FLUIDXLAB

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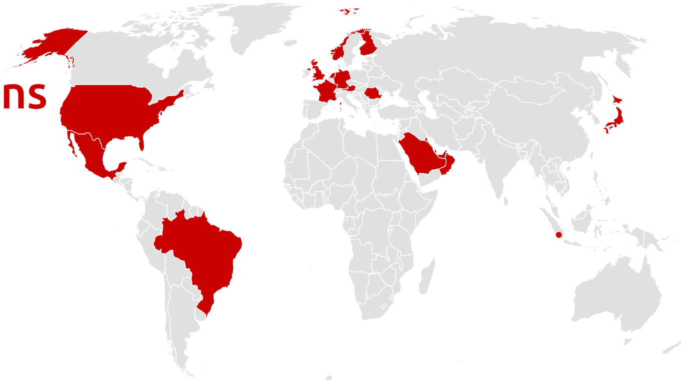
Confidential Document Prepared for UTA

NB EOR IN UNCONVENTIONALS

Chip Design Ideas & InspIOR® Configuration

Our Customers (Dec 2024)

World leading energy companies & research organisations



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Nanobubble Enhanced Oil Recovery (EOR)

Nanobubbles (50–200 nm) are stable Gas-Filled Particles in Water

- They enhance oil recovery through:

  Wettability alteration, interfacial tension (IFT) reduction, penetration into tight pores, capillary pressure modulation

- Why use them?

  They're stable, small enough for nanopores, and can carry active gases.

- Potential for "Unconventionals"!

  InspIOR & chip design to support testing up to 10.000 psi and 130 °C

  Nanobubbles are prepared using a proprietary process available only at UTA facilities.

InspIOR® - Turnkey Microfluidic Technology Platform

Developed for Oil & gas, carbon management, hydrogen, geothermal

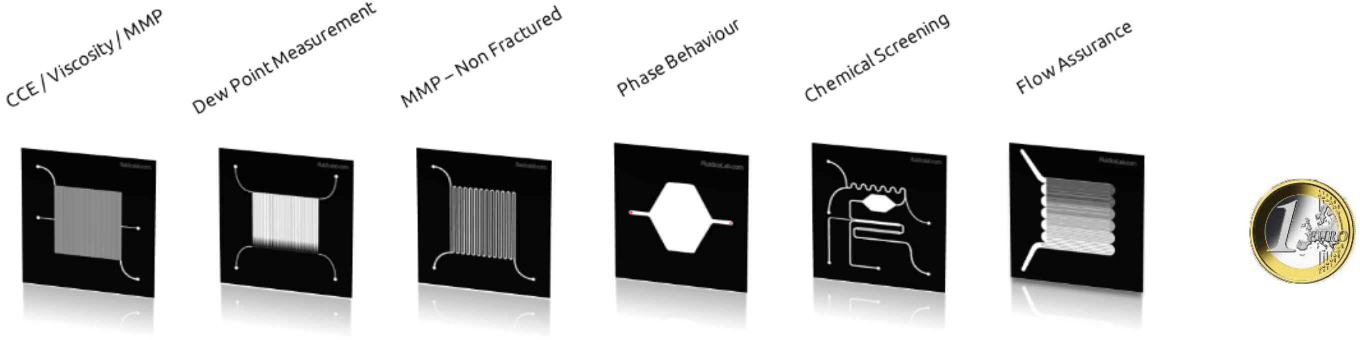
- Fast & accurate fluid testing, chemicals screening and flow in porous media analysis
- Specifically designed for high-pressure high-temperature microfluidics applications
- Fully automated system
- Based on 10+ years of microfluidic research & development

What is Microfluidics?

Miniaturized fluid control for faster, smarter lab workflows

- Microfluidics is the science of manipulating tiny amounts of fluids—often nanoliters—through channels thinner than a human hair.

It enables fast, precise, and automated experiments on a compact chip.



Nanobubble EOR - Some Experimental Studies (Only 1 on MF?)

