SHASTA

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration - 2024 Technical Workshop

April 3 2024

Wyndham Grand Hotel in Pittsburgh, PA.

TIME	PRESENTER	ORGANIZATION	TOPIC
8:00 am	Evan Frye/ Timothy Reinhardt	FECM	Welcome and program comments
8:05 am	Josh White	SHASTA-LLNL	SHASTA Project Overview
8:15 am	Leon Hibbard	SHASTA-PNNL	Regional Case Studies for H_2 Storage
8:35 am	Shruti Mishra/ Gerad Freeman	SHASTA-SNL, PNNL	Local and Regional-Scale Technoeconomic Analysis
8:55 am	Julia Camargo	SHASTA-PNNL	Reservoir Simulations and Code Comparison
9:15 am	Ryan Haagenson	SHASTA-PNNL	Core Flooding Experiments and Simulations
9:35 am	Djuna Gulliver	SHASTA-NETL	Microbial Characterization
9:55 am	BREAK: BALLROOM FOYER		BREAK: BALLROOM FOYER
10:15 am	Angela Goodman	SHASTA-NETL	H_2 Wettability, Permeability, and Diffusion
10:35 am	Gaby Davila/ Guangping Xu	SHASTA-LLNL, SNL	Geochemical Impacts of Subsurface H_2 Storage on Reservoir and Caprock Characteristics
10:55 am	Barbara Kutchko/Guangping Xu	SHASTA-NETL, SNL	Well Integrity
11:15 am	Christopher San Marchi	SHASTA-SNL	Gaseous Hydrogen Embrittlement of Metals for H_2 Storage
11:35 am	Ruishu Wright	SHASTA-NETL	Real-time Sensor Technologies for Hydrogen Subsurface Storage
11:55 am	Mathew Ingraham	SHASTA-SNL	Salt Mechanics
12:15 pm	LUNCH: KINGS GARDEN		LUNCH: KINGS GARDEN
1:15 pm	Melissa Louie/Tom Buscheck	SHASTA-SNL, LNNL	Risk Mitigation, Operations, and Recommended Practices
1:35 pm	Franek Hasiuk	SHASTA-SNL	H_2 Field Scale Test Plan
1:55 pm	Serge van Gessel	Task 42	Task 42: IEA TCP
2:15 pm	Todd Deutsch	NREL	An overview of the pipeline blending CRADA - A Hyblend Project
2:35 pm	Carolyn DesCoteaux	PRCI	PRCI - Emerging Fuels Institute Update
2:55 pm	Peter Warwick	USGS	Overview of Energy Storage & Hydrogen Research at the U.S. Geological Survey
3:15 pm	BREAK: BALLROOM FOYER		BREAK: BALLROOM FOYER
3:30 pm	Ning Lin	GEOH2	Screening & Valuation Frameworks: Paving the Way for Viable Hydrogen Storage Solutions with $GeoH_2$
3:50 pm	Scyller Borglum	WSP	Boots on the Ground: Practical Application for Storing Hydrogen
4:10 pm	Shadi Salahshoor	GTI	Subsurface Storage Technological Advancements & Innovation for Hydrogen: SUSTAIN H_2
4:30 pm	Mohamed Mehana	LANL	Overview of LANL's Underground Hydrogen Storage Projects and Future Outlook
4:50 pm	SHASTA PIs	SHASTA	Wrap-up/ Questions
5:00 pm	Adjourn		Adjourn

https://edx.netl.doe.gov/shasta/

VIRTUAL ATTENDANCE

Topic

SHASTA 2024 Technical Workshop

Time

Apr 3, 2024 8:00 AM Eastern Time (US and Canada)
The zoom meeting will open at 7:30 AM

Join Zoom Meeting

https://us02web.zoom.us/j/85991946295?pwd=SDhMZUl5UW4yd3JJdTJqeDQwVWV3QT09

Meeting ID: 859 9194 6295 | Passcode: 667306

One Tap Mobile

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+13017158592,,85991946295#,,,,*667306# US (Washington DC)

Dial by your location

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+1 301 715 8592 US (Washington DC)
+1 305 224 1968 US
+1 309 205 3325 US
+1 312 626 6799 US (Chicago)
+1 646 558 8656 US (New York)
+1 689 278 1000 US
+1 719 359 4580 US
+1 253 205 0468 US
+1 253 215 8782 US (Tacoma)
+1 346 248 7799 US (Houston)
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+1 564 217 2000 US
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Find your local number: https://us02web.zoom.us/u/klxoAuhl

https://edx.netl.doe.gov/shasta/

U.S. DEPARTMENT OF ENERGY

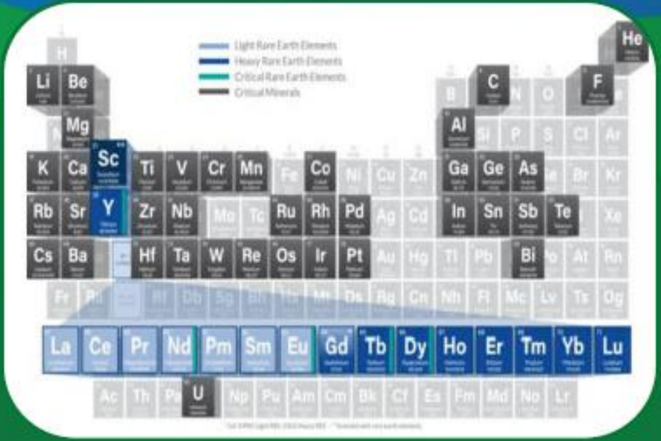
Fossil Energy and Carbon Management

Natural Gas Decarbonization and Hydrogen Technologies (NG-DHT): Underground Hydrogen Storage Workshop

2024 Resource Sustainability Project Review Meeting

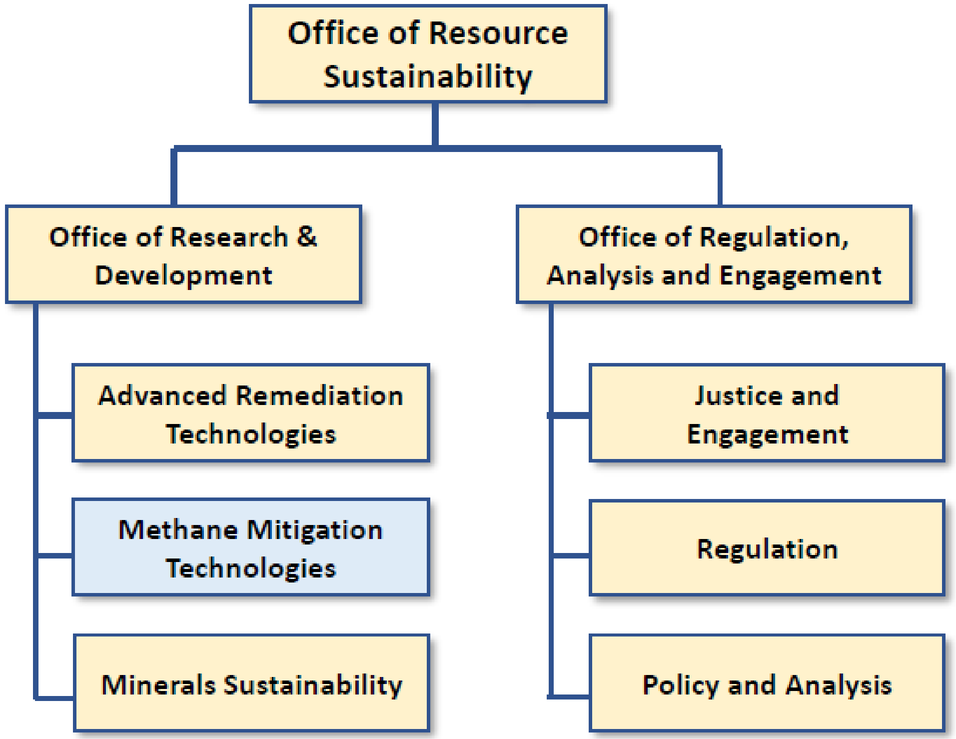
April 03, 2024

Pittsburgh, PA



Office of Resource Sustainability

- Design and administer activities associated with technologies and approaches that will reduce the environmental impacts of our historical and continued dependence on coal, oil, and natural gas:
  - Reduce
  - environmental impacts and emissions associated with fossil energy development, use, transportation, and storage - produced water, abandoned mine remediation, methane mitigation, etc.
  - Improve the economics and reduce environmental impacts of critical minerals extraction, processing, use, and disposal.
  - Regulate the import and export of natural gas.
  - Conduct analysis of oil and natural gas markets
  - Assess policy and regulatory frameworks for potential exports of hydrogen and ammonia (hydrogen carrier), and oversight of carbon offset efforts.
- Accomplish these goals through policy, research, innovation, outreach, and stewardship.



Program Area	Program Elements	2023 Enacted ($M)
Advanced Remediation Technologies	Environmental Prudent Stewardship	25
	Gas Hydrates	20
	Water Management Technologies	10
	Methane Mitigation Technologies	60
	Natural Gas Decarbonization and Hydrogen Technologies	26 23 (FY24)
Minerals Sustainability	Critical Minerals	44
	Carbon Ore Processing	10
TOTAL		195

Methane Mitigation Technologies Division

Methane Emissions Mitigation

Advanced materials, data management tools, inspection and repair technologies, and dynamic compressor R&D for eliminating fugitive methane emissions across the natural gas value chain

Methane Emissions Quantification

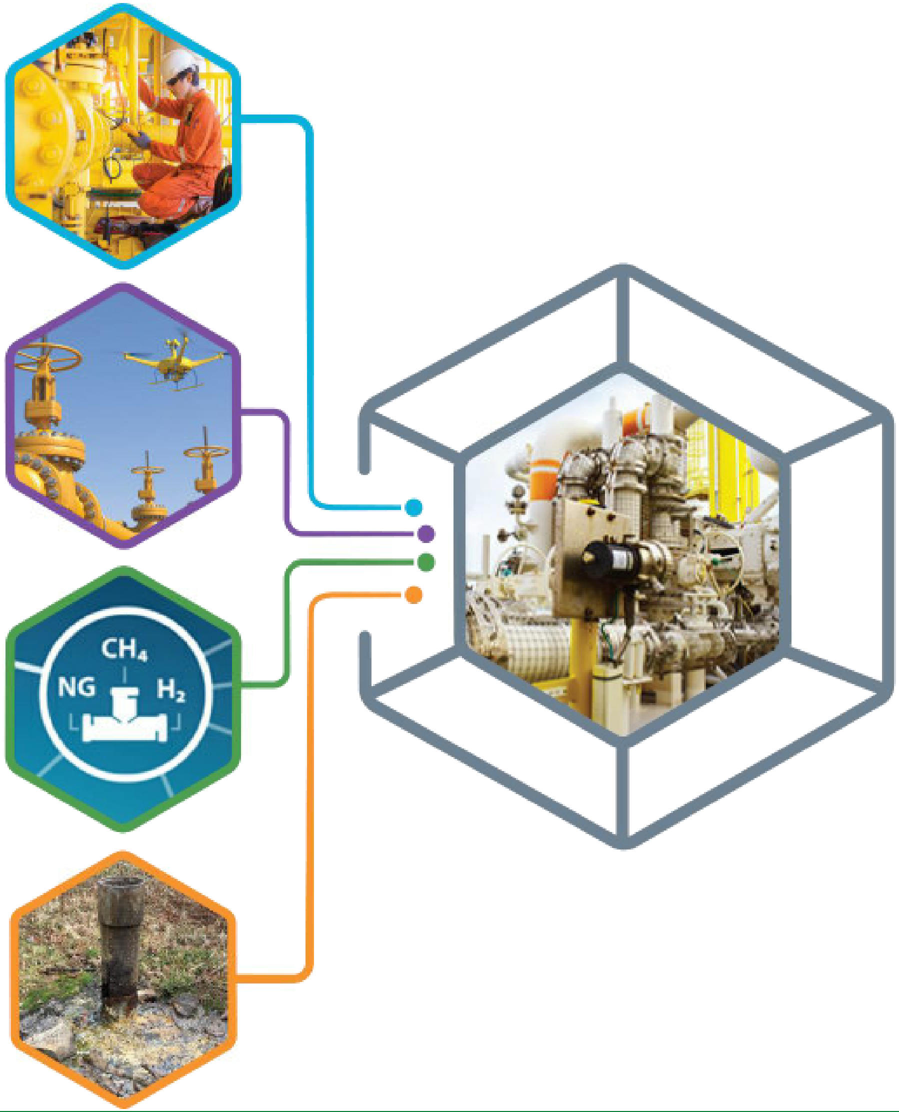
Direct and remote measurement sensor technologies and collection of data, research, and analytics that quantify methane emissions from point sources along the upstream and midstream portion of the natural gas value chain

Natural Gas Decarbonization and Hydrogen Technologies

Technologies for clean hydrogen production, safe and efficient distribution, and geologic storage technologies supported by analytical tools and models

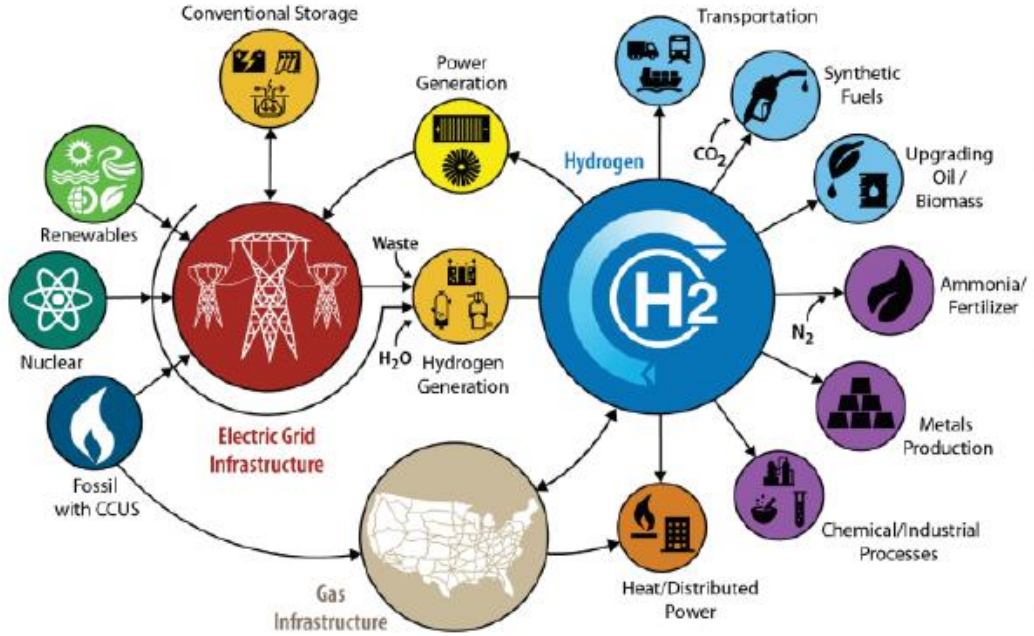
Undocumented Orphaned Wells Research

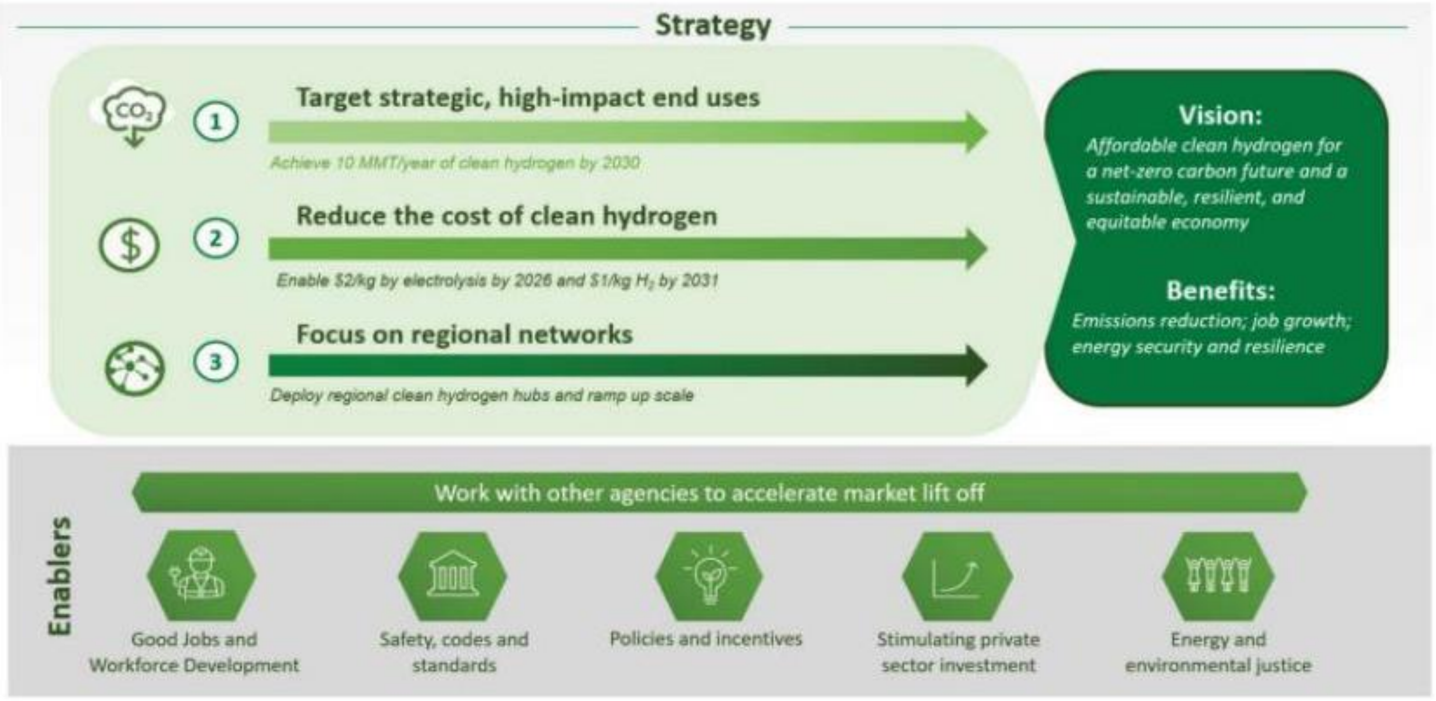
Developing tools, technologies, and processes to efficiently identify and characterize undocumented orphaned wells in order to prioritize them for plugging and abandonment.



Natural Gas Decarbonization and Hydrogen Technologies

Source: H2@Scale





Source: U.S. Clean Hydrogen Strategy and Roadmap

Hydrogen Shot™

Accelerate innovation and spur demand of clean hydrogen by reducing the cost by 80%, to $1 per 1 kilogram of clean hydroger within 1 decade.

Long Duration Storage Shot™

Achieve affordable grid storage for clean power—anytime, anywhere—by reducing the cost of grid-scale energy storage by 90% for systems that deliver 10+ hours of duration within the decade.

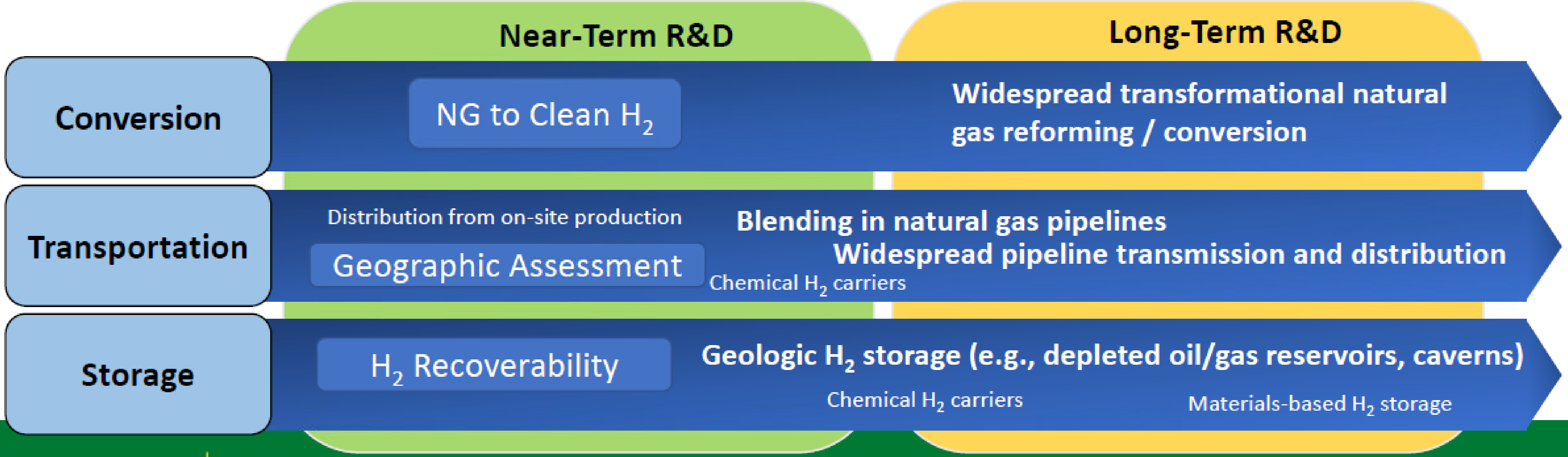
Clean Fuels & Products Shot™

Decarbonize the fuel and chemical industry through alternative sources of carbon to advance cost-effective technologies.

Source: Energy Earthshots Initiatives

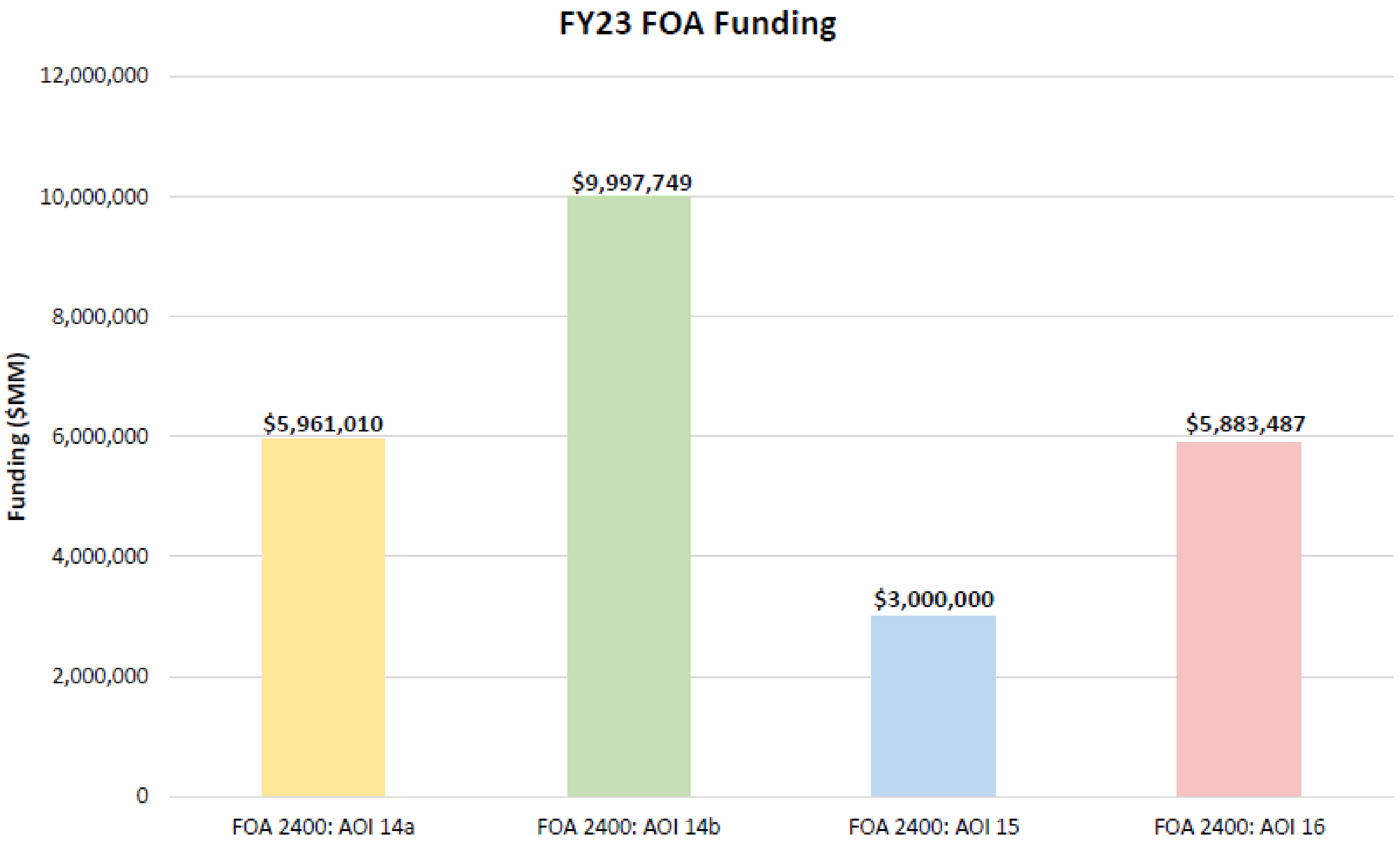
Natural Gas Decarbonization and Hydrogen Technologies

- The **Natural Gas Decarbonization and Hydrogen Technologies** (**NG-DHT**) Program was formally initiated in 2022 Omnibus.
- The NG-DHT Program coordinates with other DOE offices to support the transition towards a clean hydrogen-enabled economy through the decarbonization of natural gas conversion, transportation, and storage.
  - Supports transformational concepts for clean hydrogen production from domestic natural gas resources, with emphasis on decarbonization opportunities and value tradeoffs within energy markets.
  - Works to ensure the suitability of existing natural gas pipelines and infrastructure for hydrogen distribution, while emphasizing technology opportunities to detect and mitigate emissions.
  - Identifies underground storage infrastructure to handle high-volume fractions of hydrogen, while seeking demonstration opportunities for novel bulk storage mechanisms.



