
أدنوك
ADNOC
Webinars
EOR for Carbonate Reservoirs Under Extreme Conditions: From R&D to Field Implementation
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Outline

- Introduction: Status of EOR in Carbonate
- EOR Roadmap
- Examples of R&D Maturation to Field Application :
  - New EOR Concepts for Heterogeneous mixed to oil-wet reservoirs
  - Developing Polymers for HS/HT
  - Low Salinity Flooding
  - Gas Based EOR Options
- Conclusions

ADNOC Reservoirs and Key EOR Challenges

- Heterogeneity and thickness of the reservoirs
  - Key Challenge for gas based EOR, need mobility control
- High Salinity, High Divalent Ions and High Temperature
  - Key Challenge for cEOR
- Carbonate rock
  - High adsorption/retention of chemicals
  - Limited experience for EOR in Carbonate
- Wetting and Pore structure of the rock (often mixed to oil-wet)
  - A challenge for defining EOR target and ROS distribution
- Light oil reservoirs
  - No thermal options and no conventional polymer option
  - No Conventional polymer option

EOR for Carbonates

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- Limited mature EOR technologies available for carbonate at harsh conditions, hence:
  - ➢ Design innovative solutions to fit our own reservoirs
  - ➢ Be the first to implement innovative solutions and new technologies
  - ➢ Focus our R&D on key challenges
- Technology is key to addressing all three key drivers
  - ➢ Deployment of well-established commercial technologies and newly deployable technologies
  - ➢ Investment in new technologies
    - o Development and demonstration
    - o Research

Fast-track
Extensive R&D activates to develop and mature EOR Technologies for ADNOC

Commit
Unlock additional recoverable volumes

Collaborate
Renowned research centres and chemical providers

Industry-lead
GCC Hub of carbonate EOR

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Due to limited mature EOR technologies in carbonate, we need to take risk and be the first to implement innovative solutions and new technologies developed in our R&D

Global EOR Production

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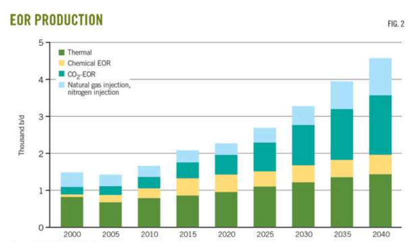
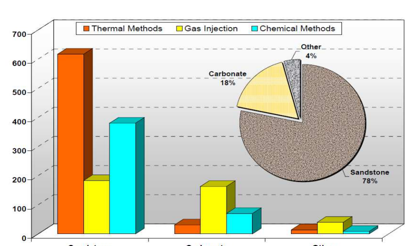
- IEA estimated EOR production worldwide to be ~ 2 million b/d in 2018, could grow to 4.5 million b/d by 2040.
- Majority is onshore EOR.
- Only 18% of EOR projects is in carbonate
- EOR is not business as usual,
  - ➢ Less oil to go after, with EOR incremental recovery 5-20%, vs 40-60% secondary recovery
  - ➢ Requirement for new or upgraded surface facilities
  - ➢ More expensive injectants
  - ➢ Slower response times, unless we act early
  - ➢ It takes time to mature and de-risk





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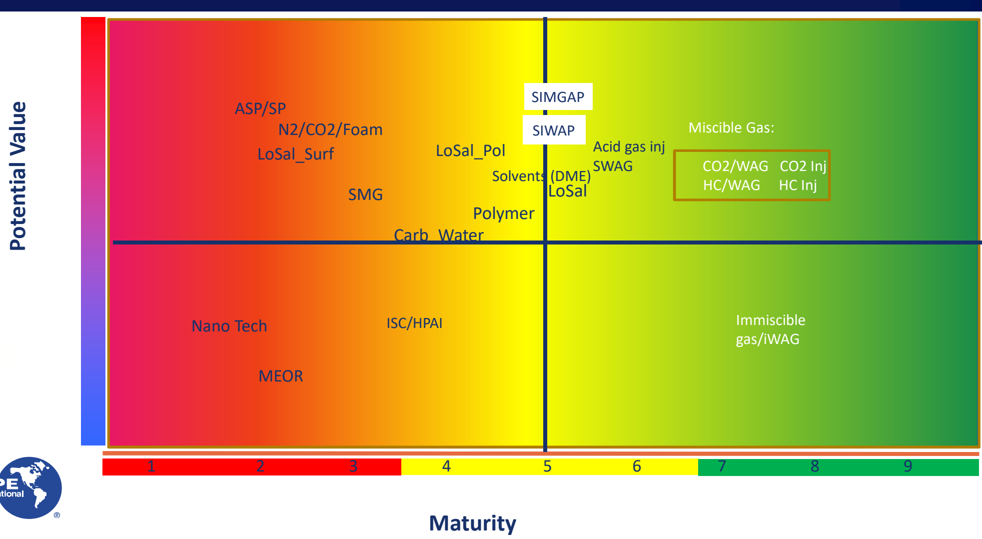
Gas Based EOR, Most Mature for Carbonate

- Miscible gas Injection including WAG (CO2 or HC gas) is mature technology and needs no further piloting, phase development is applied to build the learning curve.
- Gas has high displacement efficiency but poor sweep efficiency especially for layered and/or thick reservoirs, hence:
  - Better suited in thin homogeneous and/or coarsening downwards reservoirs
  - Needs mobility control if applied in layered or thick reservoirs
- To improve gas sweep efficiency mobility control is required:

Homogeneous or Low Permeability Contrast Reservoirs	Heterogeneous Reservoirs
WAG	Foam
SWAG	SIMGAP

