In-situ visualization of microbial hydrogen consumption using high-resolution PET-MRI

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The efficiency of short- and long-term underground hydrogen storage UHS in subsurface porous media is one of the limiting technical challenges facing the renewable energy industry. The stored H2 is one of the most important electron donors for many subsurface microbial processes, e.g., microbialinduced sulphate reduction and methanogenesis, which can convert H2 to H2S and CH4, causing permanent gas loss and H2 contamination. Therefore, understanding the microbial H2 metabolisms is essential for estimating the storage and withdrawal efficiency in UHS and improving the selection criteria for future storage sites.

A halophilic sulfate-reducing stain was used as the model bacterium to quantitatively assess the consumption of H2 in in 6 cm x 1.5 cm sand and glass bead packs. The bacterium can utilize H2 as electron donor and sulfate as electron acceptor producing H2S, for growth. Besides, the high accumulation of bacteria can form biofilms and cause pore-clogging. In this study, state-of-the art visualization techniques were utilized to study hydrogen consumption and bacteria growth in 6 cm x 1.5 cm sand and glass bead packs. A multi-modal magnetic resonance imaging (MRI)-positron emission tomography (PET) scanner was used to study both static and dynamic phenomena, respectively. Sand and glass bead packs were saturated with bacteria solution (a sulphate-reducer oleidesulfovibrio alaskensis), both without and in the presence of hydrogen.

The whole experiment was conducted under anaerobic conditions for the bacteria to survive and grow. In-situ visualization provided insight into the dynamics of bacterial growth and hydrogen consumption rates: MRI provided information on the spatial fluid saturation at micrometer scale. PET provided fluid displacement dynamics during injection. of brine, nutrients and bacteria at high temporal resolutions. We, hence, observed bacterial growth and fluid flow redistribution at resolutions not previously used to study these phenomena at the core scale.

In-situ visualization of microbial hydrogen consumption in a porous medium using high-resolution PET-MRI

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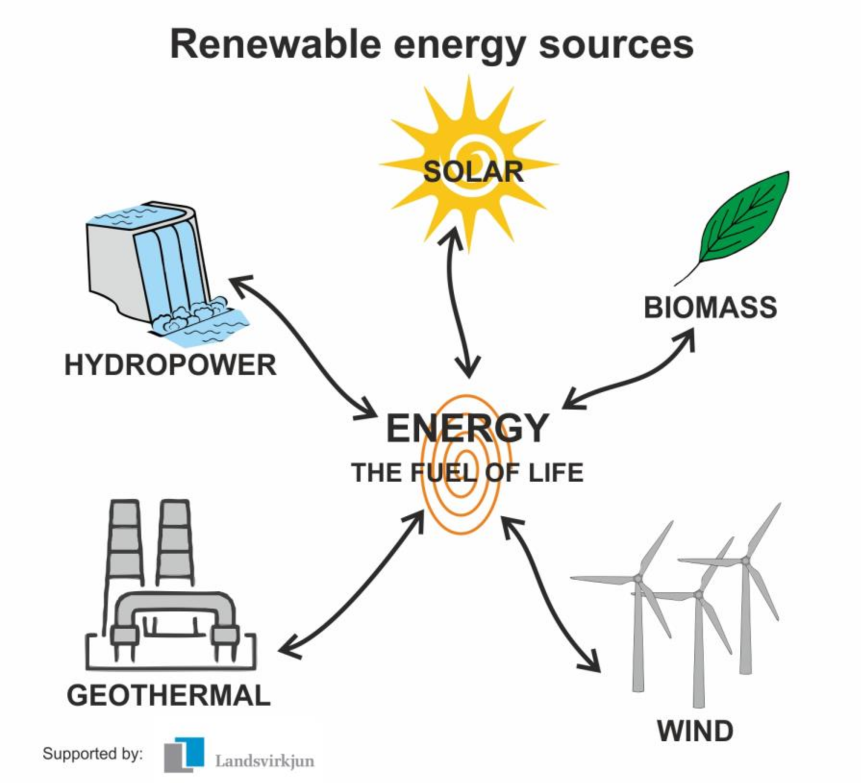
Presentation outline

The presentation looks at experimental results for hydrogen storage in the porous medium and will cover:

1. General overview of the role played by hydrogen in the energy transition
2. PET-MRI general theory
3. Experimental set up parameters (still ongoing)
4. MRI results (static)
5. PET results (dynamic)
6. Conclusions

