HyUSPRe

Hydrogen **U**nderground **S**torage in **P**orous **Re**servoirs

Webinar #3

Microbial impact on subsurface hydrogen storage

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The HyUSPRe consortium

Funded by

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Executive summary

On 23 February, 2023 HyUSPRe organized a webinar entitled Microbial impact on subsurface hydrogen storage. Two presentations were given during the webinar: [1] Microbial H2 conversions – background and HyUSPRe experimental results, and [2] Microbial H2 conversions – biogeochemical modelling for different reservoirs and experiments with samples from a salt cavern. The webinar shared results from experimental laboratory work and biogeochemical modelling exercises. Results confirm that metabolic processes of microbes living on hydrogen are not yet fully understood which makes modelling of microbe behaviour in subsurface hydrogen storages a very complex challenge. is Both webinar presentations are attached to this report.

About HyUSPRe

Hydrogen **U**nderground **S**torage in **P**orous **Re**servoirs

The HyUsPRe project researches the feasibility and potential of implementing large-scale storage of renewable hydrogen in porous reservoirs in Europe. This includes the identification of suitable geological reservoirs for hydrogen storage in Europe and an assessment of the feasibility of implementing large-scale storage in these reservoirs technologically and economically towards 2050. The project will address specific technical issues and risks regarding storage in porous reservoirs and conduct an economic analysis to facilitate the decision-making process regarding the development of a portfolio of potential field pilots. A techno-economic assessment, accompanied by environmental, social and regulatory perspectives on implementation will allow for the development of a roadmap for widespread hydrogen storage towards 2050; indicating the role of large-scale hydrogen storage in achieving a zero-emissions energy system in EU by 2050.

This project has two specific objectives. Objective 1 concerns the assessment of the technical feasibility, risks, and potential of large-scale underground hydrogen storage in porous reservoirs in Europe. HyUsPRe will establish the important geochemical, microbiological, flow and transport processes in porous reservoirs in the presence of hydrogen via a combination of laboratory-scale experiments and integrated modelling, establish more accurate cost estimates and identify the potential business case for hydrogen storage in porous reservoirs. Suitable stores will be identified and their hydrogen storage potential will be assessed. Objective 2 concerns the development of a roadmap for the deployment of geological hydrogen storage up to 2050. The proximity of hydrogen stores to large renewable energy infrastructure and the amount of renewable energy that can be buffered versus time varying demands will be evaluated. This will form the basis to develop future scenario roadmaps and prepare for demonstrations.

Document information, revision history, approval status

Document information

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HyUSPRe lead scientist	R. Groenenberg	2023.02.27
HyUSPRe consortium manager:	H. Cremer	2023.02.27

Table of Content

1 Introduction

The HyUSPRe project achieves results in seven technical work packages. Results are laid down in reports and presentations, most of them are public and as such published on the project's website.
Part of the results are shared with the hydrogen storage interested community through webinars. HyUSPRe will organize a total of five webinars. The **first webinar** was organized as knowledge sharing event in June 2022 together with the HYSTORIES project. The **second webinar** was organized in December 2022 and shared insights into the hydrogen storage potential of depleted gas fields and aquifers in Europe.

The third webinar was organized in February 2023 and shed light on microbial impact on subsurface hydrogen storage.

The webinar offered two presentations:

- Microbial H2 conversions – background and HyUSPRe experimental results, given by Anne Catherine Ahn from Wageningen University, and
- Microbial H2 conversions – biogeochemical modelling for different reservoirs and experiments with samples from salt caverns, given by Stefan Jansen from Deltares.

The webinar was moderated by Diana Sousa from Wageningen University.

2 Webinar report

A total of 47 people joined the webinar and represented the European community studying the (potential) microbial impact on hydrogen storage. The complete set of slides is attached to this report (see Attachment).
Microbes may significantly impact hydrogen storages for example by metabolic processes resulting in loss of hydrogen in the reservoir, souring and corrosion and clogging, formation of contaminating gases (H_2S, CH_4) or bio-based solids. Only a part of the mentioned processes and potential consequences for subsurface hydrogen storage have been fully studied and understood so far.
The first talk of Anne Catherine Ahn reported results of experiments studying the survivability of microbes depending on substrate (rocks from porous reservoirs and salt caverns), pressure and temperature conditions. Results show that specifications of the selected growth conditions do have a clear impact of the type of microbes that grow best under the selected conditions (acetogens, methanogens or sulfate reducers). Further experiments will study the kinetics of

microbial growth in a hydrogen atmosphere. For this the study team has access to a set of high pressure and high temperature reactors allowing conditions of up to 250 bar and 350 °C.

In the second talk, Stefan Jansen reported an example of modelling of the microbial activity in a salt cavern, using the PHREEQ-C modelling package. One of the observations is that hydrogen consumption by microbes takes years in the modelled reservoir but only weeks in laboratory experiments. The reasons for the comparably low consumption rates in the modelled reservoir are not clear – it could be that microbes adapt to the local conditions in the reservoir (cavern or porous reservoir) which are less ideal compared to a defined laboratory experiment.

Both talks and the discussion with the audience afterwards show that biogeochemical processes of hydrogen consuming microbes are very complex and not fully understood to date. That makes translating experimental results to biogeochemical models and further to practical guidelines for subsurface hydrogen storage very challenging.

3 Attachment

The following documents are attached to this report:

Presentations shown during Webinar #3:

- Microbial H2 conversions – background and HyUSPRe experimental results (Anne Catherine Ahn, Wageningen University)
- Microbial H2 conversions – biogeochemical modelling for different reservoirs and experiments with samples from salt caverns (Stefan Jansen, Deltares)

HyUSPRe Webinar

MICROBIAL IMPACT ON SUBSURFACE H_2 STORAGE

Anne Catherine Ahn (Wageningen University & Research)
Microbial H_2 conversions – background and HyUSPRe experimental results

Stefan Jansen (Deltares)
Microbial H_2 conversions – biogeochemical modelling for different reservoirs and experiments with samples from a salt cavern

Hydrogen Underground Storage in Porous Reservoirs
HyUSPRe

Clean Hydrogen Partnership

Co-funded by the European Union

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under grant agreement No 101006632. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe Research.

HyUSPRe Webinar

MICROBIAL IMPACT ON SUBSURFACE H_2 STORAGE

MICROBIAL H_2 CONVERSIONS: BACKGROUND AND HyUSPRe EXPERIMENTAL RESULTS

Anne-Catherine Ahn[1], Yehor Pererva[1], Adrian Hidalgo-Ulloa[1], Bart Lomans[1,2], Diana Sousa[1]

[1] Wageningen University and Research, [2] Shell Global Solutions International B.V.

Thursday, 23rd February 2023

Hydrogen Underground Storage in Porous Reservoirs HyUSPRe

Clean Hydrogen Partnership

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H_2 TEAM

Diana Sousa

Bart Lomans

HyUSPRe
Hydrogen Underground Storage in Porous Reservoirs

HyStoreReact

Yehor Pererva

Anne-Catherine Ahn

Ton van Gelder

Adrian Hidalgo

H_2 AS ENERGY CARRIER – WHY AND HOW IS IT USED?