FOA2400 - Fossil Energy Based Production, Storage, Transport and Utilization of Hydrogen Approaching Net-Zero or Net-Negative Carbon Emissions

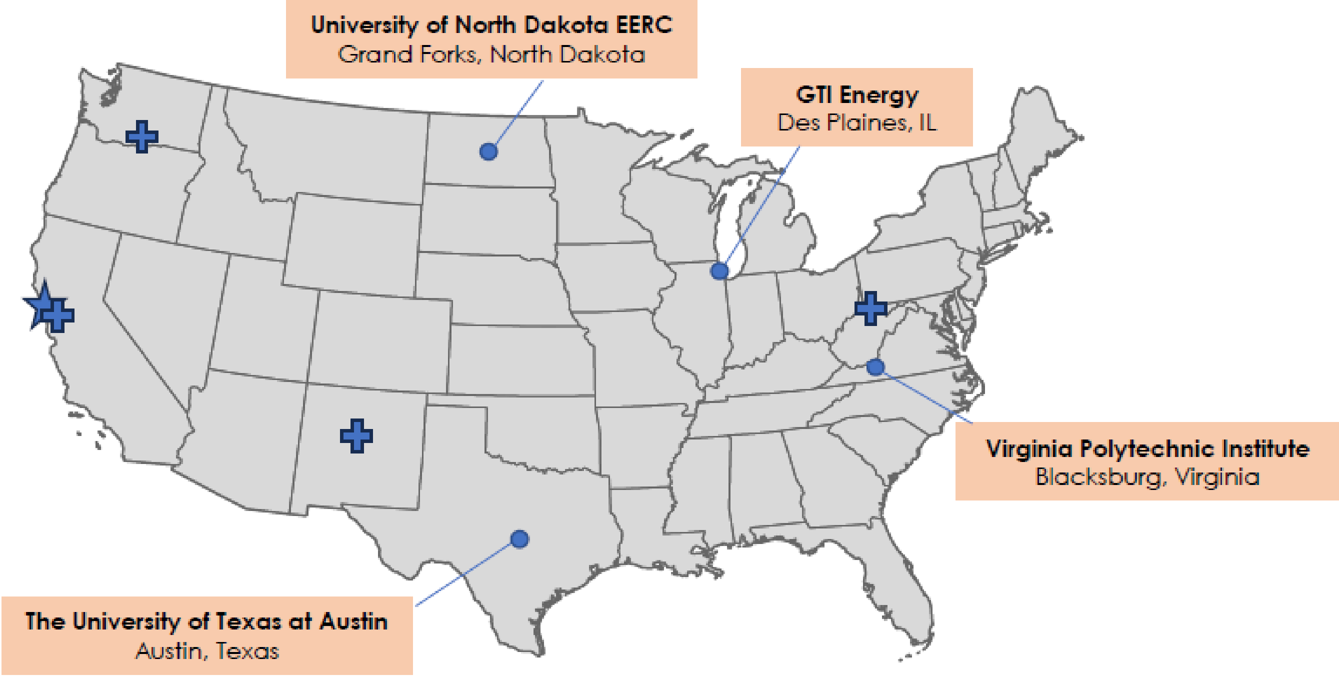
FOA 2400 Clean Hydrogen Production, Storage, Transport and Utilization to Enable a Net-Zero Carbon Economy	Area of Interest 14a: Methane Pyrolysis/Decomposition, In situ Conversion, or Cyclical Chemical Looping Reforming
	Area of Interest 14b: Hydrogen Production from Produced Water
	Area of Interest 15: Technologies for Enabling the Safe and Efficient Transportation of Hydrogen Within the U.S. Natural Gas Pipeline System
	Area of Interest 16: Fundamental Research to Enable High Volume, Long-term Subsurface Hydrogen Storage



Underground Hydrogen Storage (UHS) Projects

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Performer	Project Title	DOE Share	Non-DOE Share	Total Cost
GTI Energy	Developing & Investigating Subsurface Storage Potential And Technical Challenges for Hydrogen (DISSPATCH H2)	$1,400,000	$350,000	$1,750,000
University of North Dakota EERC	Williston Basin Resource Study for Commercial-Scale Subsurface Hydrogen Storage	$1,500,000	$375,000	$1,875,000
The University of Texas at Austin	Hydrogen Storage in Salt Caverns in the Permian Basin: Seal Integrity Evaluation and Field Test	$1,483,488	$370,873	$1,854,361
Virginia Polytechnic Institute	Assessment of Subsurface Hydrogen Storage in Depleted Gas Fields of Appalachia	$1,500,000	$375,000	$2,250,000
		$5,883,488	$1,470,873	$7,729,361



Lawrence Berkeley National Laboratory - New Geophysical Tools for Monitoring Geologic Hydrogen Storage

SHASTA Project Objective and Goals

Identify and **address key technological hurdles** and **develop tools and technologies** to enable broad public acceptance for **subsurface storage** of pure hydrogen and hydrogen/natural gas mixtures

Project Goals:

- ✓ Quantify operational risks
- ✓ Quantify potential for resource losses
- ✓ Develop enabling tools, technologies, and guidance documents
- ✓ Develop a collaborative field-scale test plan in partnership with relevant stakeholders

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

NATIONAL ENERGY TECHNOLOGY LABORATORY

Expertise across subsurface capabilities designed to enable high pressure, high temperature reactor studies that simulate wellbore and subsurface reactions and diffusivity and wettability and interfacial tension, assess the geochemistry and microbiology of reservoir types targeted for H2/CH4 storage, and develop optical fiber sensors capable of measuring H2, CH4, and pH.

Lawrence Livermore National Laboratory

Expertise in geochemical interactions in batch and flowing systems, as well as in the application of high-performance reservoir simulation and geomechanical modeling capabilities.

Pacific Northwest NATIONAL LABORATORY

Expertise across the lab related to subsurface flow and transport, biogeochemistry, and technoeconomic analysis.

Sandia National Laboratories

Expertise in applied subsurface geology, permeability testing, geomechanical rock properties testing and imaging, geochemical hydrogen-induced reaction analysis, microbiological testing, hydrogen effects on materials research and multiphaseflow and reactive transport modeling.

Project Organization

Research Focus

Research Thrusts

- Risk Quantification (Experiment & Simulation)
- Enabling Technologies to Manage Hydrogen Storage
- Recommended Practices and Industry Engagement

S&T Outcomes

- Core- to reservoir-scale performance
- Materials compatibility
- Role of microbial interactions
- Simulation and monitoring tools
- Scientifically informed pilot test plan(s)

Structure

Project Direction

- DOE-FECM
  IAA with DOT-PHMSA
- NETL-Program

Project Advice

- Stakeholder Group

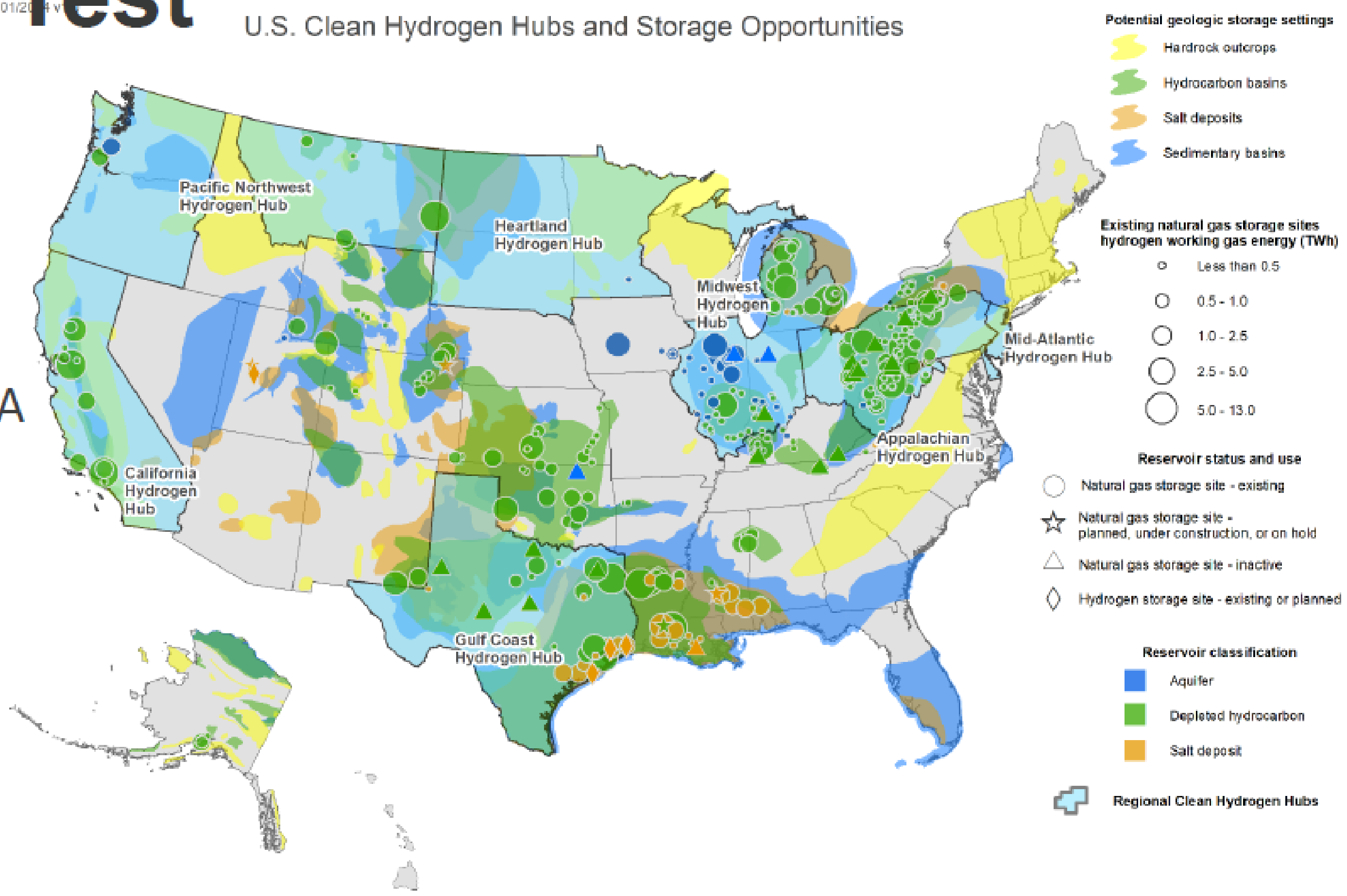
April 2- 4, 2024
Resource Sustainability Project Review Meeting at the Wyndham Grand Hotel in Pittsburgh, PA

Project Execution

- PNNL
- NETL-RIC
- LLNL
- SNL
- Industry Partner(s)

Forward Look & Field Test

- SHASTA’s ultimate goal is to enable field tests
- Continue to build relationships with industry
- Looking for site owners who may be interested in pilot-scale studies
- Subsurface Hydrogen Assessment, Storage, and Technology Acceleration Workshop, Pittsburgh, PA
  - Present a dive into final SHASTA deliverables
  - Connect with complimentary efforts
    - Intra/Inter-Agency R&D
      - FOA-2400 projects
      - HFTO projects
      - H_2 Hubs
      - Partner Government Agencies
    - International R&D
    - Industry & regulatory perspective
  - Discuss next steps/needs in UHS for research, industry, and regulators

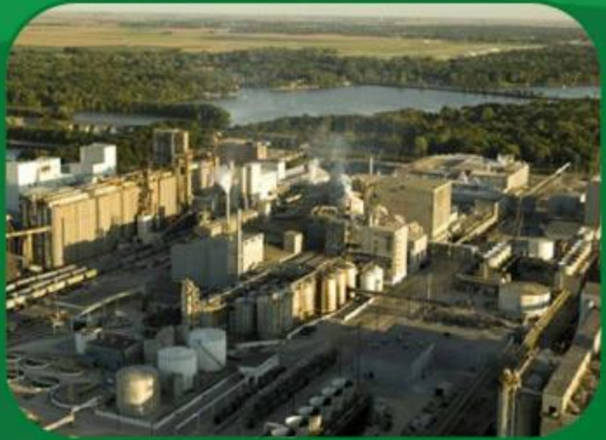


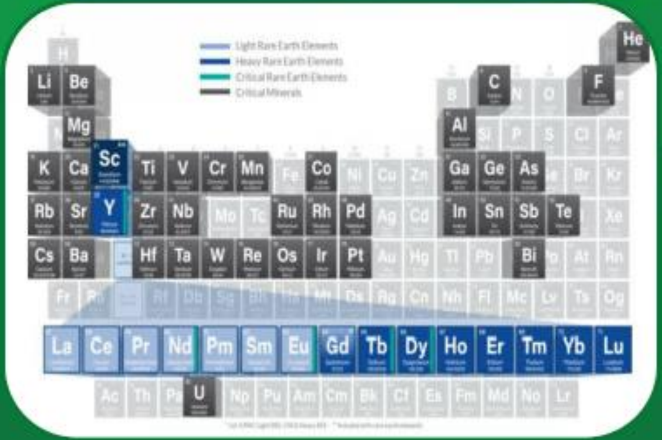
Hydrogen working gas energy of active natural gas storage sites from Lackey et al., 2023
Locations of existing natural gas storage sites (source: PHMSA)
Locations of inactive natural gas storage sites (source: EIA, HIFLD)
Generalized locations and capacities of existing Hydrogen storage locations are extracted from web resources
Generalized locations of natural gas storage sites in development represent that of the hosting county (source: EIA, FERC)
Clean Hydrogen Hubs represent the participating states in each Clean Hydrogen Hub announced by OCED
Potential geologic storage settings from Lord et al., 2014 with additional contributions from Barry Roberts and Nora Wynn (SAND2023-04266R)

SHASTA

U.S. DEPARTMENT OF
ENERGY
Fossil Energy and
Carbon Management

Questions?






SHASTA Technical Workshop

Pittsburgh, PA

April 3, 2024

Project Objectives

Address technological hurdles to enable geographically-widespread storage of pure hydrogen and hydrogen/natural gas mixtures in the subsurface.

Specific Goals:

- Quantify available resources in both porous media and cavern storage
- Quantify operational risks and potential for resource losses
- Develop enabling technologies and recommended practices
- Develop collaborative R&D and field-scale test plans in partnership with stakeholders

Project Timeline

April 2021

April 2024

Year 1 | Year 2 | Year 3 | Year 4

Phase 1

Phase 1.5

Themes:
Risk Quantification
Enabling Technologies
Recommended Practices and Stakeholder Engagement

Workshop Agenda

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12:15 pm	LUNCH		LUNCH

Workshop Agenda

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2:15 pm	Todd Deutsch	NREL	An overview of the pipeline blending CRADA - A Hyblend Project
2:35 pm	Carolyn Descoteaux	PRCI	PRCI - Emerging Fuels Institute Update
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4:50 pm	SHASTA PIs	SHASTA	Wrap-up/Questions
5:00 pm	Adjourn		Adjourn

Thank you!

Evan Frye (DOE FECM)

Timothy Reinhardt (DOE FECM)

Mathew Ingraham (SNL)

Angela Goodman (NETL)

Joshua A. White (LLNL)

Nicolas Huerta (PNNL)

SHASTA

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Regional Case Studies for H_2 Storage

Leon Hibbard

Pacific Northwest National Laboratory

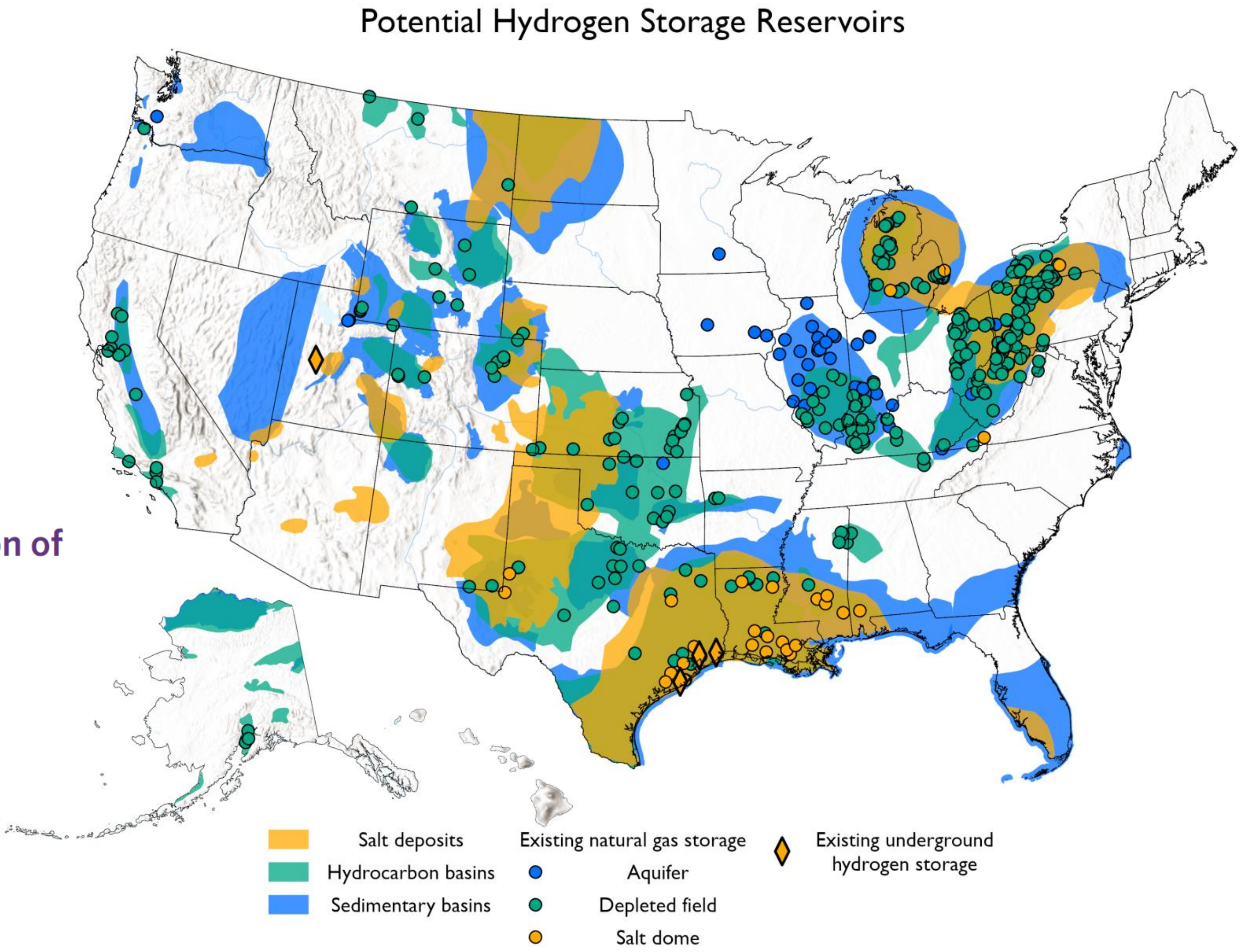
Joshua White, Gregory Lackey, Foad Haeri, Angela Goodman, Nicolas Huerta, Franek Hasiuk, Richard Shultz (SHASTA) David Clarke, Simon Harrison (Alaska Marine Power) Kristin Carter, Robin Anthony (Pennsylvania Department of Conservation and Natural Resources)

SHASTA Technical Workshop, 2024

Geologic Storage Opportunities

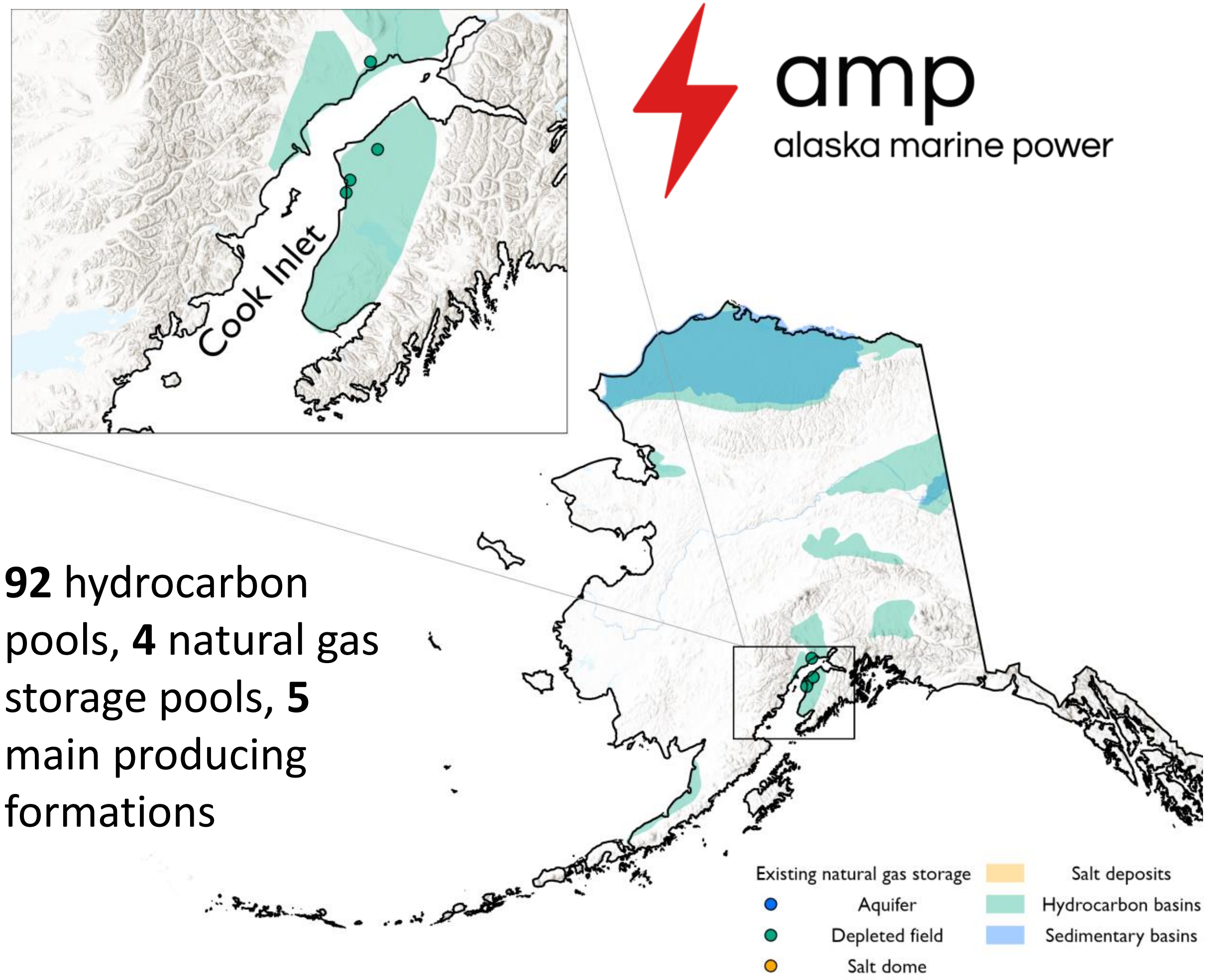
US Department of Energy Announces Selection of Seven Clean Hydrogen Hubs

November 06, 2023



Leon Hibbard, Pacific Northwest National Laboratory; Nicolas Huerta, Pacific Northwest National Laboratory; Gregory Lackey, National Energy Technology Laboratory, Clean Hydrogen Hubs and Geologic Storage Shapefiles, 1/17/2024, https://edx.netl.doe.gov/dataset/clean-hydrogen-hubs-and-geologic-storage-shapefiles

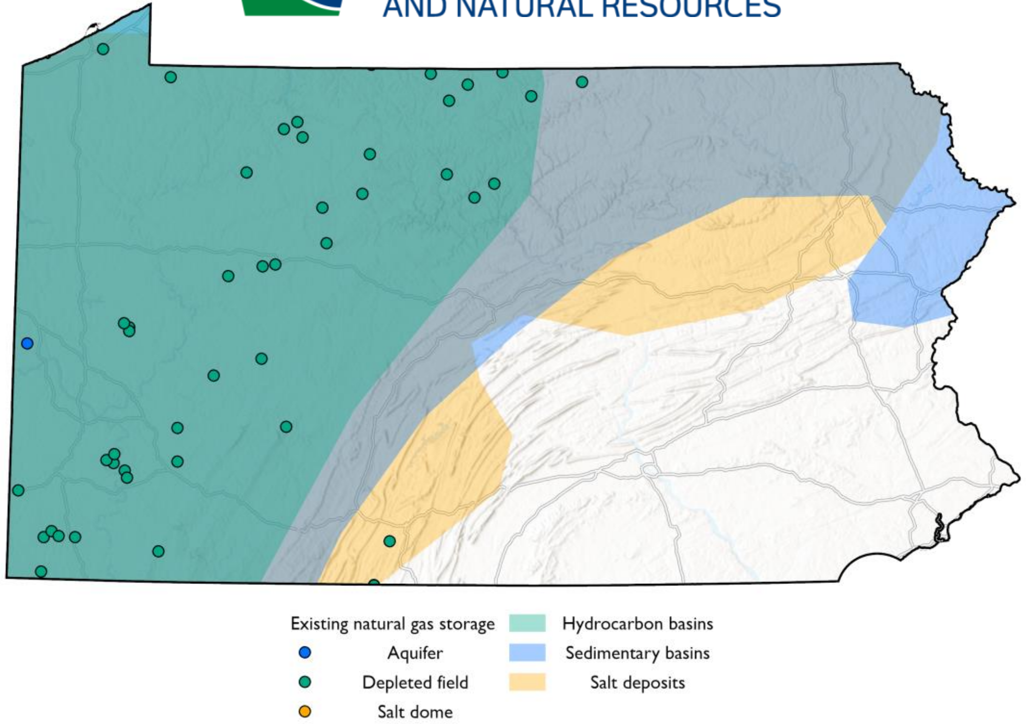
Geologic Storage Case Studies



amp alaska marine power

92 hydrocarbon pools, **4** natural gas storage pools, **5** main producing formations

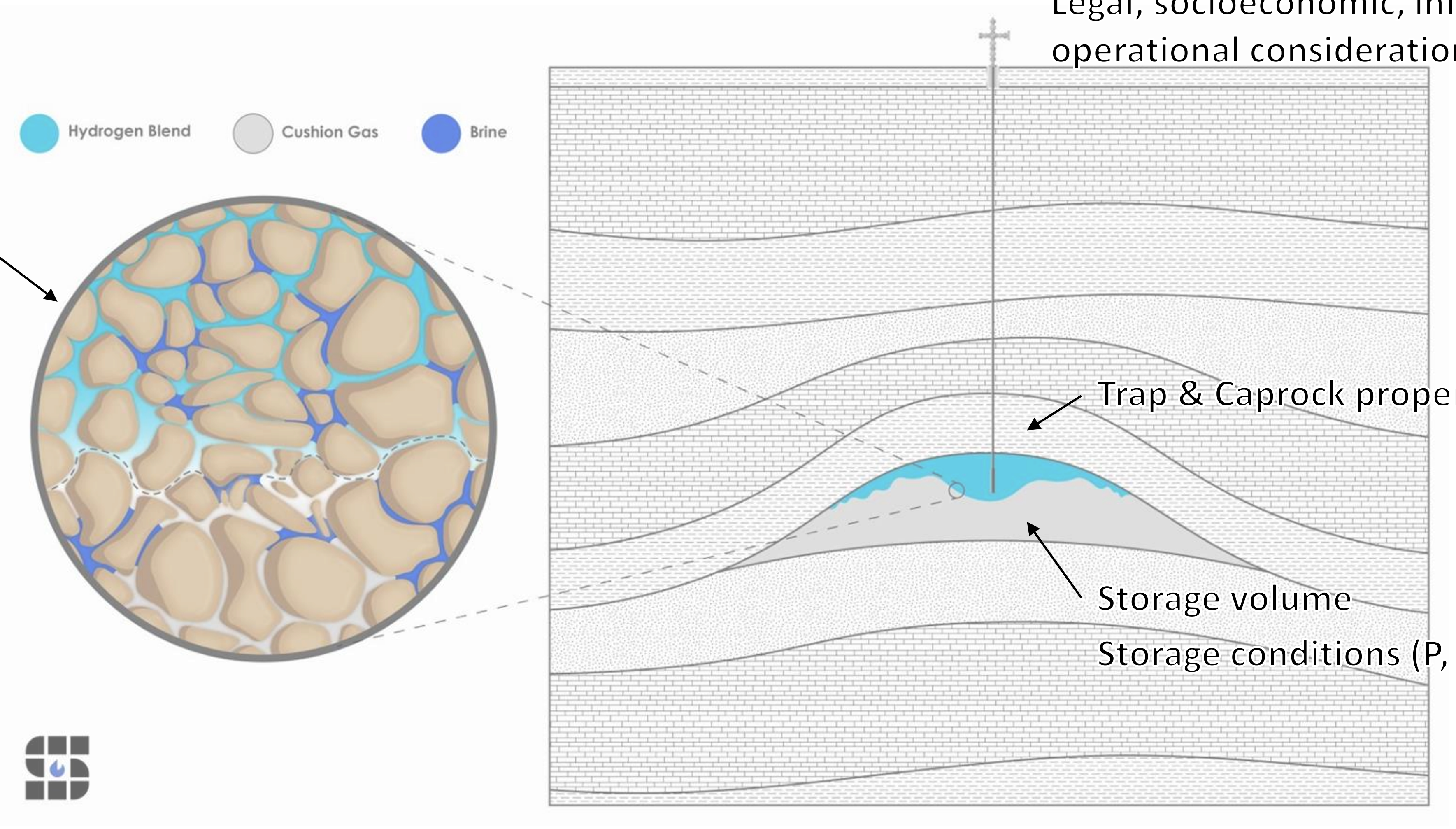
pennsylvania DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES



1,295 conventional hydrocarbon pools, **51** natural gas storage pools, ~ **10** major producing formations (> 1 % total production)

Porous Geologic Storage Considerations

Reservoir properties
- Porosity
- Permeability
- Rock chemistry
- Fluid chemistry



Goodman et al., Subsurface Hydrogen and Natural Gas Storage: State of Knowledge and Research Recommendations Report DOE/NETL-2022/3236; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2022; p 77.

