In-situ Laboratory Wellbore Cement Integrity in Simulated Field Environments for CCS:
Testing and Remediation Approaches

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Importance of Well Integrity

Wells are primary potential leakage pathways, critically affecting:

- Hydrocarbon plug and abandonment (P&A)
- CO_2 and energy storage

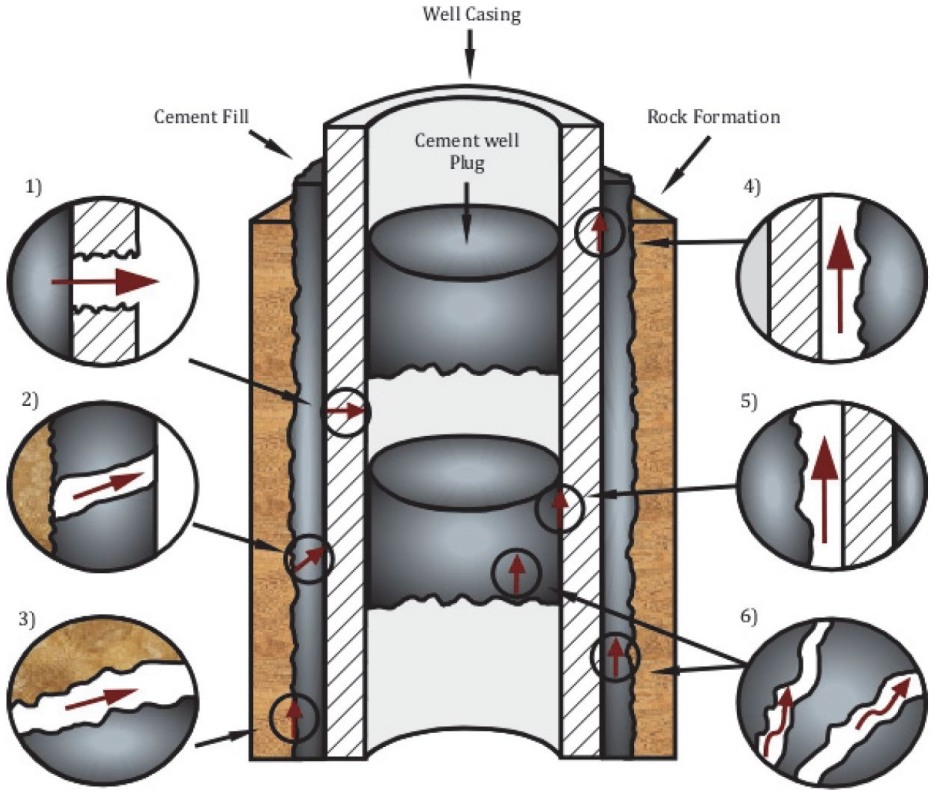
Well integrity is essential for long-term success:

- Cement failure behind casing is a major leakage source
- Common leakage paths:
  - Casing-cement and cement-formation interfaces
  - Fractures or mud channels in cement bulk

Effective prevention and remediation of leaks is vital for:

- Large-scale storage implementation
- Successful P&A operations

Post-abandonment, wells require permanent barriers across the full cross-section — analogous to restoring the caprock



After Recasens et al 2017

Study objective and experimental approach

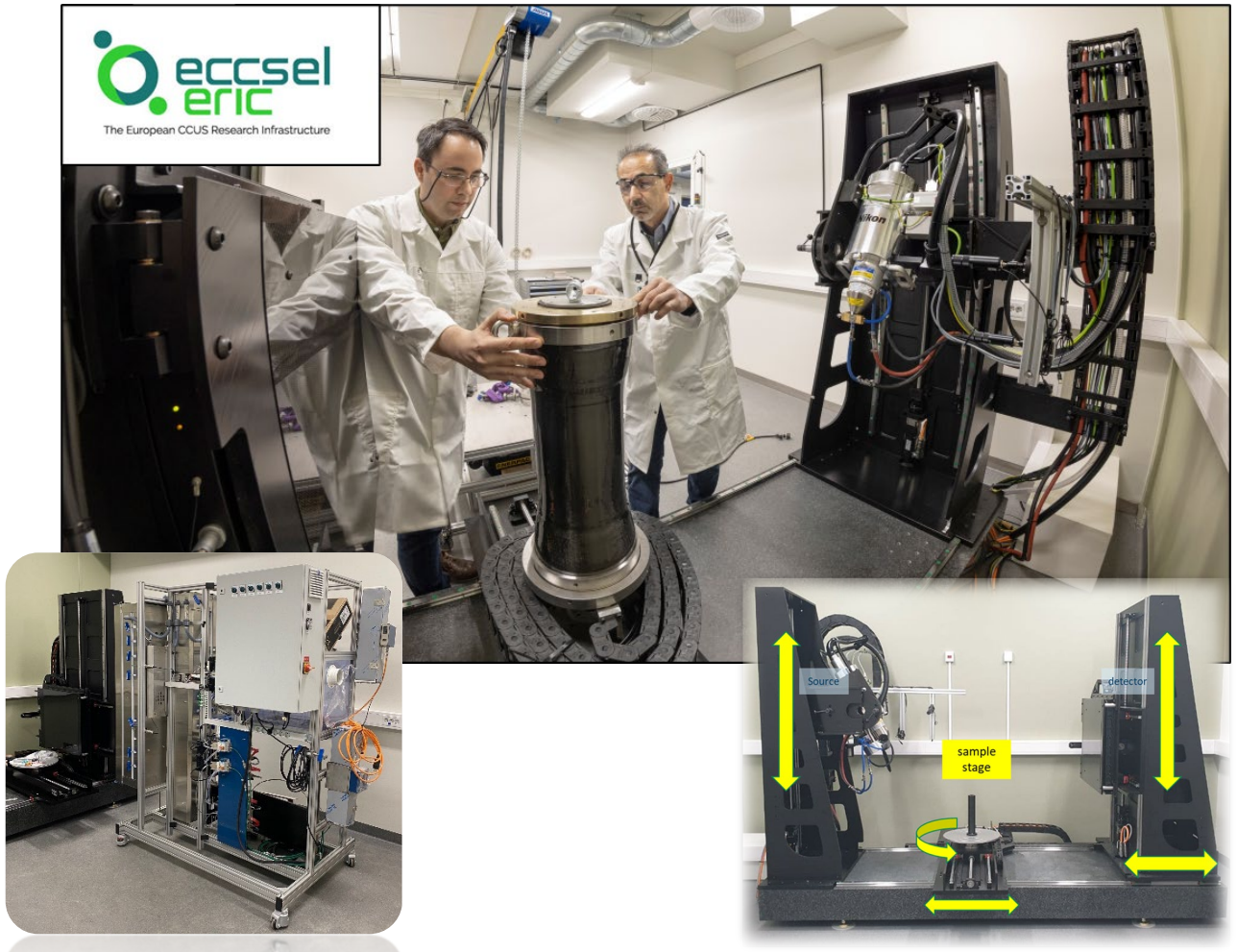
Focus of This Study:

Investigate cement integrity failure mechanisms and remediation methods

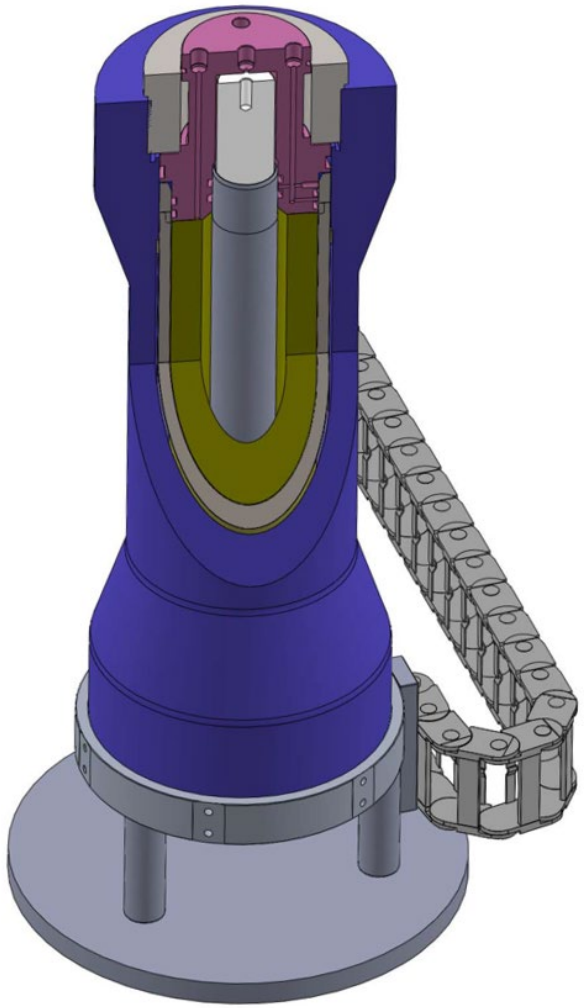
Approach:

Experimental testing using the advanced ECCSEL Well Integrity setup

- This setup:
  - Recreates realistic field conditions at lab scale
  - Provides a controlled environment for detailed analysis
  - Supports evaluation of both failure processes and repair strategies