1
H
Hydrogen

- Europe aims a zero-emissions energy system by 2050
→ H_2 used as energy carrier to balance the seasonal production and demand

- Green H_2 is formed by water electrolysis (O_2 as byproduct) from the surplus of sustainable energy

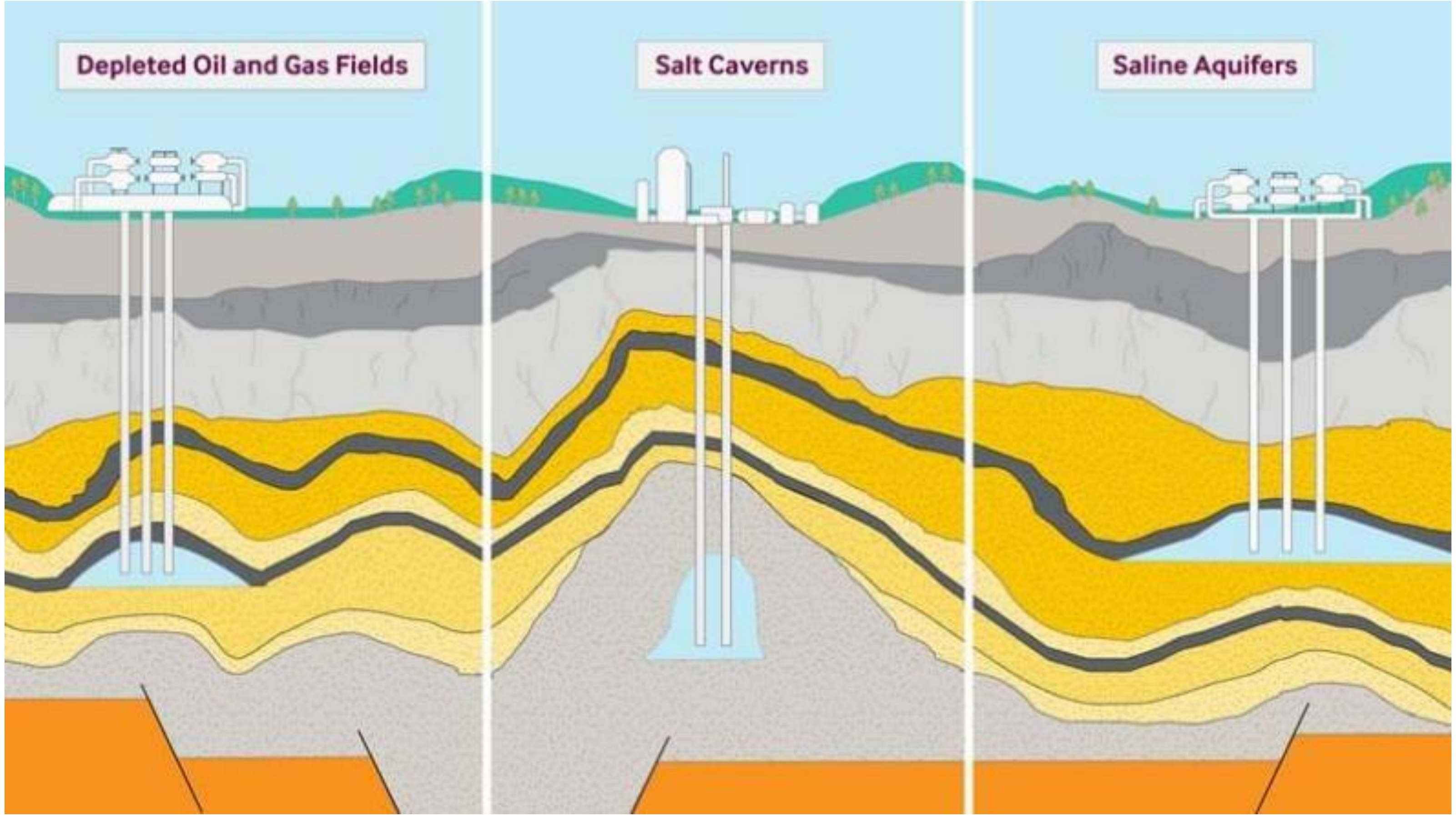
- H_2 is reconverted into energy by a fuel cell (H_2O as byproduct) → **But:** Total energy loss about 65-75%

- H_2 is envisioned to be used in:
  - Energy
  - Industry, ex: steal production
  - Heavy transportation: trucks, buses
  - Trains, ships, planes → Airbus launches 2035 three H_2-powered planes

→ H_2 fuelled cars are less cost efficient in production & driving than batterie-fuelled

SUBSURFACE H_2 STORAGE

- Aboveground storage is not feasible due to required stored H_2 volume & associated costs
- Potential subsurface storage sites are depleted oil and gas fields, salt caverns, and aquifers



MICROBIAL LIFE IN THE SUBSURFACE

- Subsurface environment harbors extreme conditions:
  - High temperature, pressure and salinity
  - Limited nutrients and energy source
  - Limited pore sizes

- Deep biosphere composes 2–19% of the Earth's total biomass

- Microbial cell number & diversity
  - Cell numbers between 8.65×10^4 - 1.01×10^6/g rock
  - Decreases over the depth
  - Depends on environmental conditions

- Life is possible until at least a depth of 5000 m

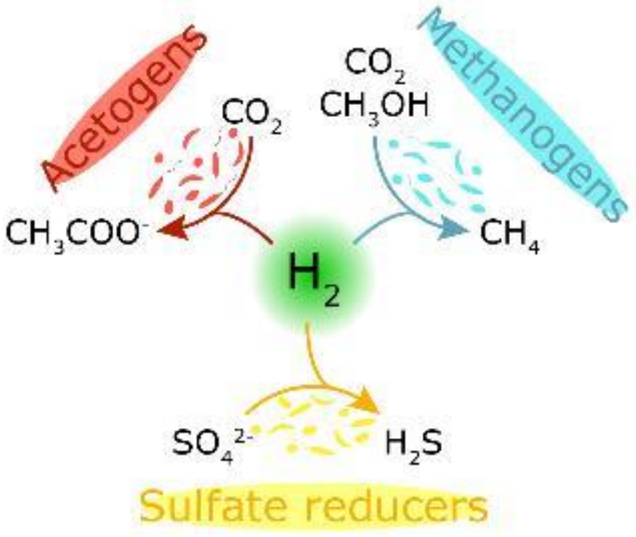
- Most microorganisms are in dormant state

MICROBIAL IMPACT ON SUBSURFACE H_2 STORAGE

- H_2 is an important, easy & high energy source in subsurface where e^- donors are scarce

- Potential impact of microbes in H_2 storage:
  - Loss of the stored H_2 through metabolic processes
  - Formation of contaminating products, such as H_2S and CH_4
  - Microbial-influenced corrosion (MIC)
  - Loss of H_2 injectivity due to bio-based solids (biomass, FeS, etc.)

- Main metabolic groups impacting H_2 storage:



Knowledge gaps:
- ➢ Microbial taxa which are relevant for potential UHS sites
- ➢ Microbial kinetics at high partial H_2 pressures and its dependency on T, P, salinity and pH

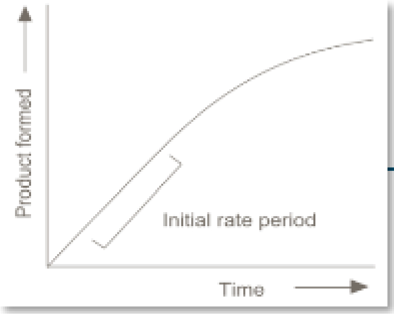
AIM OF THE HYUSPRE PROJECT

- Microbial community analysis of target UHS sites
- Determination of window of viability:

Subsurface samples → Incubations at relevant P_{H2} & T conditions → Monitoring: Methane, SO_4^{2-}, HS^-, VFAs (acetate, butyrate, etc.), Biomass → Window of viability microorganisms → Report Task D3.1

- Determination of kinetic data:

Microbial enrichments → Incubations at relevant P_{H2} & T conditions →



→ Kinetic data to populate models DuMu^x (TUC) and MoReS-PHREEQC (Shell)

- Bench-marking new-populated models:

Synthetic co-culture of microbes → Incubations at relevant P_{H2} & T conditions → Monitoring: Methane, SO_4^{2-}, HS^-, VFAs, Biomass → Competition data to populate models DuMu^x (TUC) and MoReS-PHREEQC (Shell)

- Case studies: Incubations at specific site's condition of formation water

SAMPLING & RELEVANCE OF ENVIRONMENTAL SAMPLES

- Partners provided environmental brine samples:

- 29 porous reservoir samples from 4 partners
- 2 salt cavern samples from 2 partners

→ Including potential UHS target sites and actual UHS pilots

→ Ability to use environmental microbial communities for experiments

HyStoreReact hystock power to hydrogen

FIELDWORK: H_2 STORAGE TEST IN SALT CAVERN

- After 6 months H_2 storage test phase, liquid and filter samples, and cores were retrieved

<u>Plan:</u>

- Incubations at different temperatures at low pressure and at the site's conditions at high pressure

