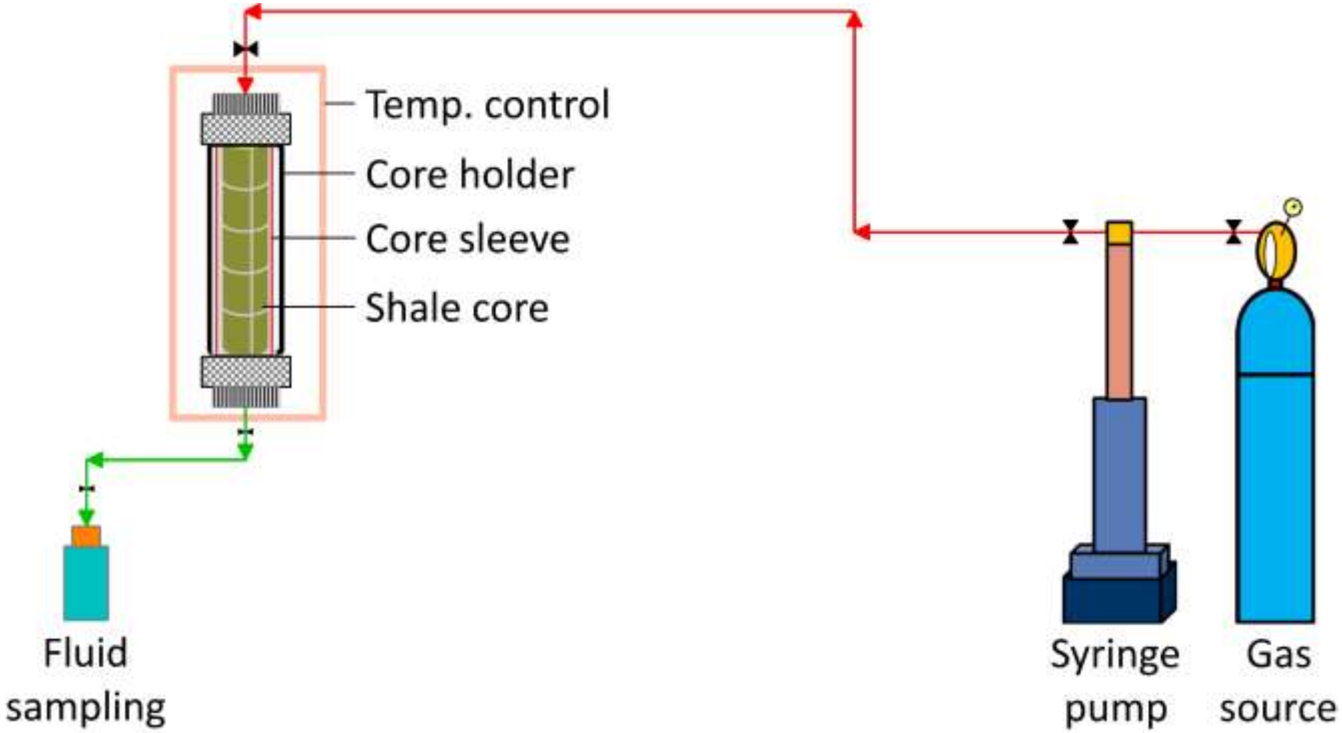
- **Huff-n-puff (core flooding) EOR experiments** in shale cores:

  1) Conducting similar experiments as in Phase I with the exception of using **recombined reservoir fluids** (real field produced oil + gas) at 240°F and 5000 psia.

