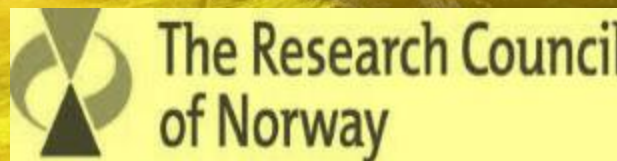


Whole Value Chain CCUS Conference Week

CO₂ Foam EOR for Mobility Control



Prof. Arne Graue
Dept. of Physics and Technology
University of Bergen, NORWAY

Whole Value Chain CCUS Conference Week, Sept. 22nd–26th, 2025, Golden, CO, USA.



18 – 20 February 2025
Kuala Lumpur, Malaysia

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Energy for all: Reflect ► Innovate ► Evolve

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IPTC-24902-EA

CO₂ Foam Enables CCUS with Low Carbon Oil Production in Asia

Arne Graue¹ and Zachary Paul Alcorn¹

¹Department of Physics and Technology, University of Bergen, Bergen Norway

Sponsoring Societies



Presentation Overview

- CO₂ EOR Background and Challenges
- CO₂ Foam Integrated Enhanced Oil Recovery (IEOR)
- CCUS Business Case
 - *Sustainable Economy*
 - *Reduced Carbon Footprint*
 - *Increased oil recovery & CO₂ utilization*
- Technical Achievements and Conclusions on a CO₂ Foam IEOR Field Pilot

R&D Approach

Implementation

Offshore Pilot

Onshore Pilot

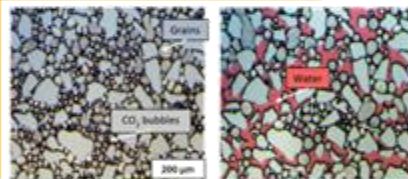
Pilot design

Field-scale

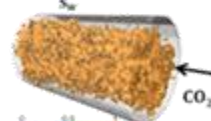
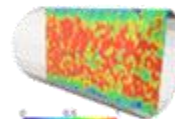
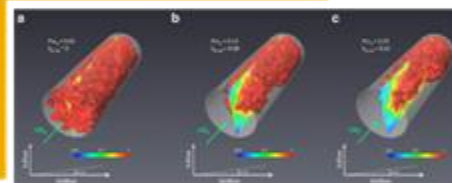
Foam system design

Core-scale

Pore-scale



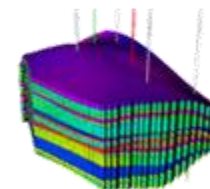
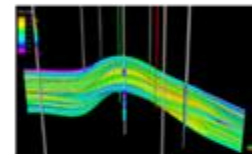
Wettability and
reactive transport



S_w
1 cm³/min
 $S_{CO_2} = 0.25$

Displacement and
storage

Model parameters
for upscaling



Improved modeling
and lessons learned
from ongoing pilot

CO₂ EOR and CO₂ Foam Fundamentals

Why CO₂ for EOR?

Advantages

- Is soluble in oil, causing the oil to swell and reduces its viscosity
- Develops miscibility at pressures lower than hydrocarbon gasses
 - Can extract components up to C₃₀ from the reservoir oil
- Potential for CO₂ storage

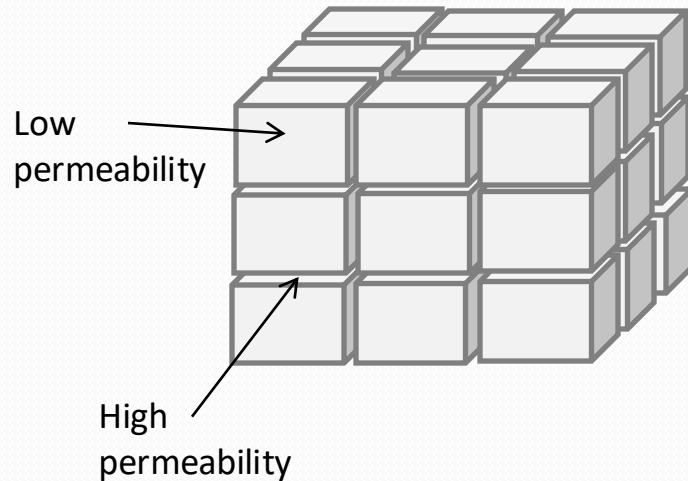
Challenges

- Low macroscopic displacement efficiency
 - Mobility ratio
 - CO₂ traveling through high permeable zones
- Operational costs
- Supplying enough CO₂ to the fields at an acceptable cost
- CO₂ and brine might cause weakening of the rock and corrosion of wells and equipment

CO₂ EOR and CO₂ Foam Fundamentals

CO₂ in fractured reservoirs

- Matrix/fracture network
- Molecular diffusion



- Mass transfer and mixing due to random motion
- Driving force:
 - Concentration gradient
 - Diffusivity of each component
- Concentration is a function of
 - Time
 - Distance
- Goal to achieve equilibrium between the injected CO₂ and the reservoir oil

Advantages with CO₂ for EOR

Low
MMP

Oil
viscosity

Swelling

CO₂
storage



Challenges with CO₂ for EOR

Corrosion

Availability

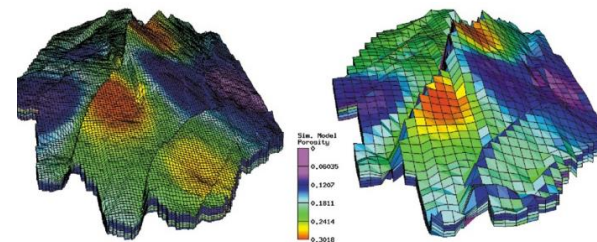
Low
viscosity

Recycling

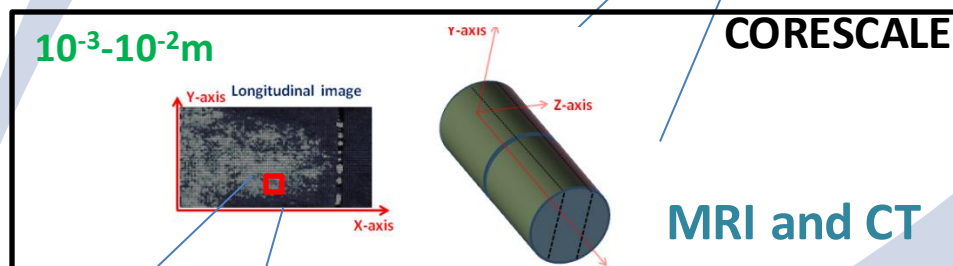
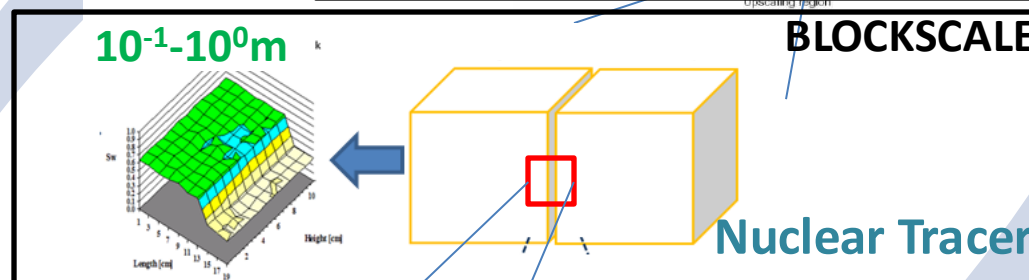
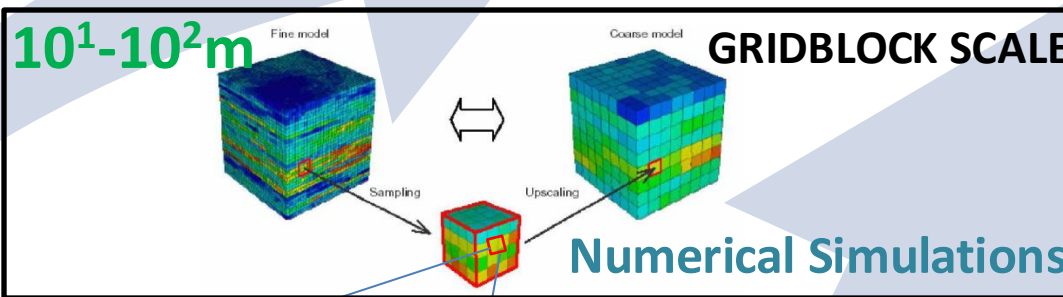


Length Scales

10^3-10^4m

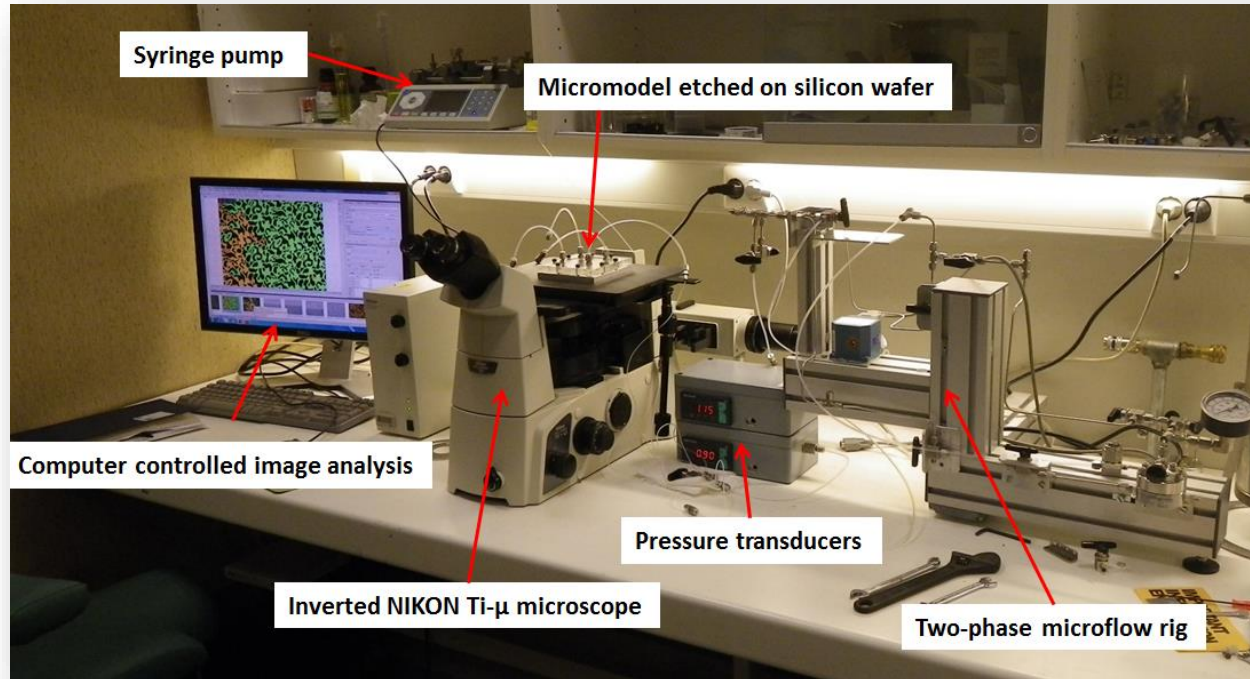


Petroleum Geo-Services Homepage
www.pgs.com



Imaging techniques

Lab Experience: PORE SCALE MOBILITY CONTROL WITH FOAM



SALIENT FEATURES

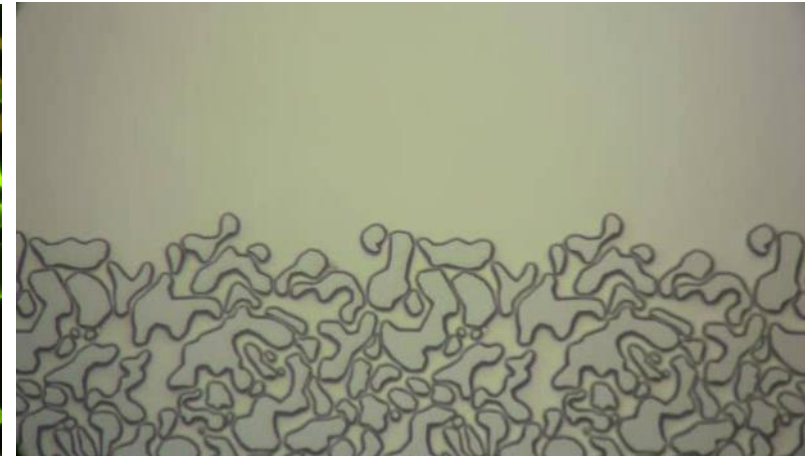
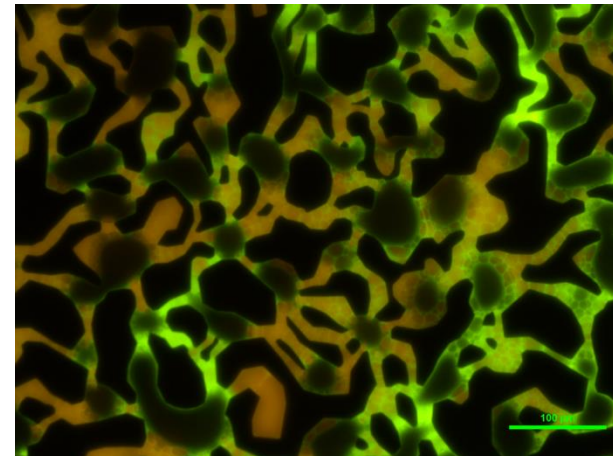
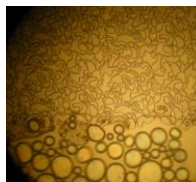
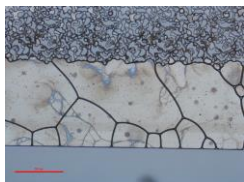
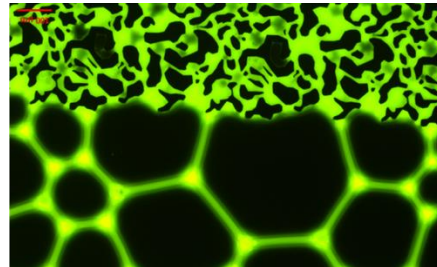
HIGH pressure
ACCURATE pore space
FRACTURE transport possible

SPECIFICS

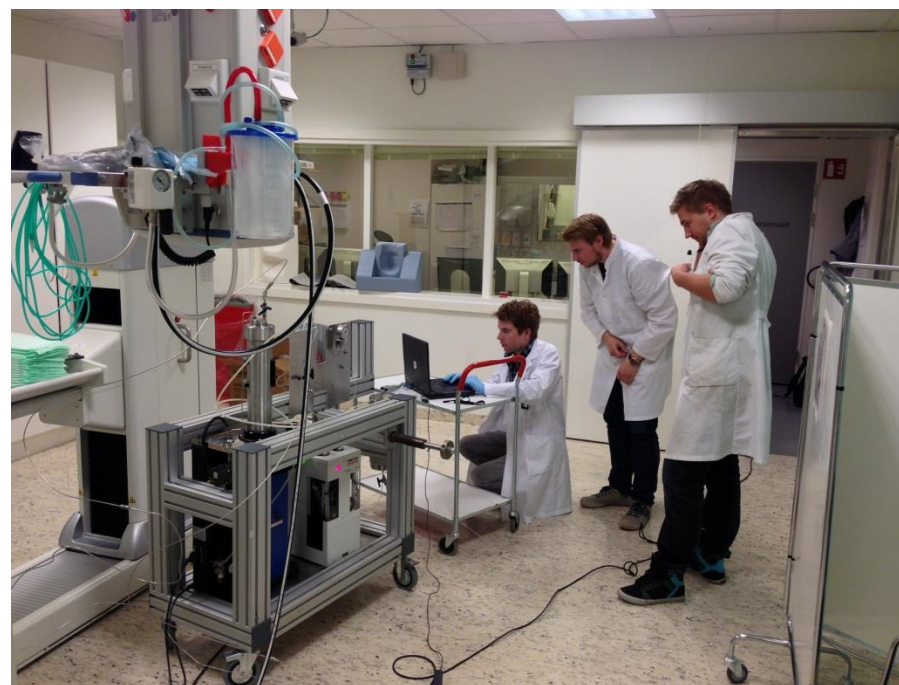
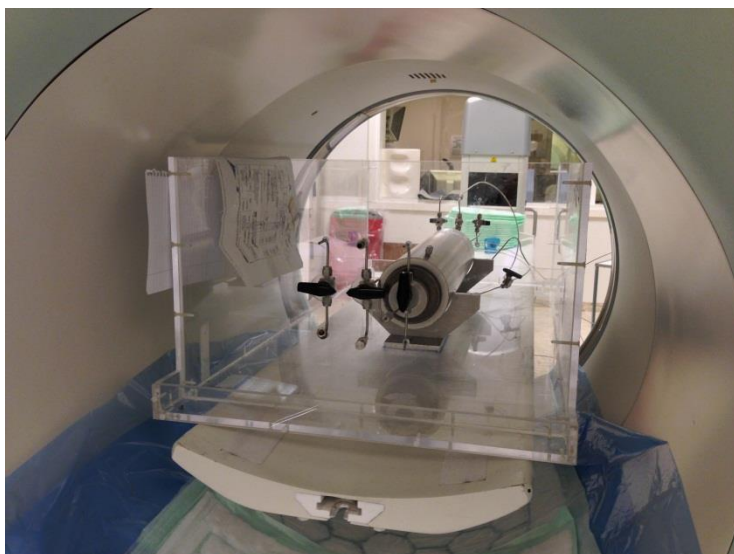
25 μ m constant depth
(typical pore size in sandstone)

Coordination numbers
4-8 (high pressure models)
1-6 (low pressure models)

Initial wetting is water-wet



PET/CT @ Haukeland University Hospital



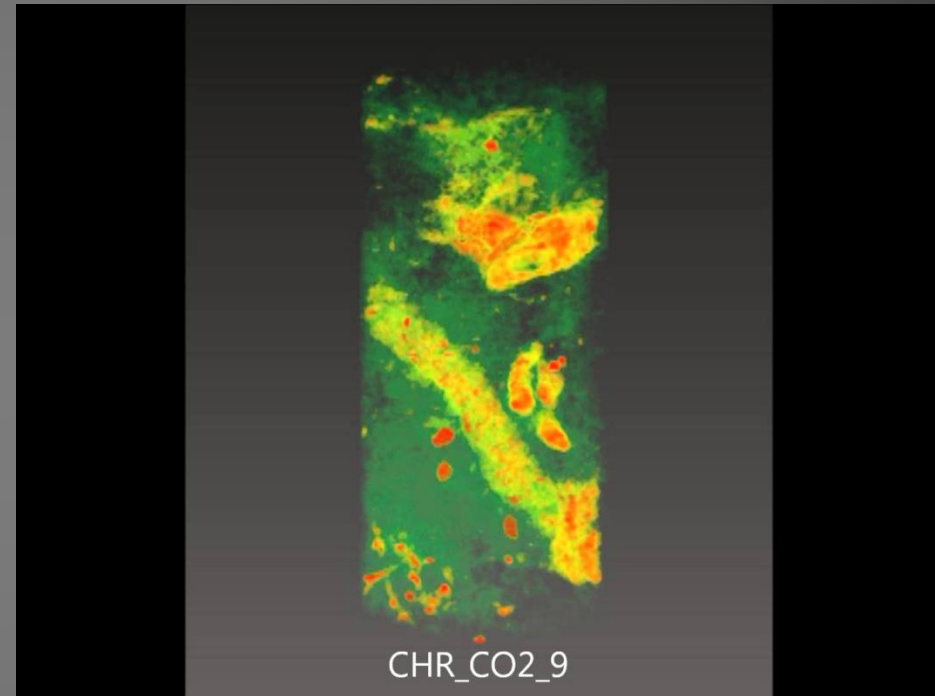
CO₂ Injection in Fractured Chalk Visualized in the Medical CT-scanner

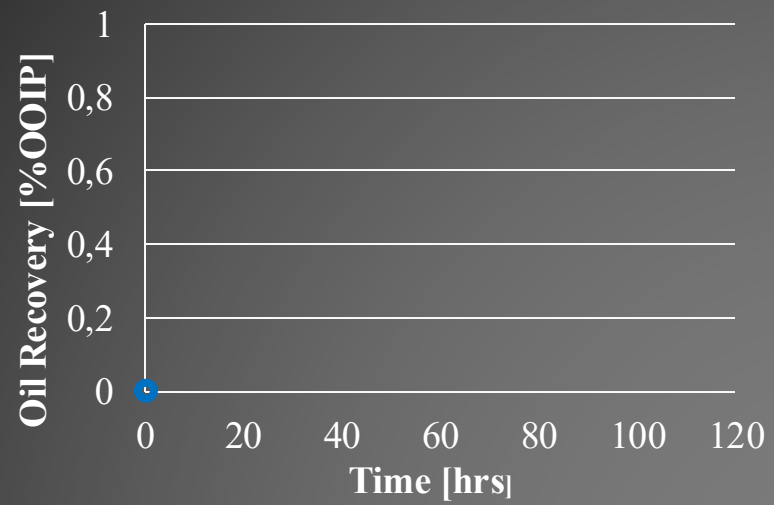


ConocoPhillips' CT lab in Bartlesville

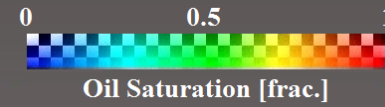
CT-imaging of CO₂ core floods

- Normalization scan:
 - Dry core
 - 100% CO₂ saturated
 - 100% oil saturated
- Provides
 - Porosity map of core
 - Spatial fluid saturation
- Resolution: 0.156mm*0.156mm*0.5 mm

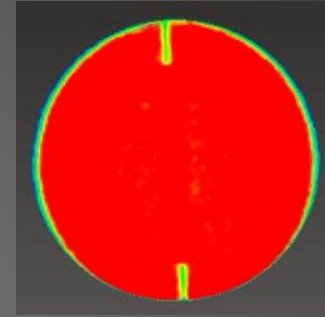
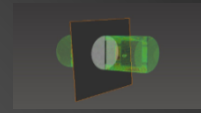




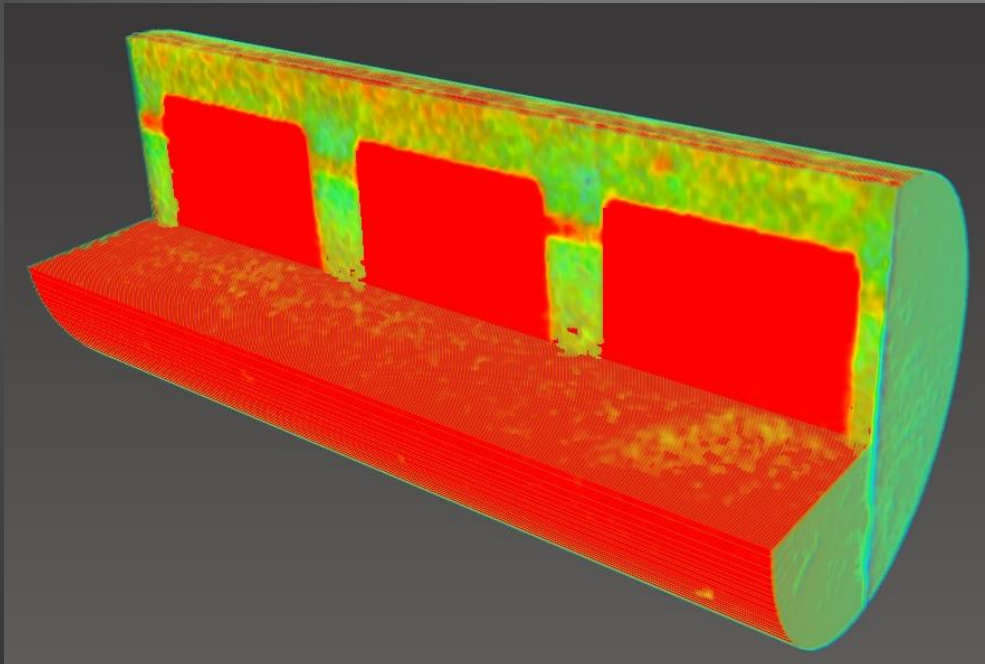
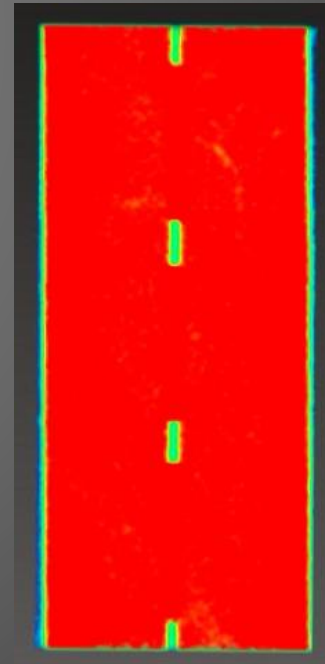
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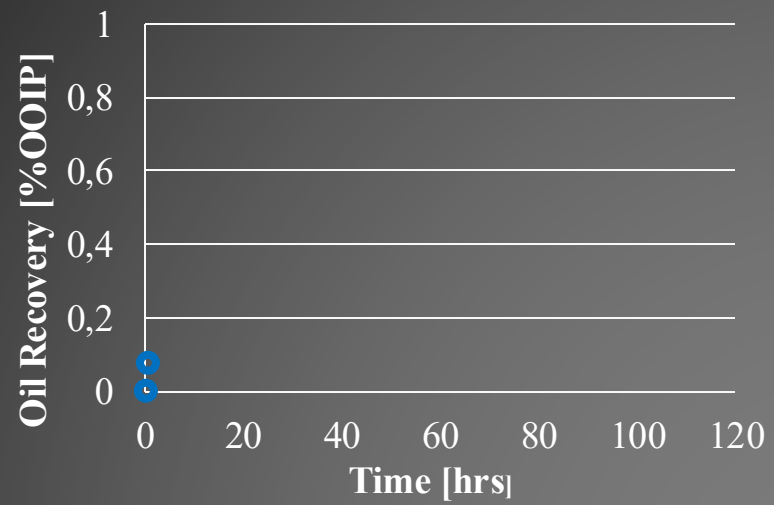


XY-plane

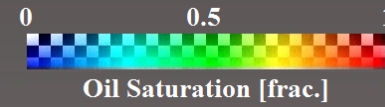


XZ-plane

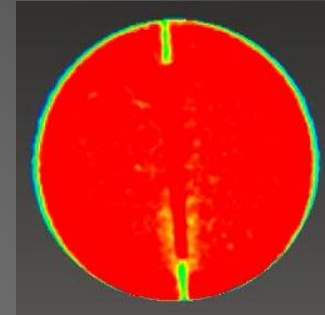
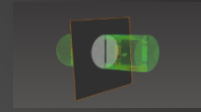




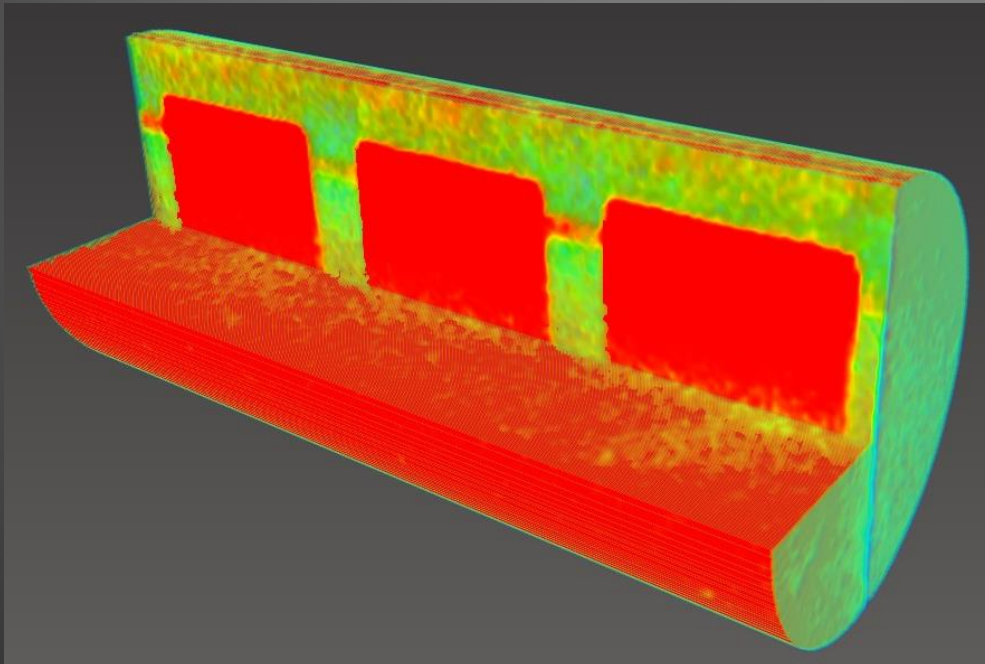
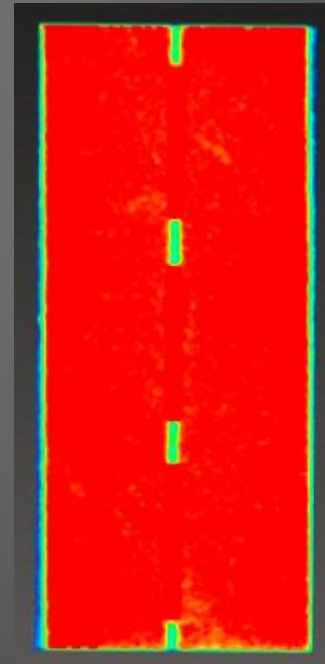
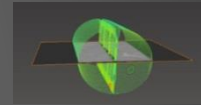
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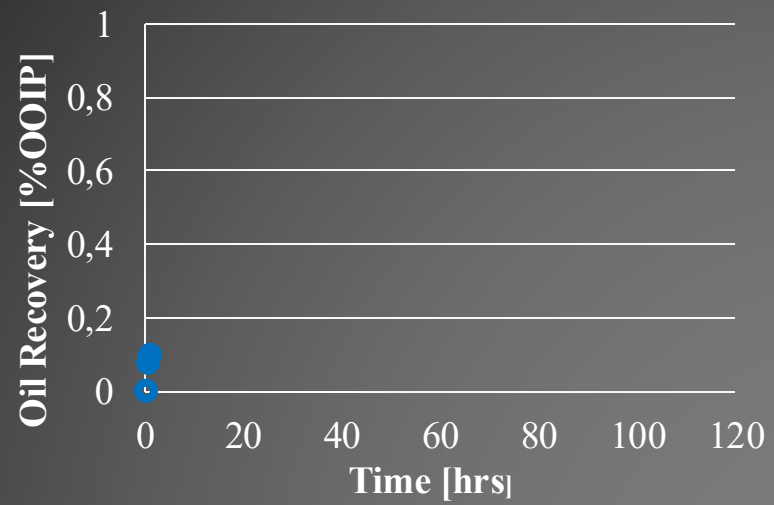


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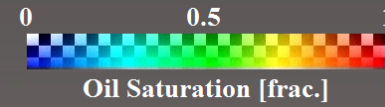


XZ-plane

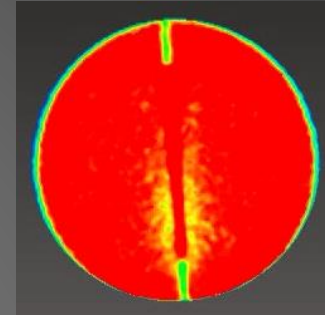
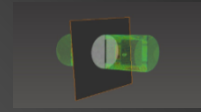




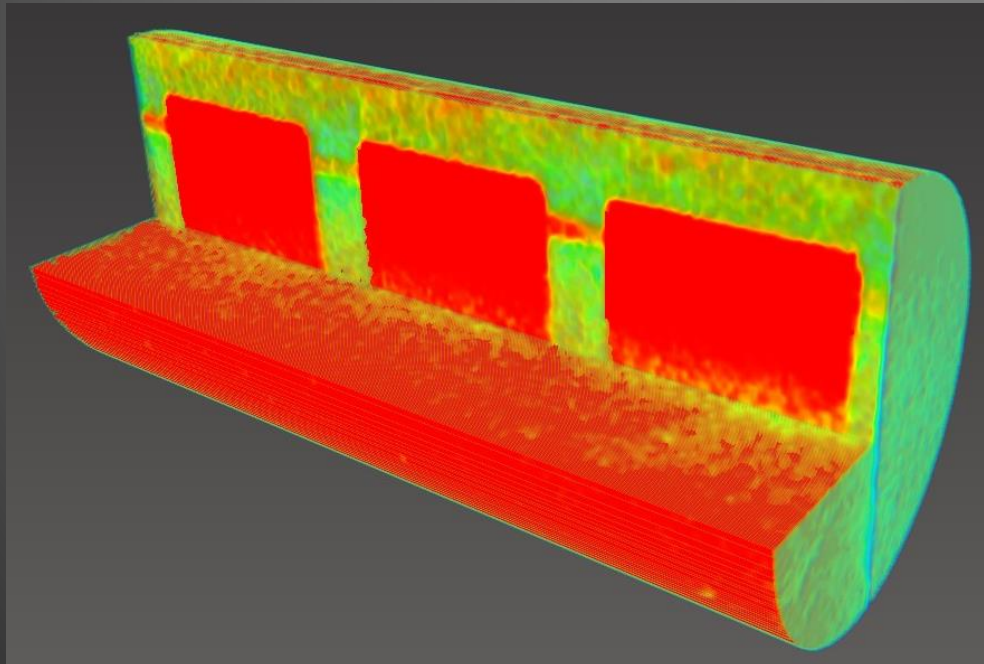
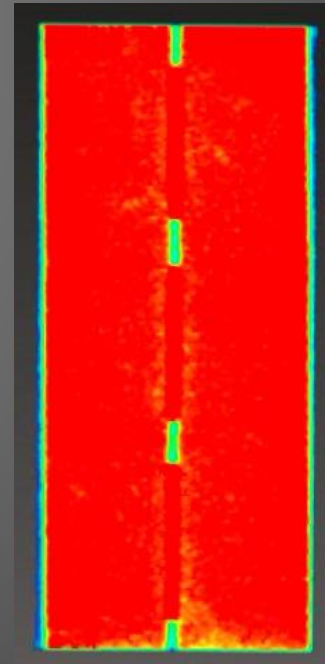
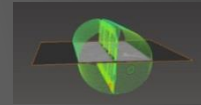
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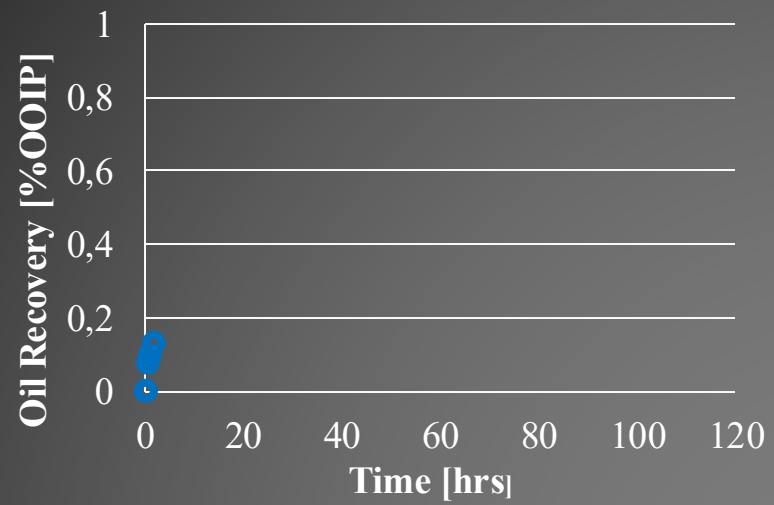


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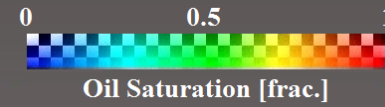


XZ-plane

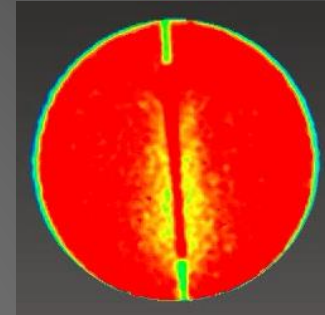
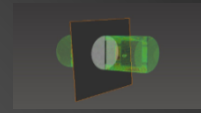




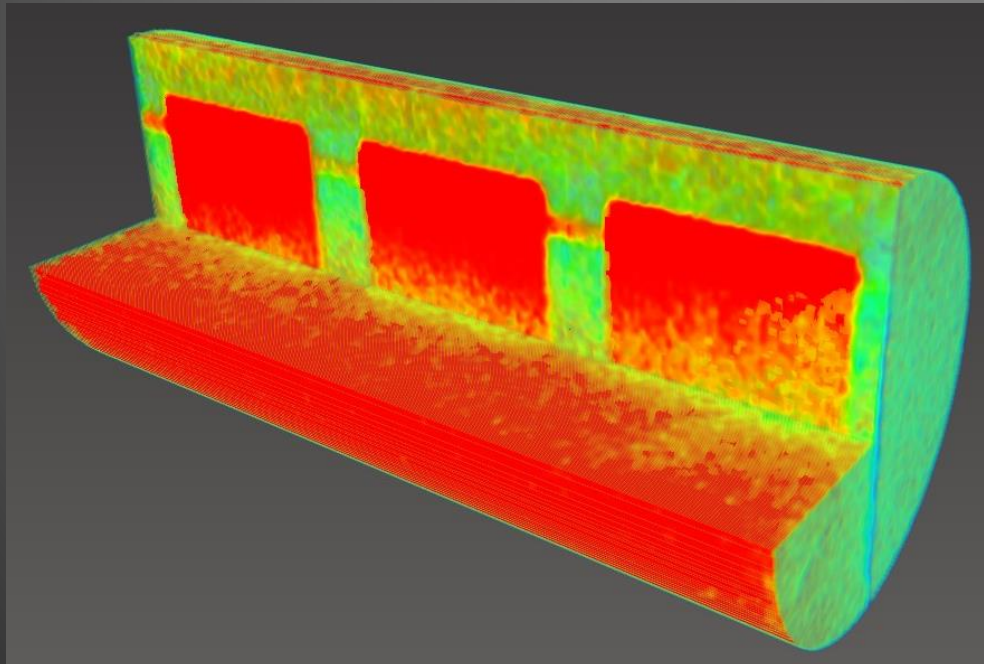
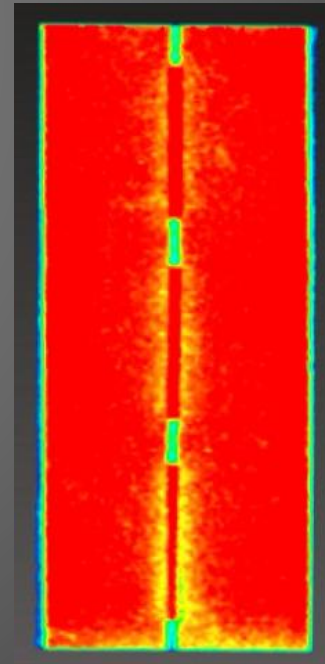
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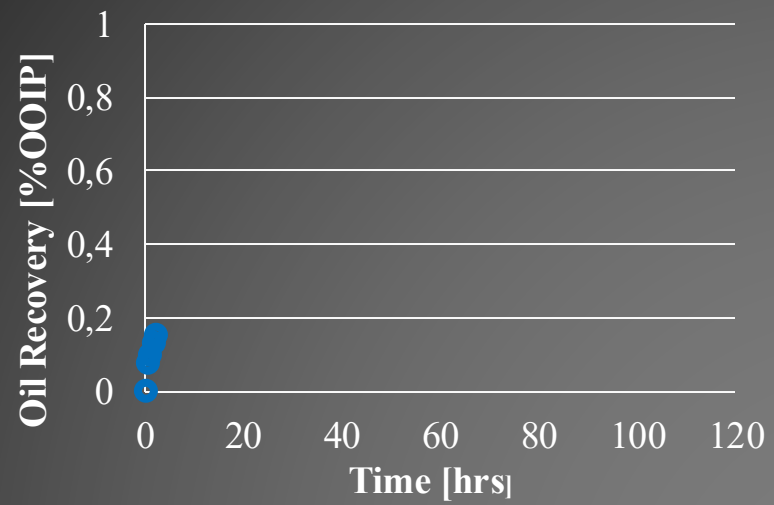


XY-plane

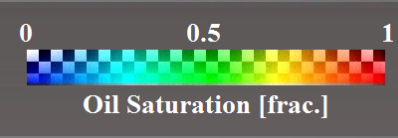


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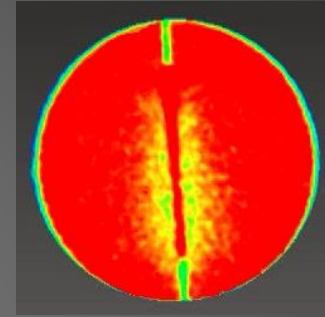
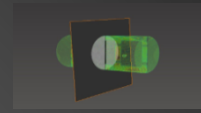




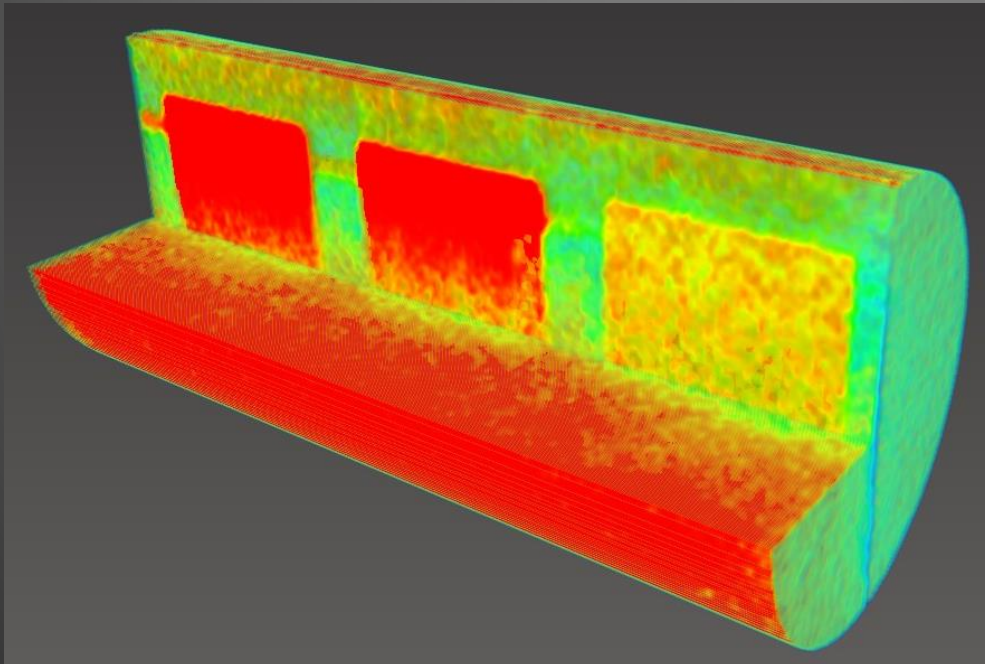
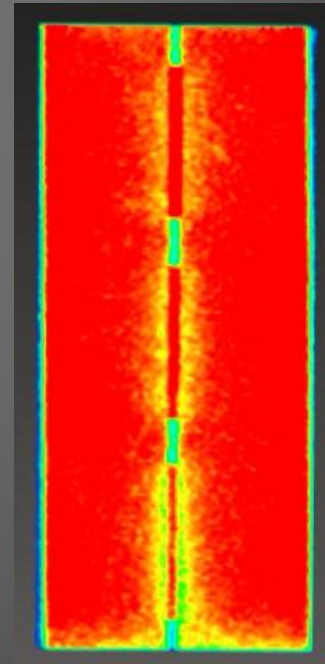
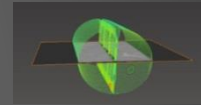
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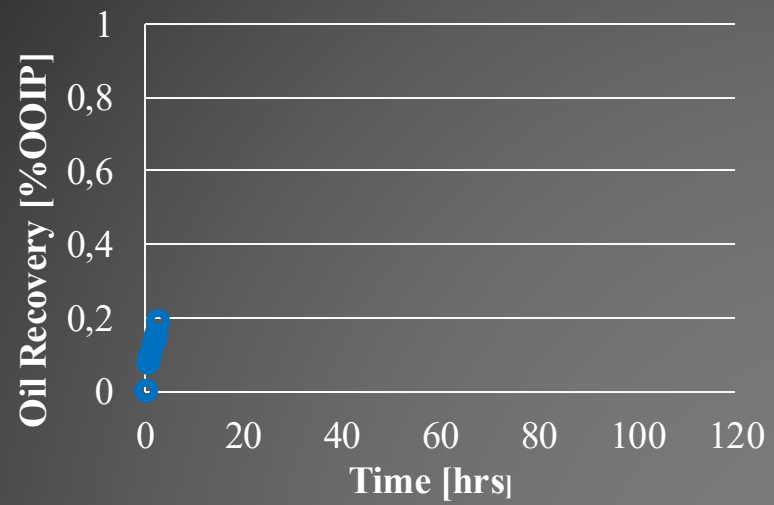


XY-plane

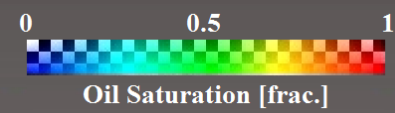


XZ-plane

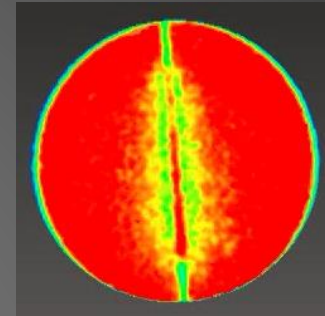
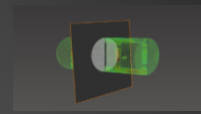




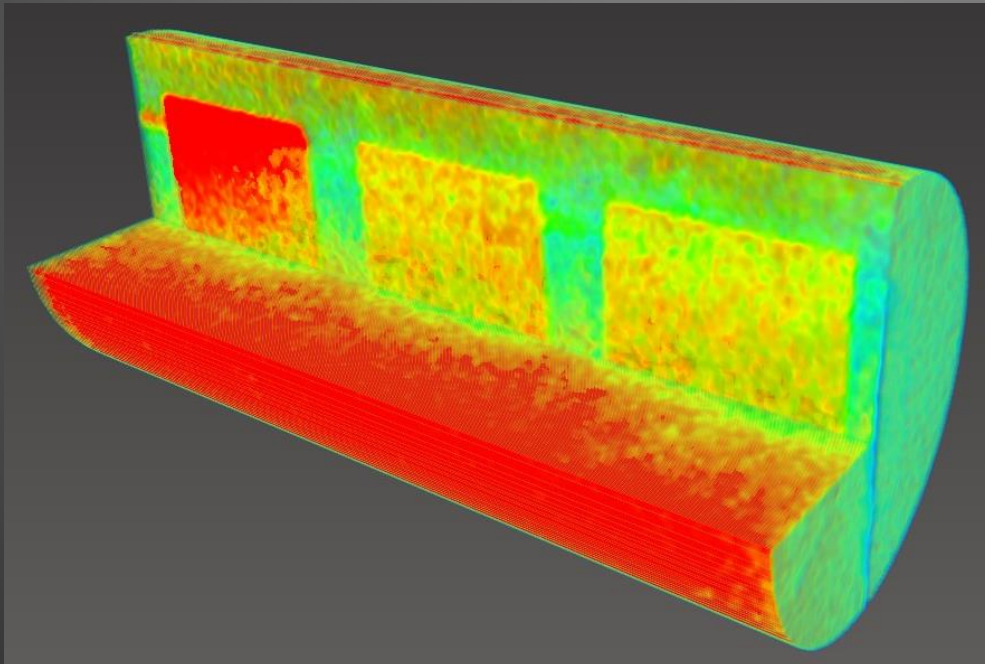
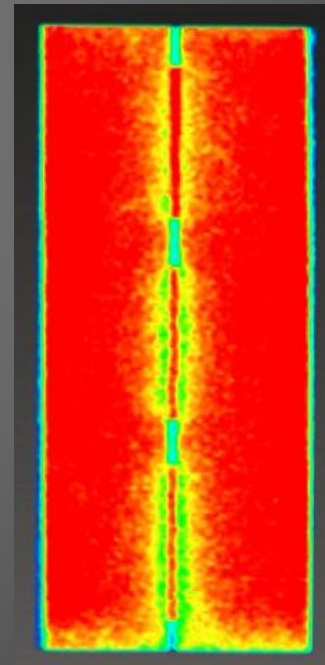
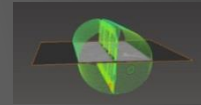
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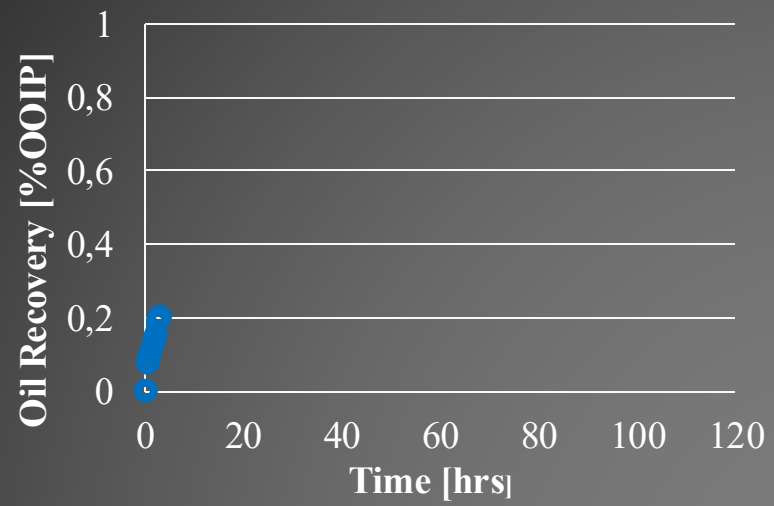


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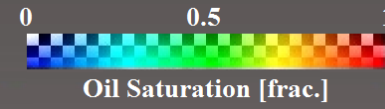


XZ-plane

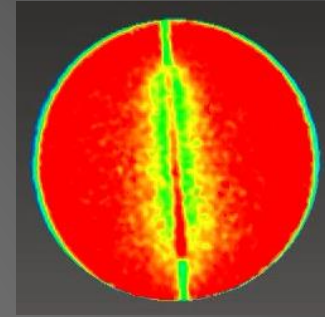
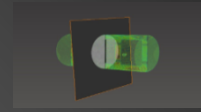