- Microbial community analysis of filter and core samples

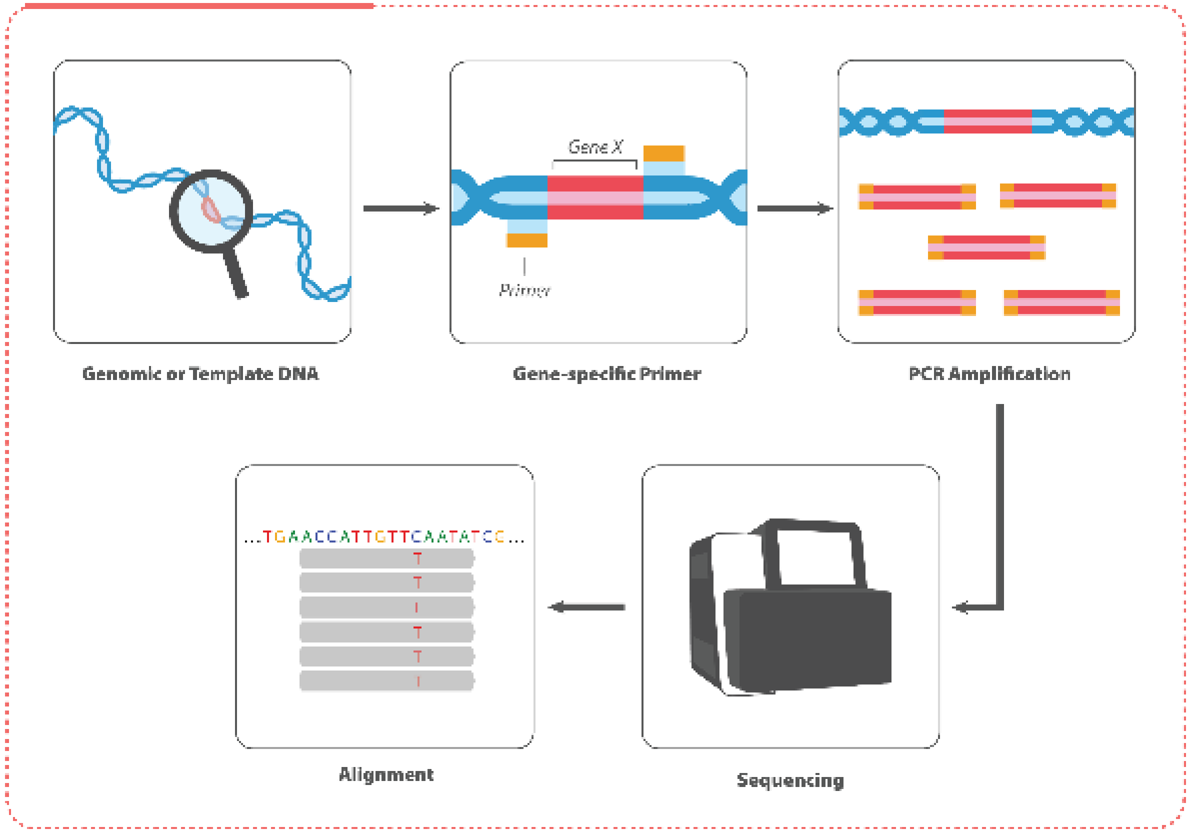
HyStoreReact

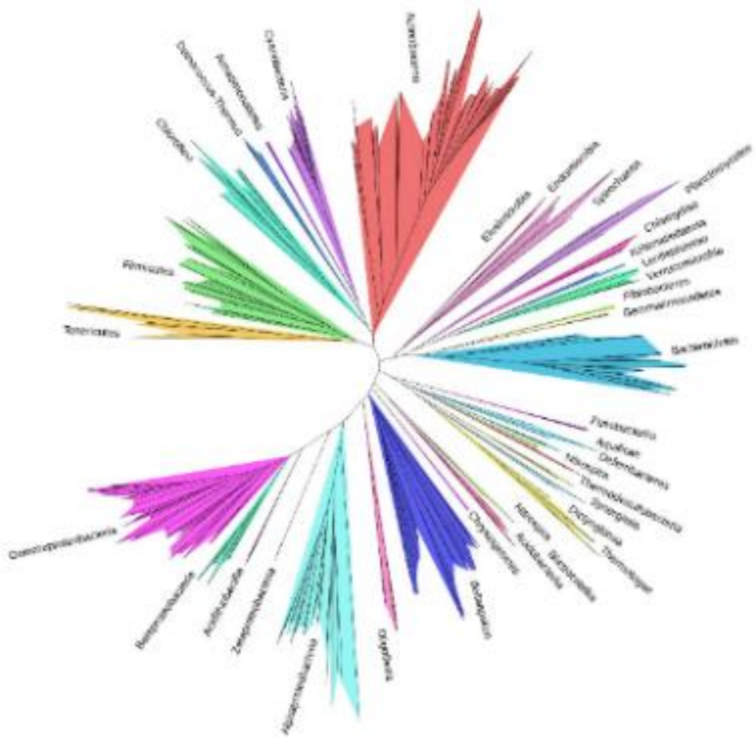
hystock power to hydrogen

MICROBIAL COMMUNITY ANALYSIS

- To determine who is there
- To determine the potential risk of these communities