NO.	REFERENCE & YEAR	INSTITUTION	SYSTEM	METHOD	P RANGE	T RANGE	HIGHLIGHTS
1	**Shoukry et al. (2025)**	University of Wyoming	CO_2 Nanobubbles	Micromodel (glass, WW/OW)	~2–6 bar	25–40 °C	Direct observation of NB transport in high-pressure chips
2	**Cai et al. (2024)**	China Univ. of Petroleum (East China)	CO_2 NB + Pickering	Coreflood (ultra-tight cores)	Up to 10 bar	25 °C	66% recovery; pore blocking, wettability shift
3	**Elnaggar et al. (2025)**	University of Wyoming	N_2 Nanobubbles	Core imbibition (Berea/carbonate)	1–15 bar	25–60 °C	Enhanced spontaneous imbibition due to NB stability
4	**Li et al. (2024)**	Southwest Petroleum Univ.	CO_2 Nanobubbles	Coreflood (low-perm sandstone)	~8 bar	30 °C	Pressure buildup indicates NB mobility control
5	**Wang et al. (2023)**	China Univ. of Geosciences	CO_2 Nanobubbles	Sandpack flooding	~10 bar	25–50 °C	Nanobubble-assisted sweep efficiency improved by 20–30%
6	**Zhou et al. (2023)**	Univ. of Sci. & Tech. Beijing	CO_2 Nanobubbles	Coreflood (tight carbonate)	~5–12 bar	25–60 °C	NB reduced IFT and improved injectivity
7	**Zhang et al. (2025)**	Xi'an Shiyou Univ. / CUP Beijing	CO_2 Nanobubbles	Coreflood (Berea sandstone)	5–15 bar	30–60 °C	Tracked NB diffusion vs CO_2 gas; improved recovery
8	**Ahmed et al. (2022)**	King Fahd Univ. of Petroleum	CO_2 Nanobubbles	Micromodel (glass, low-perm net)	3–5 bar	Room temp	Bubble retention and pathway alteration
9	**Wen et al. (2024)**	Daqing Oilfield Lab	CO_2 Nanobubbles	Coreflood (field core, sandstone)	10 bar	40–60 °C	NB performance benchmarked vs gas/surfactant
10	**Chen et al. (2023)**	China Univ. of Mining & Tech	N_2 Nanobubbles	Coreflood (tight sandstone)	5–12 bar	25–50 °C	High stability N_2 NB → 10–15% uplift in recovery