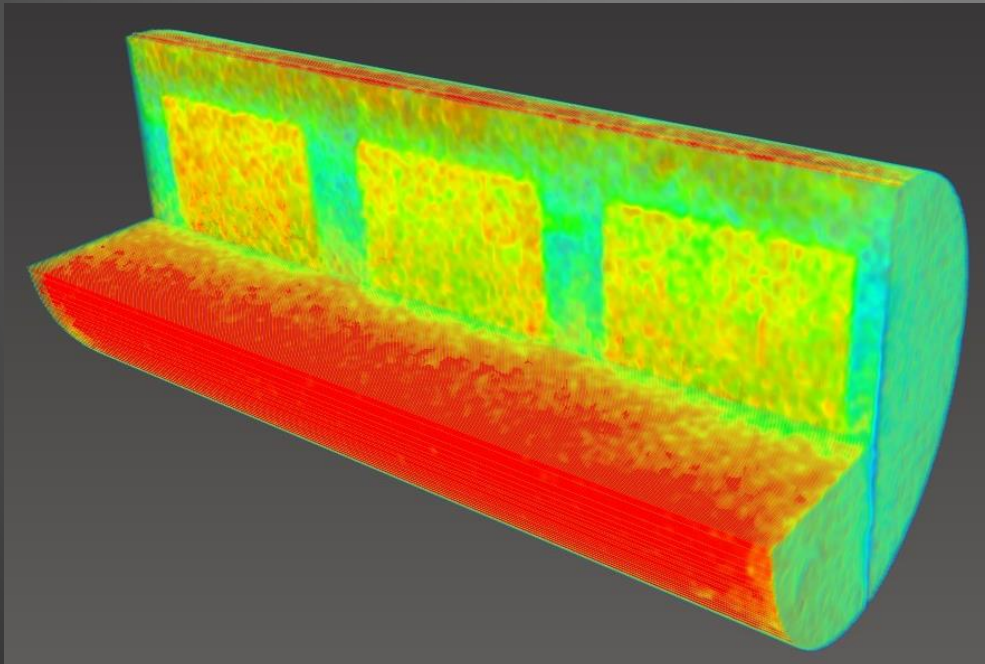
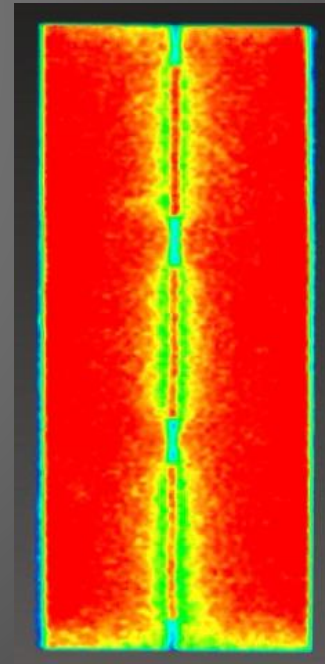
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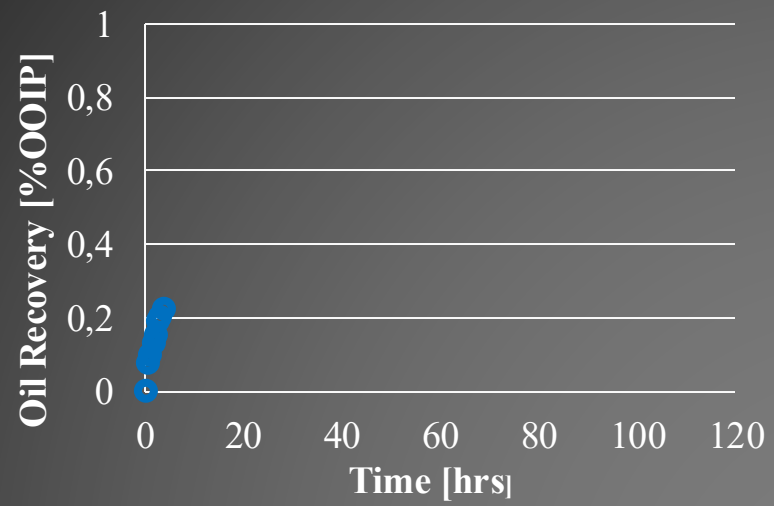


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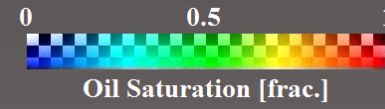


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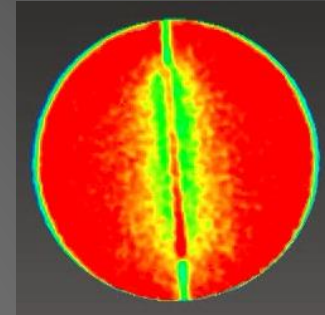
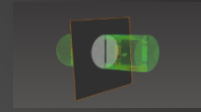




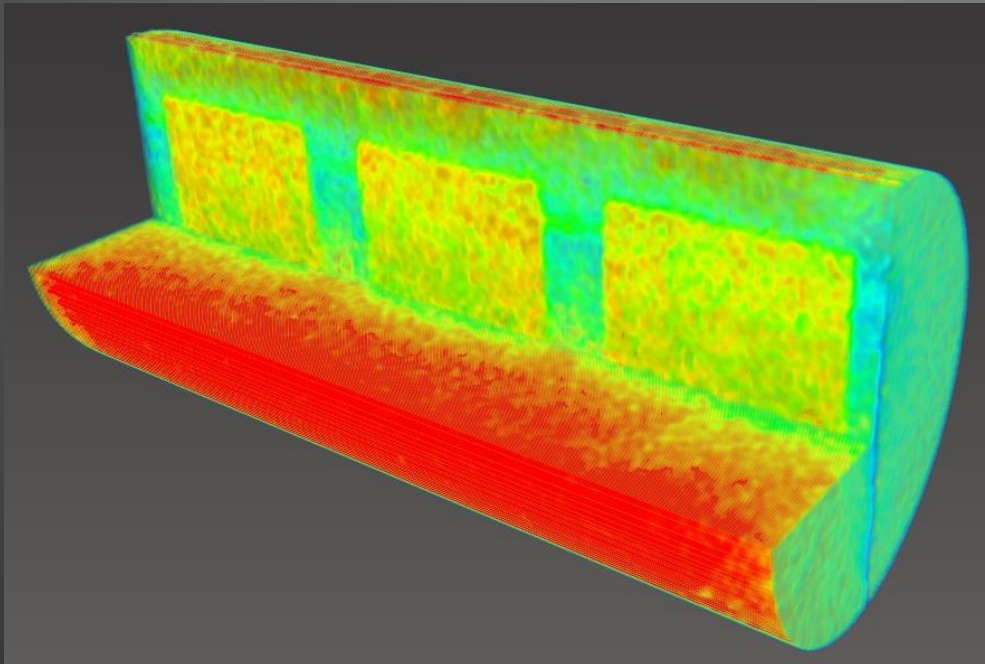
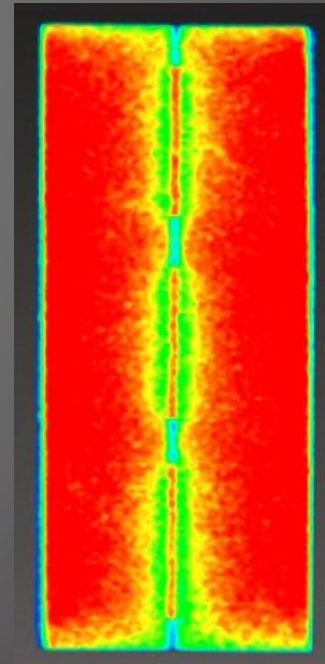
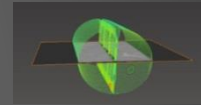
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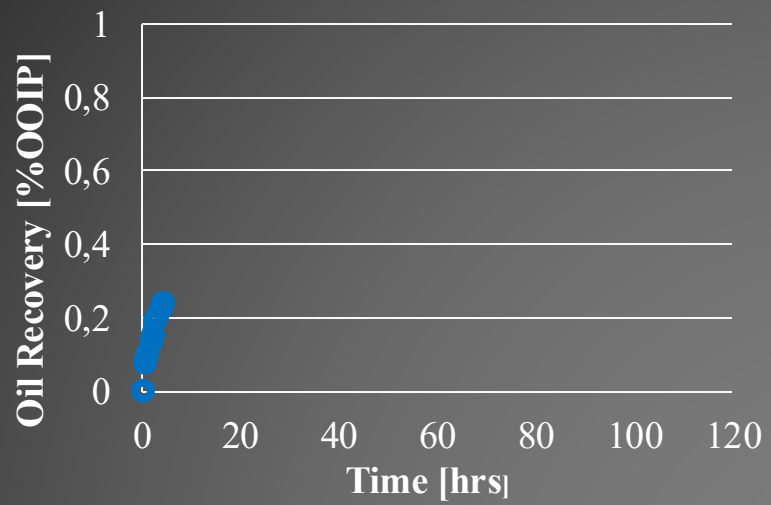


XY-plane

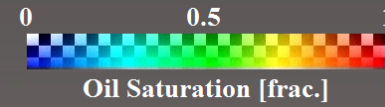


XZ-plane

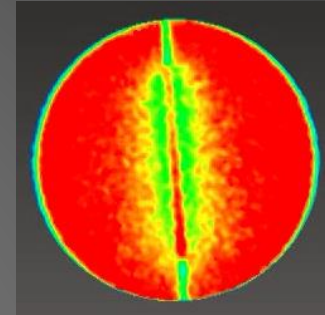
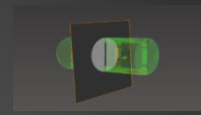




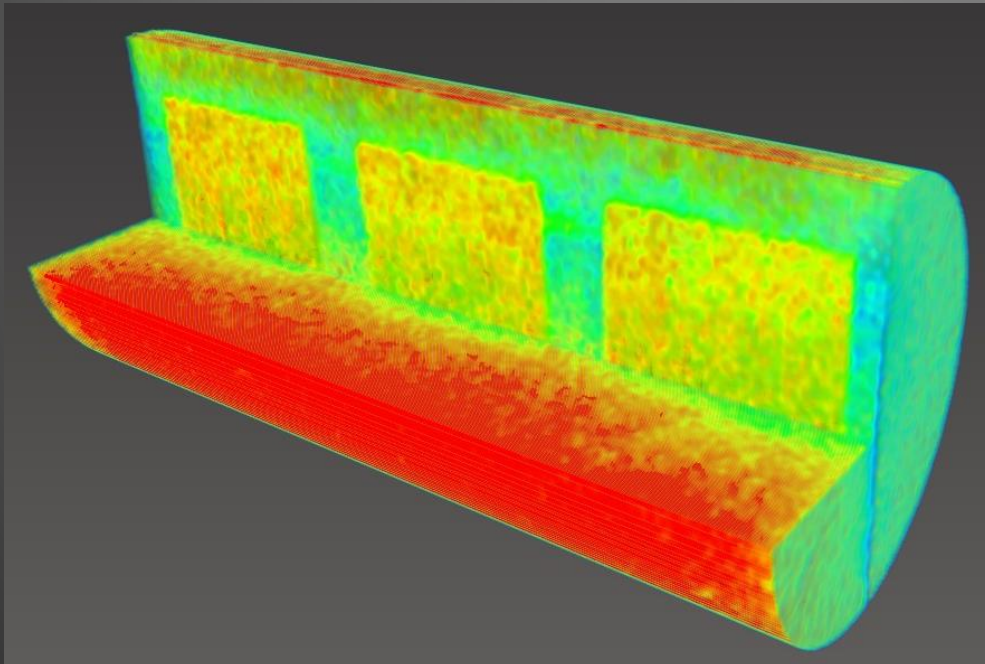
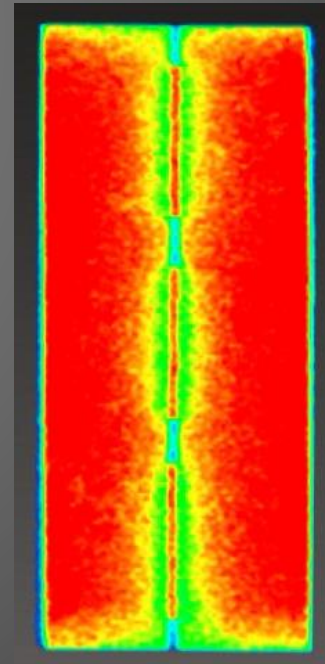
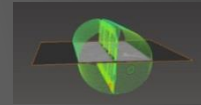
4.2 hrs

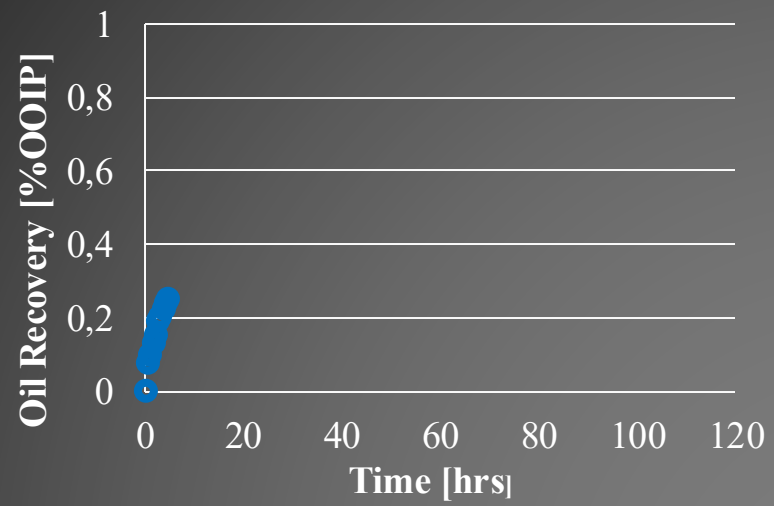


XY-plane

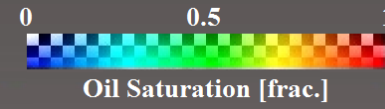


XZ-plane

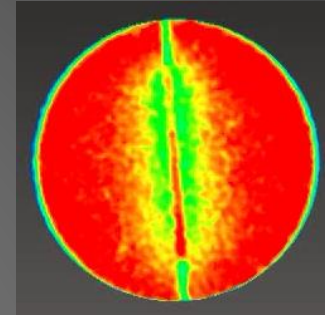
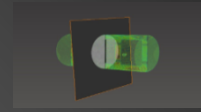




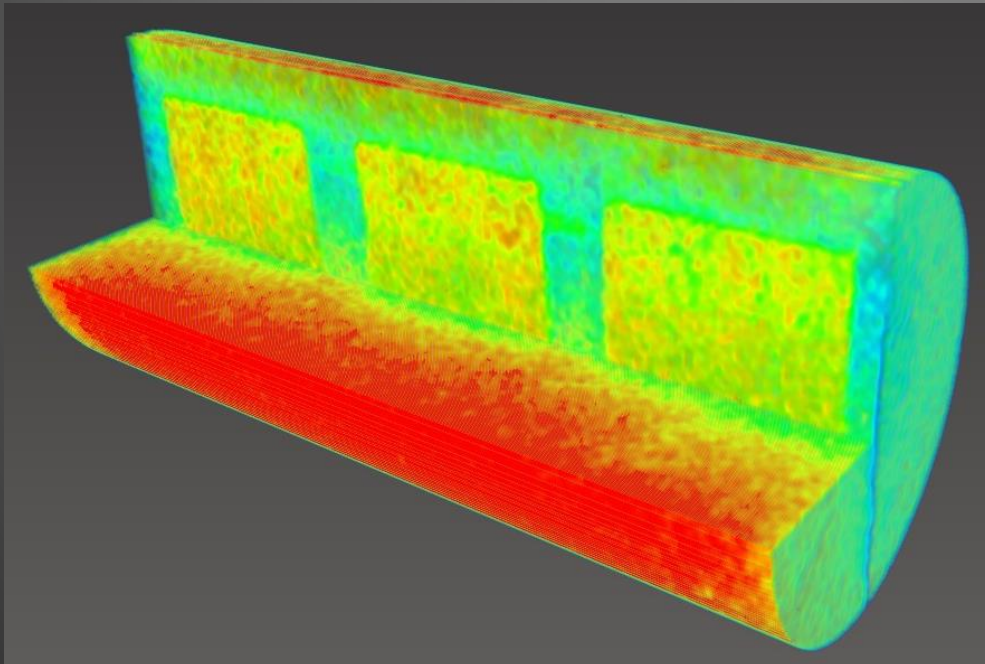
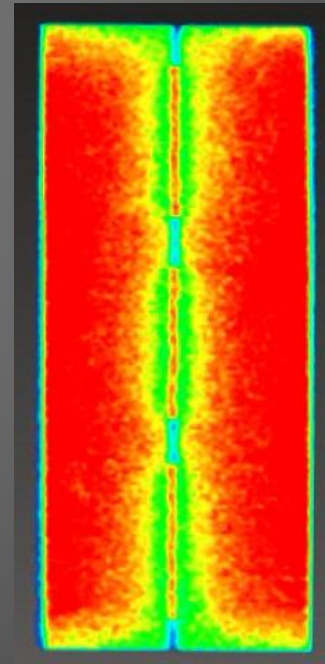
4.7 hrs

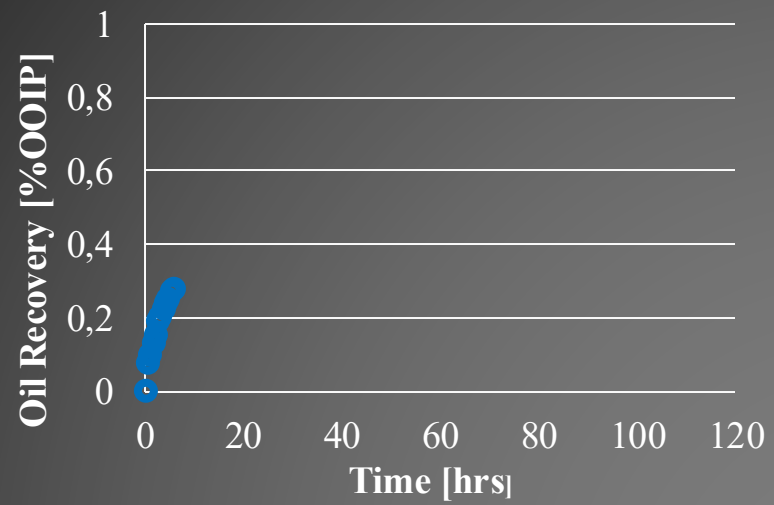


XY-plane

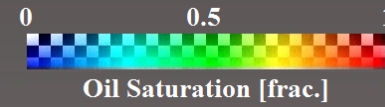


XZ-plane

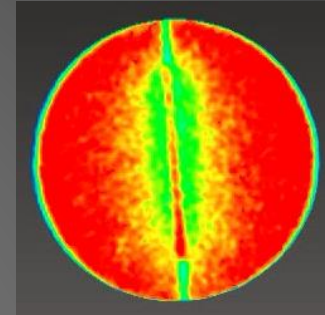
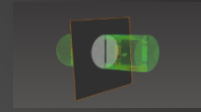




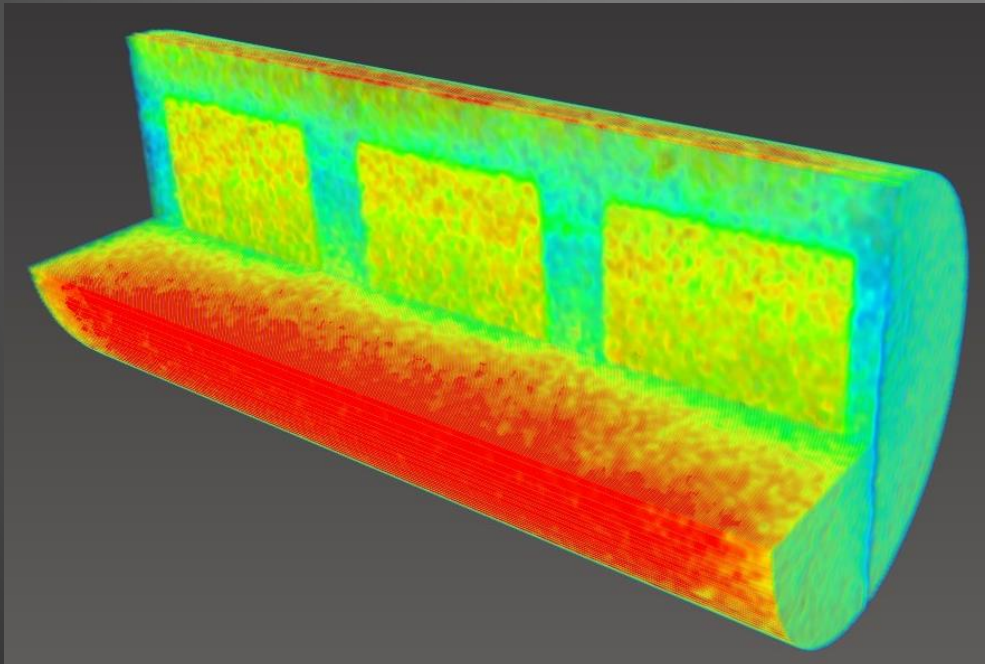
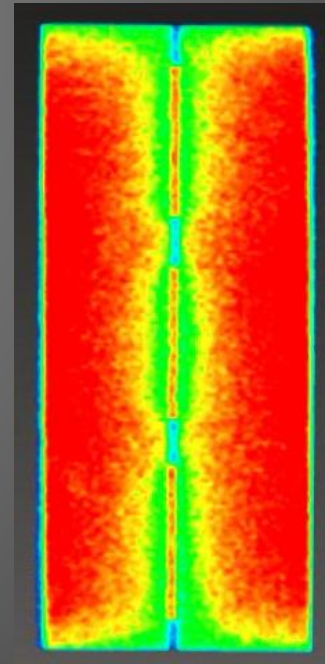
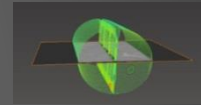
5.7 hrs

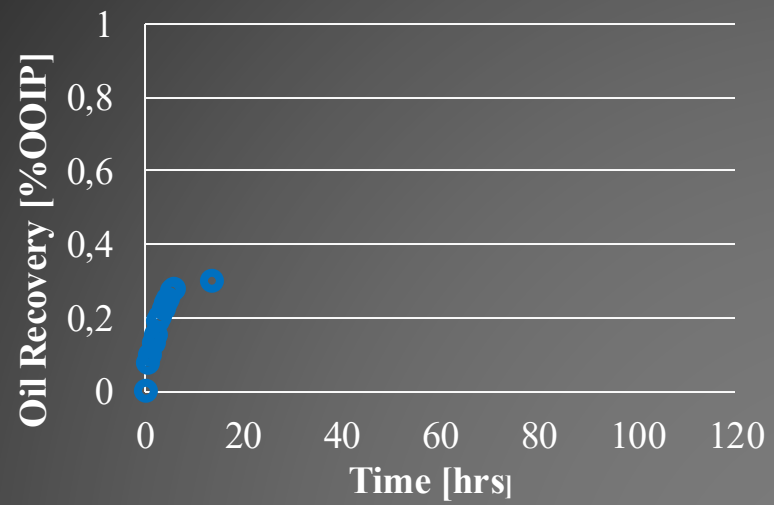


XY-plane

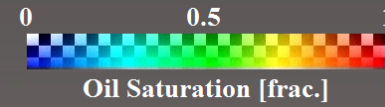


XZ-plane

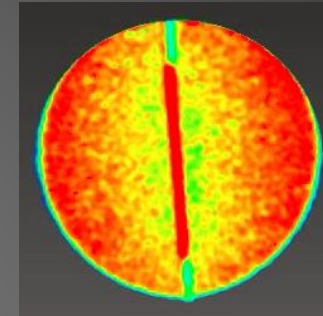
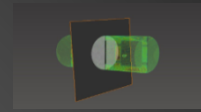




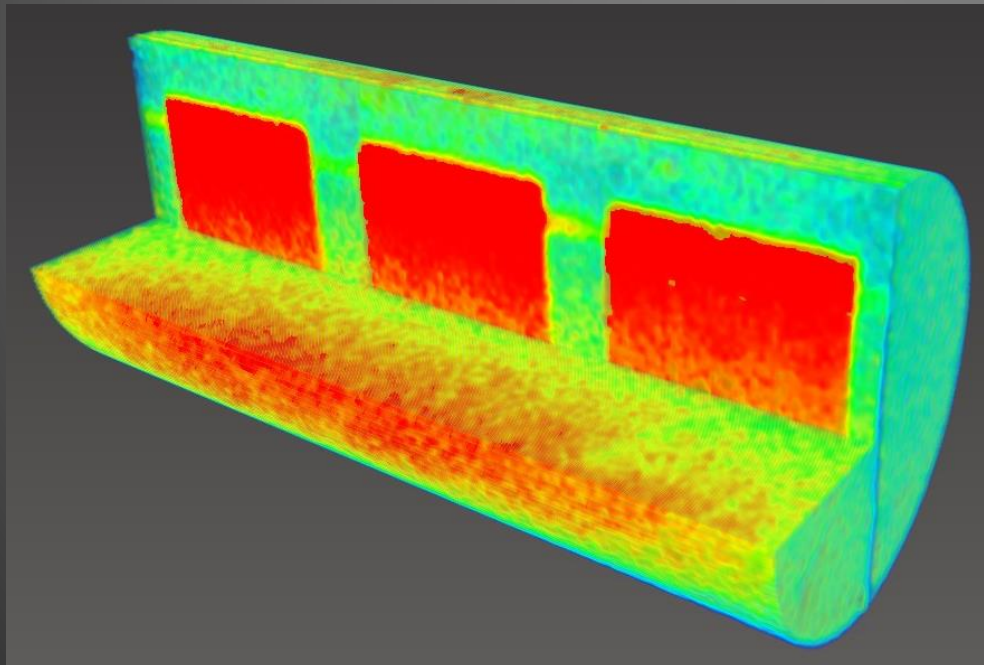
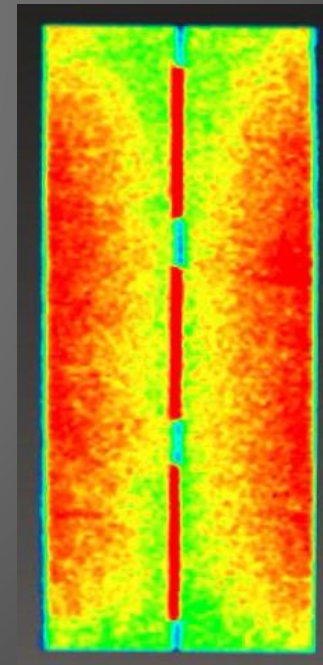
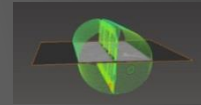
13.6 hrs

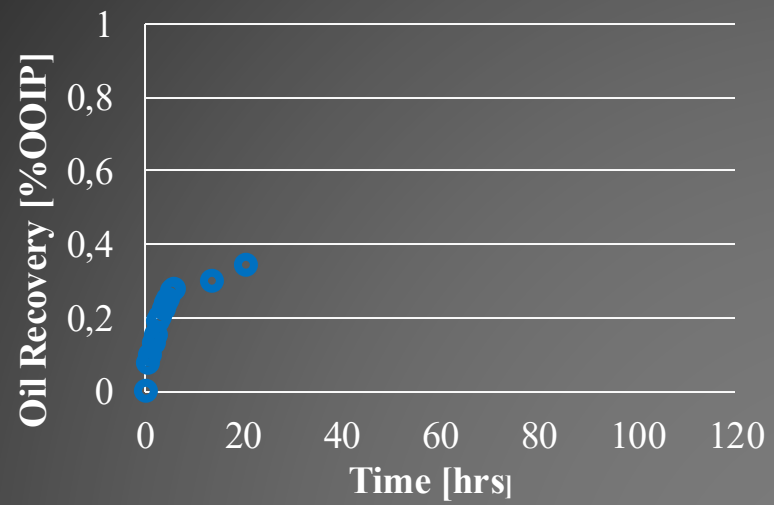


XY-plane

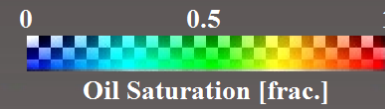


XZ-plane

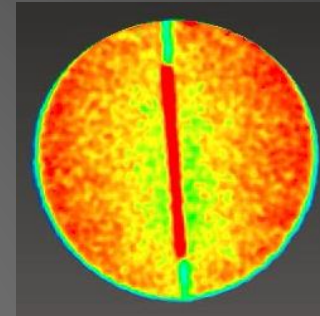
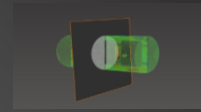




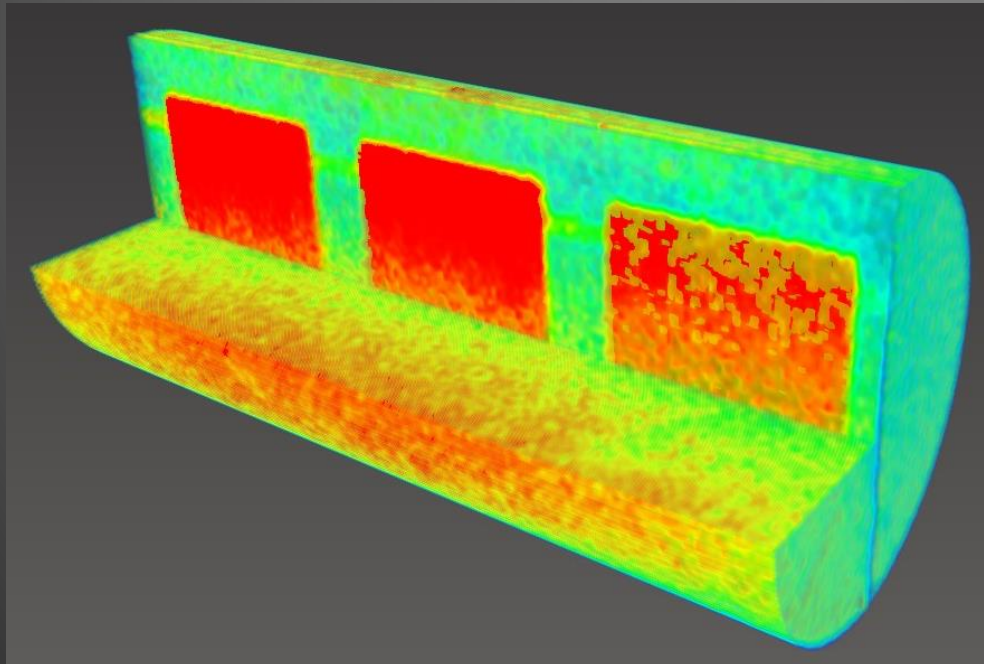
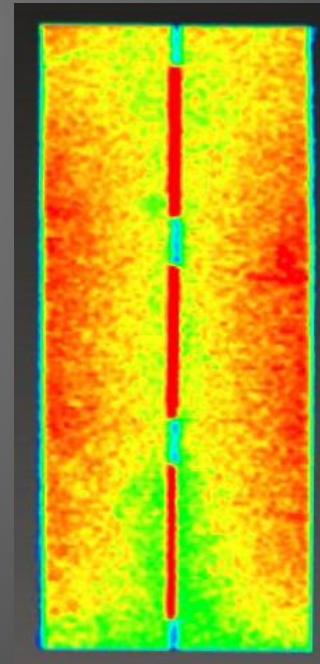
20.4 hrs

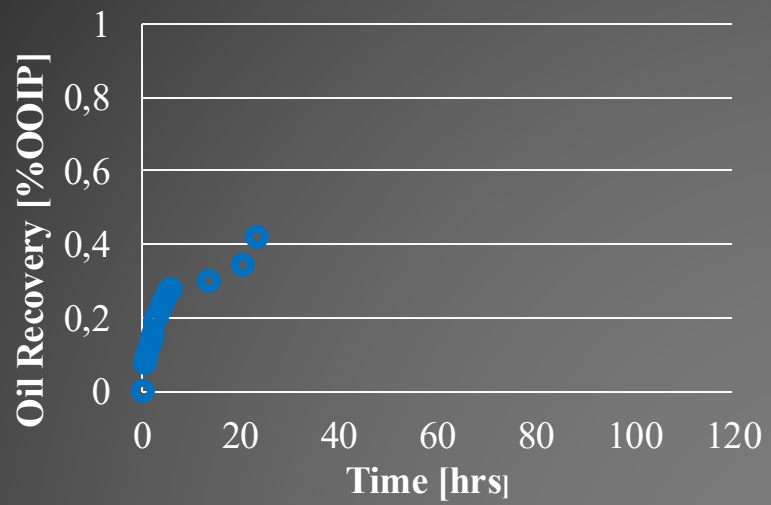


XY-plane

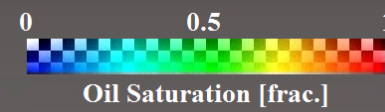


XZ-plane

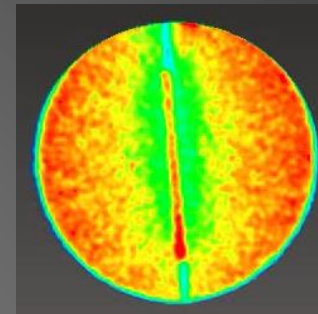
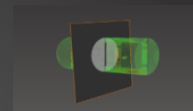




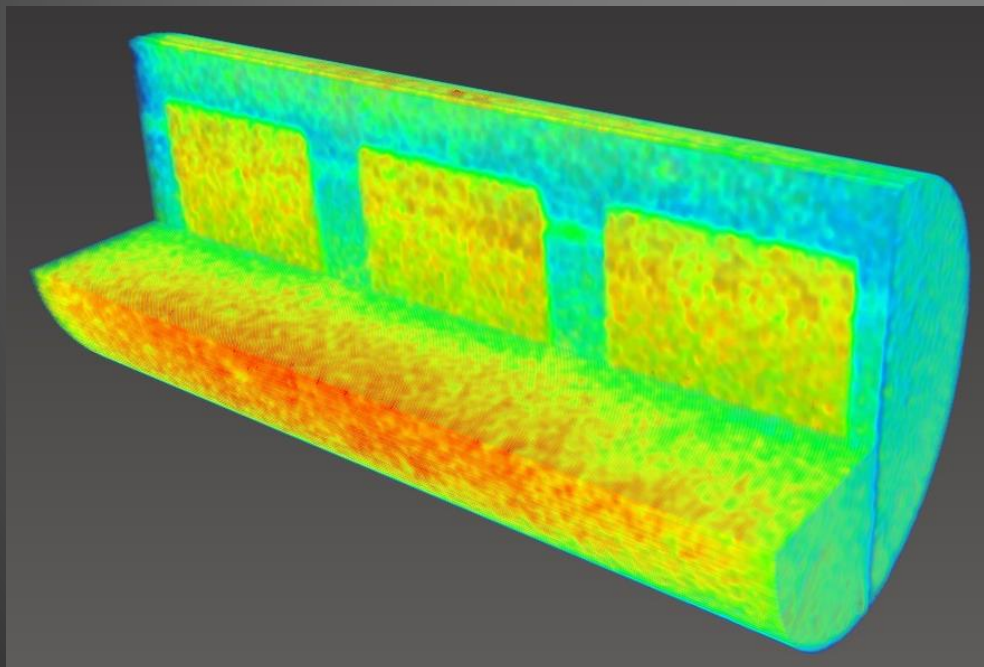
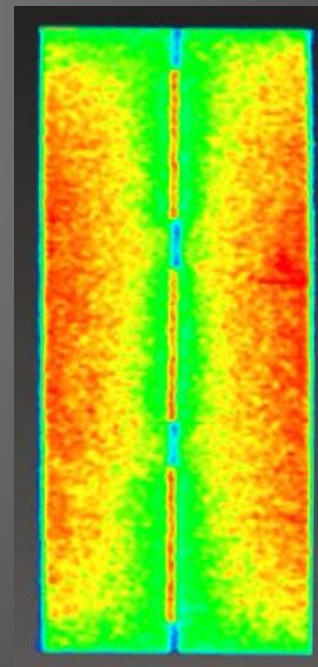
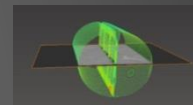
23.3 hrs

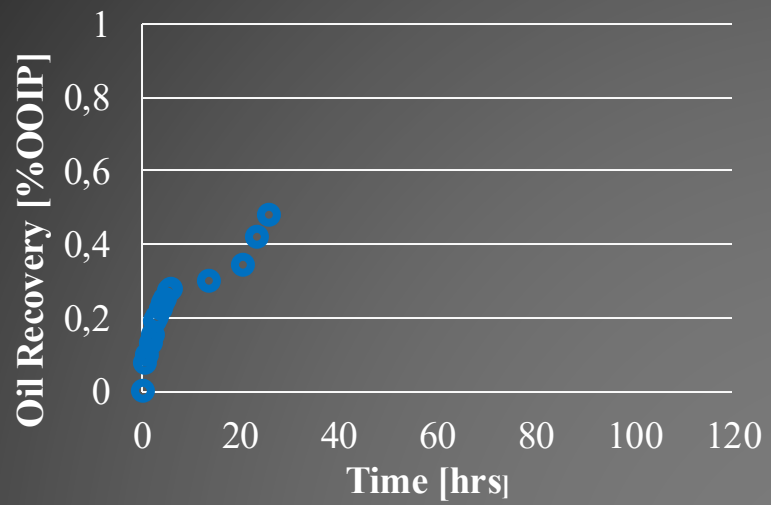


XY-plane

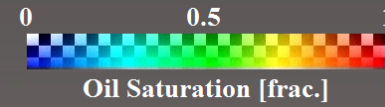


XZ-plane

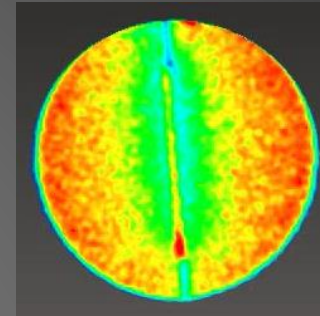
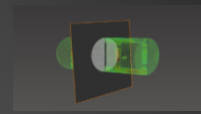




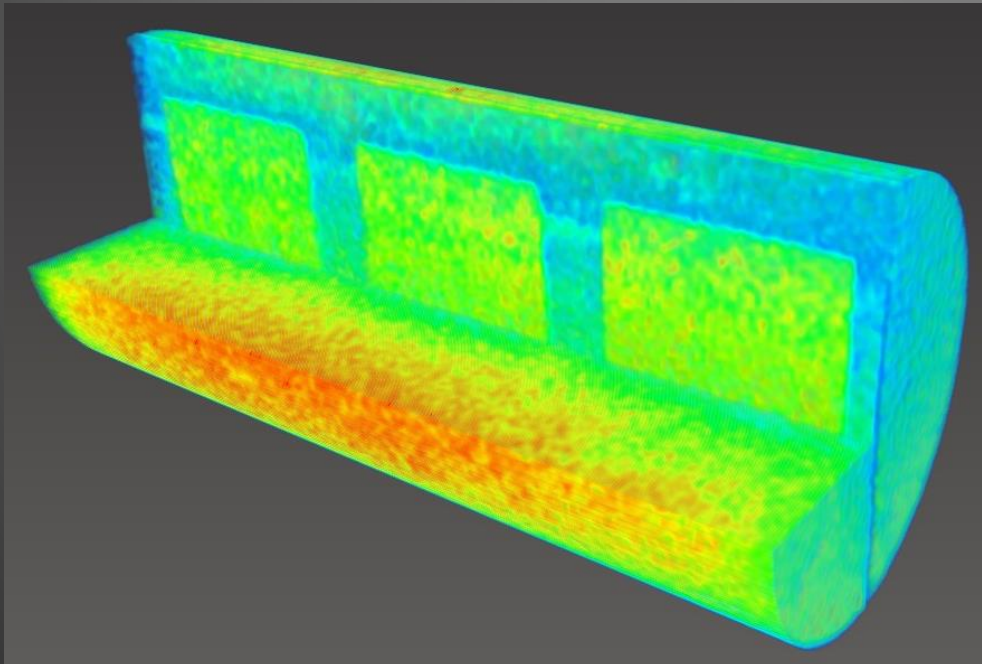
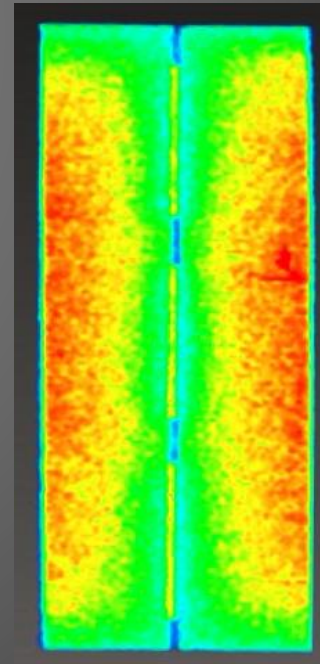
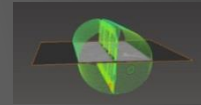
25.9 hrs

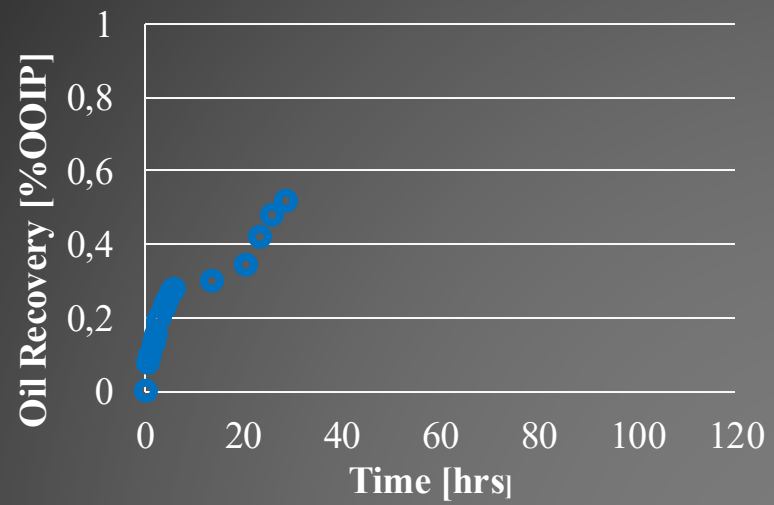


XY-plane

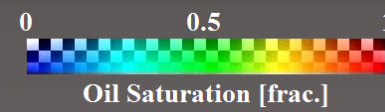


XZ-plane

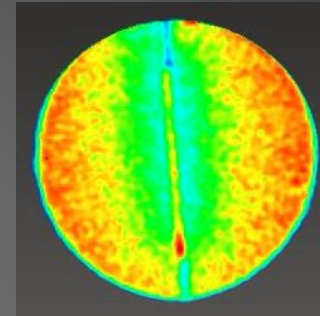
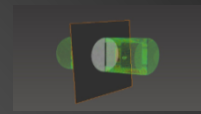




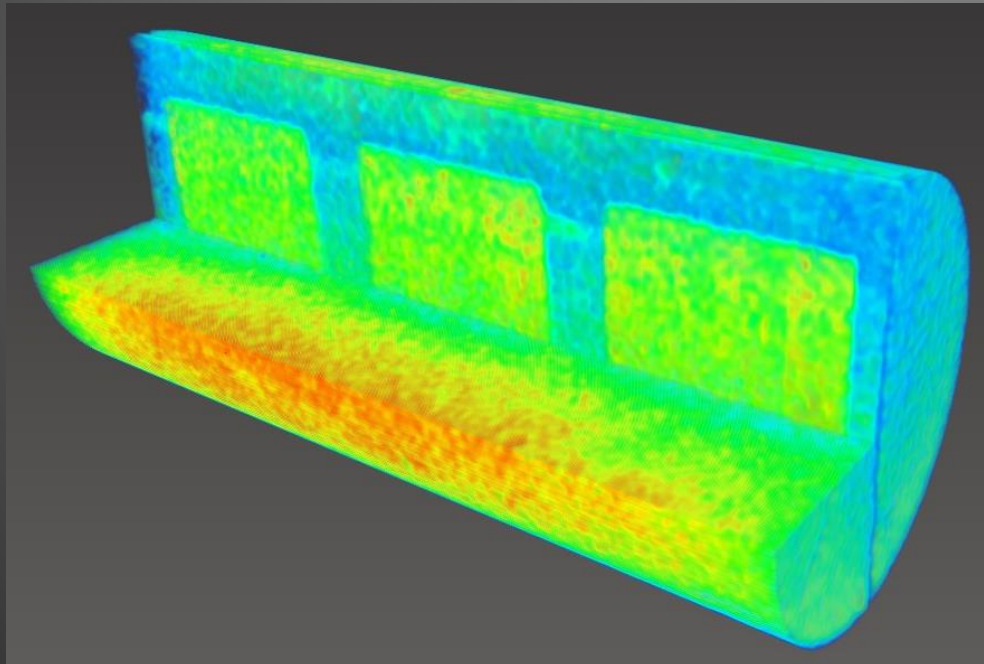
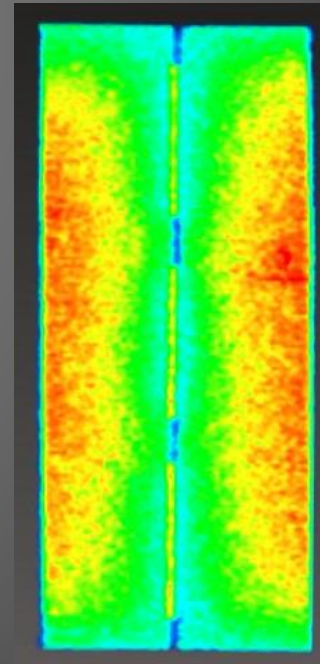
28.8 hrs

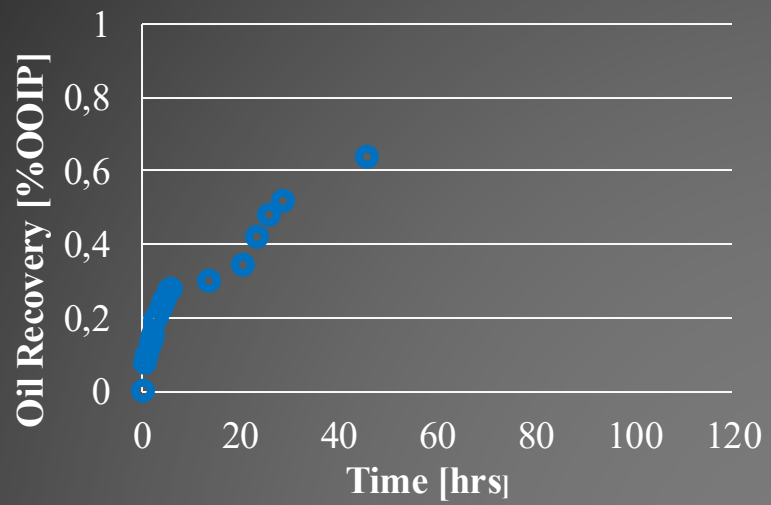


XY-plane

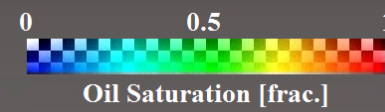


XZ-plane

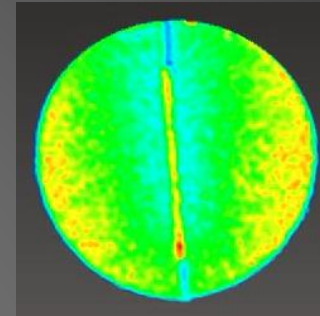
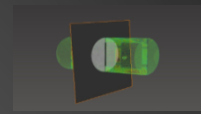




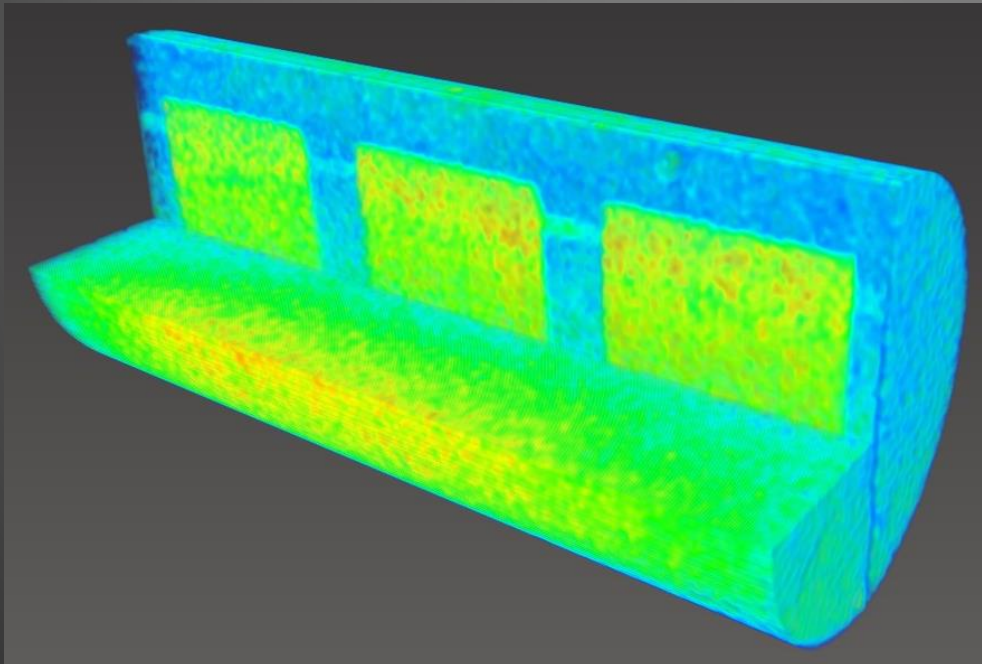
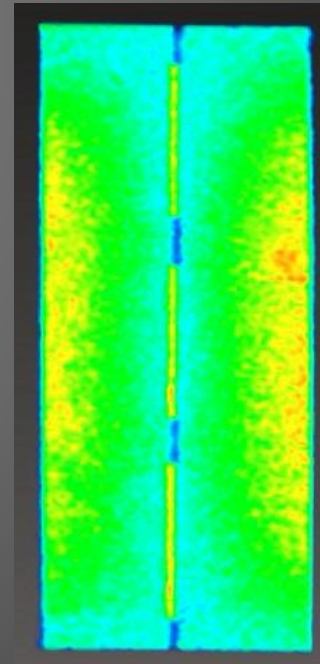
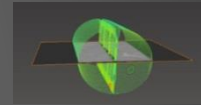
45.6 hrs

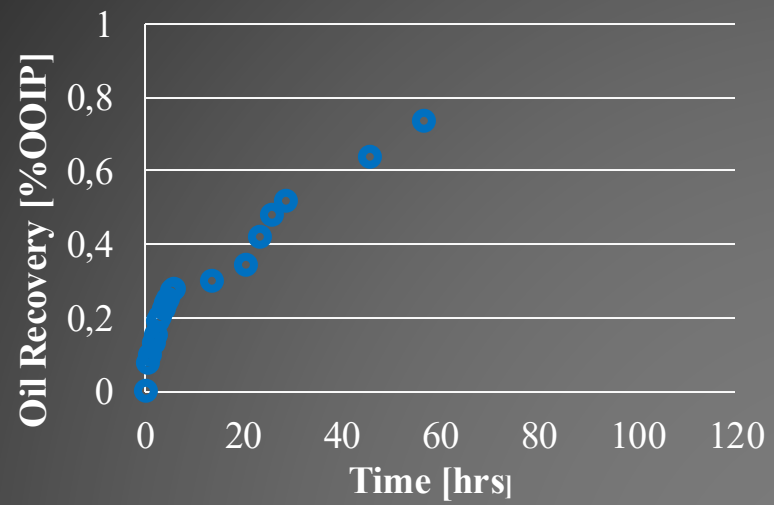


XY-plane

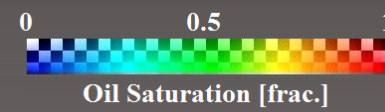


XZ-plane

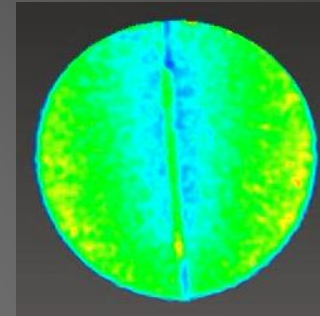
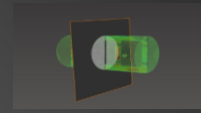




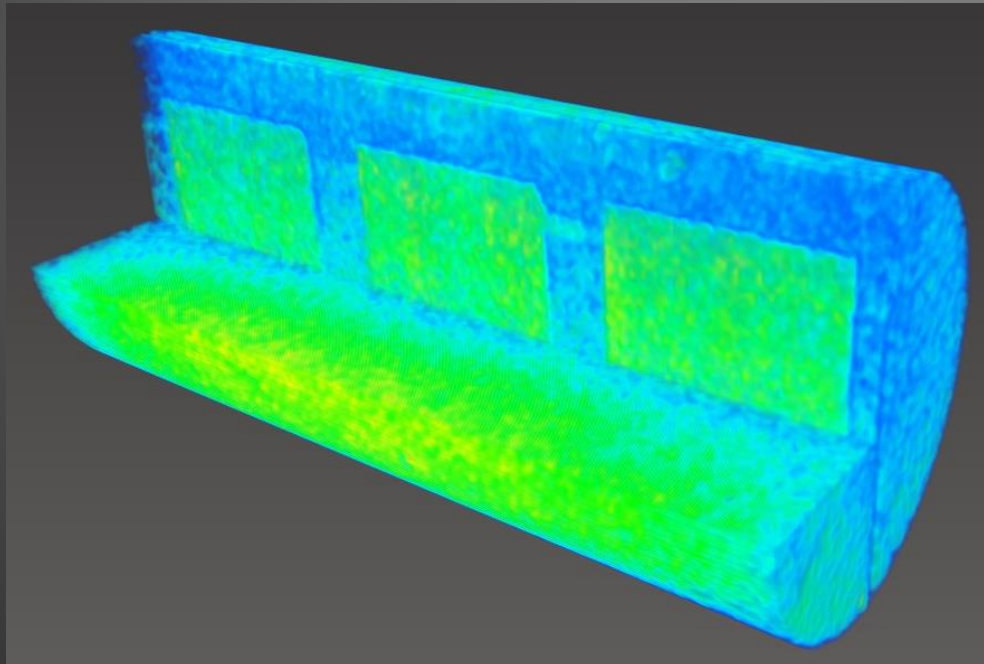
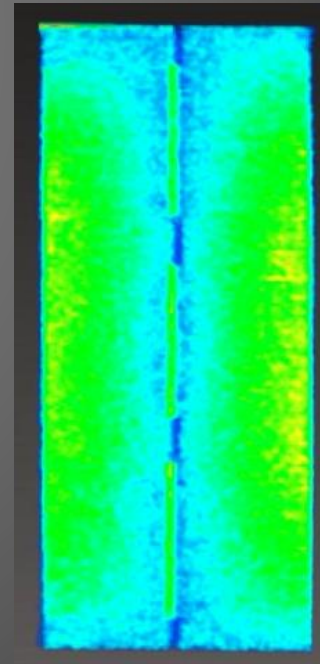
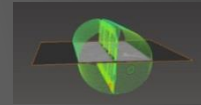
56.8 hrs