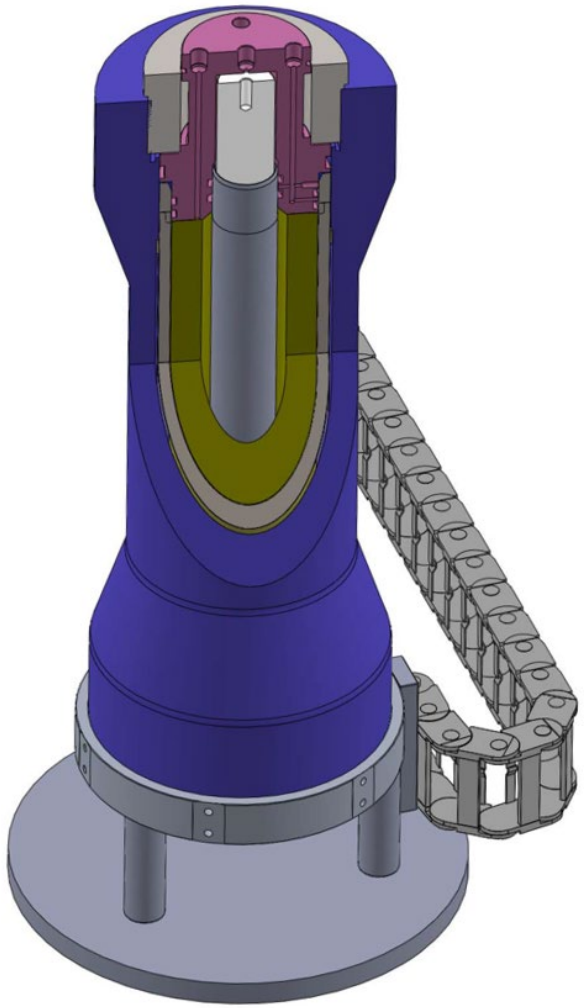
ECCSEL Well Integrity Setup

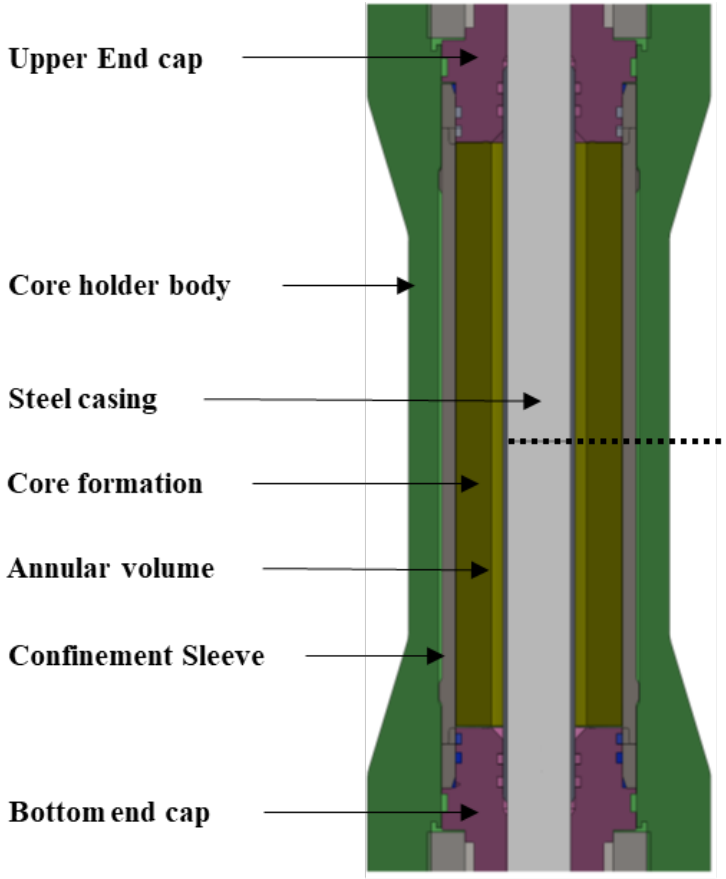


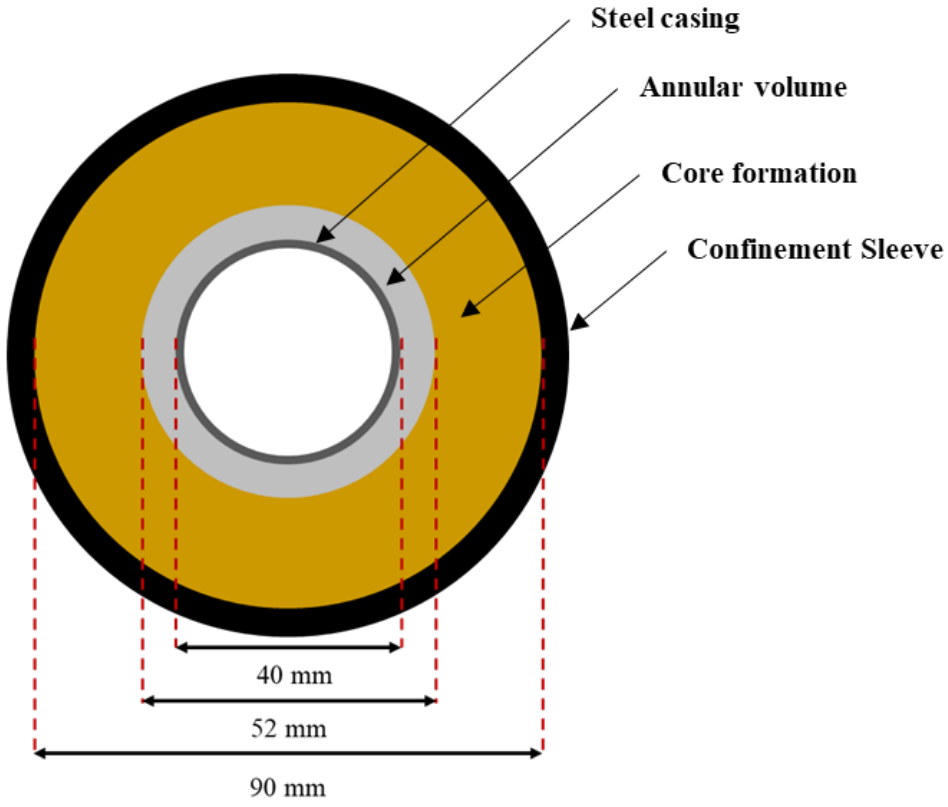
- In-situ imaging under X-ray CT
- Fluid flow core flooding and permeability measurements
- Application of remediation materials/fluids
- Annular in-situ cementing and fracking
- 3.7" x 12" cylindric core, 1.6" steel casing

Core sample	L 290 mm, OD 90 mm, ID 52 mm
Casing	OD 40 mm, ID 37 mm, L 365 mm
Confining pressure	Up to 200 bar
Casing pressure	Up to 500 bar
Pore pressure	150 bar

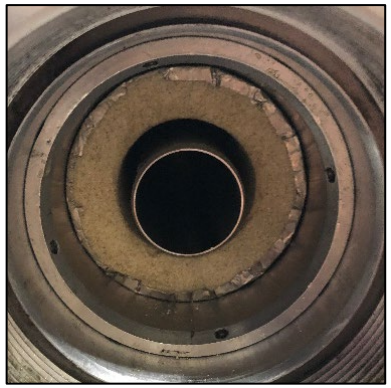
ECCSEL Well Integrity Setup

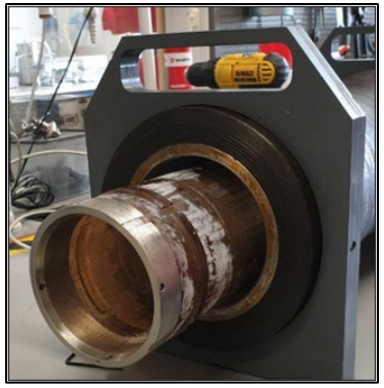


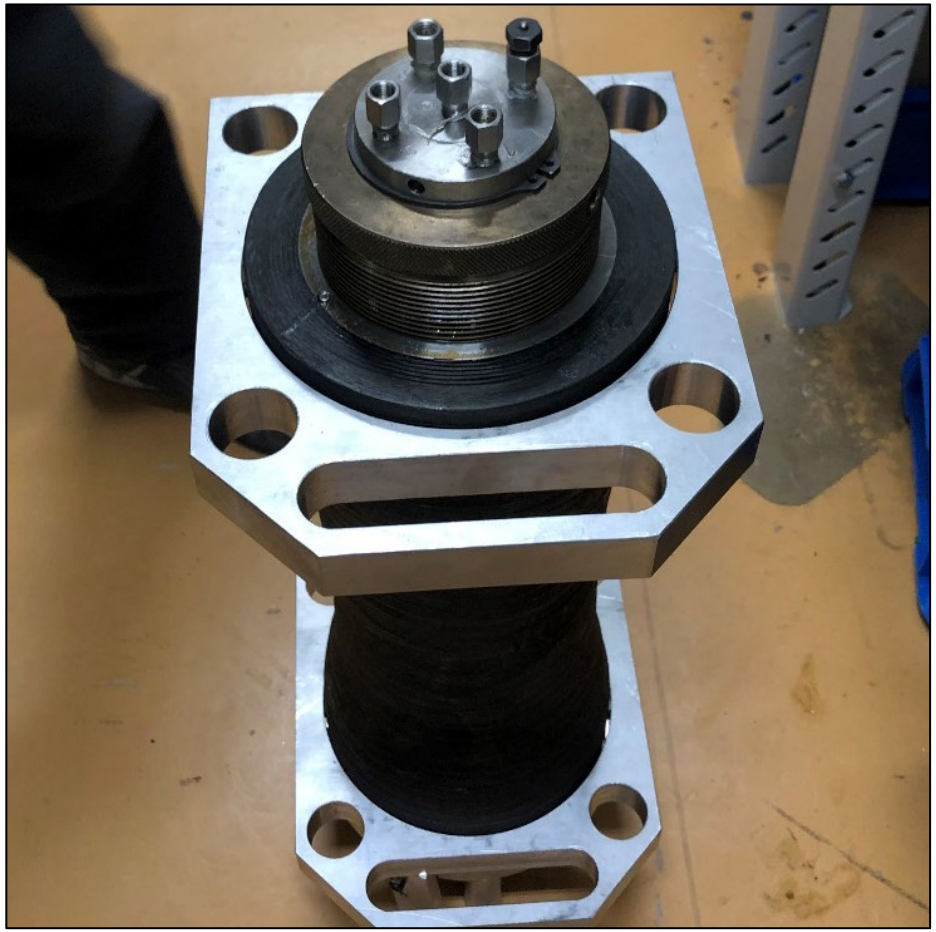




ECCSEL Well Integrity Setup







ECCSEL Well Integrity Setup

A schematic overview of the flow and pressure setup

Pump 1:

- Used to inject the brine into the rock sample and for maintaining the desired pore pressure through the entire experiment

Pump 2:

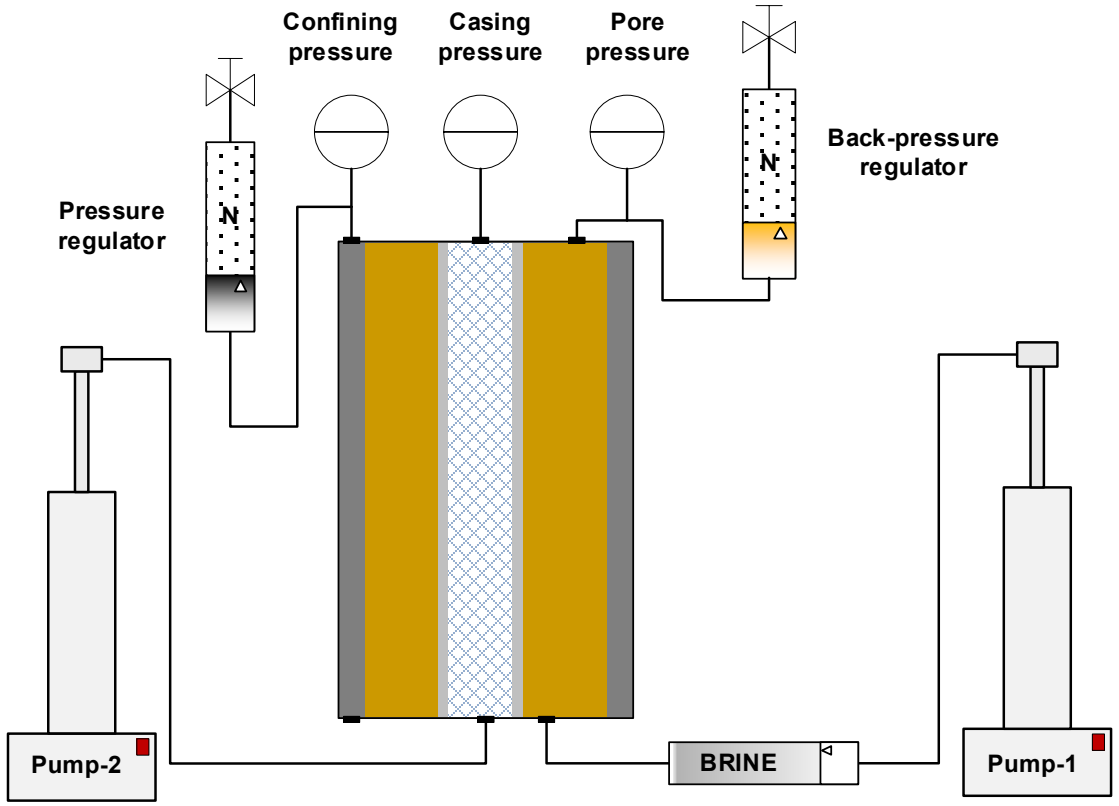
- Used to control the casing pressure

Confining pressure:

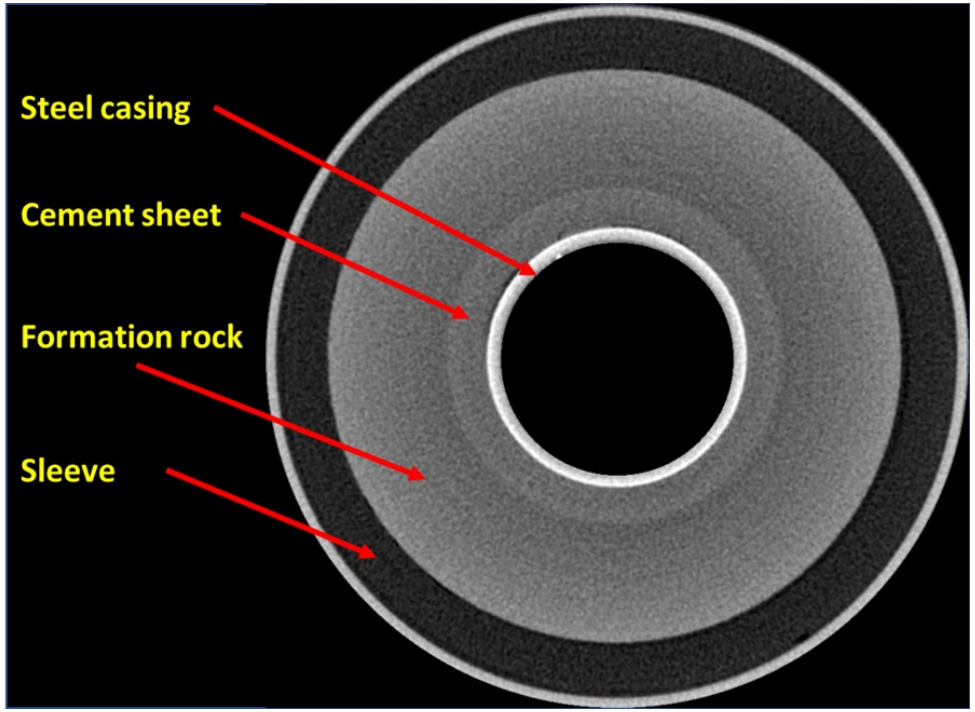
- Maintained through a buffer
- Pressure regulator: To maintain constant confining pressure