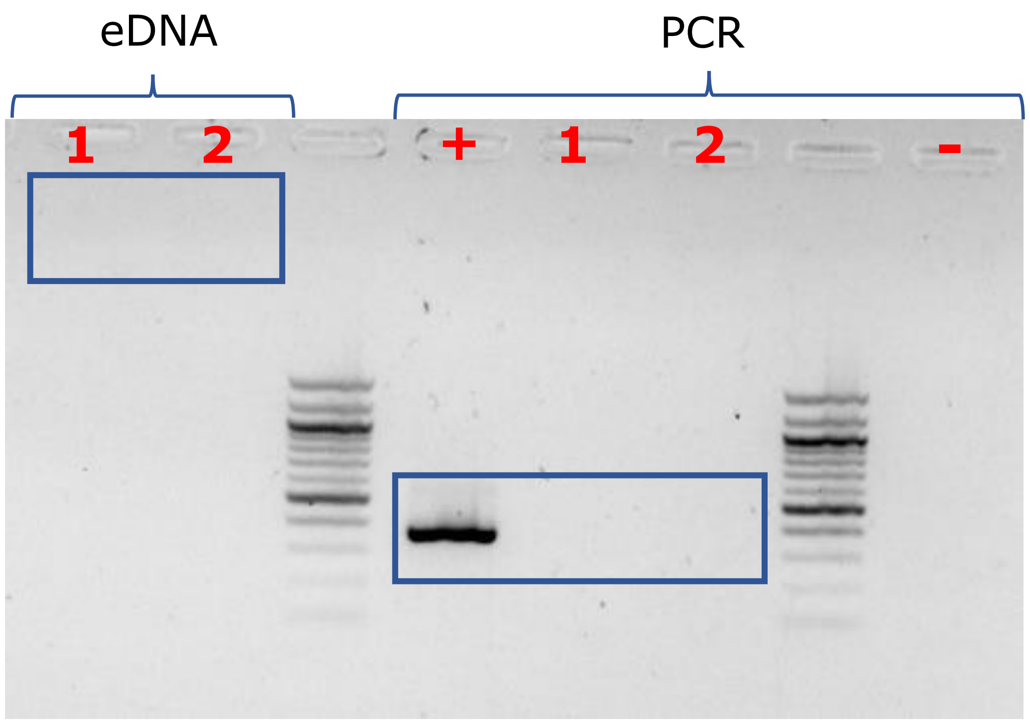
Amplicon Sequencing



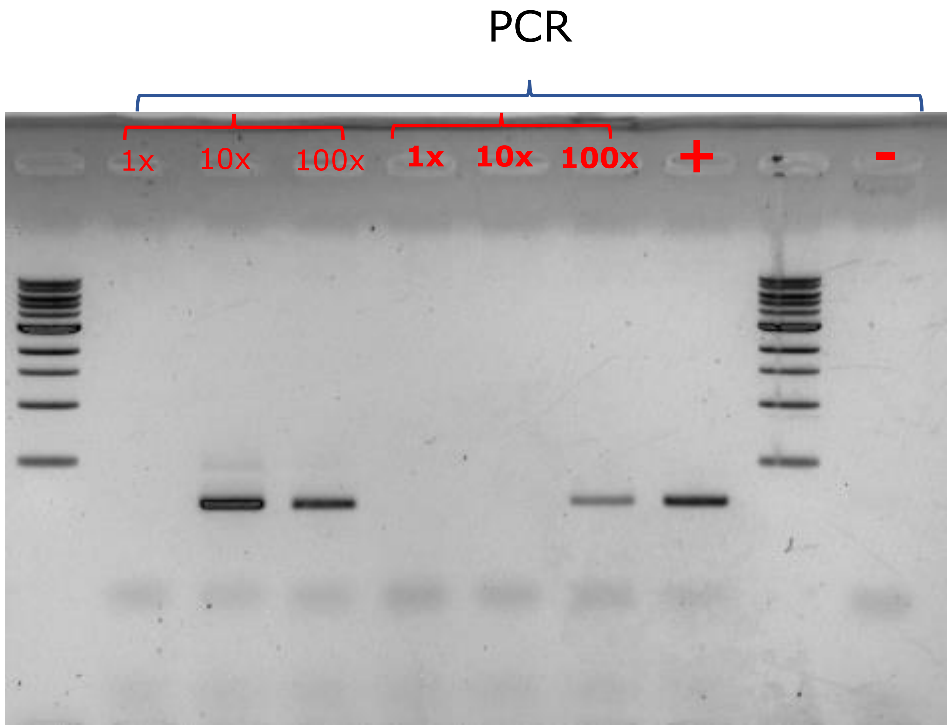


MICROBIAL COMMUNITY ANALYSIS

- My first gels being like....



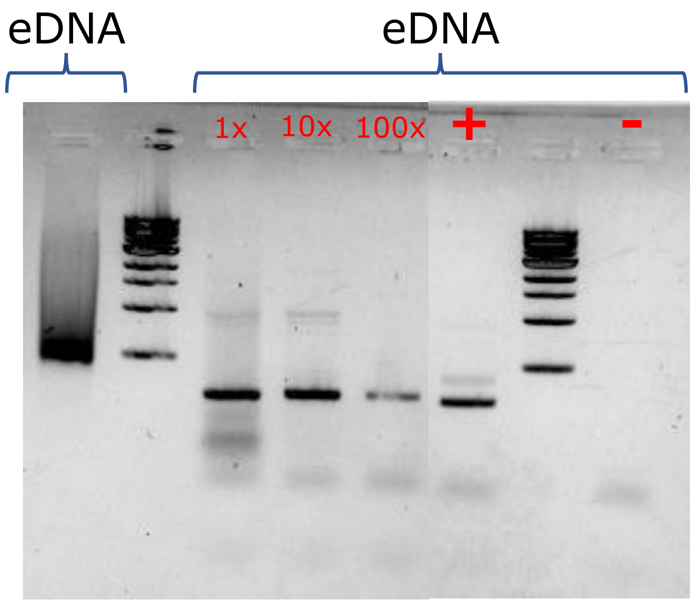
DNA dilution



Samples contain very little biomass, but lots of PCR inhibitors...

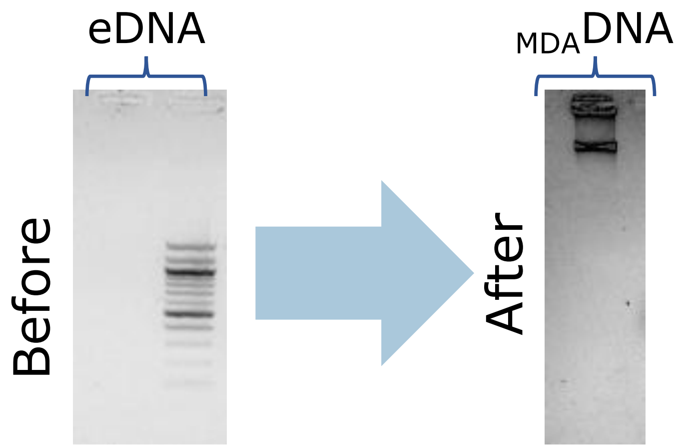
MICROBIAL COMMUNITY ANALYSIS

- After lots of tests later with….
  - Power Soil Pro Kit (Qiagen)
  - Ampliqon beads
  - High speed bead beater
  - Addition of DMSO in PCR



➡ Porous reservoir samples ok, salt caverns still problematic

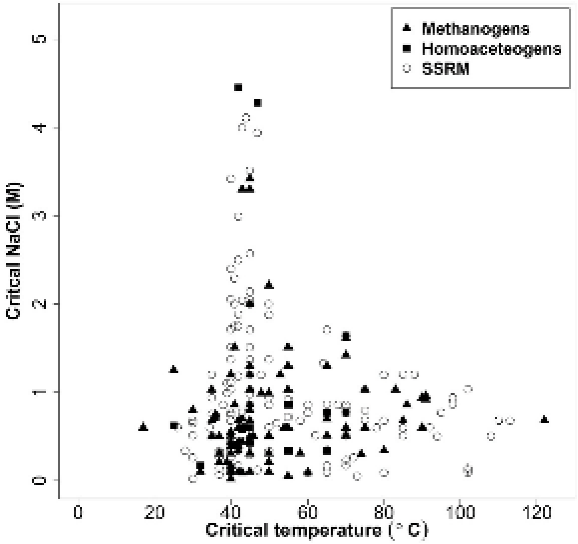
If everything else still fails: MDA



WINDOW OF VIABILITY OF MICROORGANISMS

- Current state of knowledge for microbial survivability limits under subsurface H_2 storage conditions:

Parameters	Microbial optimum & limit	Methanogens	Sulfate reducers	Acetogens
Temperature (H_2 storage: 22.5-100°C)	Optimum Limits	15-98°C 122°C	10-106°C 113°C	20-30°C 72°C
Pressure (H_2 storage: 1-50 MPa)	Optimum		0-30/50 MPa	
Salinity (H_2 storage: 0-5 M NaCl)	Optimum Limits	0-0.77 M NaCl 3.4 M NaCl	0-0.4 M NaCl 4.2 M NaCl	0-0.4 M NaCl 4.4 M NaCl
pH	Optimum Limits	4-9.5 4-10	 1-10	NA 3.6-10.7



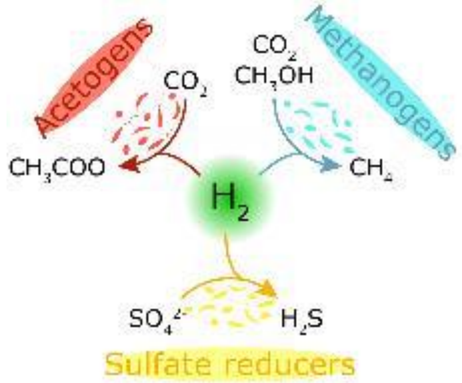
(Thaysen et al., 2021, doi: 0.1016/j.rser.2021.111481)

- Temperature and salinity are the most constraining factors
  - Temperature alone: upper life limit is 122°C
  - Combination of temperature and salinity: >55°C, and >1.7 M NaCl

WINDOW OF VIABILITY: INCUBATIONS

- Environmental samples with 80%H_2/20%CO_2 at 1.7 bar, different temperatures and media