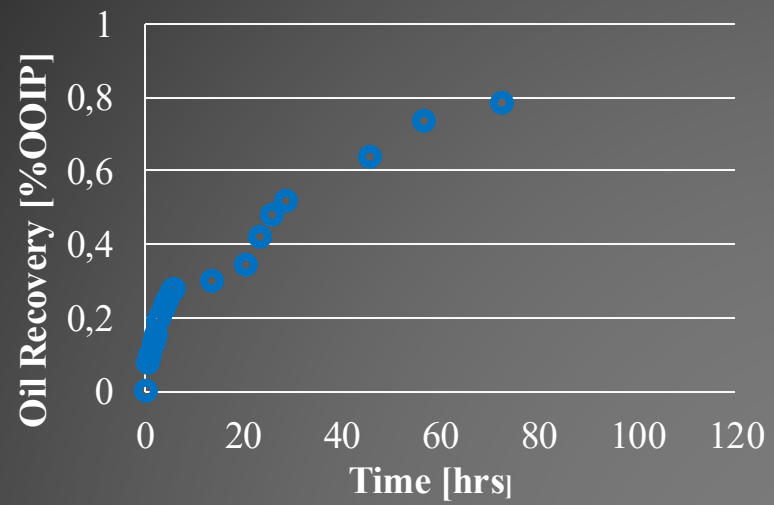


XY-plane

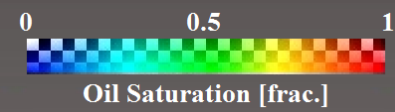


XZ-plane

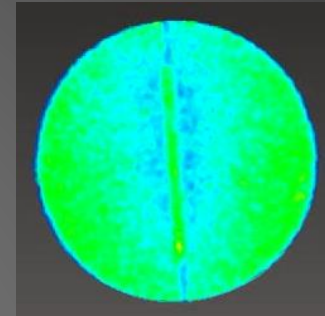
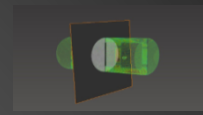




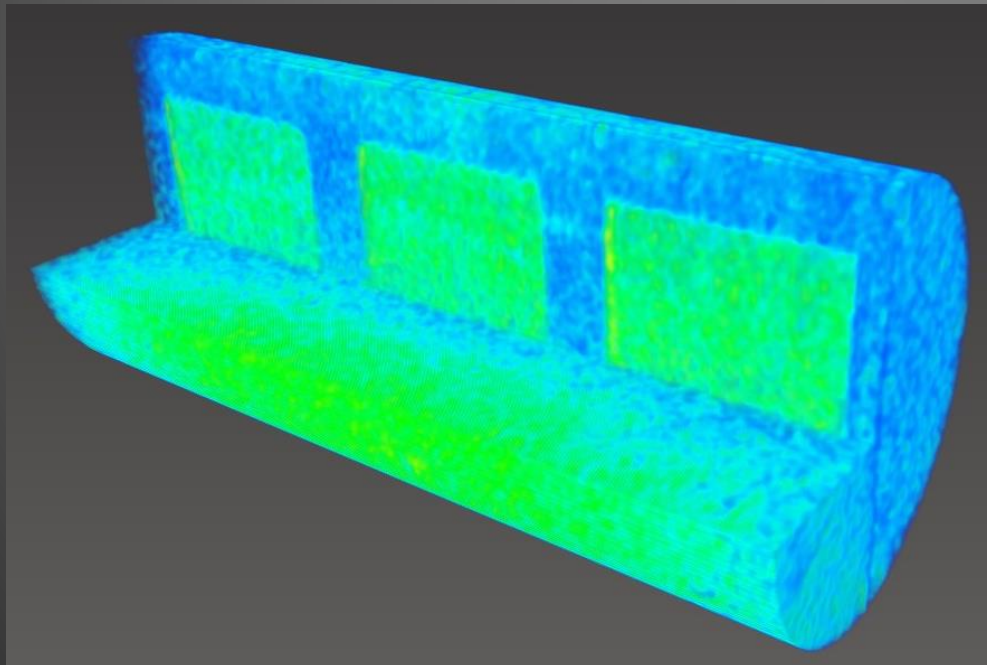
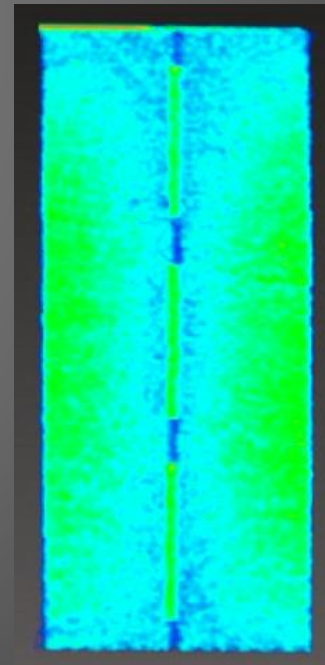
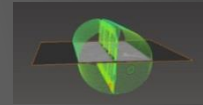
72.6 hrs

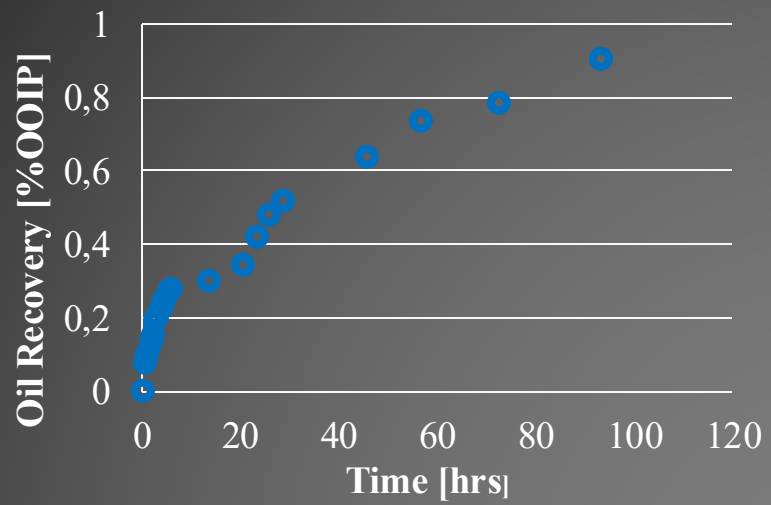


XY-plane

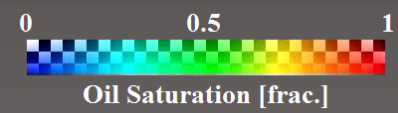


XZ-plane

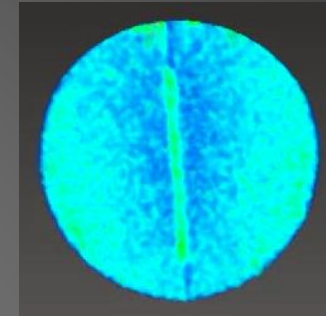
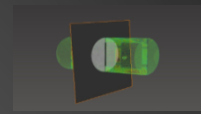




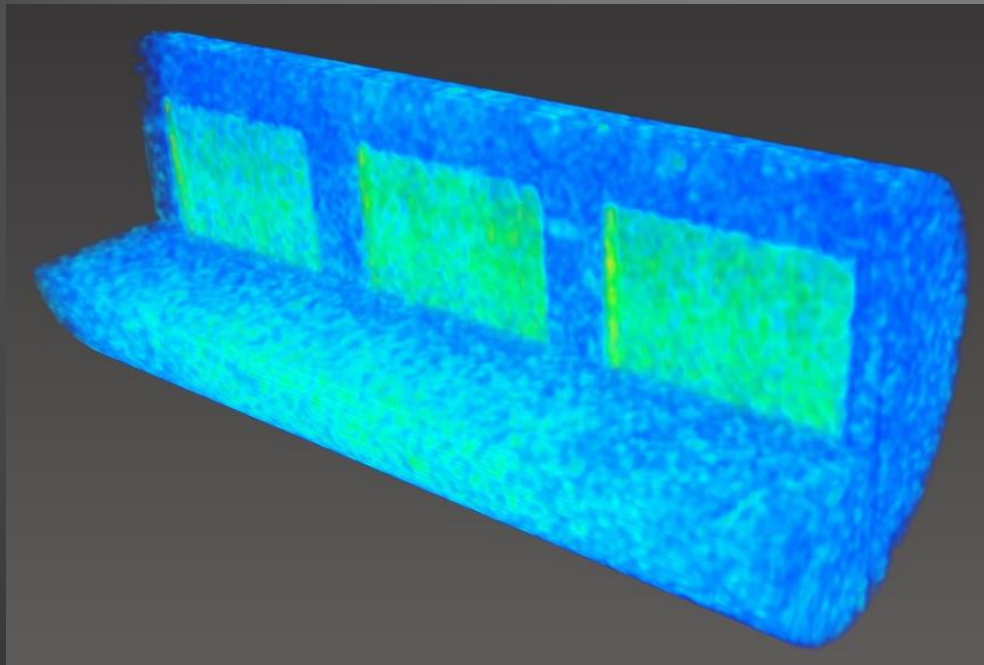
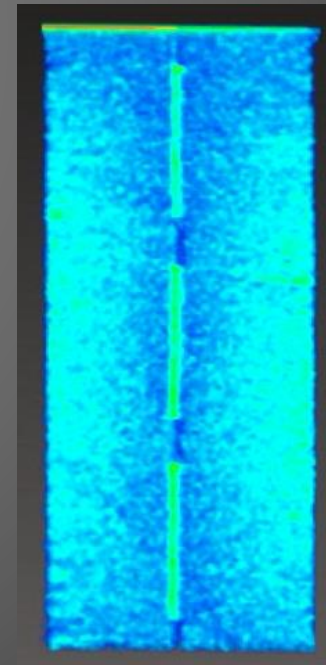
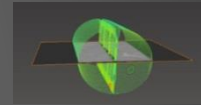
93.3 hrs

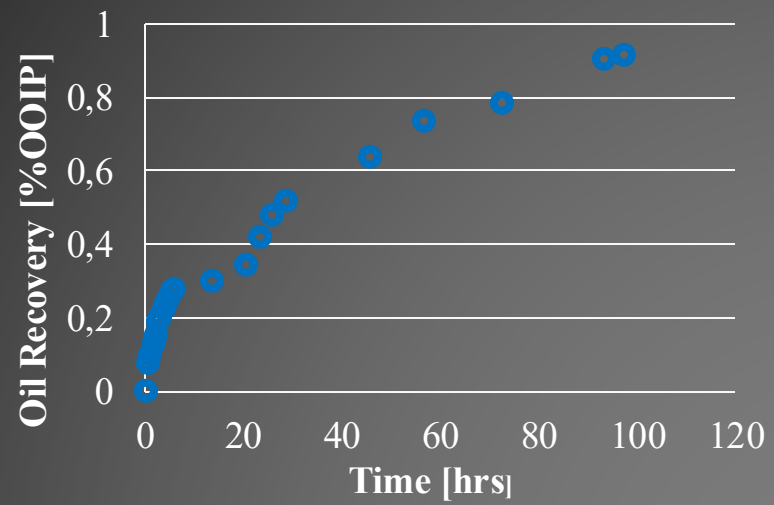


XY-plane

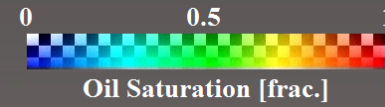


XZ-plane

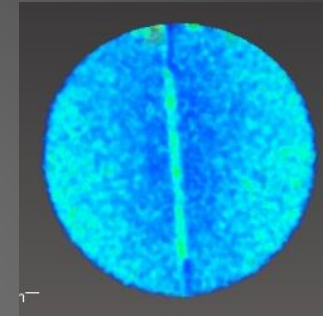
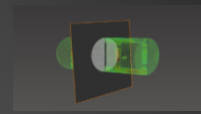




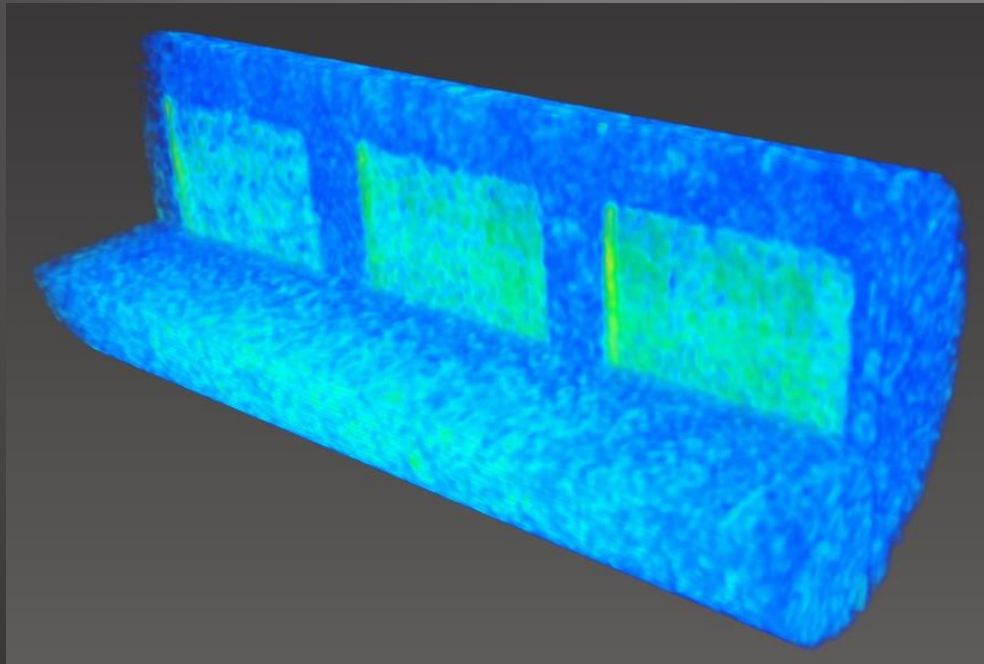
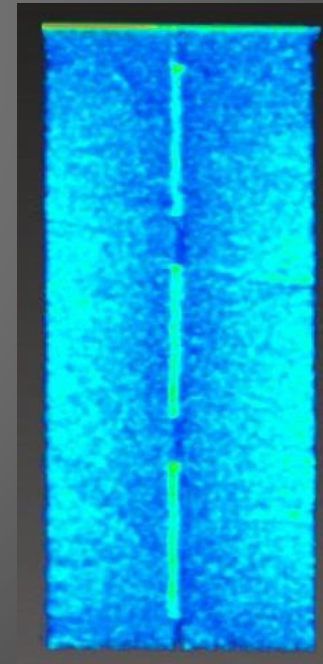
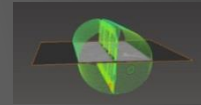
97.3 hrs

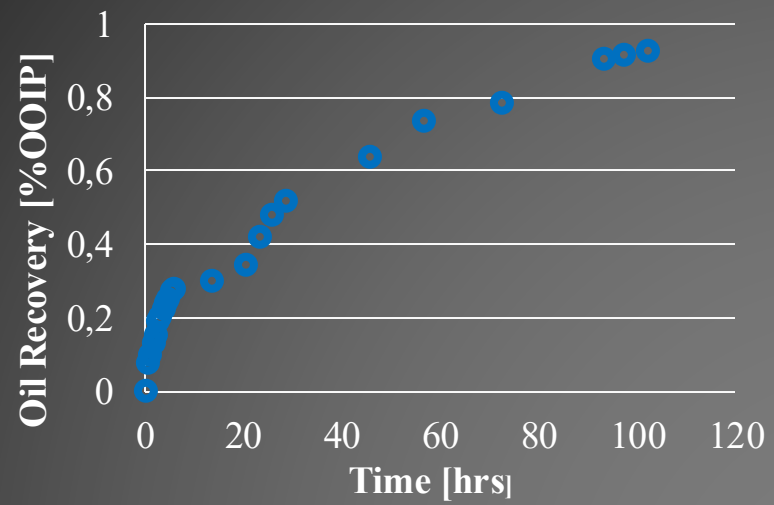


XY-plane

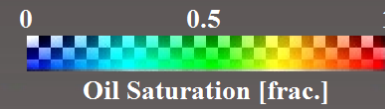


XZ-plane

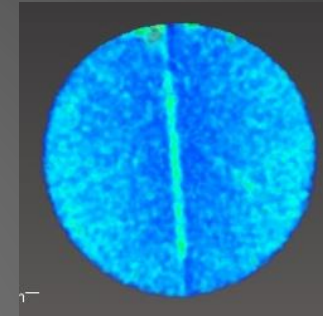
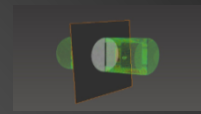




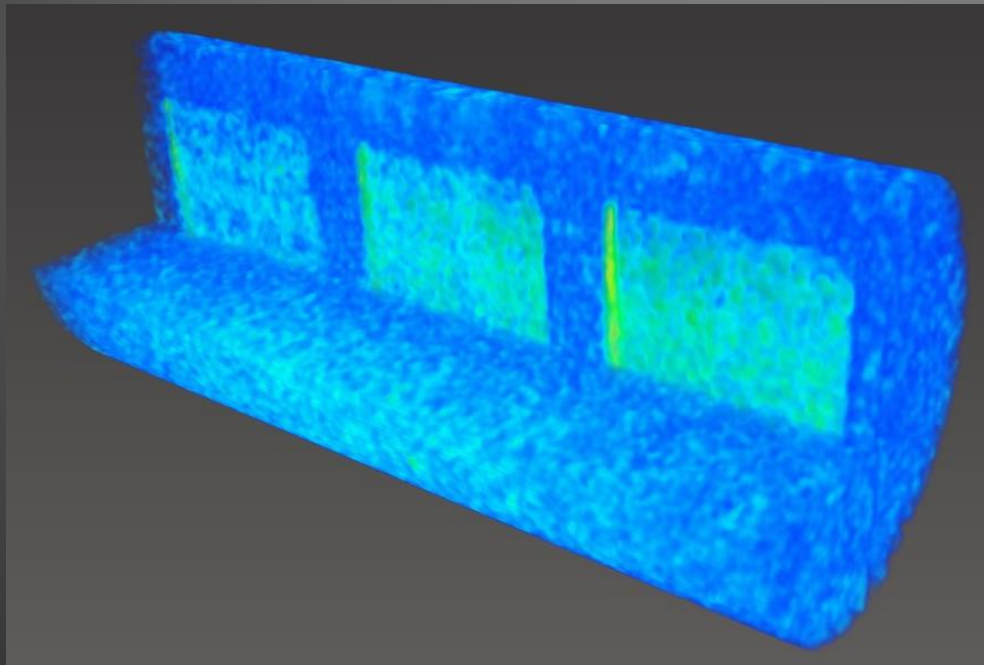
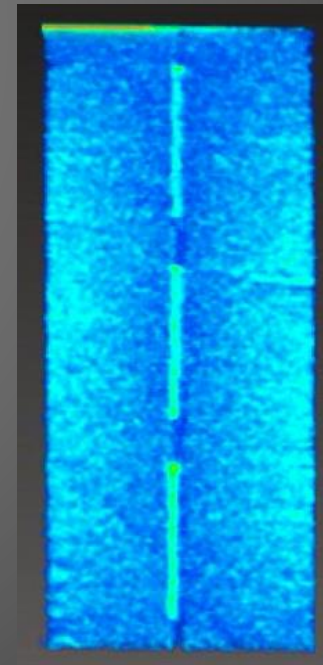
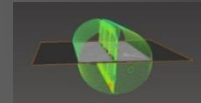
102.1 hrs

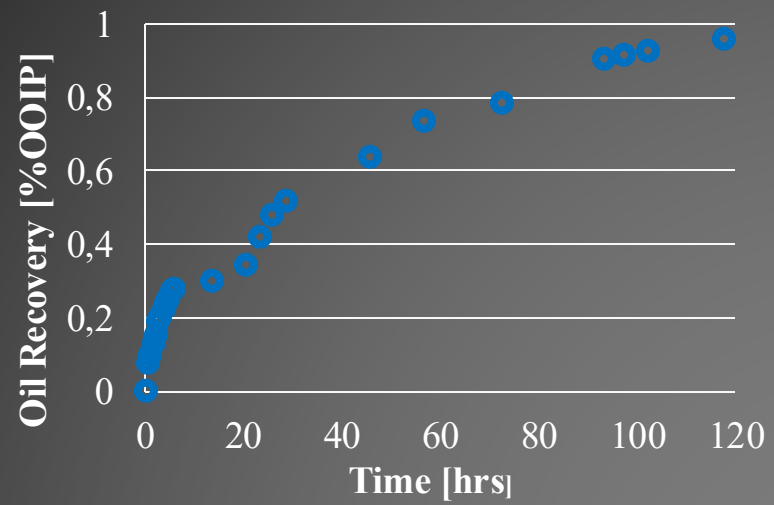


XY-plane



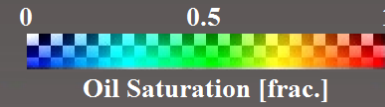
XZ-plane



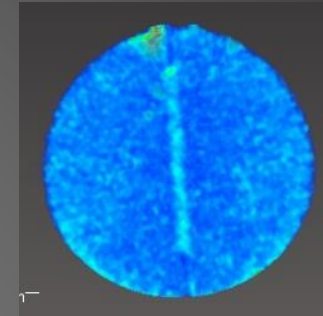
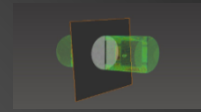


$R_f = 96.0 \%$

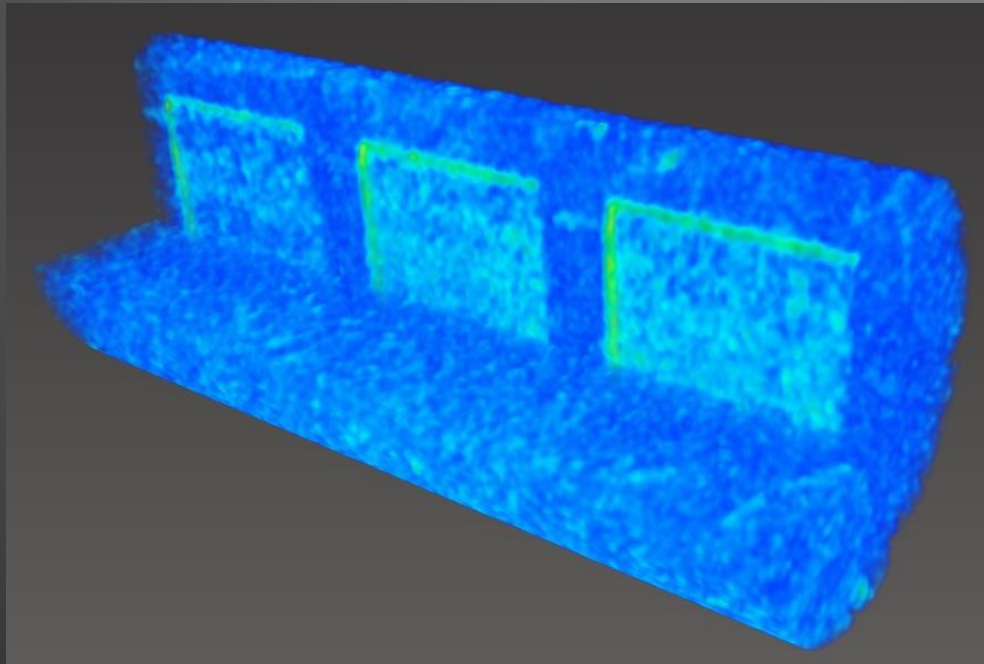
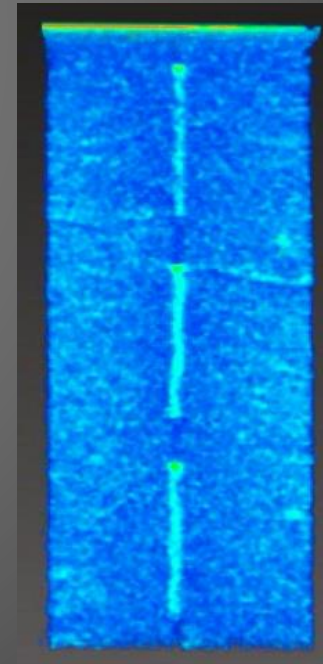
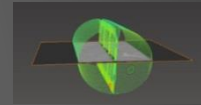
117.8 hrs



XY-plane



XZ-plane



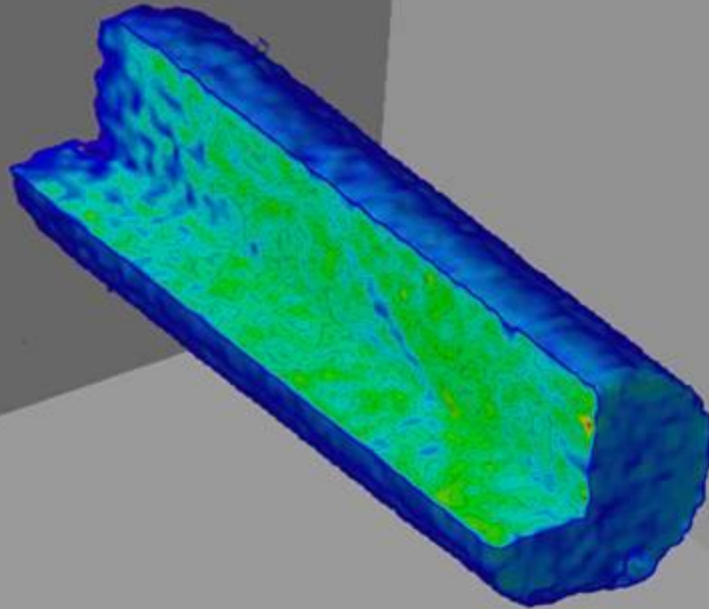
In-Situ Fluid Saturations by Magnetic Resonance Imaging (MRI)

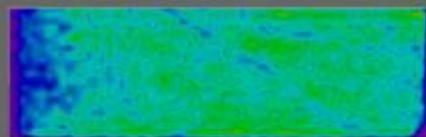


Tertiary CO₂ Injection of Neutral-Wet Chalk

Temp.: 20°C

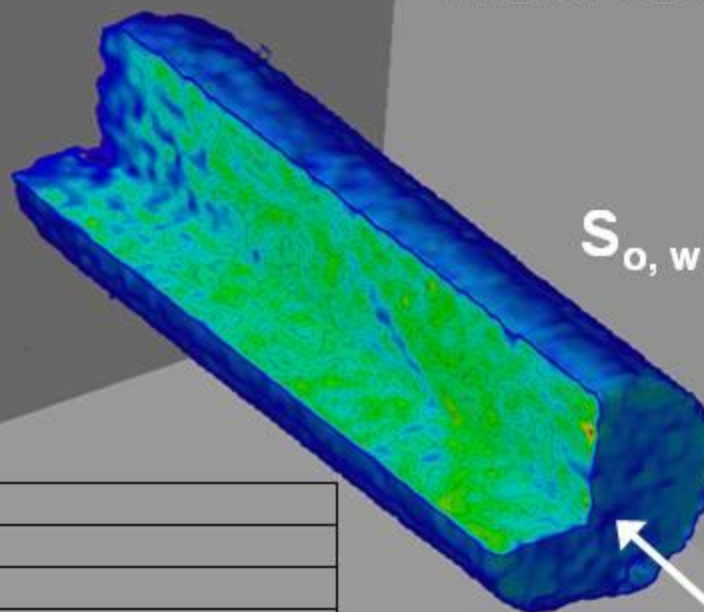
Amott Index 0.15



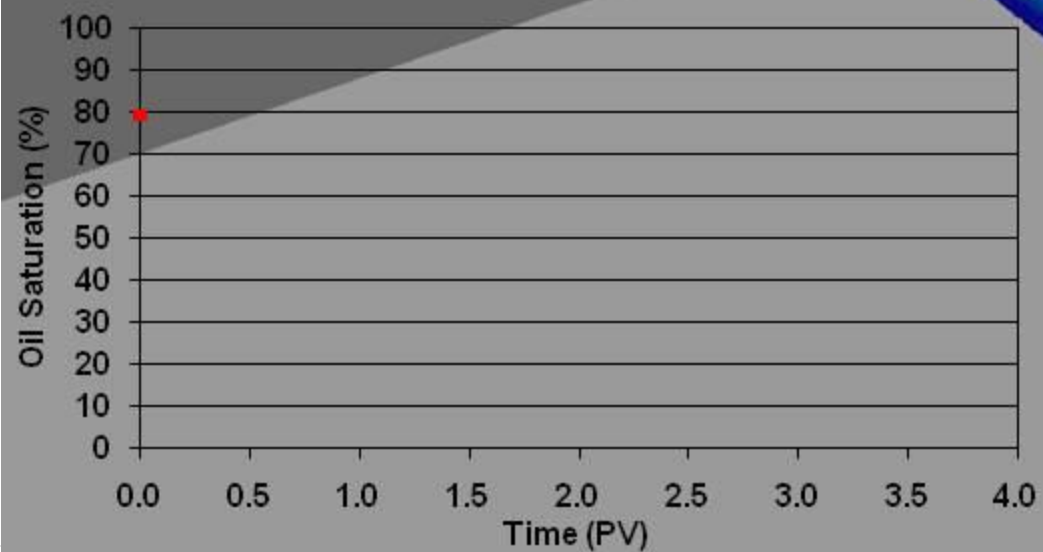


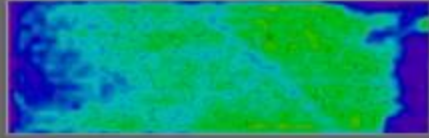
Time: 0.00 PV

$S_{o, wi} = 79.9 \%$

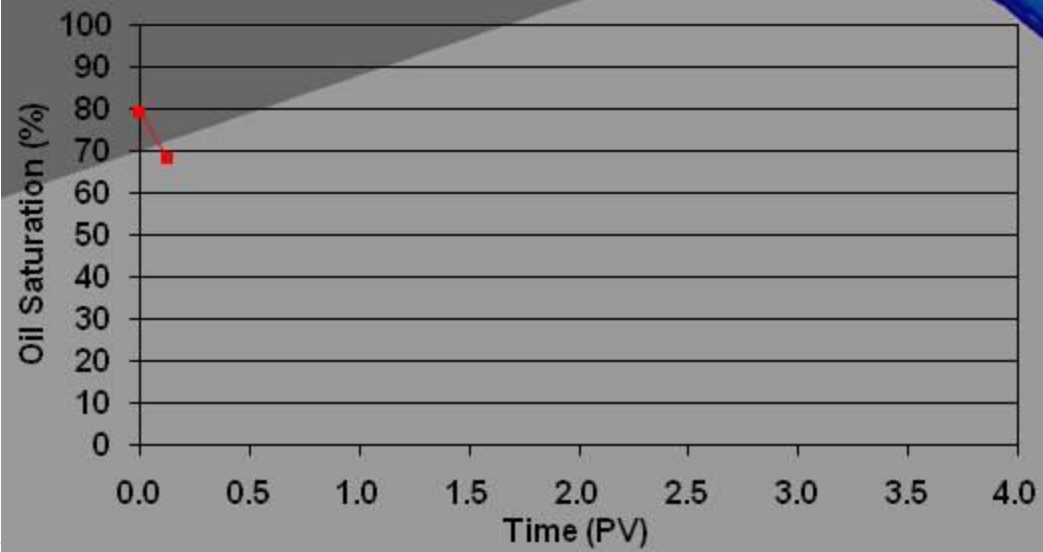
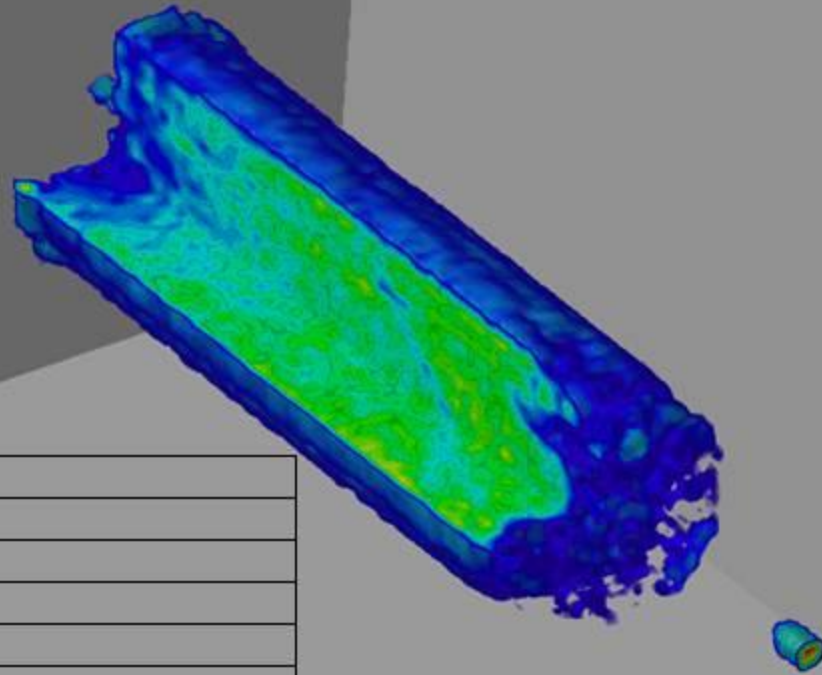


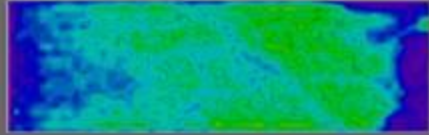
D₂O Injection



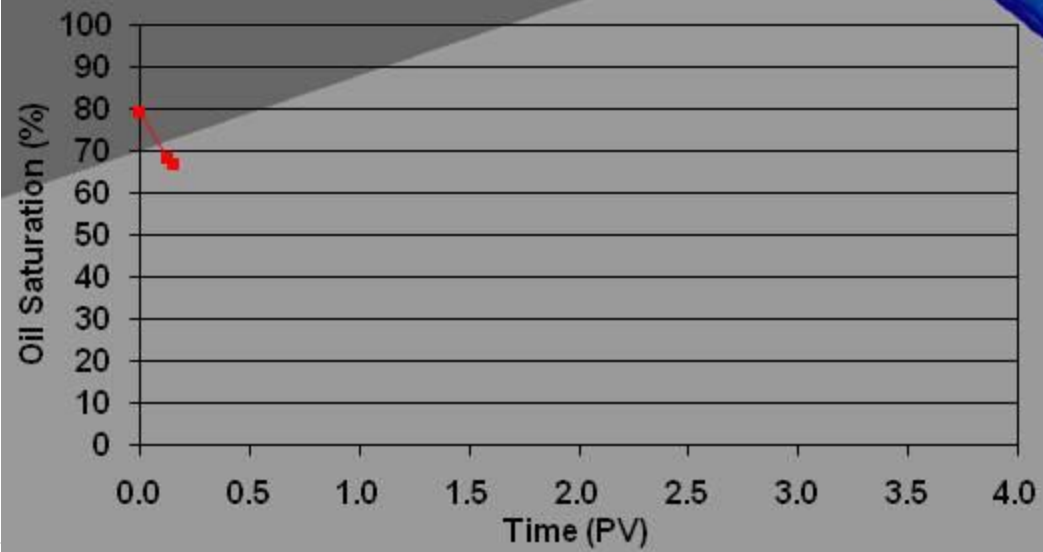
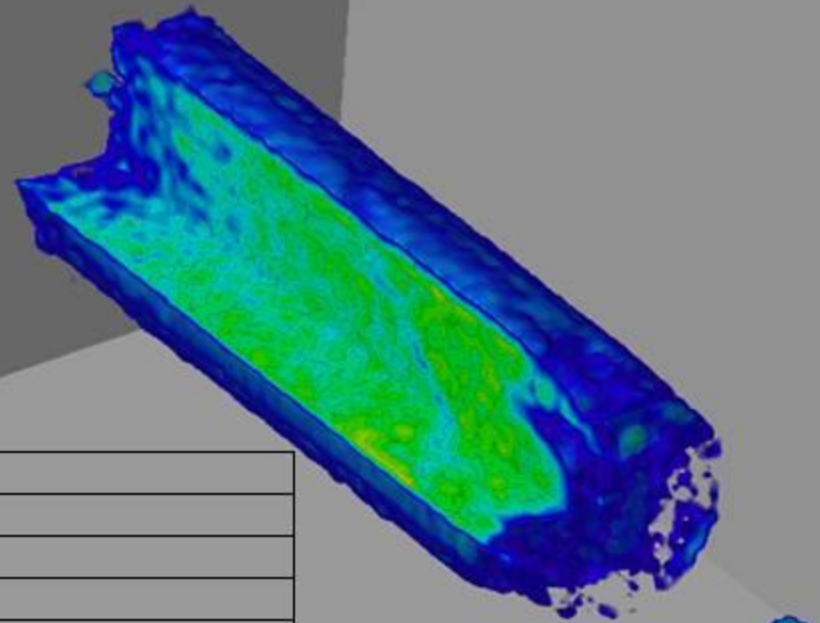


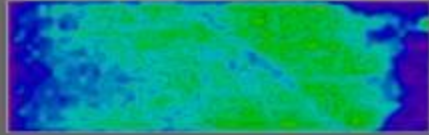
Time: 0.13 PV



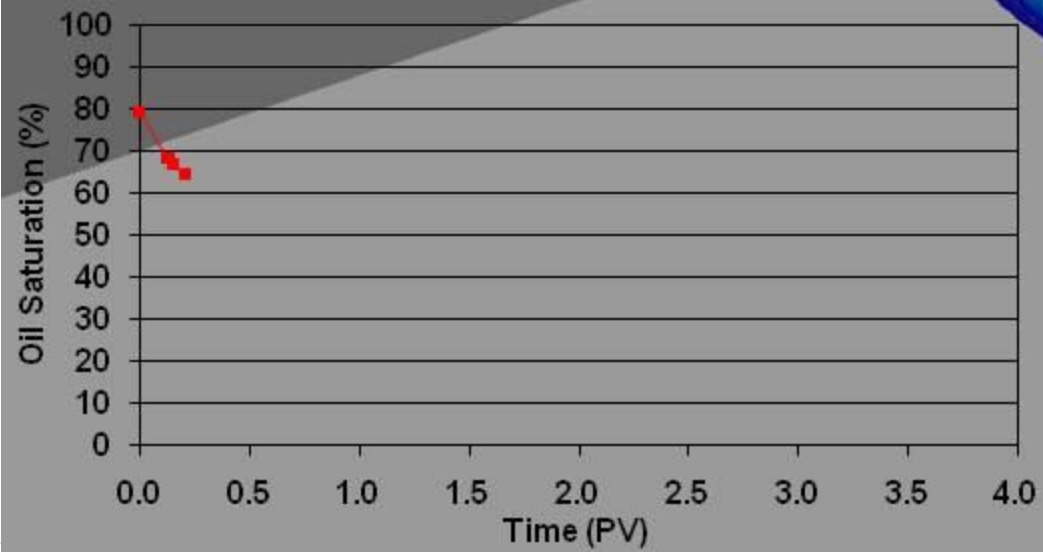
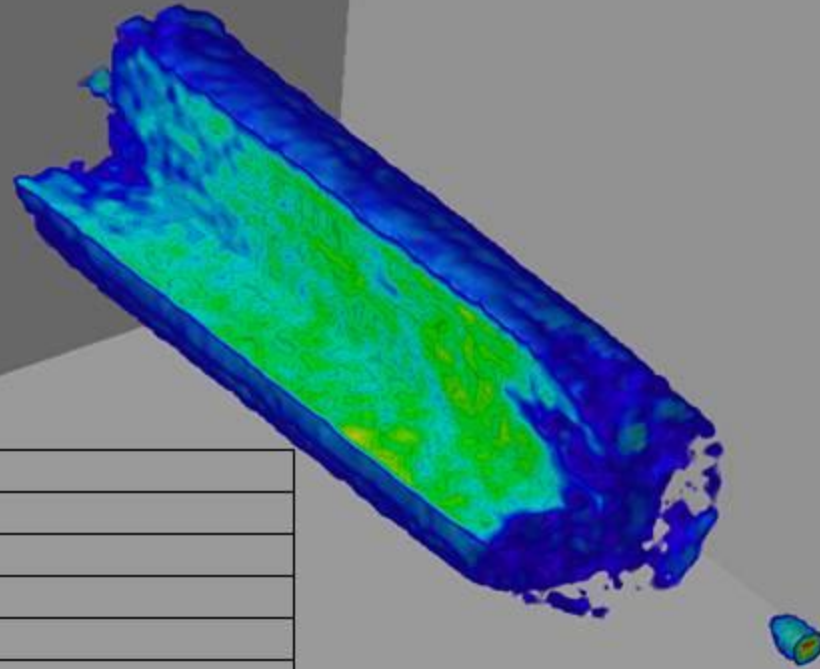


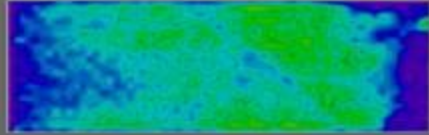
Time: 0.15 PV



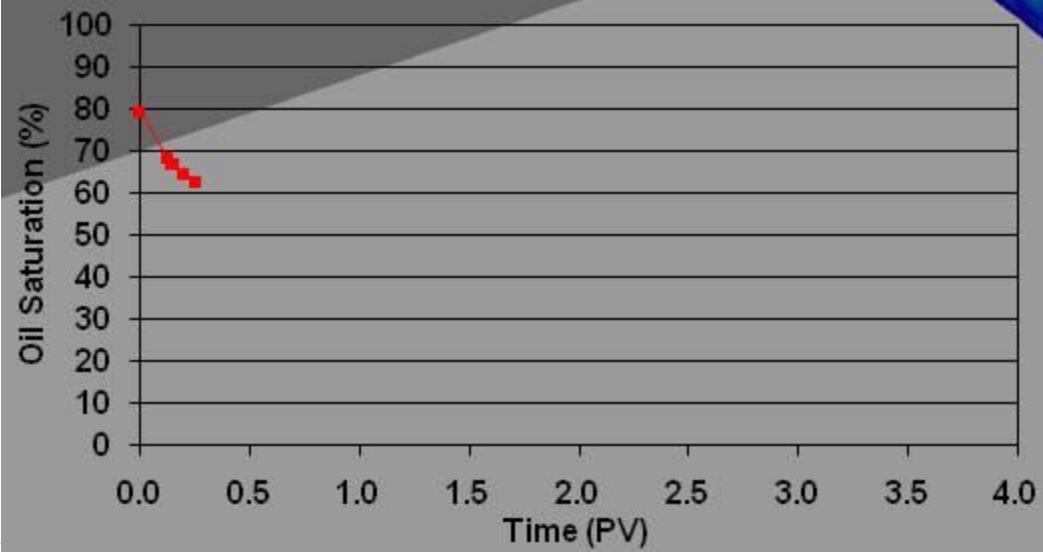
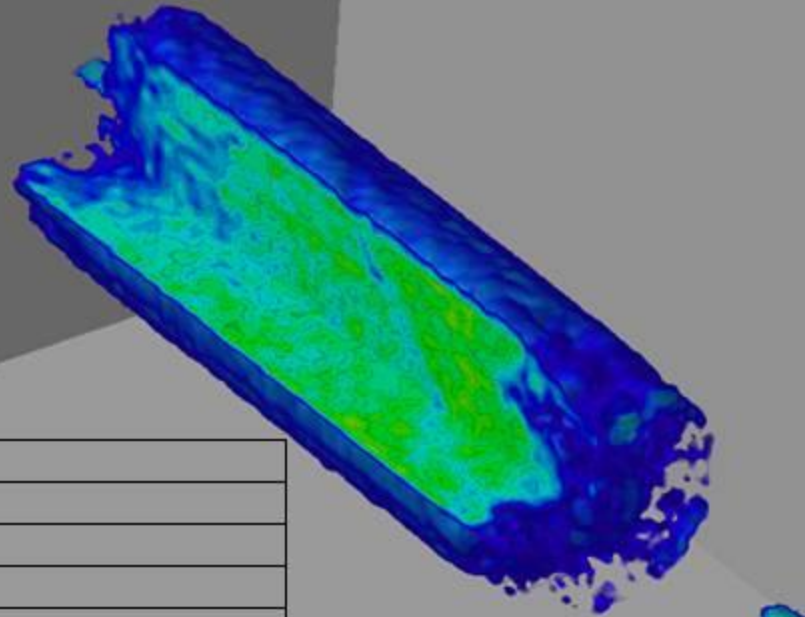


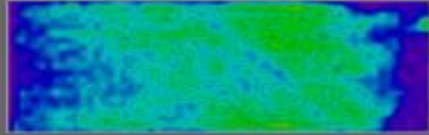
Time: 0.20 PV



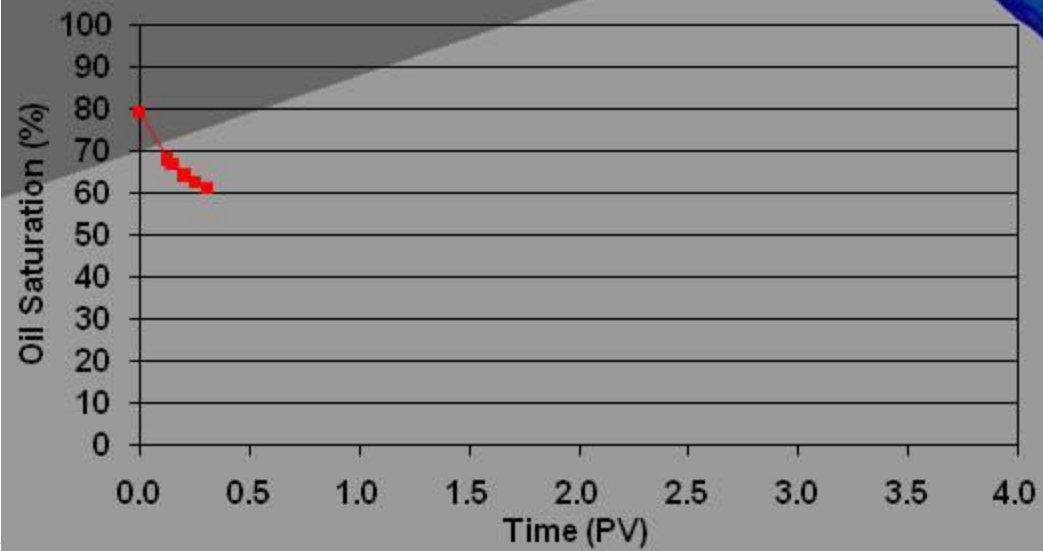
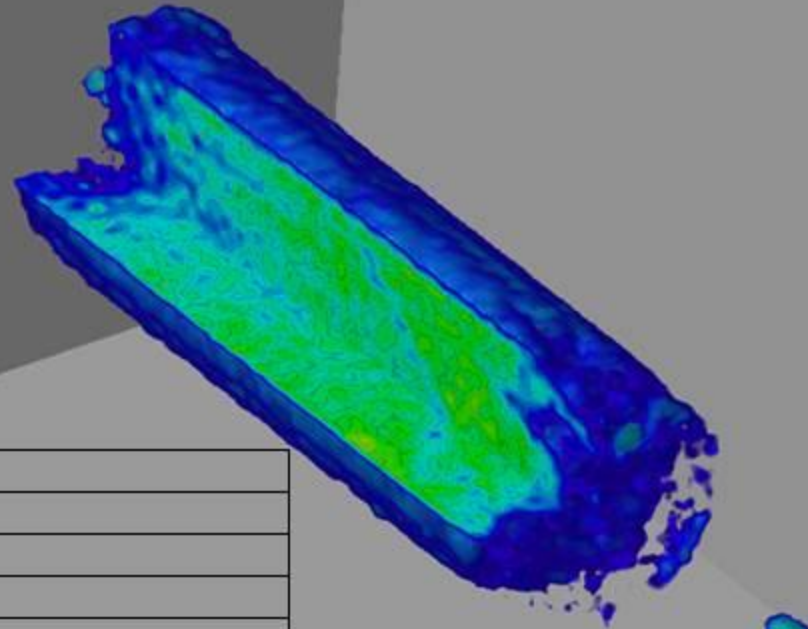


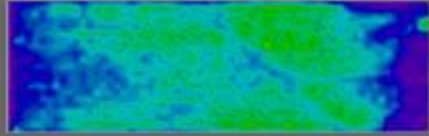
Time: 0.25 PV



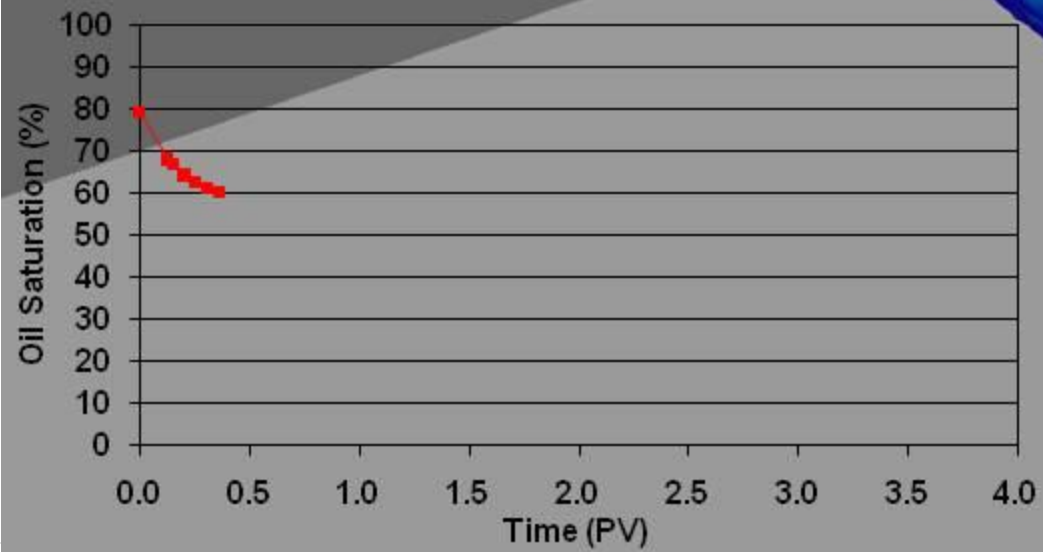
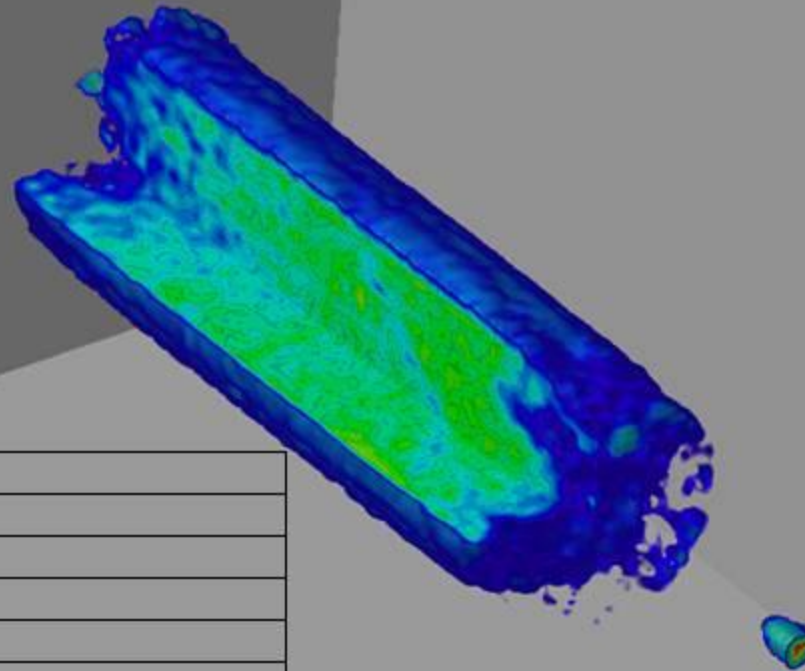