Approach

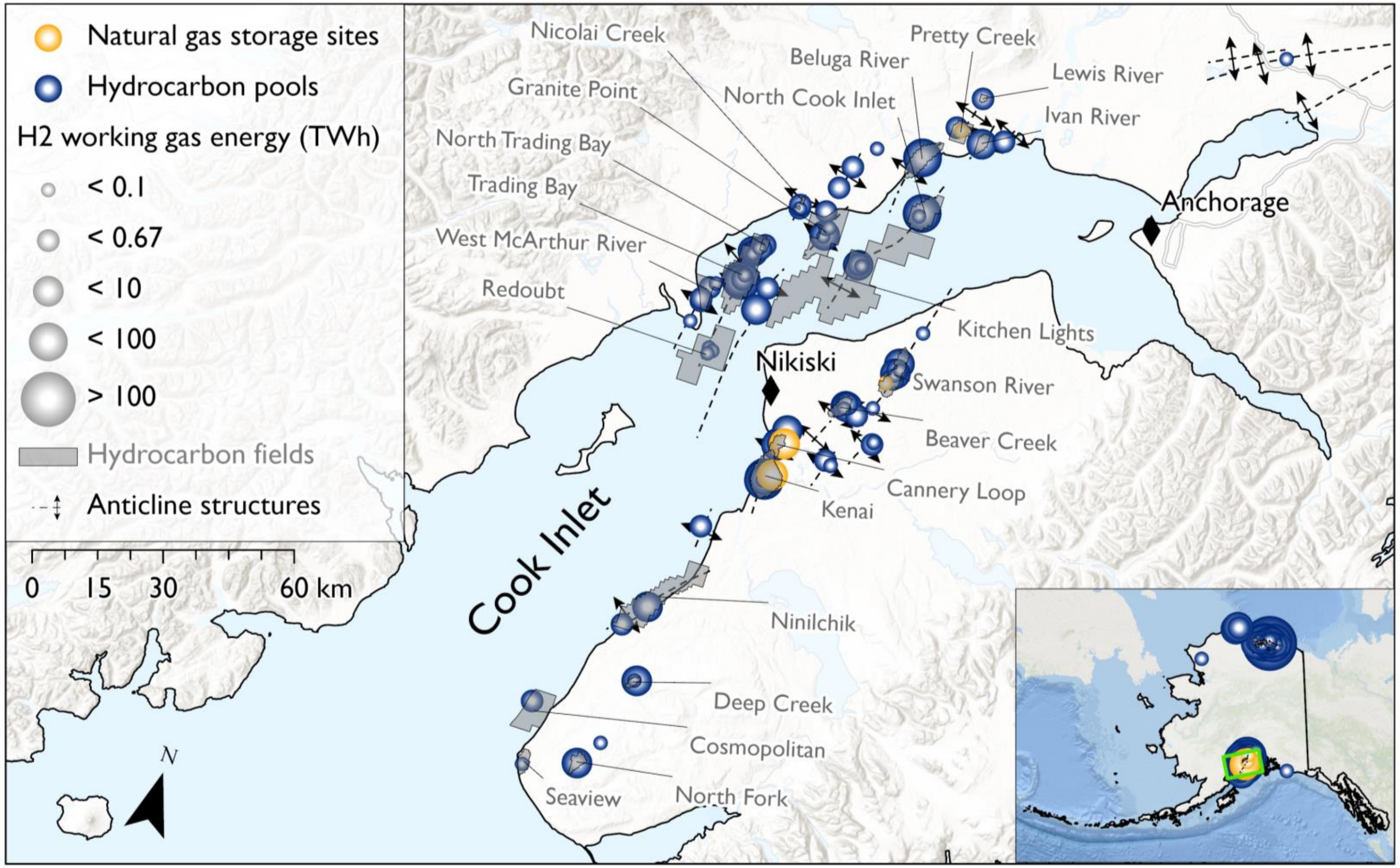
1) Storage volume assessment

*Will a storage site provide enough **storage volume** for hydrogen gas to meet storage needs?*

2) Physical and chemical suitability assessment

*Will a storage site **contain and control** the hydrogen for effective storage?*
*Will a storage site prevent adverse **biogeochemical** interactions?*

Cook Inlet, Alaska



1. Storage volume
2. Physical and chemical suitability

286 TWh H_2 working gas in the Cook Inlet

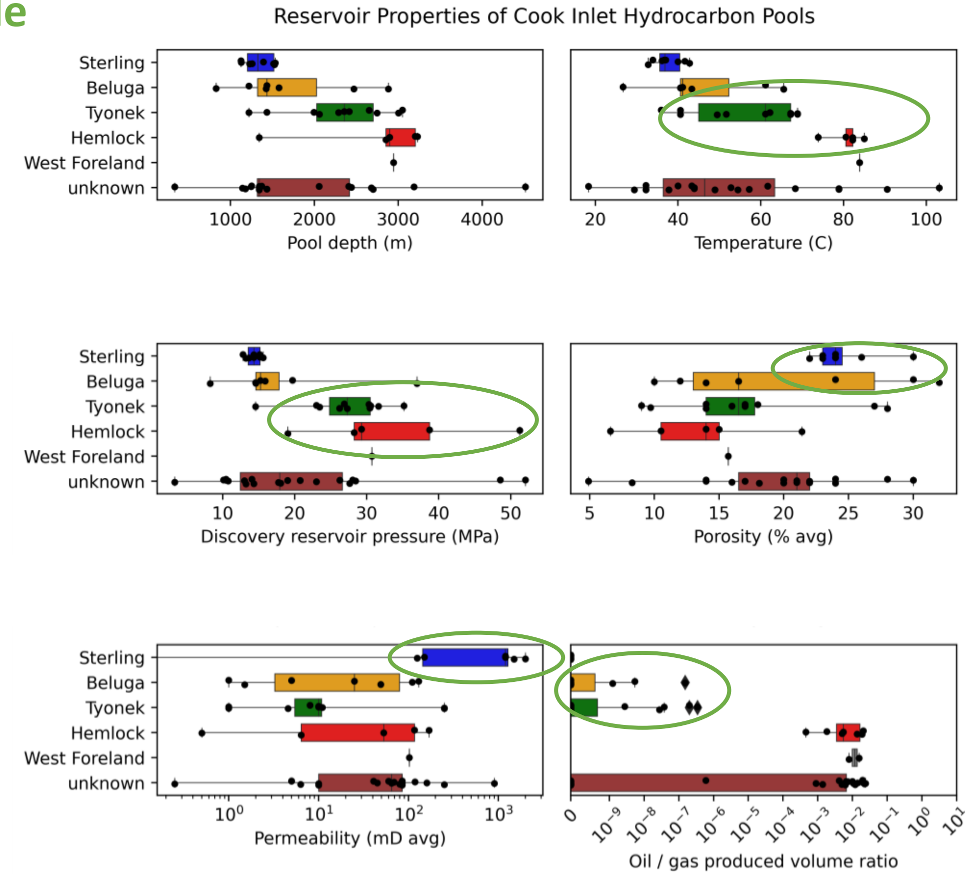
29 hydrocarbon pools and **two natural gas storage pools** could meet a theoretical H_2 storage demand

48 pools are currently unused

Cook Inlet, Alaska

= **potentially favorable**

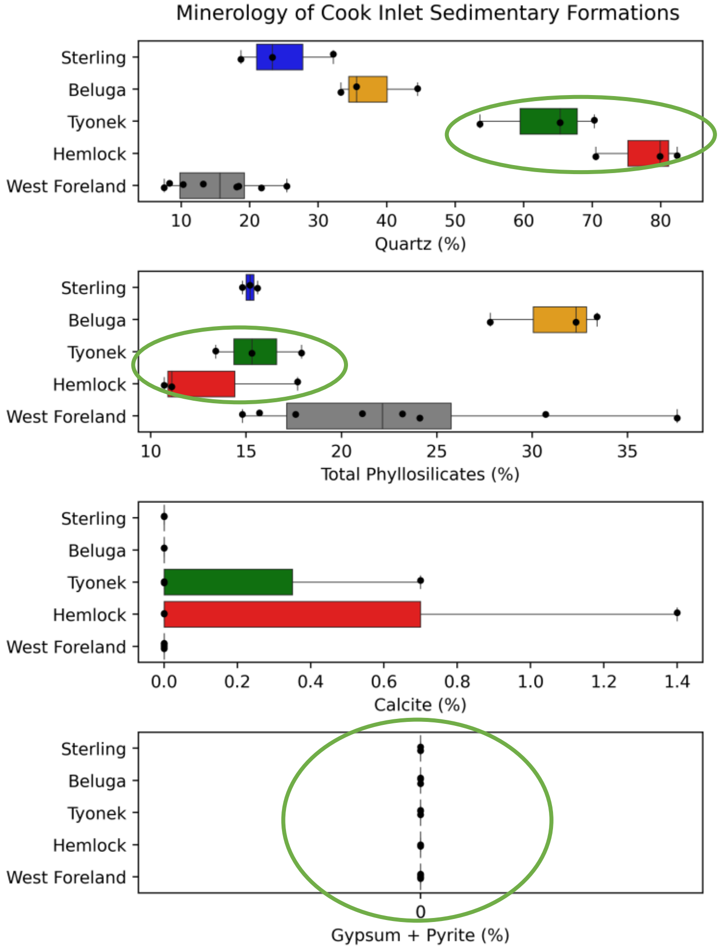
1. Storage volume
2. Physical and chemical suitability



Some formations exhibit **higher temperatures and pressures, better porosity and permeability, and lower oil saturations**

Some formations are <u>relatively</u> **quartz-rich** and **clay poor**

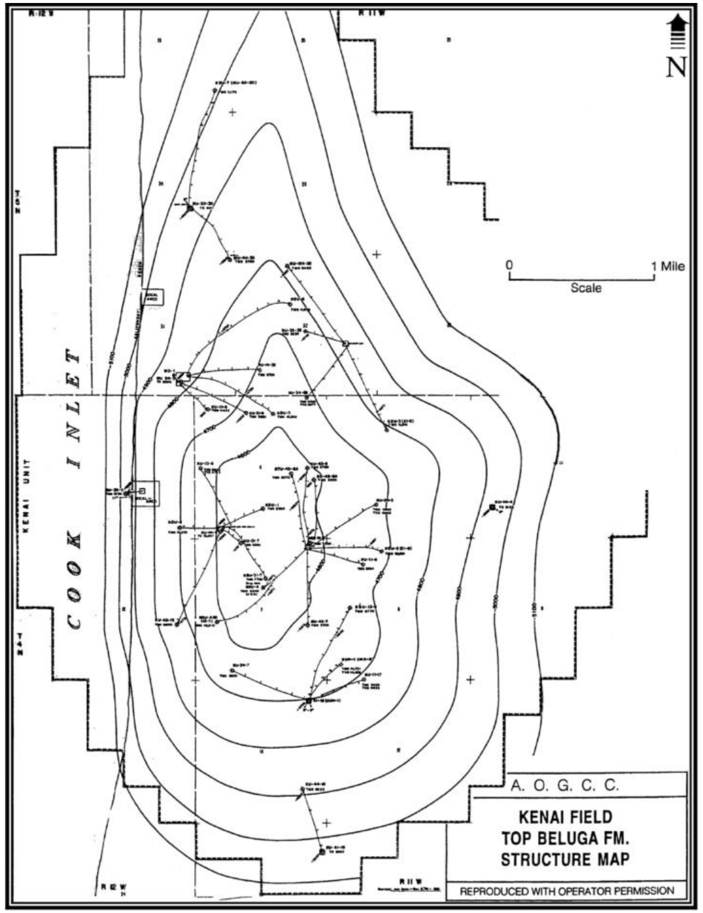
All exhibit low calcite and no gypsum or pyrite

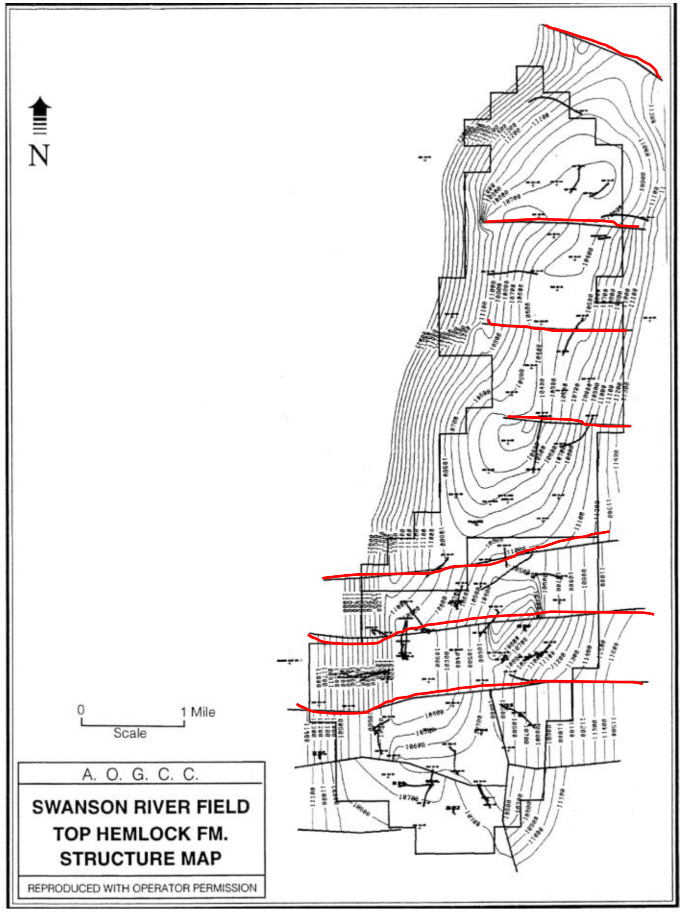


Cook Inlet, Alaska

1. Storage volume

2. Physical and chemical suitability





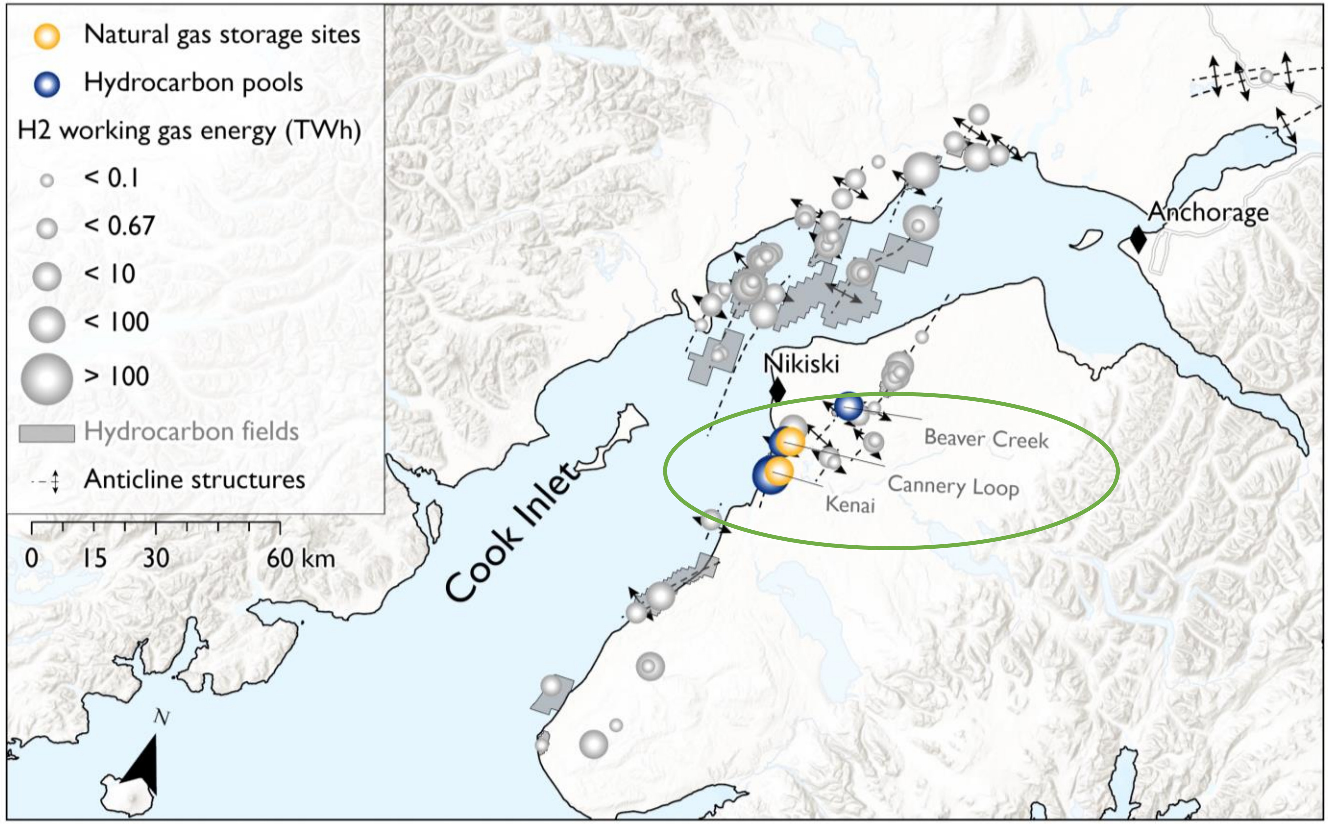
Some pools exhibit **four-way closure with minimal faulting**, others exhibit three-way closure with significant faulting

All pools likely exhibit anticlinal trapping structures with varying amounts of faulting

Cook Inlet, Alaska

- **Seven** out of 92 pools offer available and adequate storage volumes and potentially favorable characteristics for hydrogen storage

- Next steps are site characterization and development



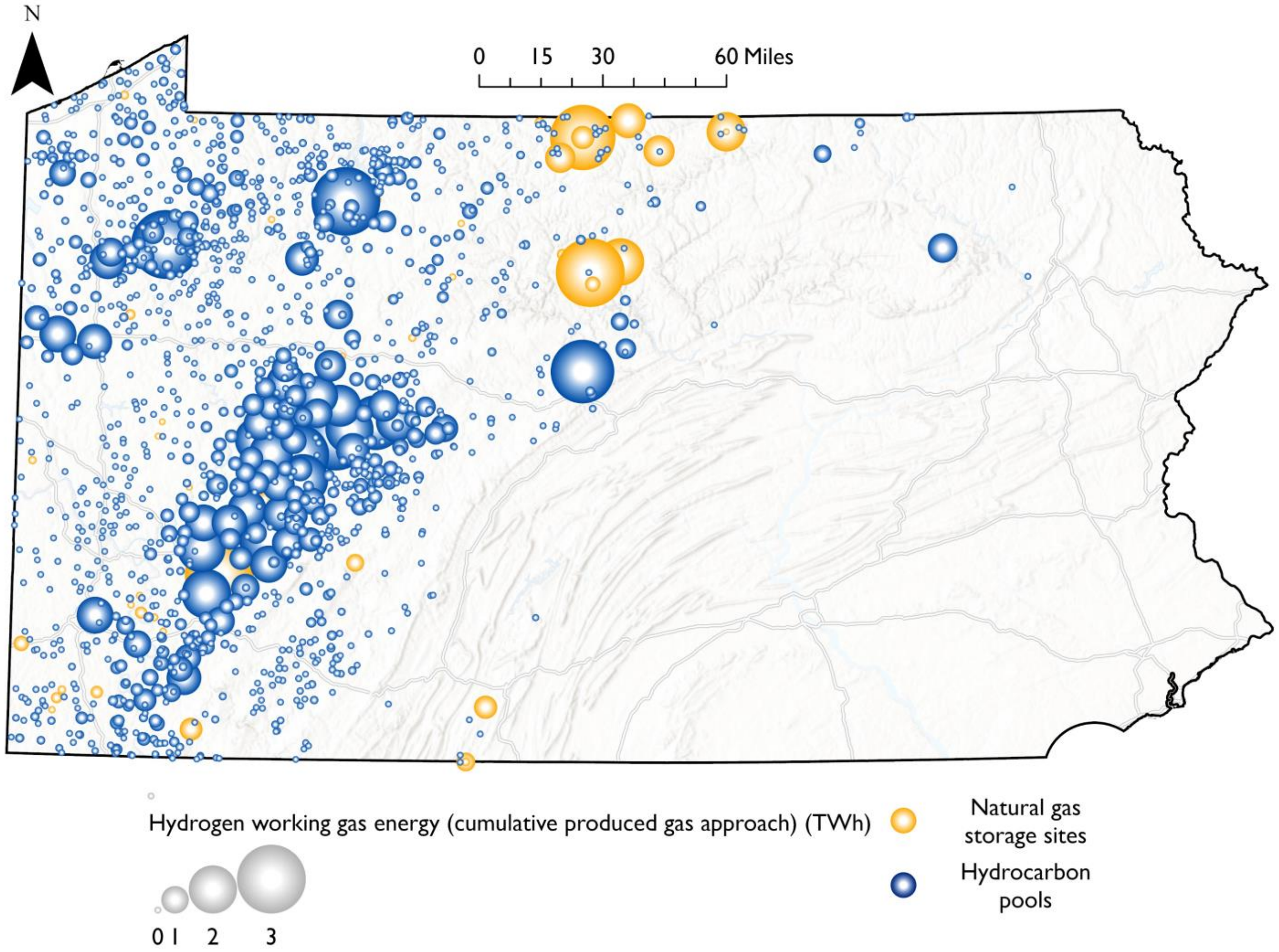
Submitted to *Applied Energy*

Underground Hydrogen Storage Resource Assessment for the Cook Inlet, Alaska

Leon Hibbard[a,*], Joshua A. White[b], David G. Clarke[d], Simon Harrison[d], Angela Goodman[e], Franek Hasiuk[c], Richard A. Schultz[f], Nicolas Huerta[a]