Design 1: Multi-Zone Injectivity Screening

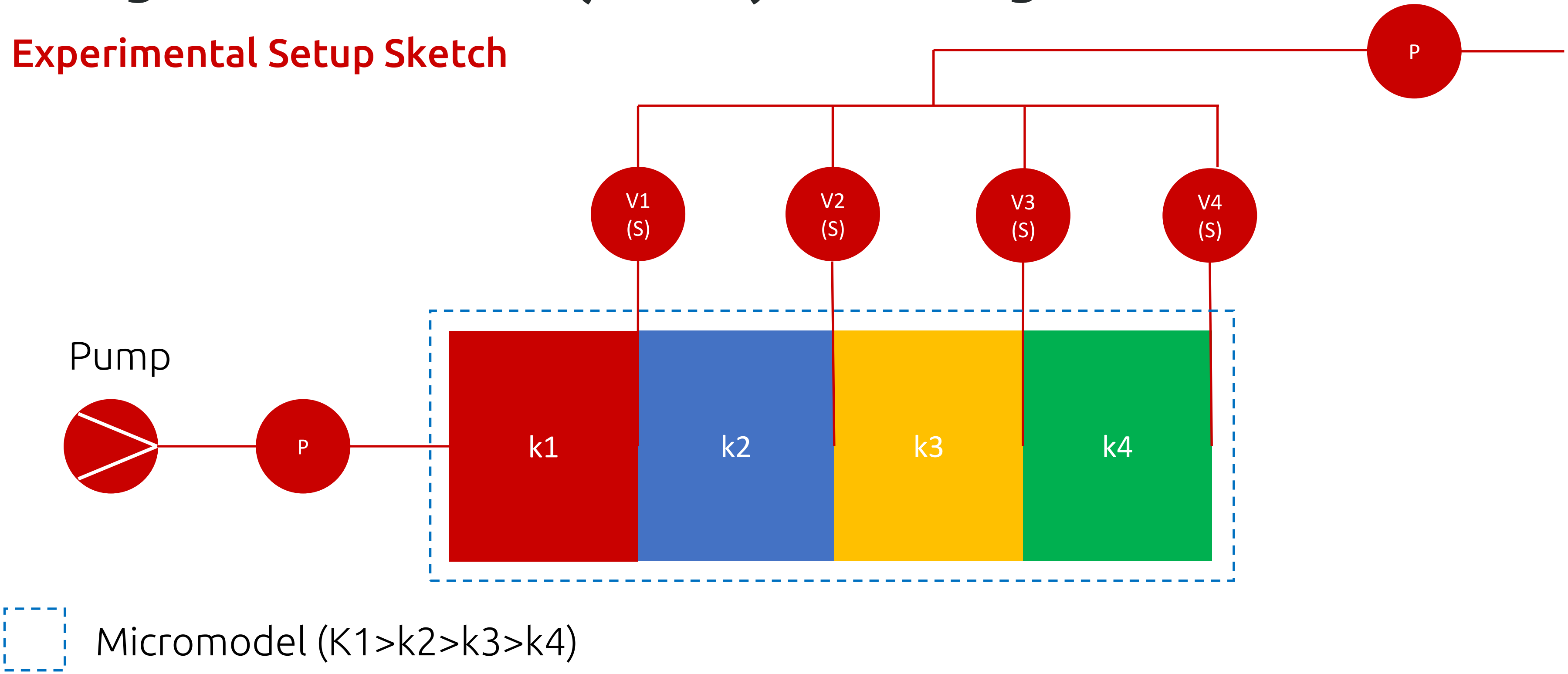
Purpose: Fast & Automated Detection of Pore Entry Threshold of Nanobubbles

- Chip Design:
  - Different zones with decreasing channel size (e.g. 1 µm, 0.5 µm, 0.2 µm, 0.1µm)
  - Each zone has an outlet and microvalve
  - Inlet pressure measured at constant flow rate
  - FXL recommends keeping channel width > 5 µm and varying edge depth for better visual access

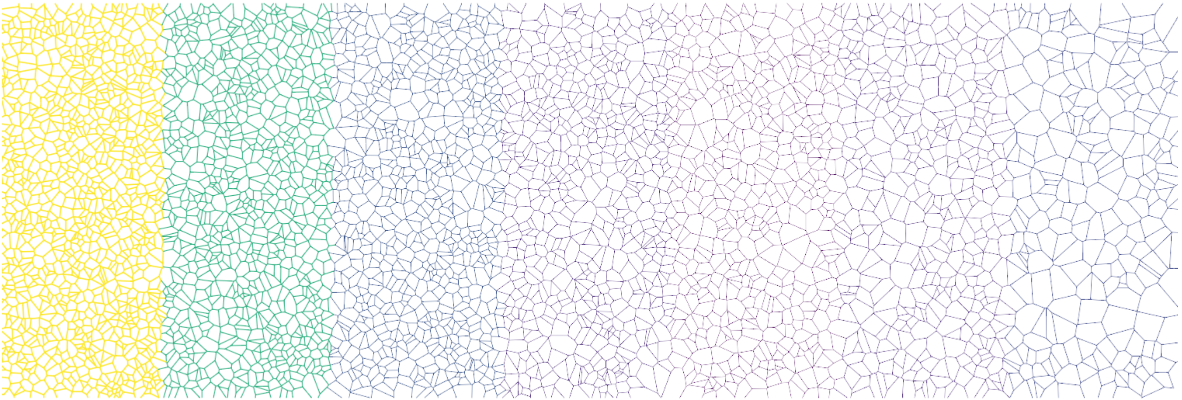
- What we learn:
  - Detect **mobility cutoff pore size**
  - Identify **collapse, retention, or plugging**
  - Compare against **brine baseline**
  - Build **injectivity map**
    - Vary p,T, salinity, NB concentration, NB size, flow rate (shear rate)