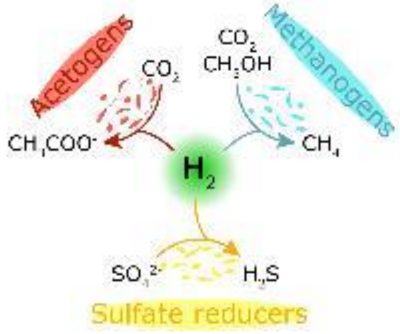
	Sample	T (°C)	P (bar)	pH	Conductivity (mS/cm)	Medium	35°C	50°C	65°C	80°C
Porous reservoirs	A	51	45	7.72	49.24	Sample amended with nutrients/trace	Acetogen	Methanogen	Methanogen	
						Mineral medium (MM)	Methanogen	Methanogen	Methanogen	
						MM with 0.5 M Na^+ + 3mM SO_4^{2-}	SO_4^{2-} reducer	SO_4^{2-}reducer		
	B	51	87	5.95	79.74	Sample amended with nutrients/trace	Methanogen			
						Mineral medium (MM)	Methanogen	Acetogen		
						MM with 0.5 M Na^+ + 3mM SO_4^{2-}	Methanogen + SO_4^{2-} reducer	SO_4^{2-} reducer		
	C	72-107	97-206	ND	ND	Sample amended with nutrients/trace	Methanogen + Acetogen	Methanogen	Methanogen	
						MM with 0.5 M Na^+ + 3mM SO_4^{2-}	SO_4^{2-} reducer + Acetogen	Methanogen	Methanogen	
	D	39-41	56	ND	ND	Sample amended with nutrients/trace	Methanogen	Methanogen		
						MM with 0.5 M Na^+ + 3mM SO_4^{2-}	Methanogen	SO_4^{2-} reducer	SO_4^{2-} reducer	
	E	109	50-150	5.2	217	Sample amended with nutrients/trace		SO_4^{2-} reducer		
						MM with 0.5 M Na^+		SO_4^{2-} reducer	SO_4^{2-} reducer	
	F	103	50-150	5.3	211	Sample amended with nutrients/trace				
						MM with 0.5 M Na^+		SO_4^{2-} reducer	SO_4^{2-} reducer	SO_4^{2-} reducer
Salt caverns	G	45	80-200	6.3	240	Sample amended with nutrients/trace	SO_4^{2-} reducer	SO_4^{2-} reducer + Acetogen		
						MM with 0.5 M Na^+			SO_4^{2-} reducer	
						MM with 2 M Na^+				
	H	20-80	40-275	6.9	219	Sample amended with nutrients/trace				
						MM with 0.5 M Na^+				
						MM with 2 M Na^+				



WINDOW OF VIABILITY: INCUBATIONS

- Environmental samples with 100% H_2 at 1.7 bar and different temperatures:

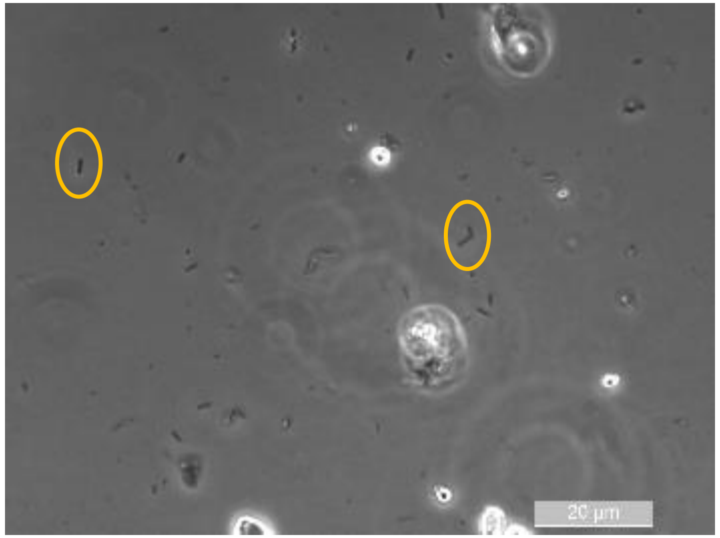
	Sample	T (°C)	P (bar)	pH	Conductivity (mS/cm)	35°C	50°C	65°C	80°C
Porous reservoirs	A	51	45	7.72	49.24	Methanogen	Methanogen	Methanogen	
	B	51	87	5.95	79.74				
	C	72-107	97-206	ND	ND	Methanogen	Methanogen	Methanogen	Methanogen
	D	39-41	56	ND	ND		SO_4^{2-} reducer	SO_4^{2-} reducer	
Salt caverns	G	45	80-200	6.3	240		SO_4^{2-} reducer	SO_4^{2-} reducer	
	H	20-80	40-275	6.9	219				



WINDOW OF VIABILITY: INCUBATIONS

- "Master mix" incubation

Medium	35°C	50°C	65°C	80°C
MM with 0.5 M Na^+ + 3mM SO_4^{2-}	Methanogen + SO_4^{2-} reducer	Methanogen + SO_4^{2-} reducer	Methanogen	
MM with 2 M Na^+ + 3mM SO_4^{2-}	Methanogen + SO_4^{2-} reducer	Methanogen + SO_4^{2-} reducer	SO_4^{2-} reducer	



2 mM sulfide produced during 7 months of enrichment

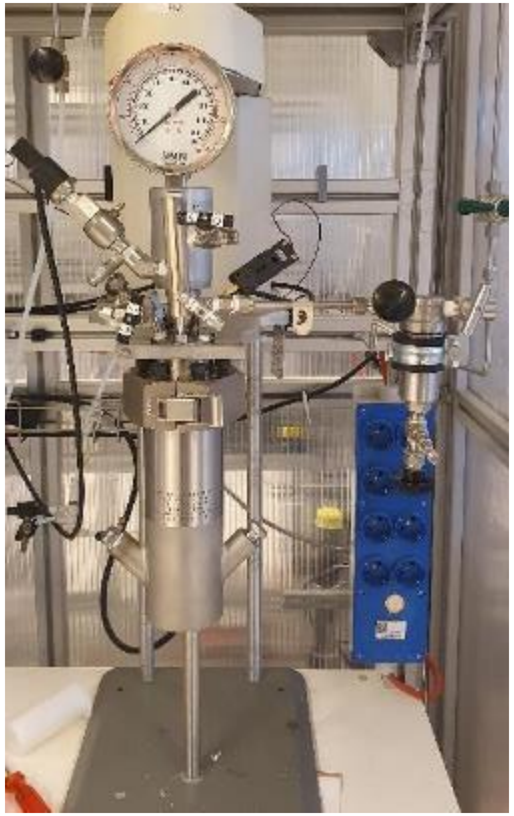
→ 16S rRNA: Peptococcaceae (amongst others)

➡ Redefines the currently known window of viability to the combination of at least >65°C, and >2 M NaCl

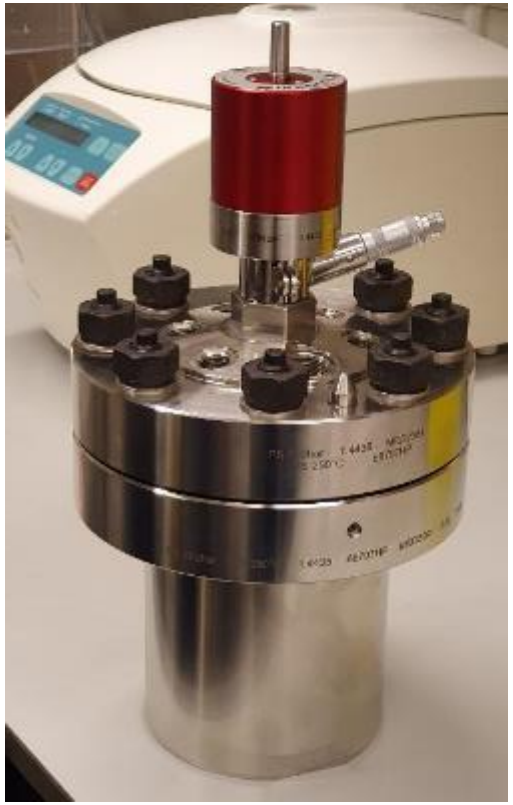
DETERMINATION OF MICROBIAL KINETICS

- High pressure & temperature reactors:

- In-house systems:
  - 3 reactors
  - 0.6 L
  - 70 Bar (56 Bar op)
  - pH/P/°T monitor
  - °T (max 350 °C)
  - SS 316
  - Lining

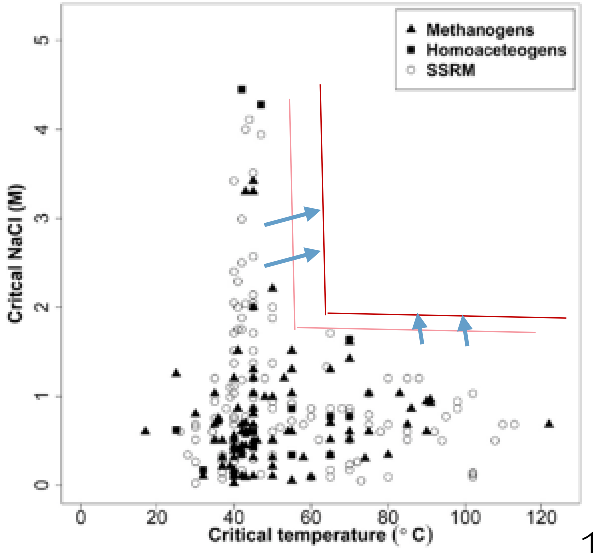


- Newly arrived systems:
  - 4 reactors
  - 0.5 L
  - 250 Bar (200 Bar op)
  - P/°T monitor
  - °T (max 350 °C)
  - SS 316
  - Lining and coating