EOR For Carbonate: Maturity vs Value



Piloting Strategy

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- Pilots are only supported for EOR concepts which are Immature and/or has not been piloted before
- EOR concepts will not be piloted in 2 different reservoirs of similar geology unless justified by a clear objective
- Mature EOR technologies such as miscible gas/WAG (HC gas or CO2) will go into phase development where applicable
- Lab work mainly done in parallel once the EOR concept is identified/selected

- Geology, well spacing, well length etc., cannot be piloted, however, geological heterogeneity must be well understood before EOR
- Avoid drawing wrong conclusions from pilots
  - Careful design and monitoring/surveillance is a must
  - Clearly articulated pilot objective(s) and success criteria
- Design fit for purpose pilots to optimize the timing, i.e,
  - Utilize SWCTT when applicable (loSal) or shorter spacing (future solvent pilots)
  - Combine piloting with phase development?
- Scalability of the pilot

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Status of EOR in ADNOC

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- Development:
  - Several onshore reservoirs with miscible gas/WAG (HC gas)
  - An onshore reservoir with continuous miscible CO2 injection (phase development)
  - Continuous HC gas in offshore reservoirs
- Ongoing Pilots: 2 miscible CO2 WAG pilots
- Planned pilots: 4 approved new pilots (SIMGAP, SIWAP, SWAG, Low Salinity)
- Several CO2-WAG EOR phase development projects in planning: No pilot needed
- Extensive R&D plan to mature more EOR technologies and collect data to optimize field application
- Most of the pilots suggested in our EOR roadmap are industry first, i.e., ADNOC is leading the development of EOR concepts for carbonate reservoirs at harsh conditions

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Example Miscible HC Gas WAG

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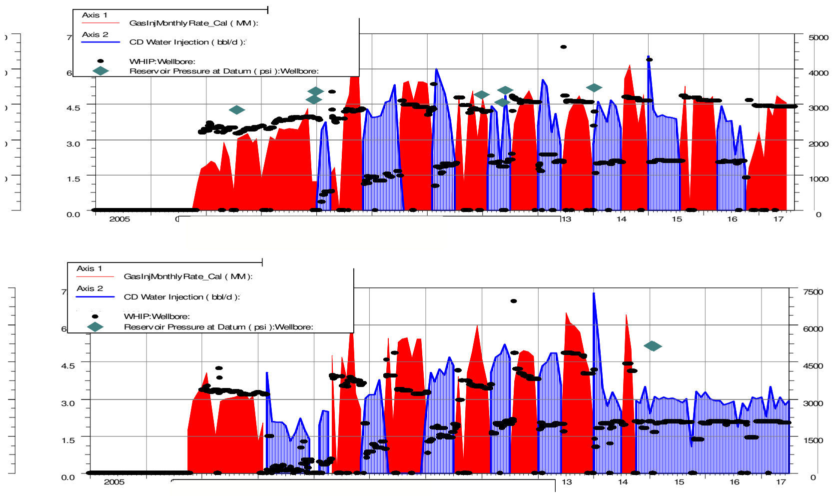
Examples of Injectivity and HC WAG Cycles in low perm reservoir:

- No major Injectivity issue in observed



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Ongoing CO2 WAG Pilots

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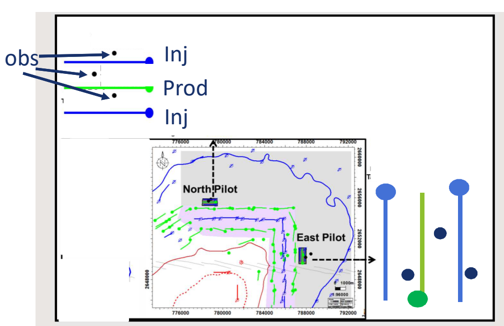
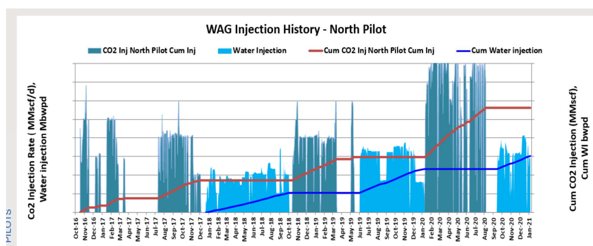
- ❑ Two WAG CO2 pilots in the same reservoir, started in 2016
- ❑ Injected already more than 6 bscf in in each of them
- ❑ FFD will start within couple of years



Pilots design Parameters			
Recovery Mechanism	CO2 WAG		
Pattern	Horizontal Line Drive		
Spacing	250m		
Well Type	Producer	WAG Injector	Observer
Wells Count	1	2	3
Well Length (ft)	3000	3000	Vertical well
Completion Layer			
Max Production / Injection Rate per well			
Injection Scheme	6 month CO2 + 6 month Water Inj		



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EOR R&D: Focus on Key Challenges

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- Gas based EOR:
  - Mobility control for gas based EOR
  - Collect data for field deployment (i.e., Sorm, cyclic hysteresis, Sgr, water blockage, IFT dependence etc.)
  - Potential of Scale for CO2-WAG injection
- cEOR:
  - Develop chemicals for HT/HS carbonate
  - Developing surfactants with low adsorption
  - Surfactants that foams in carbonates at HT/HS
  - Screen chemicals for the range of salinity sources and temperature space in ADNOC reservoirs
- Low Salinity Flooding:
  - Understand mechanism and develop screening methods to speed up application
  - Low Salinity chemical Hybrid Process
- Carbonated water:
  - Quantify benefit
  - Piloting Strategy
- Solvent (DME):
  - Manufacture cheaper DME
  - Improve DME Utilization factor and/or efficiency