Design 1: Multi-Zone Injectivity Screening

Experimental Setup Sketch

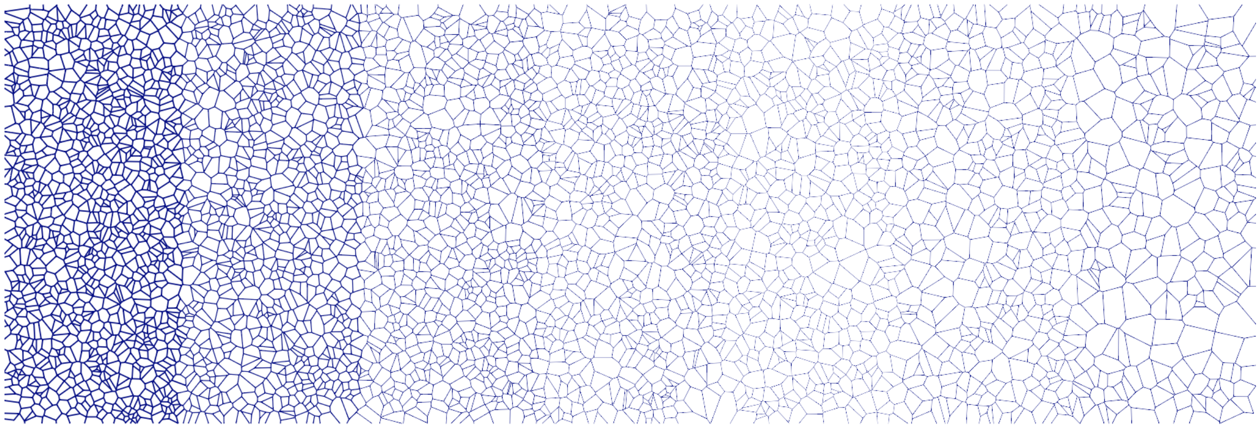


Design 1: Multi-Zone Injectivity Screening (Draft)



FXL recommends keeping channel width > 5 µm and varying edge depth for better visual access

Design 1: Multi-Zone Injectivity Screening (Draft)



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Design 1: Multi-Zone Injectivity Screening

Interpretation Matrix

ΔP Observation	Possible Interpretation
Low ΔP	Nanobubbles freely enter — no blockage or collapse
Moderate ΔP increase	Partial retention, bubble-induced flow resistance
Sharp ΔP rise at specific zone	Pore entry cutoff reached → plugging or size exclusion
Rising ΔP over time (in same zone)	Progressive accumulation → bubble jamming or adhesion
Sudden ΔP drop	Bubble **collapse** or coalescence relieved obstruction
High ΔP from Zone 1 onward	Global plugging — bubbles too large or unstable

NB too small to be visual in microscope.

Design 2: "Knudsen-Analogue" Diffusion of Nanobubbles

Purpose: Fast & Automated Detection of NB Diffusion

- **Bottom channel:** Contains nanobubble-laden brine (source)
- **Top channel:** Contains plain brine (sink)
- **Middle:** Nanochannels

- FXL recommends keeping channel width > 5 µm and varying edge depth for better visual access
- *NB detection via UV-VIS to be tested and calibrated at UTA premises!*

- What we learn:
  - Identify the smallest pore size nanobubbles can penetrate.
  - Calculate effective diffusivity from breakthrough time.
  - Detect collapse or retention in nanochannels.
  - Assess injectability in tight formations