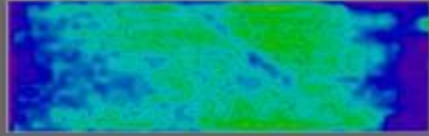
Time: 0.31 PV



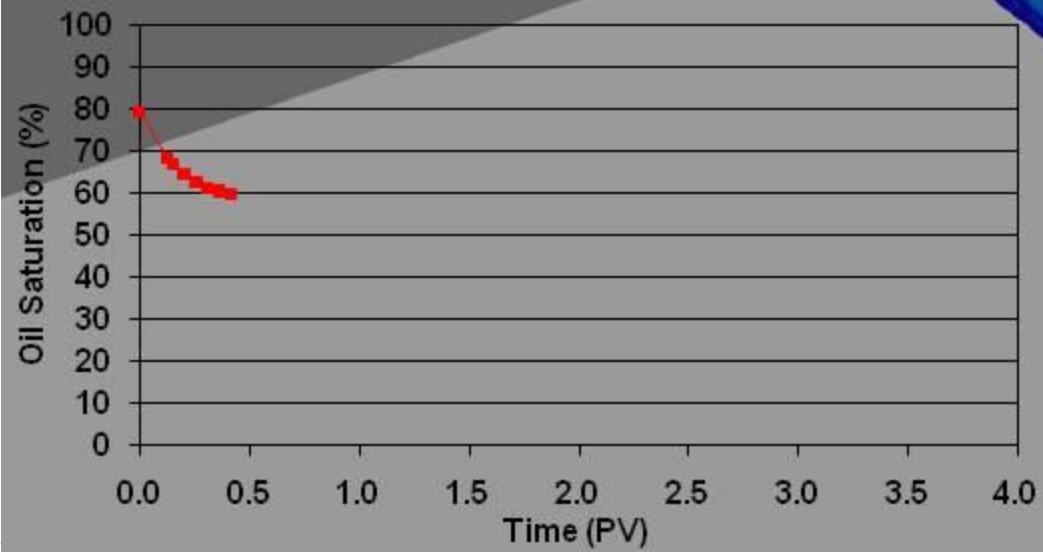
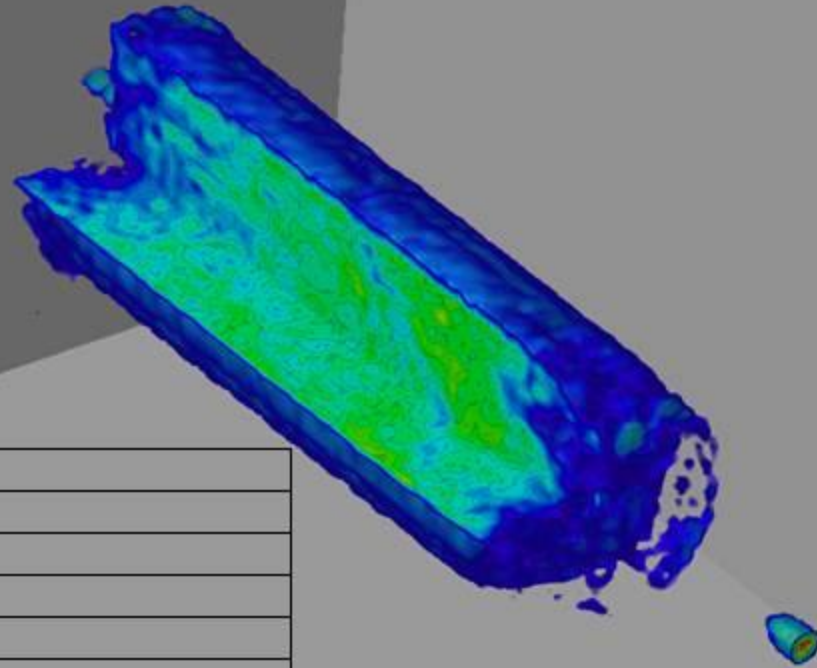


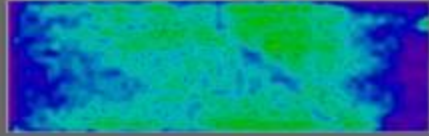
Time: 0.36 PV



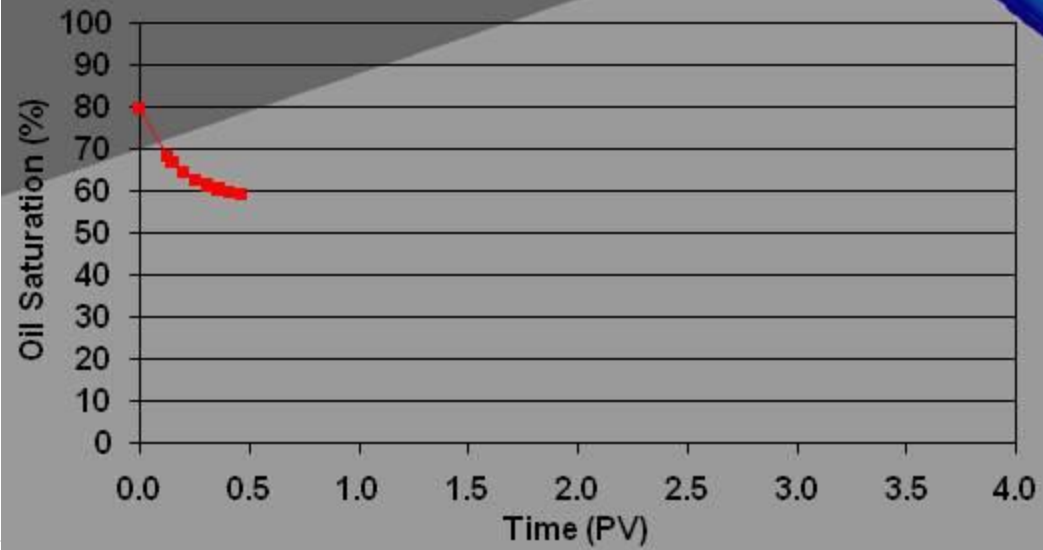
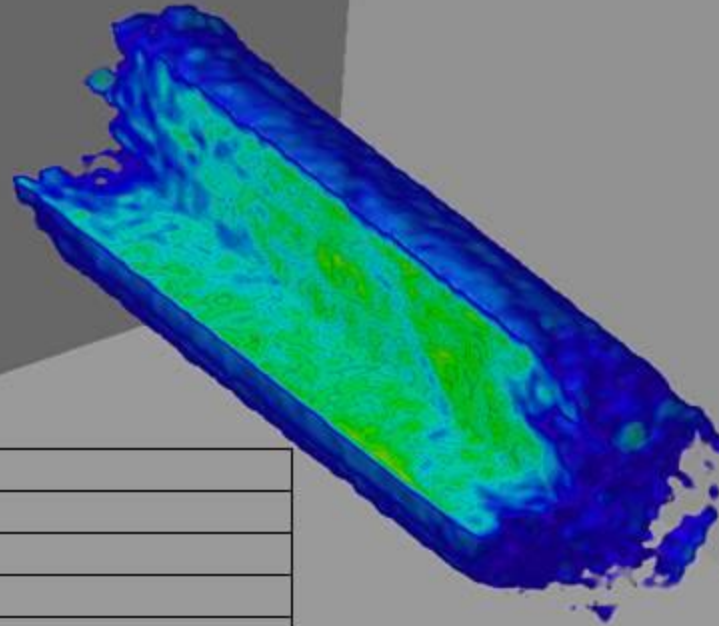


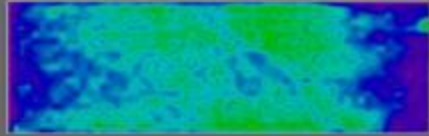
Time: 0.41 PV



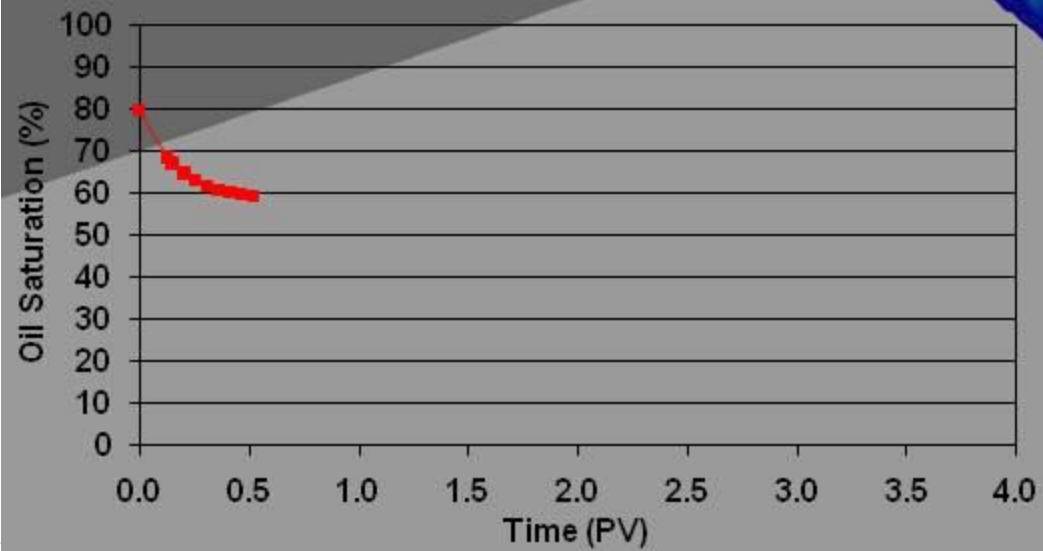
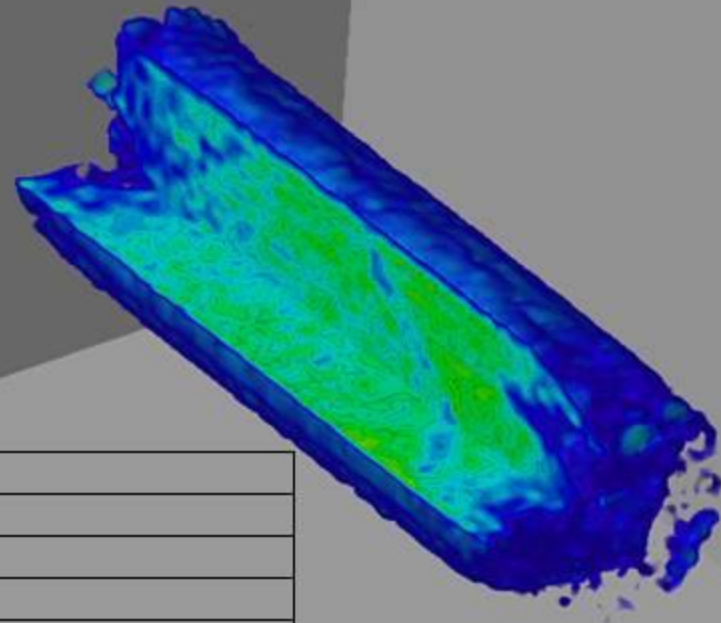


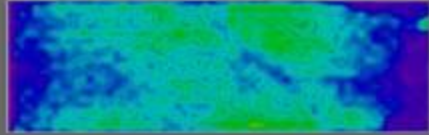
Time: 0.46 PV



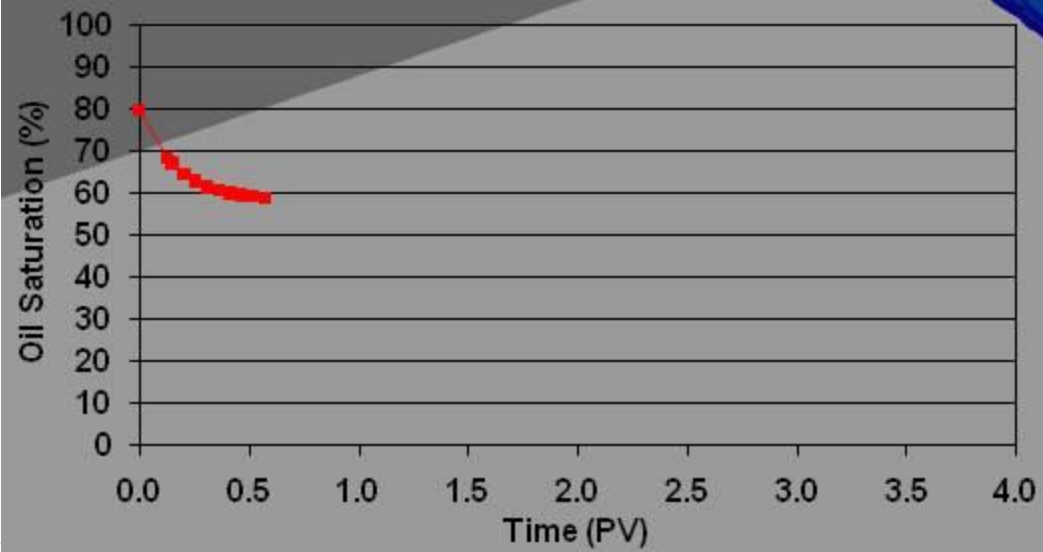
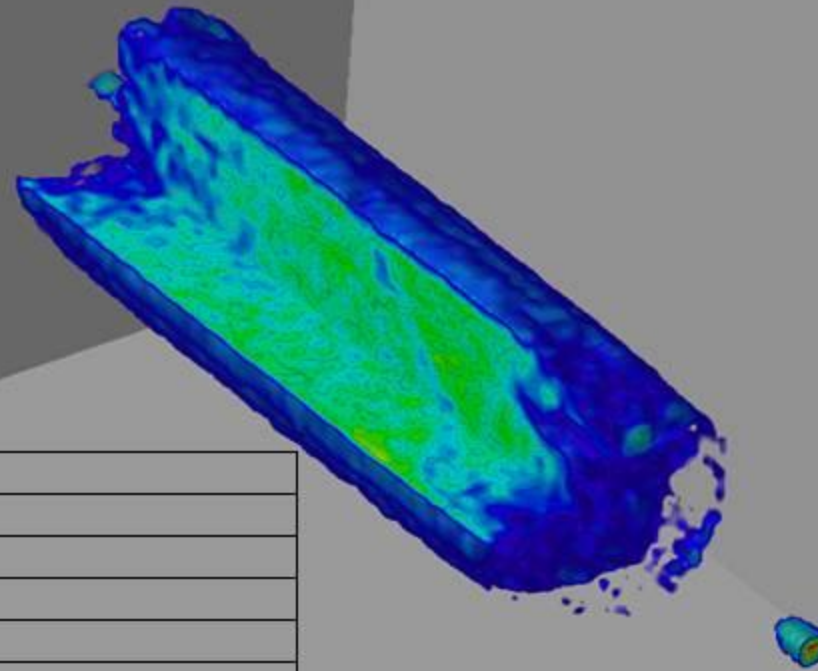


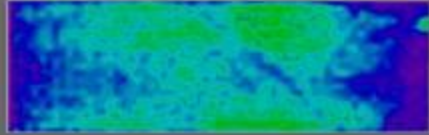
Time: 0.52 PV



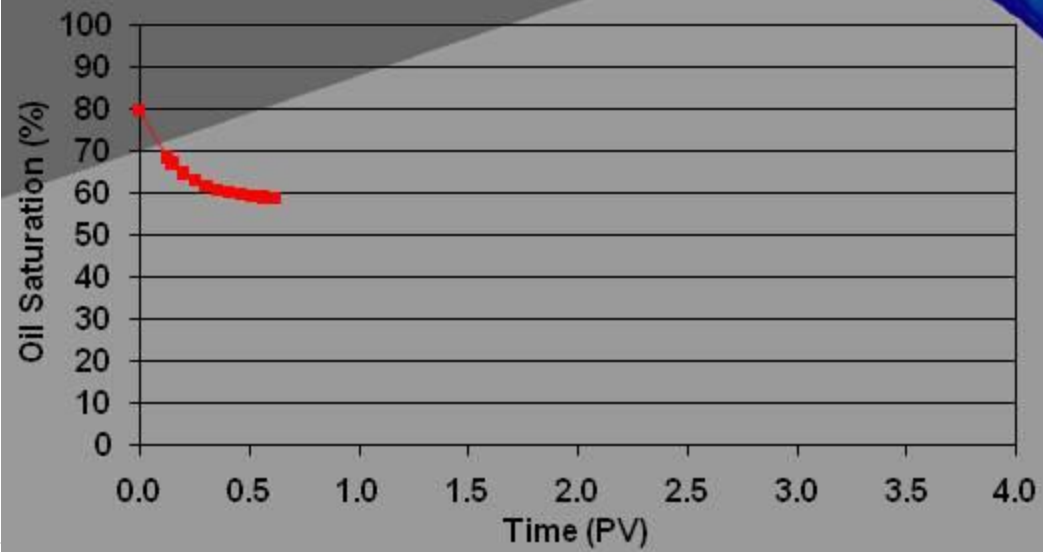
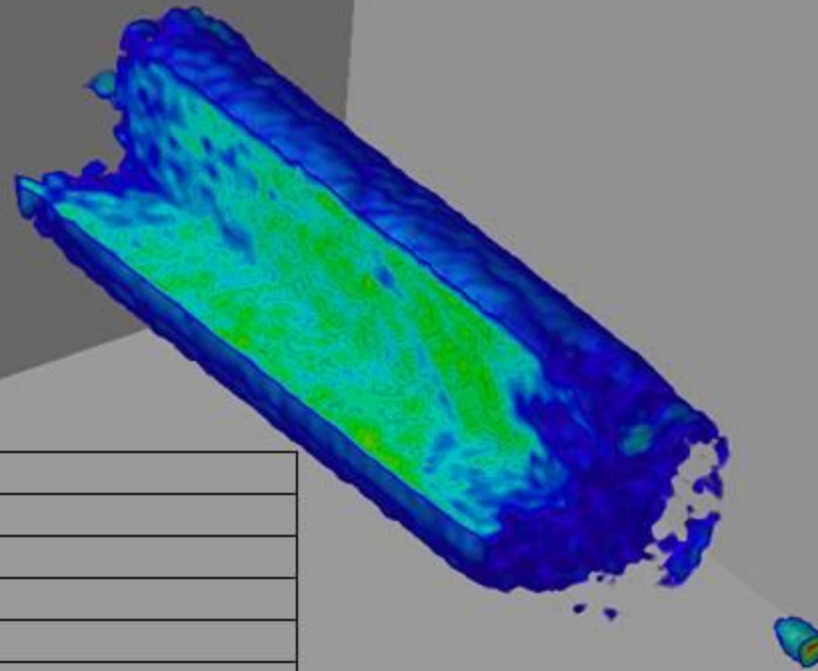


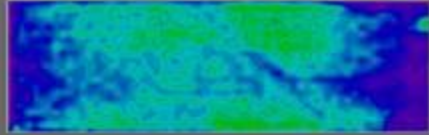
Time: 0.57 PV



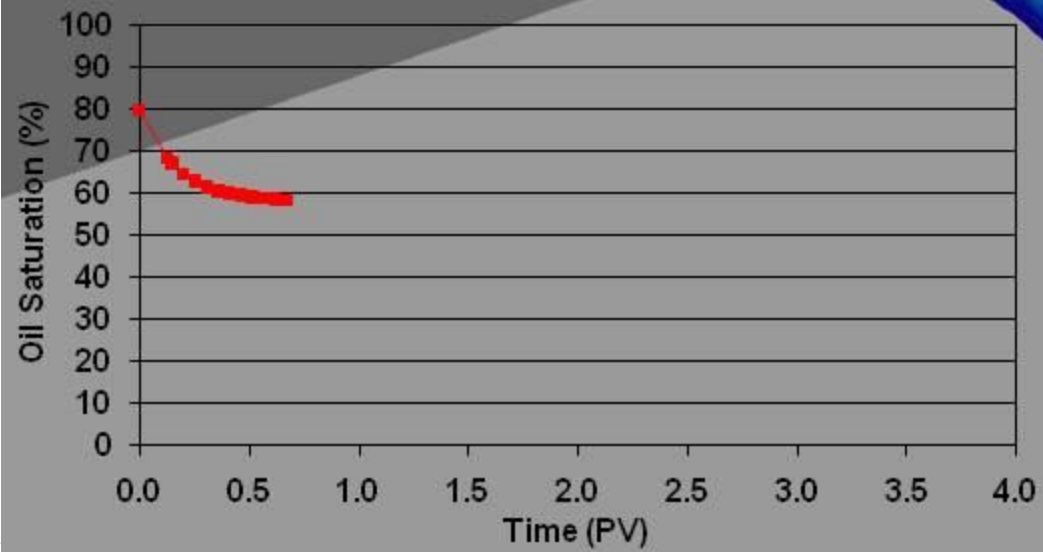
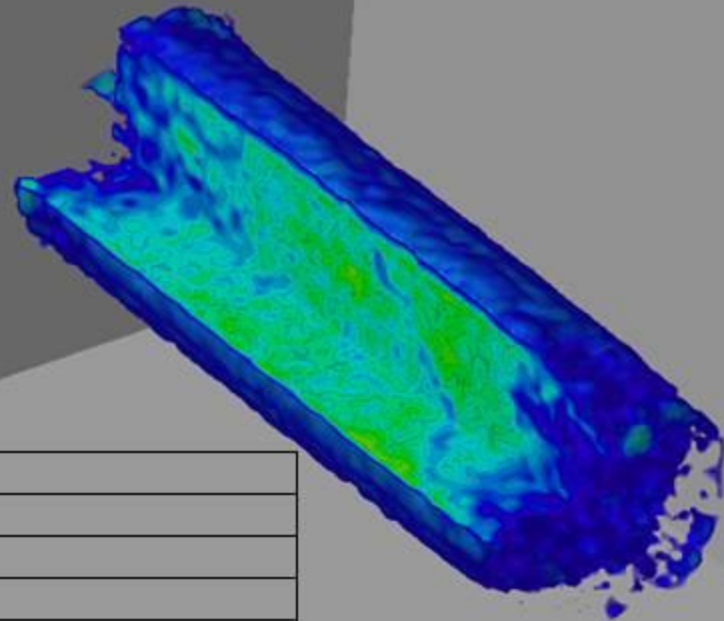


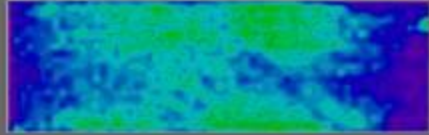
Time: 0.62 PV



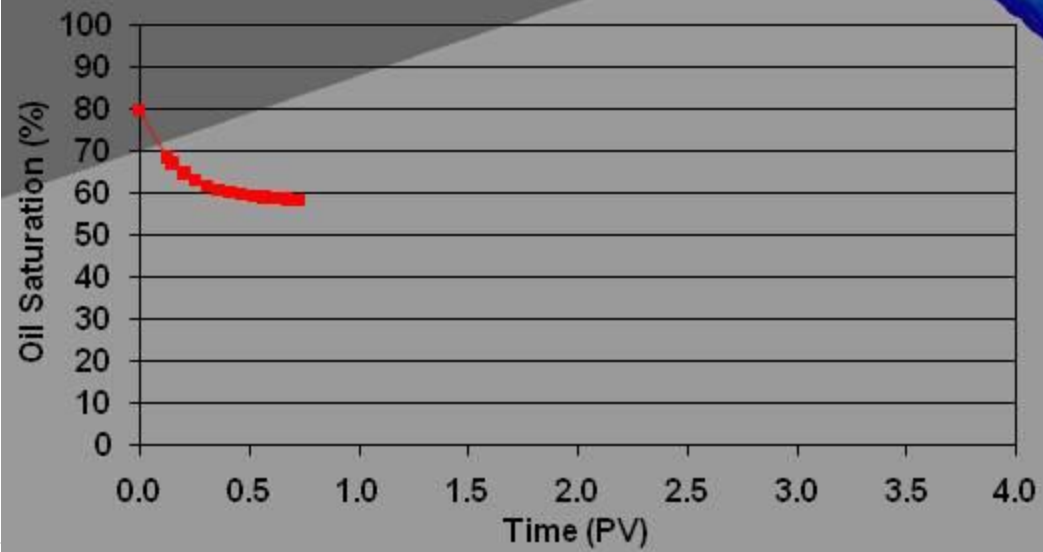
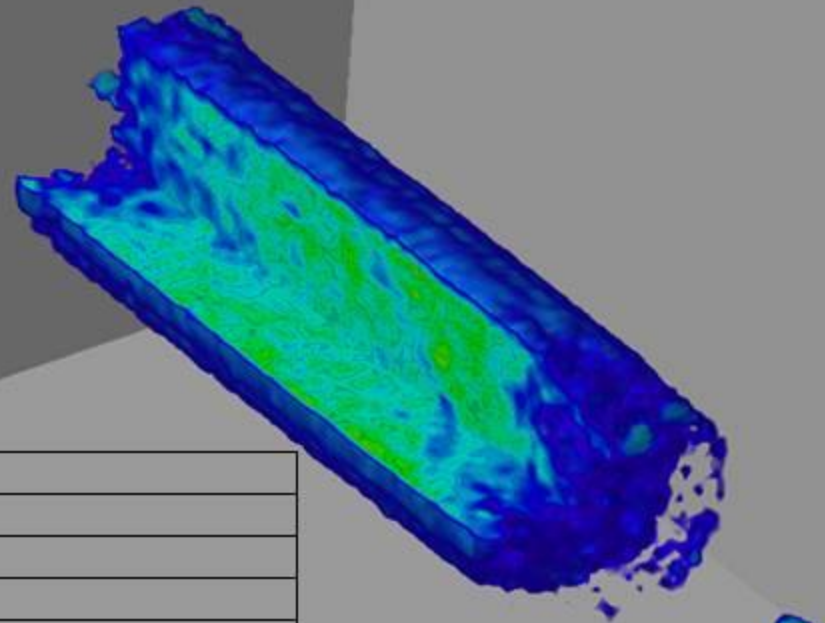


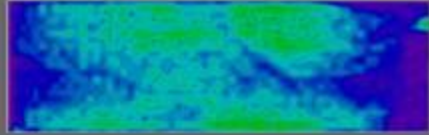
Time: 0.67 PV



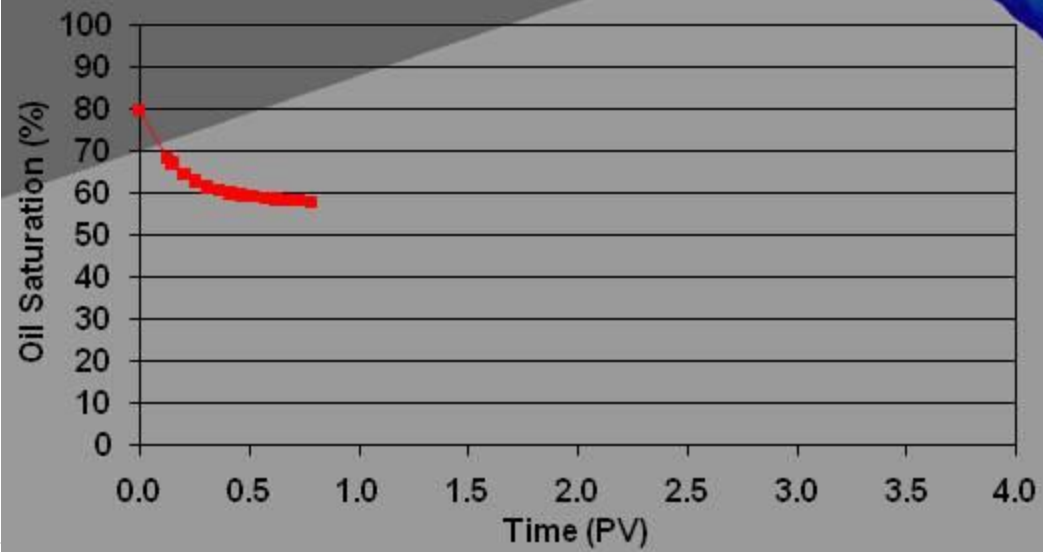
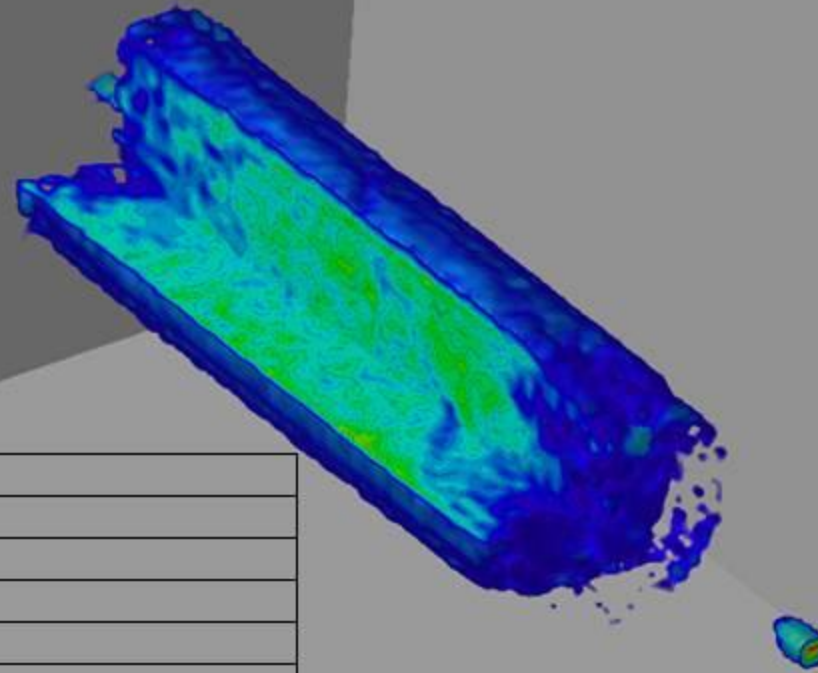


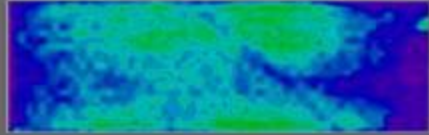
Time: 0.72 PV



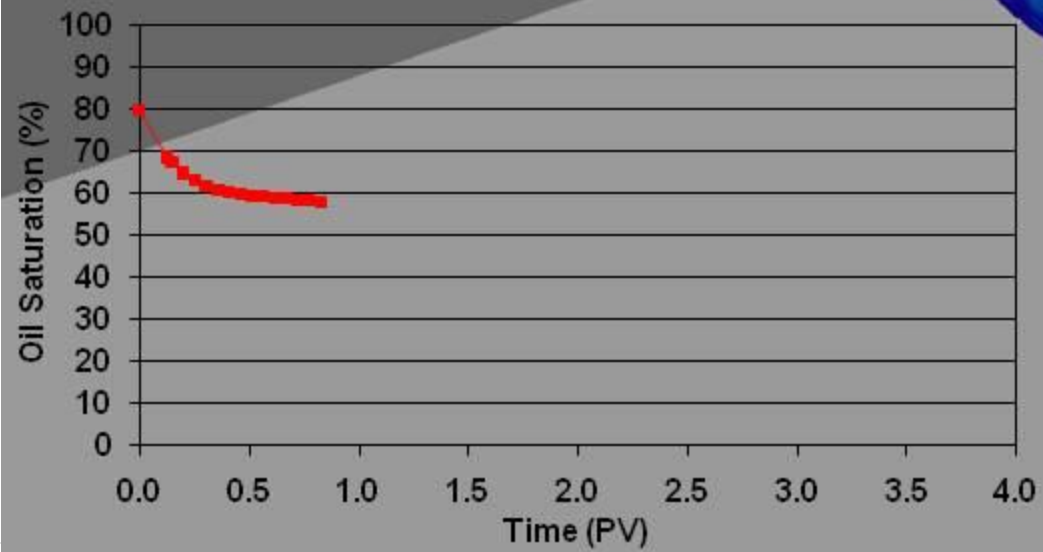
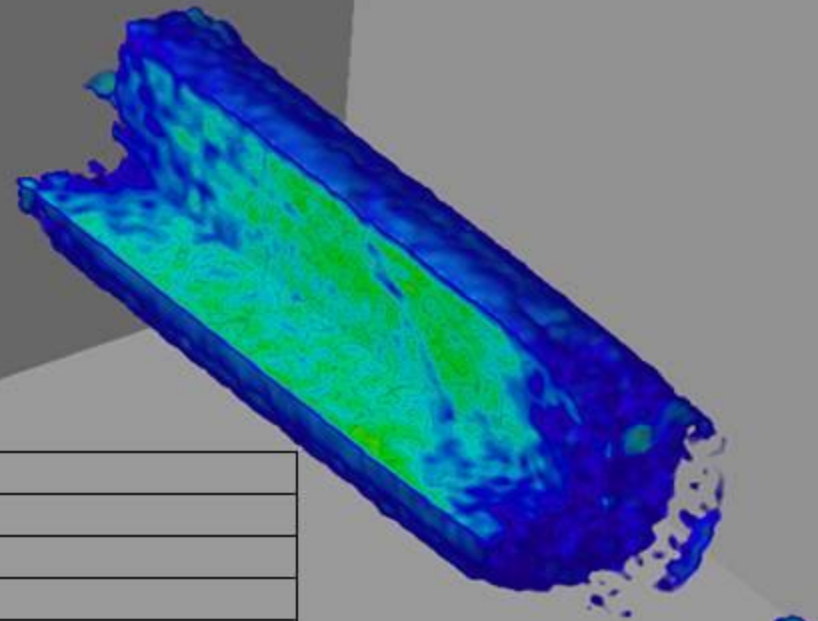


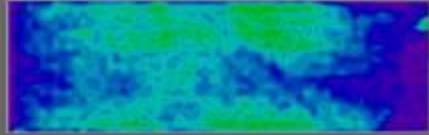
Time: 0.78 PV



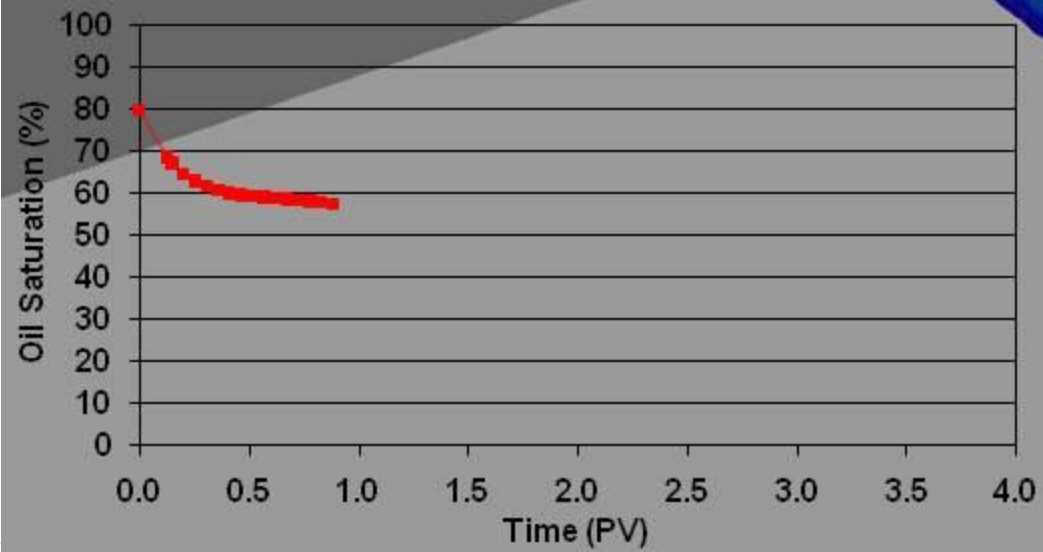
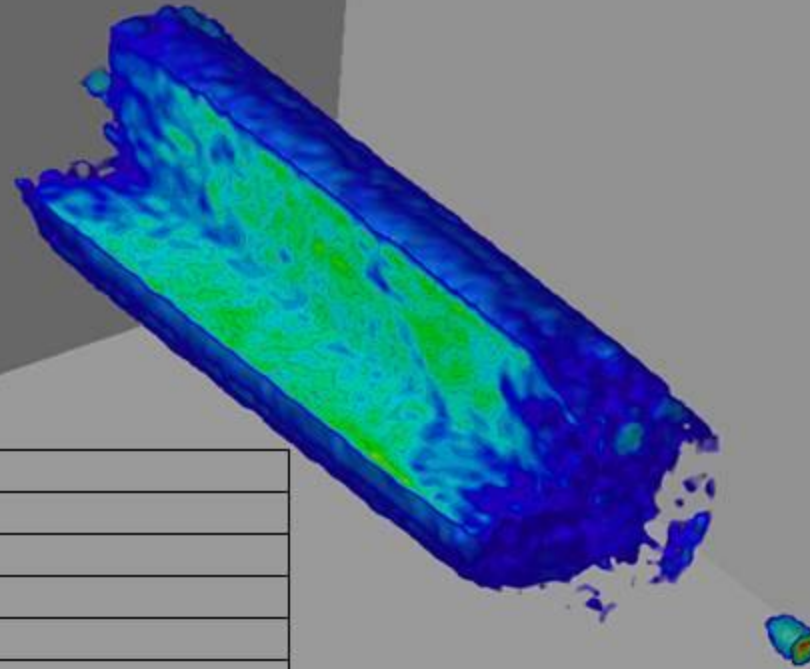


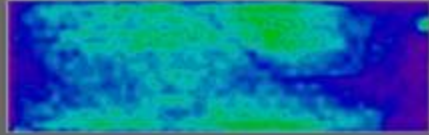
Time: 0.83 PV



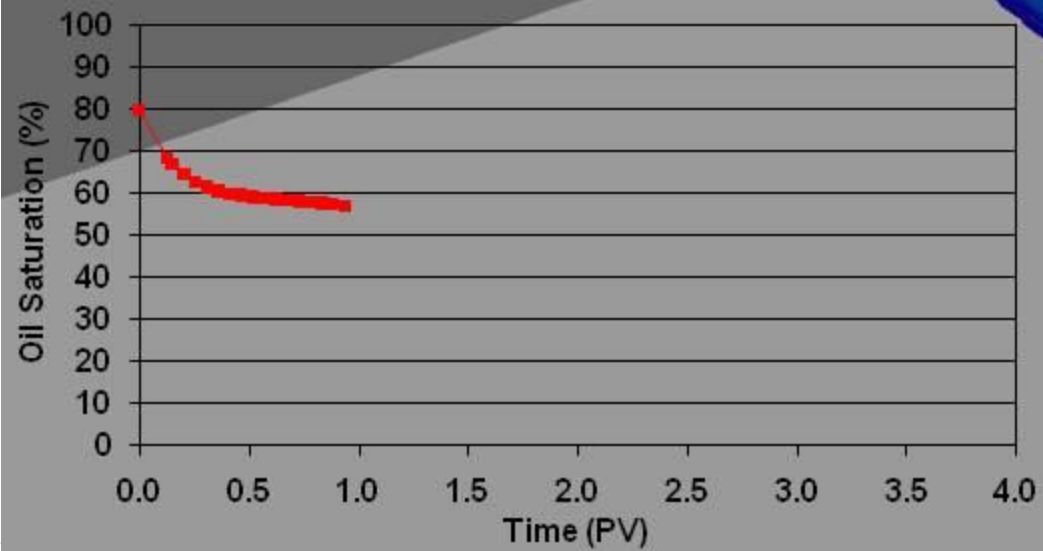
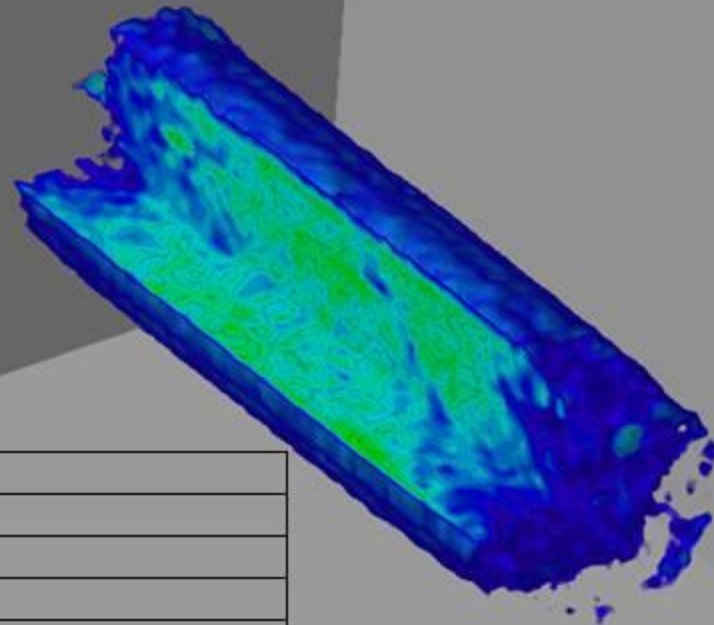


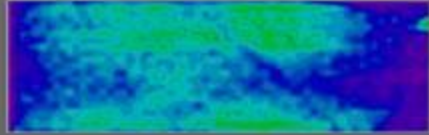
Time: 0.88 PV



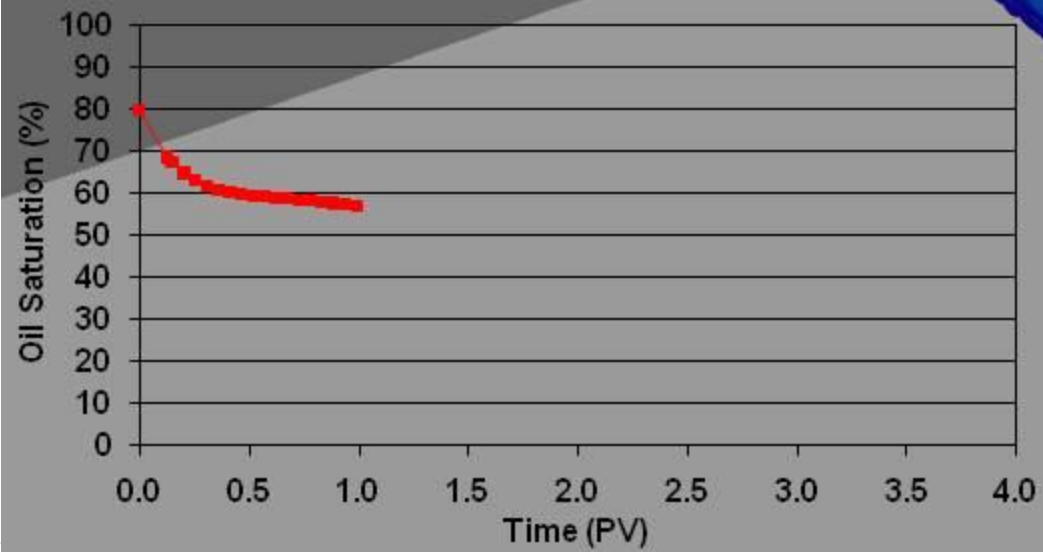
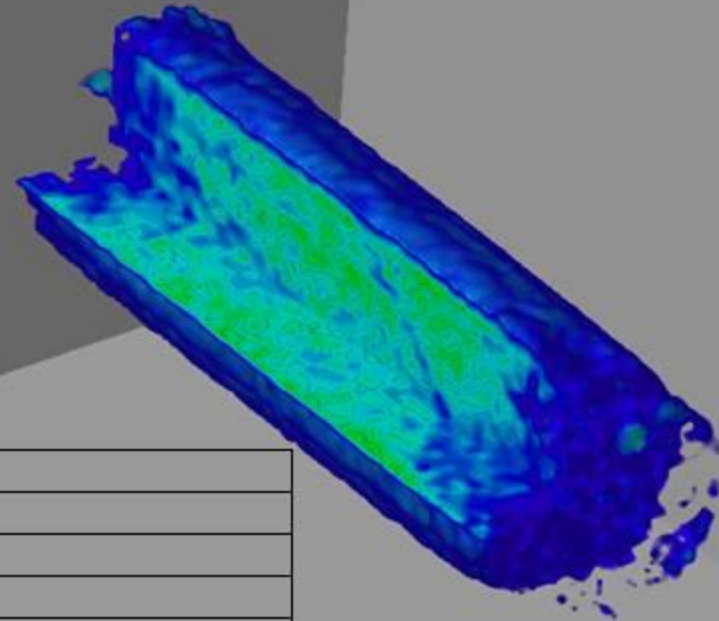


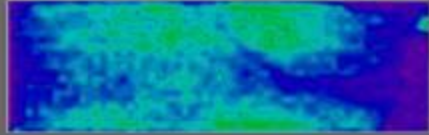
Time: 0.93 PV



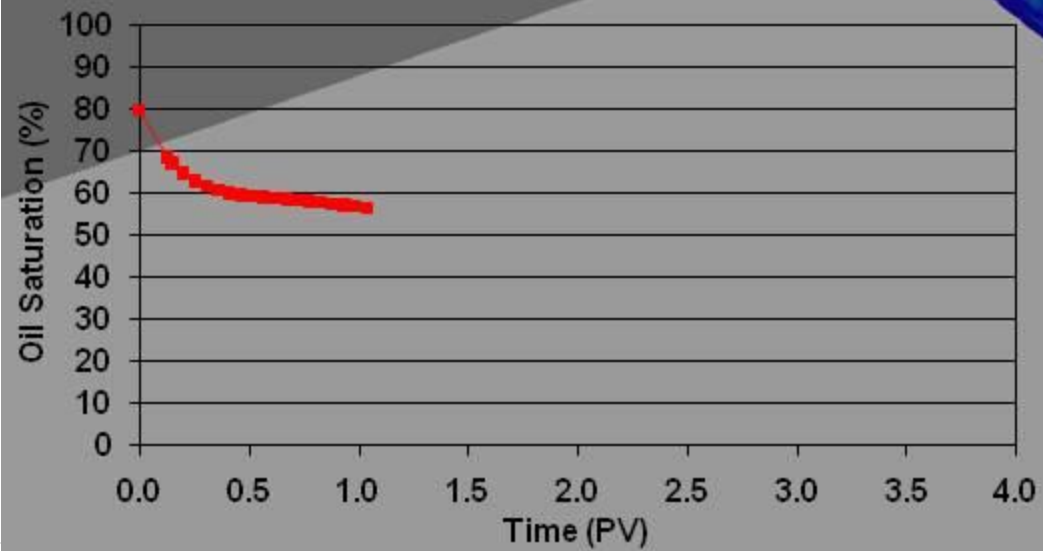
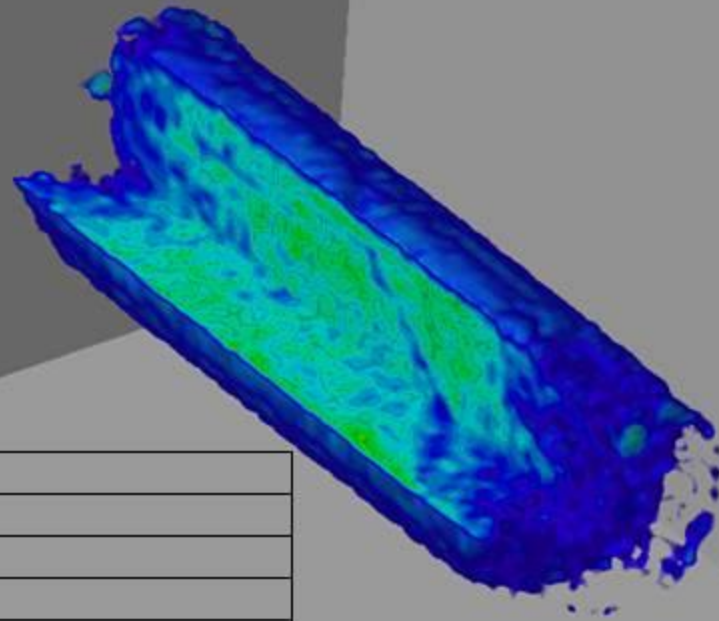


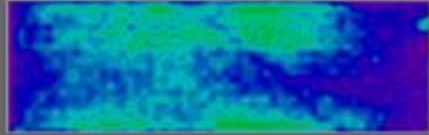
Time: 0.99 PV



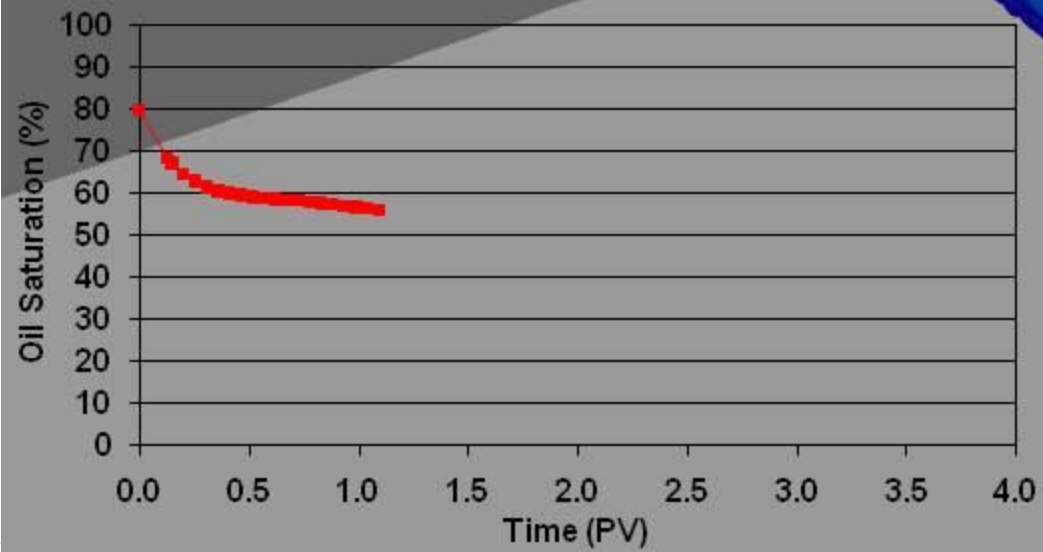
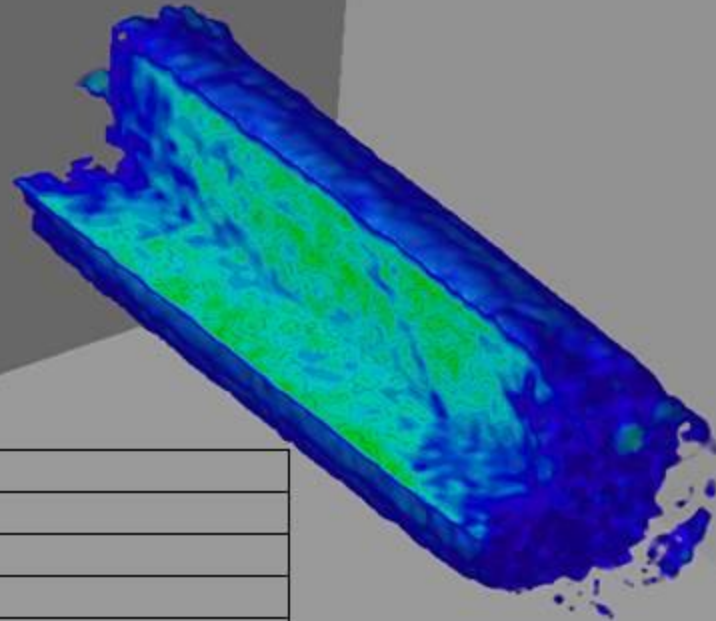