Pore pressure

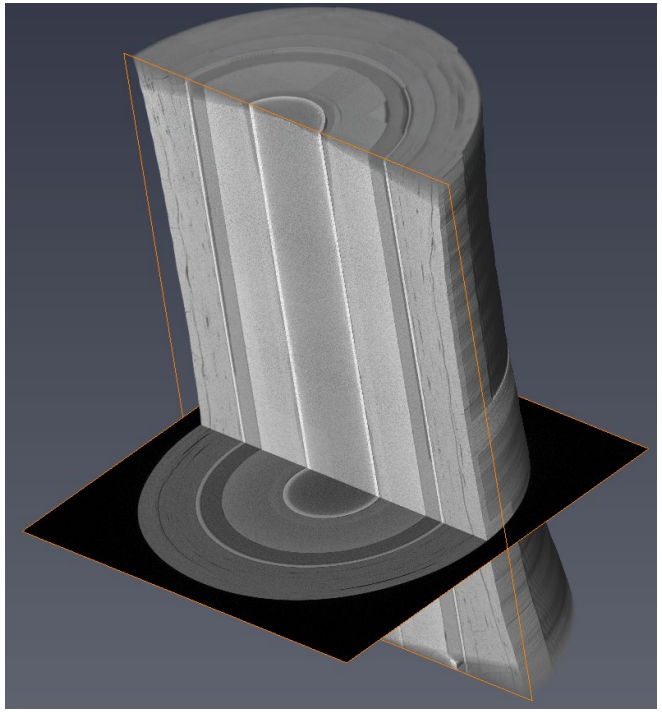
- Maintained through back-pressure regulator



In-situ images of the setup



2D planer cross section



The vertical setup

- Various components in the experiment:
  - steel casing, the cement sheet, the rock formation
  - and the sleeve separating the confining pressure from the pore pressure could be distinguished easily.

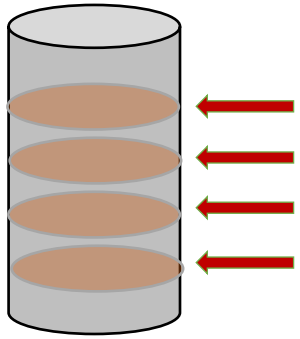
Experimental campaign

- Pressure cycling in the casing
  - Interval [0, 450 bar]
  - Casing pressures
    - 0, 50, 150, 250, 300, 350, 400, 450, 456 [bar]
- Before each increase, step down to pressure in the previous step
- Abbreviations
  - P_c= Casing pressure
  - P_{sl} = Sleeve/confining pressure
  - P_{pore} = Pore pressure

Run #	P_c [bar]	P_{sl} [bar]	Frac	X-ray image [min]
R…	50	80	No	
…	…	80	No	
R14	300	85	No	6
R15	350	85	No	6
R16	400	85	No	6
R17	450	85	No	6
R18	450	65	Yes	6
R19	450	65	Yes	6
R20	456	65	Yes	219

Results

R17 P_c=450, P_{sl}=85, P_{pore}=50



Run #	P_c [bar]	P_{sl} [bar]	Frac	X-ray image [min]
R...	50	80	No	
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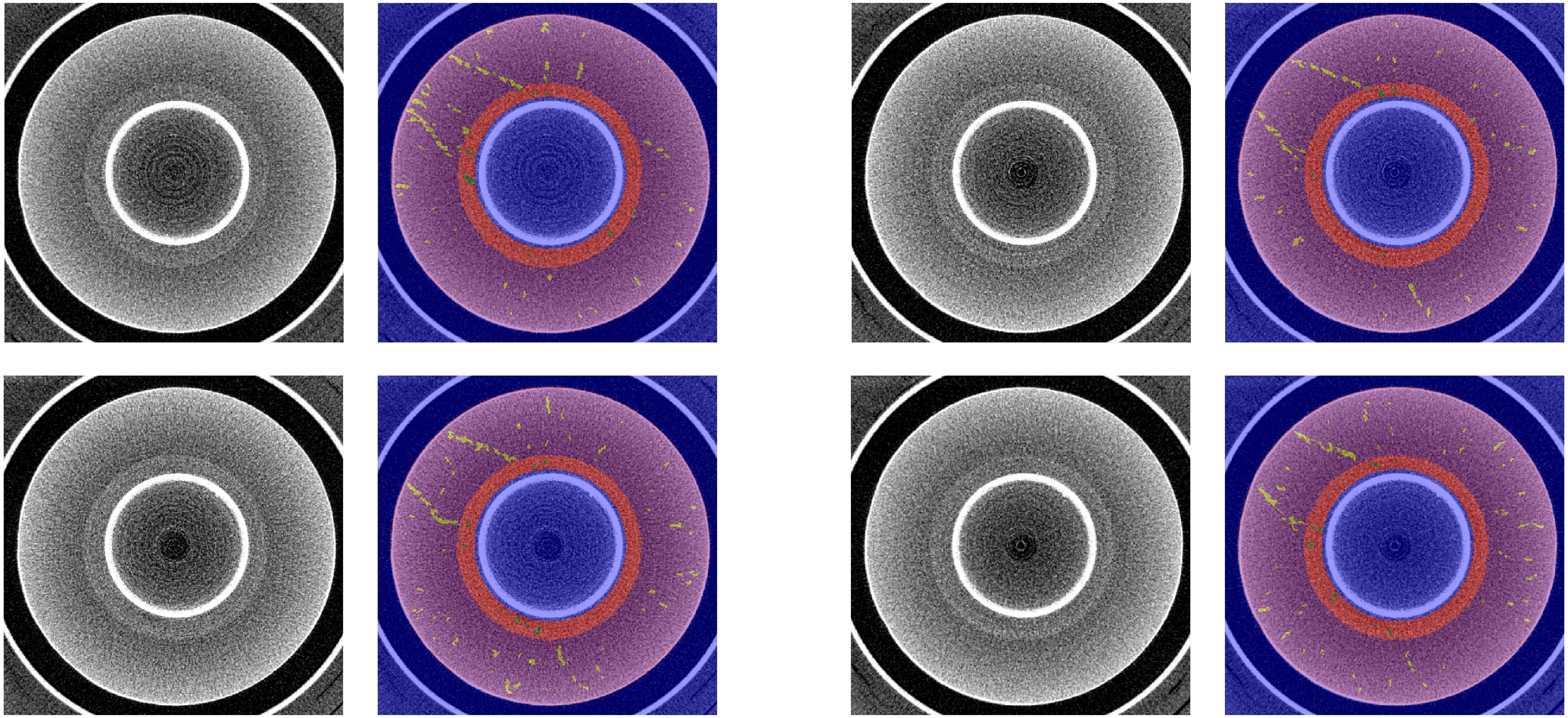
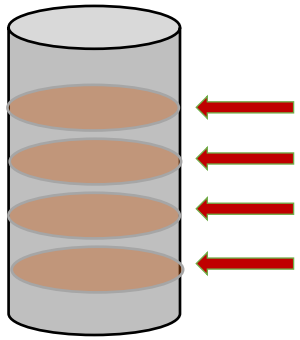
R15	350	85	No	6
R16	400	85	No	6
R17	450	85	No	6
R18	450	65	Yes	6
R19	450	65	Yes	6
R20	456	65	Yes	219



Results

R18 P_c=450, P_{sl}=65, P_{pore}=50



Run #	P_c [bar]	P_{sl} [bar]	Frac	X-ray image [min]
R...	50	80	No	
...	...	80	No	
R14	300	85	No	6
R15	350	85	No	6
R16	400	85	No	6
R17	450	85	No	6
R18	450	65	Yes	6
R19	450	65	Yes	6
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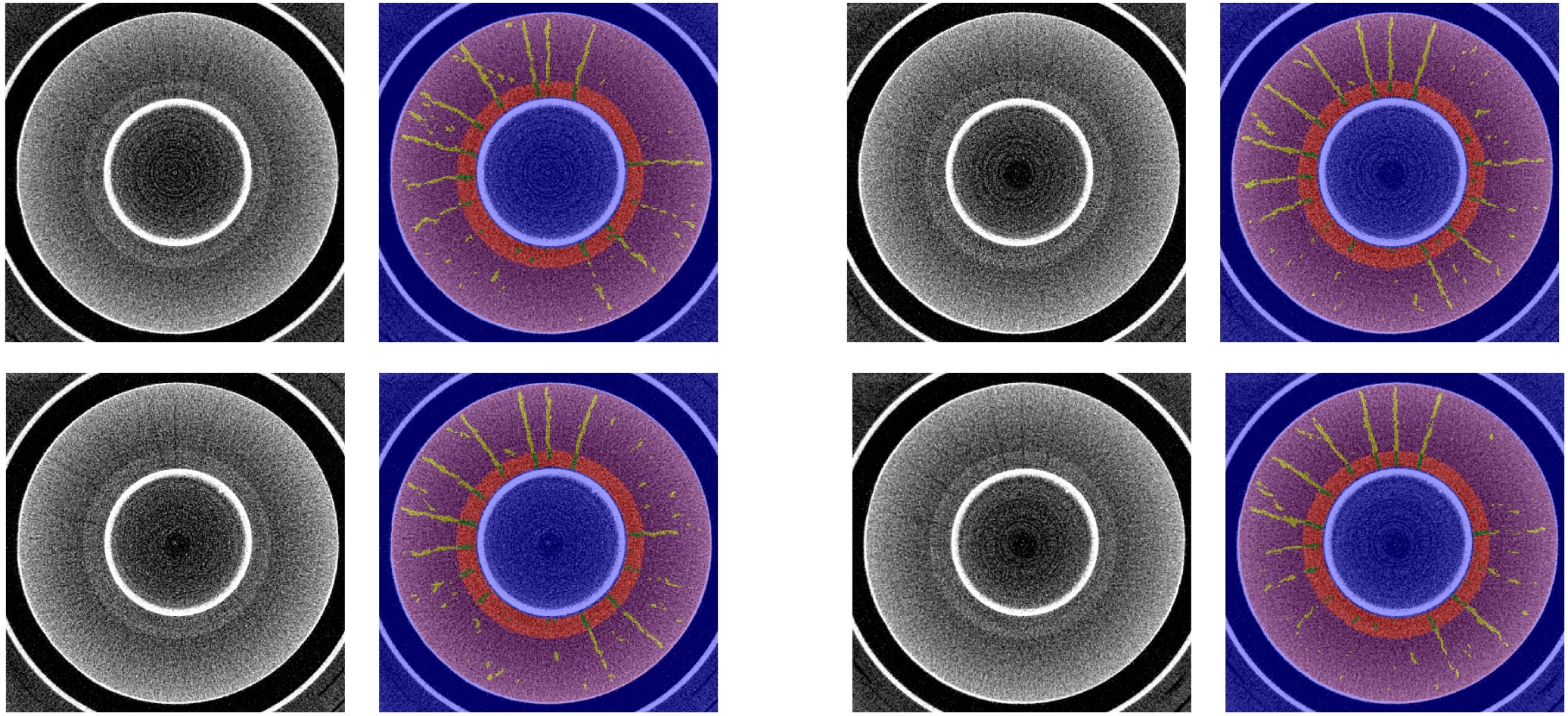
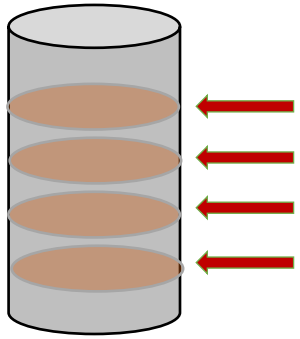