Energy transition

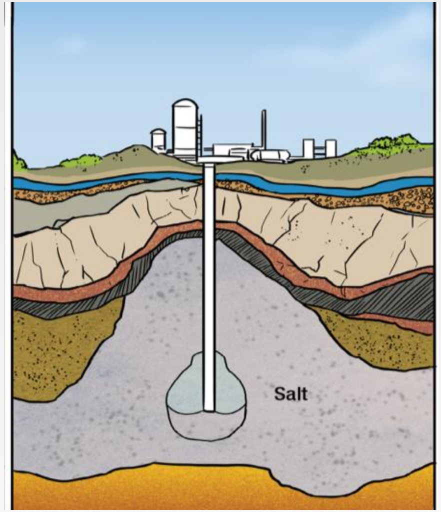


- Growing need to transition to renewable energy sources due to global warming and its adverse effects
- Wind power and solar power the leading sources for green energy
- Limited by their unreliability due to intermittent/changing weather patterns
- Hydrogen offers an alternative energy storage option
- Hydrogen storage in aquifers and depleted hydrocarbon reservoirs

Energy transition

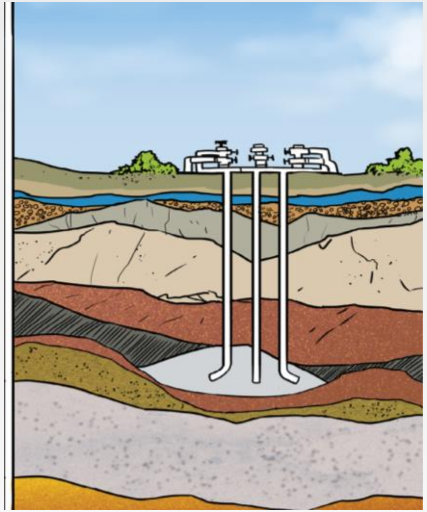
Why hydrogen storage in porous media?

- Enormous volumes and well distributed worldwide



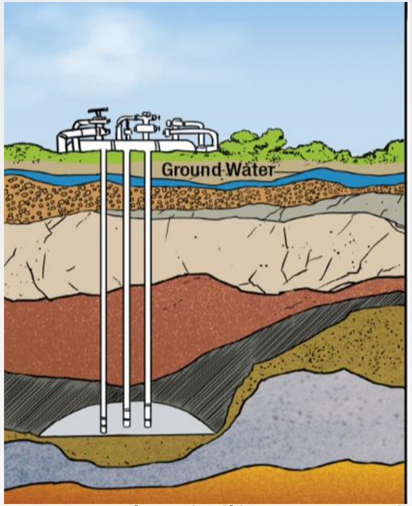
Salt Caverns

Fig.1. a) Salt caverns have been considered as a more feasible and flexible solution for pure hydrogen storage.



Aquifers

Fig.1. b) Natural aquifers may be suitable for natural gas storage but have not been proven to trap gas and must be developed.



Depleted oil/gas reservoirs

Fig.1. c) Depleted oil and gas reservoirs might be the most commonly used underground storage sites because of their wide availability and existing infrastructure.

Sources: https://www.energyinfrastructure.org/energy-101/natural-gas-storage

PET: Positron emission tomography

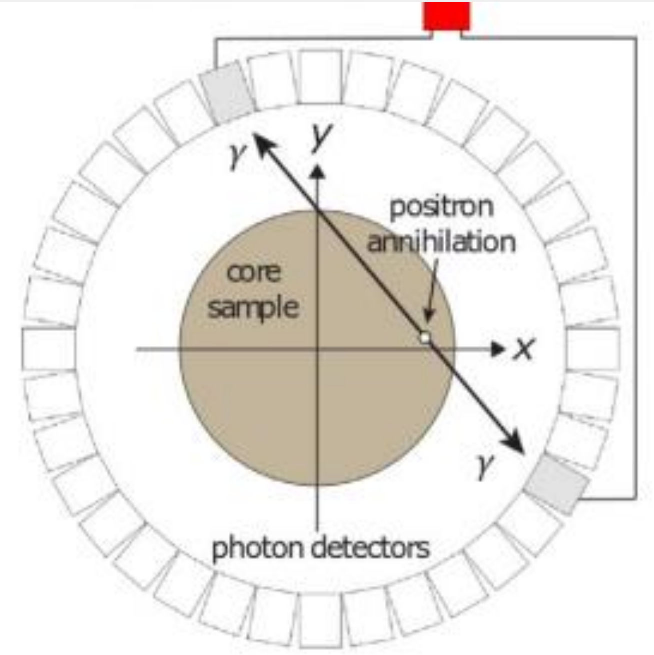


Fig.2. Illustration of fundamental physics behind PET imaging Zahansky et.al. 2019