Pennsylvania

1. Storage volume
2. Physical and chemical suitability

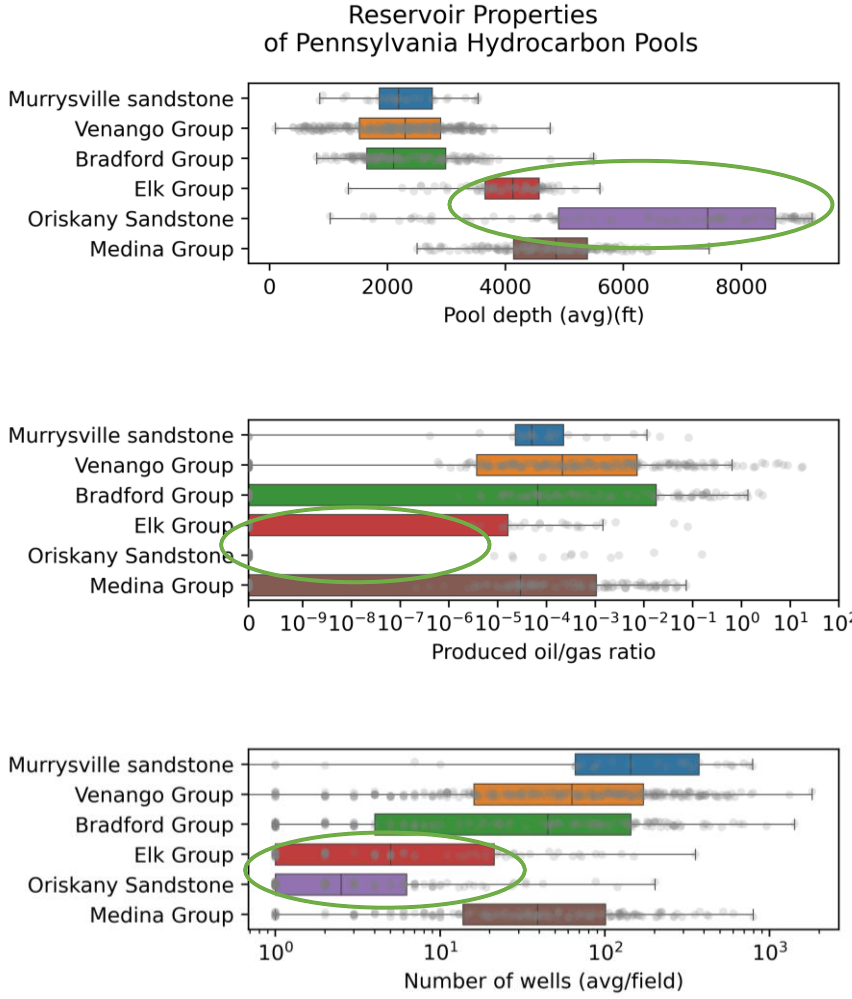


Hydrocarbon pools in Pennsylvania could store between **100 and 2,100 TWh H_2 working gas energy**, depending on estimation methods

Pennsylvania

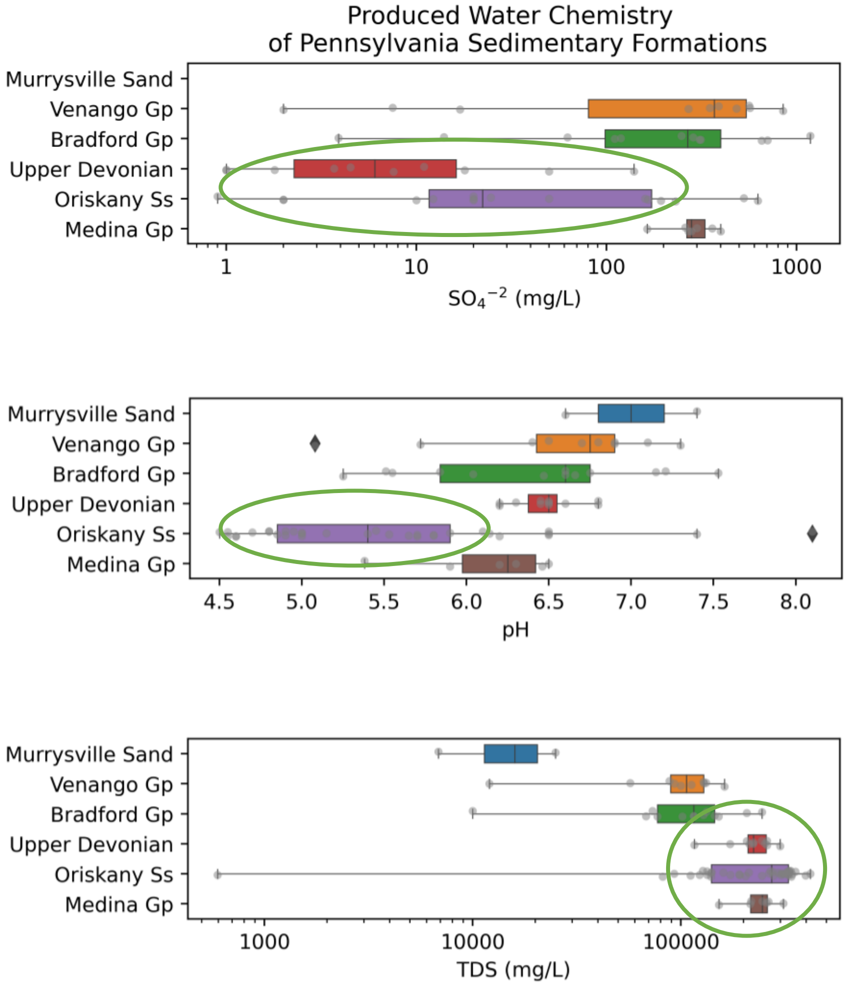
= potentially favorable

1. Storage volume
2. Physical and chemical suitability



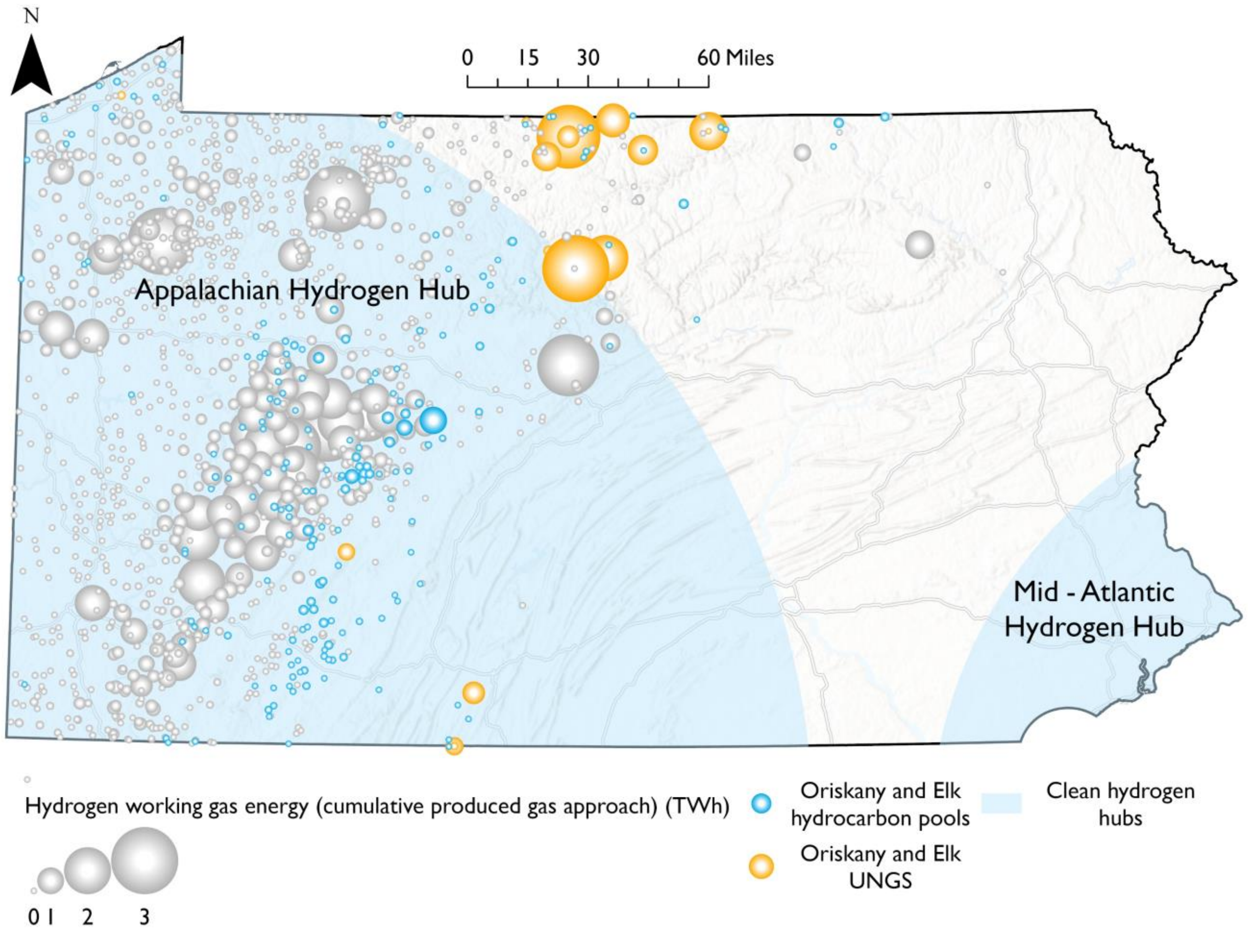
Some formations exhibit **greater depths**, **lower oil saturations**, and **less wells per pool**

Some formations exhibit relatively **low sulfate**, **PH**, and **high salinity**



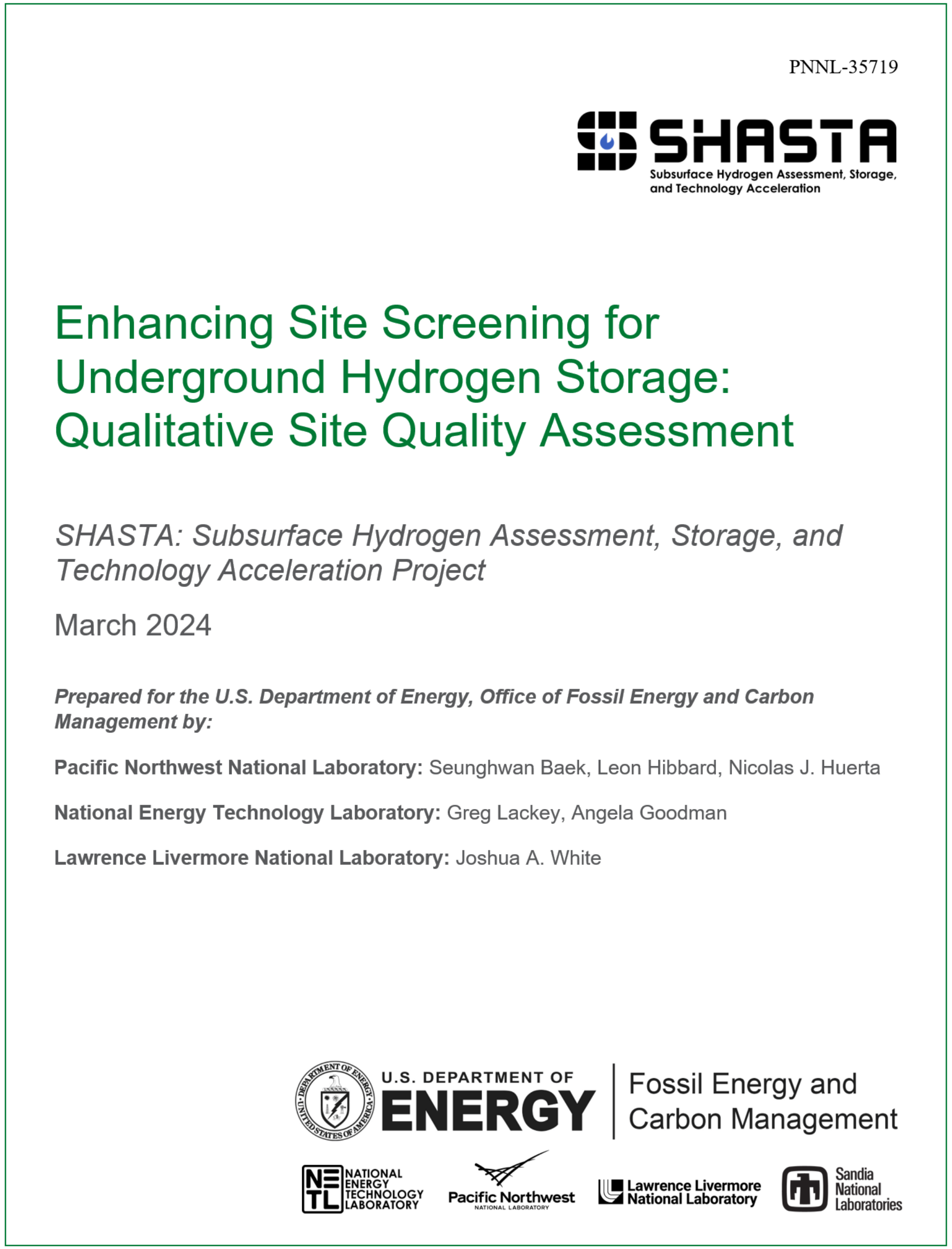
Pennsylvania

- Hydrogen storage volume estimates vary widely based on methodology
- Some formations (Oriskany, Elk) exhibit properties that might be relatively favorable for hydrogen storage
- Because of the large selection of potential sites, hydrogen hubs in different areas of the state will drive further characterization efforts



Conclusions

- Data availability and quality varies substantially between states
- Broadly, we demonstrate an adaptable **methodology for assessing hydrogen storage** opportunities on different scales
- Specifically, we **directly support hydrogen development** in the case study areas
- Future **primary research into hydrogen storage will improve regional assessments**


PNNL-35719

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Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Enhancing Site Screening for Underground Hydrogen Storage: Qualitative Site Quality Assessment

SHASTA: Subsurface Hydrogen Assessment, Storage, and Technology Acceleration Project

March 2024

Prepared for the U.S. Department of Energy, Office of Fossil Energy and Carbon Management by:

Pacific Northwest National Laboratory: Seunghwan Baek, Leon Hibbard, Nicolas J. Huerta

National Energy Technology Laboratory: Greg Lackey, Angela Goodman

Lawrence Livermore National Laboratory: Joshua A. White

U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

Underground Hydrogen Storage Resource Assessment for the Cook Inlet, Alaska

Leon Hibbard[a,*], Joshua A. White[b], David G. Clarke[d], Simon Harrison[d], Angela Goodman[e], Franek Hasiuk[c], Richard A. Schultz[f], Nicolas Huerta[a]

Thank you

- SHASTA Team

- Alaska Marine Power, Pennsylvania Geological Survey, U.S. Department of Energy, all other contributors for integral support during these case studies

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Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

amp
alaska marine power

DCNR
pennsylvania
DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

Questions?

leon.hibbard@pnnl.gov

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Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Local and Region-Scale Technoeconomic Analysis Framework for Subsurface Hydrogen Storage

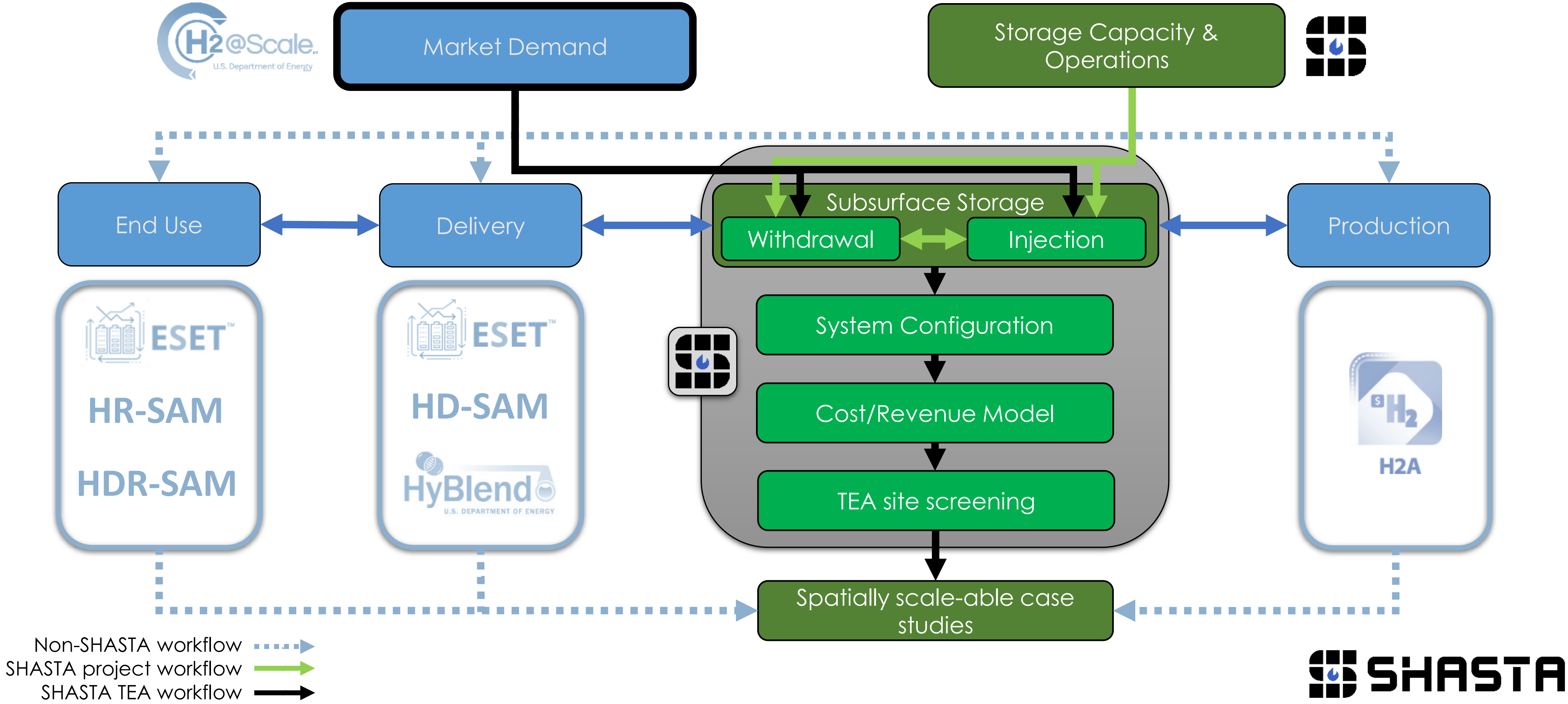
Gerad M. Freeman, Shruti Khadka Mishra, Sumitrra Ganguli, Wilfried Kabre, Candace Briggs, Nicolas J. Huerta

SHASTA Technical Workshop
2024 NETL Resource Sustainability Project Review Meeting
Wednesday, April 4, 2024
Wyndham Grand Hotel, Pittsburgh, PA

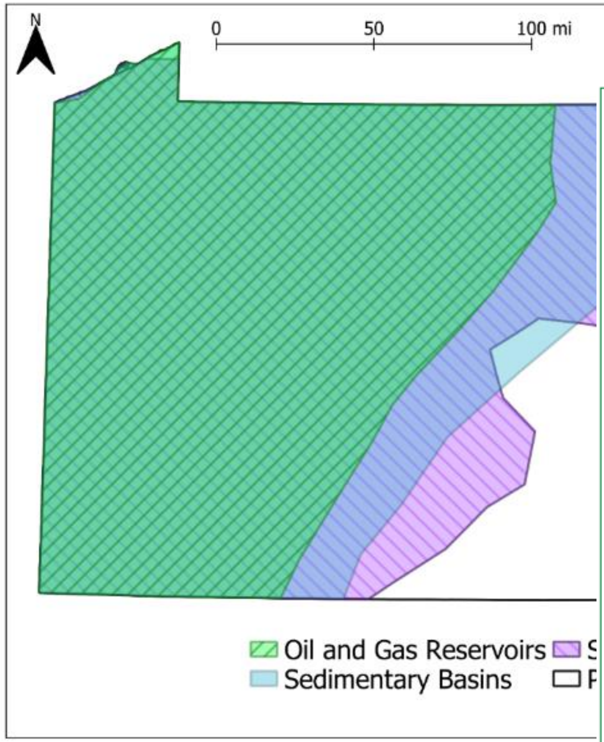
Presentation Outline

1. SHASTA Technoeconomic Analysis (TEA) Overview
2. Market & Demand Assessment Approach
3. Cost Estimation Approach
4. Conclusions and Next Steps

SHASTA-TEA New Capability Development



Study Areas



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PNNL-35058

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Local-Scale Framework for Techno-Economic Analysis of Subsurface Hydrogen Storage

SHASTA: Subsurface Hydrogen Assessment, Storage, and Technology Acceleration Project

September 2023

Prepared for the U.S. Department of Energy, Office of Fossil Energy and Carbon Management by:

Sandia National Laboratories: Shruti Khadka Mishra

Pacific Northwest National Laboratory: Sumitrra Ganguli, Gerad Freeman, Malcolm Moncheur de Rieudotte, Nicolas Huerta

https://www.osti.gov/servlets/purl/2202473

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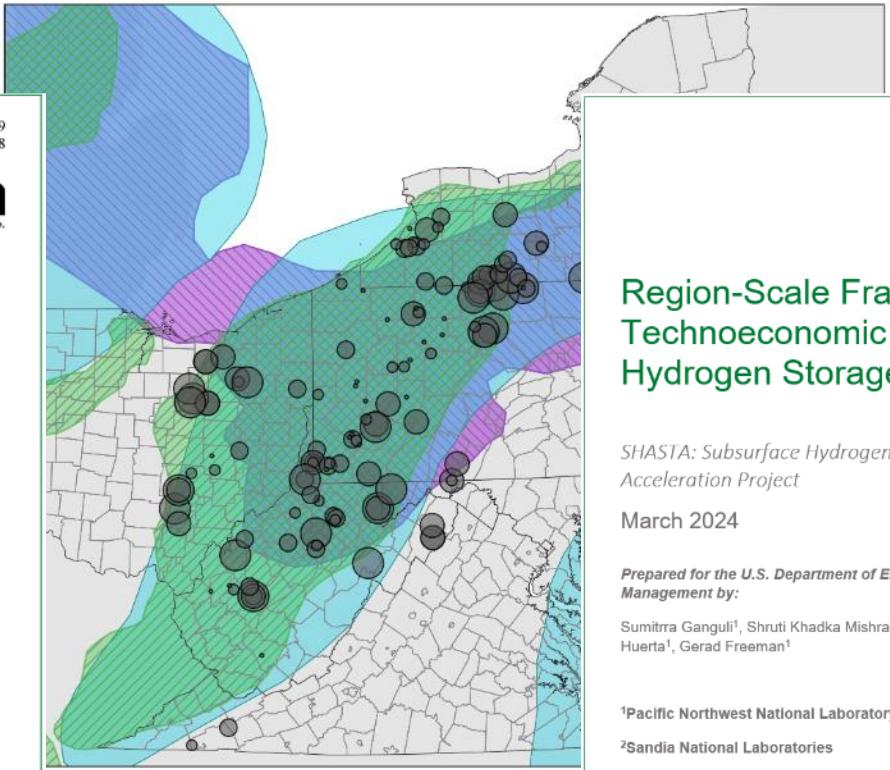

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Region-Scale Framework for Technoeconomic Analysis of Subsurface Hydrogen Storage

SHASTA: Subsurface Hydrogen Assessment, Storage, and Technology Acceleration Project

March 2024

Prepared for the U.S. Department of Energy, Office of Fossil Energy and Carbon Management by:

Sumitrra Ganguli[1], Shruti Khadka Mishra[2], Wilfried Kabre[1], Candace D Briggs[1], Nicolas Huerta[1], Gerad Freeman[1]

[1]**Pacific Northwest National Laboratory**

[2]**Sandia National Laboratories**

(Forthcoming)

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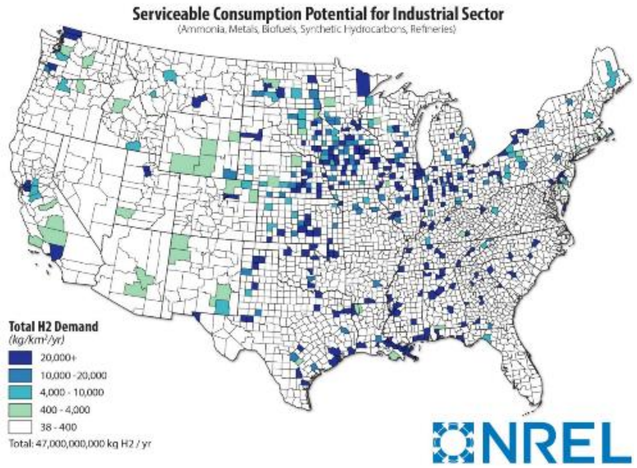
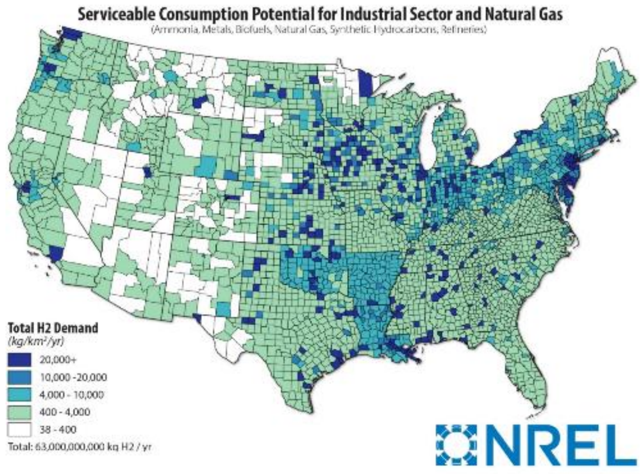
Subsurface Hydrogen Storage Market and Demand Assessment

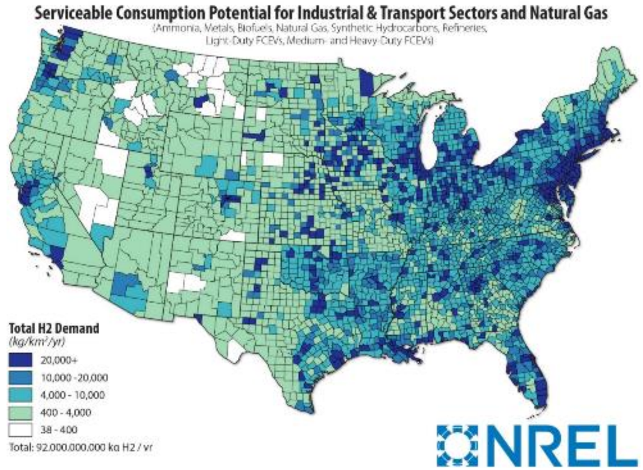
H2@Scale's 2050 hydrogen market potential estimates

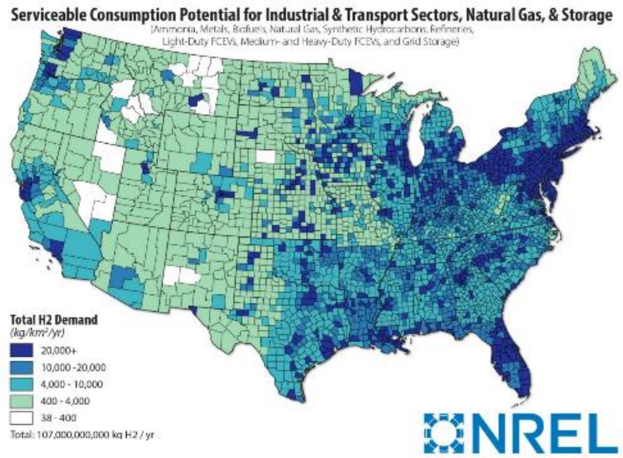
U.S. Department of Energy

- **Major H_2 Market Sectors:**
  - Industrial : petroleum refining, metals refining, ammonia production, biofuels, synthetic hydrocarbons
  - Natural Gas : blending of low H_2 concentrations (up to 20% by volume) into the natural gas pipeline system
  - Transport : light, medium and heavy-duty H_2-powered vehicle adoption
  - (Grid) Storage : modeled amount of green H_2 produced during off-peak periods and stored to later use to replace NGCT and NGCC power generation during peak electricity demand.