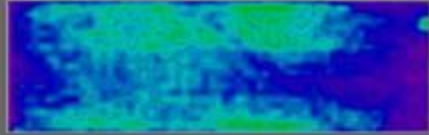
Time: 1.04 PV



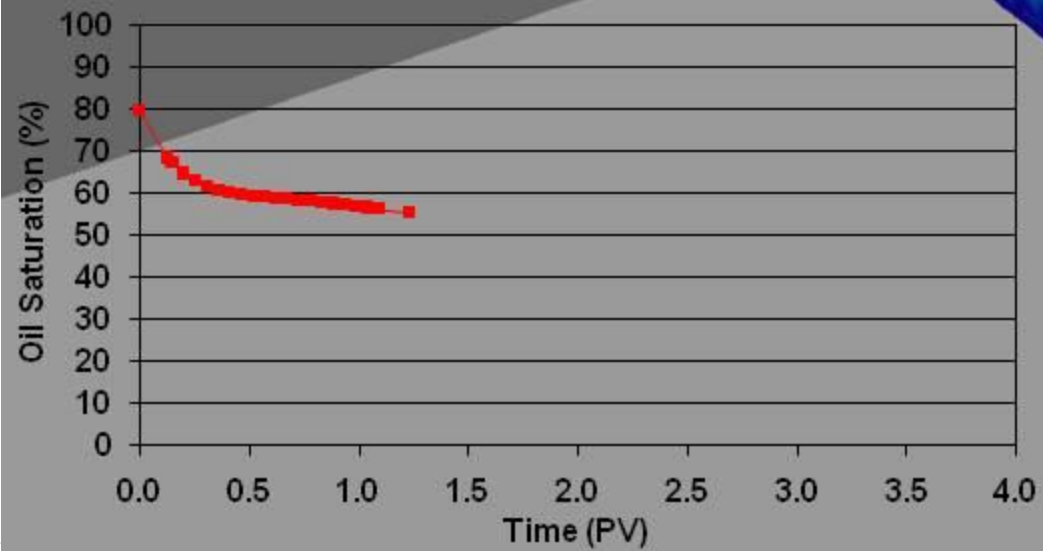
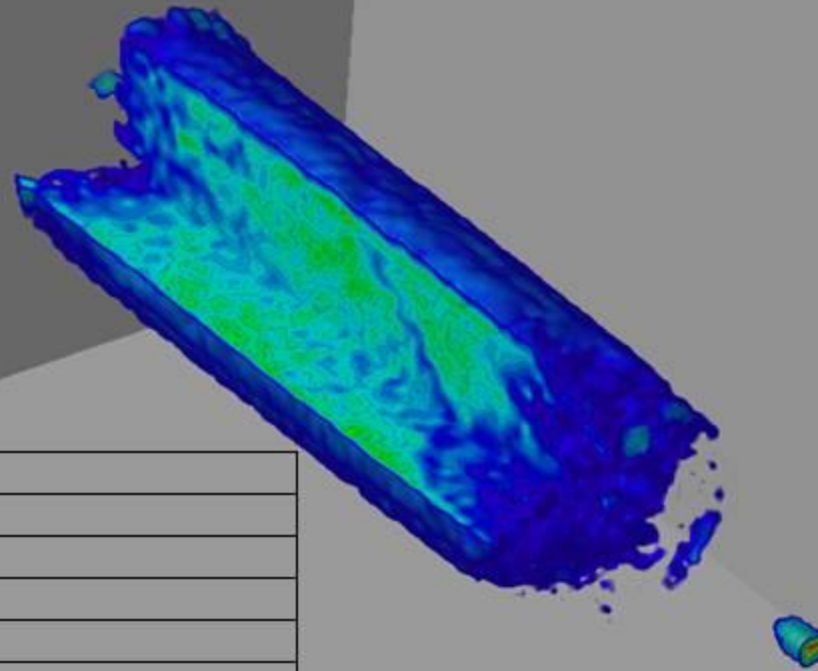


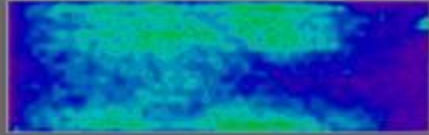
Time: 1.09 PV



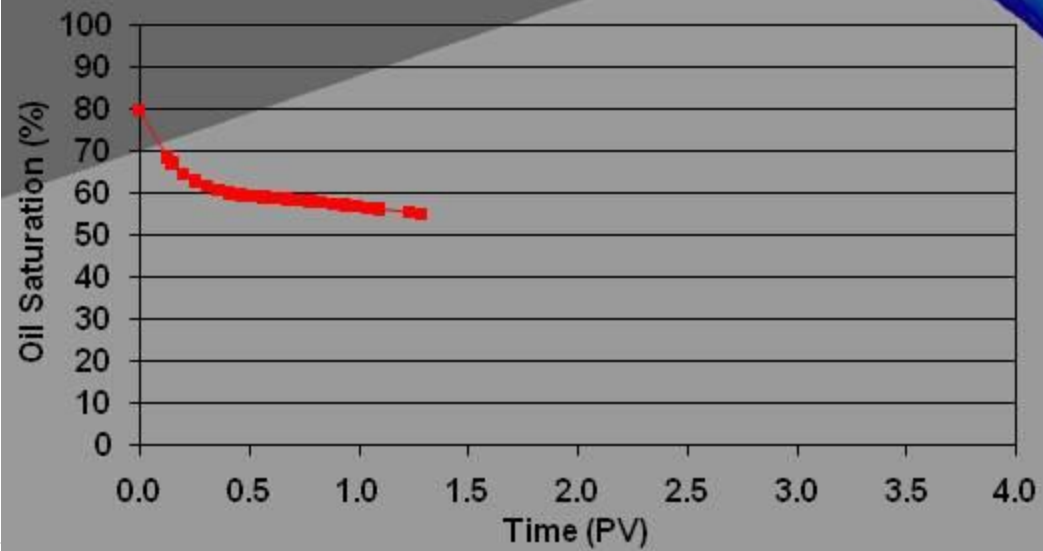
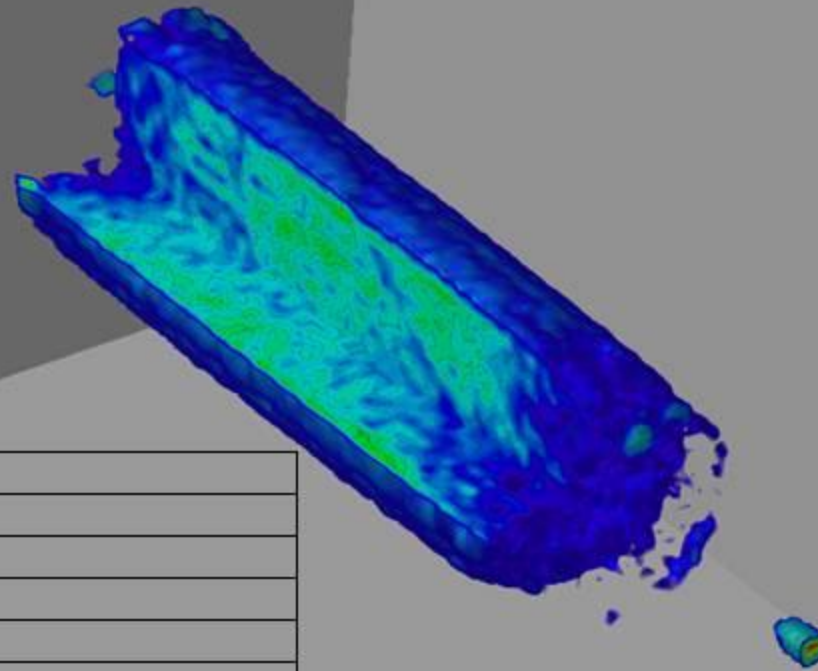


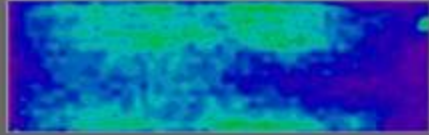
Time: 1.23 PV



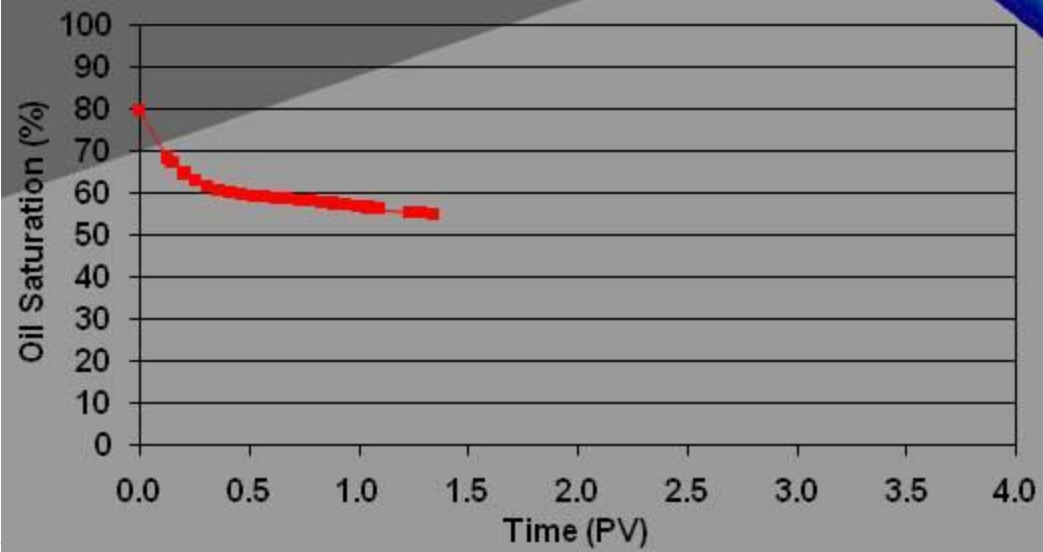
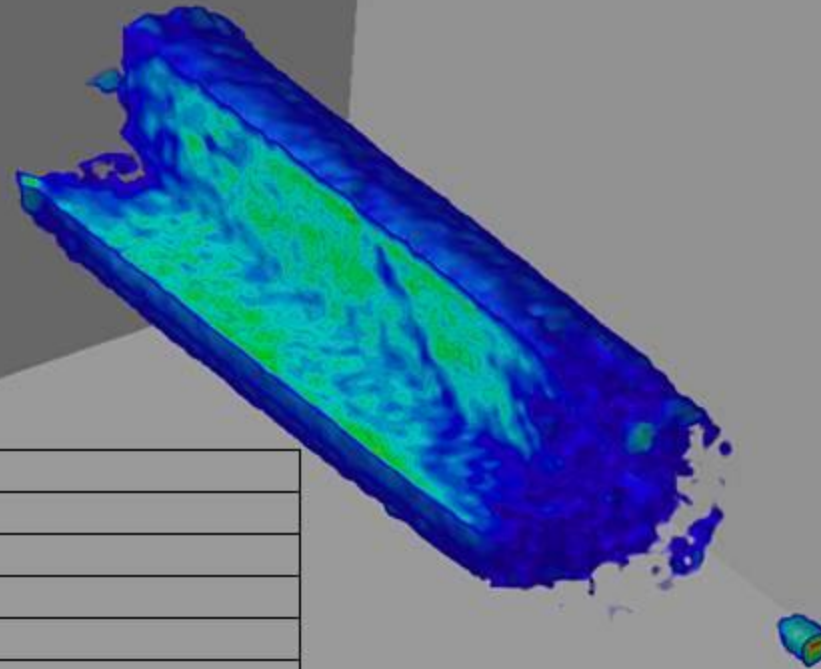


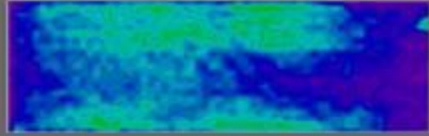
Time: 1.28 PV



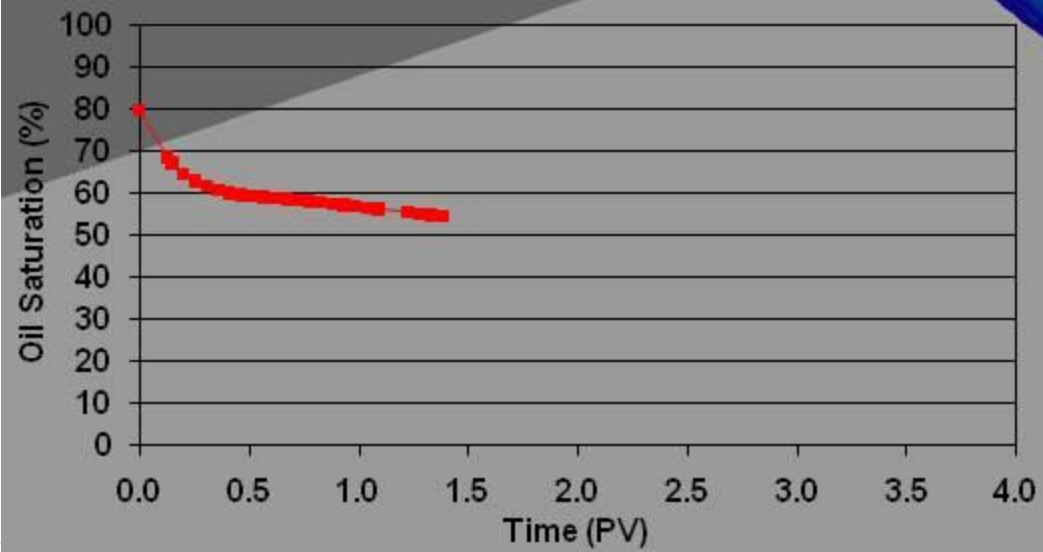
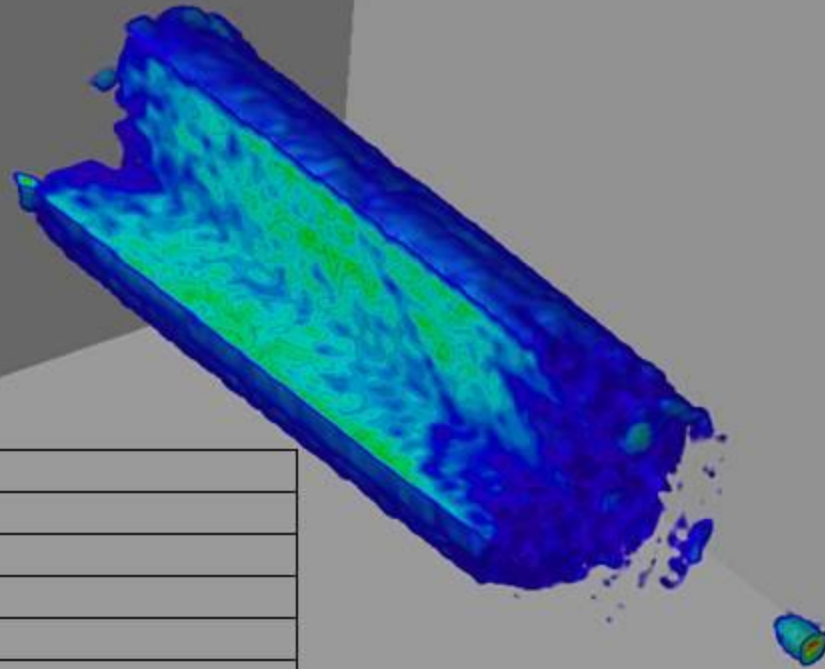


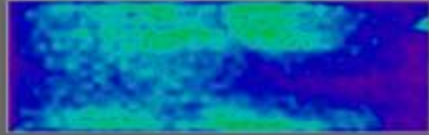
Time: 1.33 PV



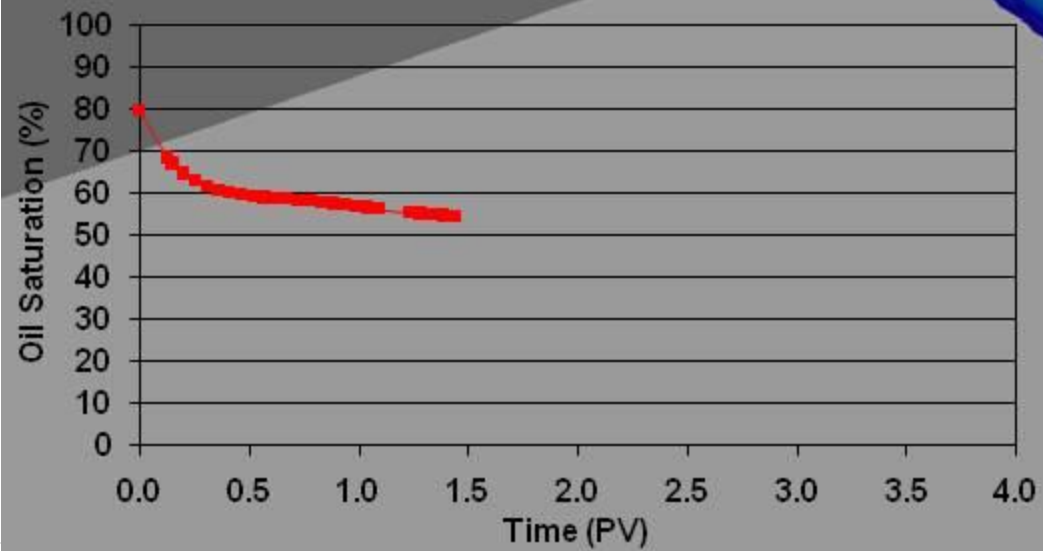
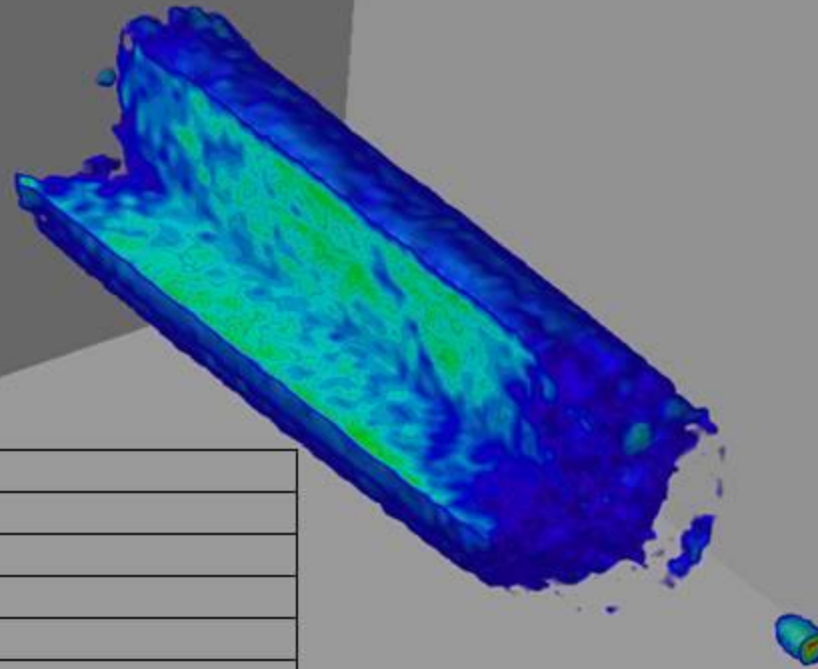


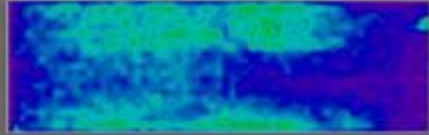
Time: 1.39 PV



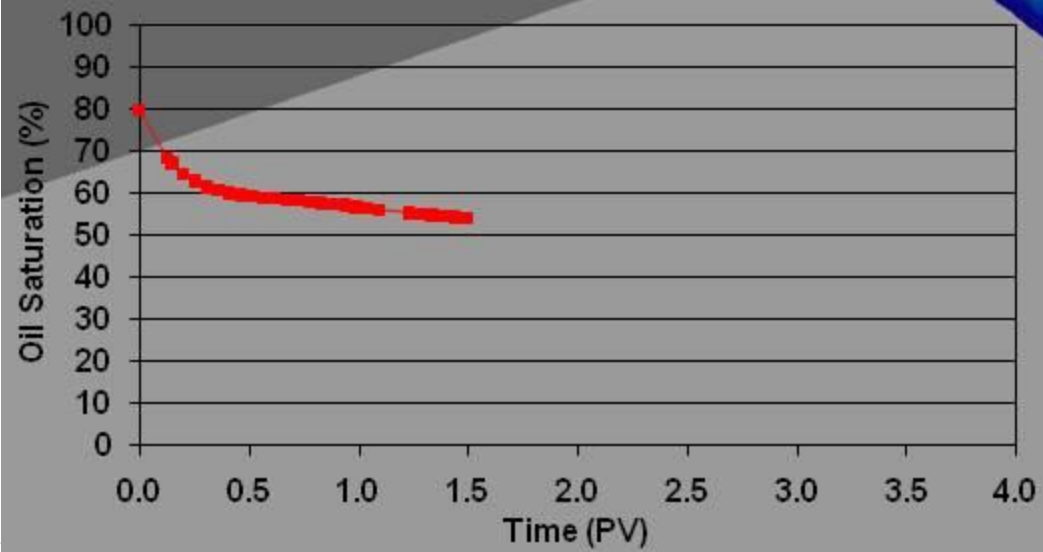
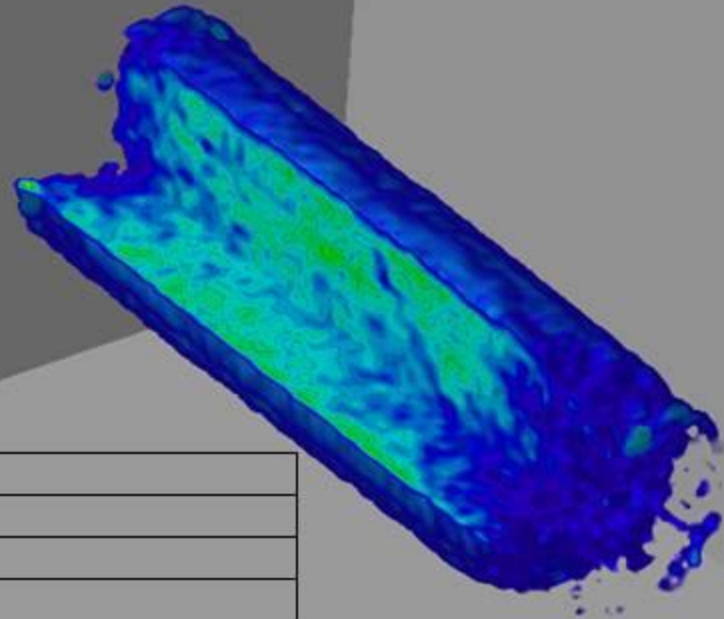


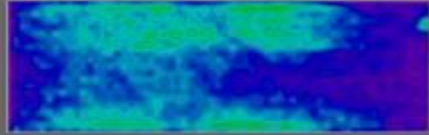
Time: 1.44 PV



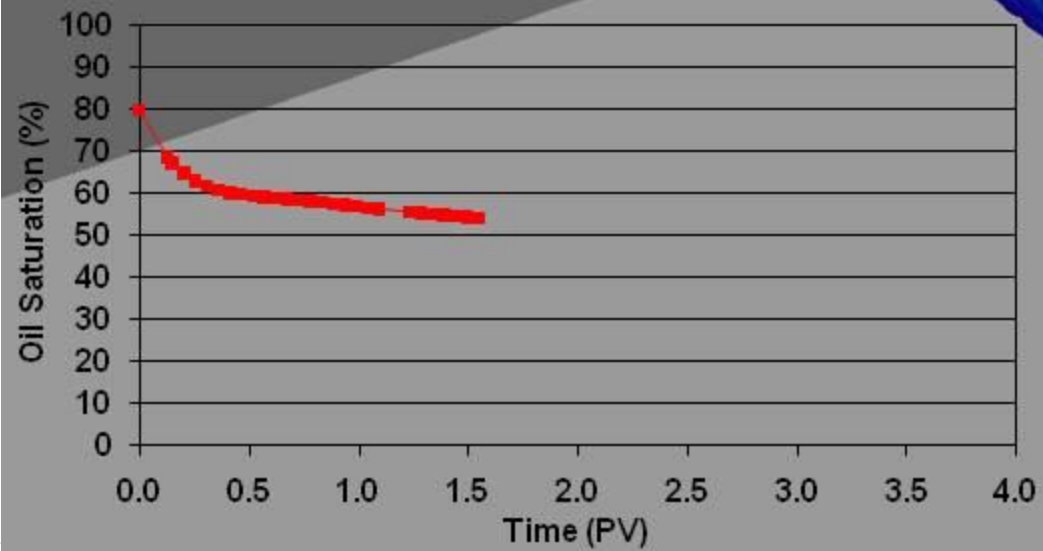
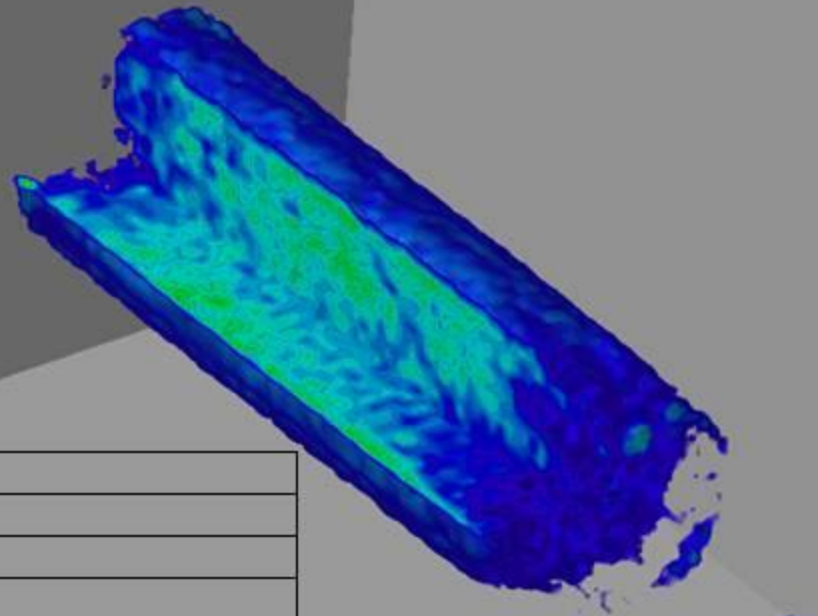


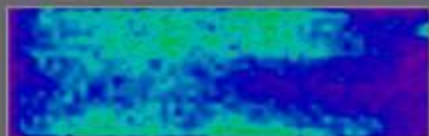
Time: 1.49 PV





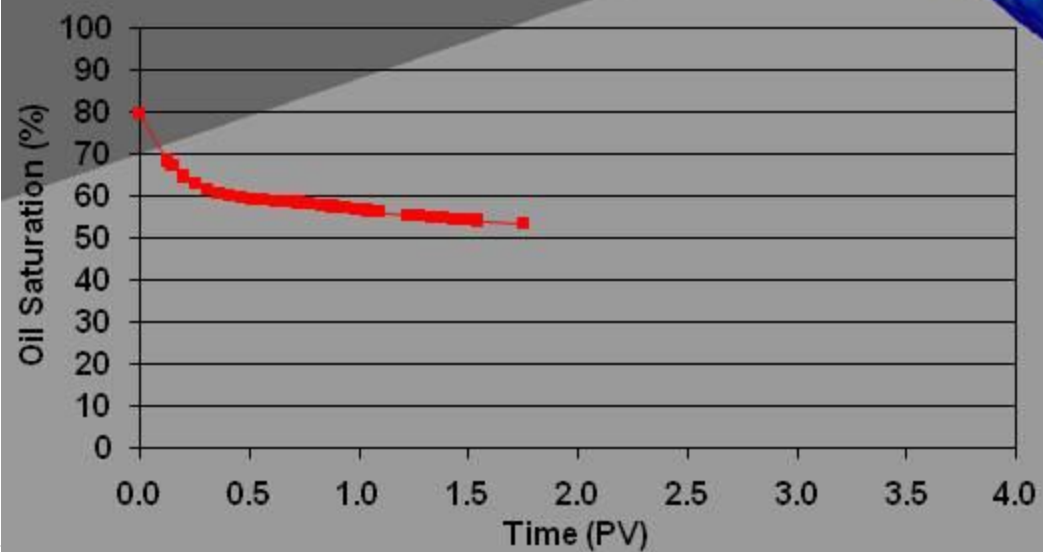
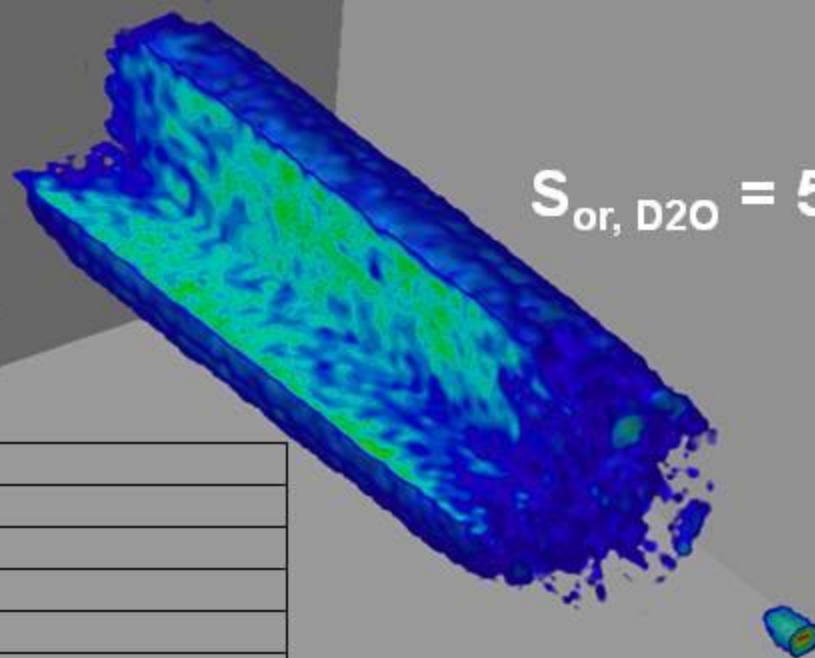
Time: 1.54 PV

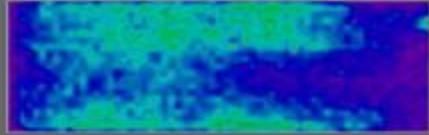




Time: 1.75 PV

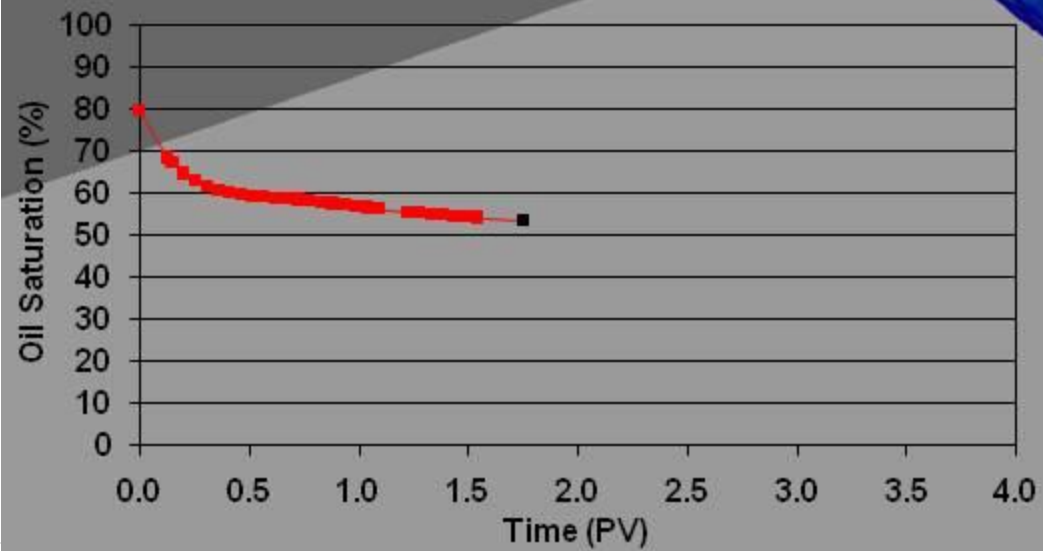
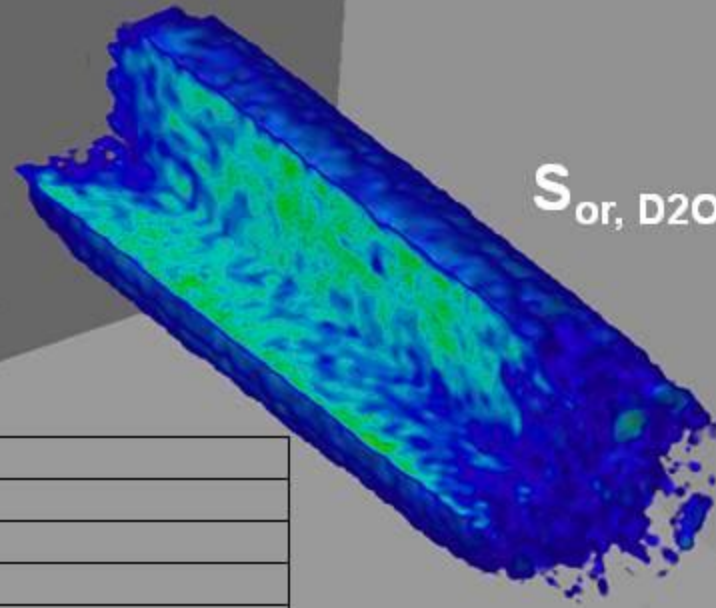
$S_{or, D2O} = 53.2 \%$



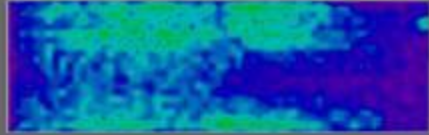


Time: 1.75 PV

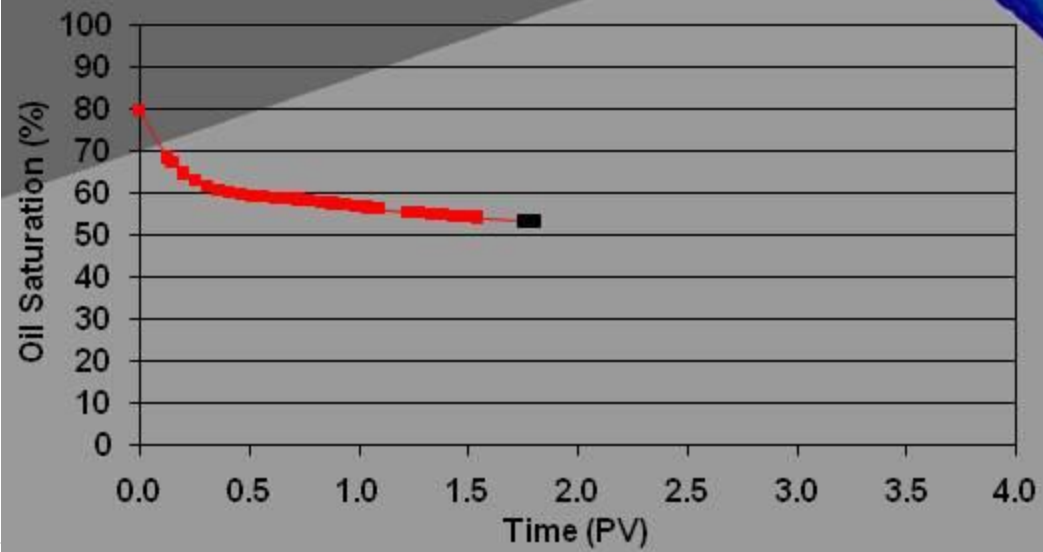
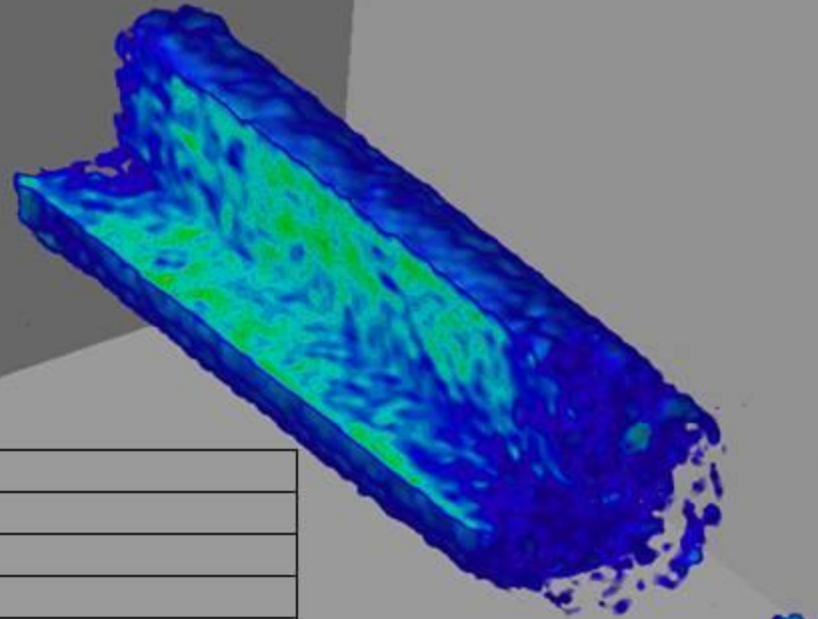
$S_{or, D2O} = 53.2 \%$

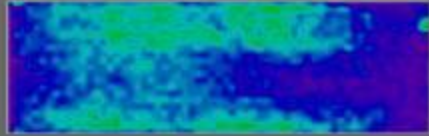


CO₂ Injection

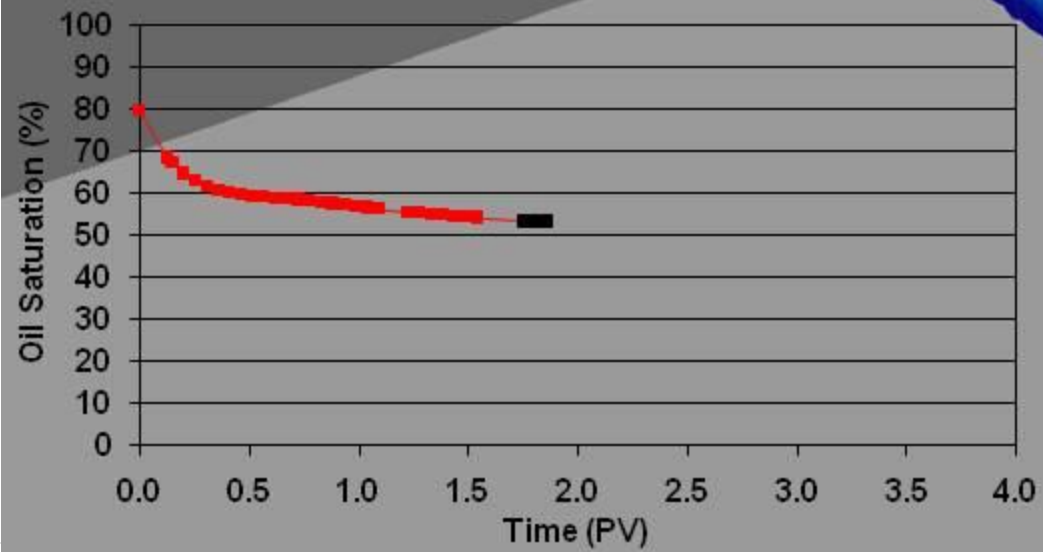
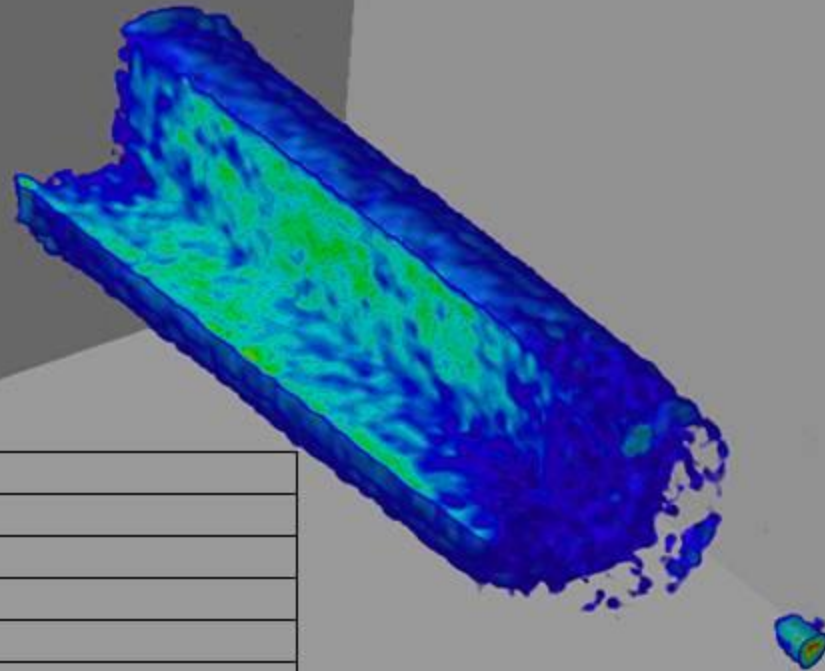


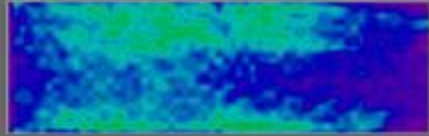
Time: 1.80 PV



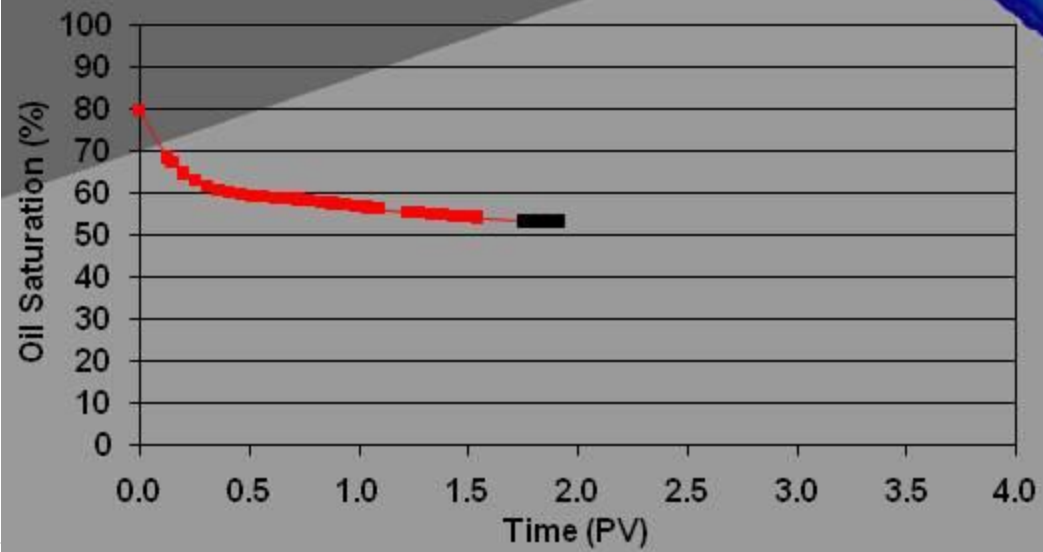
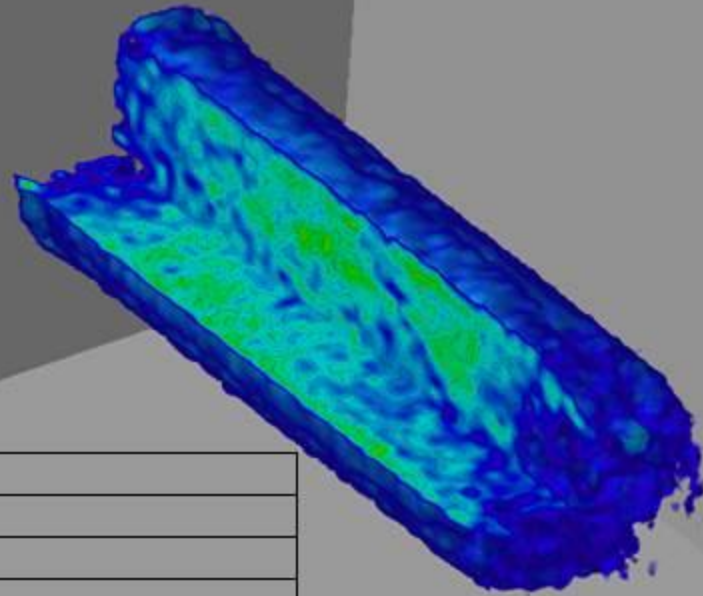


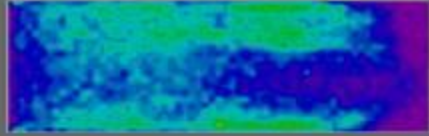
Time: 1.86 PV



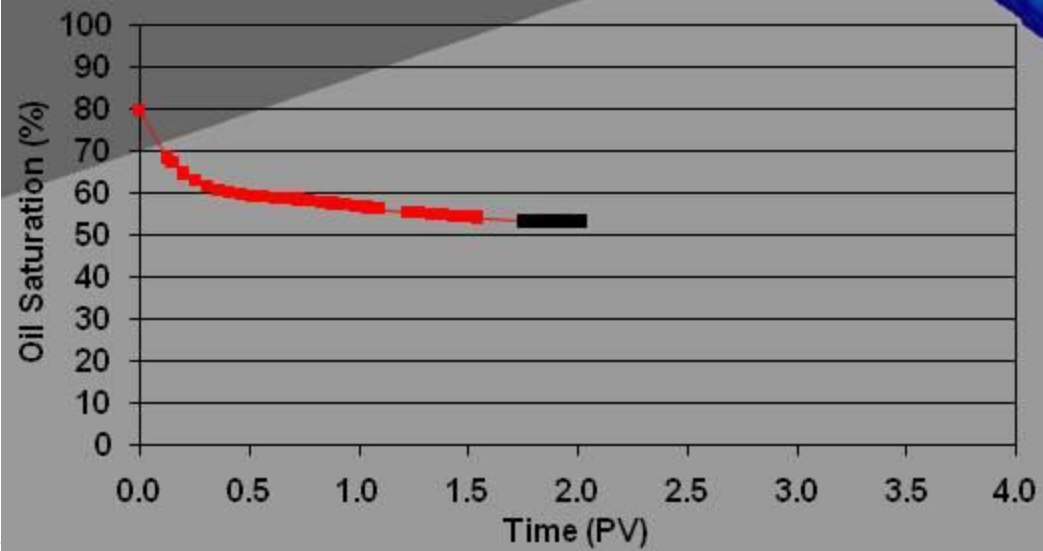
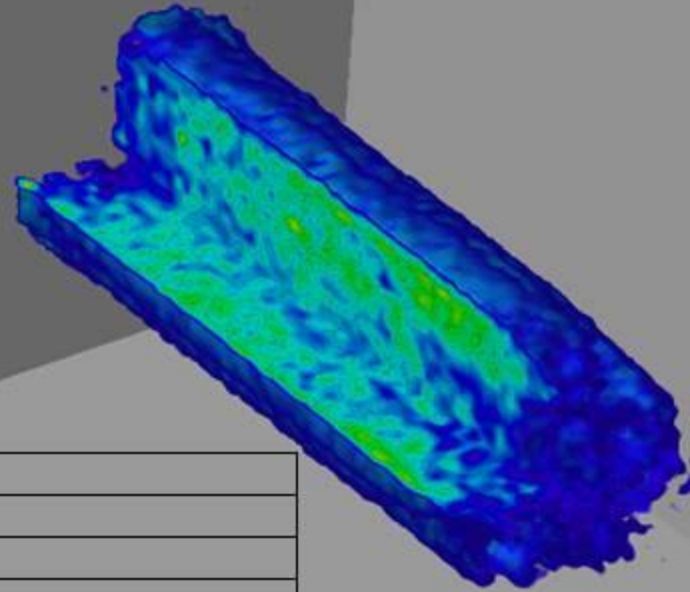


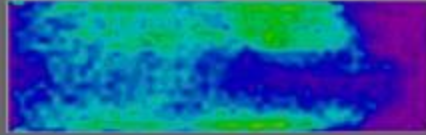
Time: 1.91 PV



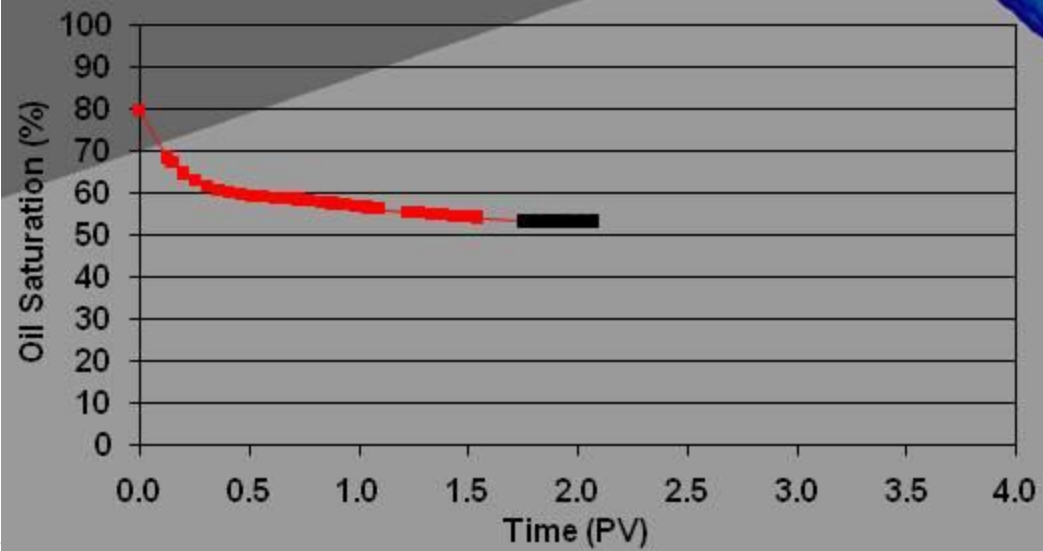
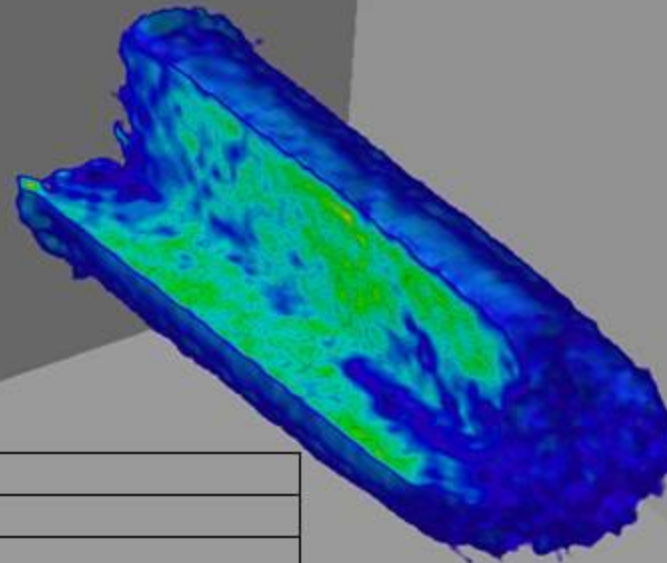


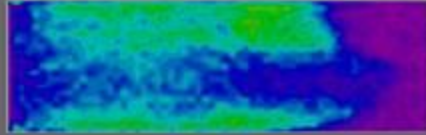
Time: 2.01 PV



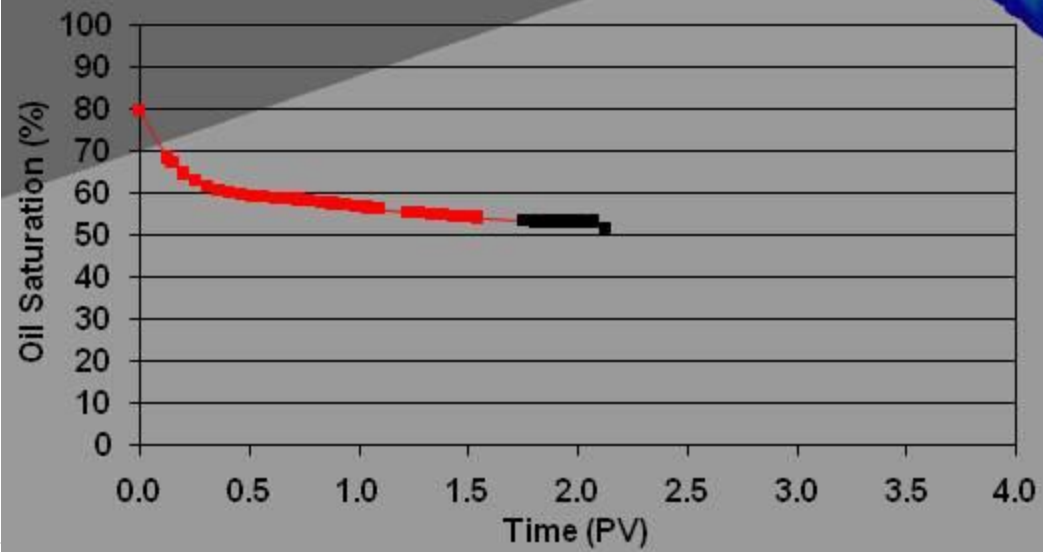
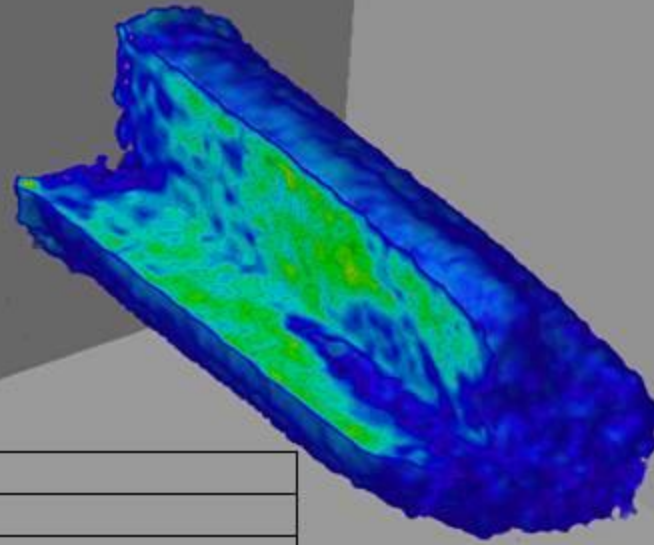