- PET is sensitive to positrons emitted by radioactive decay process of positron-emitting radionuclides
- Such radionuclides are normally added to a phase of interest to enhance signal detection.
  - Fluorodeoxyglucose (18F-FDG) was added to the water phase.
- As the emitted positrons travel through the surrounding material , they lose momentum and are eventually annihilated by free electrons.
- For every annihilated positron, two photons of 511 keV are emitted in opposite directions conserving momentum.
- Annihilation events are detected by a group of evenly distributed inorganic scintillator crystals.
- This makes it possible to make statistical maps for the annihilation events, form which we can derive explicit measurements such as saturation

MRI: Magnetic resonance imaging

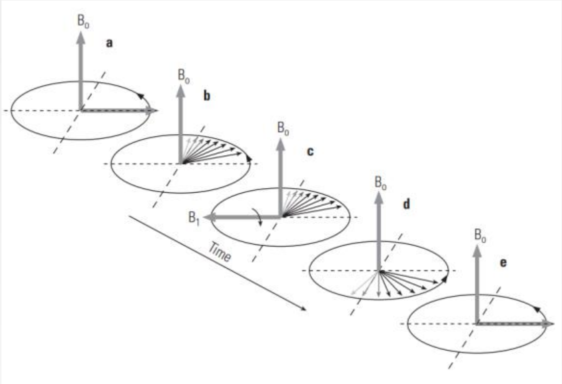


Fig.3. Proton spin dephasing and rephasing during MRI imaging Ellis, D. V et.al (2007)

- MRI works based on proton spins that are realigned when introduced to a strong magnetic
- The slice images obtained during scanning time are T1 and T2 weighted
    - T1 is a longitudinal spin relaxation time constants
    - T2 is spin relation in the transverse plane orthogonal to the applied magnetic field.
- They are both depend on the echo spacing and repetition times of the applied radio frequencies that realign the spins in respective planes relative to direction of the applied external magnetic field

Experimental set up

MRI-PET imaging was conducted on a sand pack composed of relatively well sorted sand grains (450-500 micron)
MRI images consisted of three categories based on the spatial resolutions (voxel size)

- Full sand pack image (low spatial resolution: 0.16 x 2.00 x 0.21 mm)
- Full sand pack (highs partial resolution: 0.12 x 0.6 x 0.23 mm)
- HR region specific (0.07 x 0.6 x 0.07 mm)

Sand pack properties:

- Porosity 40-45 %
- Sand pack length 6cm
- Sand pack diameter 1.5 cm

MRI images were taken under no flow conditions
PET imaging was utilised during flow through the sand pack
PET images with the 18F-FDG dosage in the displacing water phase

Results: Explicit phases

We were able to identify and distinguish between phases.

- Water phase
  - Water component
  - Bacteria/biomass component
- Water and rock
- Hydrogen and rock

- **Criteria**: The higher the concentration of mobile H^+ the brighter the spot on T2 MRI.

Bacteria saturated regions appeared brightest on both grey scale and colour images

The dark regions were rock and the free gas phase (hydrogen)