Results

R19 P_c=450, P_{sl}=65, P_{pore}=50



Run #	P_c [bar]	P_{sl} [bar]	Frac	X-ray image [min]
R...	50	80	No	
...	...	80	No	
R14	300	85	No	6
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R18	450	65	Yes	6
R19	450	65	Yes	6
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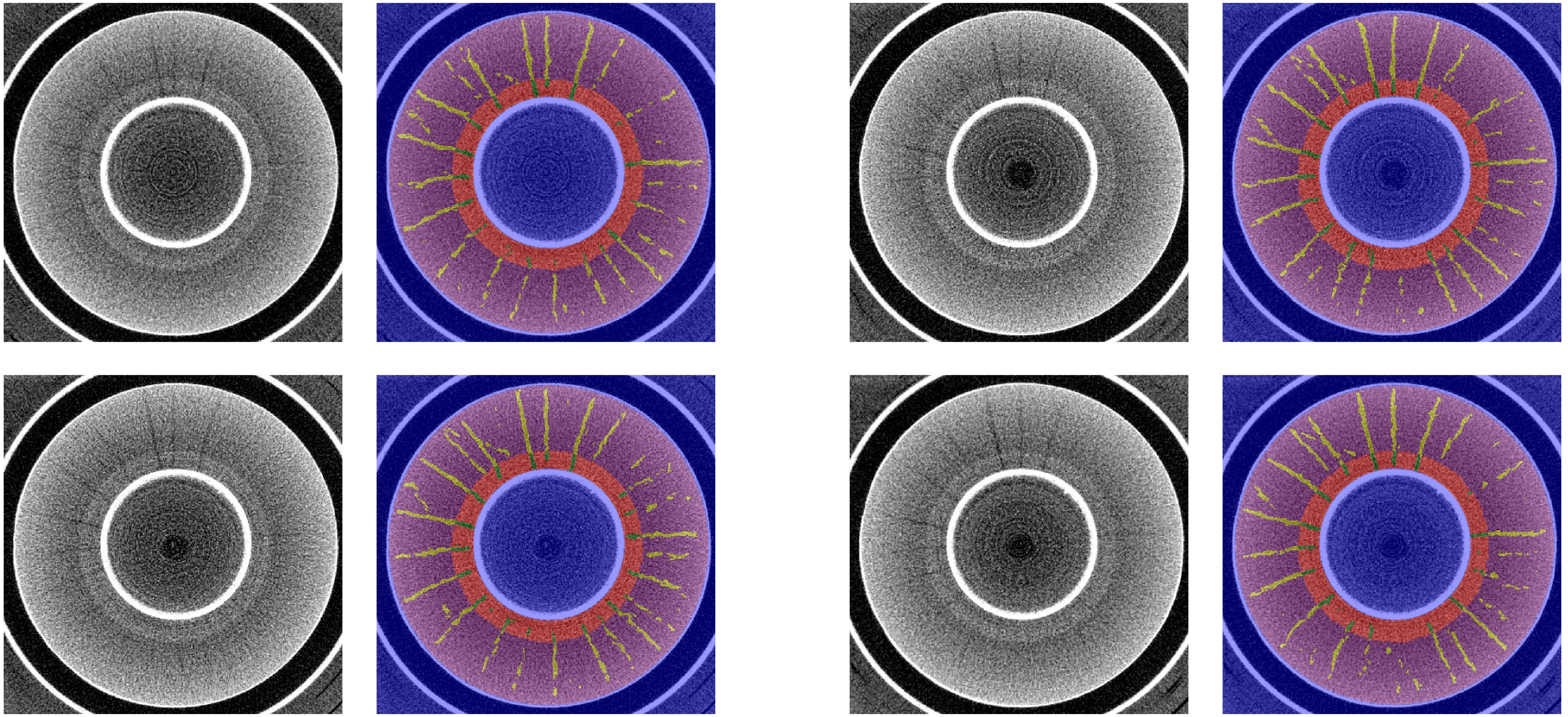
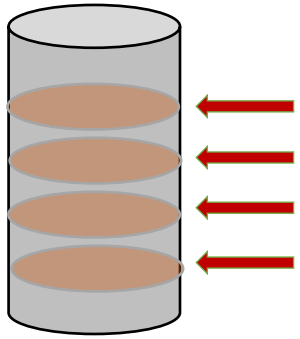


Results

R20 P_c=456, P_{sl}=65, P_{pore}=50



Run #	P_c [bar]	P_{sl} [bar]	Frac	X-ray image [min]
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R14	300	85	No	6
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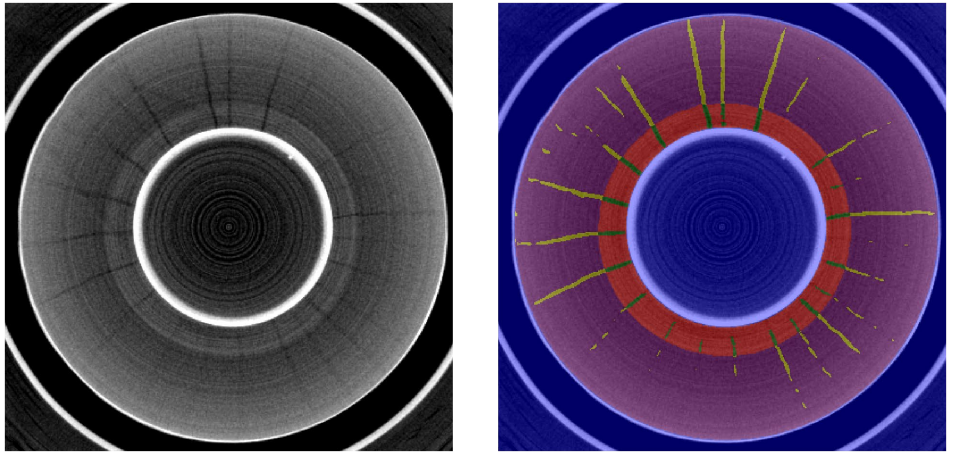
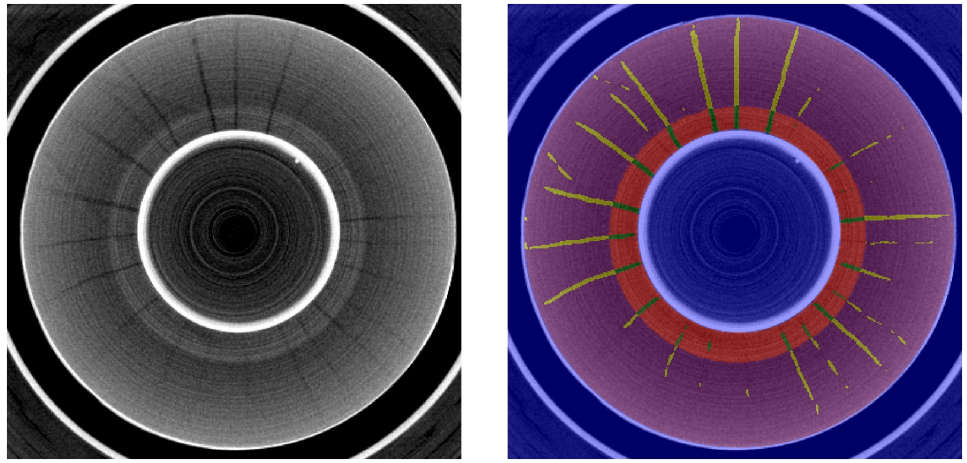
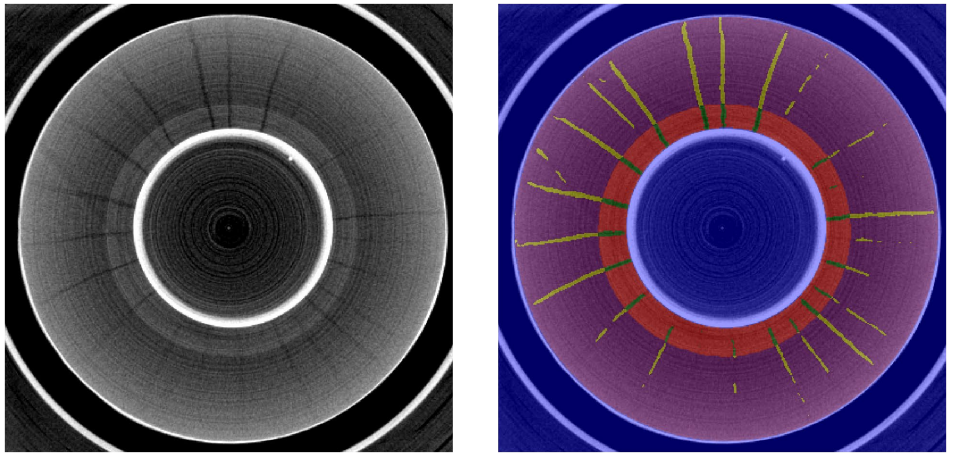
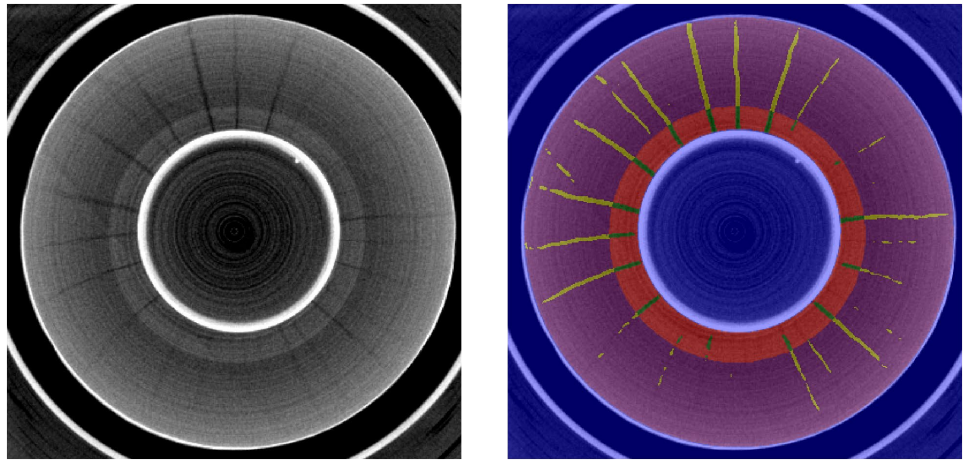
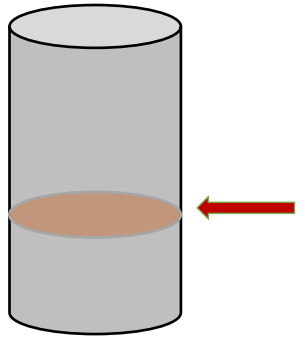


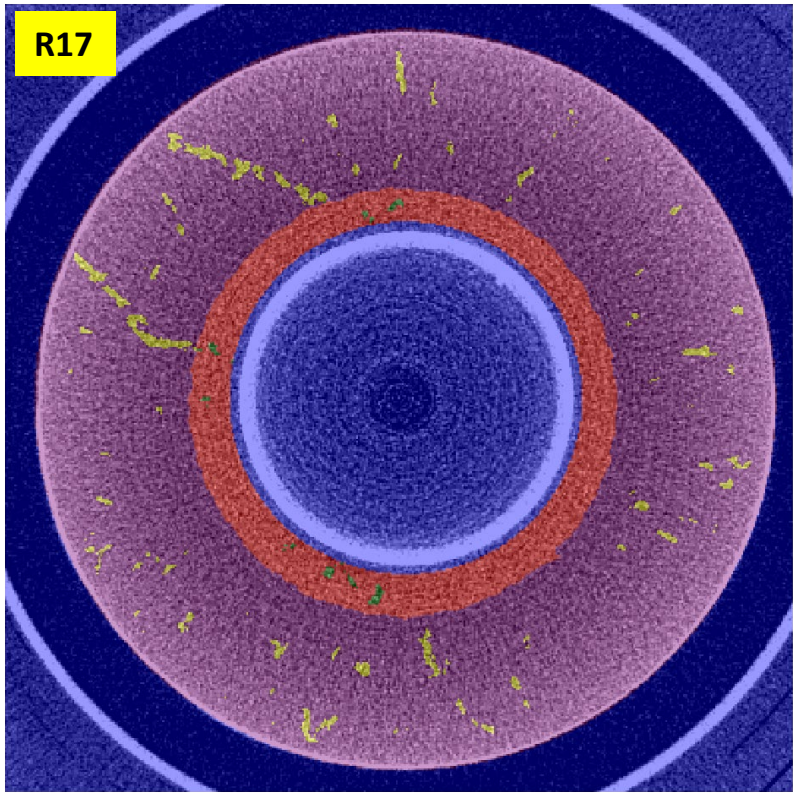






Stages of fracture development





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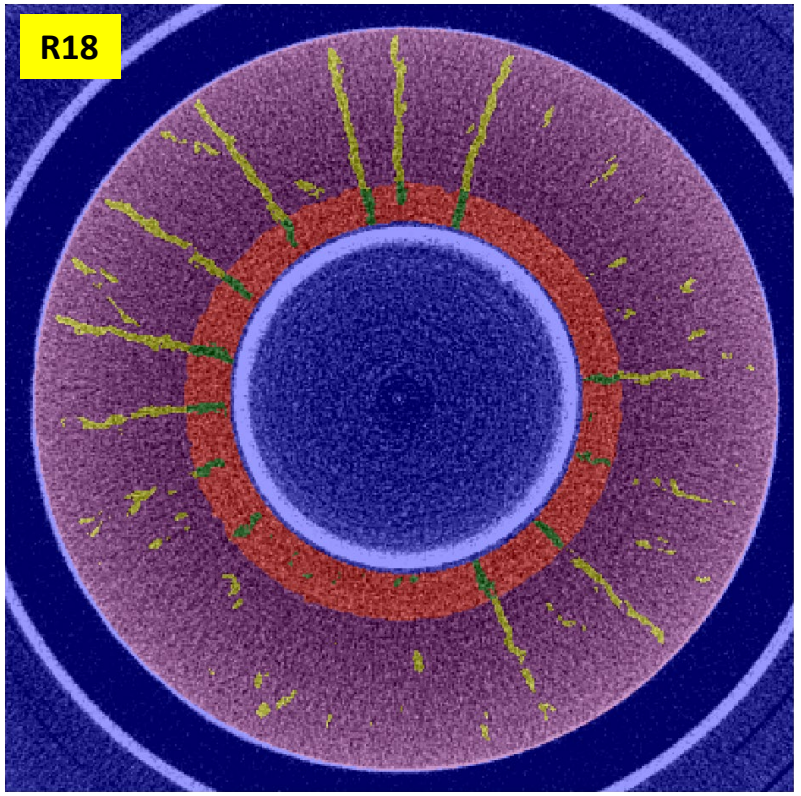