Source: Ruth, et al. 2020, *The Technical and Economic Potential of the H2@Scale Concept within the United States.* https://www.nrel.gov/docs/fy21osti/77610.pdf

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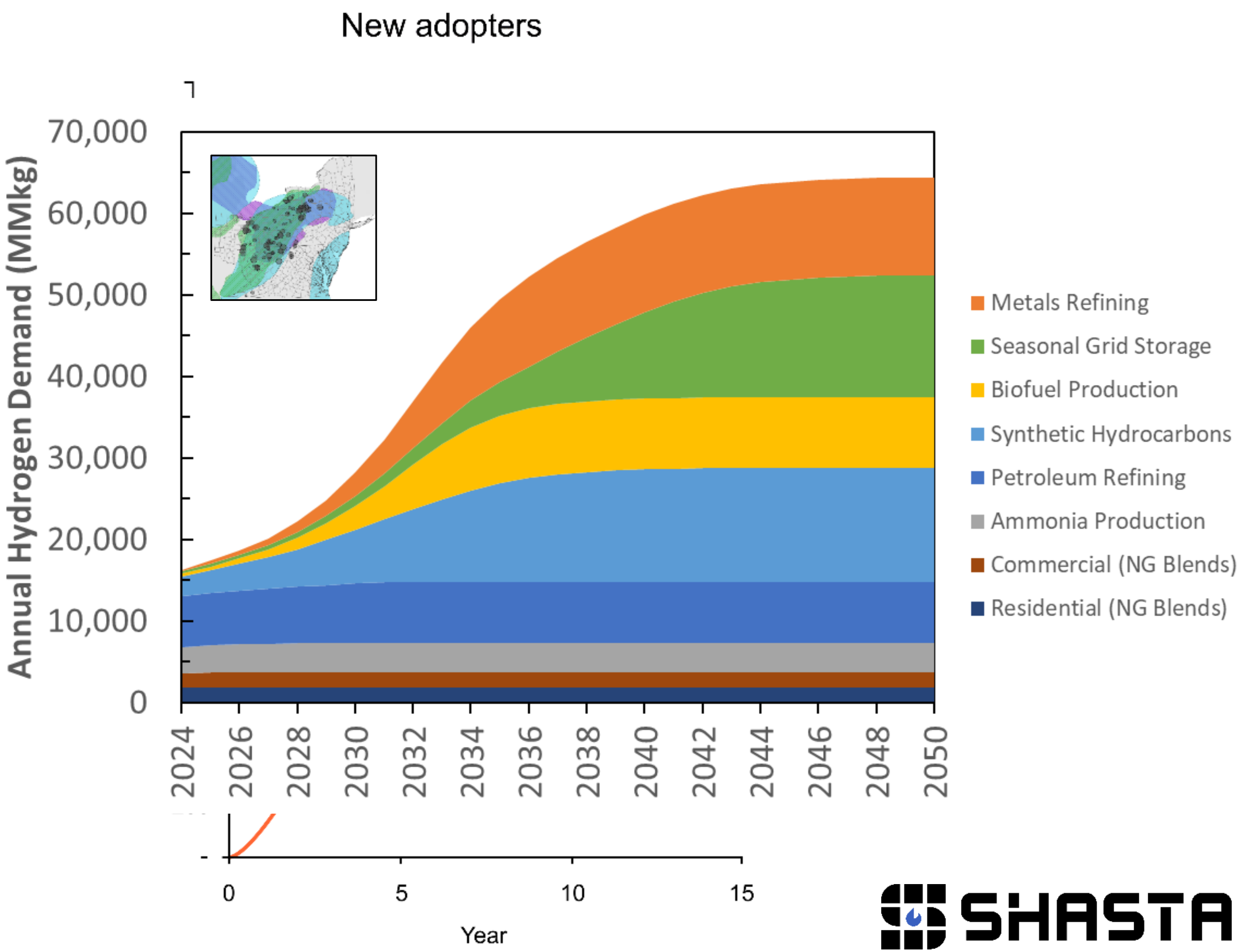
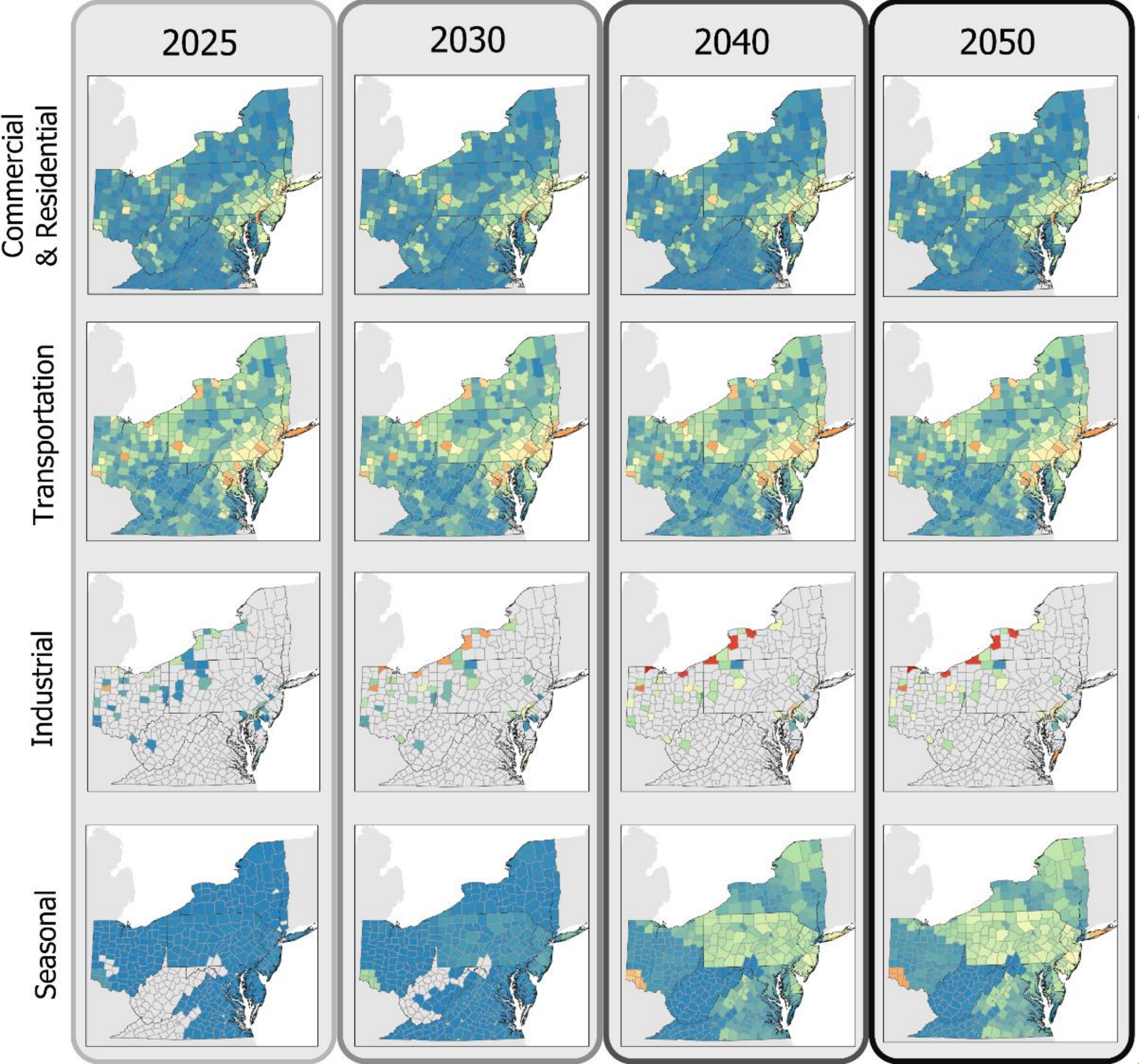
Moving from static end-point estimation to staged adoption model

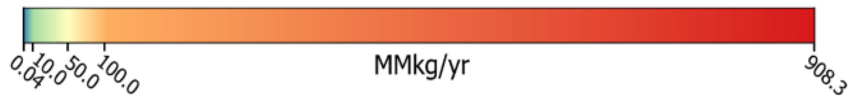
- Logistic-shaped adoption model based on Bass (1969) for new H_2 uses in industrial, chemical and power sectors
- Data-driven auto-regressive integrated moving average (ARIMA) model for natural gas blending for residential and commercial use
- Bounding by two adoption scenarios:
  - **This talk:** full market realization: "serviceable consumption potential" defines endpoint of Bass model in 2050
  - **Future work:** "economic potential" defines endpoint of Bass model in 2050



Where will H_2 demand be?



Market Size Projection



Relating 2050 total demand to annual storage need

- Current Underground Gas Storage (UGS) facilities buffer ~11% of annual natural gas consumption but available working gas volume could buffer up to 16% if needed (Lackey et al., 2023).
- Will H_2 demand patterns change UGS cycling behavior?
  - Industrial : petroleum, metals, ammonia, biofuels, hydrocarbons
    - Through 2050, timing of demands [more or less] unchanged. Just a ramp up/build more storage capacity?
  - Natural Gas : up to 20% H_2 blended with natural gas
    - Timing of demand unchanged. In the long run, will low concentrations be enough to overcome natural gas industry trends?
  - Transport : H_2-powered vehicles
    - Would switching to H_2 lead to a change in commute and travel behavior in the long run?
  - (Grid) Storage : green H_2 for peak power generation
    - If we're replacing NGCT/NGCC demand, cycling behavior created by timing of power grid peaks might not chance very much.

Pennsylvania Case Study Example:

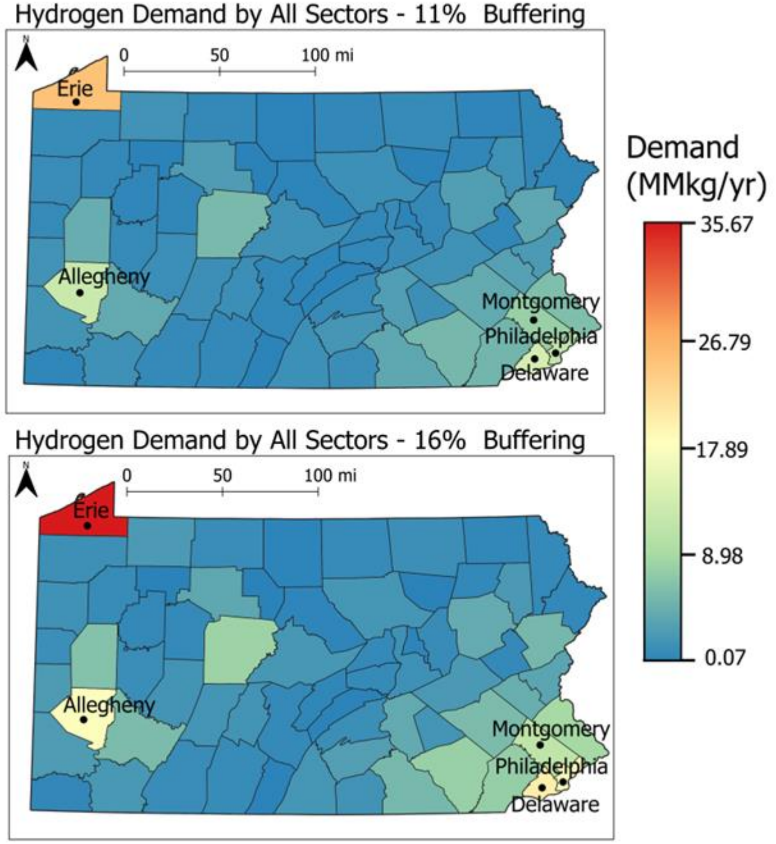
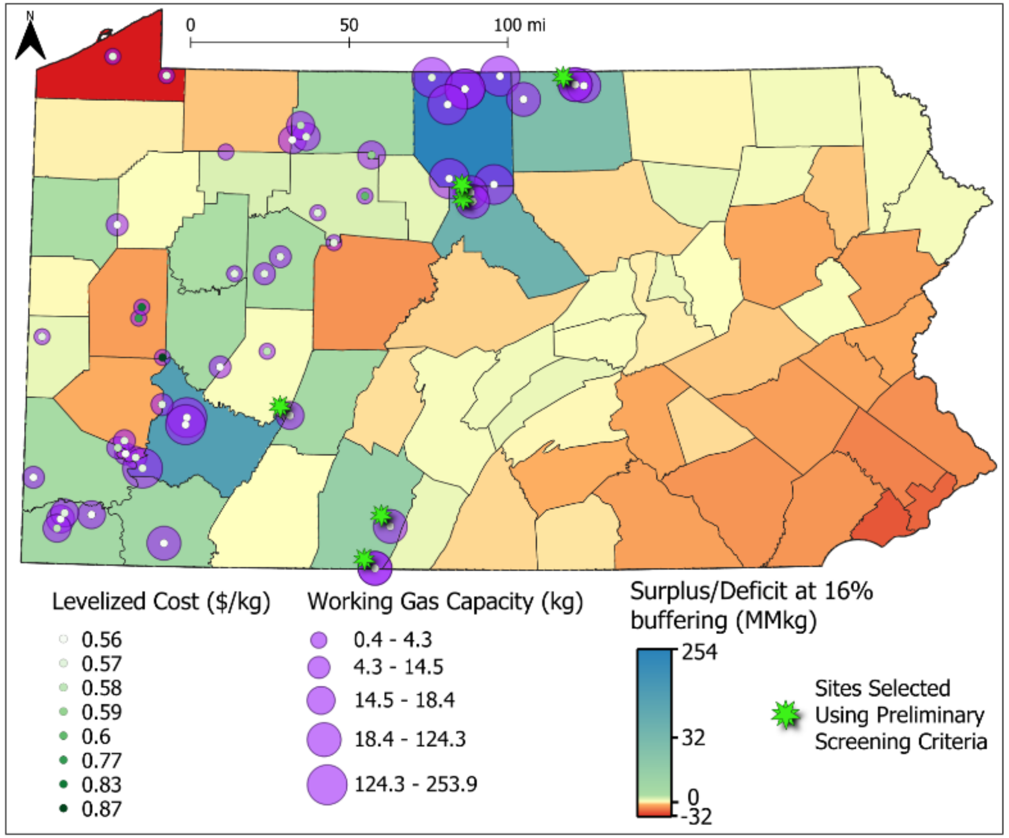


Image: Mishra, et al. 2023, *Local-Scale Framework for Techno-Economic Analysis of Subsurface Hydrogen Storage.* https://www.osti.gov/servlets/purl/2202473

Underground Hydrogen Storage (UHS) Site TEA Screening Applications

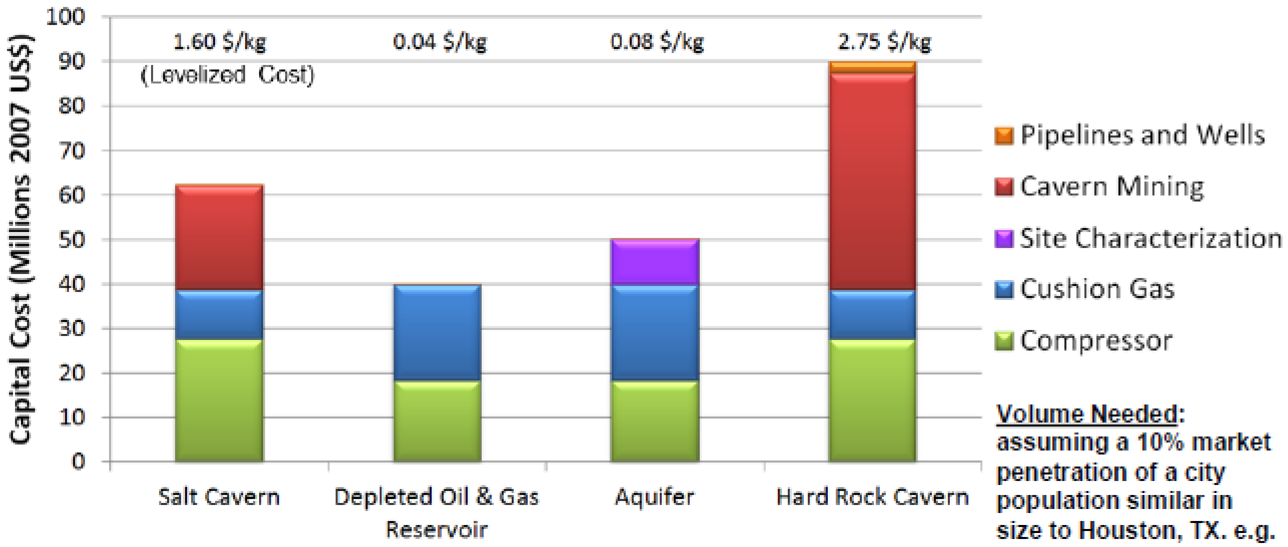


- **Possible screening criteria:**
  - Favor sites in areas that have excess working gas mass in their storage facilities relative to anticipated local storage demand
  - ***Then*** screen by cost of storage . . .

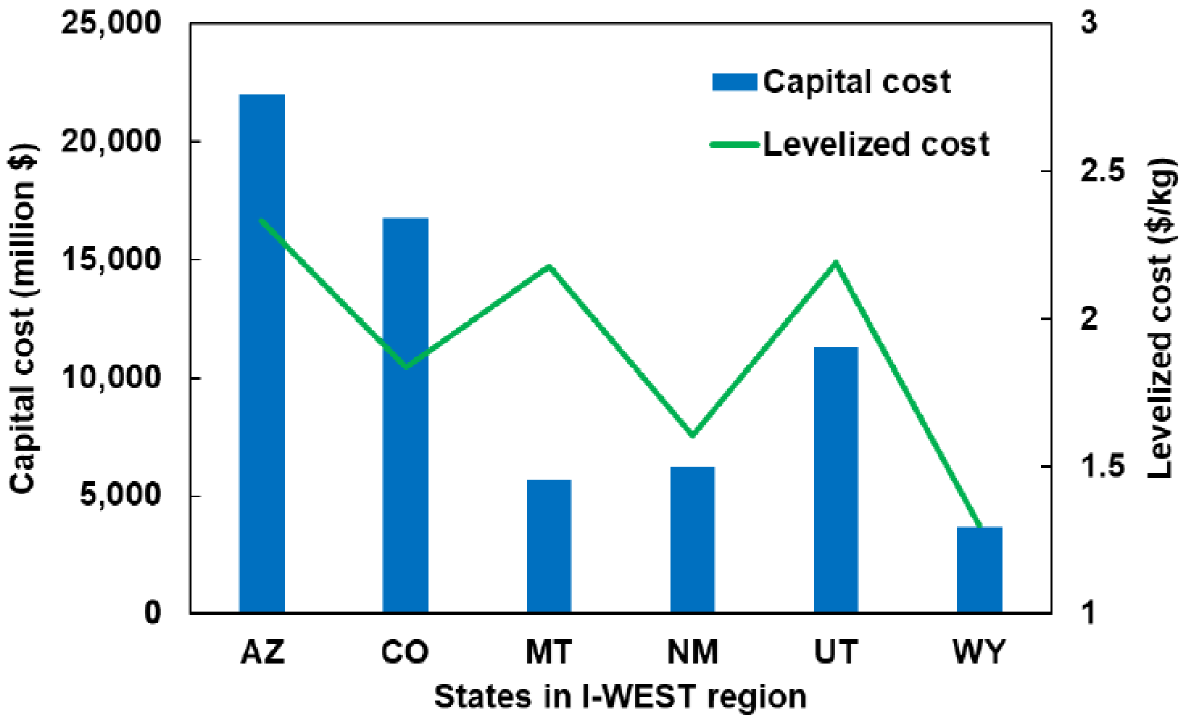
Image: Mishra, et al. 2023, *Local-Scale Framework for Techno-Economic Analysis of Subsurface Hydrogen Storage.* https://www.osti.gov/servlets/purl/2202473

Subsurface Hydrogen Storage Cost Estimation

Technoeconomic analyses of H_2 storage in the US show a wide range of costs



Capital cost of UHS – based on Houston, Detroit, Pittsburgh, and Los Angeles (Lord et al., 2014)



Capital and levelized cost of storage – based on 3 geologic sites. (Chen et al., 2022)

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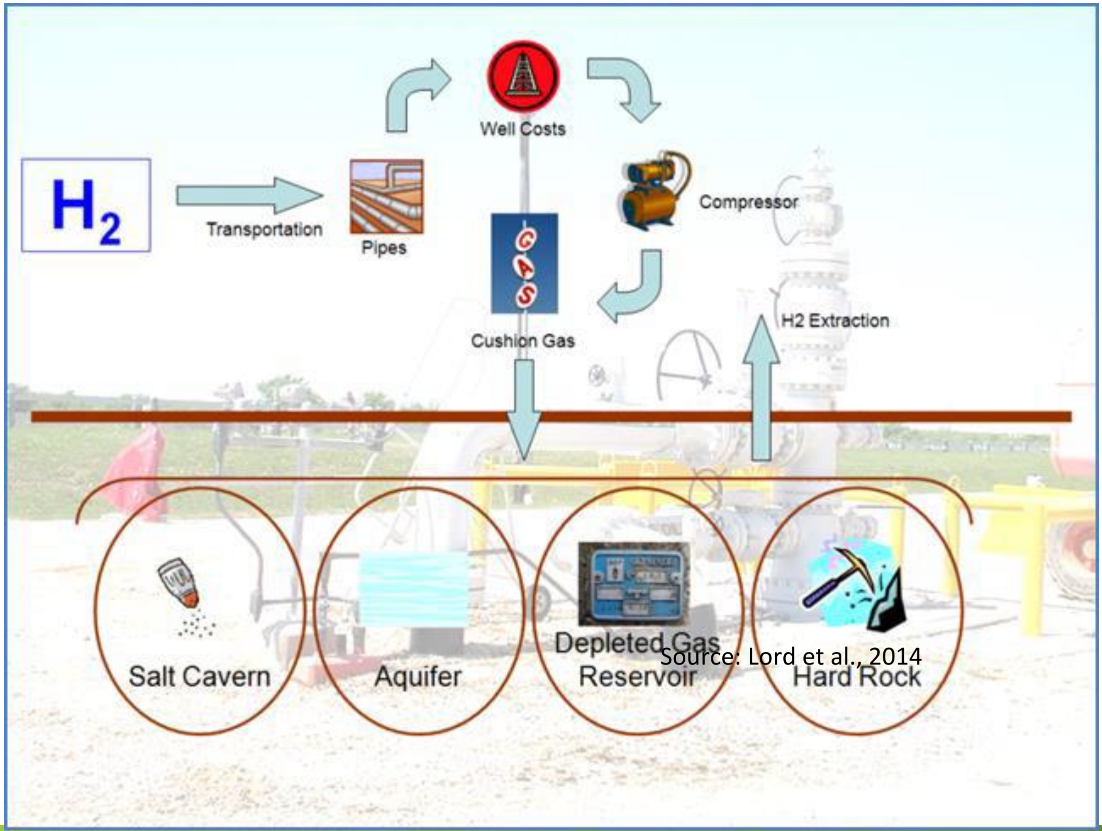
Scope of Technoeconomic Analysis of Underground H_2 Storage

- What are the major cost drivers of UHS that lead to cost minimization?
- What is the magnitude of cost reduction associated with each cost driver?
- How the cost factors affect the UHS cost across storage types?
- How the significance of the cost factors change across UHS facilities in a state?
- What factors drive UHS cost and by how much at a regional scale – multiple states?