CONCLUSIONS AND OUTLOOK

- **Microbial community analysis**
  - Development of protocols
- **Window of viability:**
  - Limits in incubations so far:
    - Acetogenesis: 50 °C
    - Sulfate reduction: 80 °C
    - Methanogenesis: 80 °C
  - Sulfate reduction could take place when sulfate was added/present
  - Window of viability shifted to at least the combination of 65°C and 2 M NaCl
- **Determination of kinetic data**
  - Design and installation of HP/HT reactors
  - Determine kinetics of microbial growth & activity
    - Implement results into DuMuX model (TU Clausthal)
    - Predict overall performance of H_2 storage in porous reservoirs



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- WUR:
  - H_2 team: Yehor Pererva, Adrian Hidalgo-Ulloa, Ton van Gelder, Bart Lomans, Diana Sousa
  - Molecular lab and MicFys group of MIB

- Laura Schwab, Nicole Dopffel, Stefan Jansen, Jan Gerritse

- Industrial and project partners:

WAGENINGEN UNIVERSITY & RESEARCH HyUSPRe Clean Hydrogen Partnership Co-funded by the European Union

THANK YOU FOR YOUR ATTENTION!

Questions?

Deltares

Microbial H_2 conversions: biogeochemical modelling for different reservoirs and experiments with samples from a salt cavern

Stefan Jansen, Jan Gerritse, Lina Piso

Deltares

23 – 2 - 2023

Supported by the Dutch Ministry of Economic Affairs & Climate

In close cooperation with WUR, Shell and TNO

Microbiology and Underground Hydrogen Storage

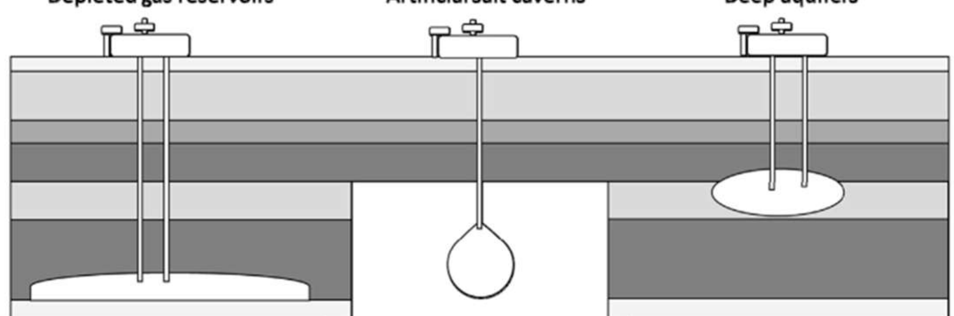
Potential effects can be predicted:

- Gas mixture changes/H_2 loss
- Souring
- Corrosion
- Clogging
- Dissolution of minerals
- Indirect: effects of leakage

Process	Reaction	ΔG⁰	Main storage impact
Methanogenesis	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	-33.9	H_2 loss by CH_4 production, clogging
Homoacetogenesis	$2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O$	-26.1	H_2 loss by CH_3COOH production, clogging
Sulfate reduction	$SO_4^{2-} + 5H_2 \rightarrow H_2S + 4H_2O$	-38.0	H_2 loss by H_2S formation, corrosion, clogging
Iron reduction	$3Fe_2O_3 + H_2 \rightarrow 2Fe_3O_4 + H_2O$	-228.3	H_2 loss by Fe(II) production, clogging

But…

- What happens in practice? → Experiments
- Difference between sites? → Modelling
- How to store hydrogen safely: design, monitoring and mitigation → Toolbox



	Depleted gas reservoirs	Artificial salt caverns	Deep aquifers
Temperature range	high range	mostly 20 – 35°C	7 – 174 °C
Salinity	high range	in sump up to saturation	5 – 52.000 ppm
Experience for H_2 storage	low	high	very low
Knowledge on microbial activity during H_2 storage	low	very low	low

Deltares

Modelling microbiological effects of UHS: different storage locations

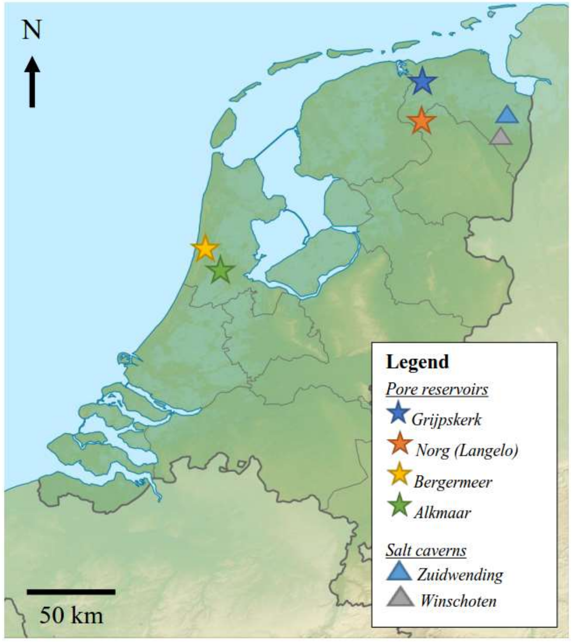


Figure 2: Map of the location of the porous reservoirs and salt caverns in the Netherlands (Lencer, 2013).

Table 2: Properties of the porous reservoirs in the Netherlands (DBI, 2017).

Reservoir	Formation	Seal	Depth (m)	Temperature (°C)	Pressure (bar)
Grijpskerk	Upper Rotliegend	Zechstein	3300	115	392
Norg (Langelo)	Upper Rotliegend	Zechstein	2670	95	328
Bergermeer	Upper Rotliegend	Zechstein	2200	80	238
Alkmaar	Zechstein	Zechstein	2025	80	196

Table 3: Properties of the salt caverns in the Netherlands (DBI, 2017).

Reservoir	Formation	Seal	Depth (m)	Temperature (°C)	Pressure (bar)
Zuidwending	Zechstein	Zechstein	1000-1550	30 (gradient)	120
Winschoten	Zechstein	Zechstein	450-1650	30 (gradient)	100