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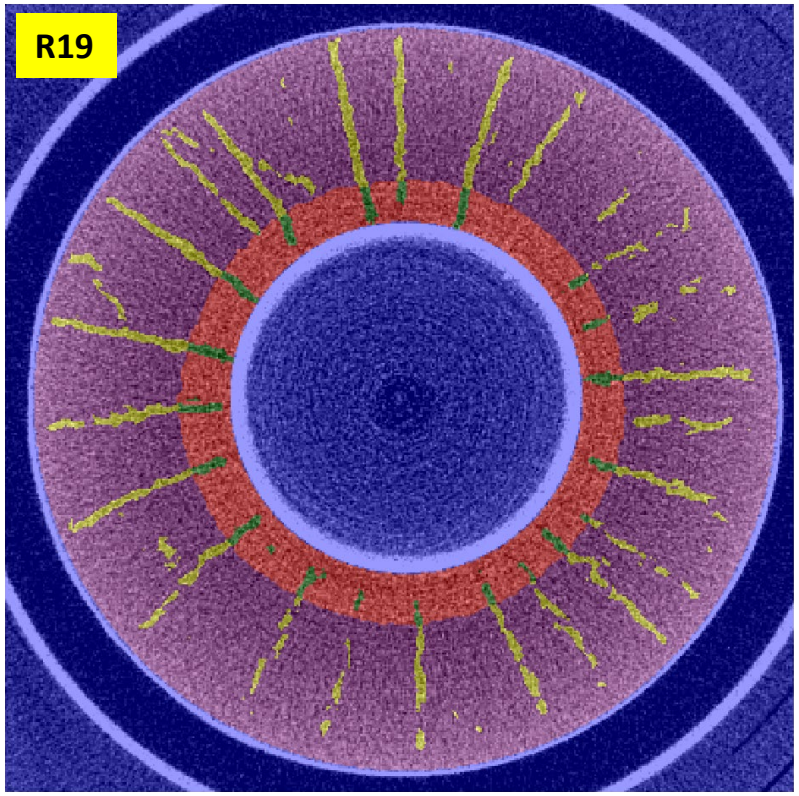
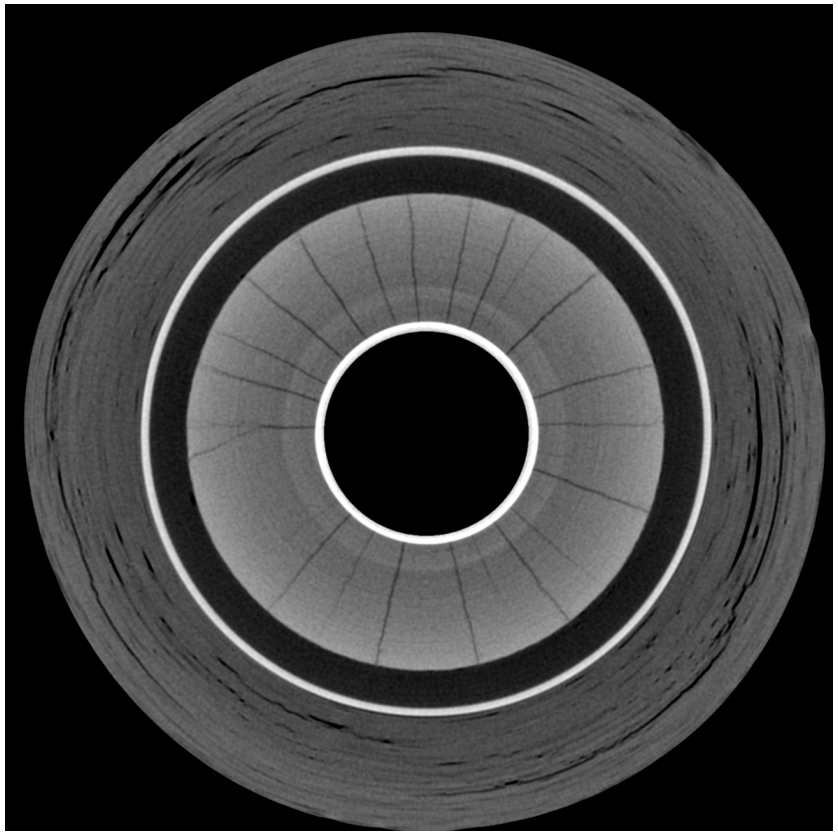
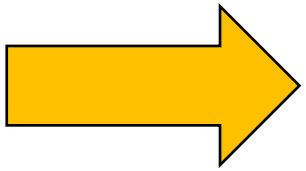


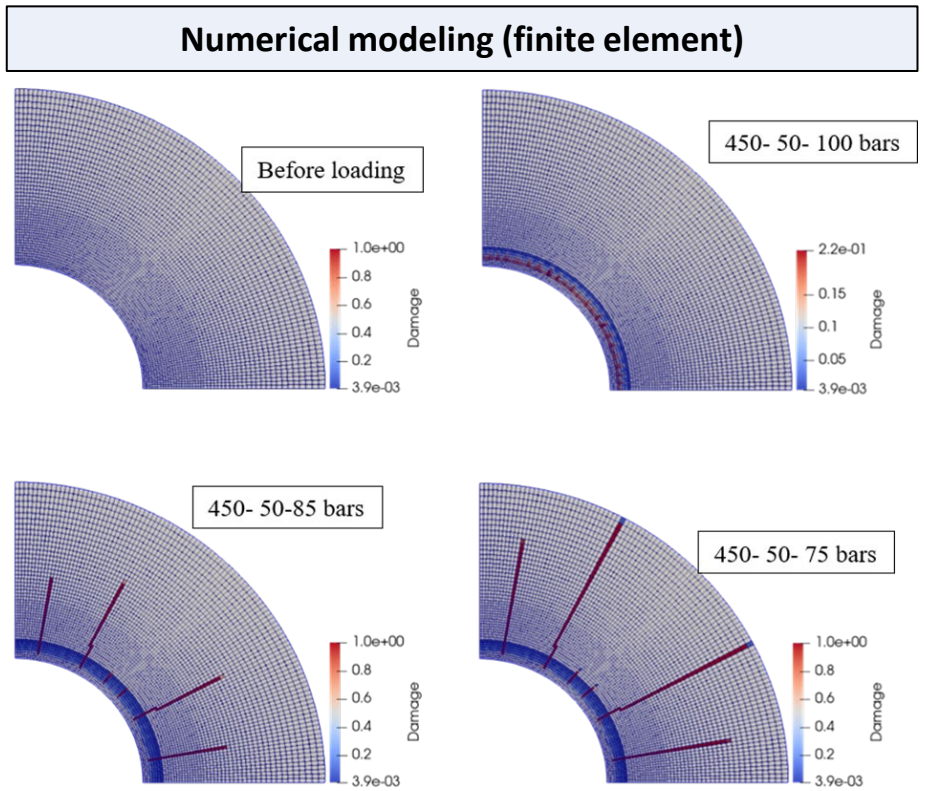
P_c=450, P_{sl}=65, P_{pore}=50

Measurement vs Numerical results

- Comparison with an earlier experiment







Evolution of the radial cracks under P_c=450 casing, P_{pore}=50 and different confinement pressures P_{sl}=0, 75, 85, 100 bars

Remediation

Polyfluoroacrylate (PFA) polymer as P&A agents

Context:

- Viscosification of CO_2 for Mobility Control

- High solubility in CO_2
- Is the only known high molecular weight (Mw>200 000) polymer that can dissolve in dense-CO_2 above 1 wt.%

Remediation

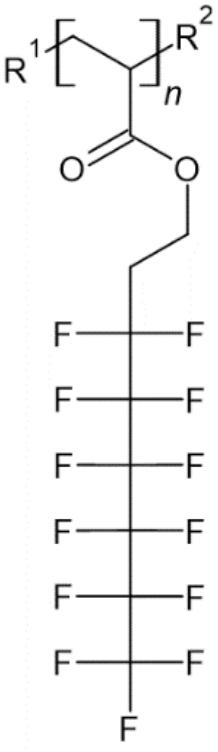
Polyfluoroacrylate (PFA) polymer as P&A agents

Context:

- Viscosification of CO_2 for Mobility Control

Characteristics:

- Completely Amorphous
- Elastic
- Extremely sticky
- Water repellent
- Oil repellent
- CO_2 soluble



Hydrolysis – Perfluorohexanoic acid (PFHXA) more benign than perfluorooctanoic acid (PFOA)

Remediation

Polyfluoroacrylate (PFA) polymer as P&A agents

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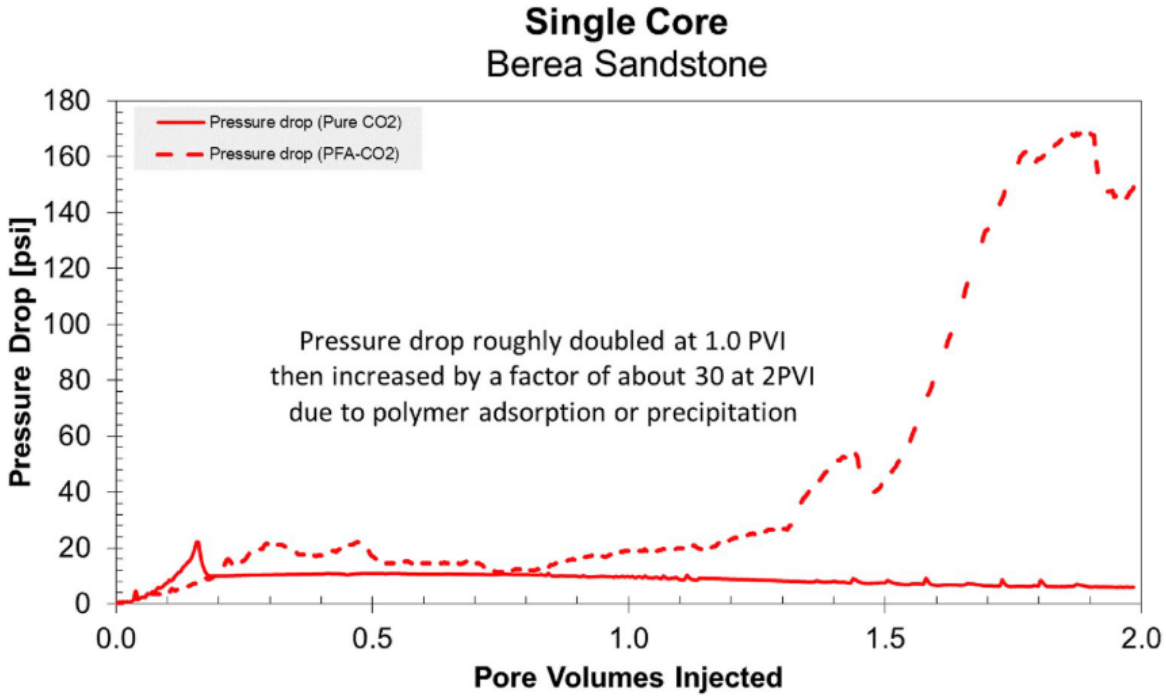

From Zaberi et al. 2020

- PFA 1 wt.% in CO_2,
- q = 0.25 ml/min, 3000 PSI (206.8 bar) at 25°C
- Core = 31 mD Berea sandstone

Remediation

Question 1

Could PFA-CO_2 solutions have a potential use for near-wellbore conformance control?