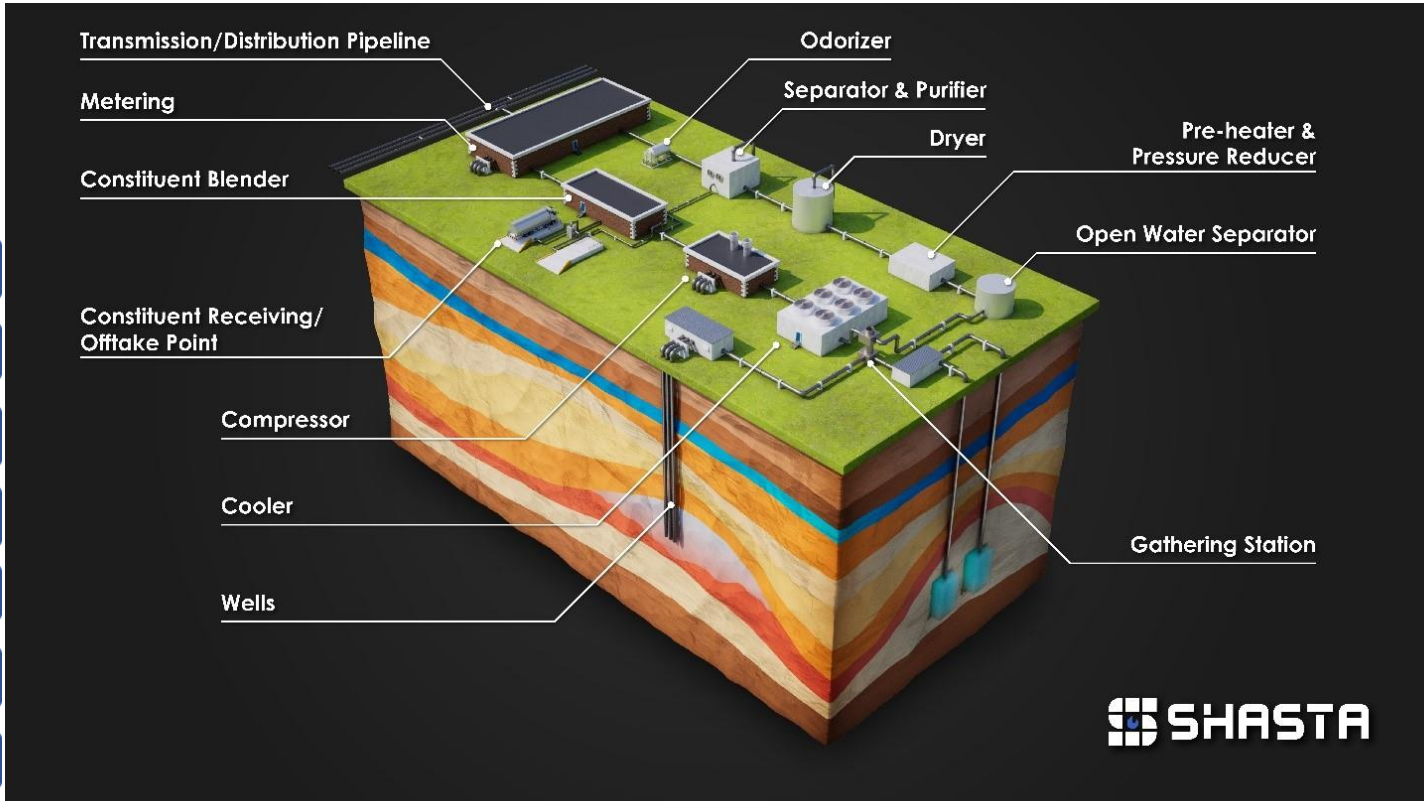
Source: Lord et al., 2014

Cost Estimation Framework for Underground Hydrogen Storage

CAPEX
- Site characterization Cost
- Cushion Gas Capital Cost
- Compressors Capital Cost
- Well construction (or upgrading) Cost
- Monitoring Cost
- Surface Equipment Costs
- Salt Cavern Cost

Levelized Cost ($/kg H_2)

OPEX
- Compression Cost
- Well Operating Cost
- Transportation Cost



For the cost equations for each item, please refer Mishra et al., 2023)

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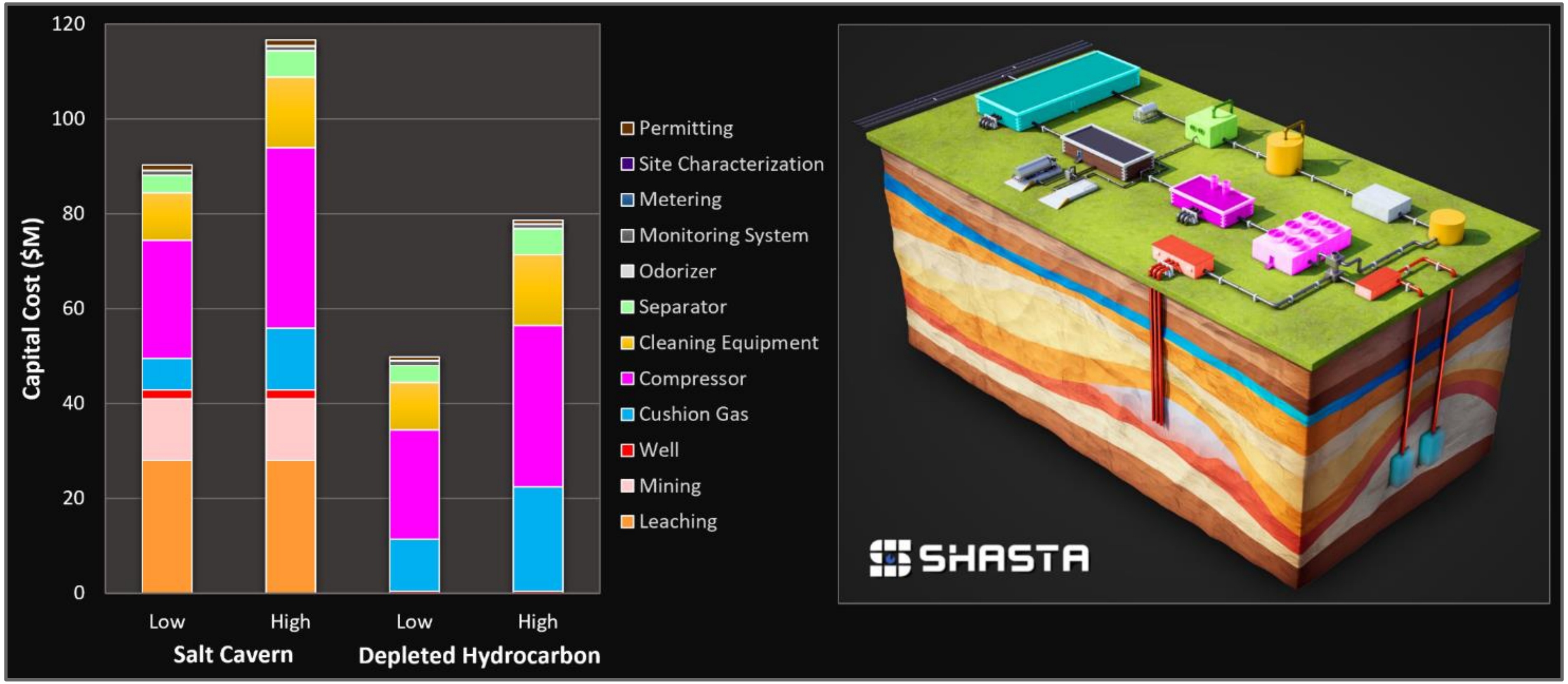
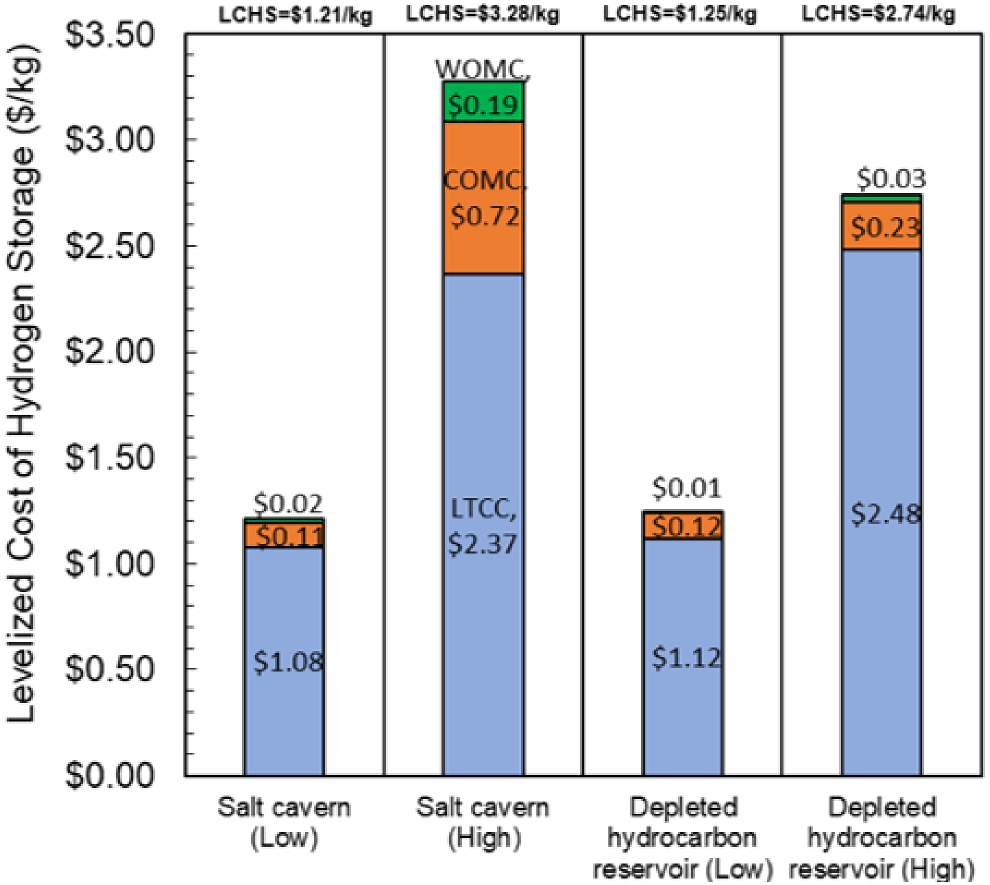
Capital Cost Drivers for Different UHS Types

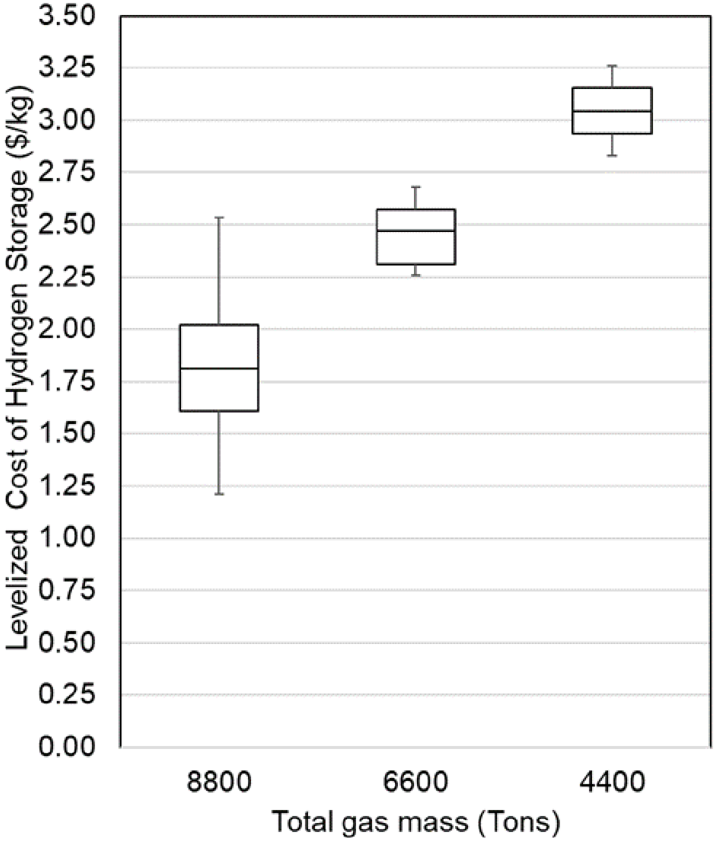


Note: literature-driven results for an example 20 MMcf, single-well facility

Image: Mishra, et al. 2023, *Local-Scale Framework for Techno-Economic Analysis of Subsurface Hydrogen Storage.* https://www.osti.gov/servlets/purl/2202473

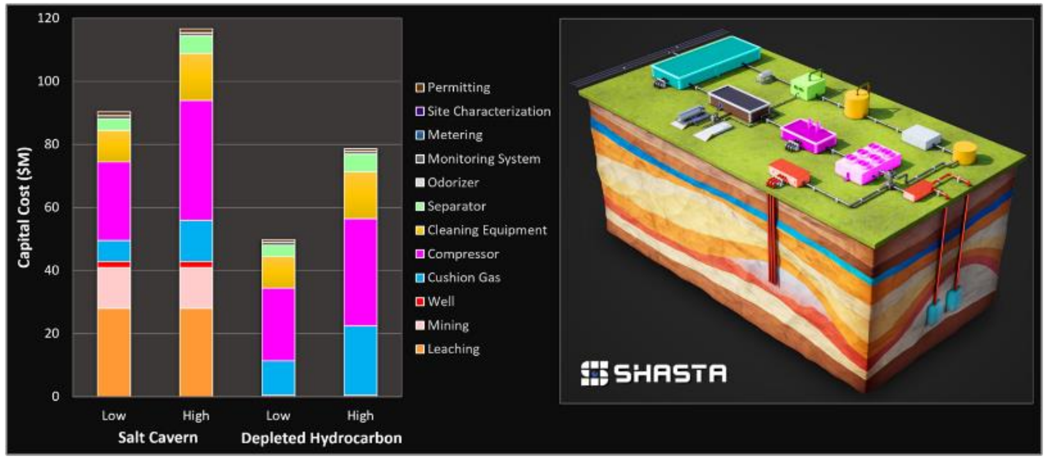
Levelized Cost Drivers for Different UHS Types and Storage Capacity



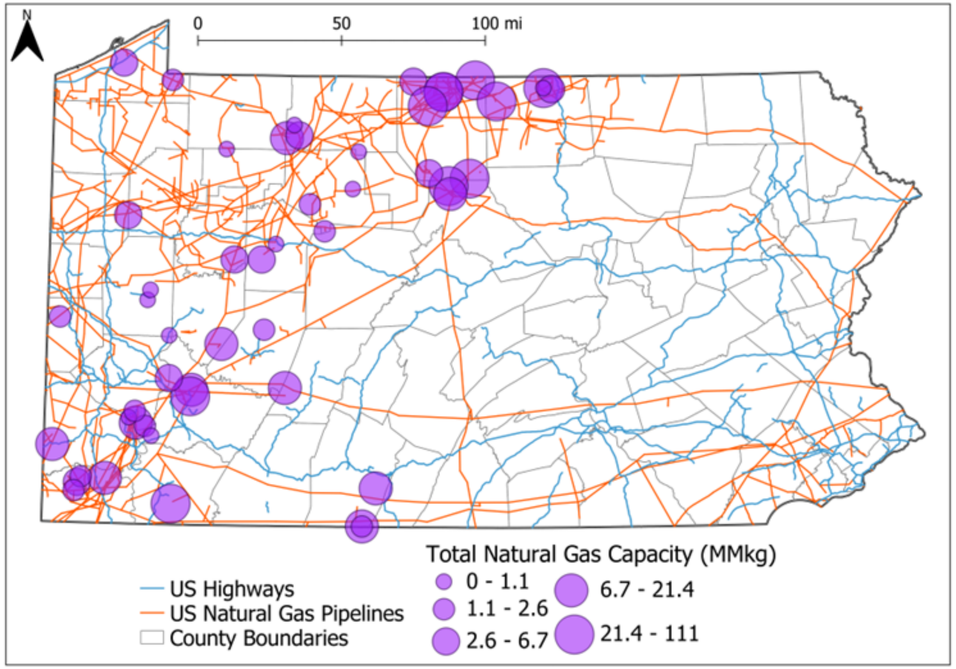


Images: Mishra, et al. 2023, *Local-Scale Framework for Techno-Economic Analysis of Subsurface Hydrogen Storage.* https://www.osti.gov/servlets/purl/2202473

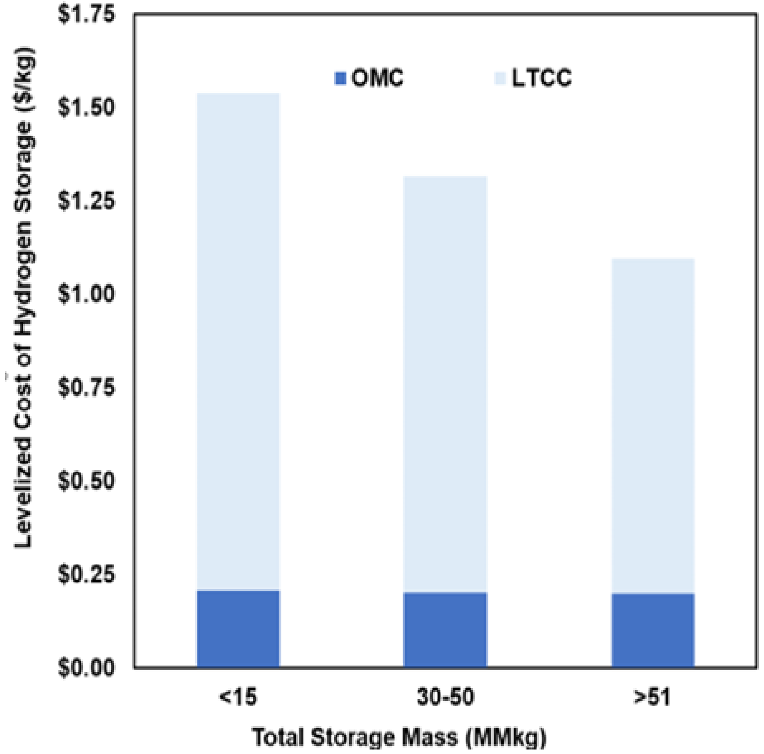
The Cost Factors that Drive the UHS Costs at Sites Across a State

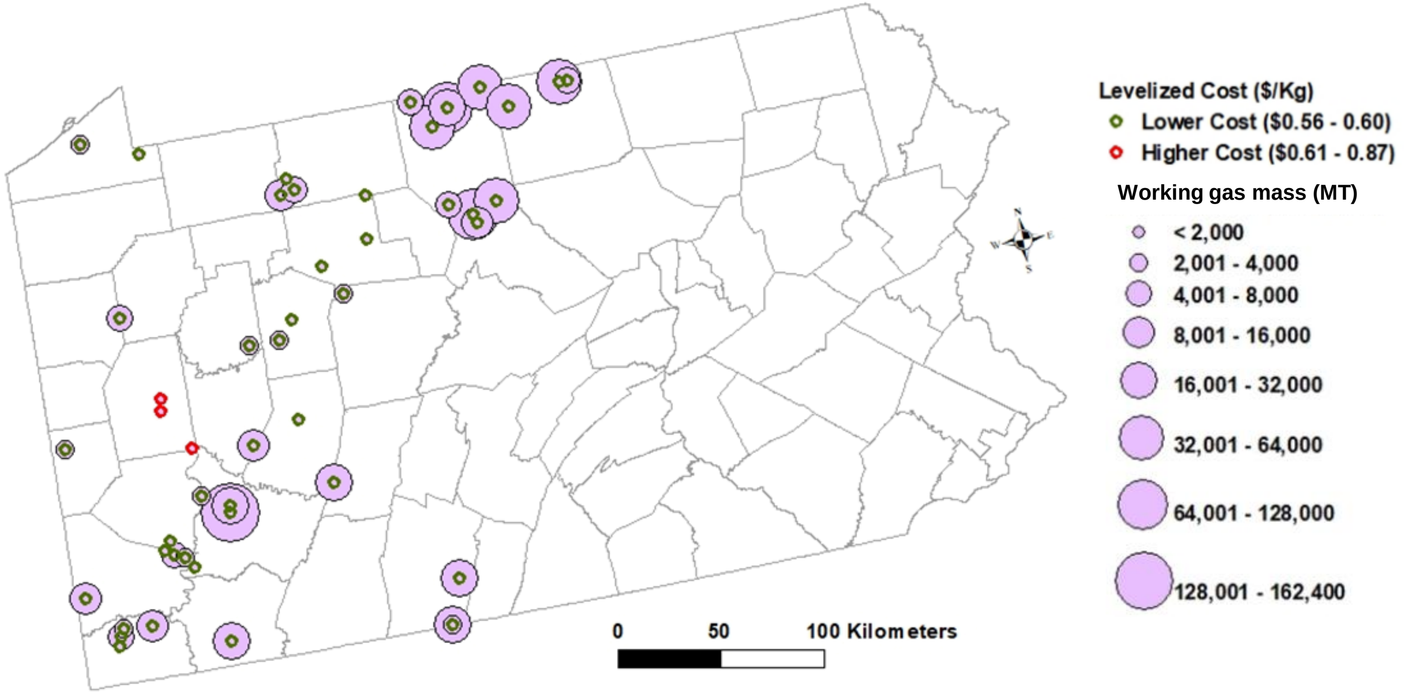


- Working Gas Capacity
- Depth
- Pressure Differential
- Cushion Gas
- …



Levelized Costs Vary Significantly by Storage Sites Characteristics

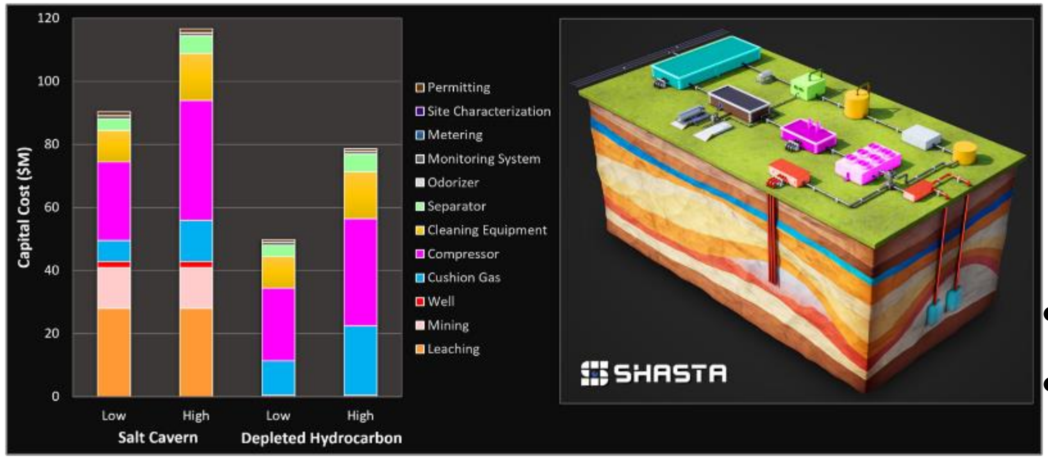




- Levelized cost of hydrogen storage (LCHS) for facilities of the size currently operating in PA were significantly lower than the example facility
- If cushion gas cost is 25% lower, the median LCHS could be reduced by 17- 33%
- If the electricity cost is reduced by 50%, the LCHS could be reduced by an 11% - 29%
- With a lower cushion-gas price and electricity price, the median LCHS could be reduced by 45%.

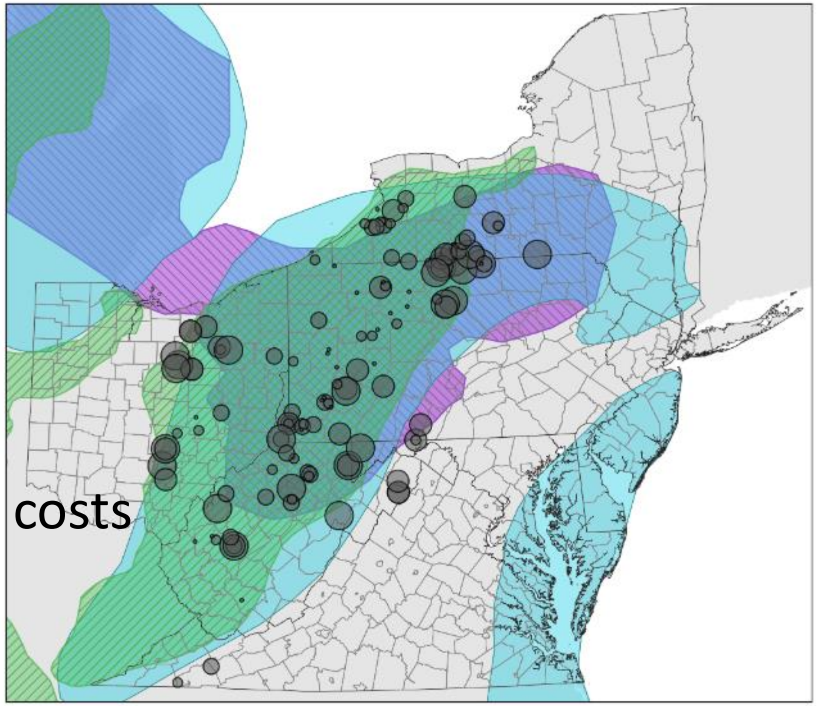
Image: (L) Mishra, et al. 2023, *Local-Scale Framework for Techno-Economic Analysis of Subsurface Hydrogen Storage.* https://www.osti.gov/servlets/purl/2202473

Which cost factors change by site and by state? And, by how much?



?