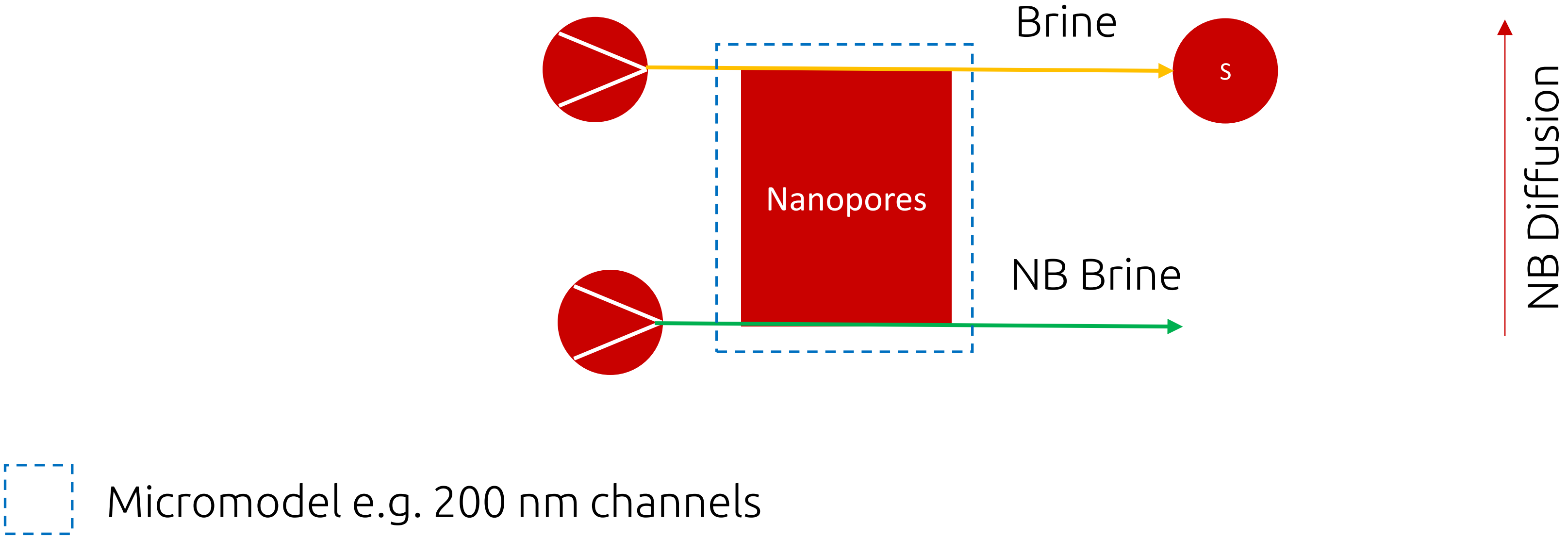
Nanobubble – Detection Methods (inline, low volume)

Method	Principle	Detects	Notes
DLS (Dynamic Light Scattering)	Measures size distribution of particles	Size + presence	Standard for nanobubbles; microfluidic version currently developed by FXL; R&D state
UV–Vis Spectroscopy (Transmission)	Measures total extinction (scattering +abs)	Presence (quantitative)	Inline-compatible; expected range 450–600 nm; available at FXL up to ~300 bar; upgrade to 700 bar with nanobubbles to be tested at UTA
Conductivity	Non-conductive phase displaces ions	Presence (quantitative)	Δ may be small; affected by ionic strength; needs to be tested; available at FXL; cheap
Conv. Microscope	Visual	Size + presence	Challenging to implement; need to test at UTA

- Other methods not considered due to larger sample volumes required…

Design 2: "Knudsen-Analogue" Diffusion of Nanobubbles

Experimental Setup Sketch – Challenging due to Analytics and dp Requirements



S: Sensor (UV-Vis or DLS) to be tested and calibrated at UTA

Design 2: “Knudsen-Analogue“ Diffusion of Nanobubbles

Interpretation Matrix

Observation	Possible Interpretation
Bubbles appear quickly	Free diffusion through pores
Bubbles appear slowly	Hindered diffusion
No bubbles appear	Size exclusion or collapse
Signal reaches low plateau	Partial transport, some retention