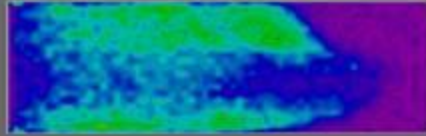
Time: 2.07 PV



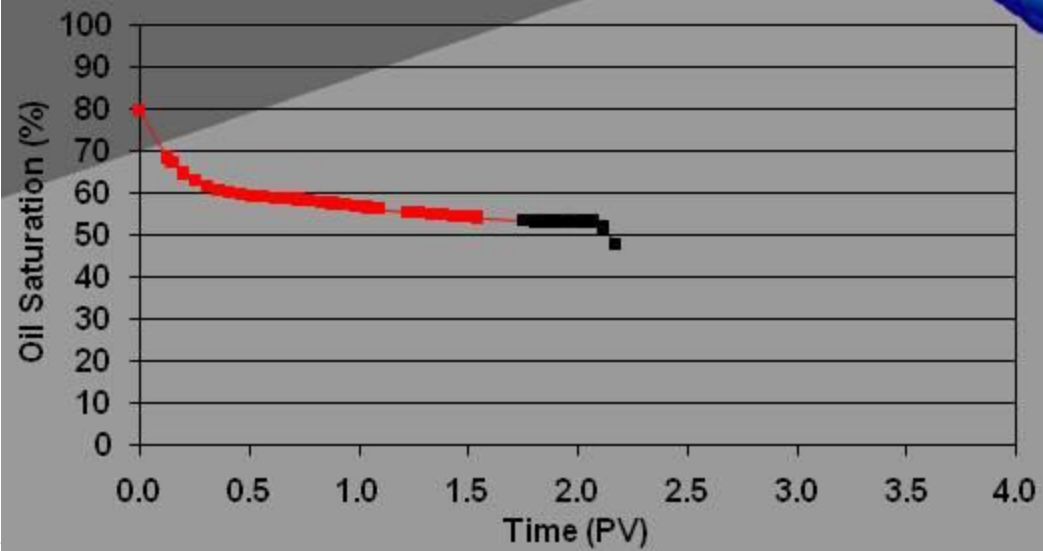
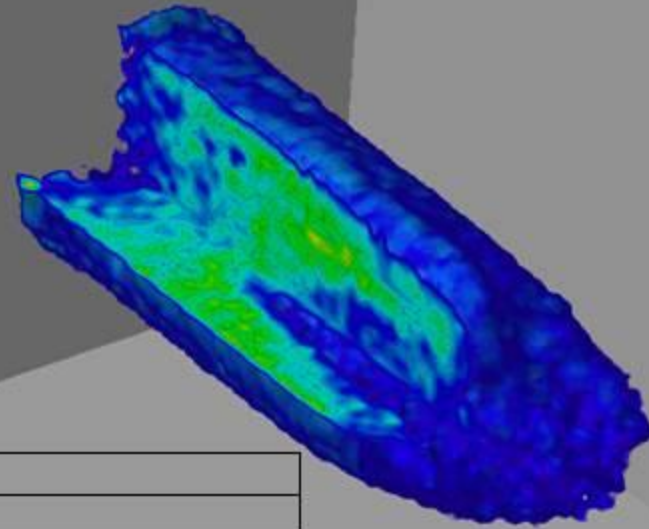


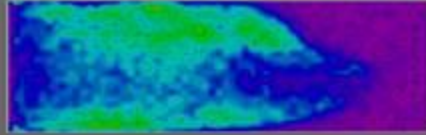
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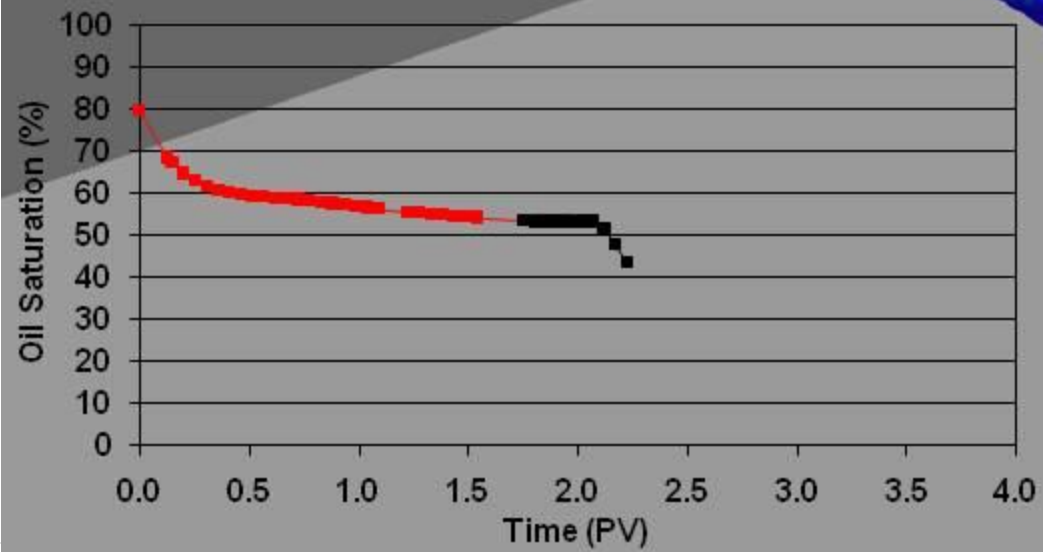
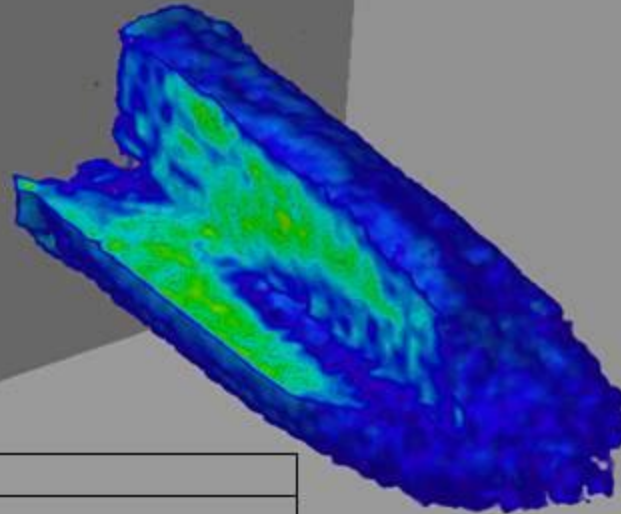


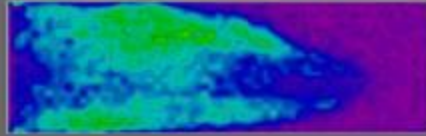
Time: 2.17 PV



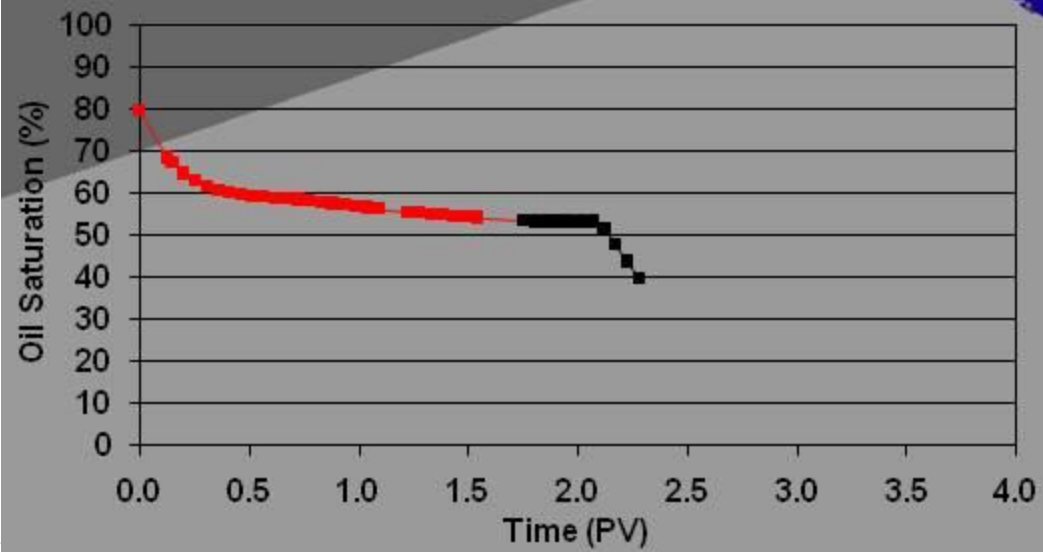
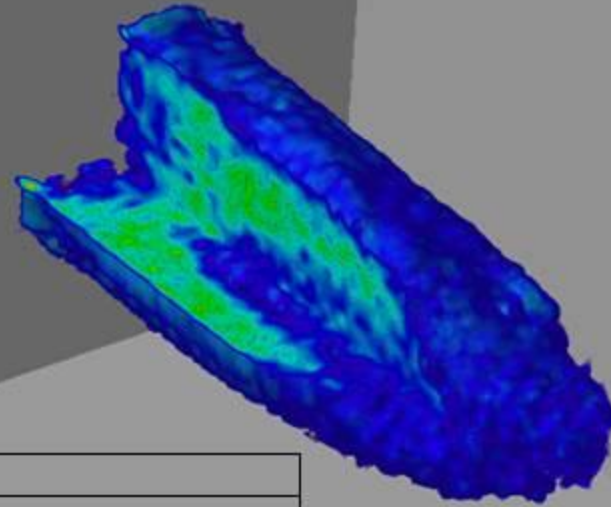


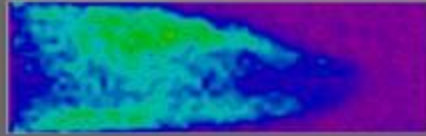
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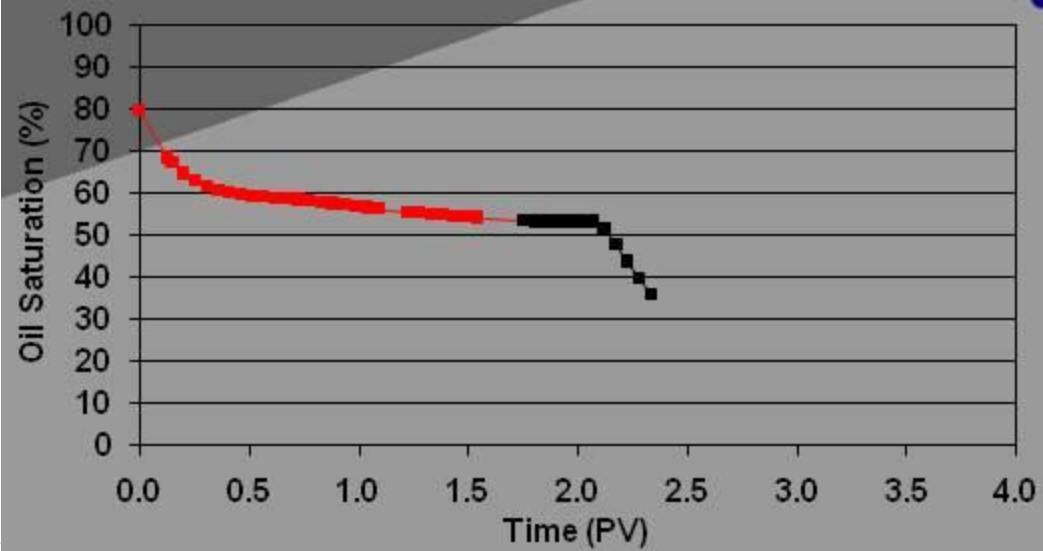
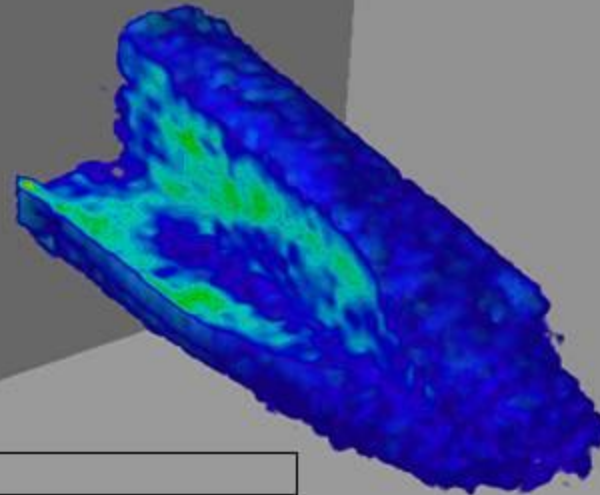


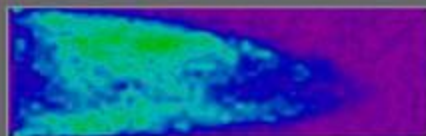
Time: 2.27 PV



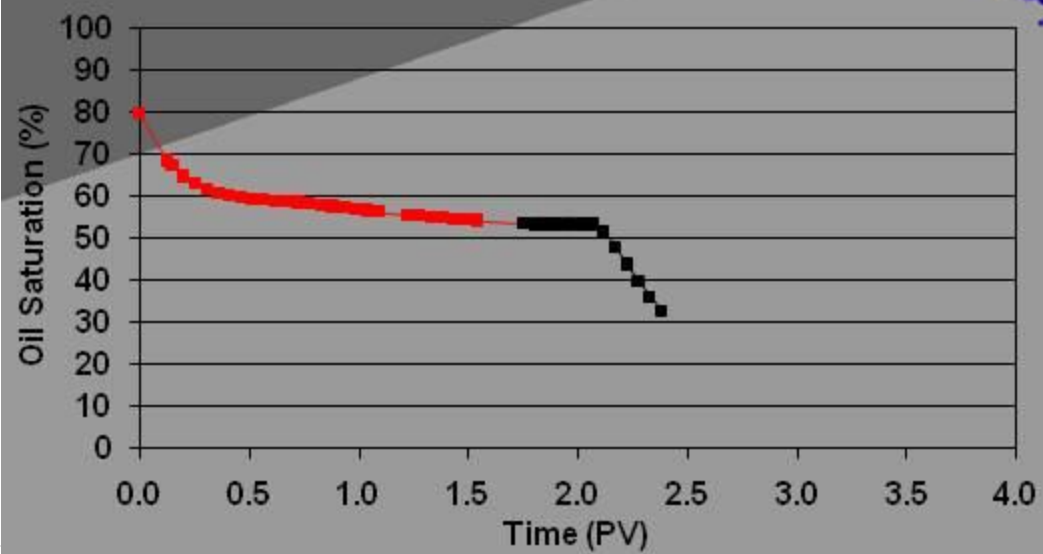
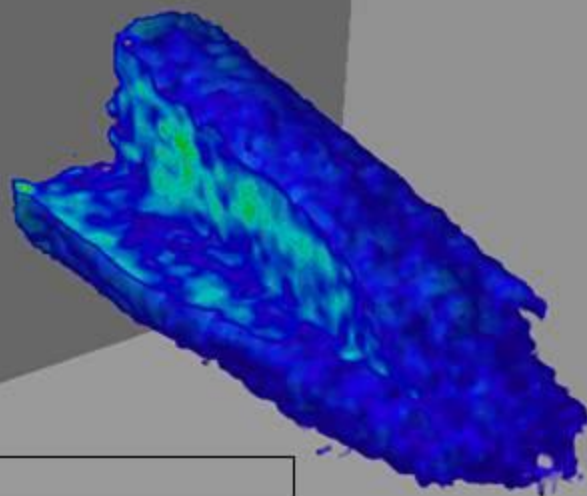


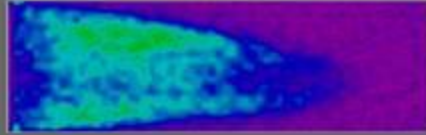
Time: 2.33 PV



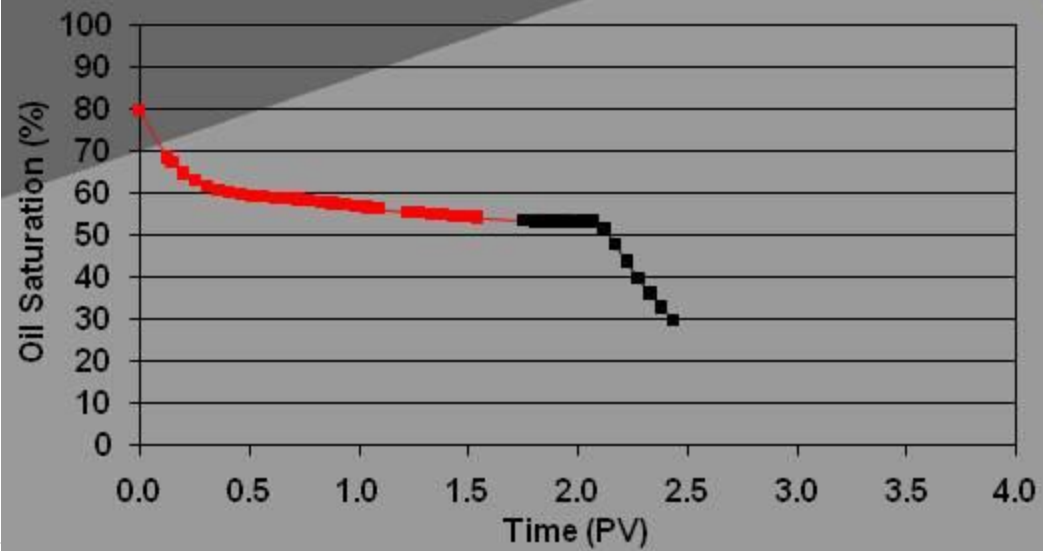
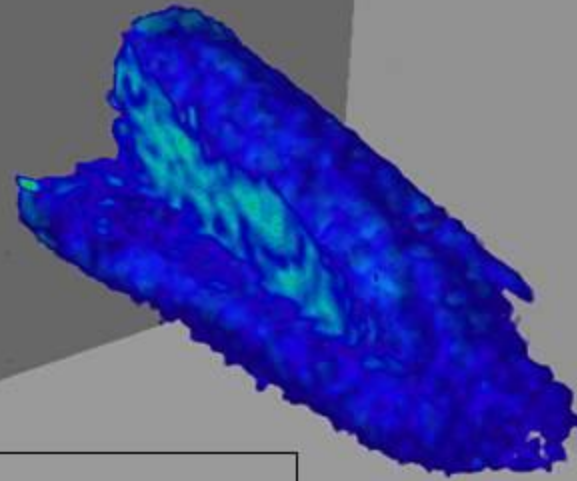


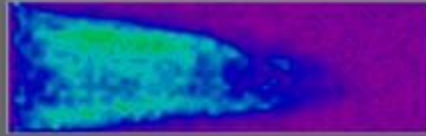
Time: 2.38 PV



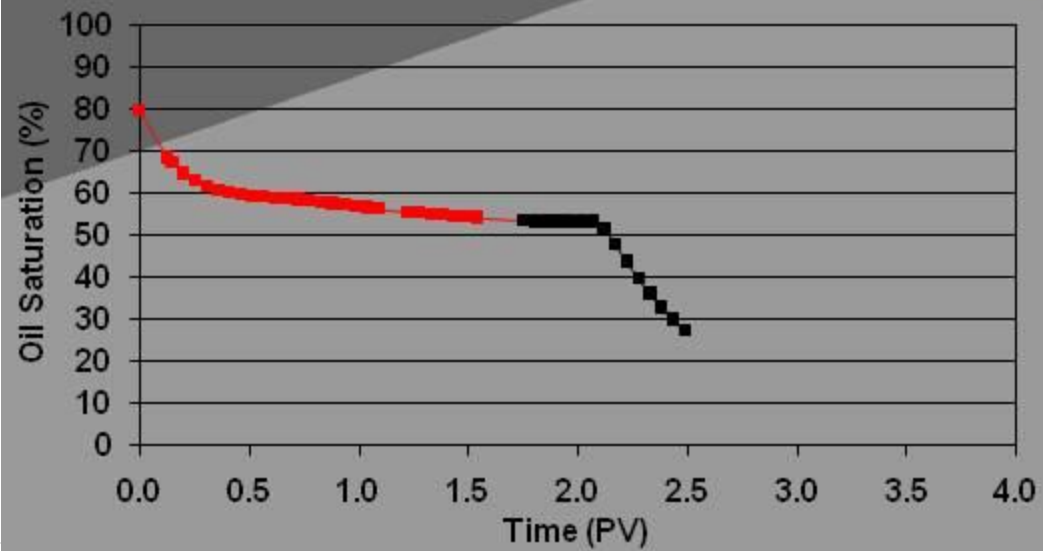
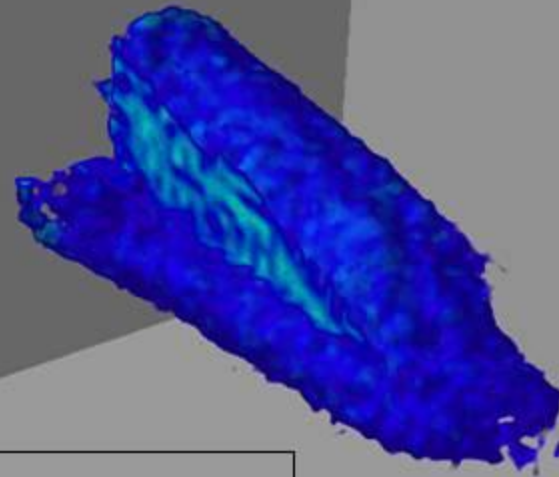


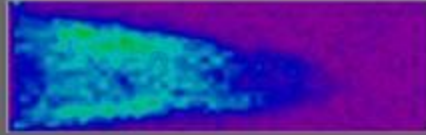
Time: 2.43 PV



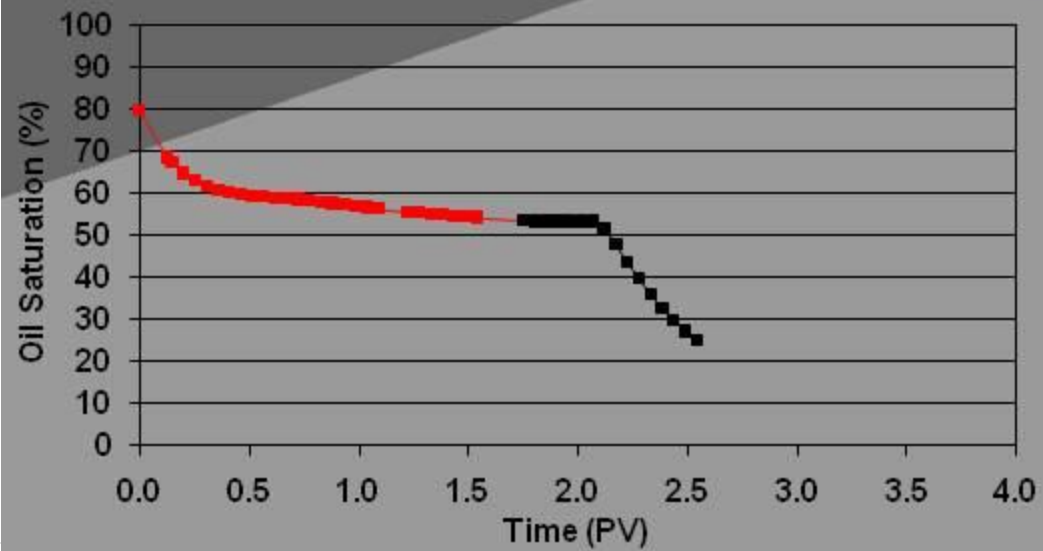
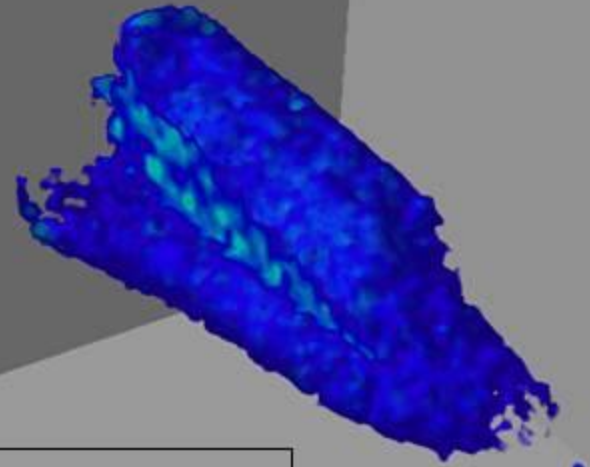


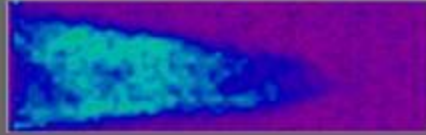
Time: 2.48 PV



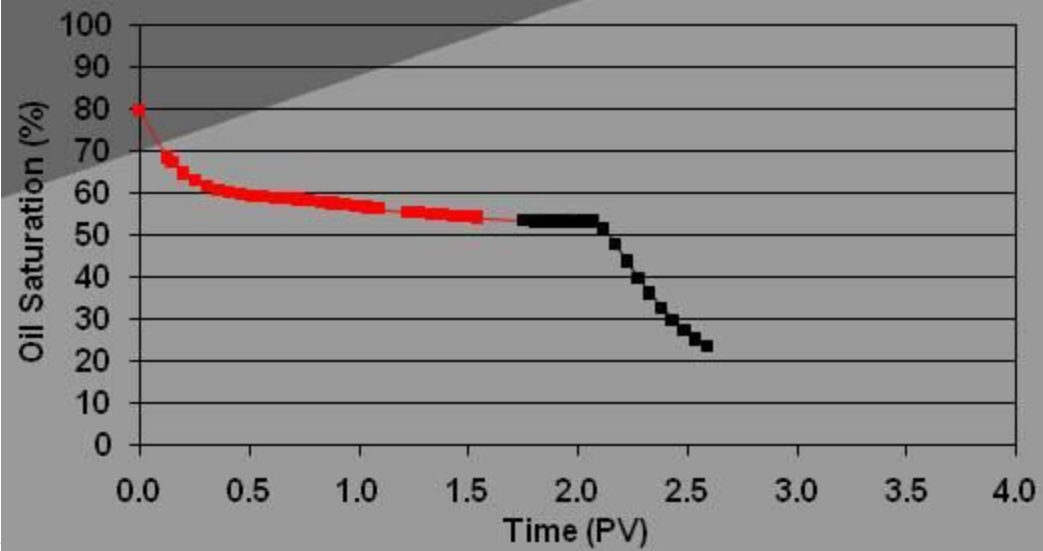
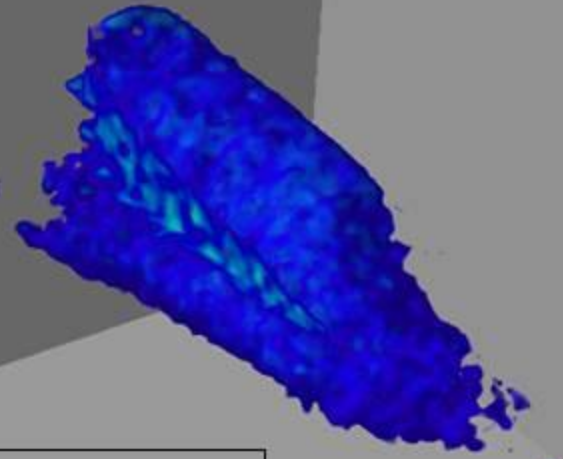


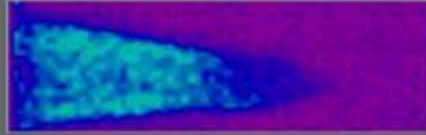
Time: 2.54 PV



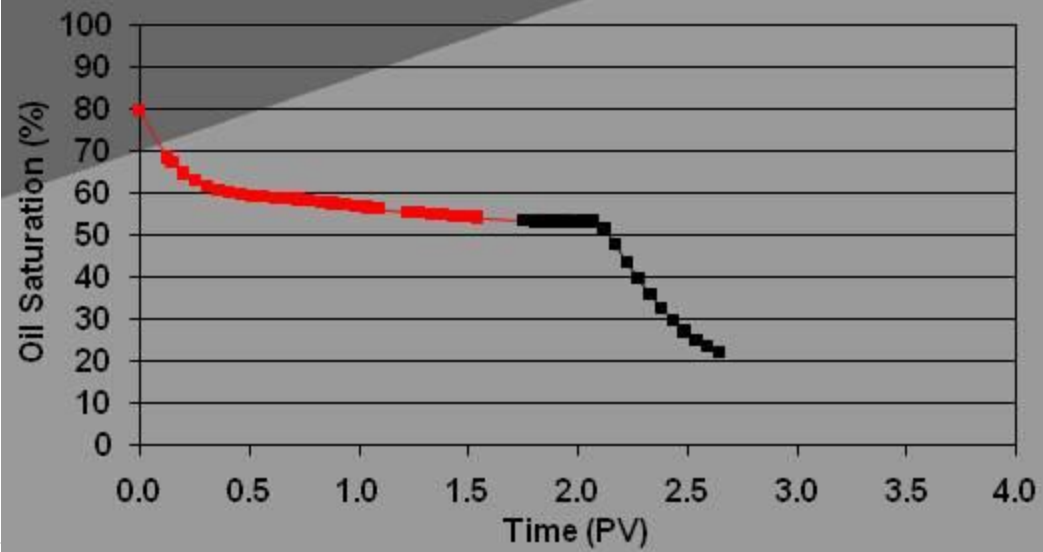
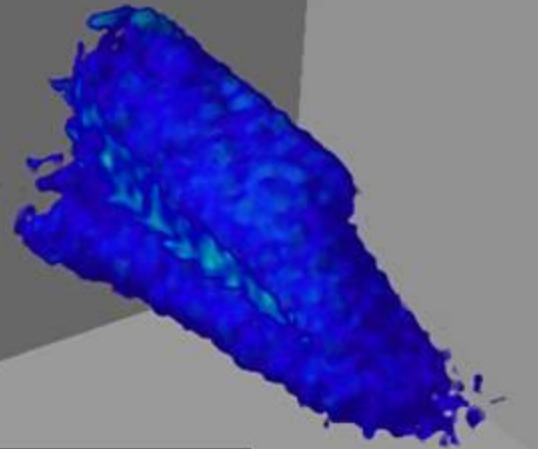


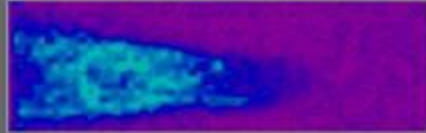
Time: 2.59 PV



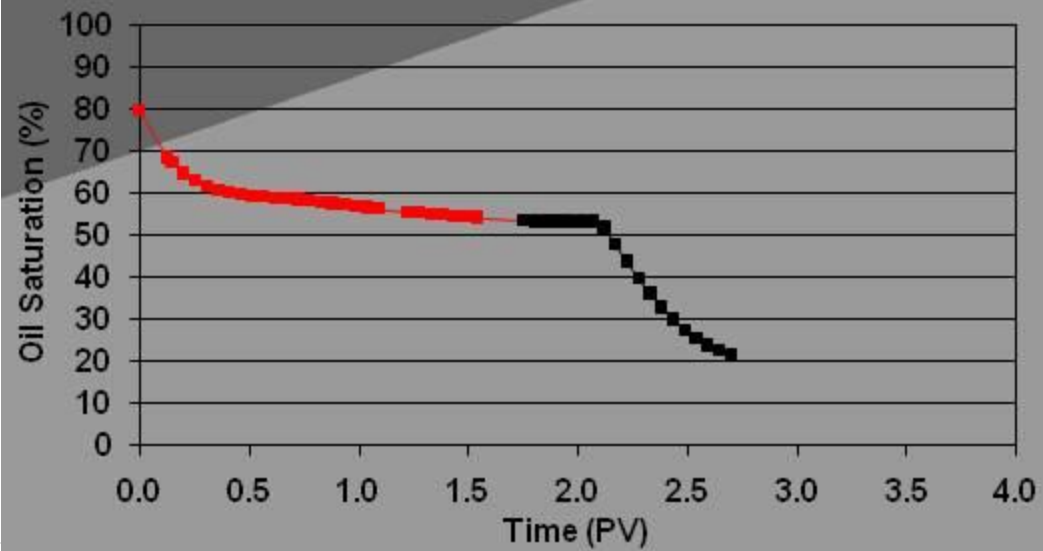
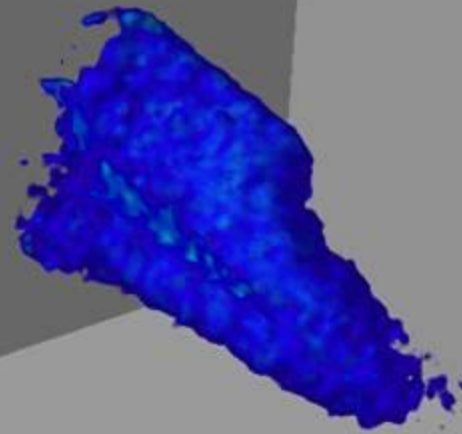


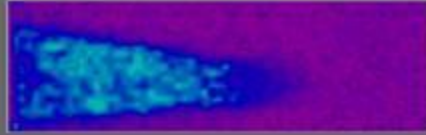
Time: 2.64 PV



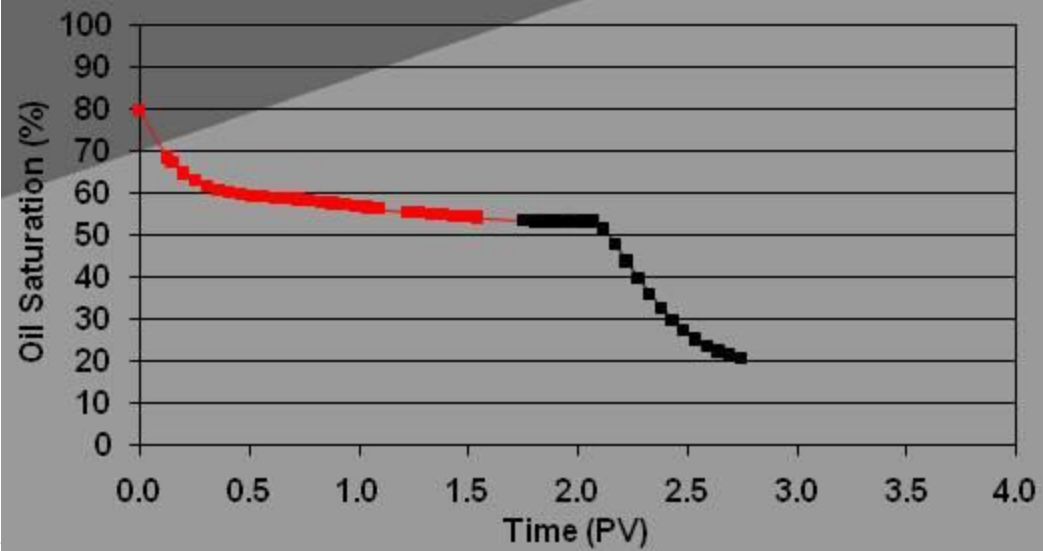
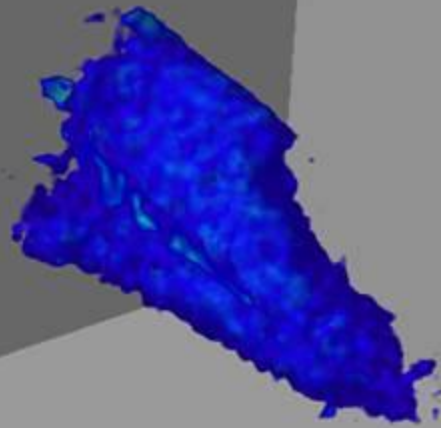


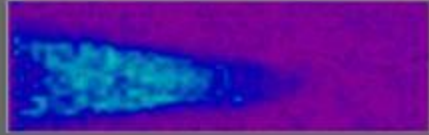
Time: 2.69 PV



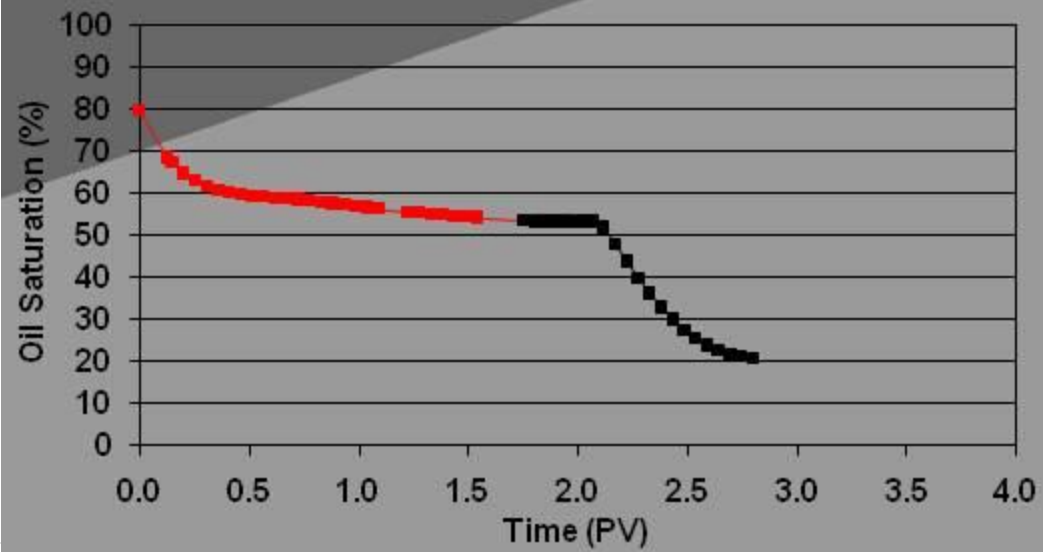
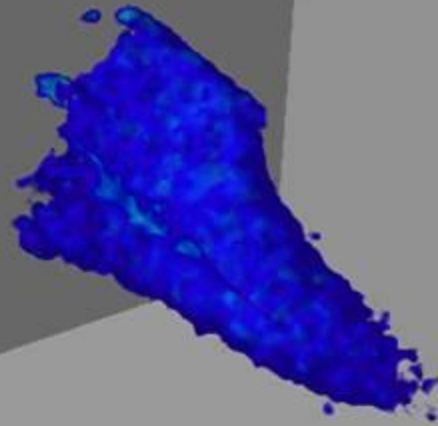


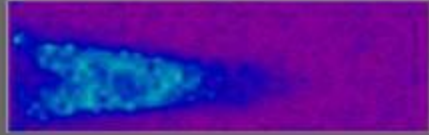
Time: 2.75 PV



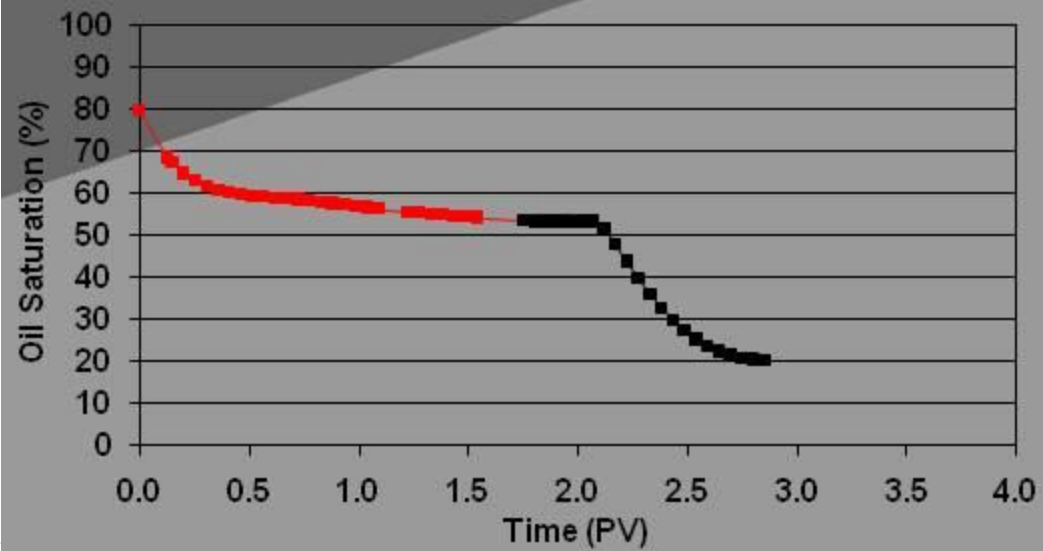
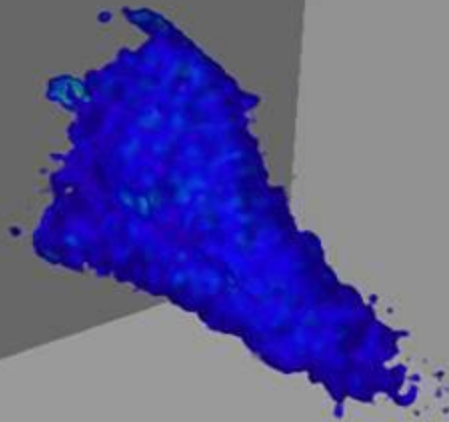


Time: 2.80 PV



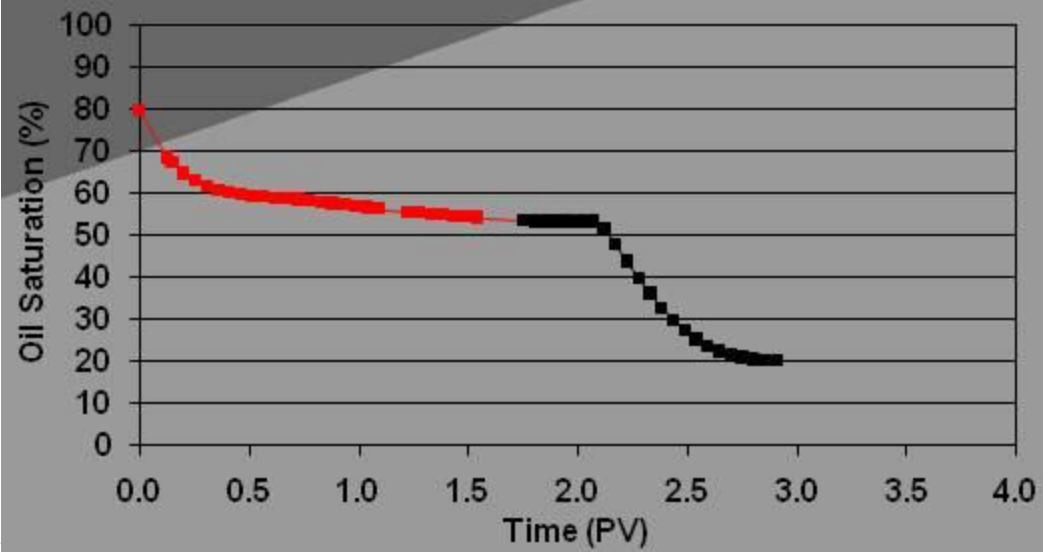


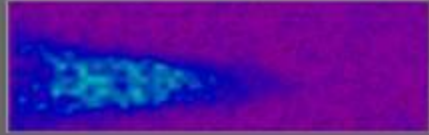
Time: 2.85 PV



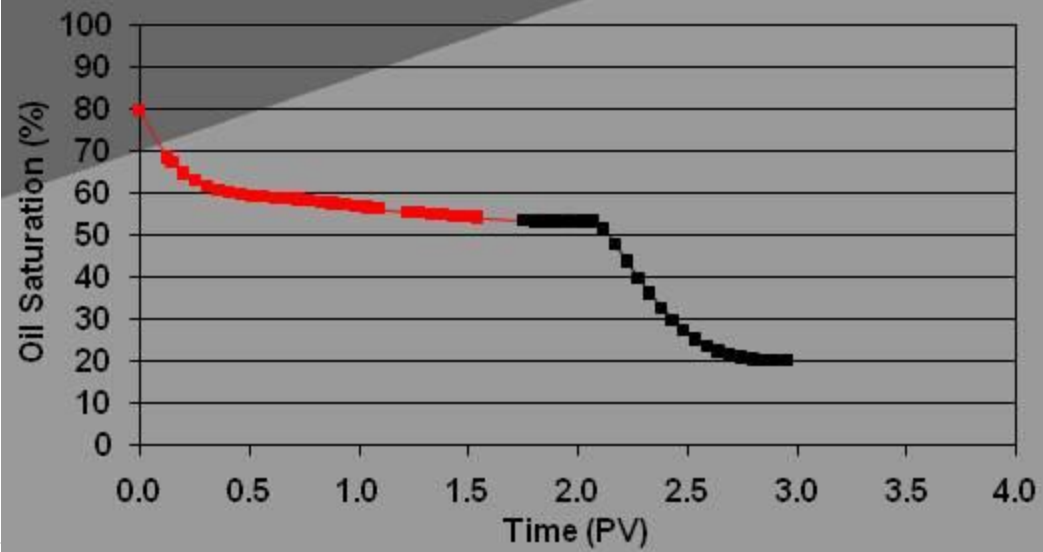


Time: 2.90 PV



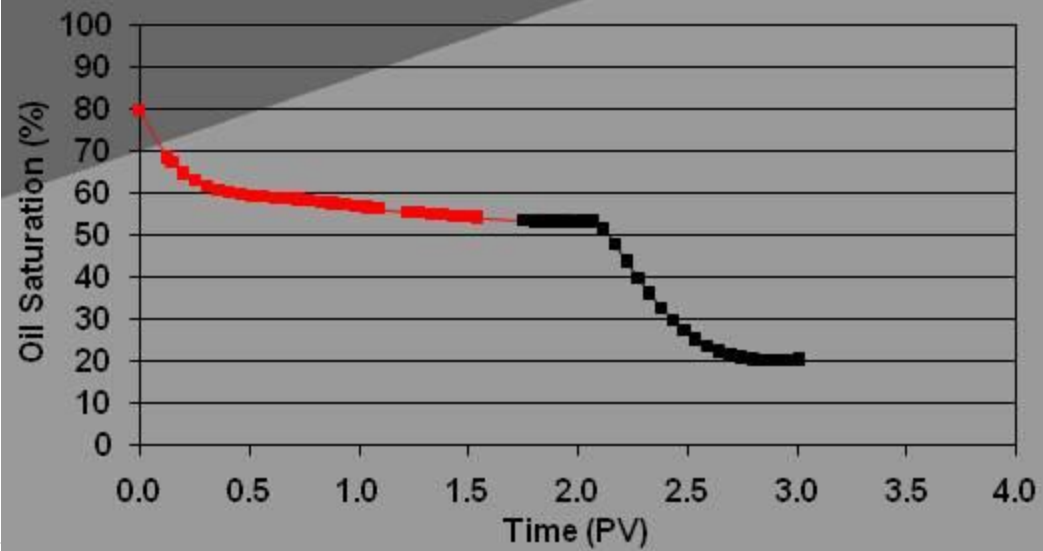


Time: 2.95 PV



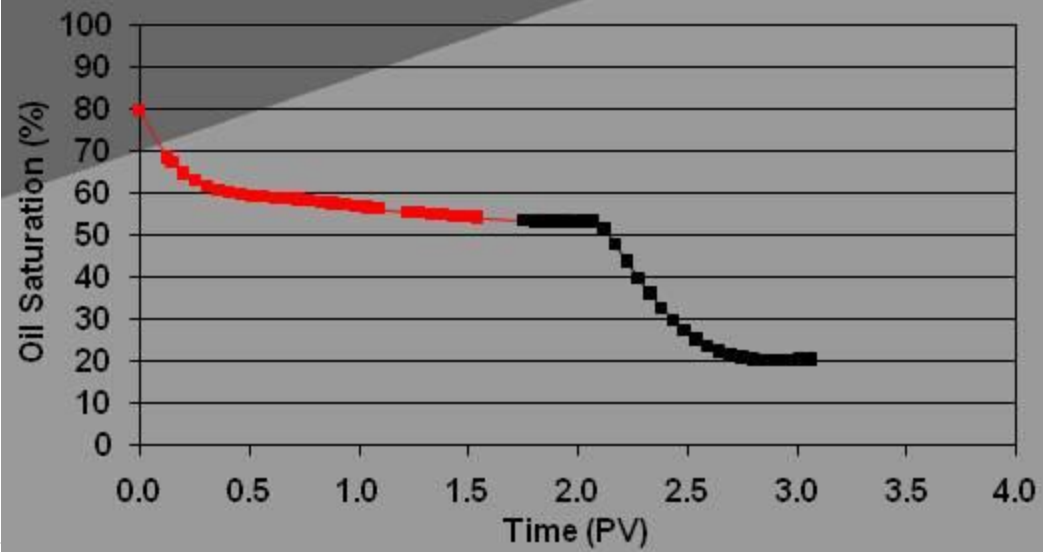
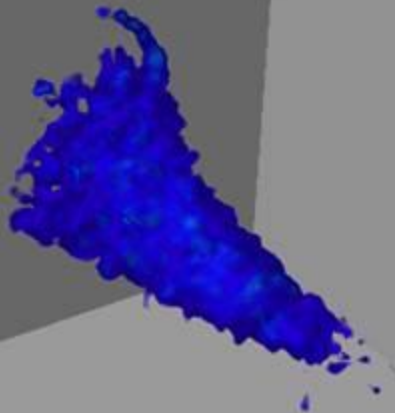