- Site characteristics
- State-wise variabilities in costs
  - Site preparation cost
  - Permitting cost
  - Well drilling cost
  - Electricity cost
- Cushion gas cost
- …



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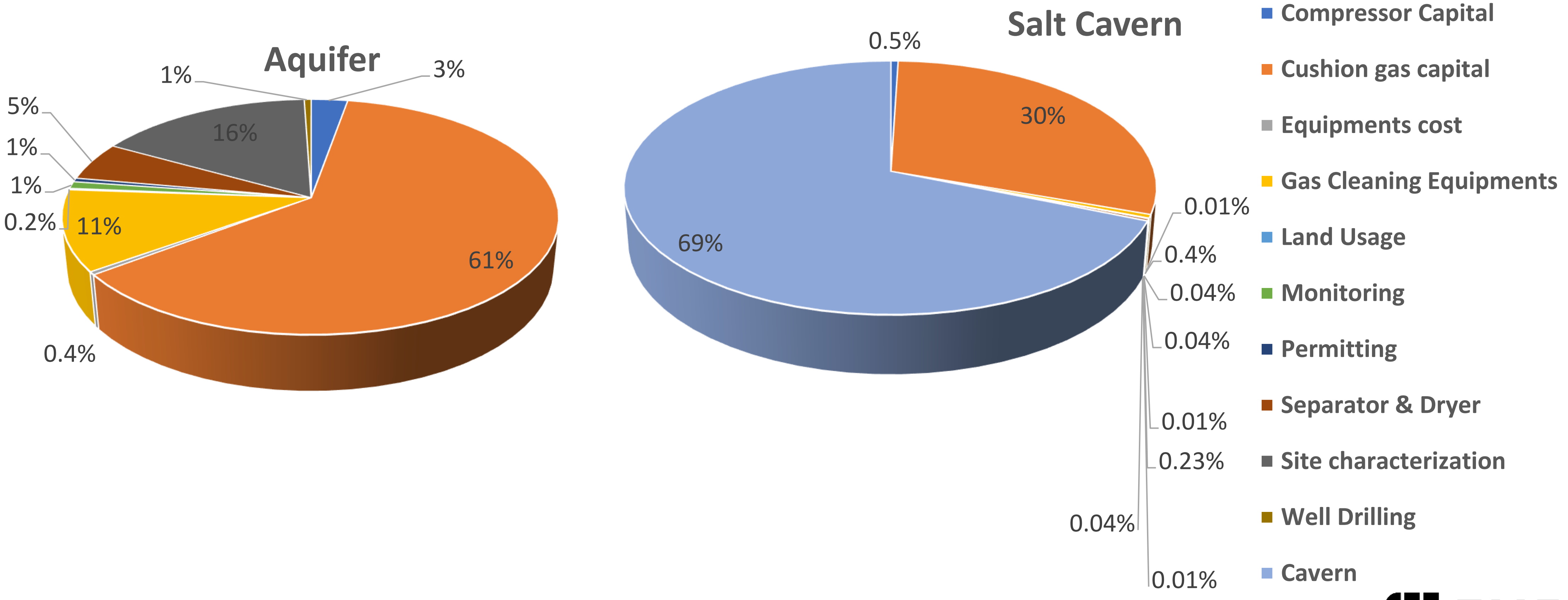
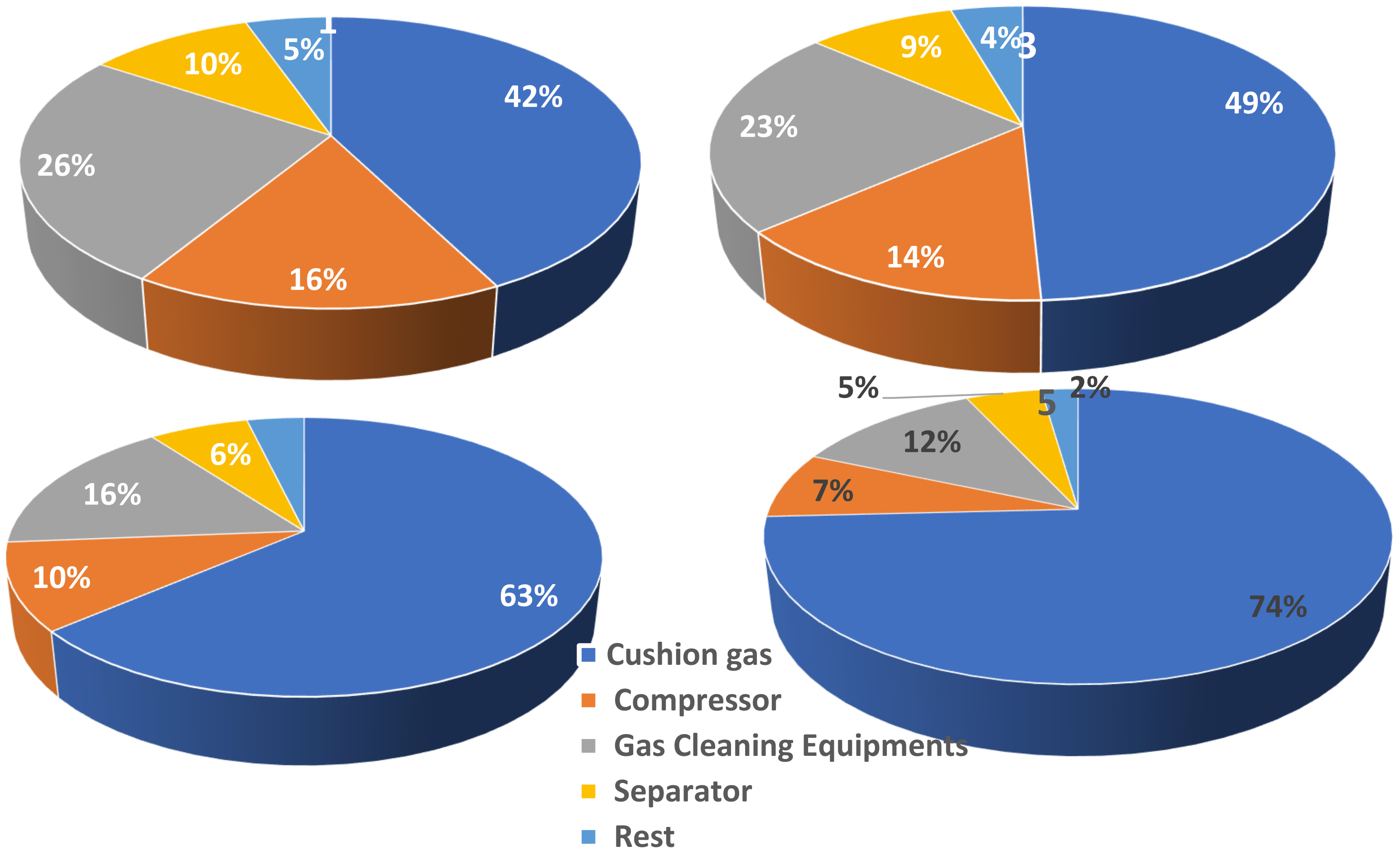
Capex for Aquifer and Salt Cavern sites

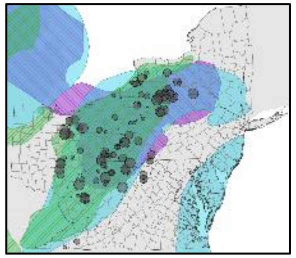


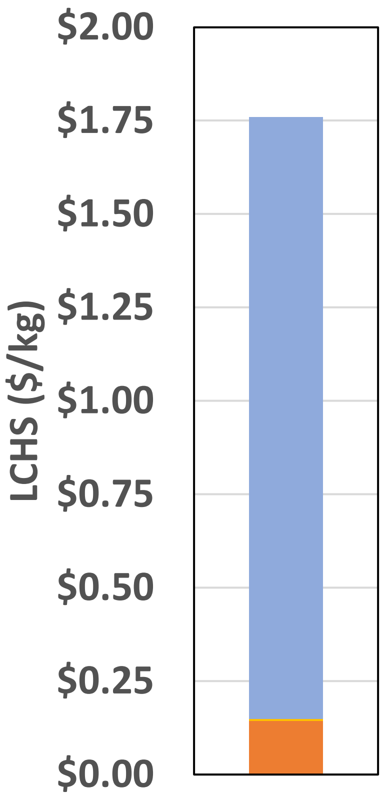
Capex Across Various Hydrocarbon Reservoir Sites



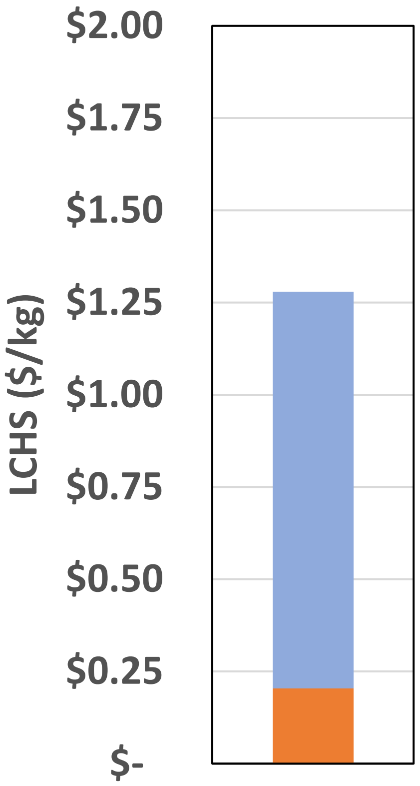
Cost analysis across storage types in Northern Appalachia

Study Area

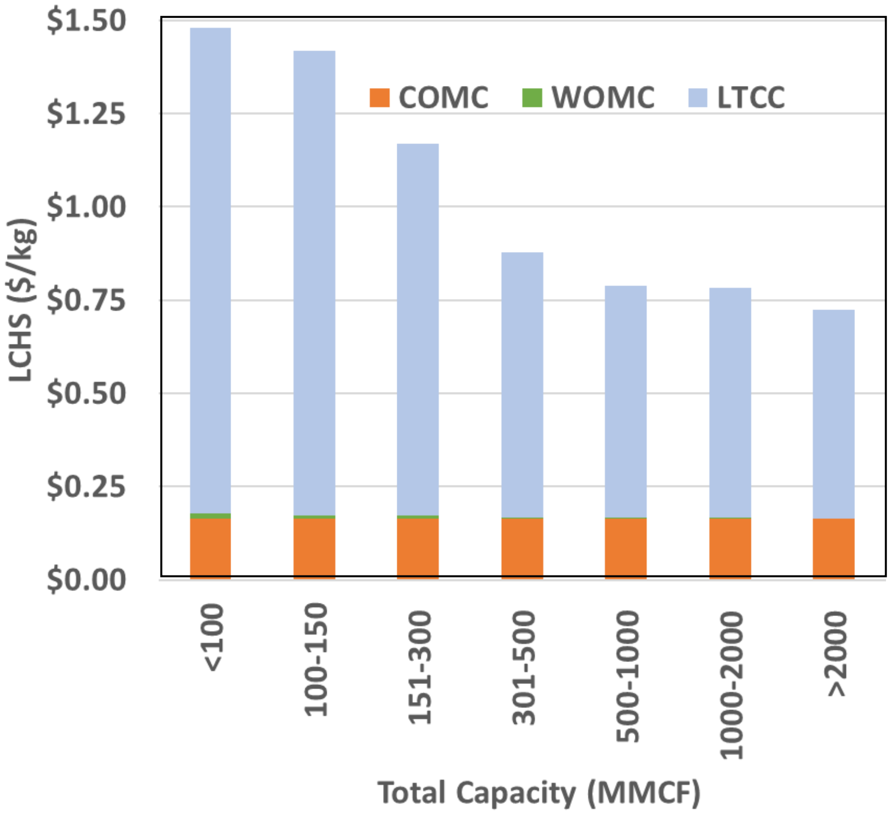




Aquifer
(WV, 0.21 BCF)



Salt Cavern
(NY, 2.34 BCF)



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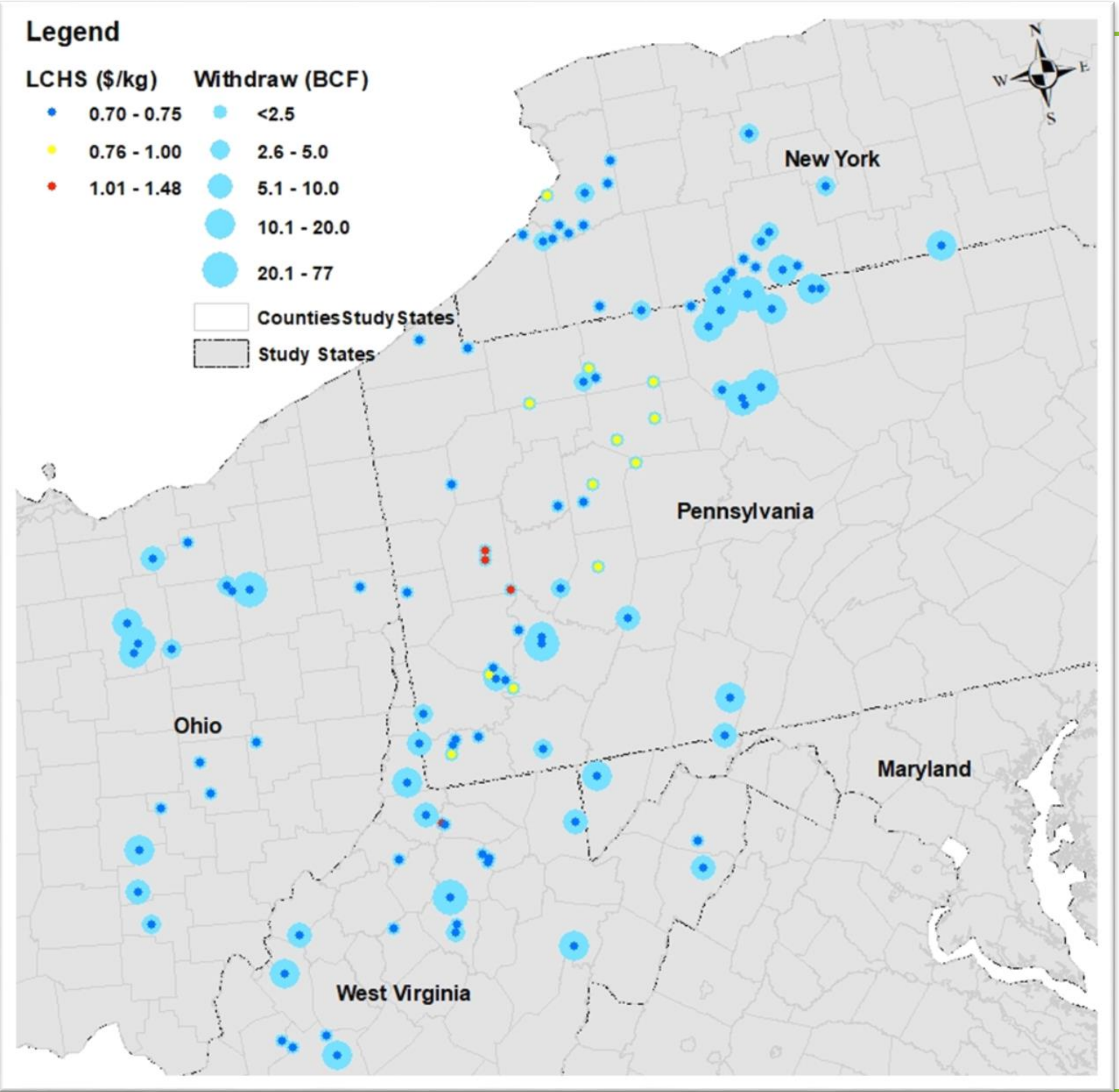
Spatial variabilities of LCHS across Northern Appalachia



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Summary, Remaining Challenges, & Outlook

- We identified the cost drivers including storage size and type, demand (withdrawal volume), depth, pressure, and costs of cushion gas and electricity and quantified their impacts on LCHS
- The interaction between the site specific variables, state specific costs, and local scale demand needs to be considered in regional scale technoeconomic analysis
- Future work could include:
  - Integrating UHS TEA with costs of production and delivery to evaluate where we might focus cost reduction efforts to reach <$1 per kg delivered
  - Developing data-driven, estimates of storage adoption for a single operator or site
  - Building on these efforts to conduct inter-regional comparisons and a nation-scale TEA

Contacts and Acknowledgements

Gerad M. Freeman, Ph.D.

Pacific Northwest National Laboratory

gerad.freeman@pnnl.gov

Shruti Khadka Mishra, Ph.D.

Sandia National Laboratories

skhadka@sandia.gov

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Portions of this work were performed under the auspices of the U.S. Department of Energy by Pacific Northwest National Laboratory under contract DE-AC05-76RL01830.

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Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Reservoir simulations and code comparison study

Julia Camargo (PNNL), Joshua White (LLNL), Ryan Haagenson (PNNL), Tom Buscheck (LLNL), Foad Haeri (NETL), Nik Huerta (PNNL), Mathew Ingraham (SNL), Angela Goodman (NETL)

SHASTA workshop

April 3, 2024

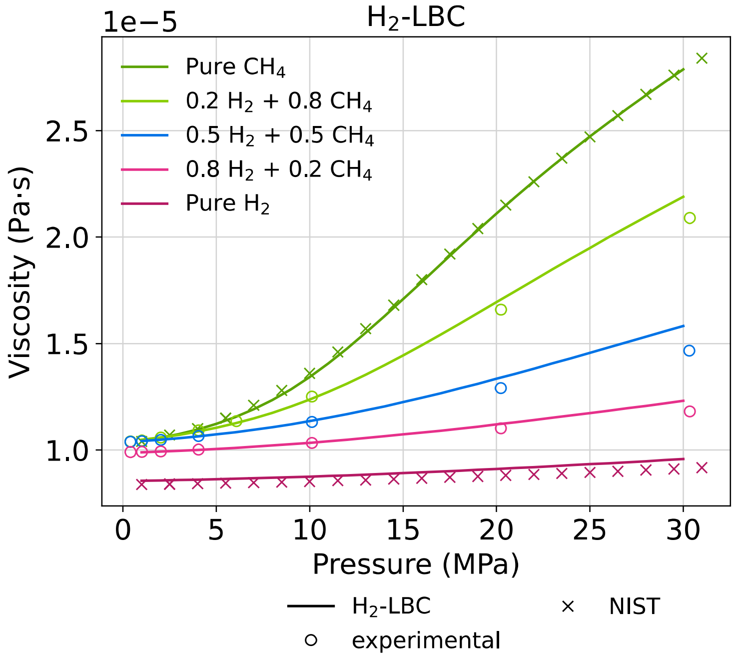
Contents

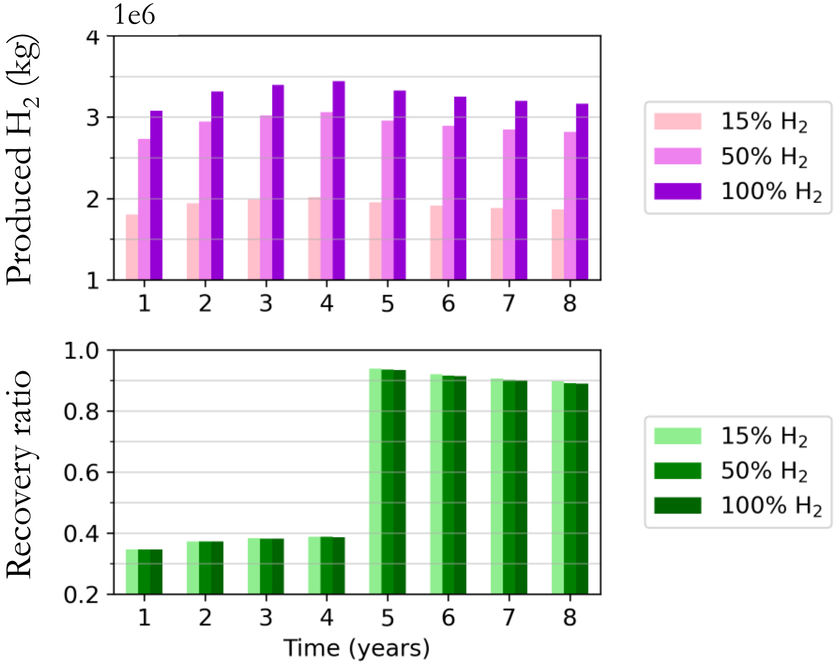
Part I – recap

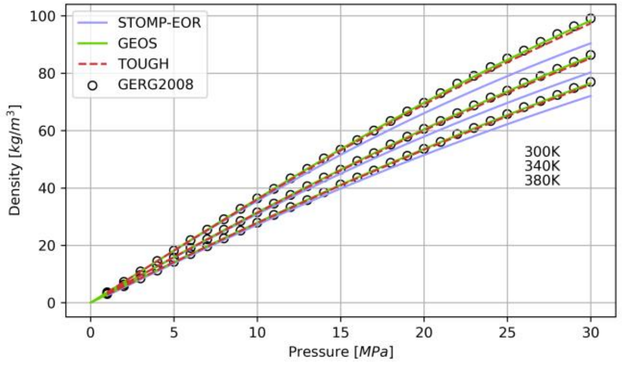
- **Upgrades** to reservoir simulator
- Investigate **reservoir behavior** when converting existing **natural gas storage fields to UHS**

Part II – ongoing work

- Code comparison study







Reservoir Performance

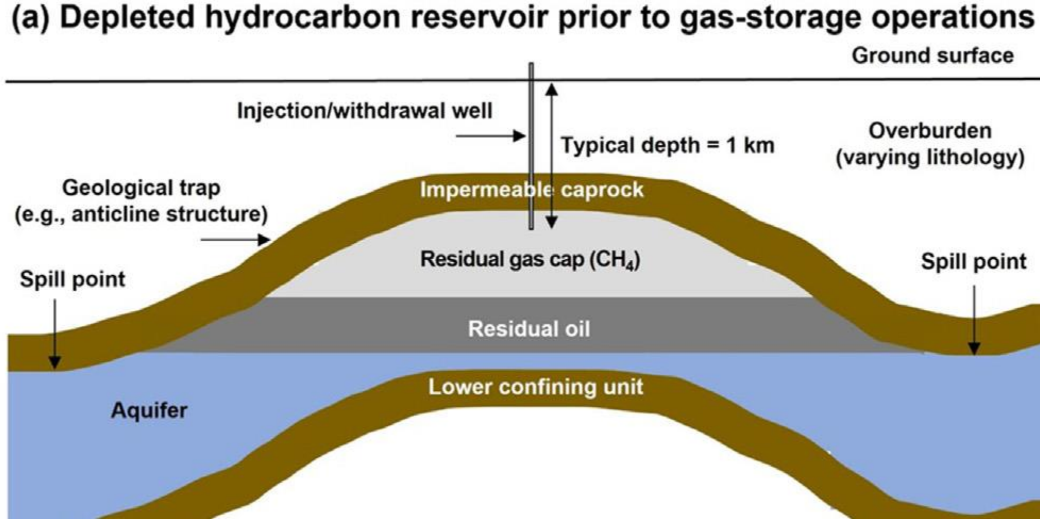
Goal

- Investigate **reservoir behavior** when converting existing **natural gas storage fields to UHS**

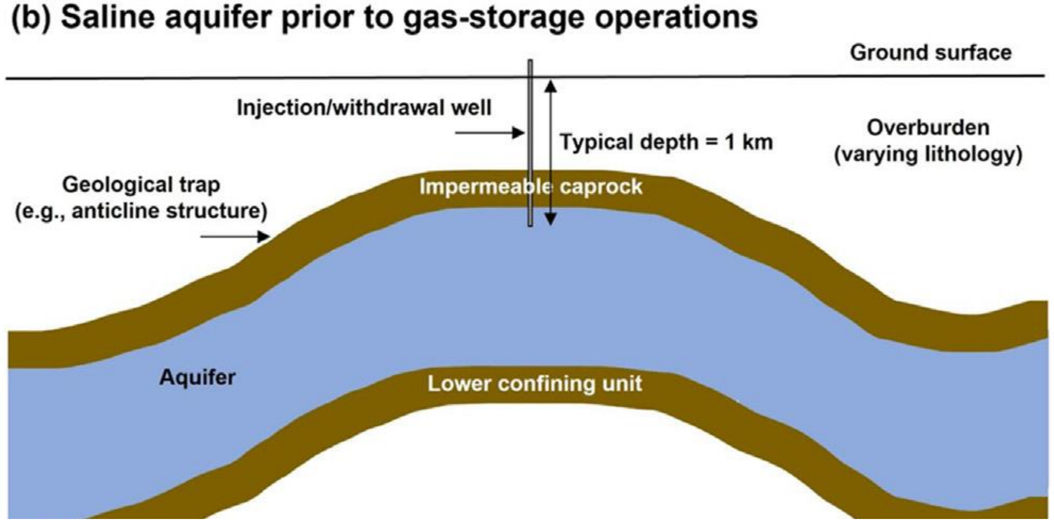
Key questions

- What is the impact of rock and fluid properties on storage efficiency and energy availability?
- How can H_2 / NG / brine flow dynamics be managed?
- What mechanisms could lead to resource loss?

Existing UGS Reservoir



Converted UHS Reservoir



Buscheck et al., IJHE, 2023

https://doi.org/10.1016/j.ijhydene.2023.07.073

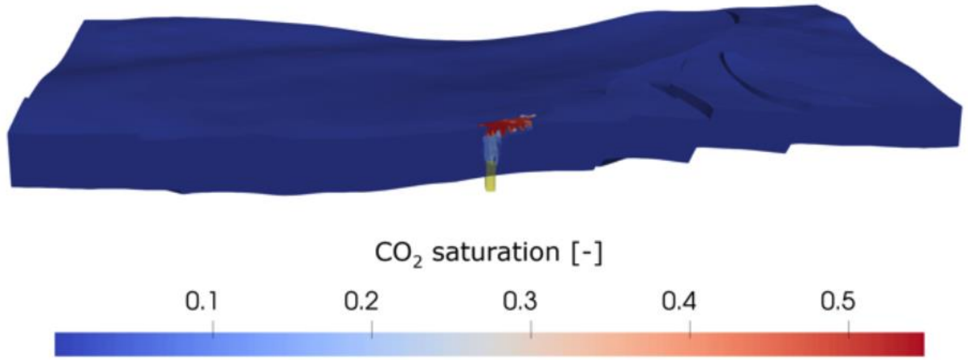
Compositional Reservoir Simulation

Tracking the evolution of …

1. One or more components (H_2, CH_4, H_2O, CO_2, …)
2. One or more fluid phases (gas, aqueous, oil, …)

Satisfying …

1. Component-wise mass conservation
2. Phase and component summation constraints
3. Multiphase Darcy's law
4. Thermodynamic equilibrium ("flash calculation")
5. Various constitutive models: density, viscosity, rel-perm, capillary pressure, etc.



Time: 3 years

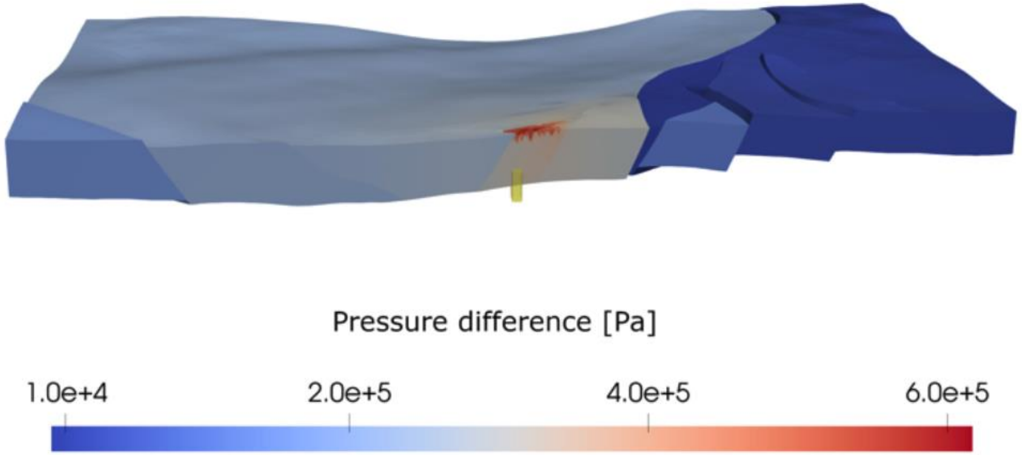


Figure: Side view of a two-phase, two-component model of CO_2 injection into a saline aquifer.

[Camargo et al., GHGT-16, 2022. http://dx.doi.org/10.2139/ssrn.4296637]

Part I

Viscosity

Lohrenz-Bray Clark (1964)

- LBC is the most widely used hydrocarbon viscosity model in commercial reservoir simulators.
- Typically very accurate for natural gas and other hydrocarbon mixtures.
- Unfortunately, loses significant accuracy for hydrogen-bearing mixtures.
- We have developed a modified **H_2LBC** model to address these shortcomings.
  - Dilute gas viscosity for H_2
  - Mixing rule for gas viscosity

Fig. 1. Relationships of $\mu^*\xi$ and T_R for nonpolar gases at moderate pressures.

ut also of z_c. Therefore the product *ξ becomes a unique function of both and T_R when experimental evidence utilized to support this conclusion.