MRI images of the full sand pack

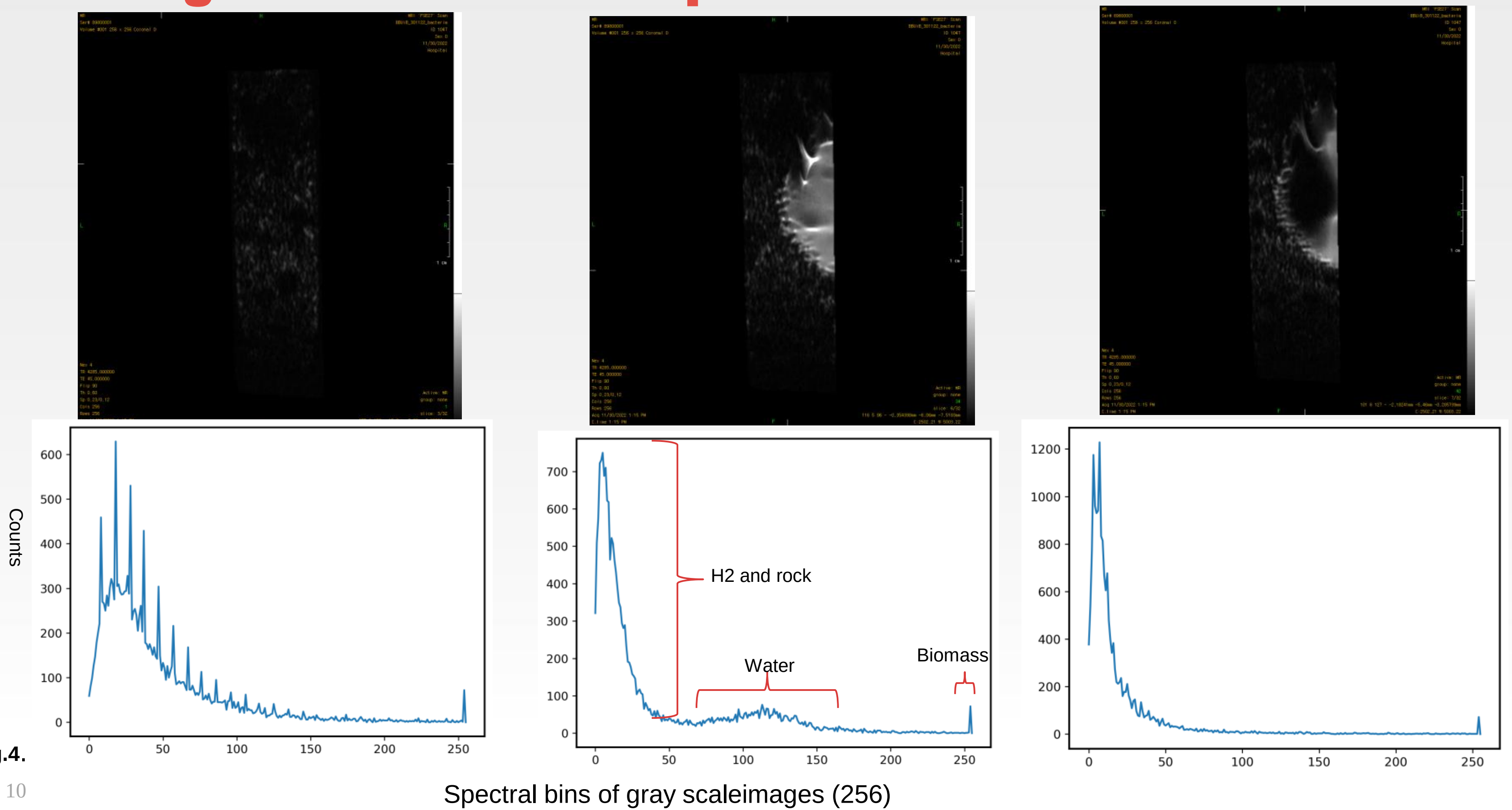


Fig.4.

High resolution MRI Bacteria signal

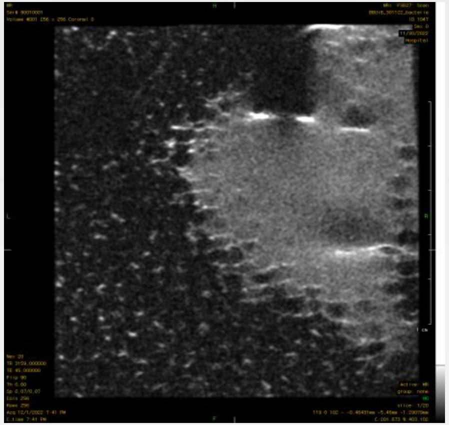
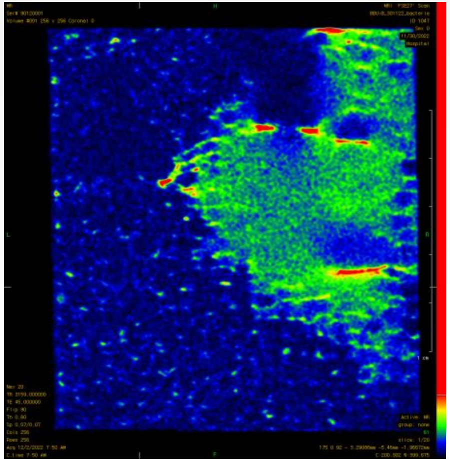
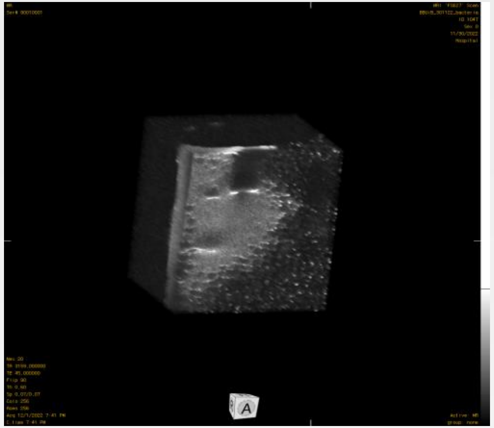


Fig.5. Left: Gray scale (top) and colour (bottom) MRI slice of the HR images depicting bacteria spots as the brightest regions