Design 3: Nanobubble-Based Oil Displacement Micromodel

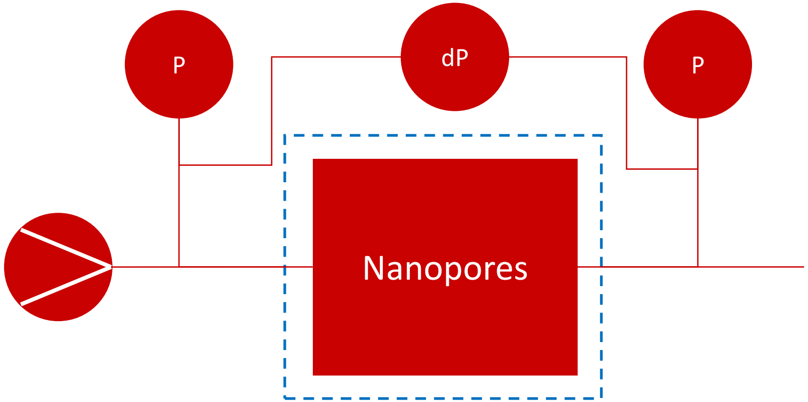
Visualize and quantify how NB displaces oil in a nanostructure micromodel.

- Inlet / outlet port:
  - Inject / produce oil / brine / NB
- Nanopores:
  - Based on MICP data to resemble real geometrical features of rock
- FXL recommends keeping channel width > 5 μm and varying edge depth for better visual access

- What we learn:
  - Oil recovery efficiency
  - Displacement mechanism
  - Sweep pattern and front behavior
  - “Residual” oil saturation
  - Effect of pore geometry

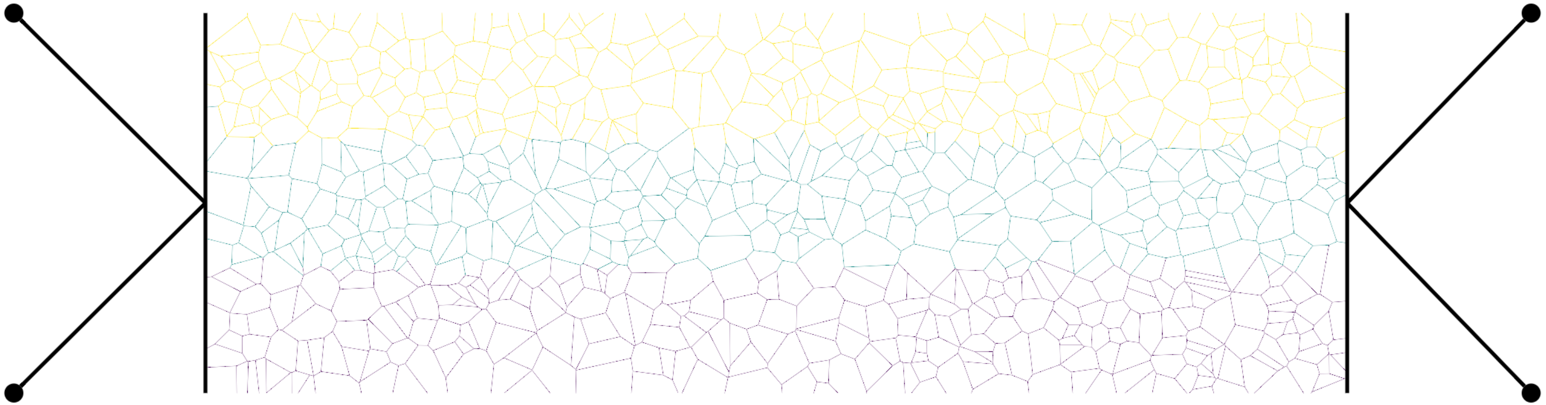
Design 3: Nanobubble-Based Oil Displacement Micromodel

Experimental Setup Sketch



Micromodel with MICP data-based structure
Homogeneous, vertically or horizontally layered