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ADNOC EOR R&D

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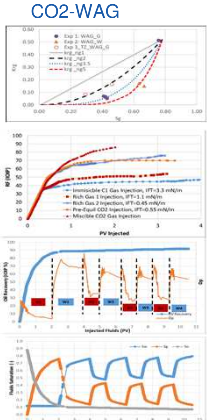
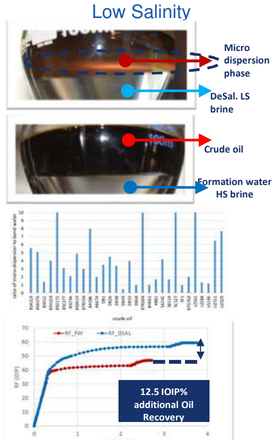
CO2-WAG

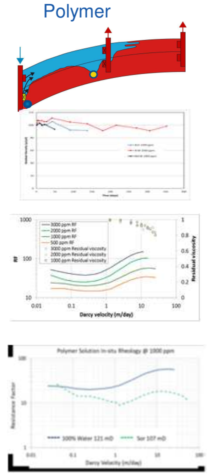


Low Salinity



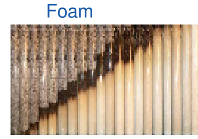
Low-salinity hybrid process (LS_polymer, LS_surfactant, CO_2/Polymer interaction)

Polymer



Surfactants

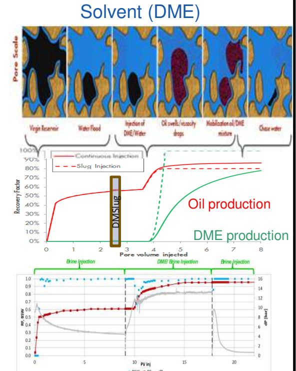
Foam



Find/develop chemicals for HS/HT

Foam for CO2 mobility control

Solvent (DME)



Main challenge of DME EOR is cost, so focus is on:

- Manufacture cheaper DME
- Improve DME Utilization factor and/or efficiency

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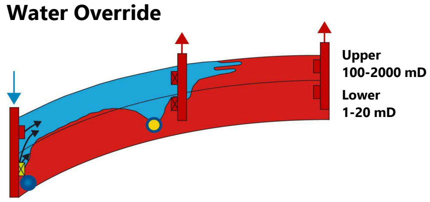
Examples of R&D Maturation to Field Application

- EOR for Heterogeneous Reservoirs
- Developing Polymer for HS/HT reservoirs
- Low Salinity waterflooding
- Gas EOR: Laboratory Programs and Experimental data

Understanding Heterogeneity of the Reservoirs

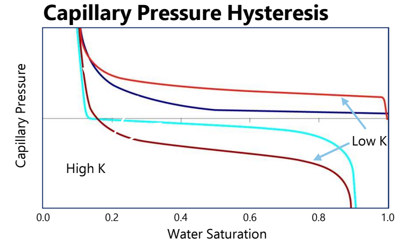
Water Override



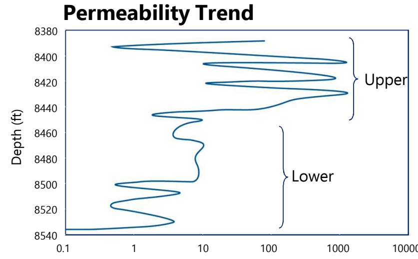
- Water Flooding Behaviour:
  - Water injected into Lower Zone moves to Upper Zone
  - Producers in the Lower zone draw water down from Upper zone
  - Poor sweep and recovery of the Lower zone

SPE 161485

Capillary Pressure Hysteresis



Permeability Trend



Understanding Heterogeneity of the Reservoirs

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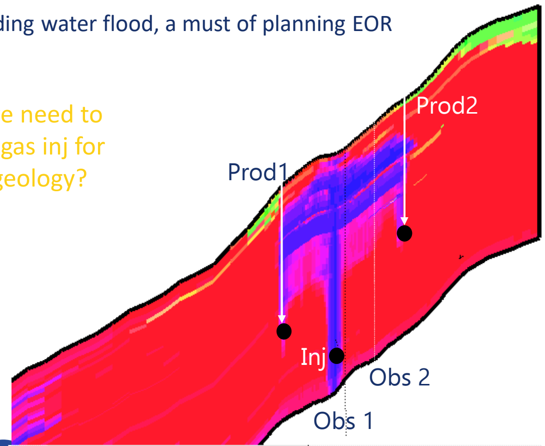
Understanding water flood, a must of planning EOR

Do we need to pilot gas inj for this geology?



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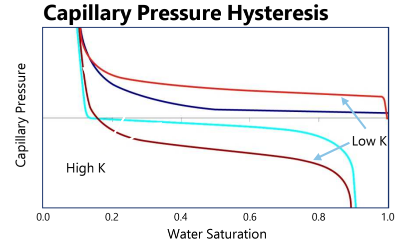
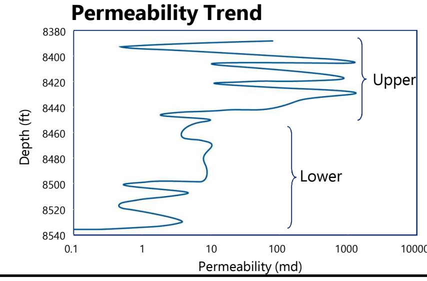
Capillary Pressure Hysteresis