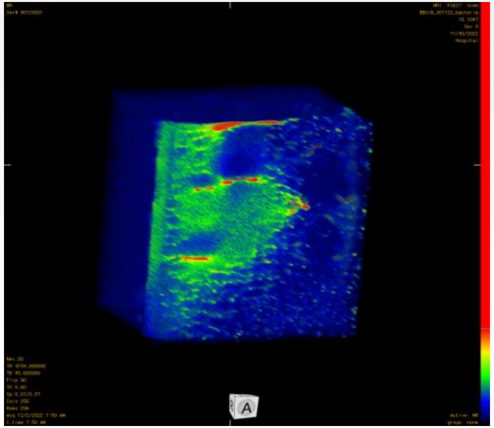


Fig.5. Right: Gray scale (top) and colour (bottom) 3D construction of the 20 slices with voxel size 0.07 x 0.6 x 0.07 mm. Th bright regions covered 2 to 4 slices in thickness in different regions

Biomass accumulation

The brightest regions grew in surface area and volume over time as the hydrogen volume reduced.

The dark region (hydrogen) almost disappeared in a matter of hours in regions contact with the bacteria-saturated brine

The engulfing shape stayed relatively the same over time

0 hours **4 hours** **20 hours**

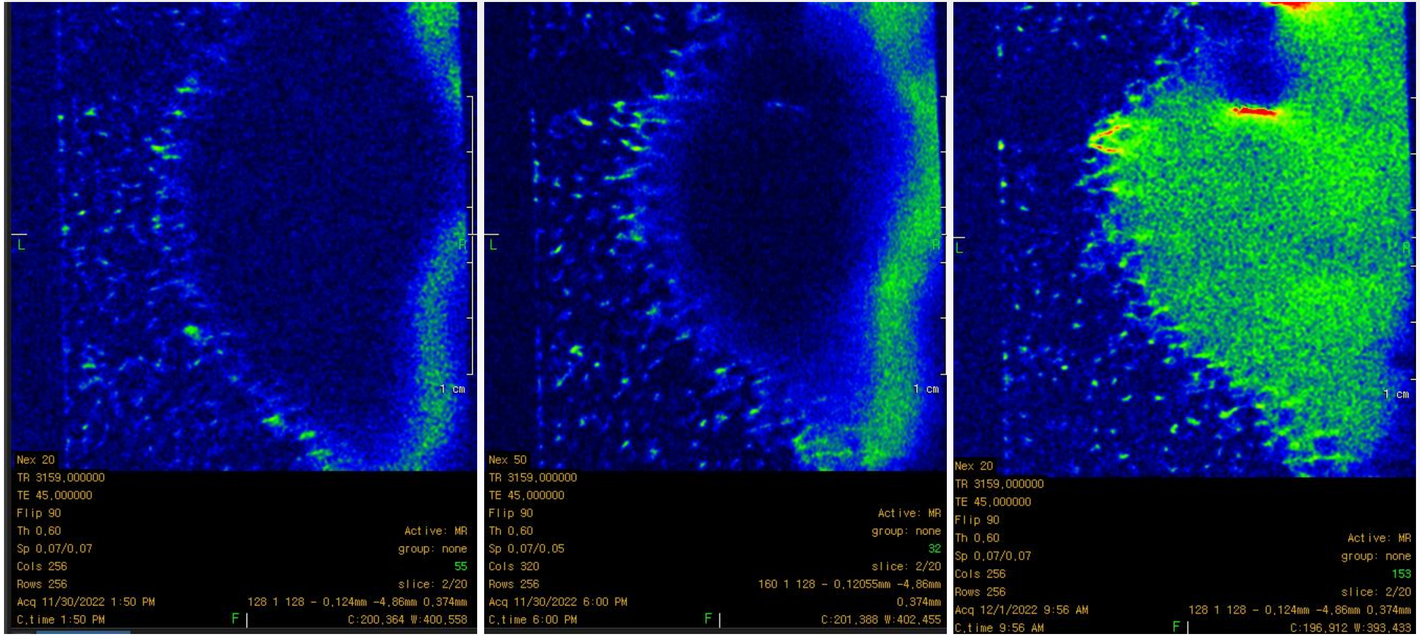


Fig. 6 The bacteria region grew inwards as the hydrogen region reduced in size. Same slice imaged every 24 hours