Modelling microbiological effects of UHS: different storage locations

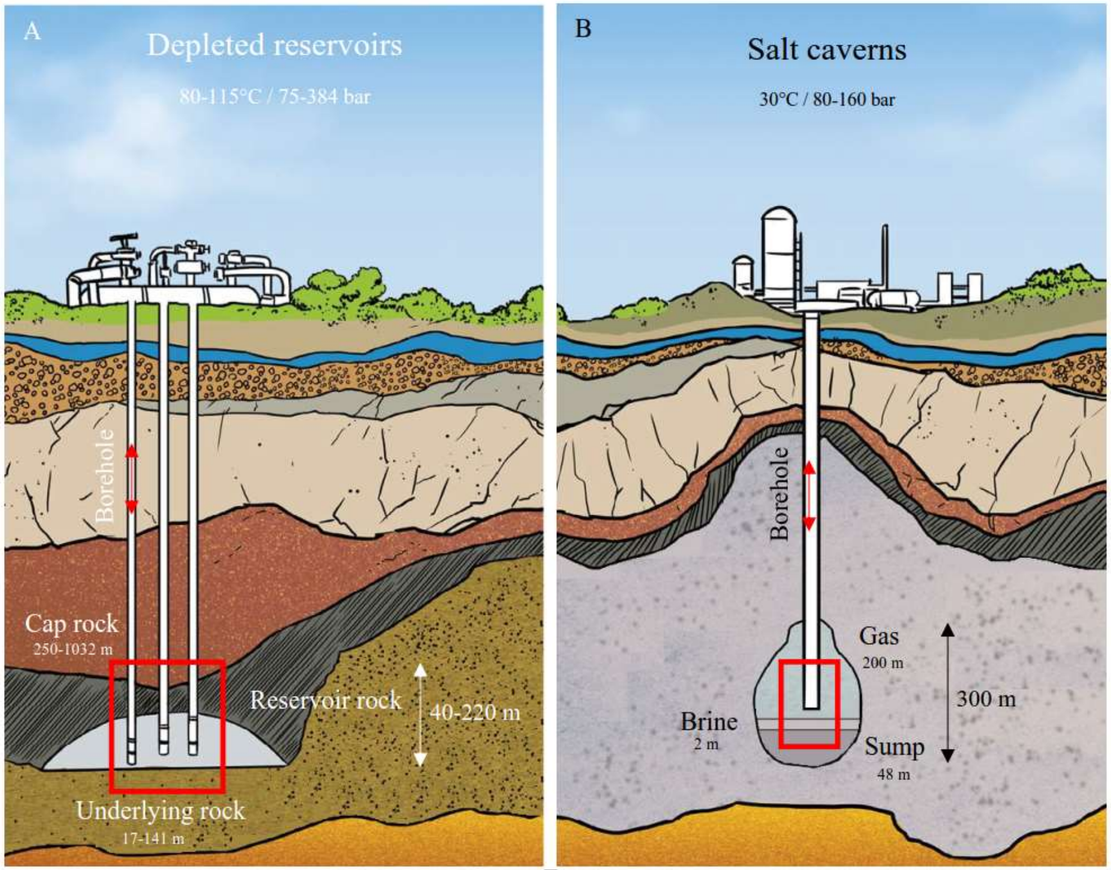


Figure 3: Schematic of the model for underground H_2 storage in depleted oil-/gas reservoirs (Figure 2A) and salt caverns (Figure 2B). The three parts of the model are indicated with a red square in the schematics. This schematic is modified from DanaEnergy (2022).

PHREEQ-C model based on Hemme & Berk, 2018

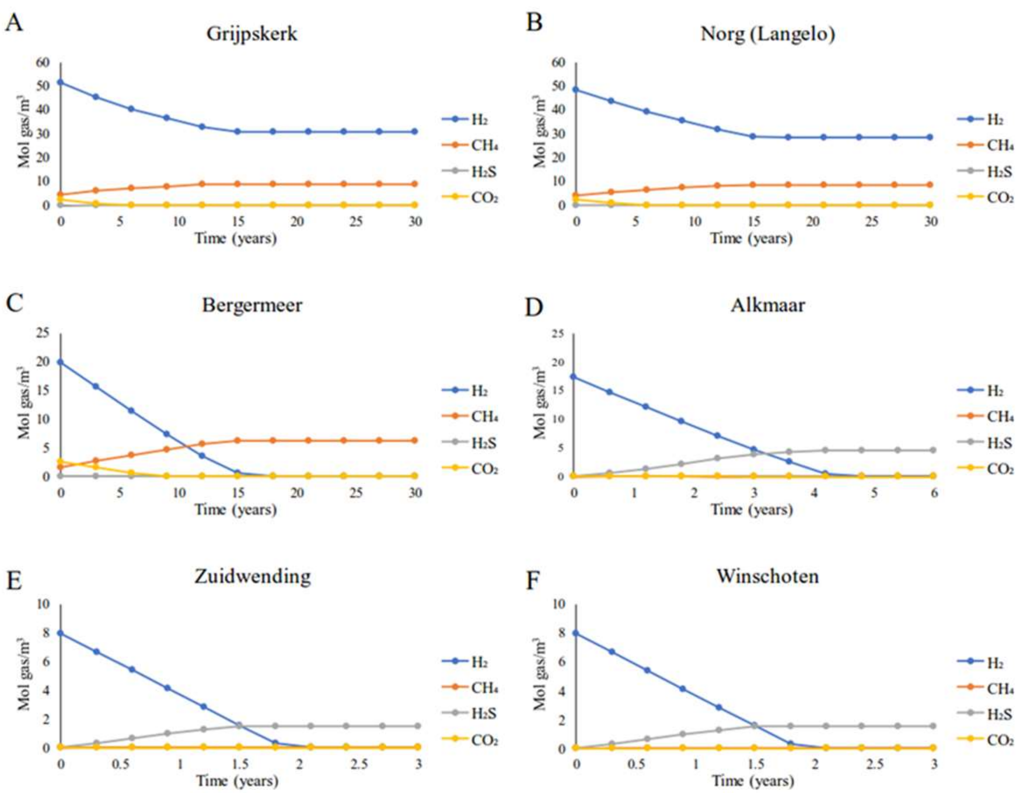
Dimensions, temperature, pressure and rock and water composition based on data available for the sites

Microbiology:

- methanogenesis,
- acetogenesis,
- sulfate reduction,
- iron reduction

- kinetically controlled
- temperature-dependent rate
- nutrient limitation (N, P)

Modelling microbiological effects of UHS: results



A – D: gas reservoirs
E, F: salt caverns

Significant H_2 depletion on timescale of 1 – 20 year

Different removal rates

Differences in production of CH_4 and H_2S

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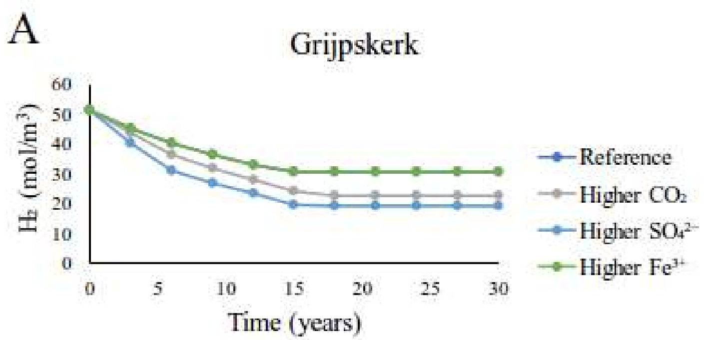
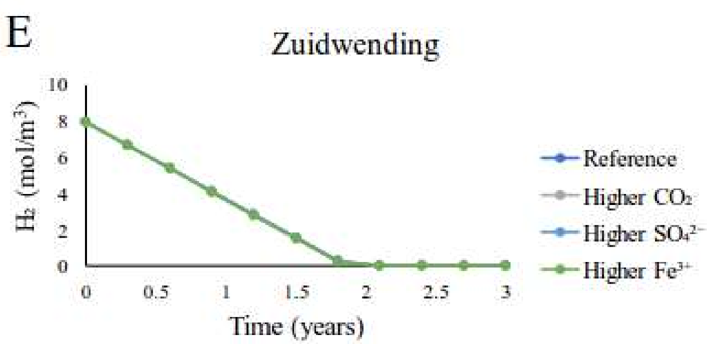
Modelling microbiological effects of UHS: influencing factors

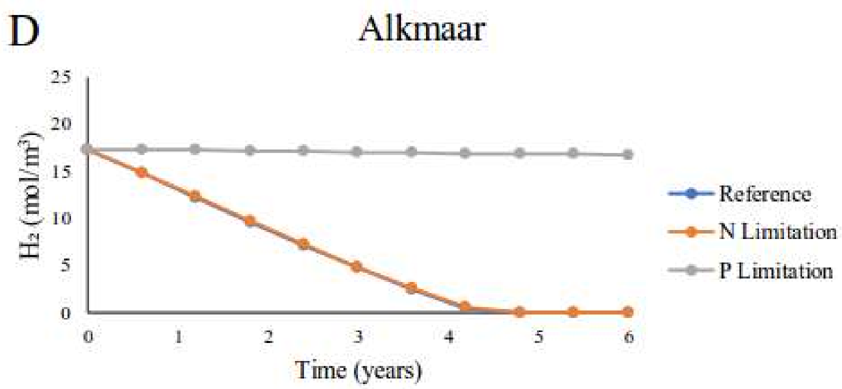




Availability electron acceptors (CO_2, SO_4, Fe_2O_3):