Permeability Trend



Target for EOR: Residual or Bypassed Oil

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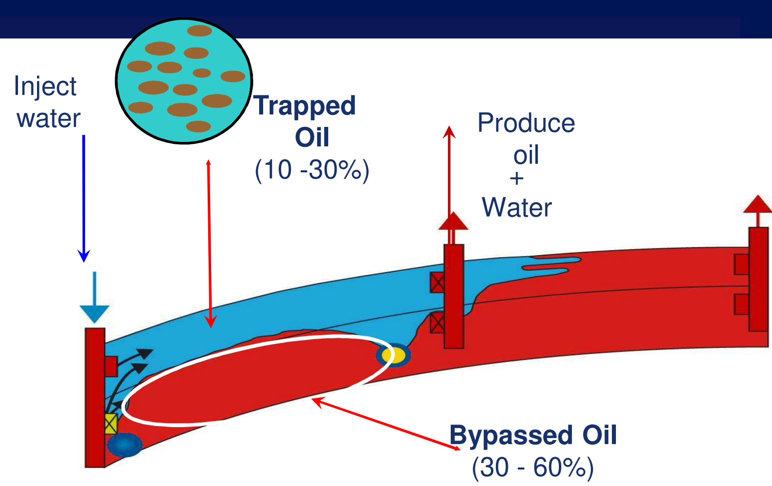

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Gas Injection: Impact of Gravity and Heterogeneity

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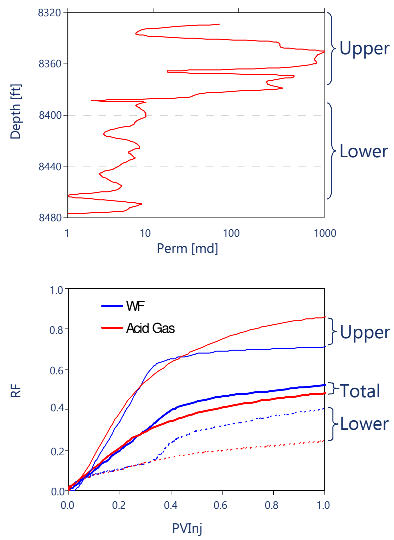
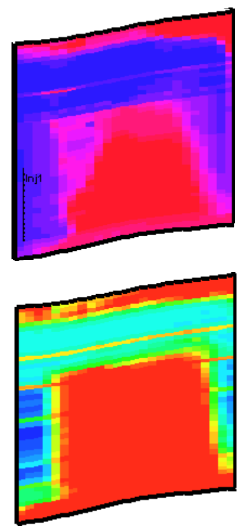
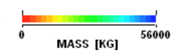




Waterflood

permeability layers and does not sweep Lower zone

Acid Gas



SPE 129645, SPE 171900

Simultaneous Injection of Water/Polymer and Miscible Gas (SWAG/SIMGAP)

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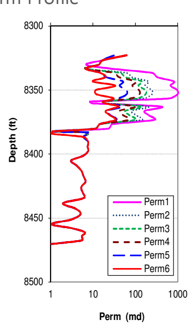
Objective: Improve sweep efficiency and recover by-passed oil in heterogeneous reservoirs

- Perm contrast 10 or lower use water (SWAG)
- Perm contrast 20 or higher use polymer (SIMGAP)

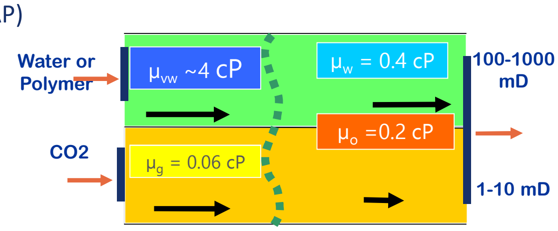
Perm Profile



May 2010

$$\Delta P_{Low} \le \Delta P_{Upp} \longrightarrow \frac{q_g \mu_g}{K_l k_{rg} h_l} \le \frac{q_w \mu_w}{K_u k_{rw} h_u}$$

$$v_w \ge v_g \longrightarrow \mu_w \ge \mu_g \left(\frac{\varphi_l K_u k_{rw}}{\varphi_u K_l k_{rg}} \right)$$



Gas is maintained in the lower zone by:

- Pressure gradient due to continuous polymer/water injection
- Miscibility of injected gas with reservoir oil

Masalmeh et. al. SPE 129645, SPE 142542, SPE 144865, SPE 171900

Design and SIMGAP Pilot

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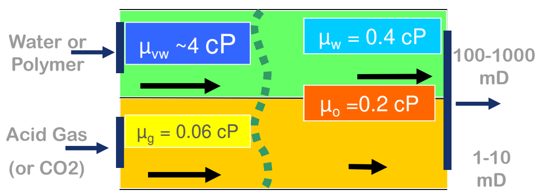

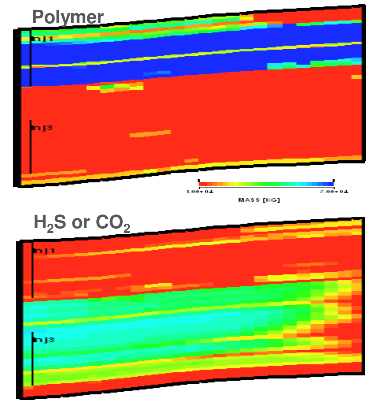

$$\Delta P_{Low} \le \Delta P_{Upp} \longrightarrow \frac{q_g \mu_g}{K_l k_{rg} h_l} \le \frac{q_w \mu_w}{K_u k_{rw} h_u}$$

$$v_w \ge v_g \longrightarrow \mu_w \ge \mu_g \left(\frac{\varphi_l K_u k_{rw}}{\varphi_u K_l k_{rg}} \right)$$

- Be the first to implement innovative solutions and new technologies
- Design solutions to fit our own reservoirs
- Focus our R&D on key challenges

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Masalmeh et. al. SPE 129645, SPE 142542, SPE 144865, SPE 171900