Biomass growth/accumulation

Growth occurred in a matter of hours

0 hours **20 hours** **42 hours**

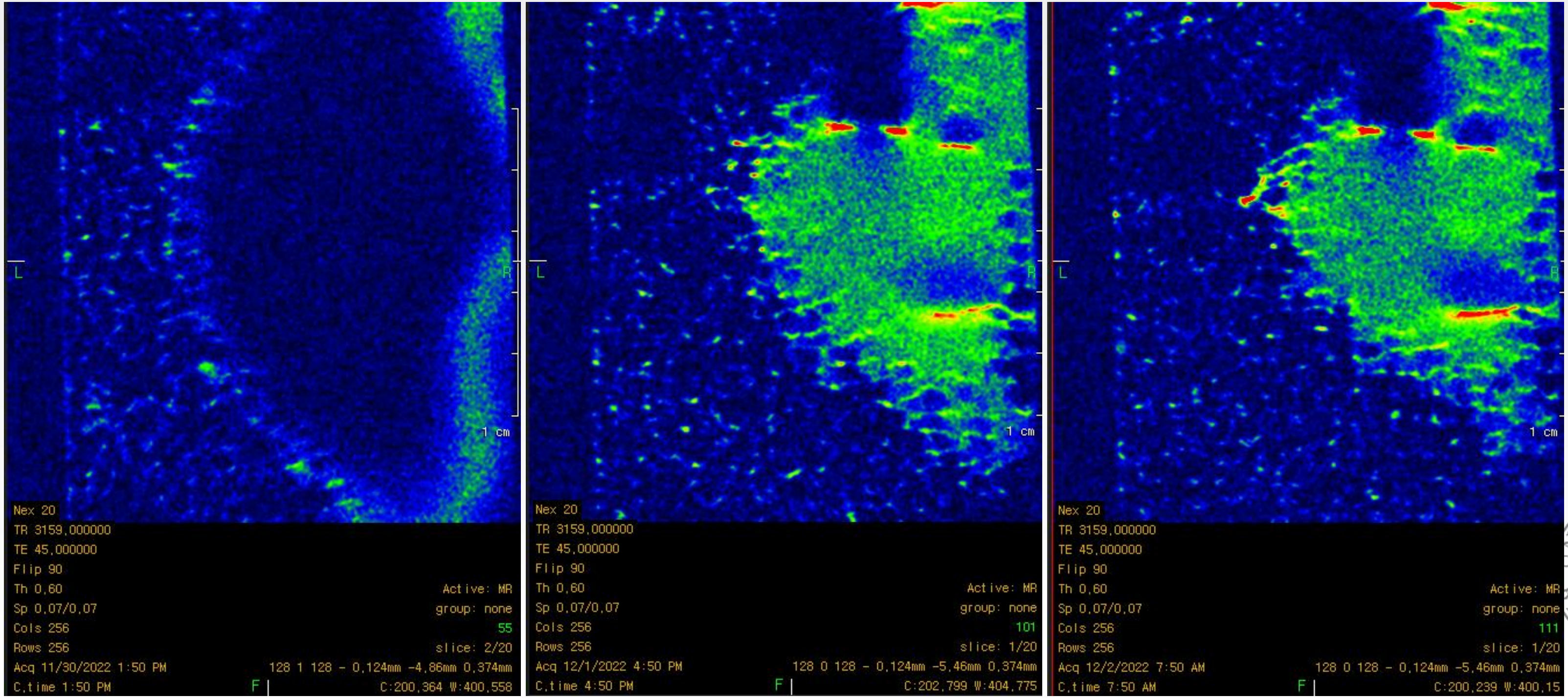


Fig. 7

Biomass migration/redistribution

Over time, the biomass reduced in some areas of the core as it increased in others

- This could be related to both localised food shortage or other physical parameters such as pH

It was at this stage that bacteria and biomass growth was confirmed in the sand pack saturated with water and hydrogen

PET image analysis investigated how this matter migration and growth affects fluid flow and distribution in

PET- Effect of biomass on fluid flow

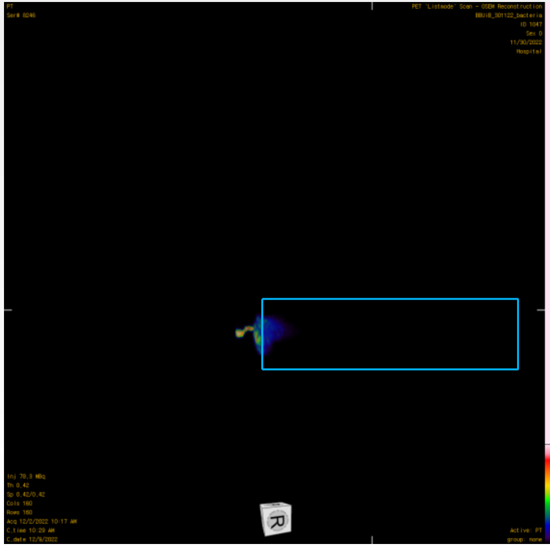
Biomass accumulation and growth affected both fluid distribution and flow.