Time: 3.01 PV



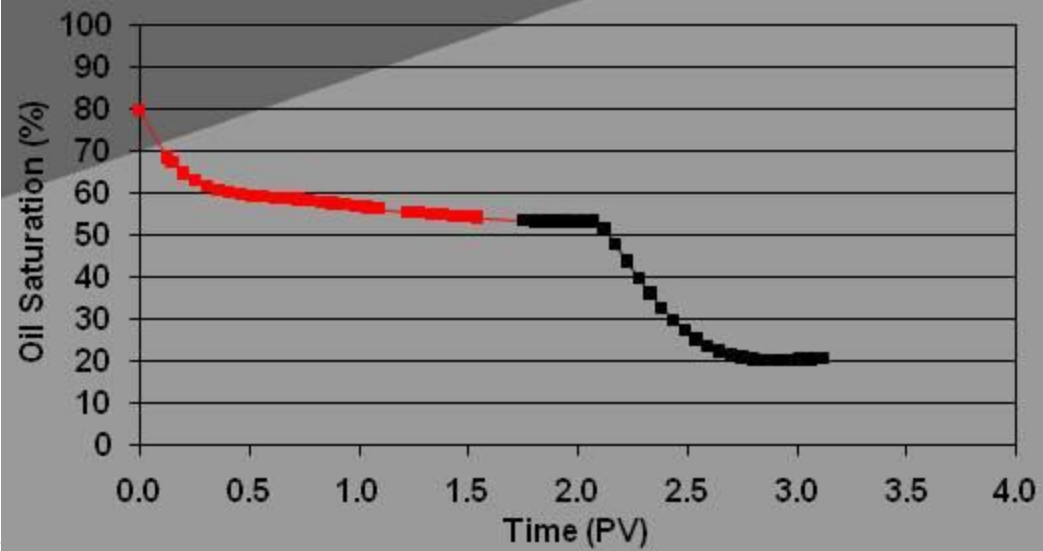


Time: 3.06 PV



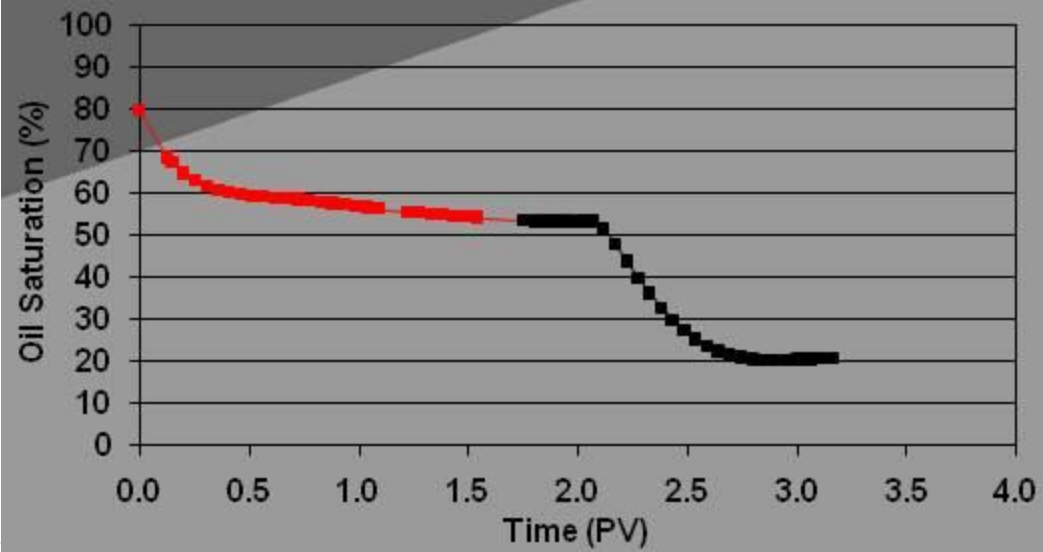


Time: 3.11 PV





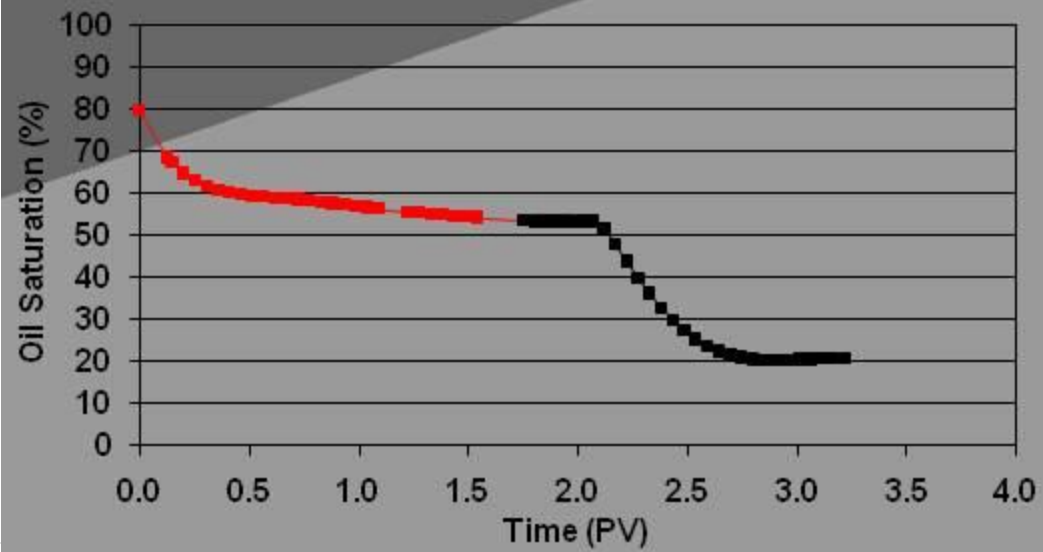
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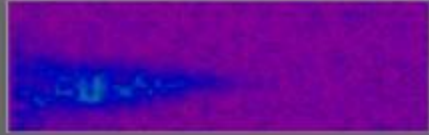


SCA2008-41

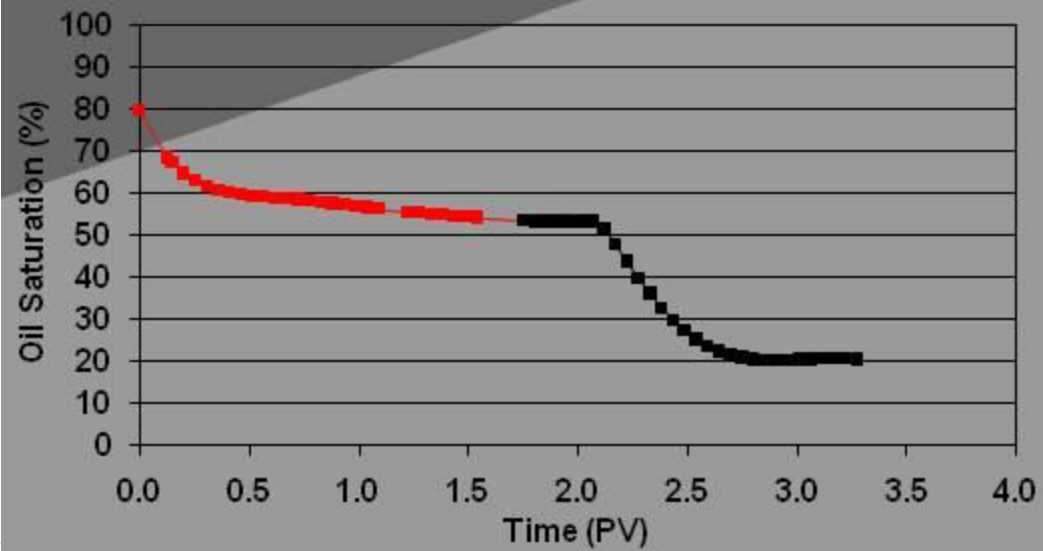


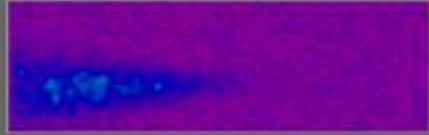
Time: 3.22 PV



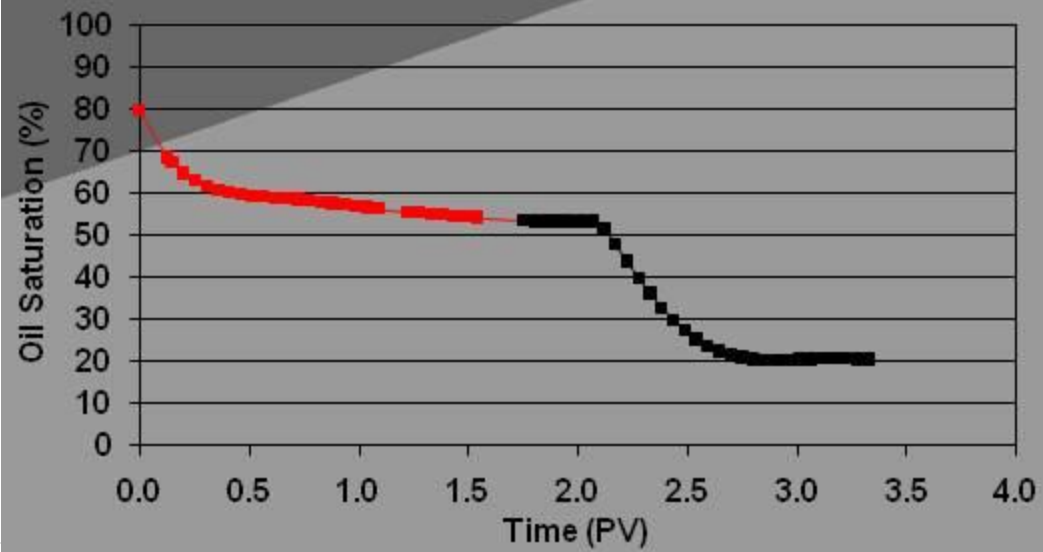


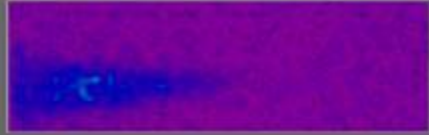
Time: 3.27 PV



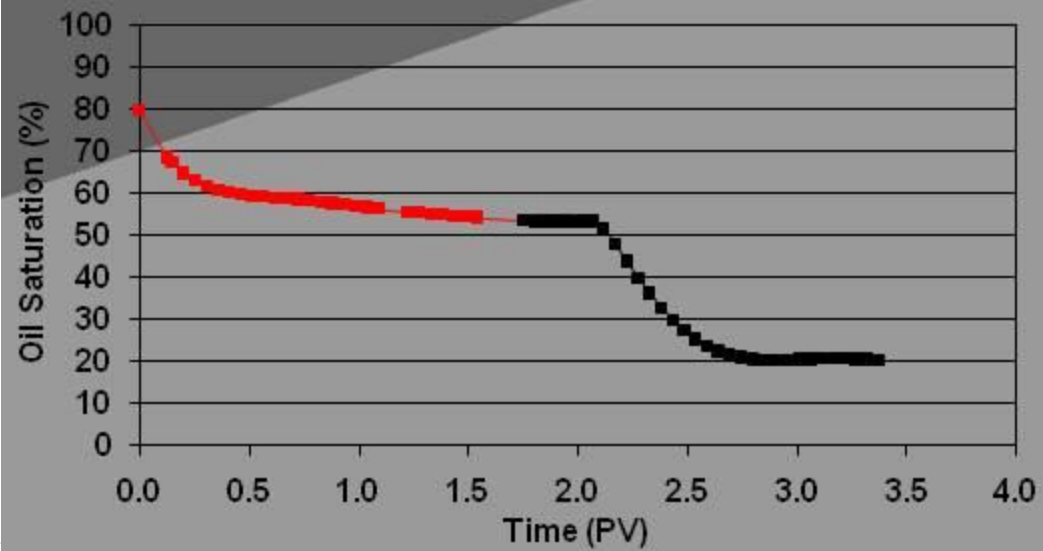


Time: 3.32 PV

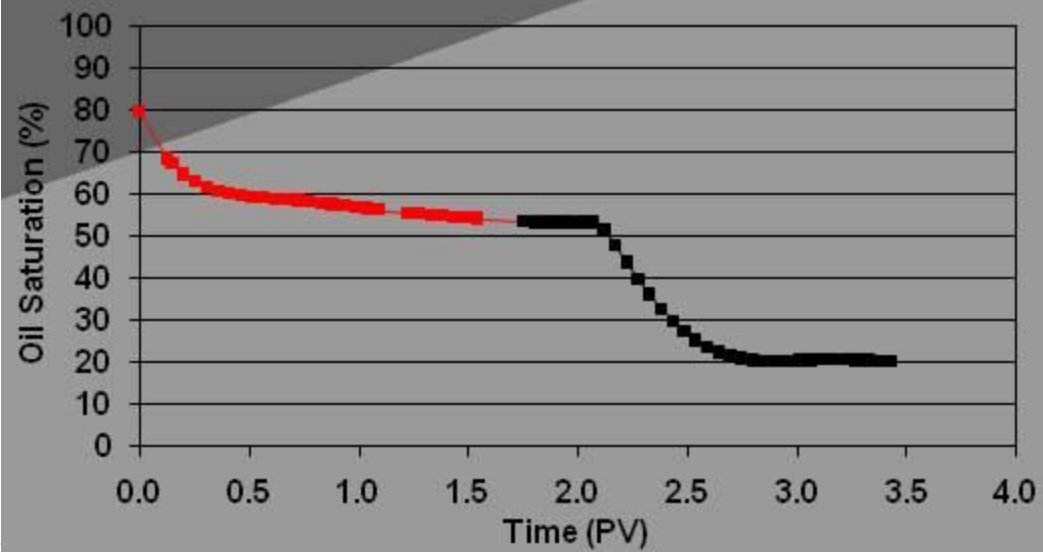




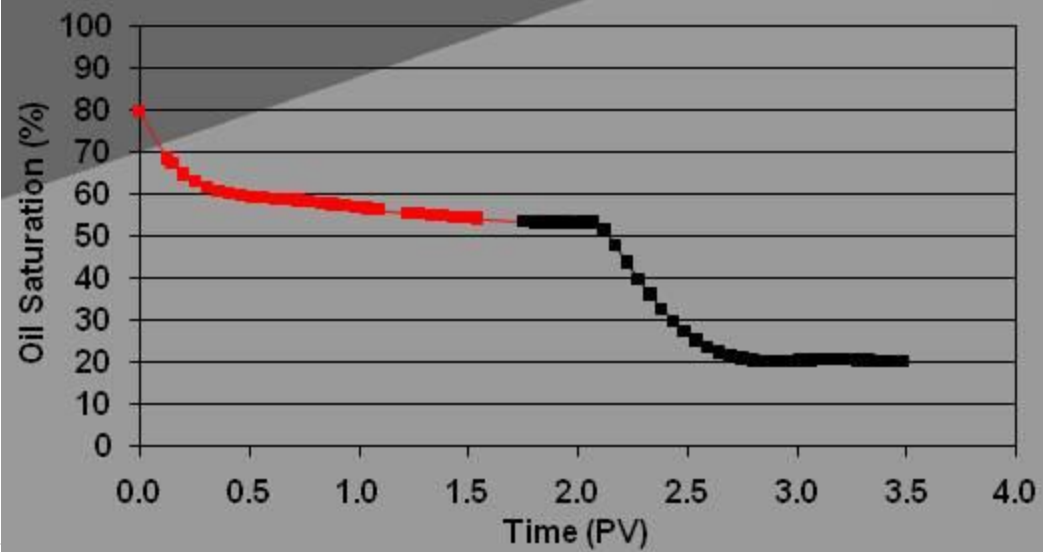
Time: 3.37 PV



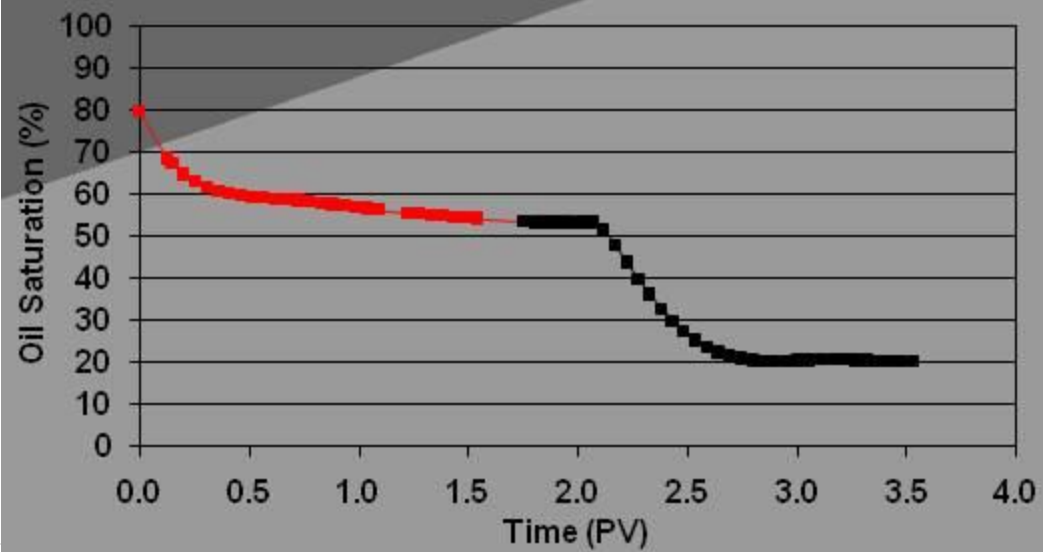
Time: 3.43 PV



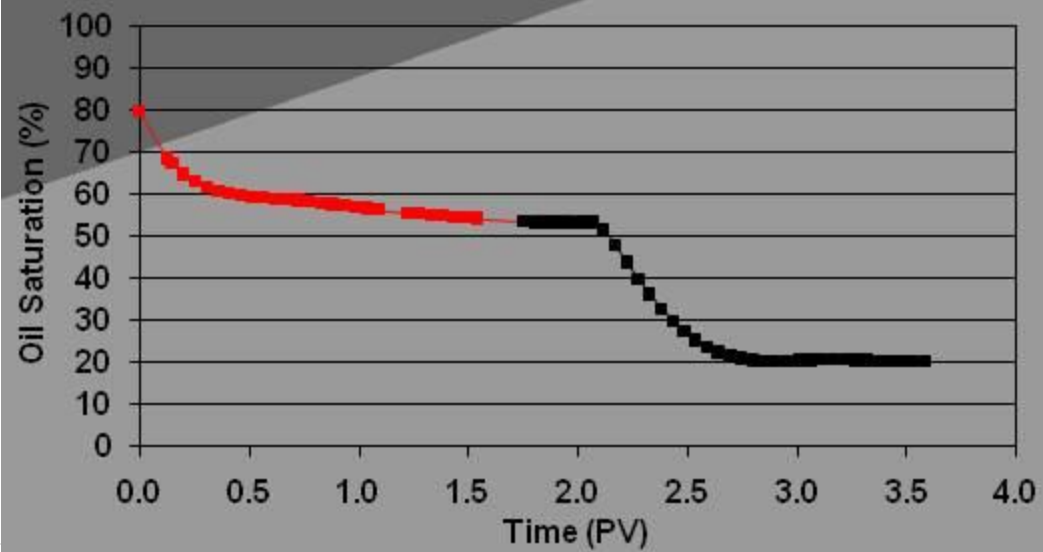
Time: 3.48 PV



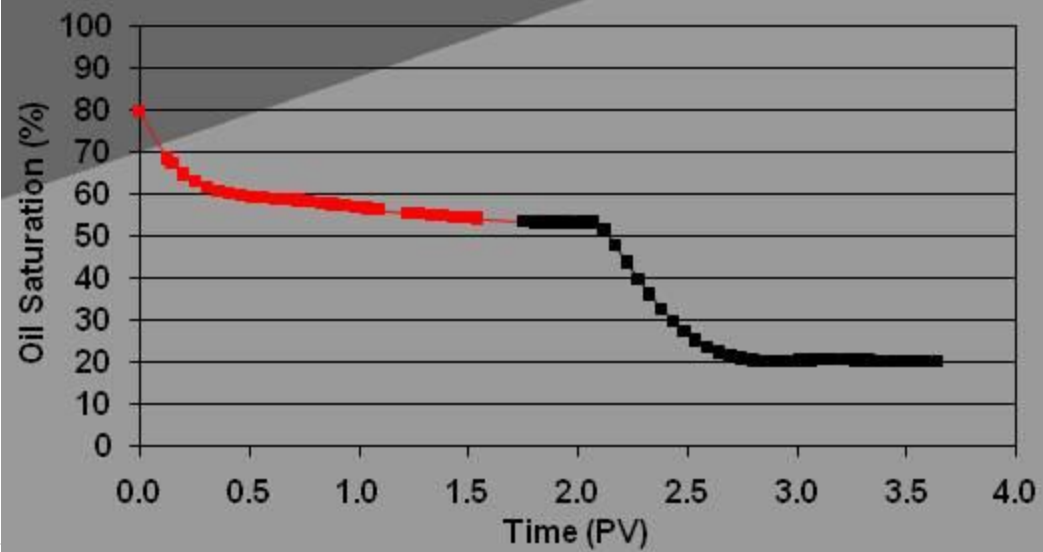
Time: 3.53 PV



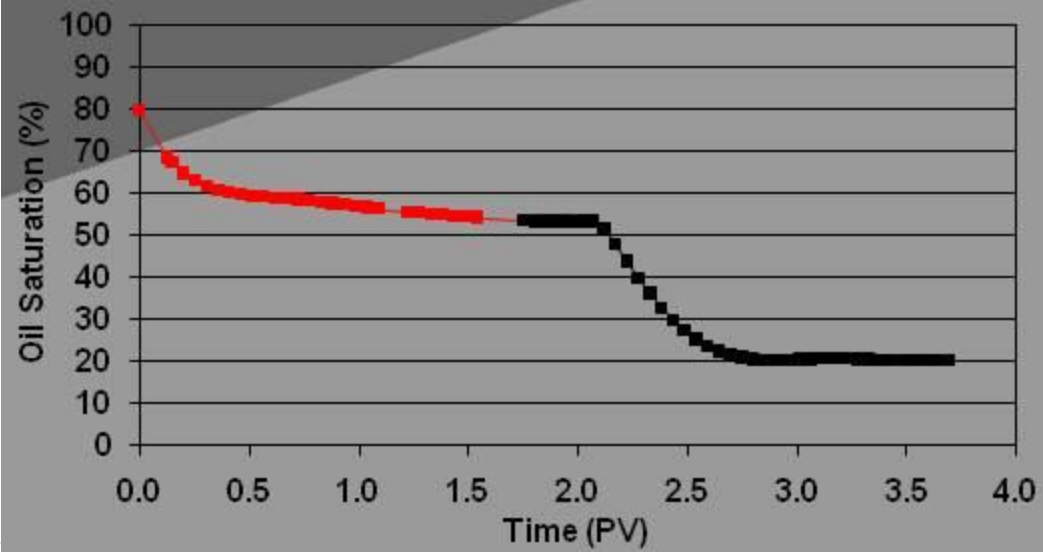
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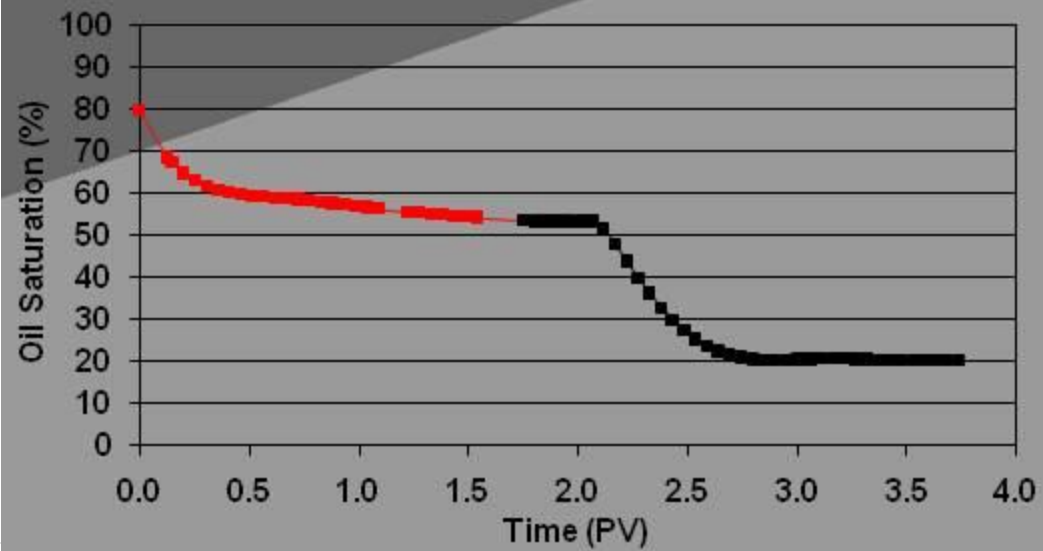
Time: 3.63 PV



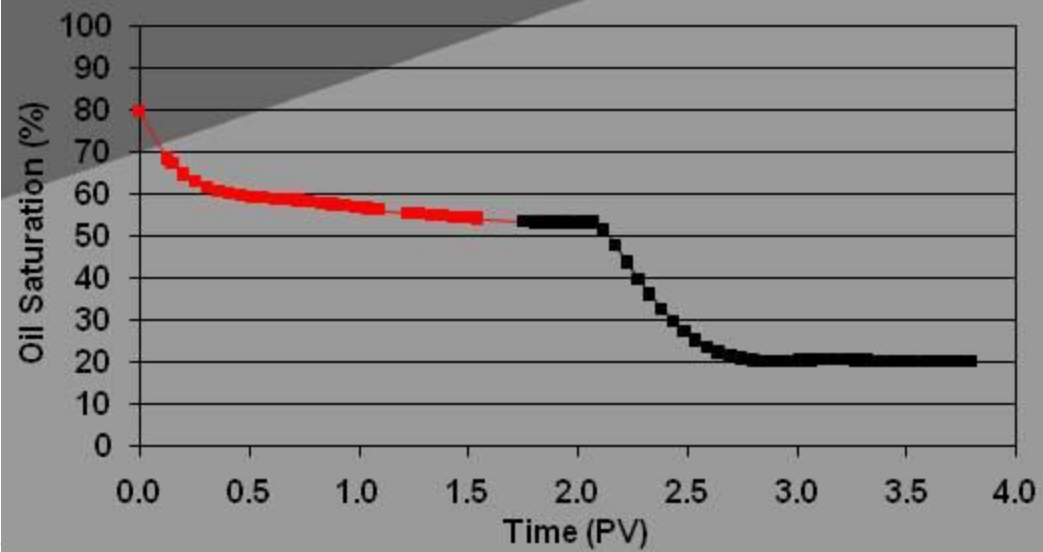
Time: 3.69 PV



Time: 3.74 PV



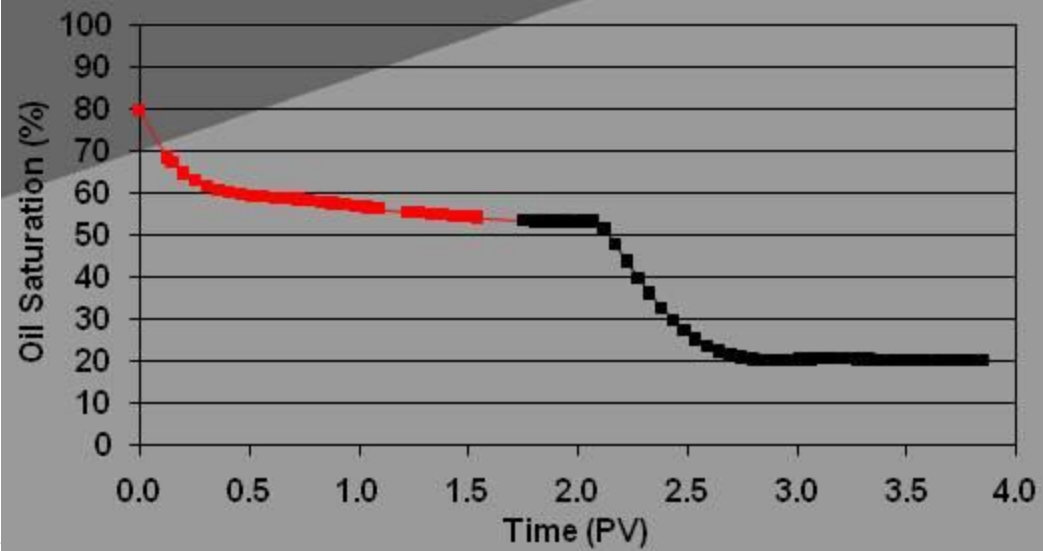
Time: 3.79 PV





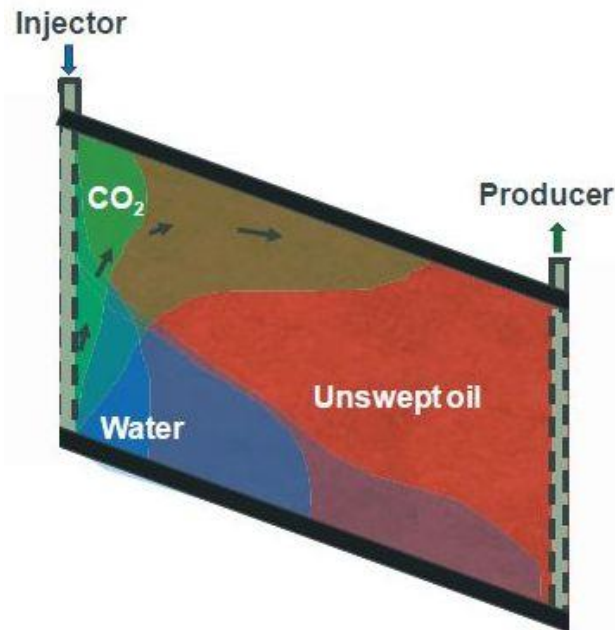
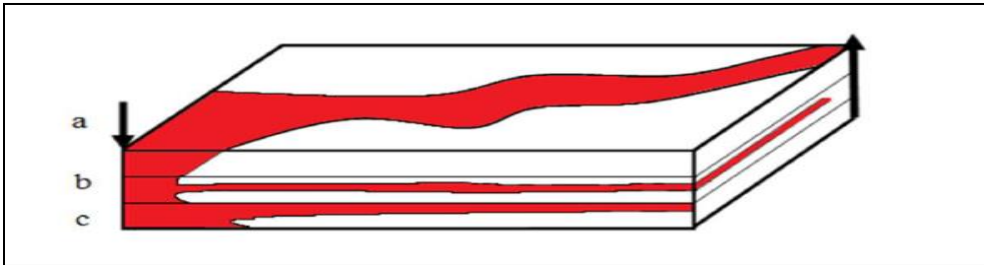
Time: 3.84 PV

$S_{or, CO_2} = 20.3 \%$



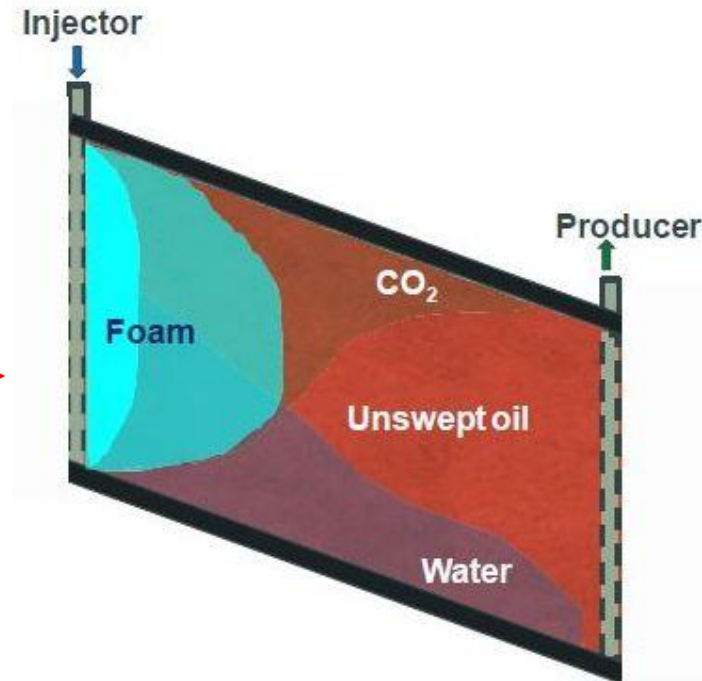
CO₂ Injection

- Poor aerial sweep
- Gas channeling
- Gravity override (Hanssen et al., 1994)



CO₂ Foam Injection

- Mitigates gravity override
- Improves sweep efficiency



Experimental Setup

Fracture networks

Outline

Background

Objective

Introduction

Core material

Experimental

- Setup
- Core preparation
- Schedule

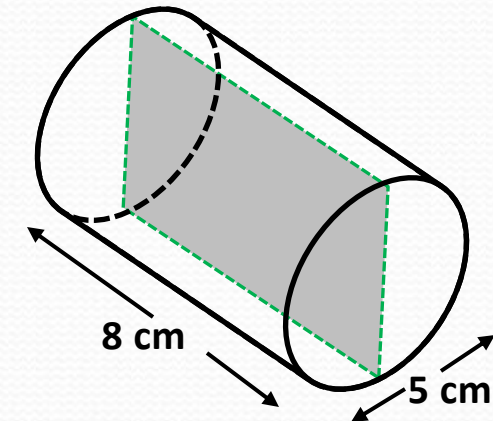
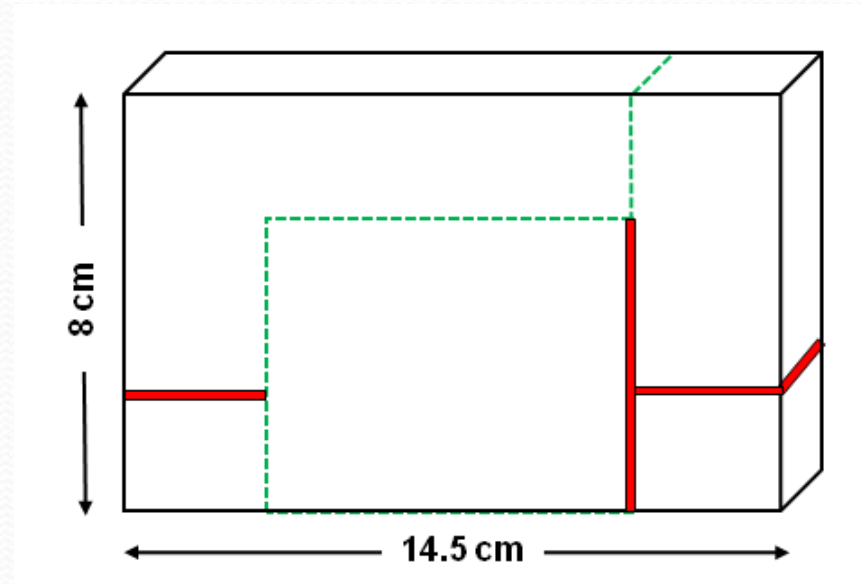
Results

- Core properties
- Core 1: Foam generation
- Core 2: Gas injection
- Block 1: WF + Foam
- Block 2 : WF + Foam
- Fracture/matrix ratio

Summary

Conclusions

Acknowledgement



----- Small aperture
— Open fracture

Results - Foam Generation

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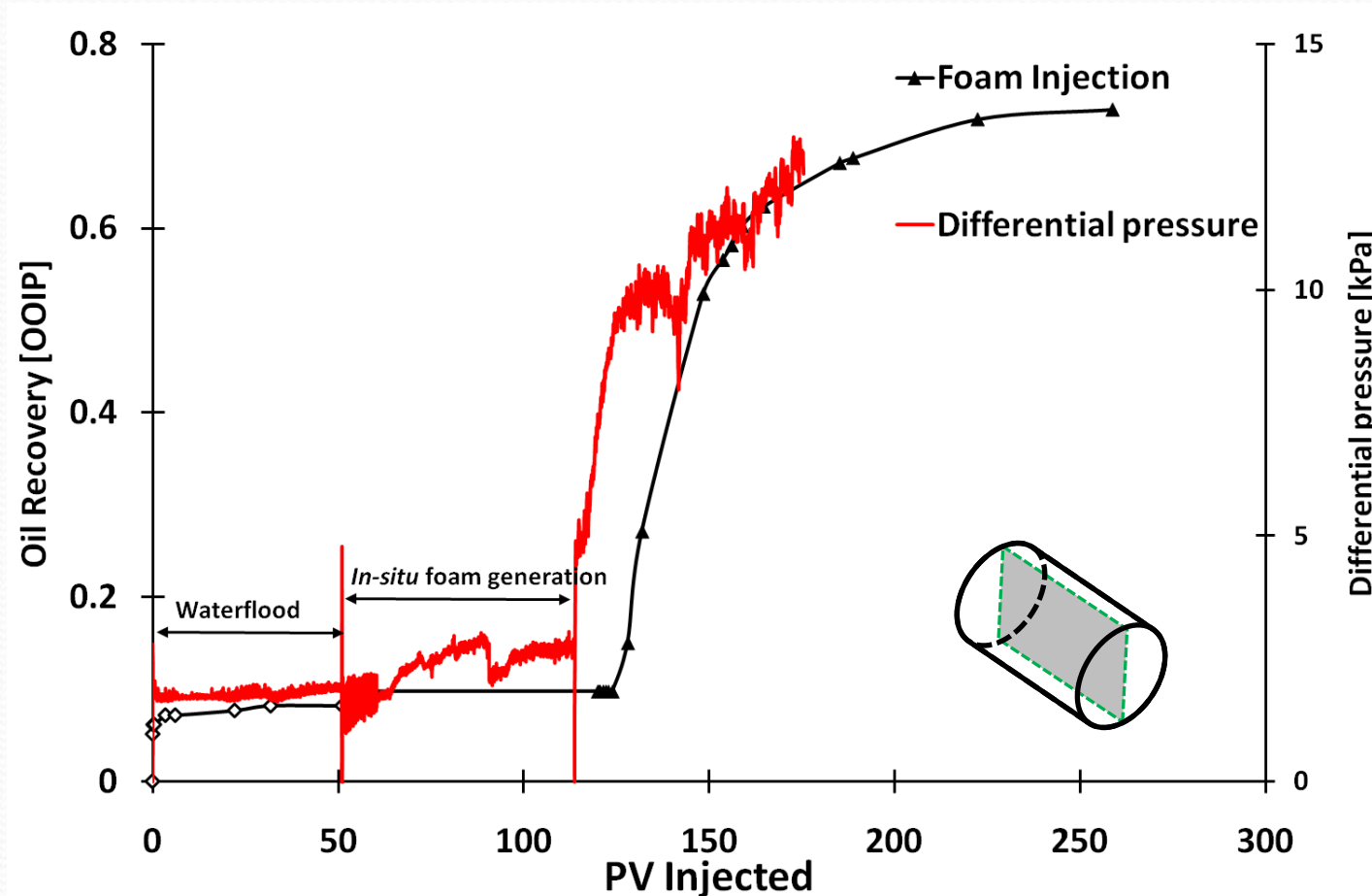
Results

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Results - WF + Foam injection

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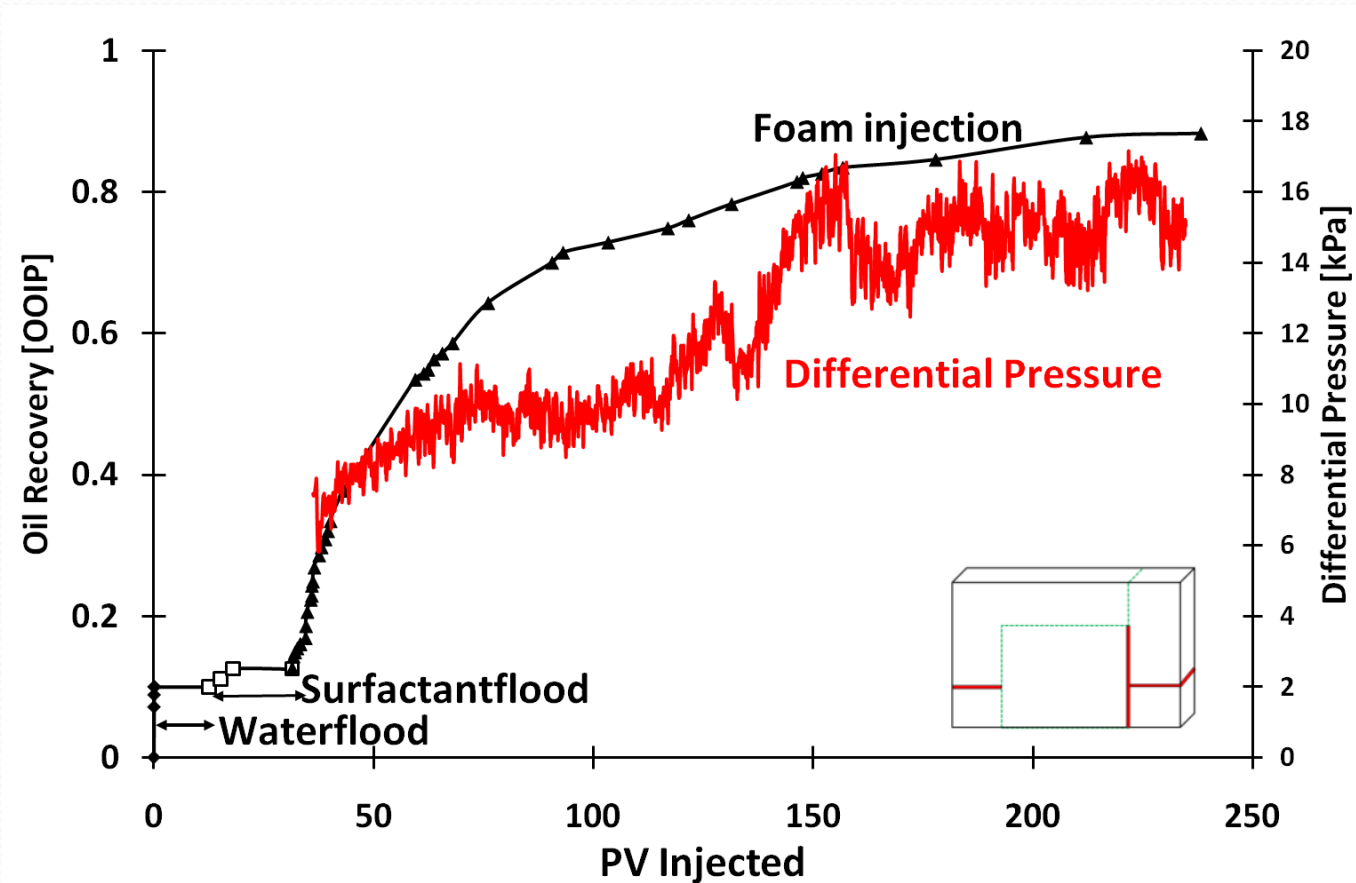
Results

- Core properties
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- Block 1: WF + Foam
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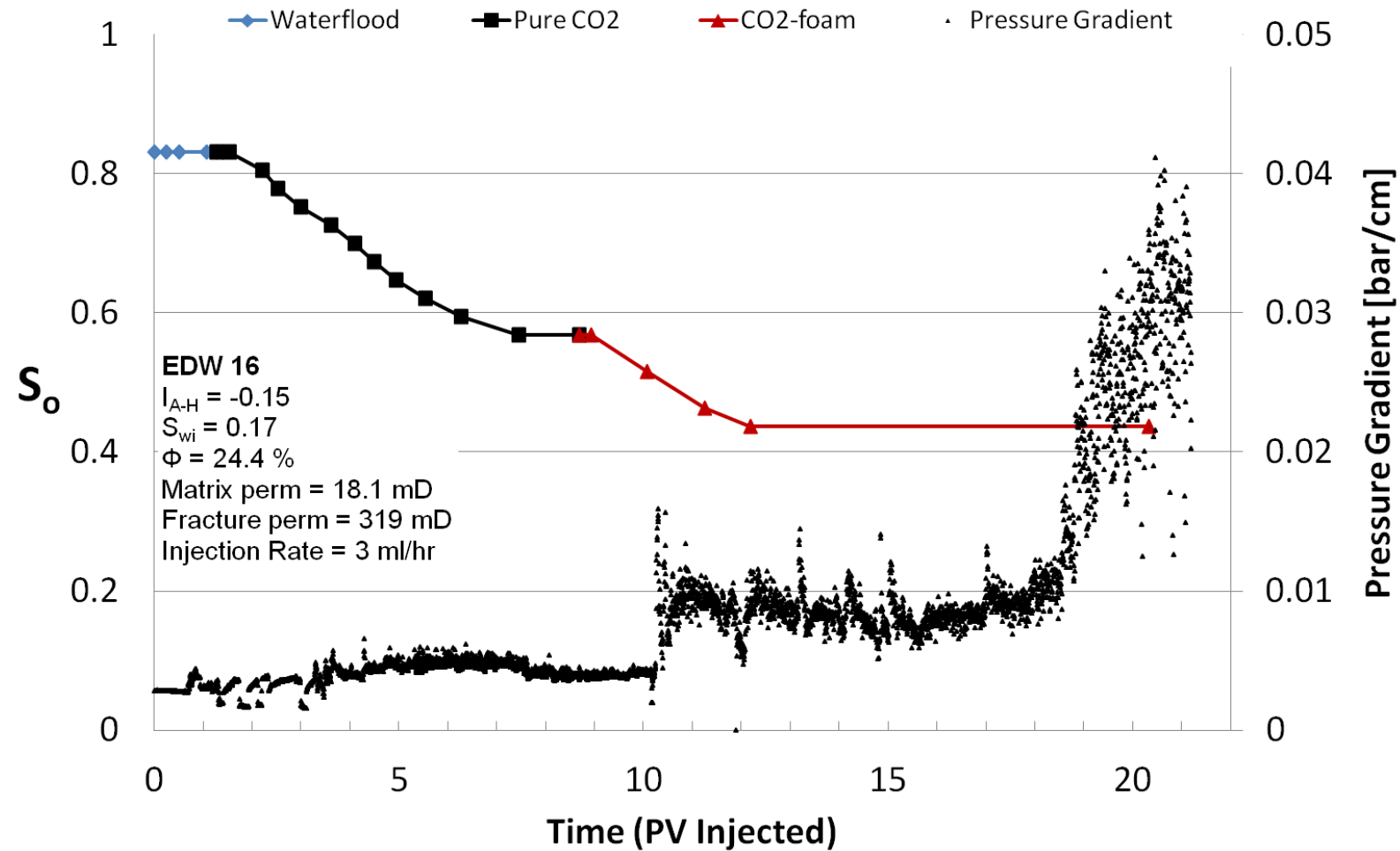
Summary

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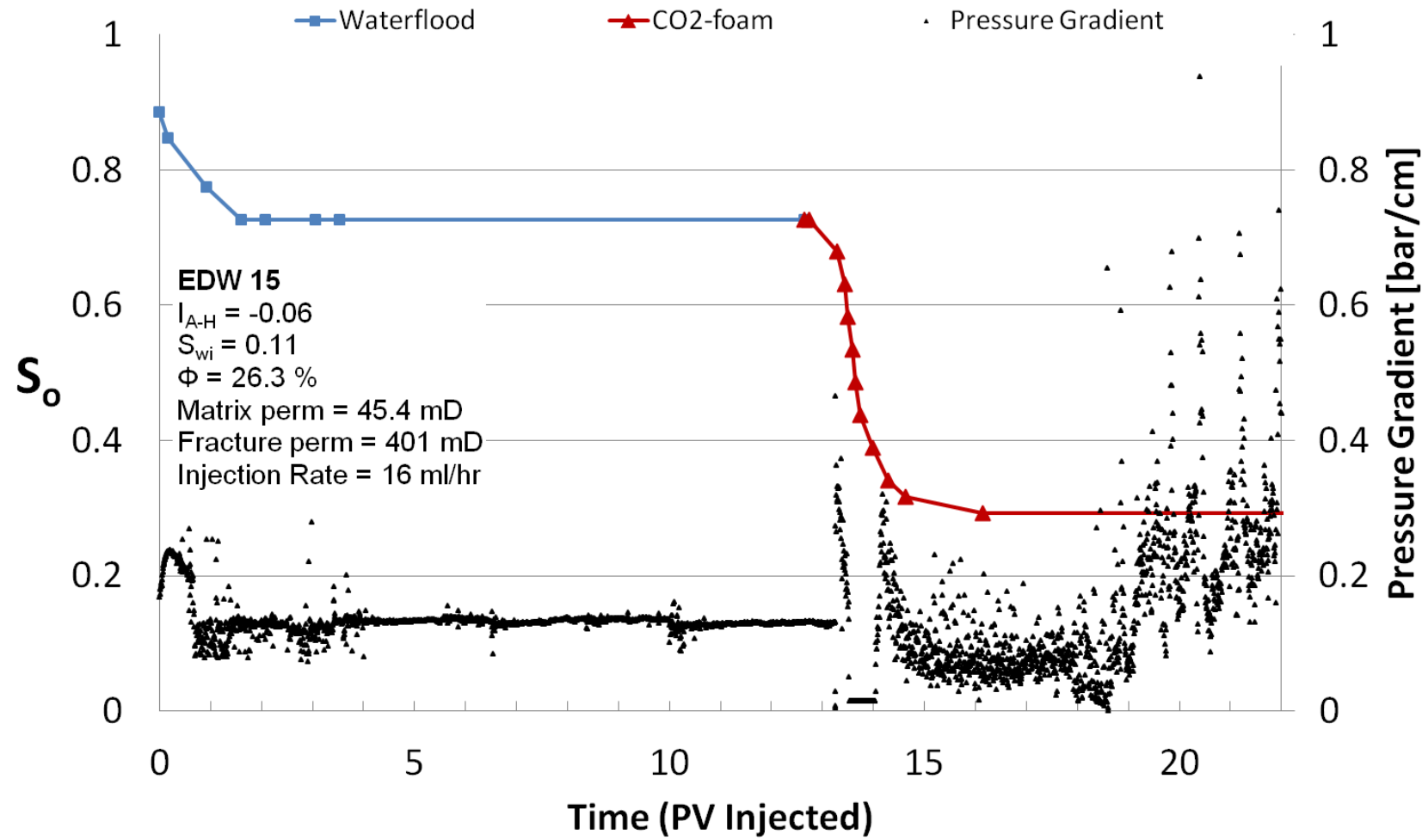
Acknowledgement



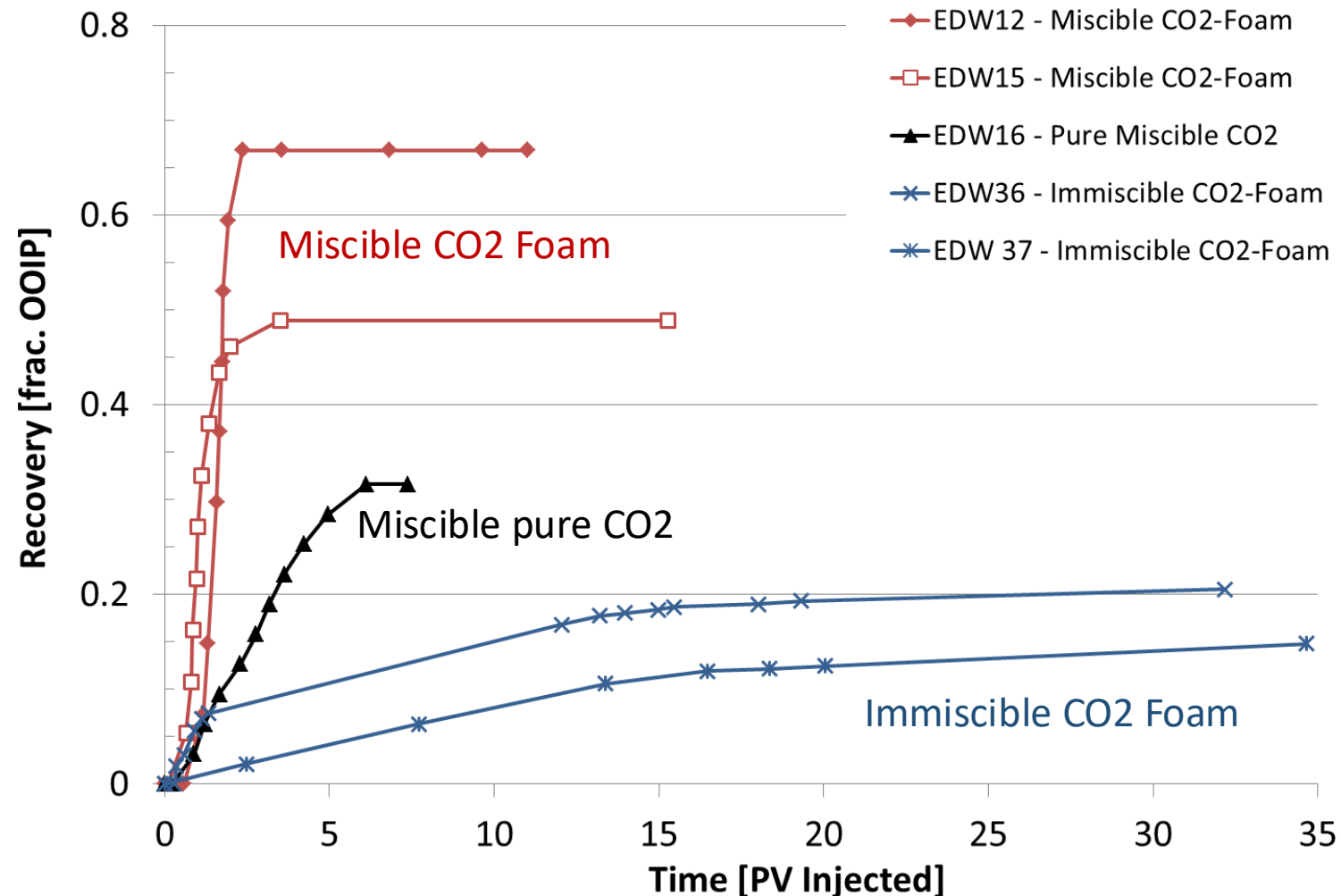
Oil-Wet Carbonate Core Plugs: IEOR (WF + CO₂ + CO₂-foam)