Water flooding vs SWAG

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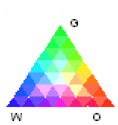
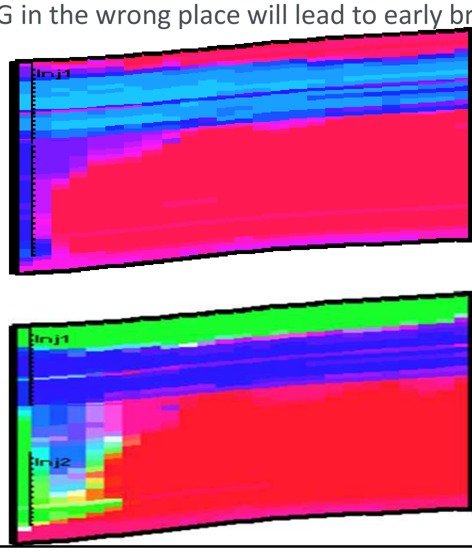
Applying SWAG in the wrong place will lead to early break through and poor sweep





Movie to show water override and capillary hold-up

Movie showing both water and CO2 override in simultaneous injection of water (upper zone) and CO2 (lower zone)

Results of Horizontal Injectors are similar

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SWAG for Reservoirs of Low Permeability Contrast

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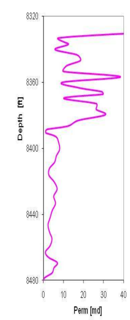
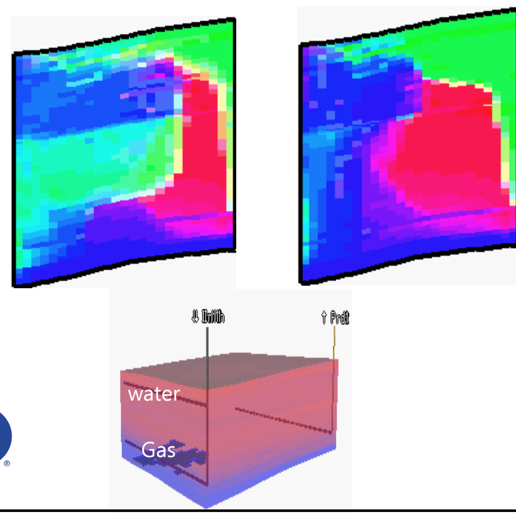
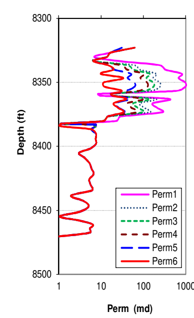
Applying SWAG in the wrong place will lead to early break through and poor sweep

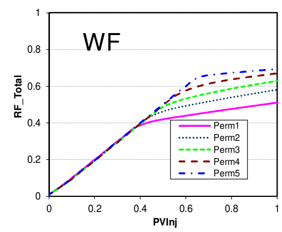
Perm Profile

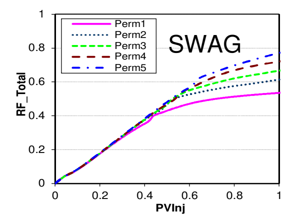




Perm Profile







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Polymer Based EOR De-Risking Strategy

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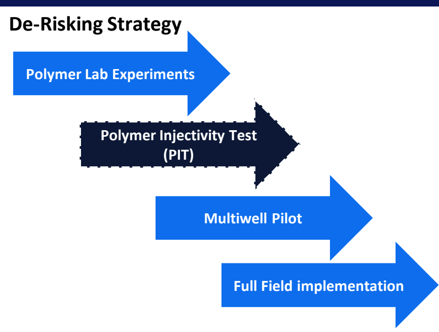

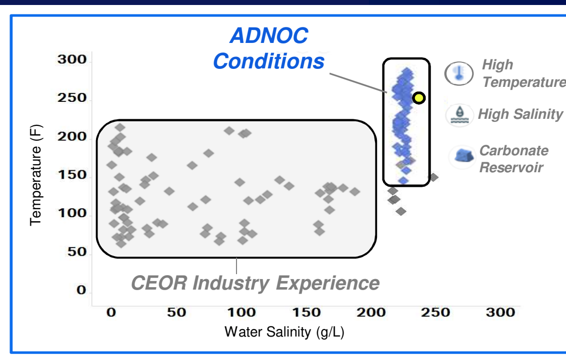

PIT Primary Objectives

- To demonstrate the ability to inject and propagate the qualified polymer in the carbonate reservoir.
- To improve the design and implementation of the inter-well pilot and full field.

"World's first polymer field test in carbonate under combined harsh conditions".

Temperature: *250°F,* ***Salinity:*** *250 g/l TDS*

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High-temperature / high-salinity polymer tests

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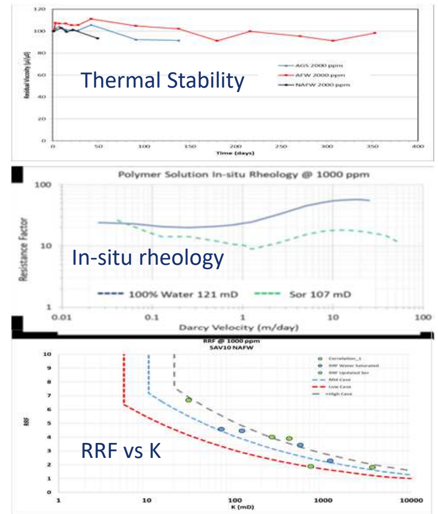
- HPAM polymers are not thermally stable above 60 to 80 C
- Thermal stability can be improved by incorporating monomers such as NVP and ATBS
- Polymer lab work:
  - Thermal Stability
  - In-situ rheology
  - Injectivity
  - RF and RRF
  - Adsorption and IPV