Design 3: Nanobubble-Based Oil Displacement Micromodel



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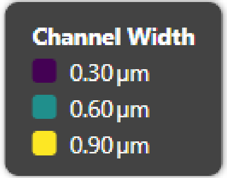
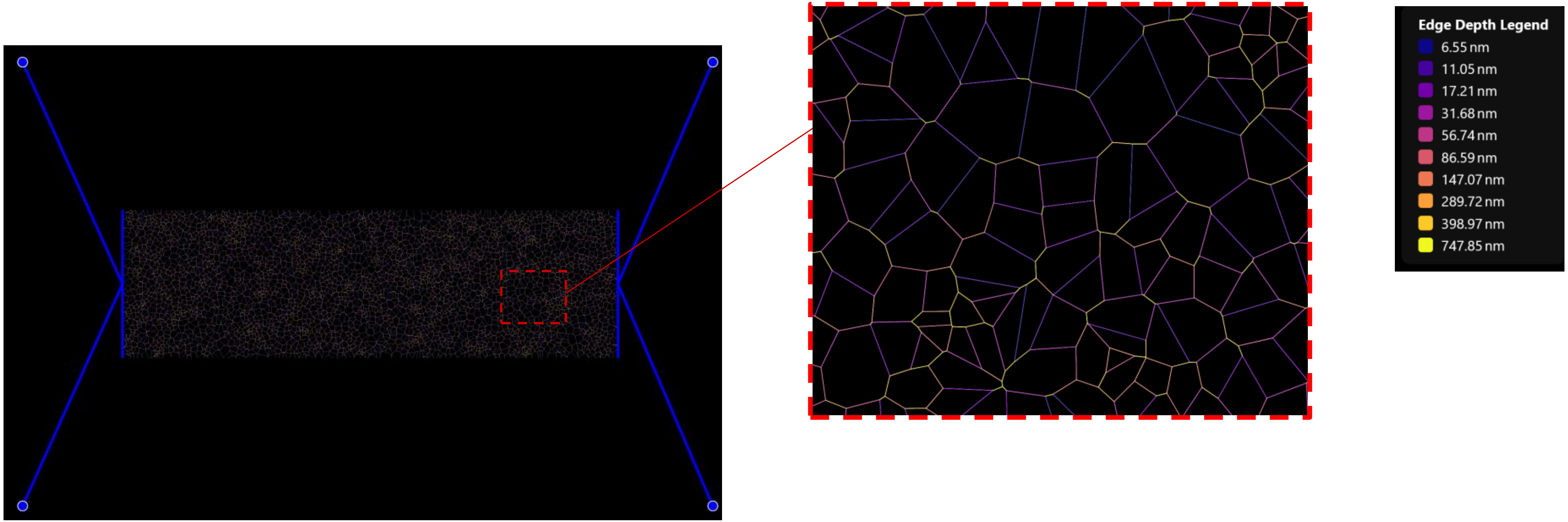


Design 3: Nanobubble-Based Oil Displacement Micromodel



FXL recommends keeping channel width > 5 µm and varying edge depth for better visual access.
Continuous path from left to right / (start with conventional chips e.g. sandstone)
May be second step after understanding injectivity. Other data than MICP available? MICP/TS/NMR/FIB-SEM

Design 3: Nanobubble-Based Oil Displacement Micromodel

Interpretation Matrix

Observation	Possible Interpretation
High oil recovery compared to brine	Nanobubbles enhance recovery via wettability or IFT reduction
Uniform displacement	Efficient sweep; improved flow
Fingering or bypass	Mobility mismatch or channelling; nanobubbles less effective
Early breakthrough with low recovery	Poor displacement efficiency; limited bubble function
Oil detachment from surfaces	Wettability alteration likely caused by nanobubbles
Formation of oil emulsions in effluent	Interfacial disturbance or emulsification during flow
Oil remains trapped in corners or dead ends	Insufficient capillary disruption; trapped residual oil

Way Ahead?

Next Steps and Action Point

- Feedback draft chip designs – anything we missed or should improve?
- What can FXL do to further support process?
- Timeline experimentation at UTA

Adaptive Microfluidics:
Systems that learn, optimize & transform labs

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