Question 2

How PFA-CO2 mixtures will behave on cement-cement cracks?

Remediation

Question 1

Could PFA-CO_2 solutions have a potential use for near-wellbore conformance control?

Question 2

How PFA-CO2 mixtures will behave on cement-cement cracks?

Remediation

Answer:

- 3 cement samples
  - ½ inch diameter
  - Ca. 80 mm length
  - Split longitudinally in two parts
  - Fractured in several pieces
- PFA/CO_2 4.0 wt.%

Remediation

Answer:

- 3 cement samples
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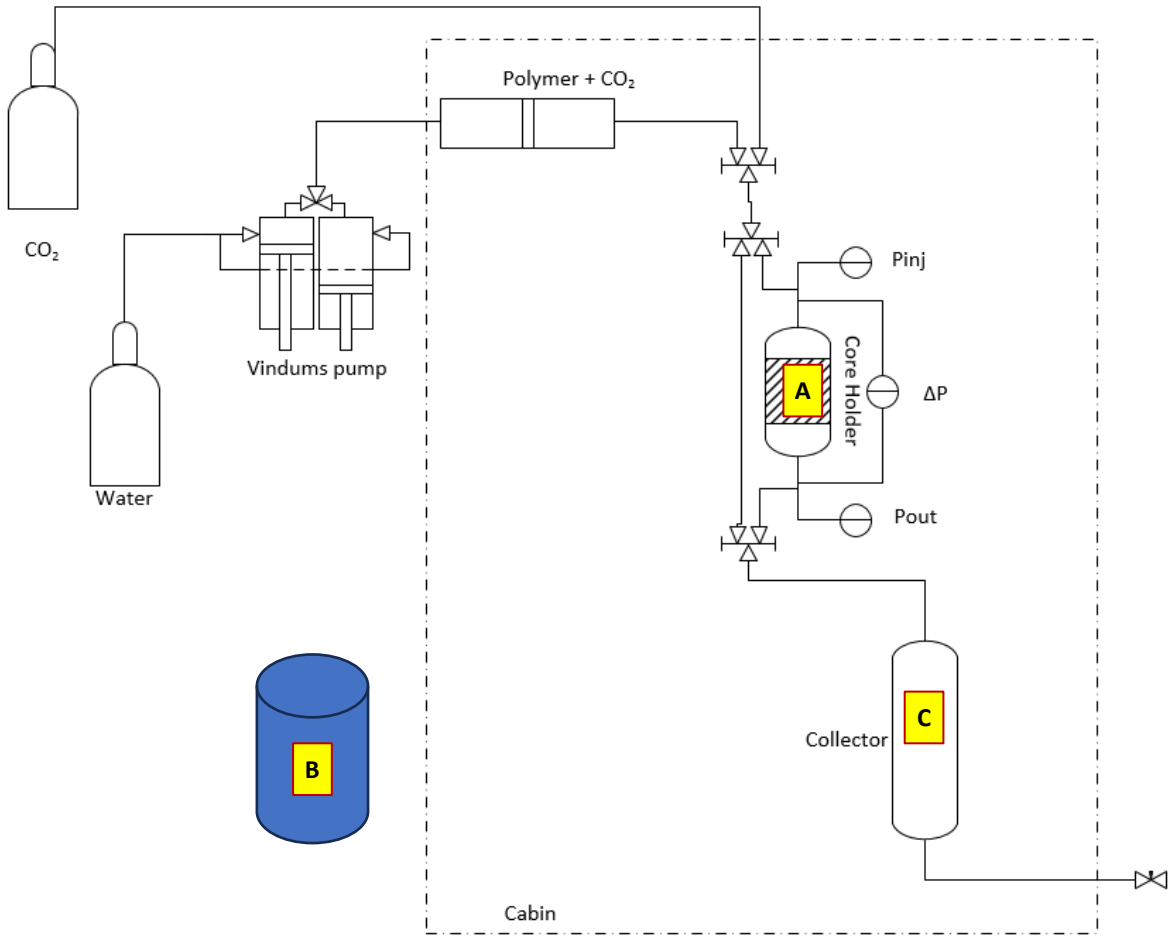
Mini-experiment



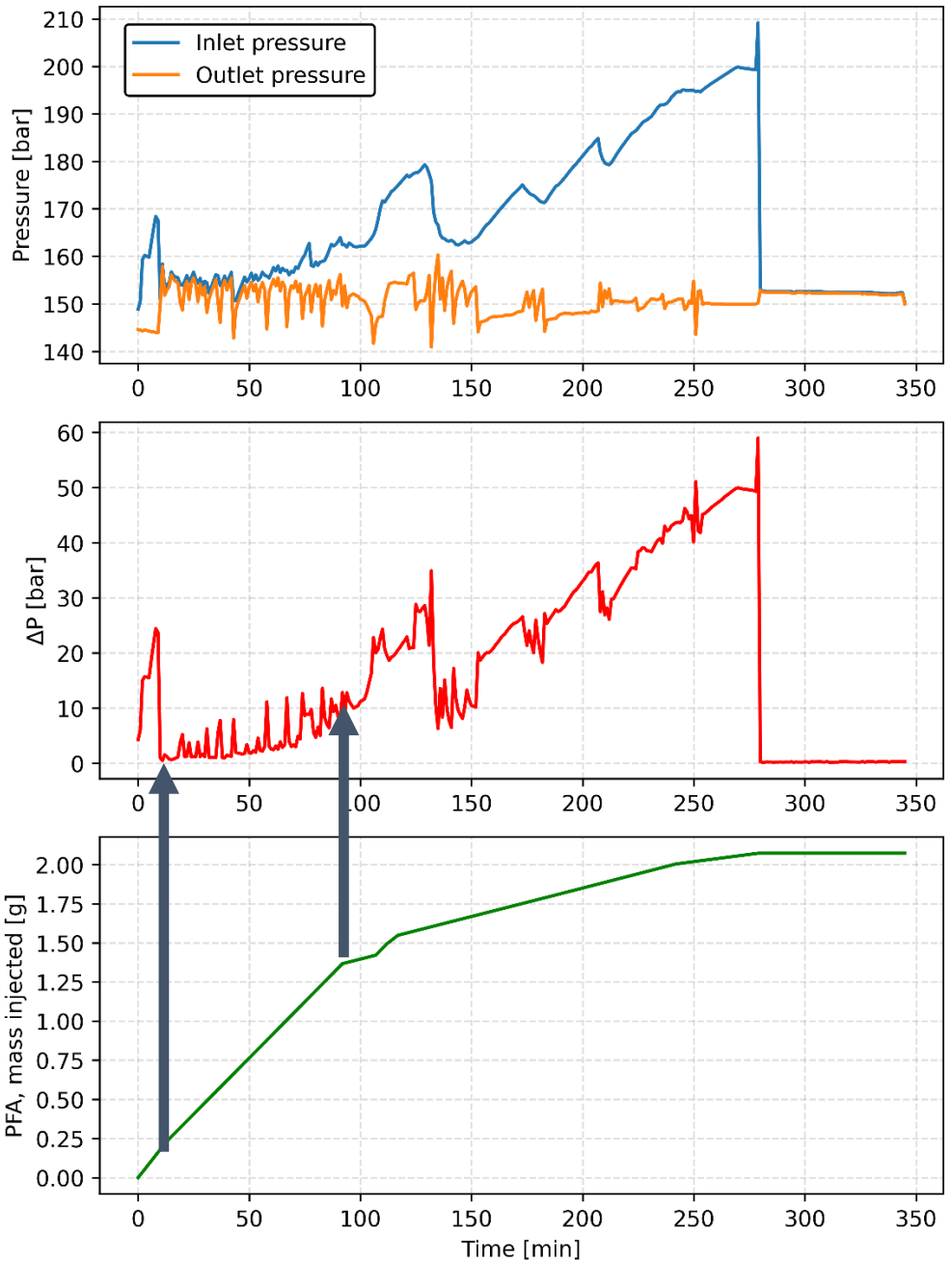
- **Sample A:**
- **Sample C: Placed in the collector**
- **Sample B: Placed in a bottle, submerged in PFA/CO_2 mixture (24h)**

Remediation

Answer:

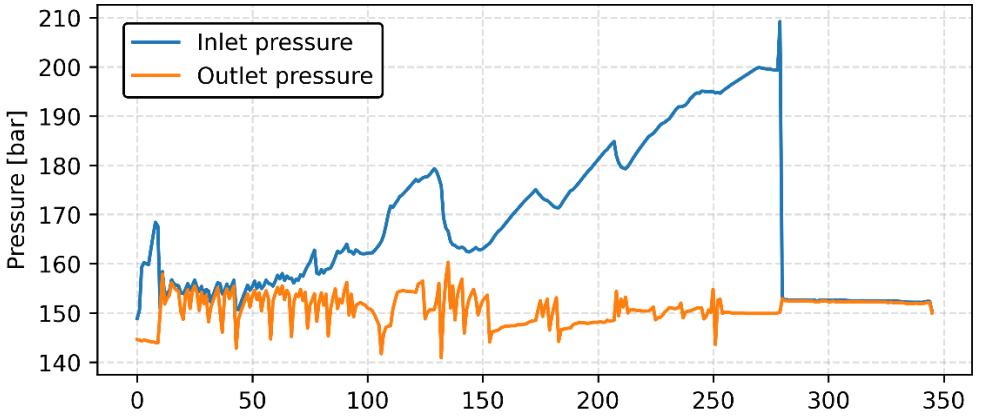
Sample A: Flooding results

- All the pieces of cement were easily separated, without evidence of PFA adsorbed on the surfaces
- How was the flow through the core blocked? Where is the PFA?
- Wettability tests with distilled water
  - PFA did clearly adsorb onto the cement surface in some zones of the surface area



Remediation

Answer:



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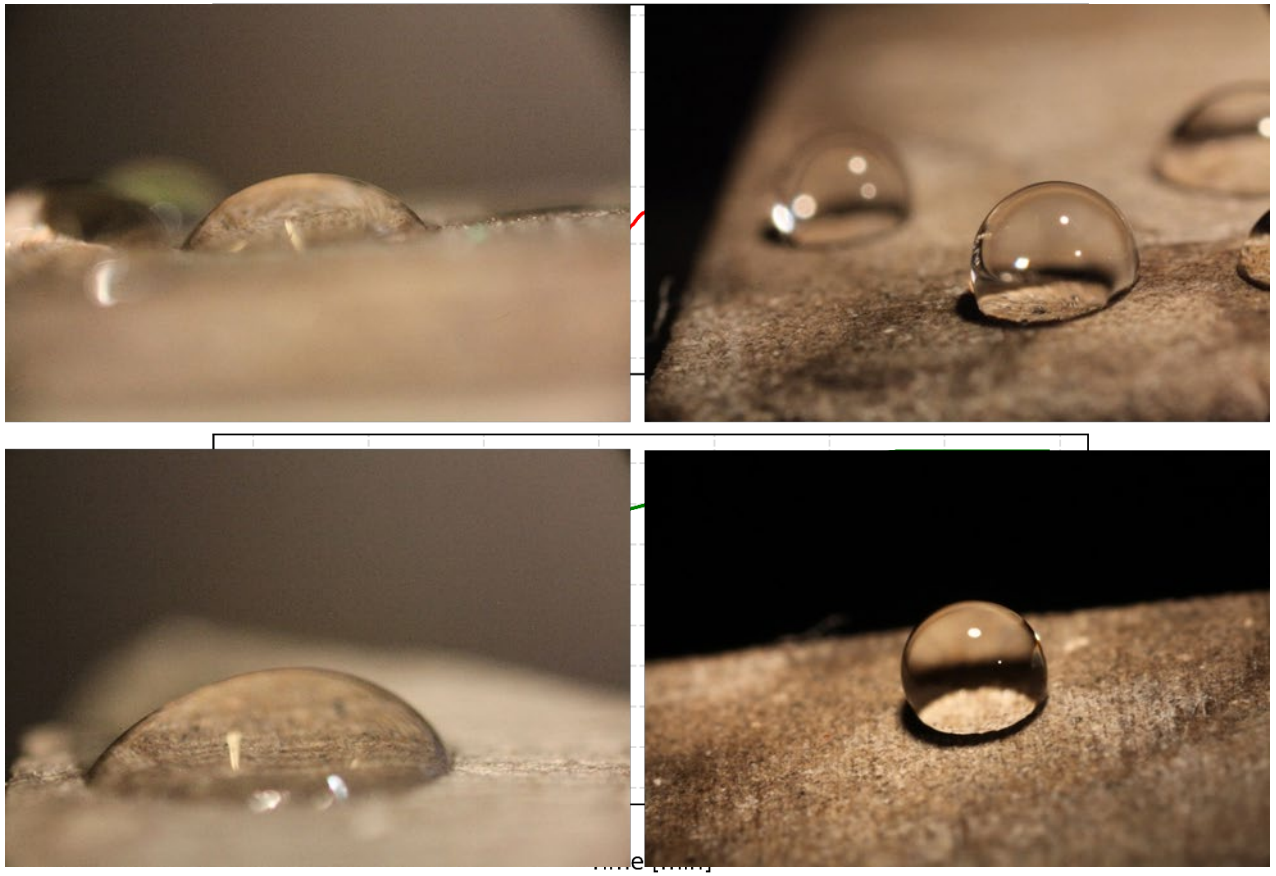
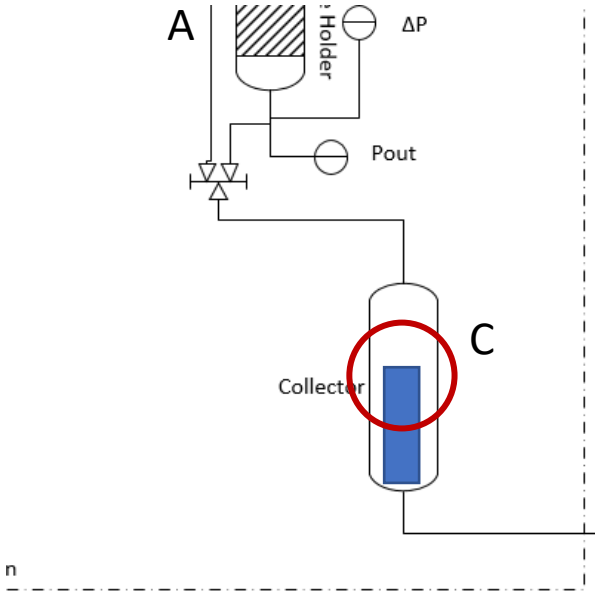


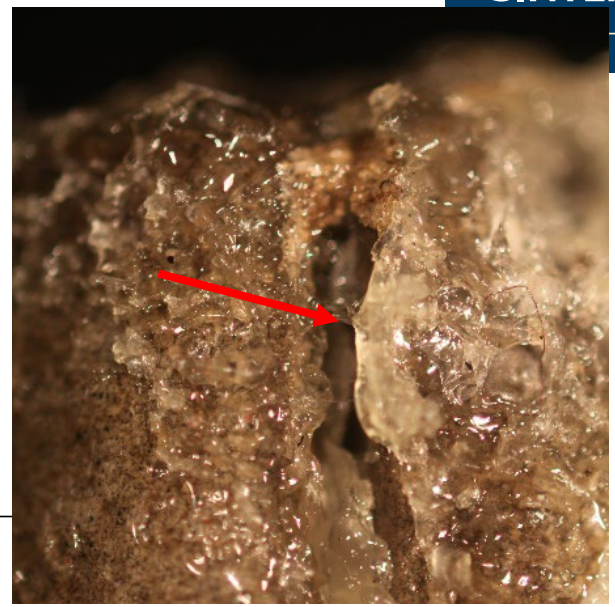
Remediation

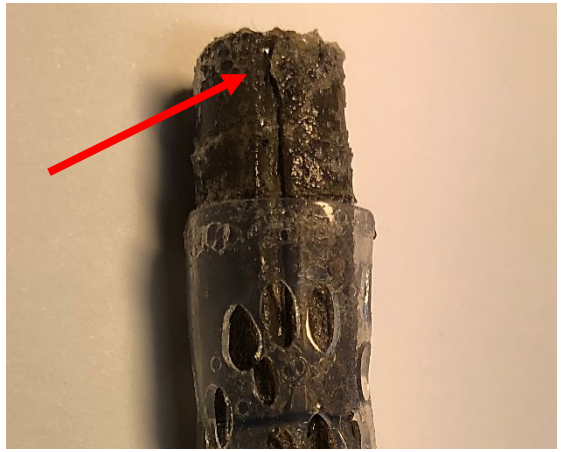
Answer:

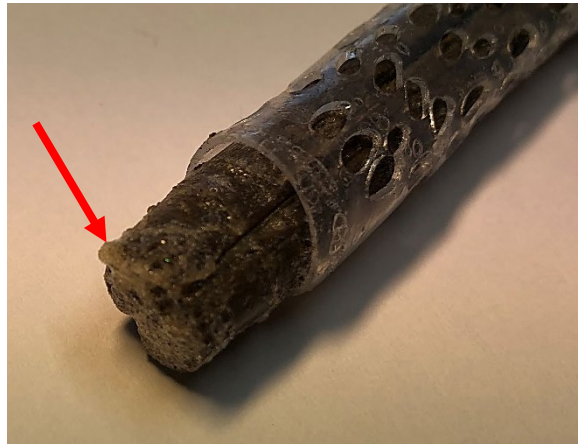
Sample C: In collector

- PFA on the inner walls of the collector
- Marked in red is the area showed in the pictures
- PFA identified









Remediation

Answer:

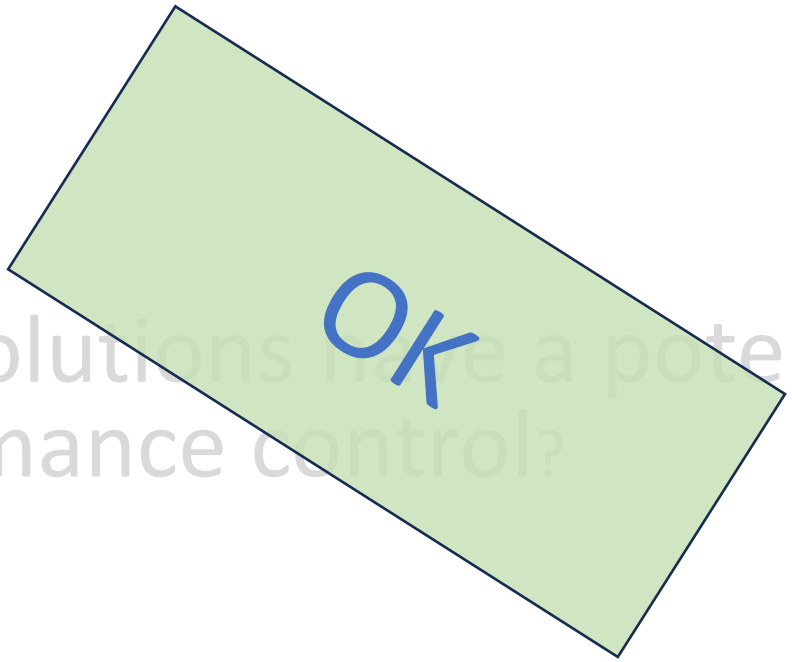
Sample B: Submerged

- The crack volume was not fully occupied by the PFA.
- Instead, PFA "spiderweb" structures were seen within the crack

Remediation

Question 1

Could PFA-CO_2 solutions have a potential use for near-wellbore conformance control?

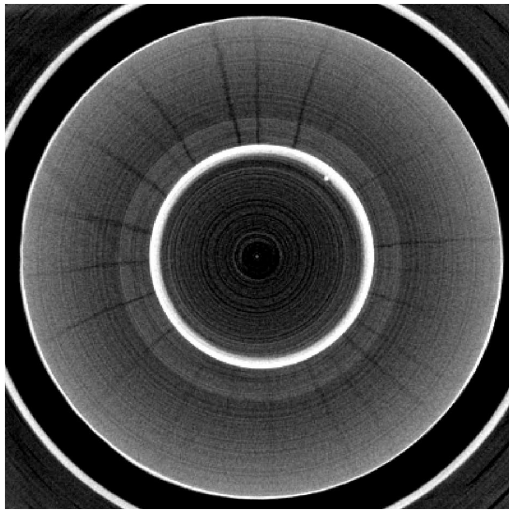


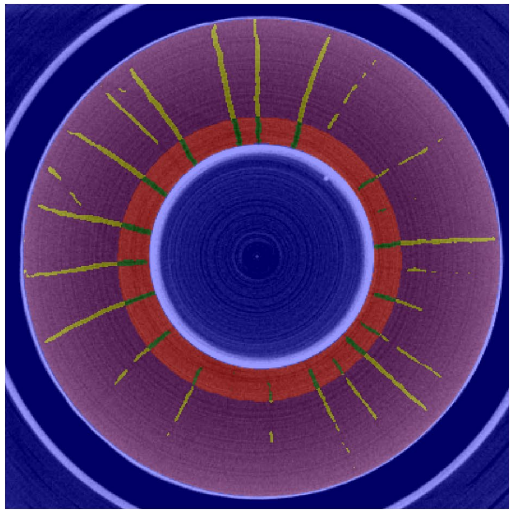
Question 2

How PFA-CO2 mixtures will behave on cement-cement cracks?

Remediation – Well Integrity Setup

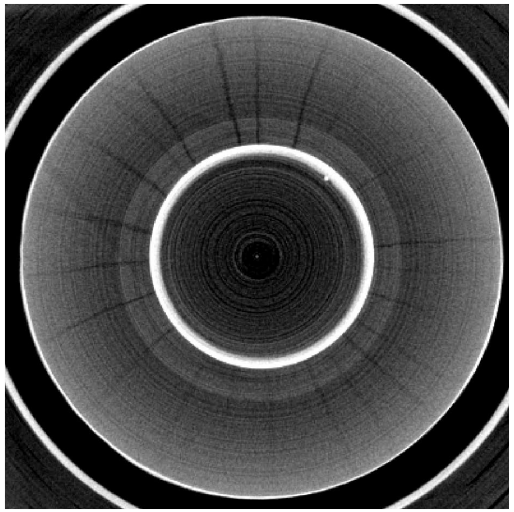
- **Procedure (at field conditions):**
  - The fractured core was flooded with brine
  - Permeability determination
  - Injection (pre-flush) of 0.2 PV of CO_2
  - Injection of 1 PV of 4wt.% PFA in CO_2
  - Core closed. Aged for 65 h
  - Permeability determination with brine

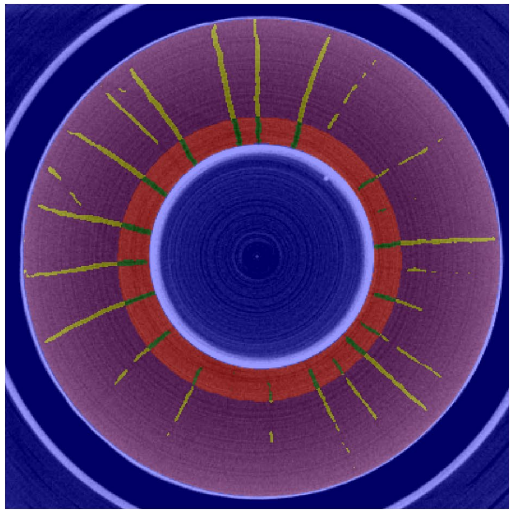




Remediation – Well Integrity Setup

- **Procedure (at field conditions):**
  - The fractured core was flooded with brine
  - Permeability determination
  - Injection (pre-flush) of 0.2 PV of CO_2
  - Injection of 1 PV of 4wt.% PFA in CO_2
  - Core closed. Aged for 65 h
  - Permeability determination with brine





- **Results**
  - 1PV PFA/CO_2 4wt.% mixture decreased systems permeability from 0.99 D to 0.27 D → 73% reduction
  - PFA observed adsorbed in all spaces/surfaces:
    - Rock-rock, cement-rock, cement-cement, cement-casing.