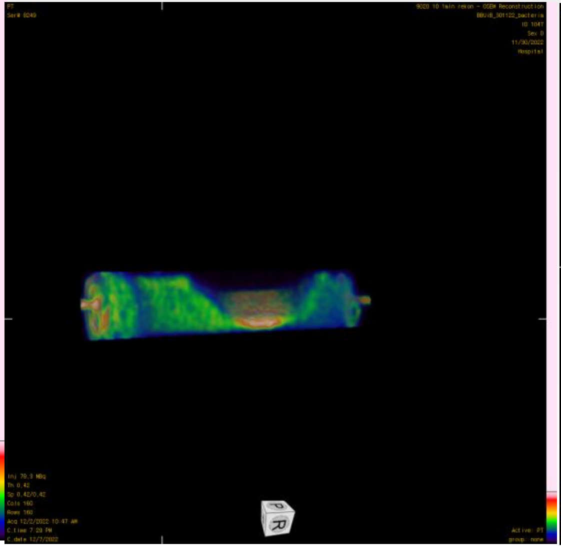
The PET signal (FDG-18) increased with time during flow around the bacteria saturated regions.

The accumulation of FDG-18 shows increase in water wittiness

Initial flow was piston like

10 min **30 min** **40 min**





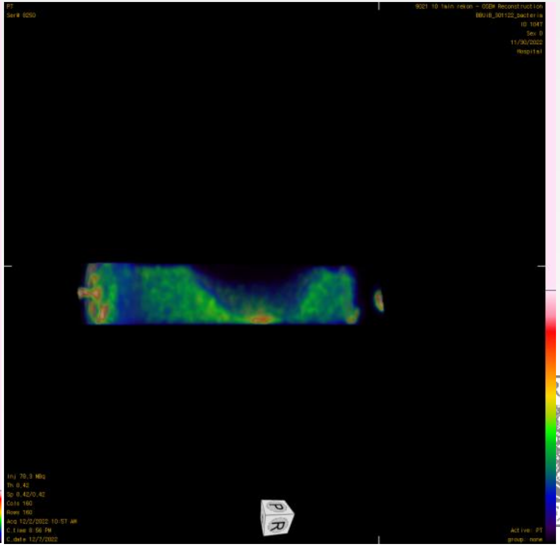


Fig.8. 3D reconstruction of PET image slice at different times during flow. Each is a minute recontruction.