Adsorption & IPV

Parameter	Low	Mid	High
IPV	0.1	0.25	0.3
Adsorption (µg/g)	30	50	70



More on polymers and their stability can be found in SPE 141497, 177073, 188479, 190200, 197647

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PIT Results and History Match

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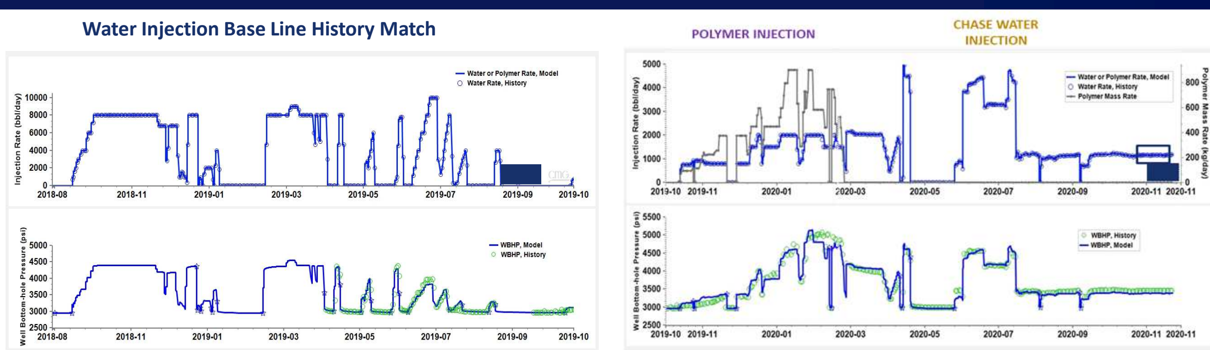

- First time field application of new polymer at 120 Deg F & 250 K salinity in Carbonate Reservoir
- First step towards Hybrid chemical EOR implementation at ADNOC fields
- Good history match obtained using lab parameter ranges and consistent with PFOs interpretation.
- De-risking completed to progress for implementation of the multi-well pilot for SIMGAP/SIWAP

SPE 203405, Paper 38 EAGE IOR 2021

Low Salinity Waterflooding

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- LoSal for carbonate is still in demonstration phase, no field implementation
- Microscopic mechanism is not well understood
- Lab work is required for every reservoir to test the applicability of loSal
- Expected oil production improvement in field scale is up to 5% STOIIP
- Cheapest EOR technique and Operationally very similar to WF
- Improves general WF performance as desalination improves water quality:
  - it reduces souring and scaling
  - It reduces injectivity decline
- LSF is the first step in the EOR staircase
  - ex. enables cheaper Polymer/surfactant Flooding
- In principle all waterfloods are targets for LoSal.
- It is very difficult to pilot unless significant reduction in Sor is obtained in the lab

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Low Salinity Flooding: Fluid-Fluid Interaction Results

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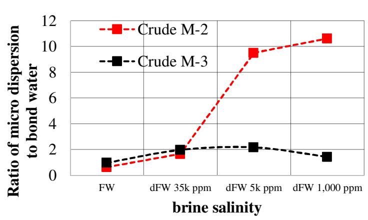
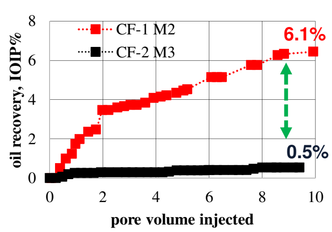
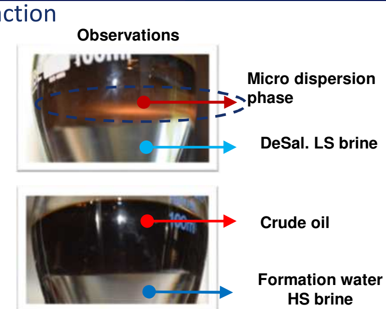
- Develop new screening method for LSF EOR based on fluid-fluid interaction







- More than 100 different crude oils were tested (onshore and offshore)
- Database will be developed for major reservoirs to screen low-salinity flooding and perform flooding experiments to confirm EOR potential

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Masalmeh et. al., SPE-197314

Alhammadi M, et. al., SCA 2017

01 June 2021

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Low Salinity Flooding: Fluid-Fluid Interaction Results

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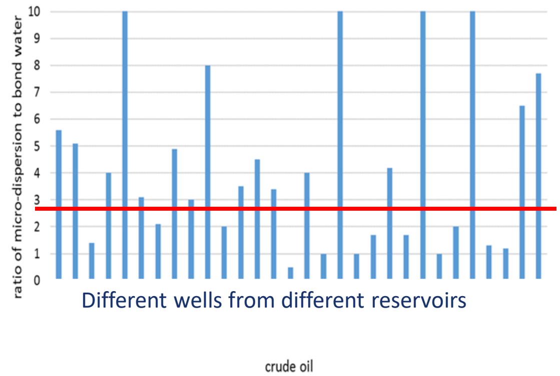
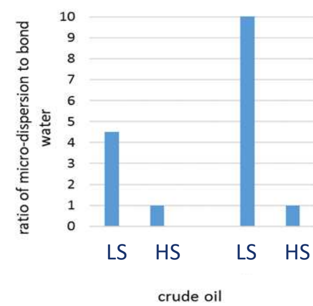
Low and high salinity brines used in the Study

Ion/Brine	FW	DSAL
na	57997	87
ca	17535	1
mg	1975	2
Br	0	0
Sr	0	0
k	0	4
so4	775	2
cl	124986	143
TDS	204201	241
Viscosity, cP	0.368	0.186