Meas.	Information	P_{sleeve} [bar]	$P_{process}$ [bar]	T[°C]	Perm [Darcy]
1	Before flooding	55.65	Atm	22.1	1.12
2	Before flooding	85.41	Atm	22.1	0.87
3	Before flooding	85.07	5.25	22.1	1.05
4	Before flooding	55.09	7.61	22.1	1.01
5	Before flooding	152.15	106.31	22.1	0.99
6	After PFA/CO_2	150.25	106.05	22.1	0.27

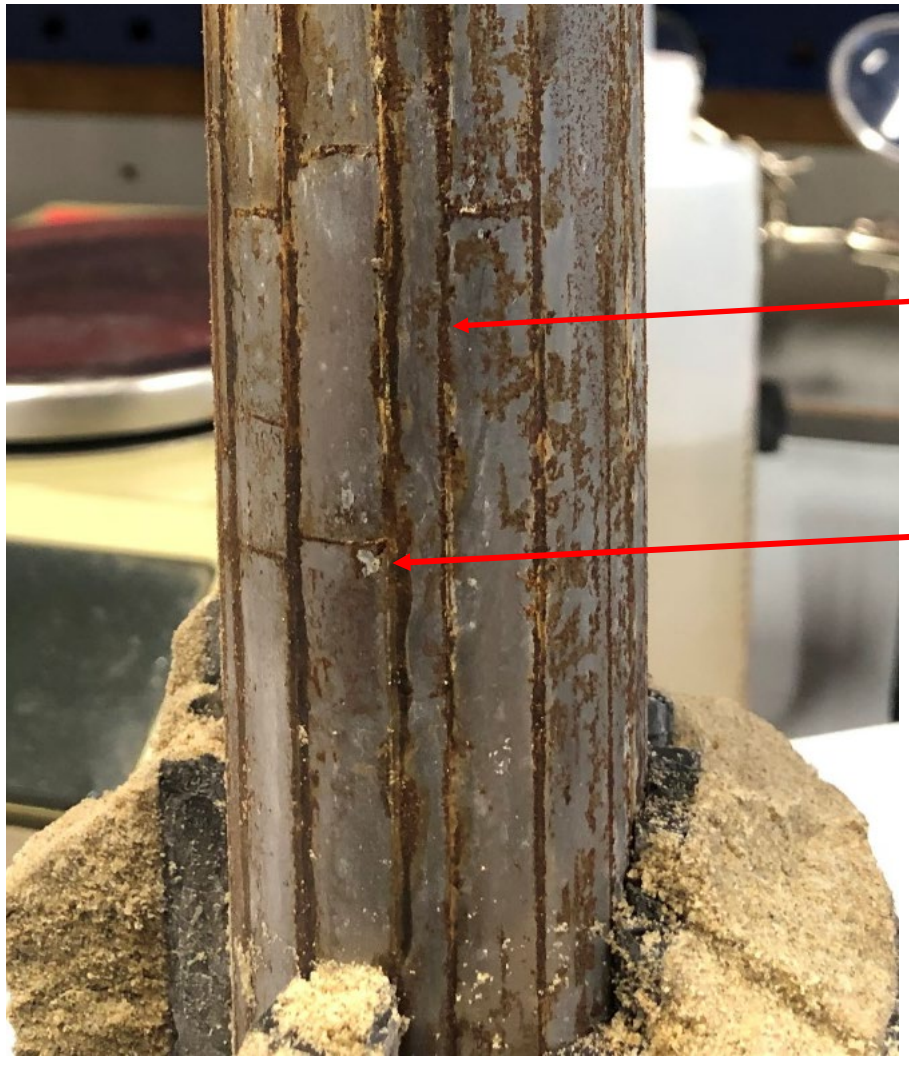
Remediation – closer examination

PFA

Remediation – closer examination

Casing initial state

Casing removed



Remediation

Question 1

Could PFA-CO_2 solutions have a potential use for near-wellbore conformance control?

OK

Question 2

How PFA-CO2 mixtures will behave on cement-cement cracks?

OK

Summary

- A robust experimental setup for studying near wellbore integrity is capable of replicating field conditions
  - The setup integrates in-situ capabilites with simultanous X-ray imaging
- Cement integrity failure and its remediation was investigated in a series of tests relevant to field condition
- Remediation with CO_2-PFA mixture:
  - Observations suggest that the PFA/CO_2 mixture effectively seals pore spaces and interfaces
  - Highlighting its strong potential as a candidate material for P&A applications

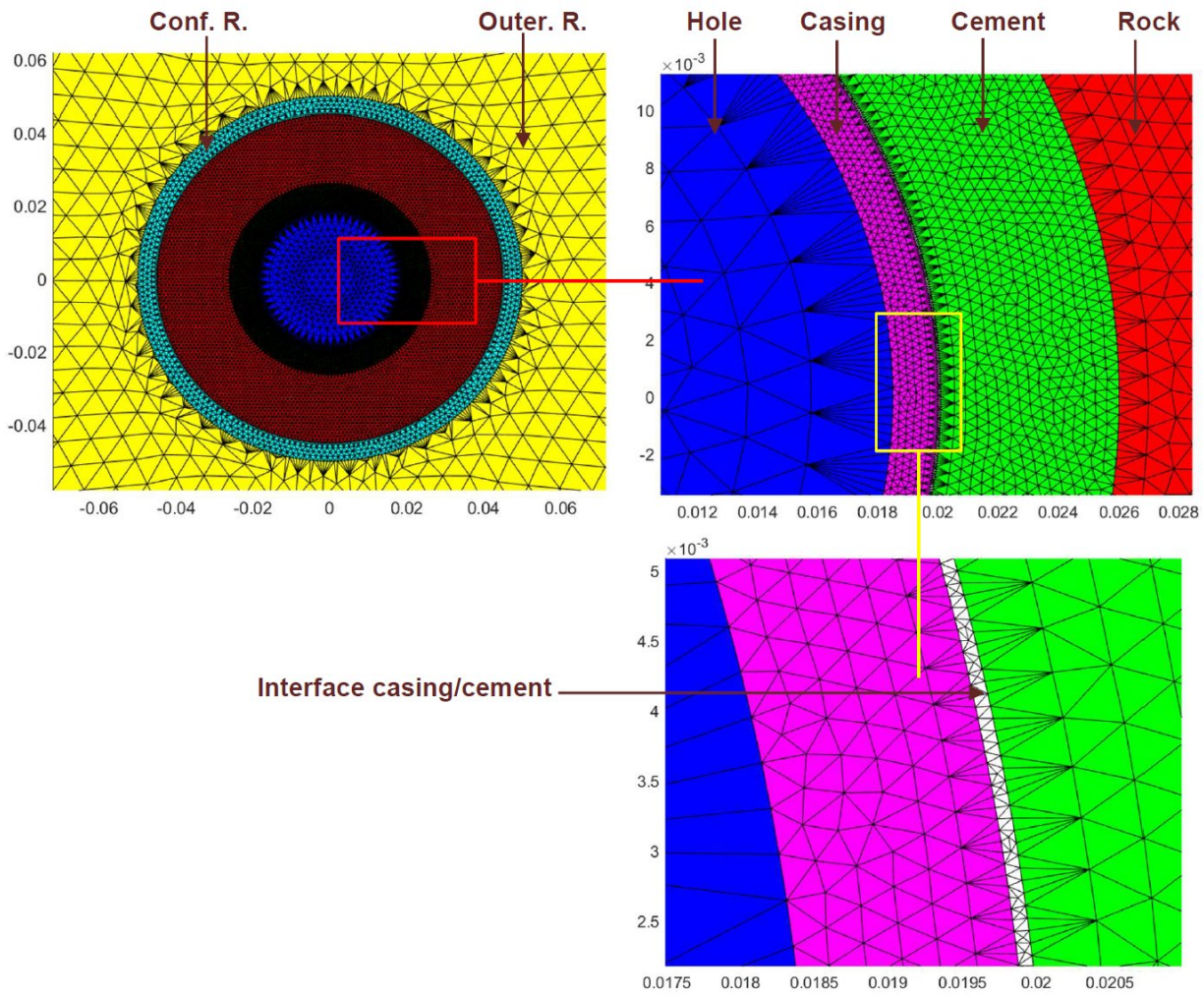
Relevant questions

Modeling

- Robust geomechanical model for the lab experiments
- Upscaling to field scale

Remediation

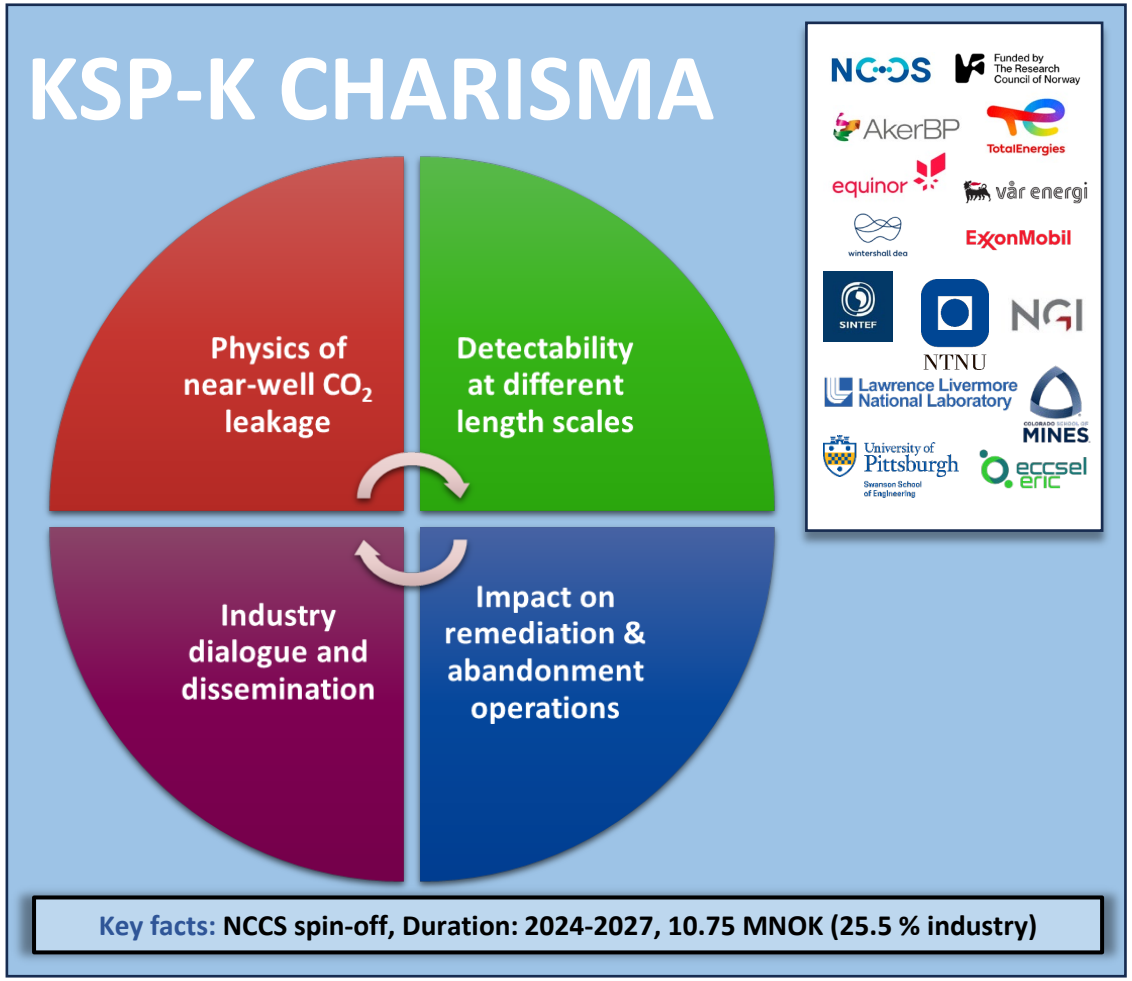
- Possible benchmarking with altenative remediation strategies
  - Self healing cement
  - CO_2-fracture healing



Outlook

Continued Study in Relevant Projects

- NFR Funded KSP Project: CHARISMA
  - *CHARacterization and 4D Imaging of near well CO_2 flow in fractureS and Micro-Annuli*
- **Further Instrumentation**
  - Well Integrity setup with fiber optics
- **Knowledge transfer to near wellbore monitoring**
  - Cement and formation properties before and after integrity failure (e.g., changes in Young's modulus, anisotropy, etc.)
  - Quantifications of borehole wavefield response



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Thank you