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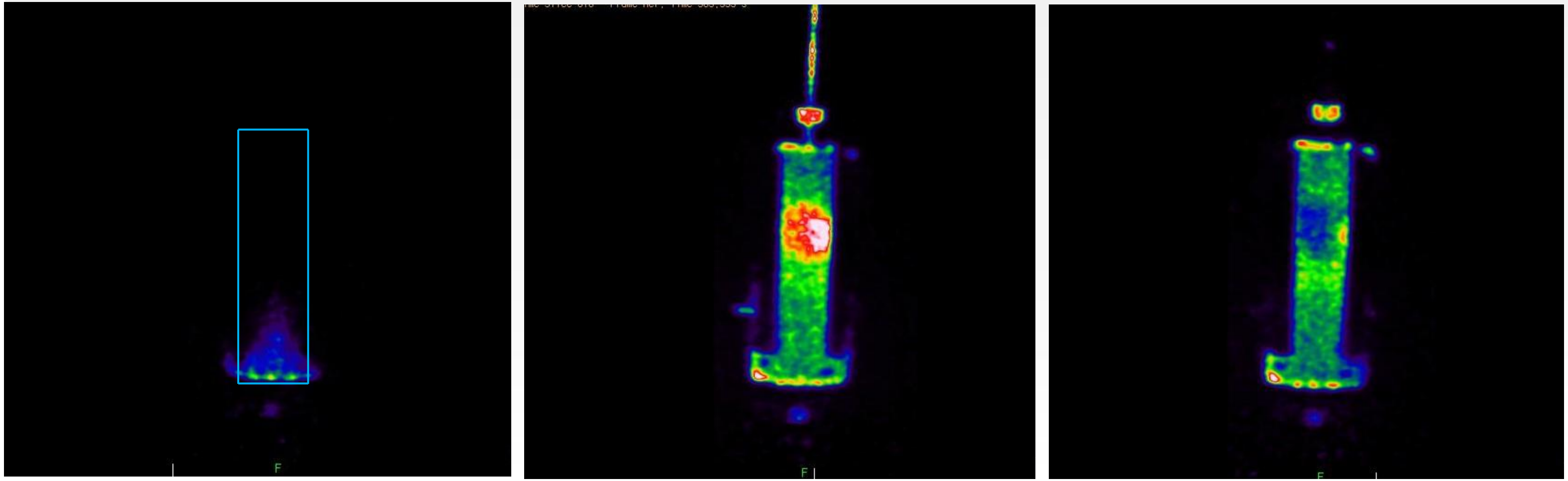
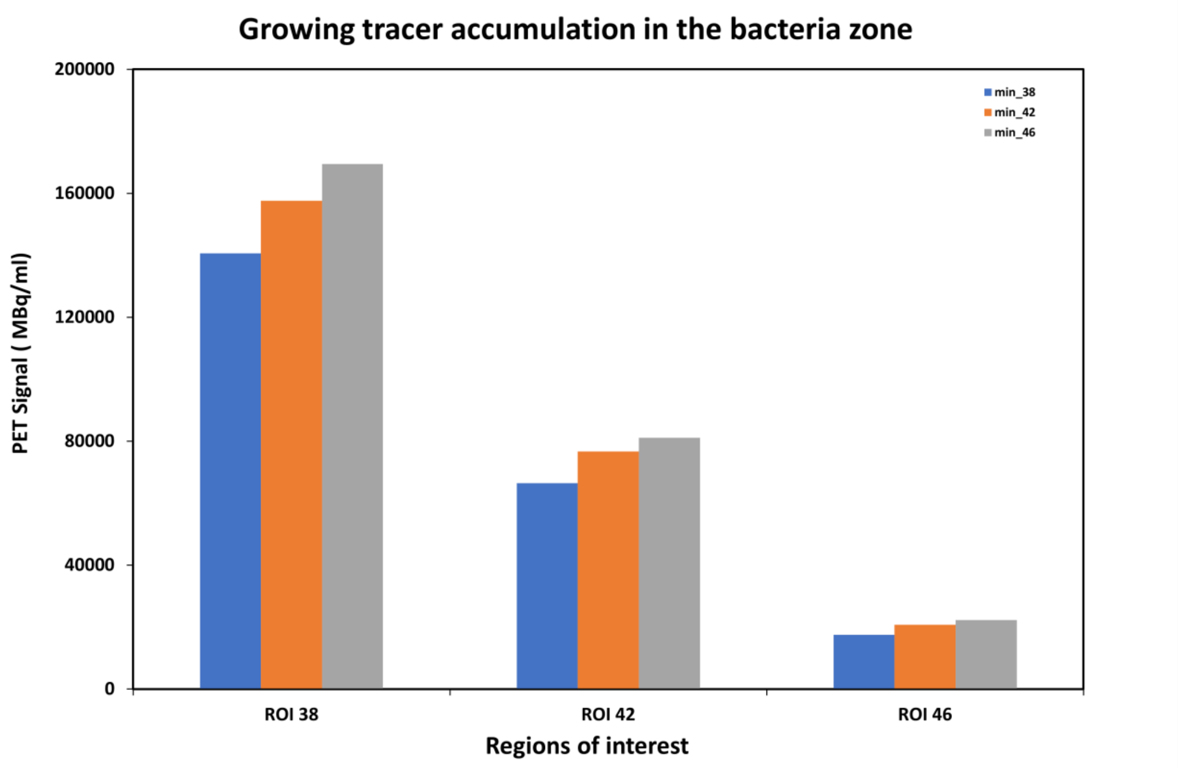


Fig.9. 2D image coronal slices at showing flow through the bacteria setions at different times during flow.

PET- Tracer absorption/accumulation



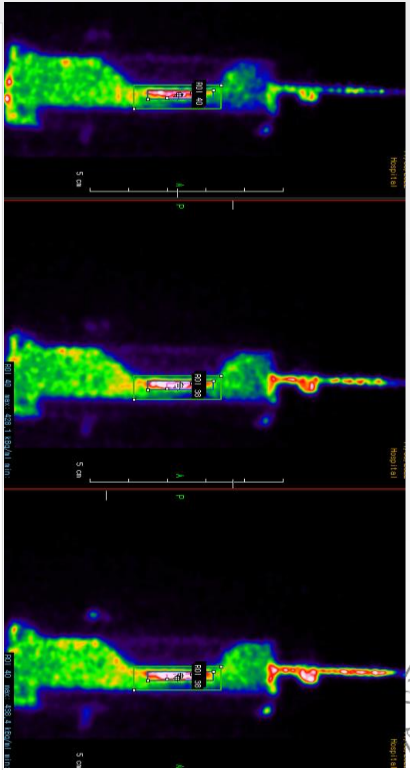


Fig. 10. Different regions of interest showing increasing tracer accumulation over time

Conclusions

- Possible to identify and quantify phases with a PET/MRI combination

- Observed biomass with HR under MRI at different spatial resolutions – bacteria stain **Oleidesulfovibrio alaskensis**

- General distribution of bacteria, water, hydrogen in a clean sand pack
- Bacteria growth and accumulation

- Bacteria migration over time

- Fluid flow behaviour controlled by bacteria and hydrogen presence in the porous media. Rel perm and Pc measurements need to consider this when effect in future experiments

- Bacteria seem to affect the wetting state in the presence of hydrogen and water
- Relative residual hydrogen saturation

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