Micro-dispersion formed upon contact crude oil with low salinity



4 crude oils selected to perform LSF experiments to confirm the fluid-fluid interaction results



Masalmeh et. al., SPE-197314

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Low Salinity Flooding: Experimental Results, Reservoir A

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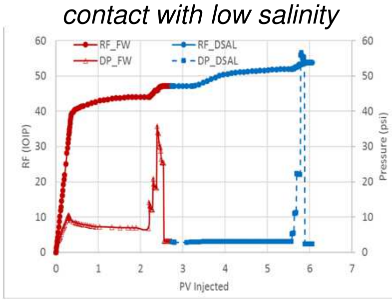
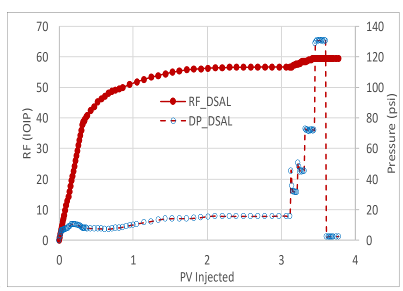
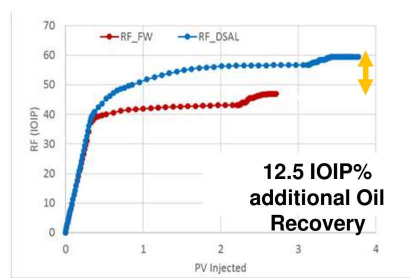
Low salinity flooding using a positive crude oil, i.e. formed high micro-dispersion upon contact with low salinity



Tertiary low salinity water flood



Secondary low salinity water flood



Secondary low salinity vs High salinity water flood

Reservoir A: Secondary low salinity vs tertiary low salinity

- Tertiary low salinity leads to 6% extra recovery
- Secondary low salinity leads to 12.5% extra recovery

Masalmeh et. al., SPE-197314

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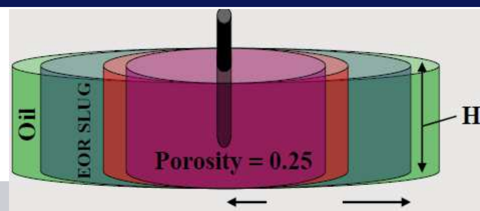
Single well chemical tracer Test

Reservoir A (positive reservoir)

- Tertiary Low Salinity SWCTT
- Secondary Low Salinity SWCTT



Reservoir B (negative reservoir)

- Tertiary Low Salinity SWCTT

phase1	phase2	phase3	phase4	phase5	phase6	phase7
WF to immobile So High Sal.	SWCTT-1 High Salinity Sor1	Low salinity water injection	SWCTT-2 Tertiary Low Salinity Sor2	Well production to Soi	Low salinity water injection	SWCTT-3 secondary Low Salinity Sor2

- It is not recommended to start playing with the ion content of the brine as:
  - Some of these recommended ions could lead to potential scaling problem.
  - Changing the composition of the brine will add extra cost, which could be a show-stopper
- The practical low salinity options to consider would be desalinating formation, aquifer or sea water.

Summary Of LSF Laboratory Experiments

- The results show that the use of fluid-fluid interaction experiments is a robust screening method for low salinity water flooding.
  - this screening method can lead to significant saving in both time and cost of running low salinity flooding experiments.
- Based on the fluid-fluid interaction test, almost half of the crude oils tested in this study reacted positively upon contact with low salinity water
- A strong qualitative correlation was demonstrated between core flooding and fluid-fluid interaction
- The flooding experiments showed up to 6.5% extra recovery in tertiary mode and up to 12.5% extra recovery in secondary mode.
- ADNOC is planning at least two SWCTT /LIL to be conducted in the near future.

Gas Based EOR

Webinars

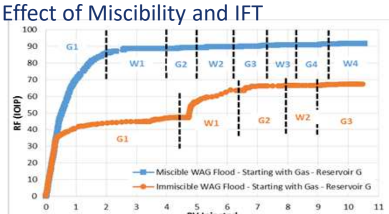
- Gas based EOR laboratory work:
  - Mobility control for gas based EOR
  - Sorm (effect of gas either CO_2 or HG, miscible or Immiscible)
  - Trapped saturation
  - Cyclic hysteresis
  - the impact of IFT in gas-based EOR processes,
  - Impact of miscibility or near miscibility on oil recovery
  - Impact of water blockage on WAG processes
  - Gas injection in Transition zone

SPE International

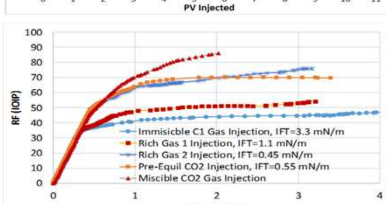
Gas Based EOR

Webinars

Effect of Miscibility and IFT

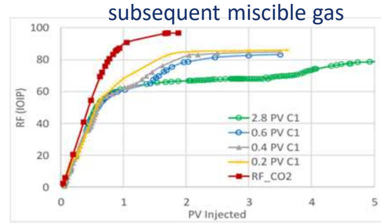


Effect of miscibility on Oil Recovery (miscible and immiscible injection): Significant different in RF due to miscibility

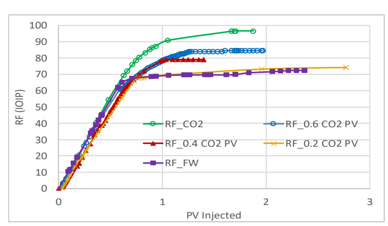


Effect of IFT on oil recovery: RF increases as IFT decreases, however, part of the results are due to experimental artefact