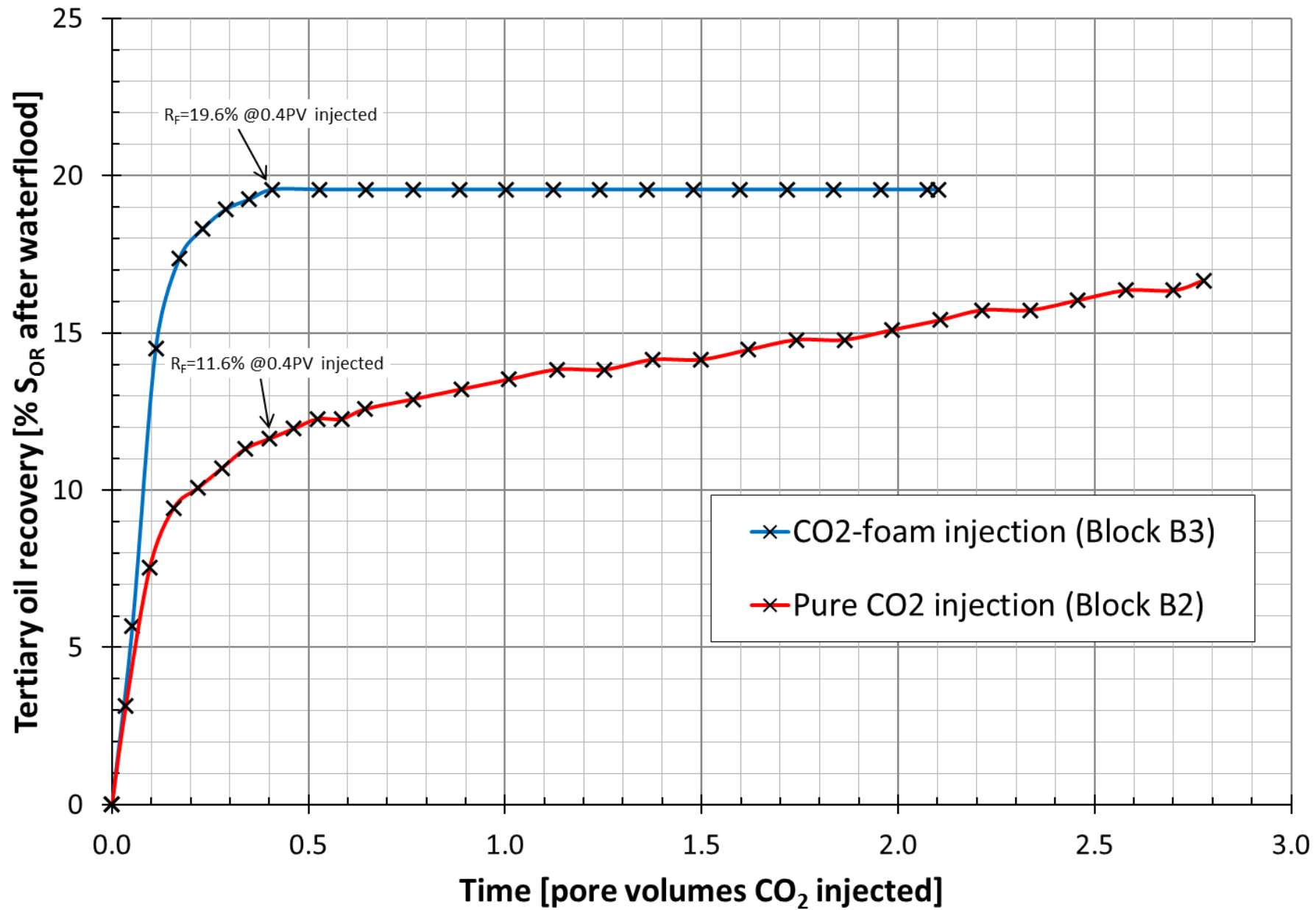


Oil-Wet Carbonate Core Plugs: IEOR (WF+CO₂-foam)



Comparison between miscible CO₂ injection and immiscible and miscible CO₂-foam





Laboratory results indicated: Up to 40% more oil recovered at significantly lower costs




Oil Production

Up to 40% more oil recovered, increased sweep & CO₂ utilization



Production Time

Reduced operational time; less than 1 HCPV of CO₂ foam needs to be injected to produce the residual oil after waterflooding




CO₂ Cost

CO₂ injected volume reduced by more than 30%



CO₂ Foam Less Expensive Than CO₂

At 70% Foam Quality more than 20% cost reduction



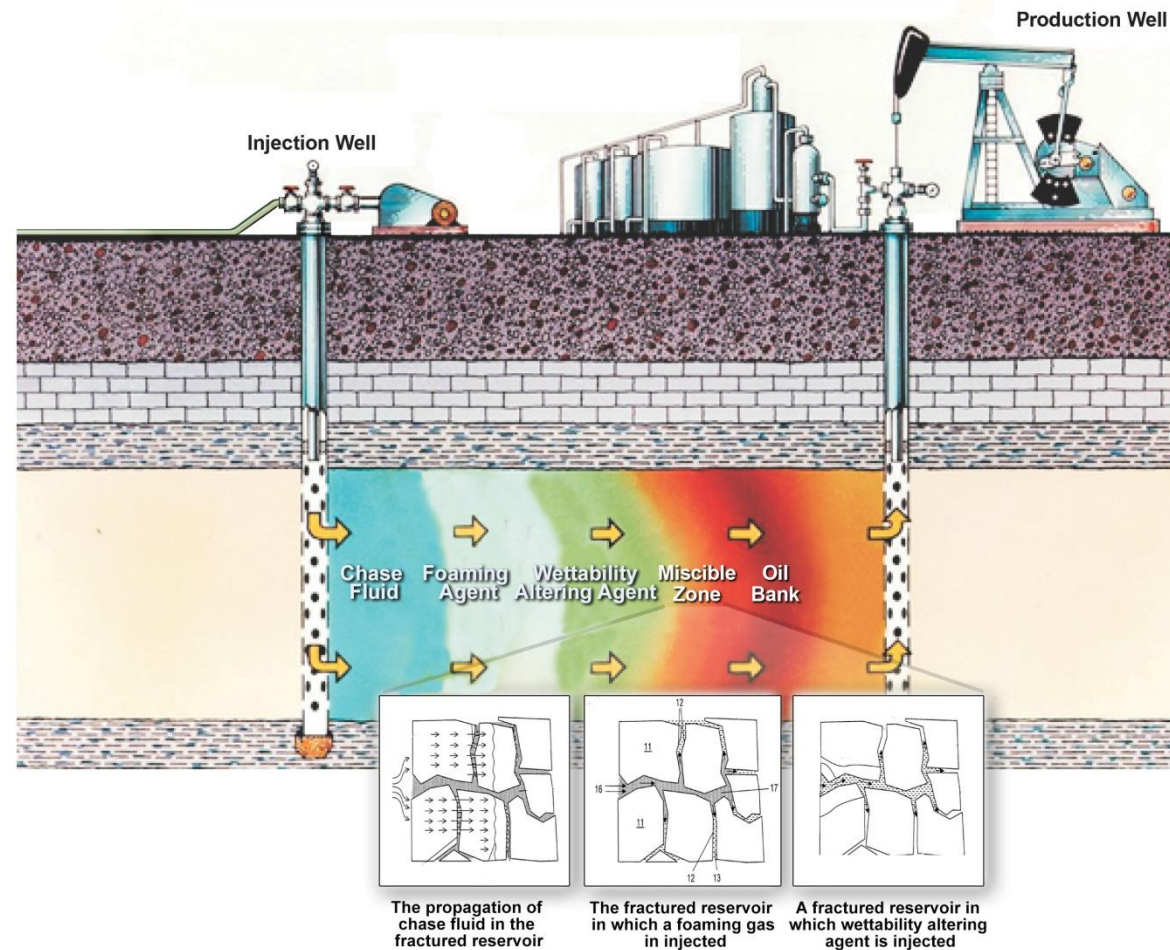
More CO₂ may be sequestered behind the foam front leaving behind more pore space available for CO₂ storage

Reduced Carbon Footprint

Next Generation CO₂ Flooding

- Main challenges in CO₂ EOR:
 - Early CO₂ breakthrough and poor sweep efficiency
 - Up-scaling laboratory EOR to field performance
- US White Paper:
 - Mobility control in CO₂ EOR, USDOE/Advanced Resource International Inc.
 - Target: 137 Billion bbl
- US import of foreign oil may be reduced by 30%
- “Next generation CO₂ EOR technology” based on mobility control
- 68 billion barrels of oil: 1,35 billion bbl of oil every year for 50 years
- Similar results in the North Sea; pilot in the Snorre Field
- Economic at oil price of US\$ 85 and CO₂ price of US\$ 40/ton
- Need more CO₂
- Carbon Capture Utilization and Storage (CCUS) a win-win situation

Integrated CO₂-EOR provides the possibility of CO₂ long-time storage



Source: USDOE

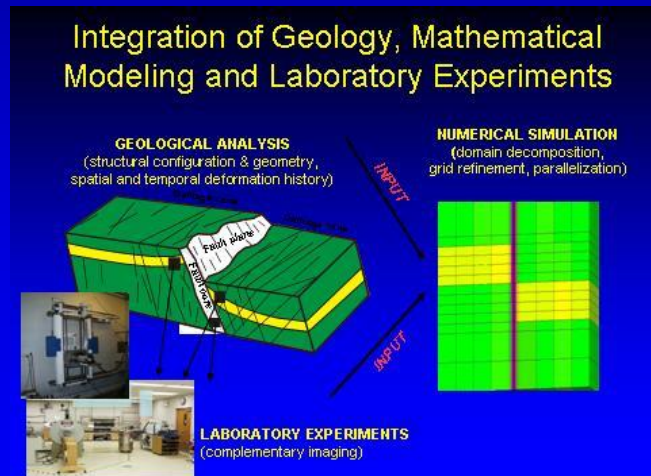
CO₂ EOR Enables CCUS: Integrated EOR (IEOR) for CO₂ Sequestration

CO₂ Foam EOR Mobility Control in Field Pilots in Texas

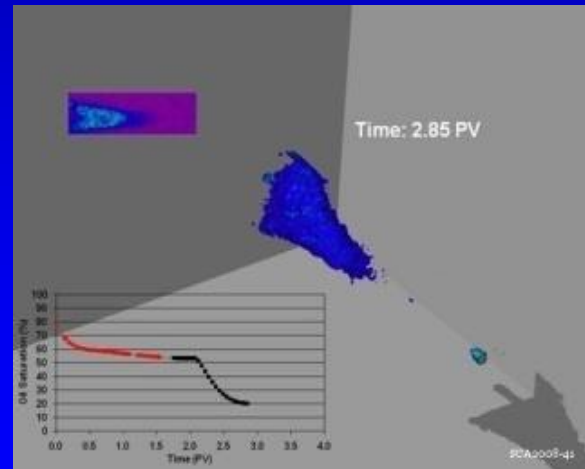
Collaboration: 11 Universities in France, The Netherlands, UK, USA and Norway

Coordinator: Arne Graue, Dept. of Physics, University of Bergen, NORWAY

Funding: CLIMIT Program at the Research Council of Norway and 7 oil companies



Lab to pilot field test



MRI of CO₂ injection



Complementary NTI & MRI facilities

CO₂ Foam for Mobility Control for EOR in Fractured Reservoirs in Texas

Project advantages:

- CO₂ is commercially available
- Foam as mobility control
- Researchers from 11 reputational universities
- Up-scaling; major challenge in oil recovery
- Fraction of costs of off-shore field tests
- Fast results: short inter-well distances
- 30 years experience in Texas on CO₂ EOR
- 4D seismic establishes a field laboratory

Large Scale Collaboration Emphasizing Mobility Control and CO2 EOR in Field Pilots in Texas

11 universities :

- Rice University**
- University of Texas at Austin**
- U. of Houston**
- Stanford U.**
- Imperial College, London**
- TREFLE, Bordeaux, France**
- New Mexico Tech**
- TU Delft, The Netherlands**
- NTNU, Trondheim, Norway**
- University of Stavanger, Norway**
- University of Bergen, Norway**

6 Oil Companies:

- Statoil**
- Shell** (Advisor Ft. Stockton)
- Total** (Advisor East Seminole)
- Tabula Rasa** (Operator ES)
- StableRock Energy** (Operator FS)
- Schlumberger**



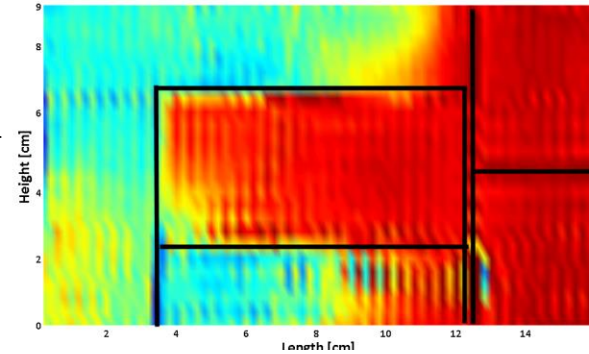
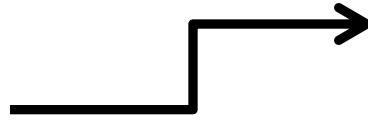


Wettability effects in fractured blocks

Waterflood in Fractured Blocks

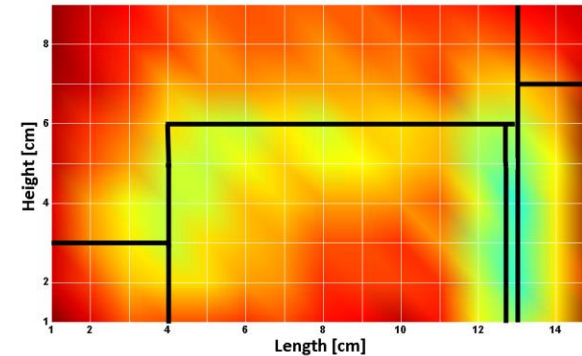
- **Strongly water-wet**

- Block-by-block displacement
- Recovery determined by potential for spontaneous imbibition



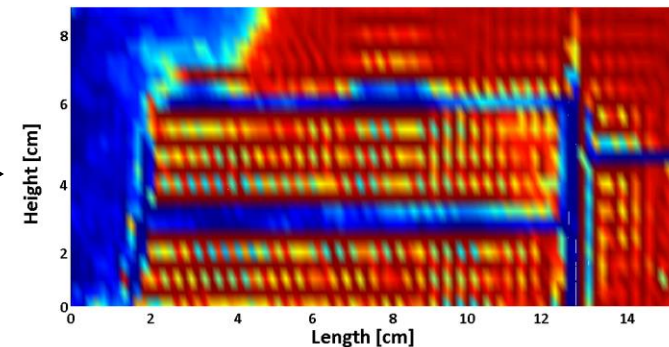
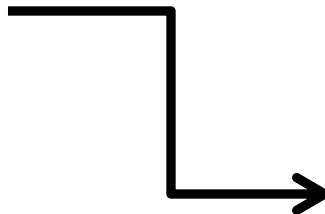
- **Weakly water-wet**

- Spontaneous Imbibition
- Low oil recovery



- **Weakly oil-wet**

- Water fingers through fracture network
- Low sweep efficiency
- Low oil recovery by waterflood



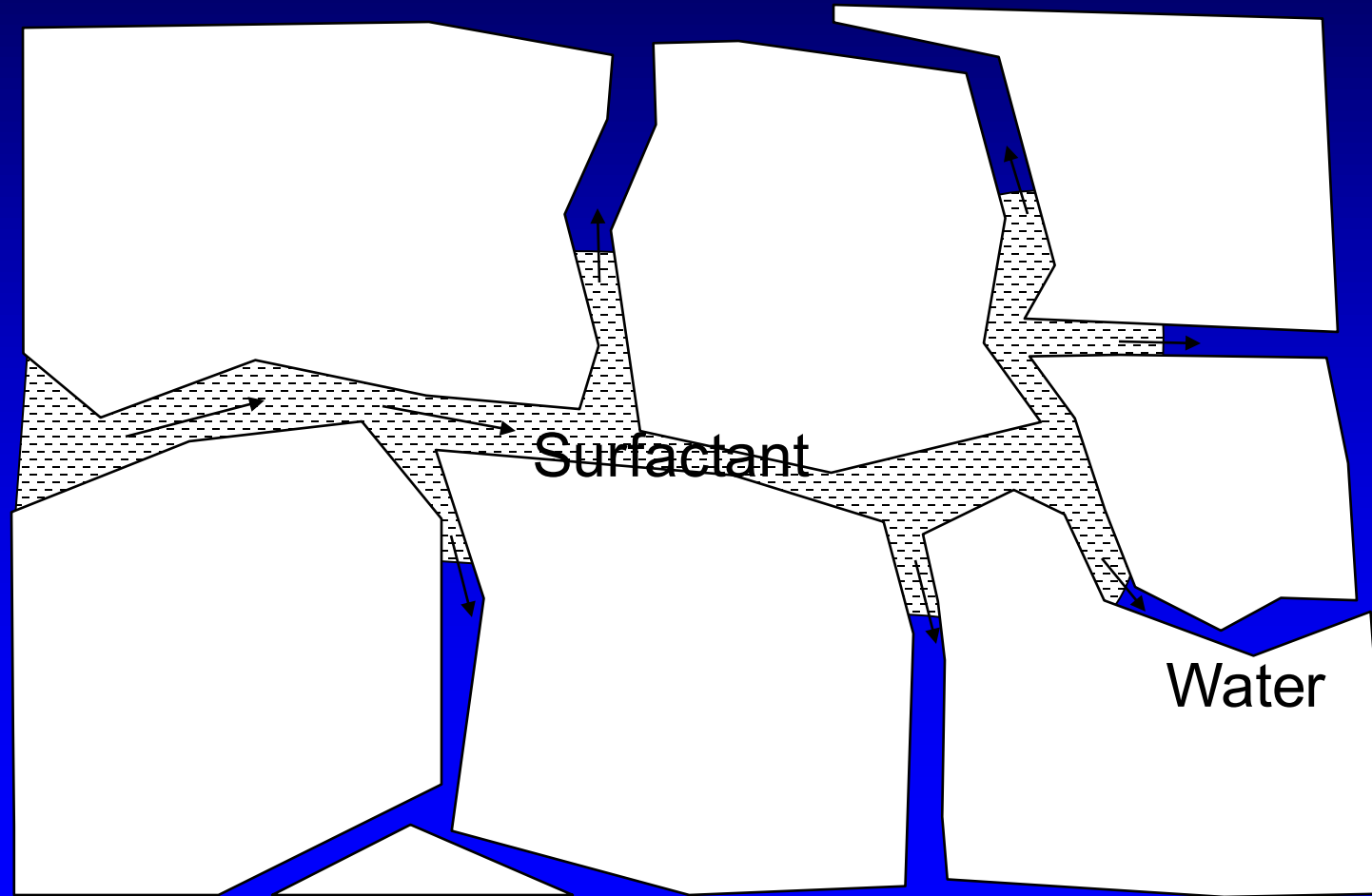
Fractured and heterogeneous reservoirs

- **Challenges**
 - **Early water breakthrough**
 - **Poor sweep efficiency**
 - **Low oil recovery**
 - **High Oil production costs**

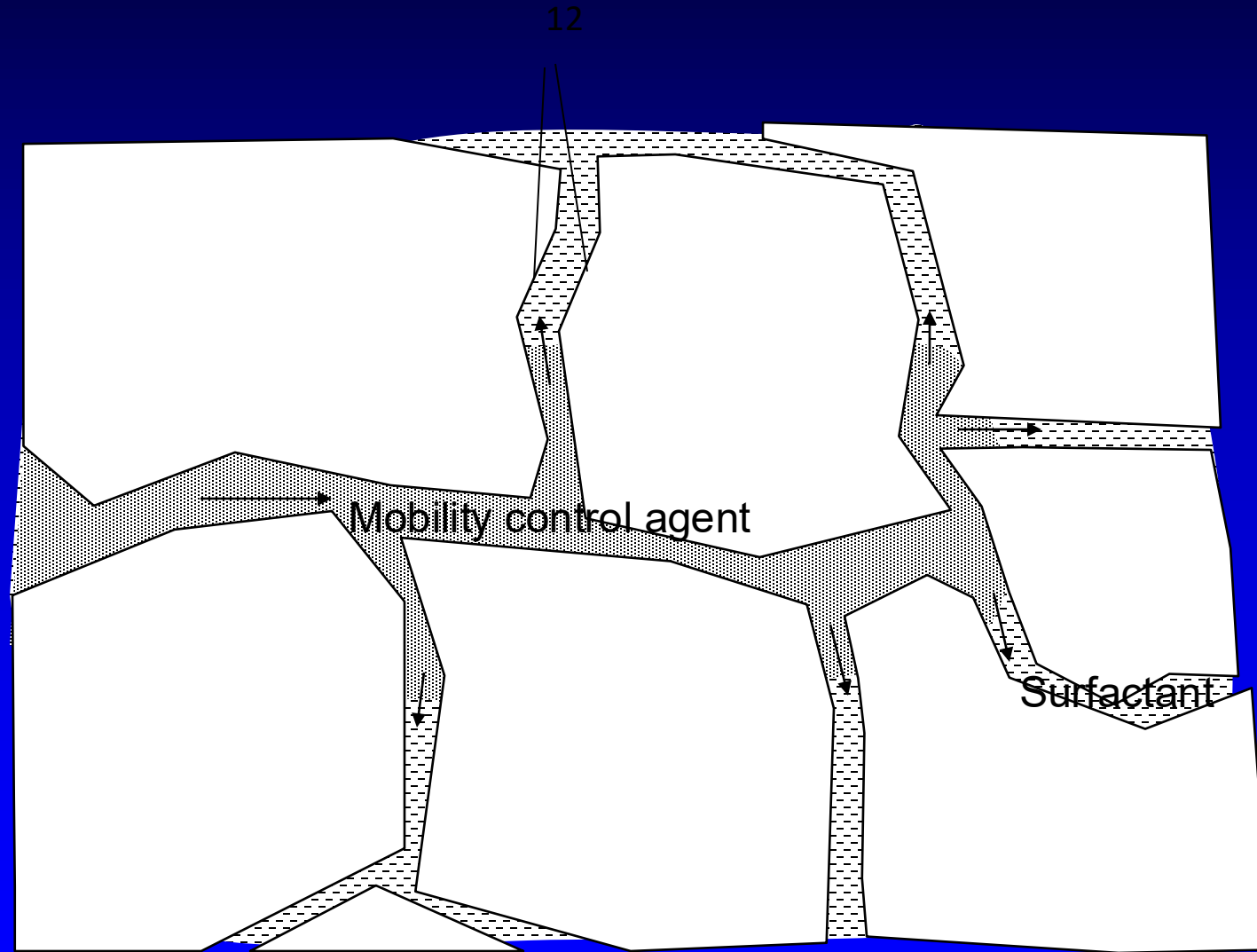
CO₂ Foam with Surfactant Preflush

- Surfactant preflush < 1 %PV (1FV)
- Establishing capillary continuity:
 - viscous oil recovery
 - gravity drainage
- Improved sweep efficiency
- Increased oil recovery
- Reduced operational time
- CO₂ storage technology

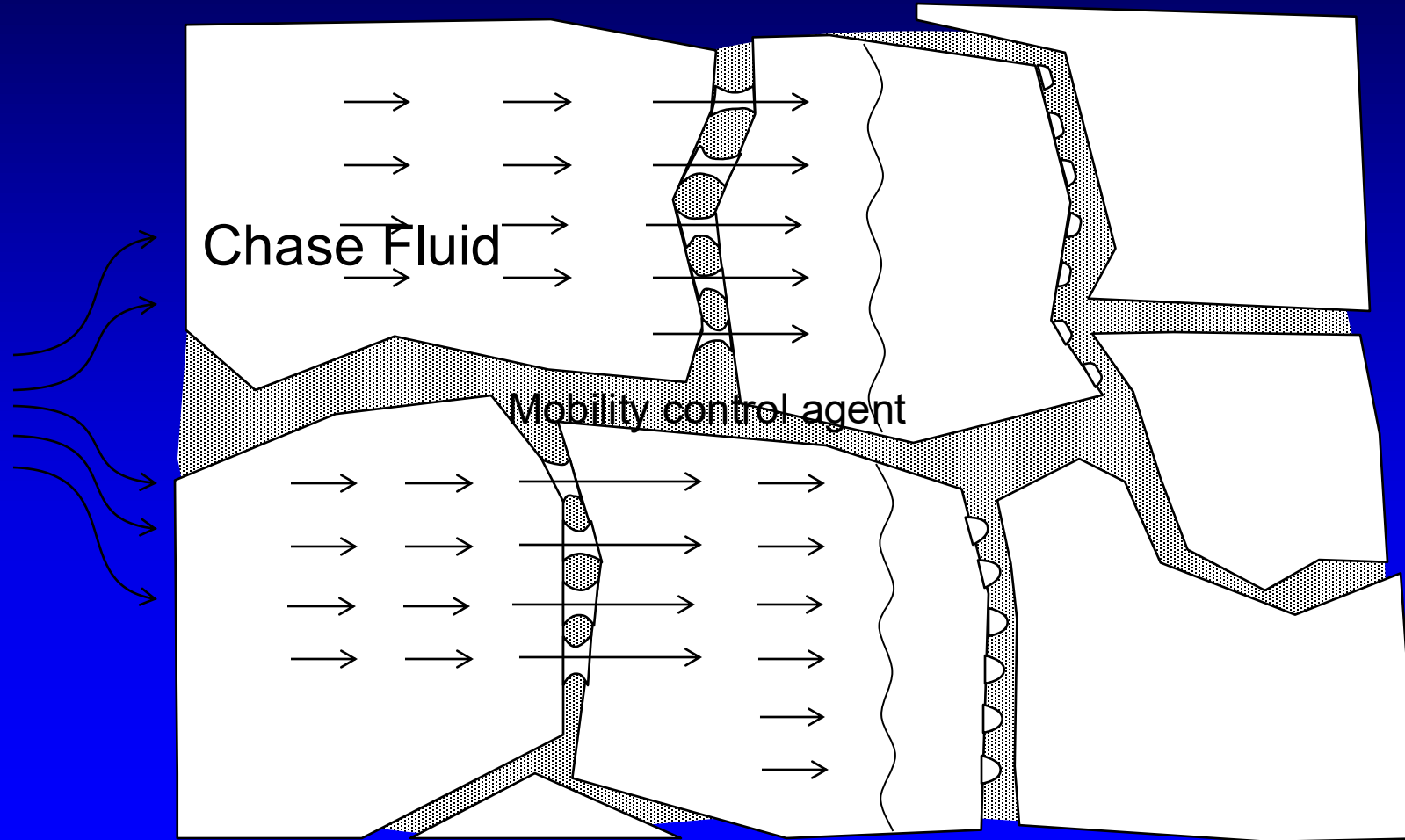
Pretreatment: Surfactant flood $< 1\%PV$



Mobility control: Foam injection



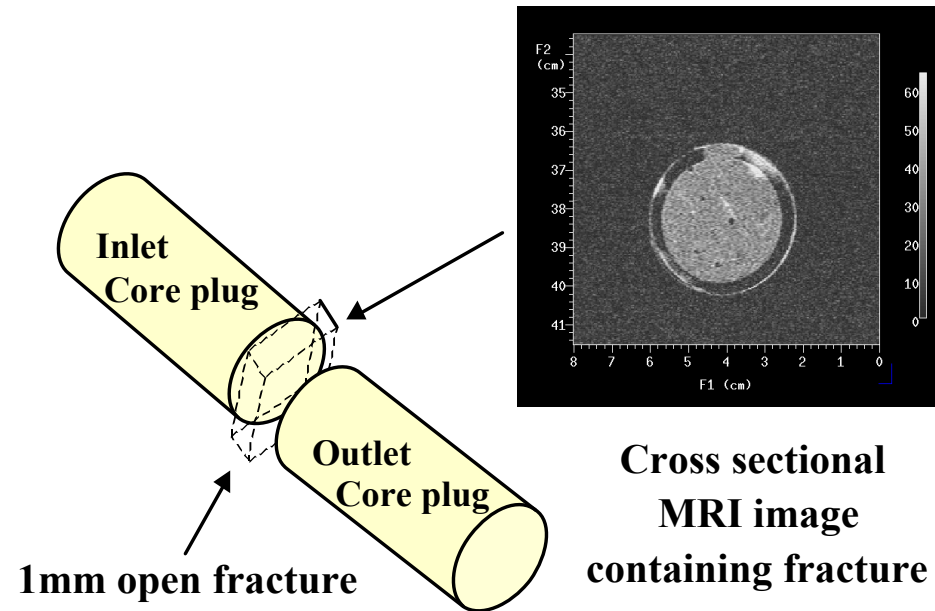
Oil recovery: Chase Fluid injection



What happens inside the fractures during fluid flow?

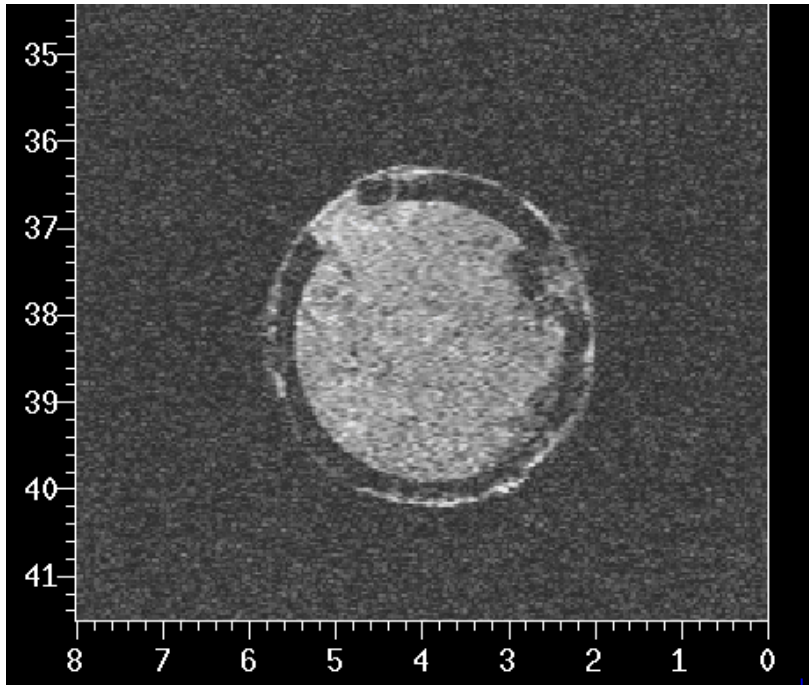
- MRI (Magnetic Resonance Imaging)

The high spatial resolution allow visualization of fluid flow patterns inside a 1mm fractures between stacked core plugs. The high resolution reveal wetting phase bridging phenomena inside the fracture.

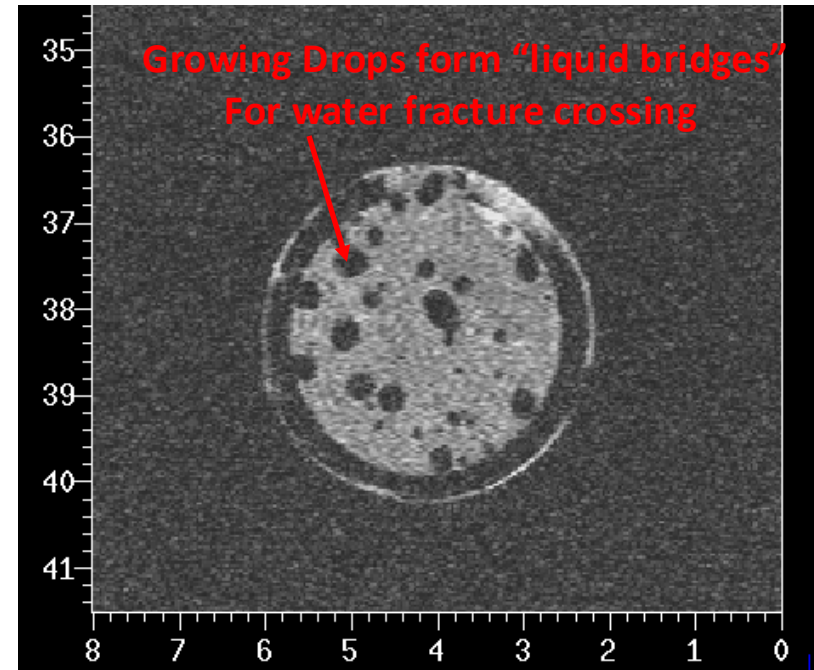


Recap: WF in **water-wet** fractured chalk

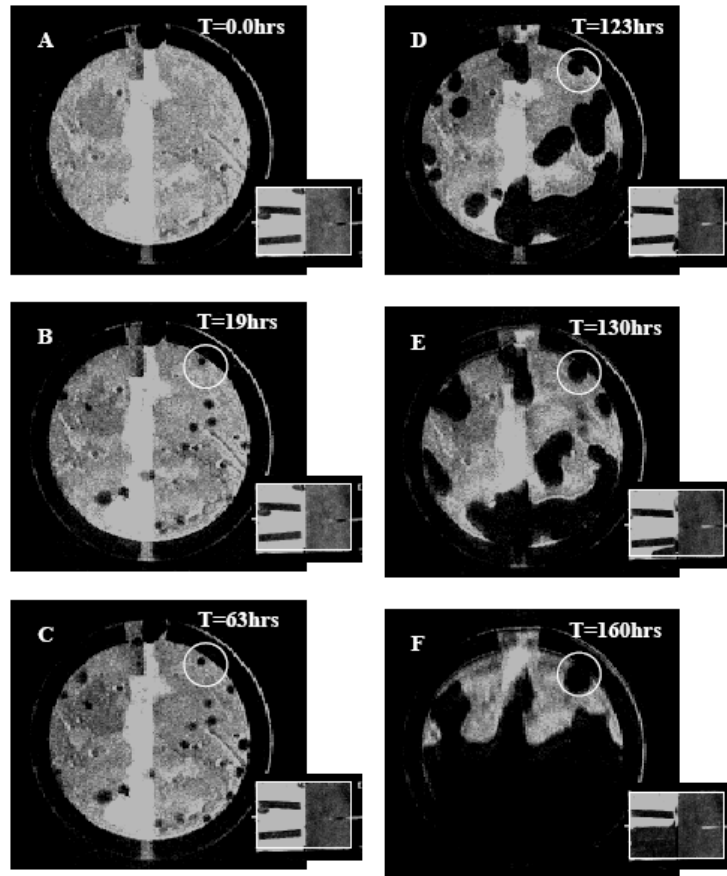
Wettability: $I_w = 1.0$



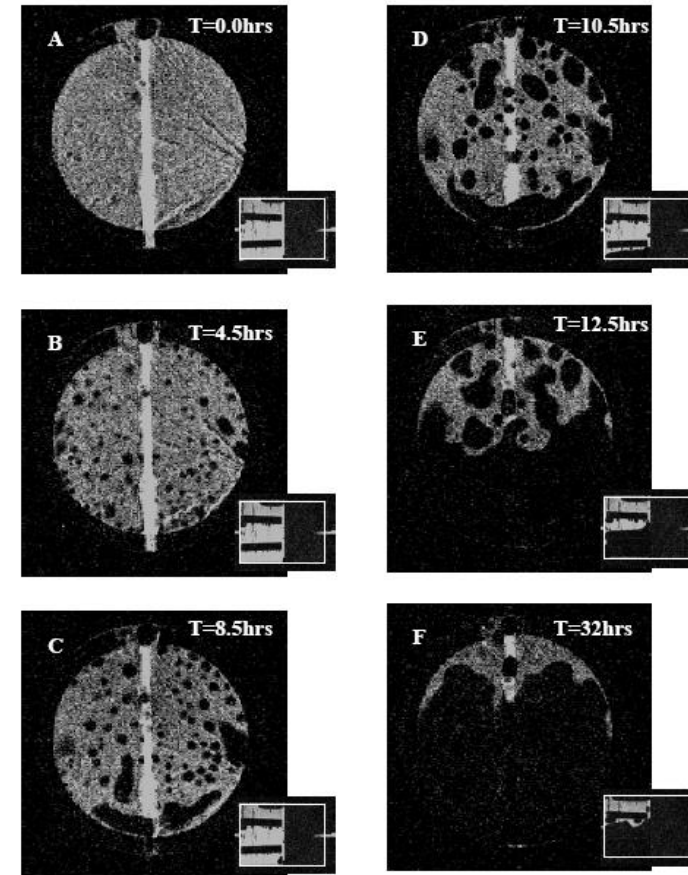
Wettability: $I_w = 0.7$



Water Bridges with Escape Fracture



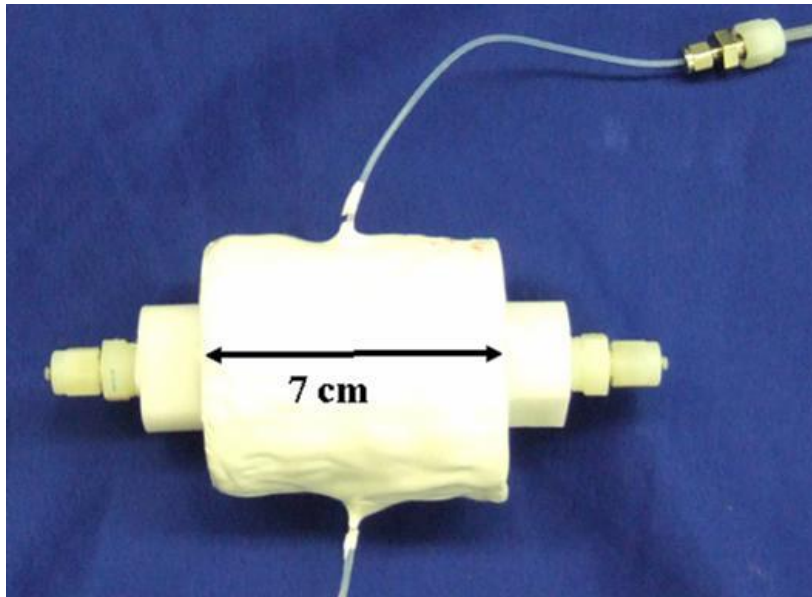
Constant differential pressure



Constant flow rate

Experimental setup

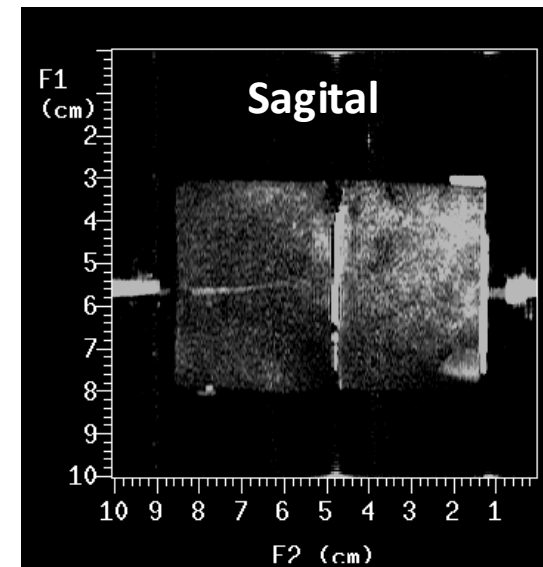
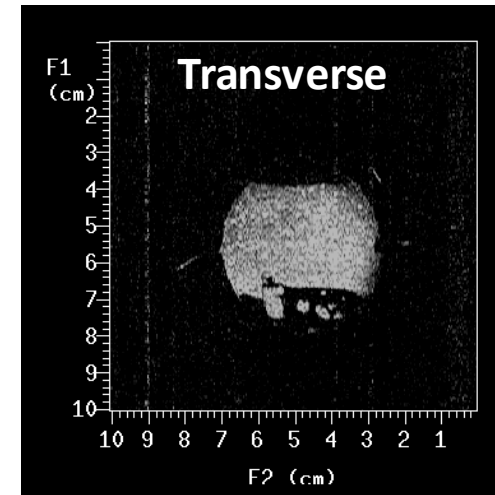
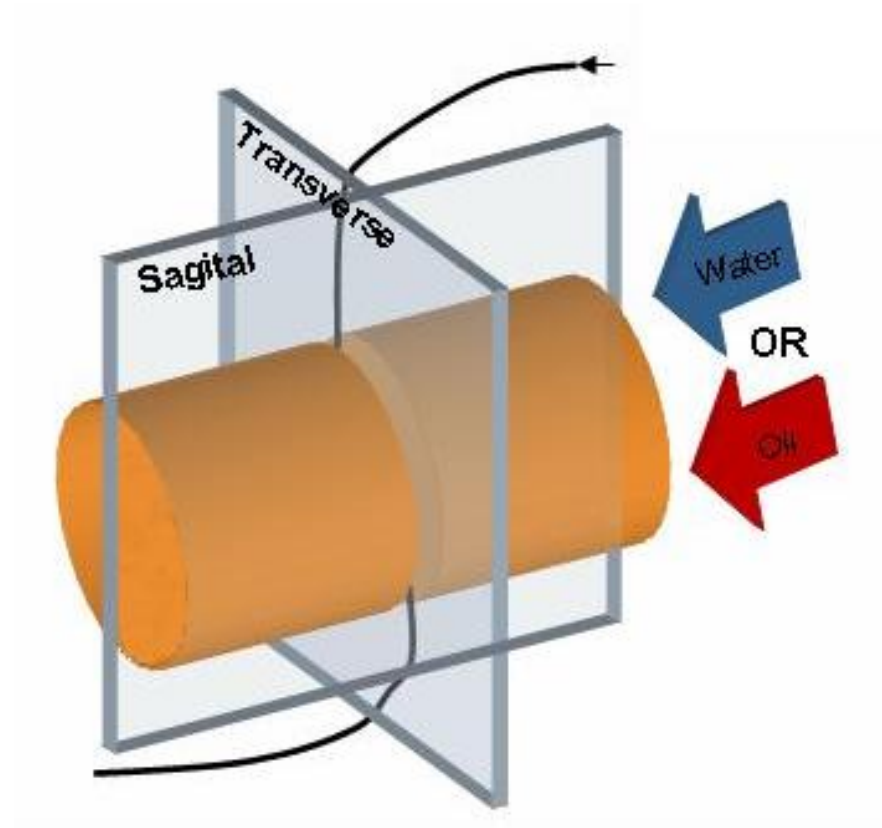
Whole view



Cut in two



Fracture flow in **oil-wet** limestone



Waterflooding

Fracture filling at strongly **water-wet** conditions



Fracture filling at moderately **oil-wet** conditions

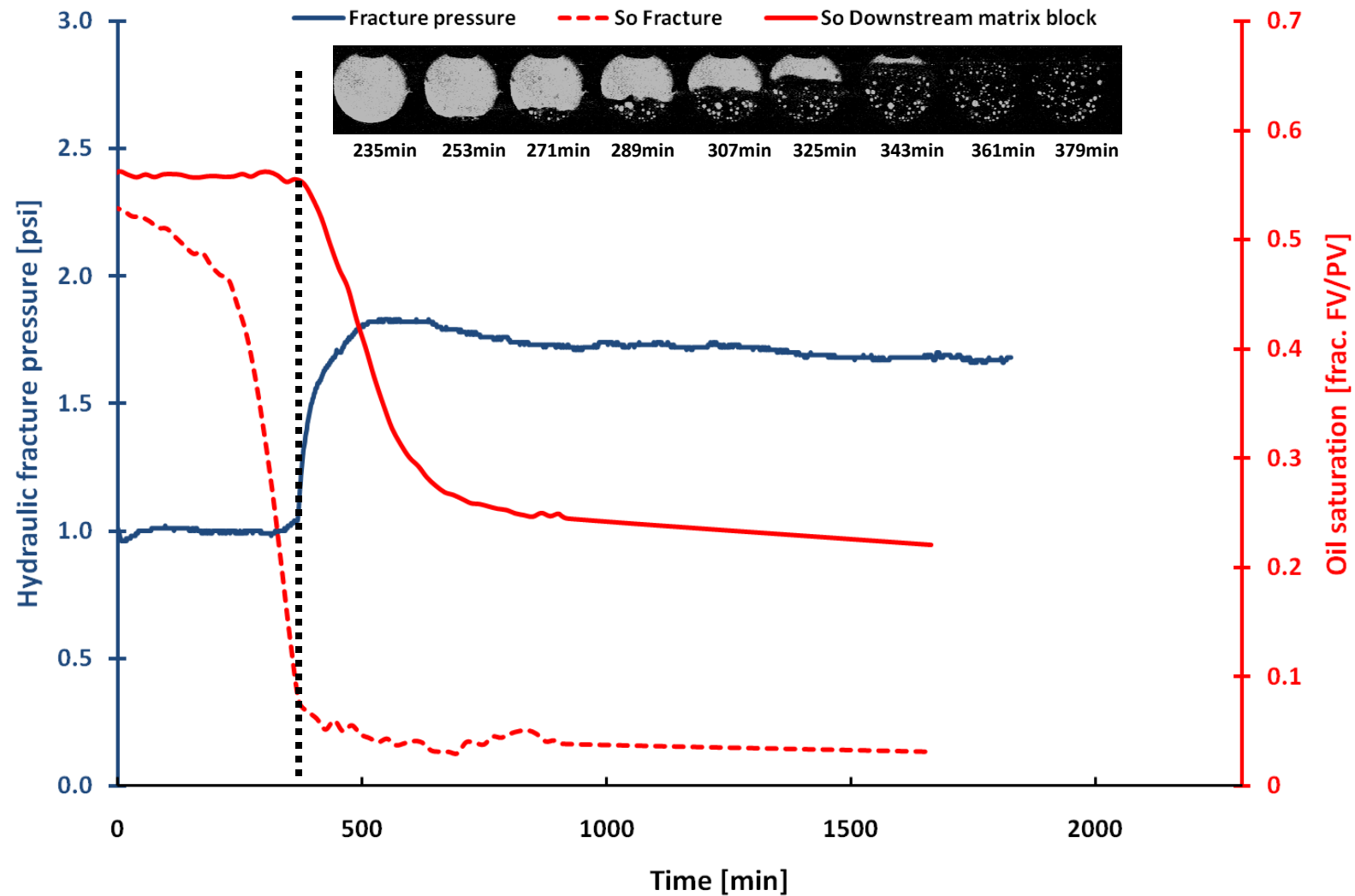


Start

TIME

end

WF oil-wet conditions



SPE-190168-MS

Surfactant Pre-floods during CO₂ Foam for Integrated Enhanced Oil Recovery in Fractured Oil-Wet Carbonates

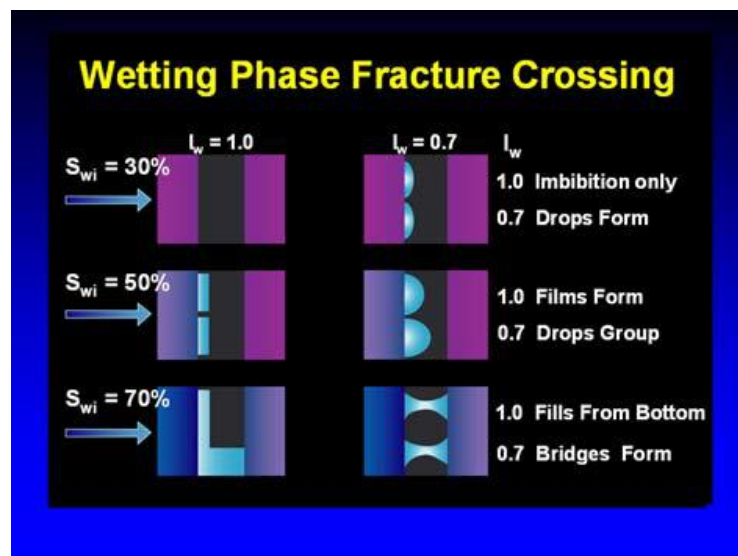
S.B. Fredriksen, Z.P. Alcorn, A. Frøland, A. Viken, A.U. Rognmo,
J. G. Seland, G. Ersland, M.A. Fernø, and A. Graue,

University of Bergen
Norway

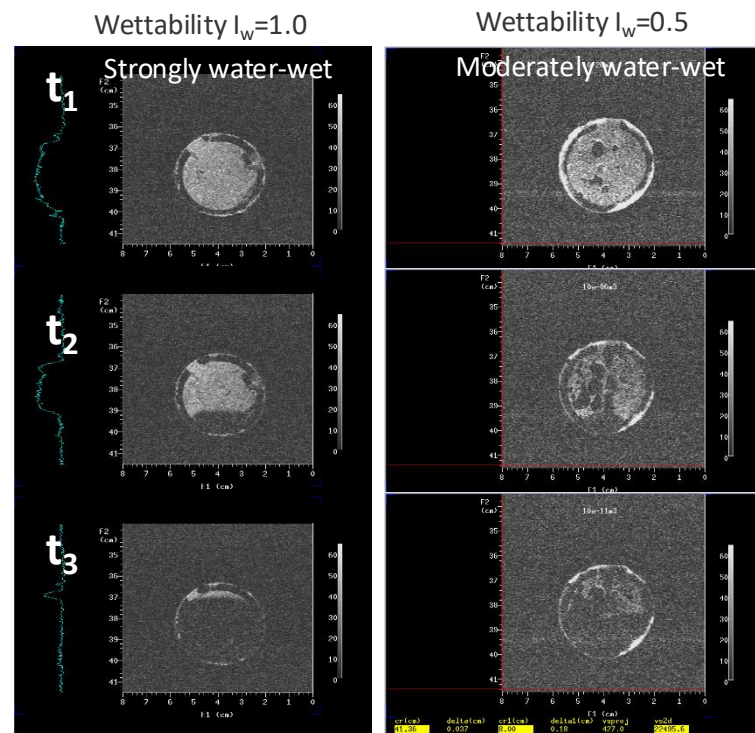
UNIVERSITY OF BERGEN



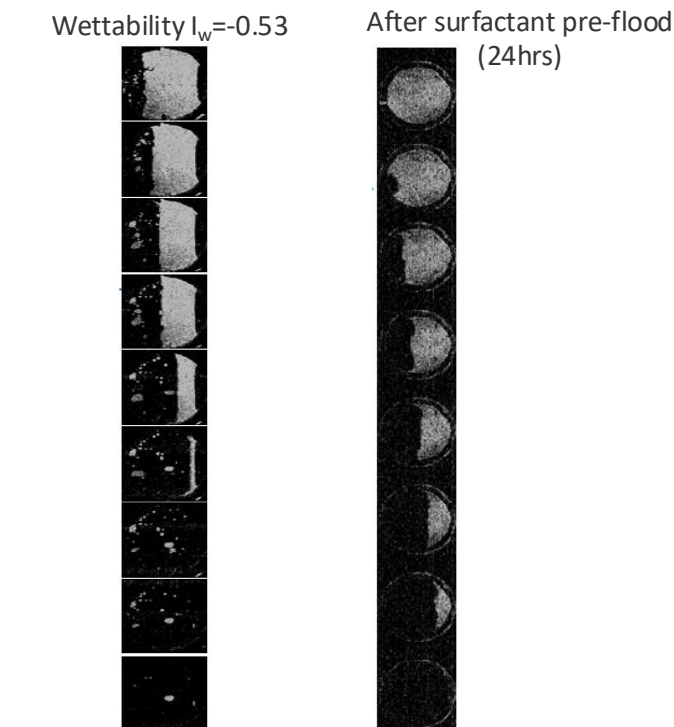
Background



Aspenes, E., Erslund, G., Graue, A., Stevens, J. and Baldwin, B.A. 2008. Wetting Phase Bridges Establish Capillary Continuity Across Open Fractures and Increase Oil Recovery in Mixed-Wet Fractured Chalk. *Transport in Porous Media* 74 (01): 35-47. <http://dx.doi.org/10.1007/s11242-007-9179-3>.



Graue, A., Bognø, T., Baldwin, B.A. and Spinler, E.A. 2001b. Wettability Effects on Oil-Recovery Mechanisms in Fractured Reservoirs. *SPE Reservoir Evaluation and Engineering* 4 (06): 455-466. SPE-74335-PA. <https://doi.org/10.2118/74335-PA>.



Fernø, M.A., Haugen, Å. and Graue, A. 2012. Surfactant Prefloods for Integrated EOR in Fractured, Oil-Wet Carbonate Reservoirs. SPE Annual Technical Conference and Exhibitions, San Antonio, Texas, 8-10 October. SPE-159213-MS. <https://doi.org/10.2118/159213-MS>.

Our objective → Use this concept of a surfactant pre-flood to reverse the wettability of oil-wet fracture surfaces towards neutral/weakly water-wet to create water capillary bridging and improve conditions for CO₂ foam generation, sweep efficiency and recovery.

CO₂ Foam EOR for Mobility Control

- Increased oil production, early injection - improved impact
- Less expensive than CO₂ EOR (20-30% less CO₂)
- Reduced operational cost; more efficient displacement (70-80%)
- Easy remediation (waterflooding)
- More CO₂ stored than in conventional CO₂ EOR (behind the foam front)
- Reduced carbon footprint
- Social license to operate
- Enable vast additional energy resources
- Attracts new generation energy engineers

CCUS: (Carbon Capture, Utilization & Storage):

- Huge Opportunity for the Petroleum Industry

**Advantages with CO₂
compared with water/ HC gas**



**Improved
miscibility**

**Decrease
oil viscosity**

**Increase
oil flow**

**Associated
CO₂ storage**

Challenges with CO₂ Injection



**Low
viscosity**

Availability

Recycling

Corrosion