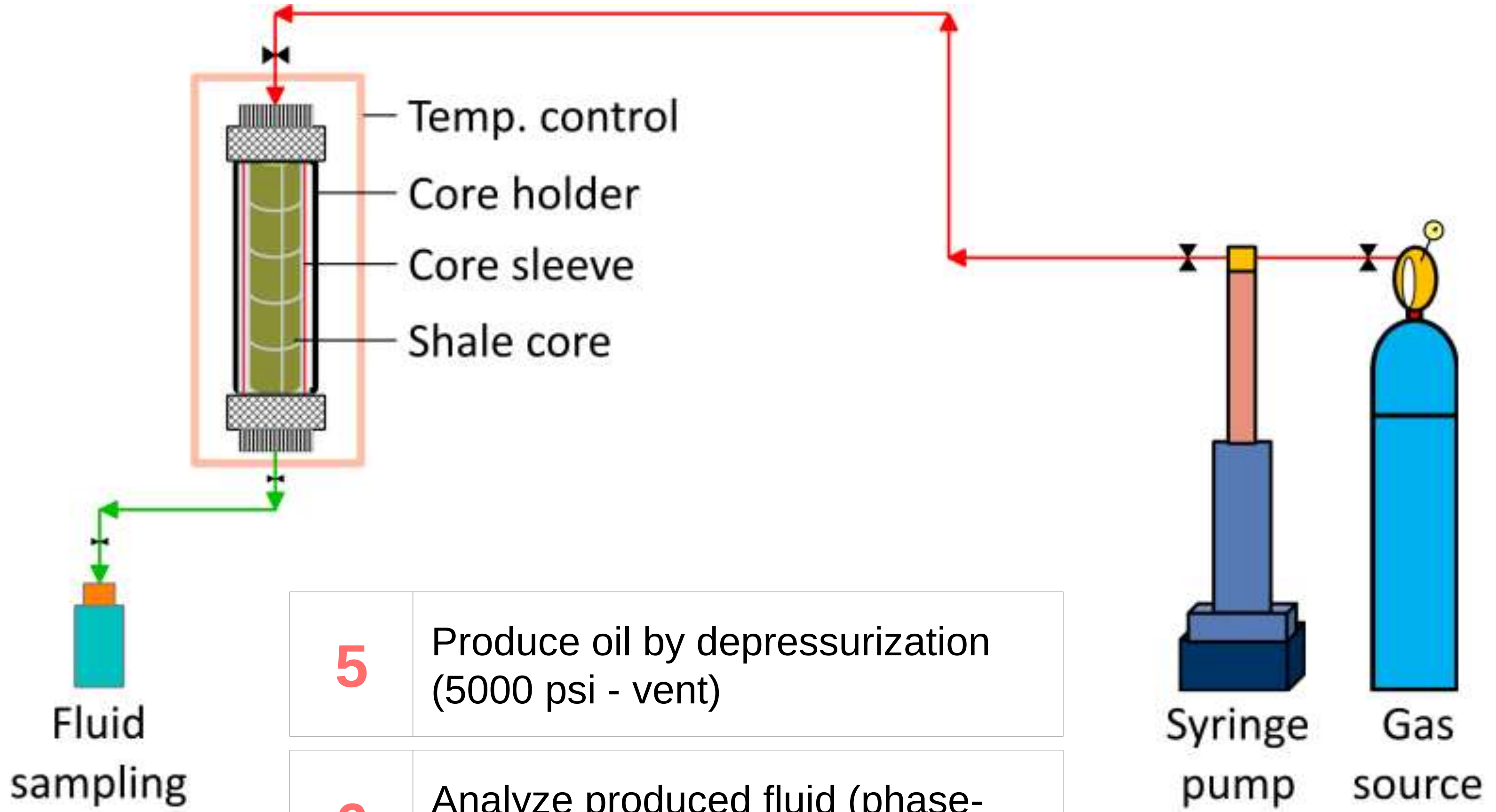
  2) Measure **acoustic (P and S) velocities** during core flooding experiments (w/ Prof. Manika Prasad from Geophysics Dept, CSM).

  3) Conduct reservoir simulation to analyze the laboratory PVT and EOR results.

Experimental apparatus for Phase II



Planned EOR Study – Phase II Lab Procedures



1	Precondition sample for initial water saturation (5000 psia)
2	Saturate the sample with live oil at 5000 psia pore pressure and 5500 psia confining stress.
3	Drain out excess oil under pressure (240ºF and 5000 psia)
4	Soak the sample with injected gas (5000 psia)
5	Produce oil by depressurization (5000 psi - vent)
6	Analyze produced fluid (phase-behavior, compositional analysis)
7	Change test variables and repeat the process

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devon
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