Effect of Immiscible gas on subsequent miscible gas



Effect of Immiscible Gas Injection (C1) on Subsequent Miscible Gas Injection (CO_2): The more immiscible gas injected the higher the impact on RF



Effect CO2 slug length

Impact of CO_2 Slug length on recovery factor: The higher the slug length the higher the recovery However, this only addresses displacement efficiency

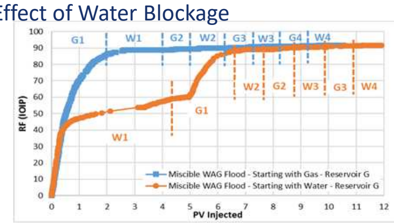
SPE International

Masalmeh et. al., SPE 200057
Paper 38 EAGE IOR 2021

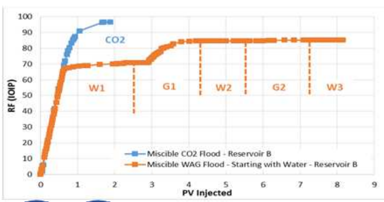
Gas Based EOR

Webinars

Effect of Water Blockage

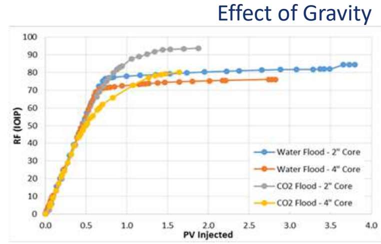


Same RF in WAG experiments starting with water or gas injection: No water blockage effect

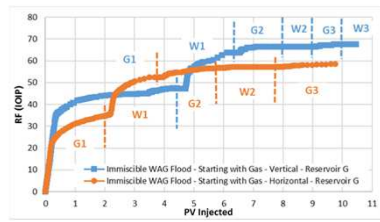


Starting with water injection leads to higher Sorm: Water blockage effect

Effect of Gravity



Effect of Gravity: 4 inch vs 2 inch diameter core for miscible CO2 or water: Significant impact on CO2 but hardly any impact on WF



Effect of Gravity: Using horizontal vs vertical core samples

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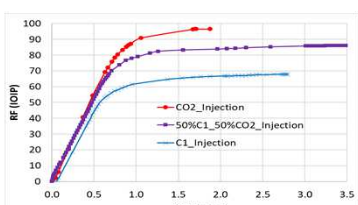
Gas Based EOR

Webinars

Effect of MMP on oil recovery



Experimental Pressure	4485 psi
CO2 MMP	2570 psi
C1 MMP	>5500 psi
50%C1+50%CO2 MMP	4050 psi

Masalmeh et. al., SPE 200057
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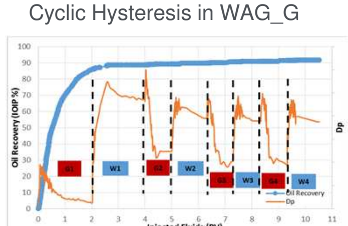
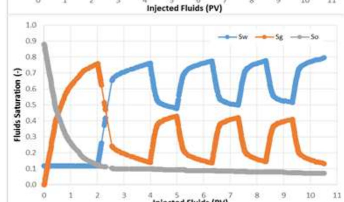
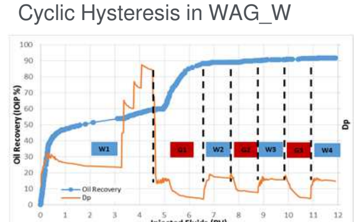
Cyclic Hysteresis in WAG_G

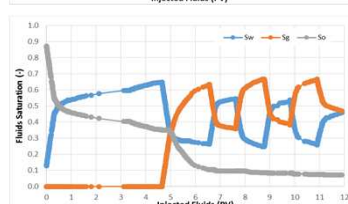




Cyclic Hysteresis is observed between the first and second gas cycle only, this could be due to that gas is displacing different fluids in these cycles

Cyclic Hysteresis in WAG_W





Water mobility slightly improves between first and subsequent cycles and no gas hysteresis between gas cycles

Summary of Gas Injection Laboratory Experiment

- Collected very rich laboratory data for gas based EOR, the data is used in our EOR pilot and FFD modelling
- Immiscible gas injection or gas coming out of solution will negatively impact any subsequent miscible flood
- Cyclic hysteresis in gas mobility was only observed between first and second gas cycle
- A strong impact of miscibility pressure is measured, recovery increases with increasing the pressure difference between experimental condition and MMP
- Longer CO_2 cycles lead to higher displacement efficiency; however, this may reduce sweep efficiency due to override, check by modelling
- Rich trapped gas saturation data is collected, to address both CO_2 EOR and sequestration

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Concluding Remark

- Limited mature EOR technologies in carbonate:
  - We need to take risk and be the first to implement innovative solutions and new technologies
  - We have aggressive and comprehensive EOR plans
- Characterising remaining oil distribution is foundation for field redevelopment project
  - Unswept mobile oil vs. Sorw
  - IOR scope vs. EOR scope: Importance of direct observation of sweep
- Must do EOR well before end of conventional development otherwise EOR will be very expensive

- The ability to innovate and challenge the status quo
- IOR/EOR target depends on both remaining oil saturation and its distribution:
  - **How** much is ROS?
  - **Where** is the remaining oil?
  - **Why** is it there?
  - **What** can improve recovery?
- Experienced staff using structured workflows but with flexibility to innovate
- Close links with research
  - Early action on emerging issues on recently deployed technologies

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Acknowledgement

I would like to thank ADNOC management for granting permission to present this work and thank the colleagues in ADNOC for contribution and insightful discussion.

We also acknowledge and appreciate the contribution of all our R&D partners for very cooperative working relationship and high-quality data and results