Some effect in some reservoirs, none in others

Modelling microbiological effects of UHS: influencing factors

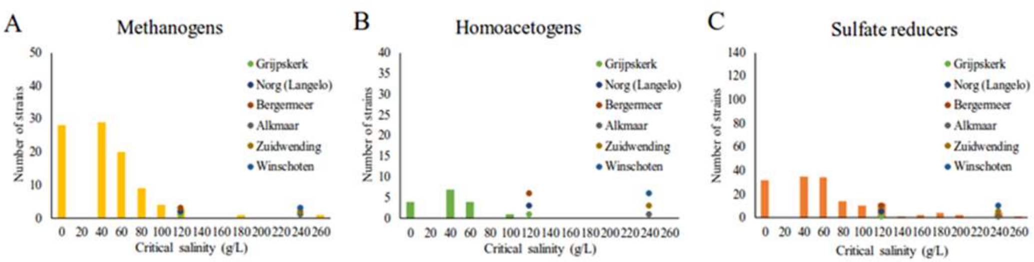


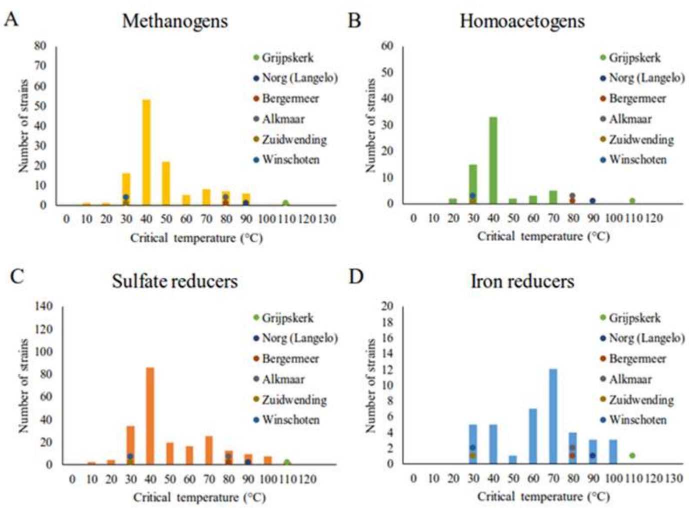
Nutrient limitation:

- No/neglible effect of N
- Strong effect of P

Potential option to limit microbial activity: reduce P in input water

Assessment of microbial activity based on pH, salinity and temperature tolerance (based on Thaysen et al., 2021)





pH not selective

Salinity and temperature selective

Careful: based on known tolerances for pH, salinity, temperature for microorganisms tested

Microbes in the caverns will adapt to the local conditions

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Experiments: how active are storage locations?

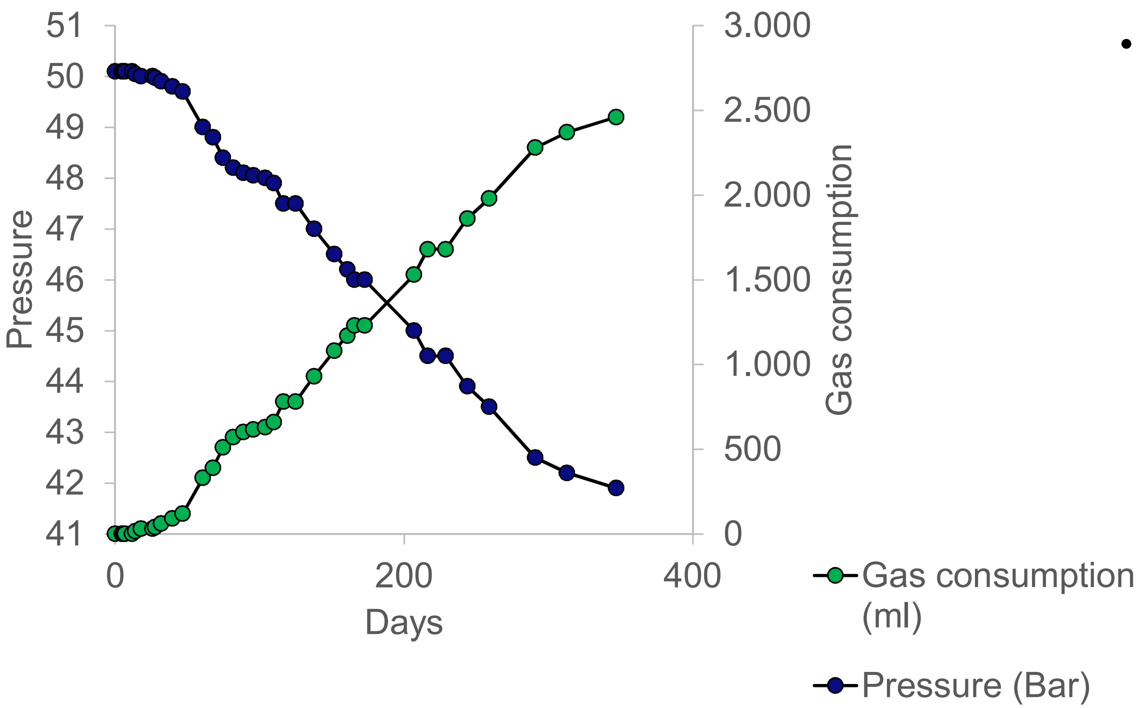
Brine from salt cavern

First tests including:

- Agar plates with *Halobacterium* medium
- Bottle incubations
- High temperature, high pressure reactor incubations

Experiments: how active are storage locations?

Gas depletion salt mine brine with 80% H_2 / 20% CO_2



First results:

- Agar plates and bottle incubations: activity
- Reactor incubations:
  - Pressure decreases
  - Uncertain: chemical/biological/physical processes?
  - Strong effect CO2 on pH (acidification): buffering important

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Experiments: how active are storage locations?

- Batch cultures: sulfate reduction at 37 and 60°C, not at 20 and 30°C
- No methanogenesis, probaly due to high concentrations of sulfate in brine

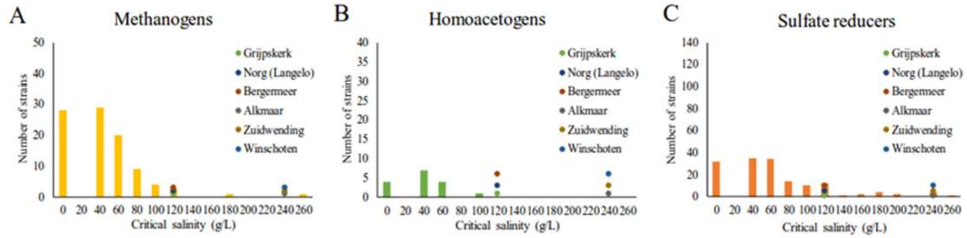
Experiments: how active are storage locations?

To be continued:

- Reactor incubations under different conditions:
  - Nutrient limitation
  - CO_2 availability
  - Reference without H_2

Conclusions & outlook

- Modelling and experiments give insight into:
  - Microbial activity and effects
  - Differences between reservoirs
  - Strategies to minimize negative effects (choice of reservoir, mitigation options)
- First outcomes:
  - Microbial activity cannot be ruled out
  - Clear differences between reservoirs expected
  - Influence of nutrients and mineral
- To be continued:
  - Further understanding of processes
  - Experiments under in-situ conditions
  - Samples/information from sites
- Collaboration between research, industry, etc
- Collaborative initiatives such as HYUSPRE, IEA – TCP, etc.



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Conclusions & outlook

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Thank you!
Questions?

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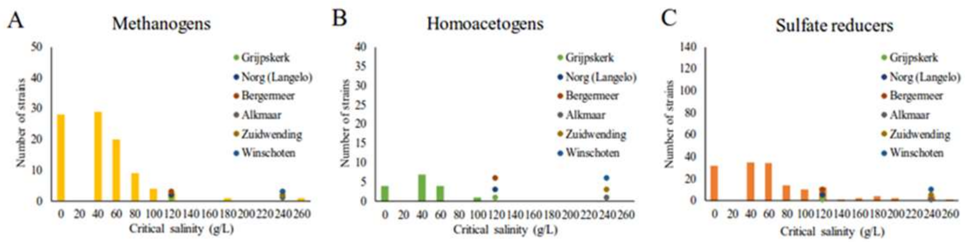

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