REATMENT OF VISCOSITY DATA

The experimental viscosities at at-nospheric pressure for fifty-two non-olar gases were used to establish the onstant β and the exponents m and n f Equation (7). The only experimen-al data used were those that were ound to be internally consistent for ach gas. For those gases for which a arge number of data was available nly the best values of each investiga-or were included. The gases considered ncluded the monatomic and diatomic ;ases, carbon dioxide, carbon disulfide, arbon tetrachloride, and hydrocarbons, ncluding normal paraffins, isoparaffins, lefins, acetylenes, naphthenes, and

behavior. This figure indicates that th exponent n is constant for $T_R < 1.$ but varies with reduced temperatur above $T_R = 1.5$. The relationship fc $T_R < 1.5$ has been determined to be

$$\mu^*\xi = 34.0 \times 10^{-5}\, T_R^{0.94}, \quad (T_R \leq 1.5) \qquad (9$$

Above $T_R = 1.5$ the group $\mu^*\xi$ can b related to temperature as follows:

$$\mu^*\xi = 17.78 \times 10^{-5}\, [4.58\, T_R - 1.67]^{5/8}, \quad (T_R > 1.5) \qquad (10$$

These equations are applicable t all nonpolar gases at atmospheric pre: sure with the exceptions of helium an hydrogen, whose relationships are als presented in Figure 1. The abnorm: behavior of these gases results fro their significant quantum deviatior (5). Figure 1 shows that the hydroge curve is parallel to the curve for tl

Figure: Non-dimensionalized pure-component viscosity data from Stiel & Thodos (1961) in dilute gas conditions.

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Viscosity

Impact of Mixing Rule

Traditional LBC Mixing Rule

H_2 LBC Mixing Rule

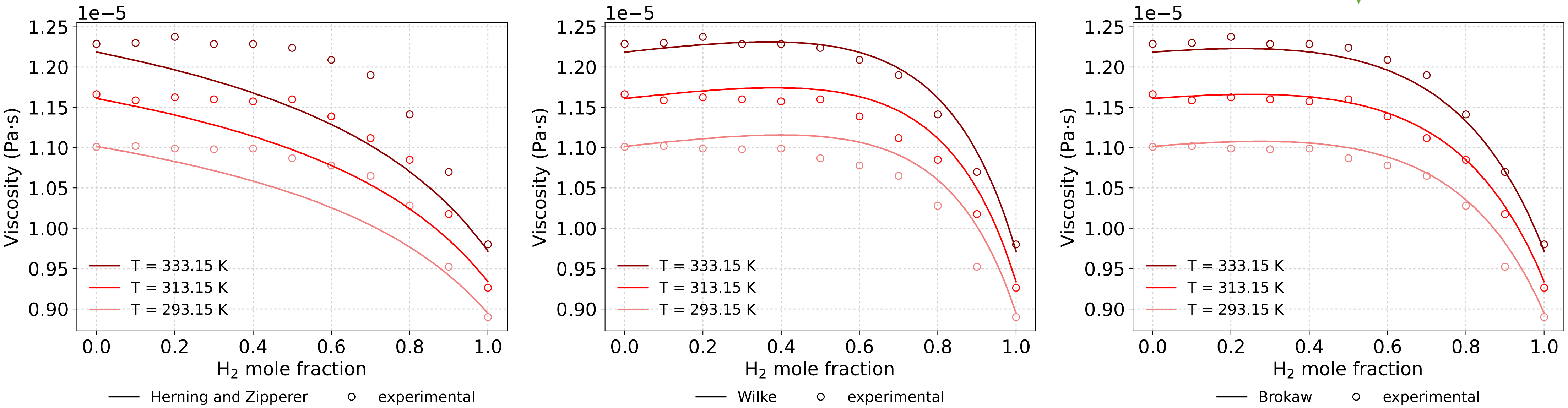
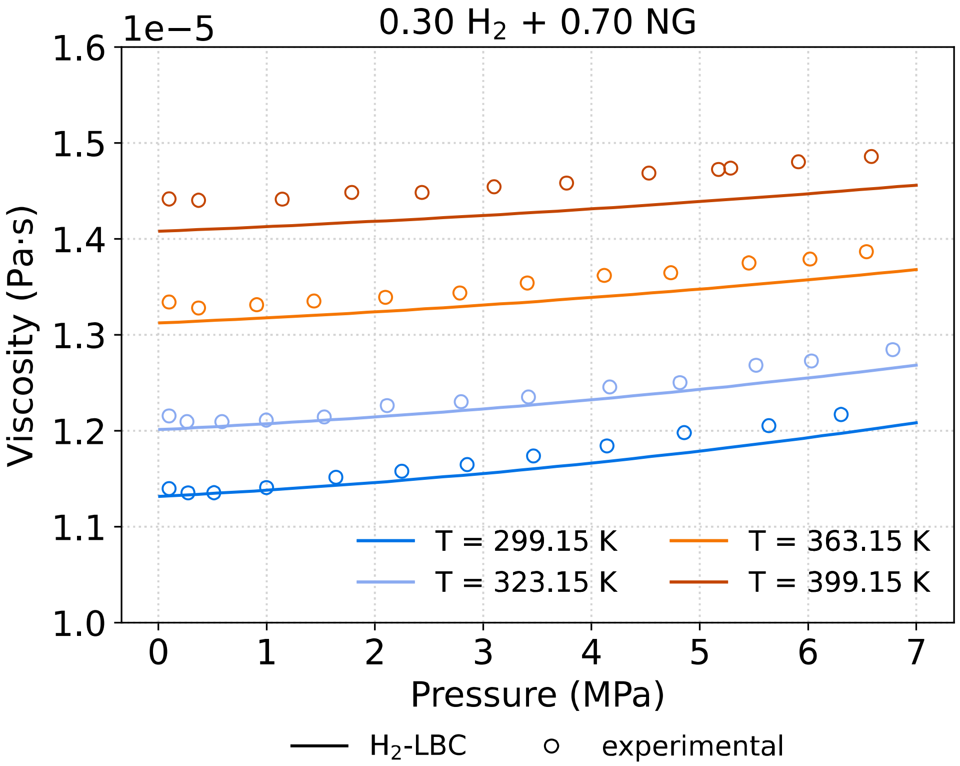


Figure: Comparison of three mixing rules for viscosity of various hydrogen/methane blends at atmospheric pressure and different temperatures against experimental data from Kobayashi et al. (2007)[1].

[1] Kobayashi, Kurokawa & Hirata (2007) J Therm Sci Technol, 2(2).

Modify Viscosity Model

H_2LBC

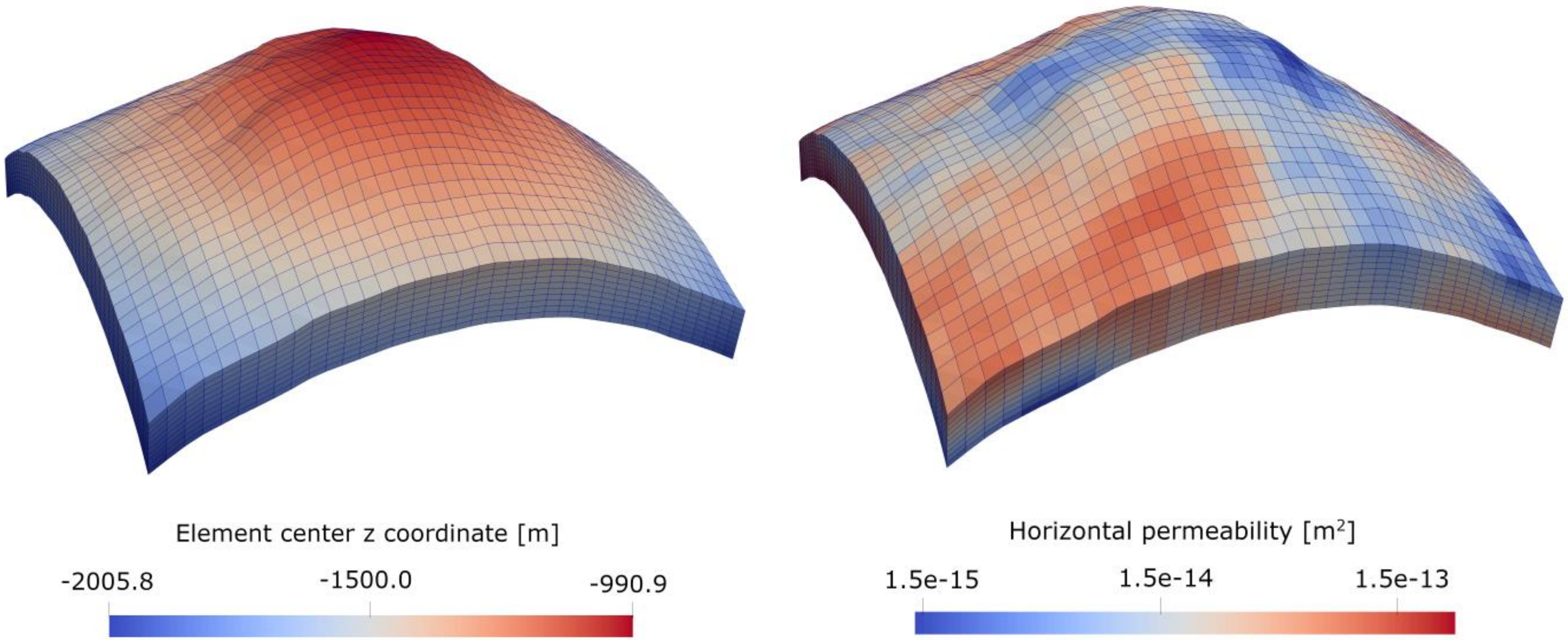


Revised viscosity model is …

- Simple to implement
- Fast and robust to evaluate.
- Only free parameters are the critical component properties (physical constants)

Field SHASTA

Synthetic Hydrogen Storage Model



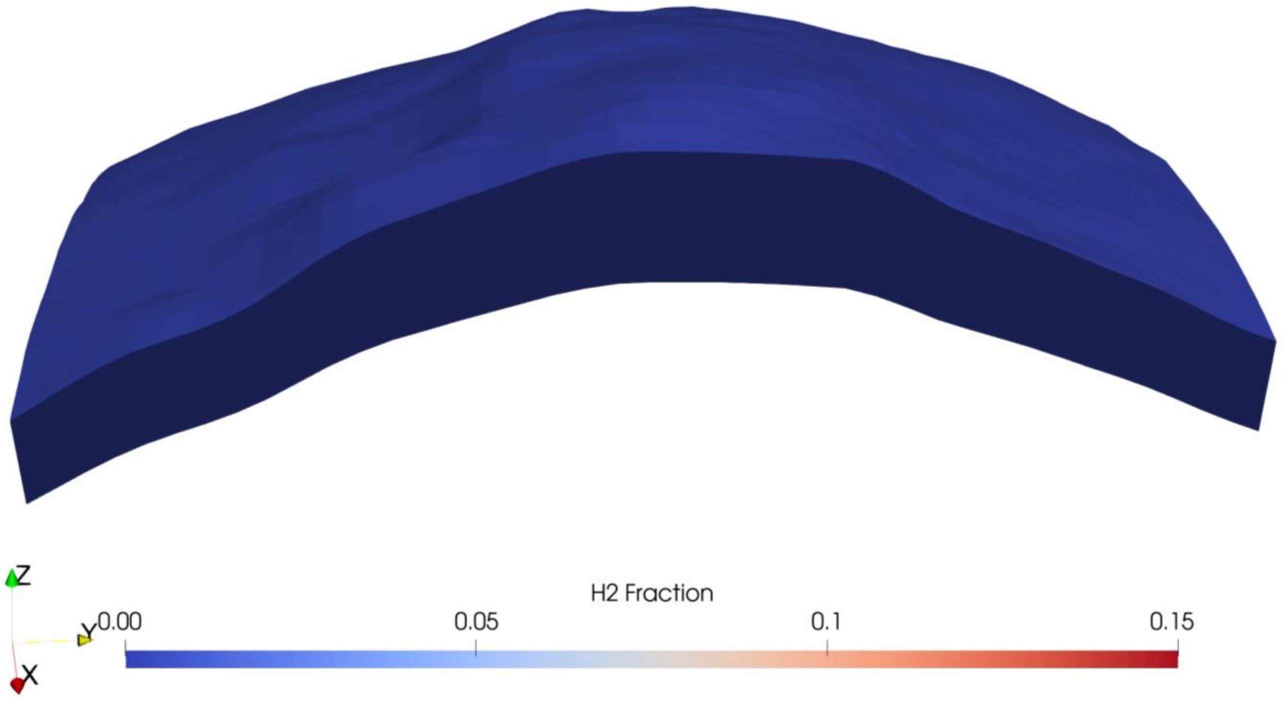
(a) (b)

Table 1: Rock properties

Parameter	Units	Min – Max	Mean
Porosity	fraction	0.05 – 0.25	0.15
Permeability	mD	1.4 - 265	51

Field SHASTA

- Field is initially saturated with CH_4
- H_2 (pure or blended) is cyclically injected in various design configurations
- Gas-water contact dynamics ignored for the moment (single-phase, two-component system)

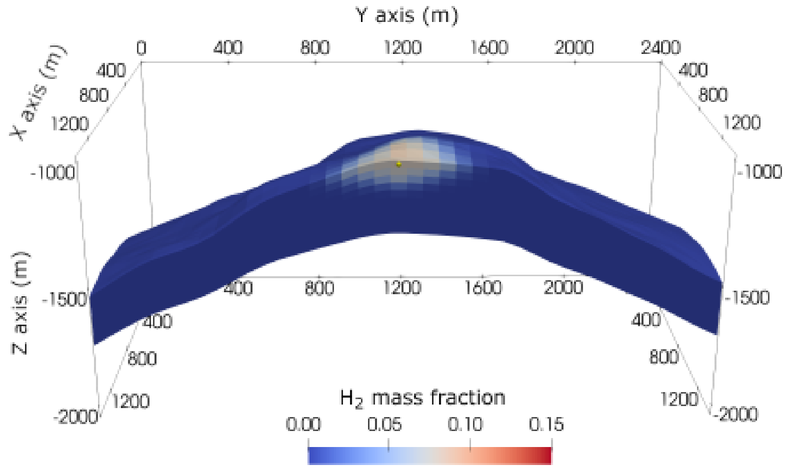


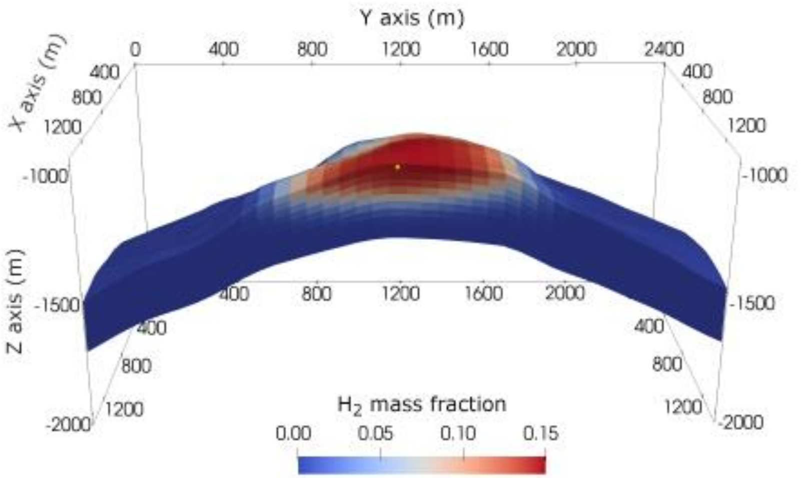
A stable hydrogen cap is essential to stable production rates

After **1st** production cycle:

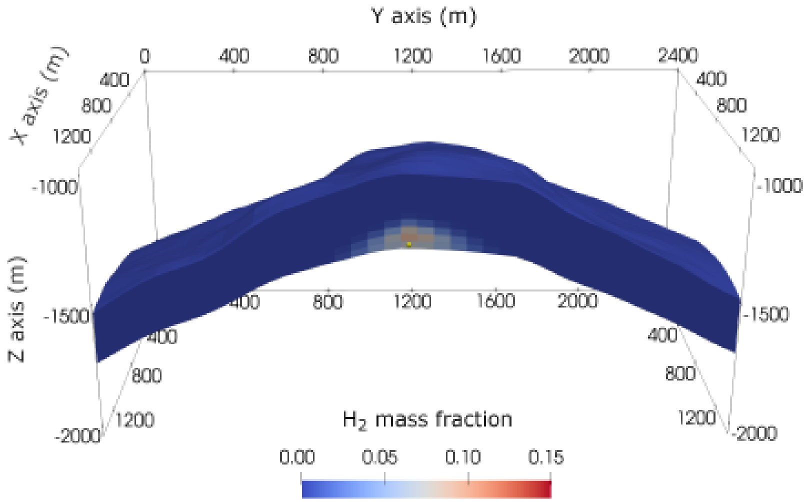
After **15th** production cycle:

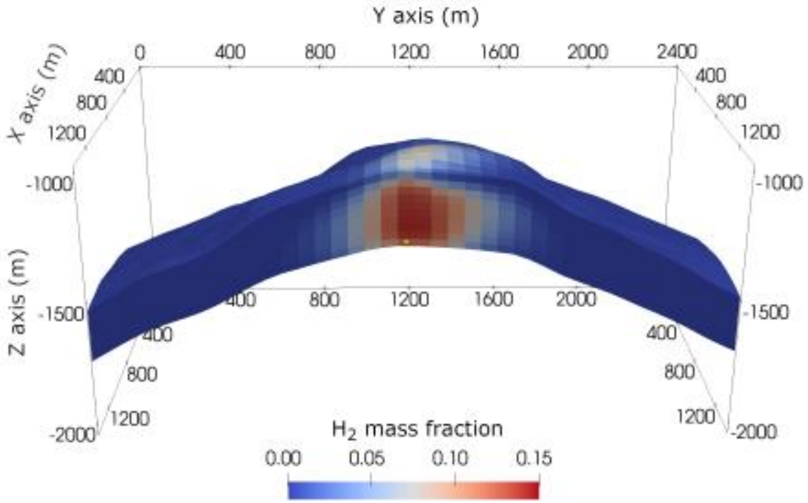
Perforations at **top** of storage formation:





Perforations at **bottom** of storage formation:



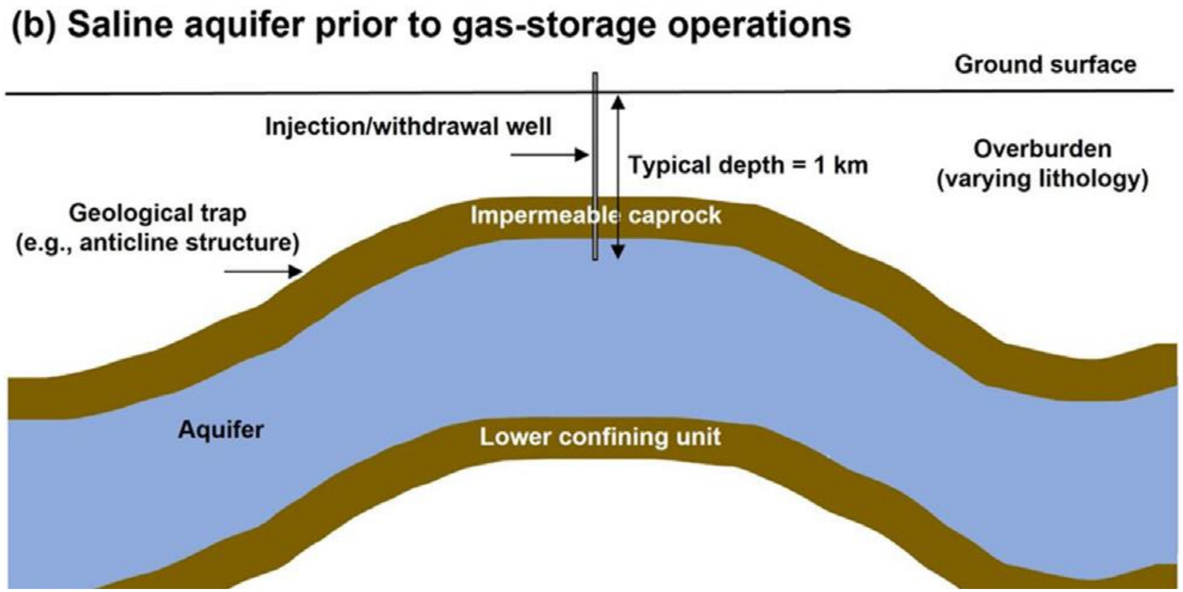


Conclusions

1. Standard reservoir simulators are well suited to H_2 simulations with modest upgrades (e.g. improved viscosity models).

2. A stable H_2 gas cap is essential to stable production rates.

3. Stability is favored by:
    - Good trapping structure
    - Low vertical permeability and/or baffling
    - Perforations near top of storage formation



Buscheck et al., IJHE, 2023

https://doi.org/10.1016/j.ijhydene.2023.07.073

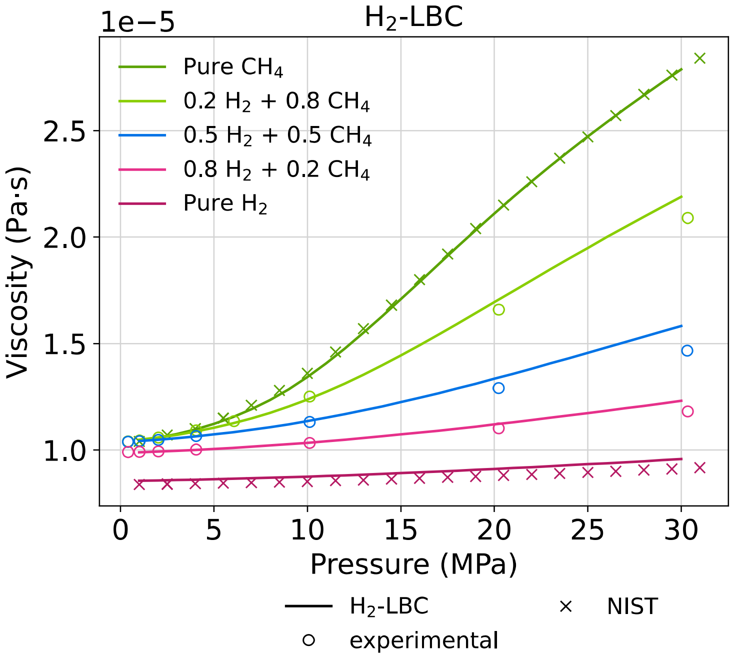
Contents

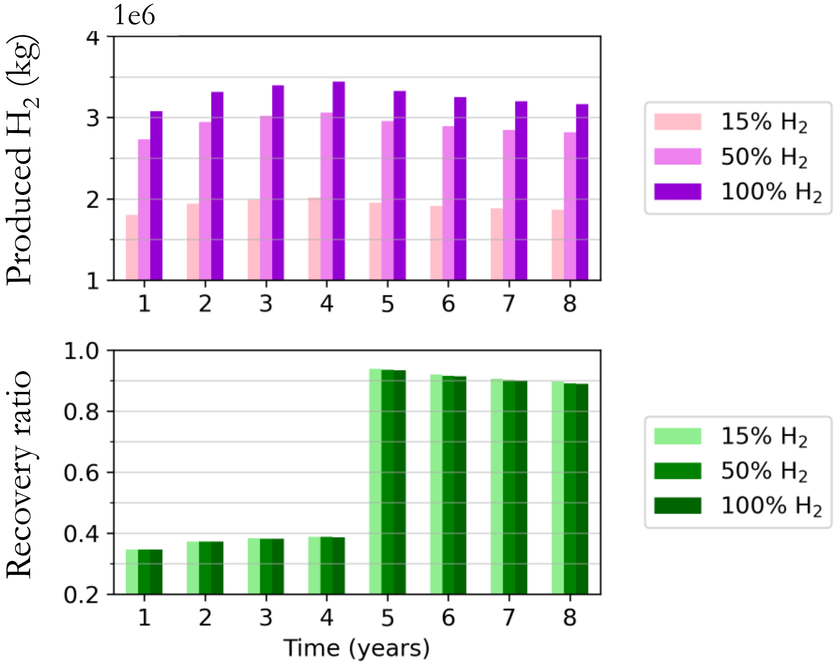
Part I – recap

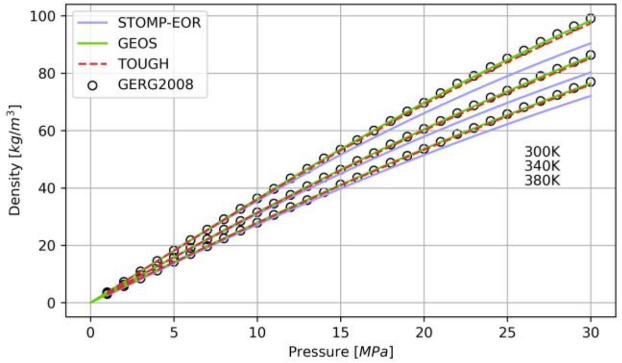
- **Upgrades** to reservoir simulator
- Investigate **reservoir behavior** when converting existing **natural gas storage fields to UHS**

Part II – ongoing work

- Code comparison study







Ongoing work – code comparison study

Why do we need a code comparison study?

Simulators may employ different

- numerical schemes
- constitutive relationships
- solvers
- temporal discretization methods
- approaches tailored to hydrogen storage applications

Benefits?

- Illuminate discrepancies between simulators
- Identify issues and limitations in the current code implementation
- Provide a documented record of benchmark problems for hydrogen storage simulation

Participating codes

Code Name	EOS	Viscosity relationship	Solubility relationship	Numerical scheme
GEOS[1]	SRK, PR	H2-LBC	Henry's Law	TPFA-FVM
STOMP-EOR[2]	PR	LBC	Torin-Ollarves & Trusler (2021)	FDM
TOUGH[3]	SRK, PR, RK	FT-SRK	Henry's Law	IFDM

[1] Settgast, R. R., White, J. A., Corbett, B. C., Vargas, A., Sherman, C., Fu, P., & Annavarapu, C. (2018). Geosx simulation framework. Lawrence Livermore National Laboratory, Livermore, CA.

[2] White, M. D., & Oostrom, M. (2003). STOMP subsurface transport over multiple phases version 3.0 User's guide. Pacific Northwest National Lab., Richland, WA.

[3] Pruess, K., Oldenburg, C., & Moridis, G. (2012). TOUGH2 User's Guide, Version 2.1, Lawrence Berkeley National Laboratory, Berkeley, CA.

Additional simulators will likely join the effort once benchmarks have been simulated by the three codes listed above.

Benchmark problems

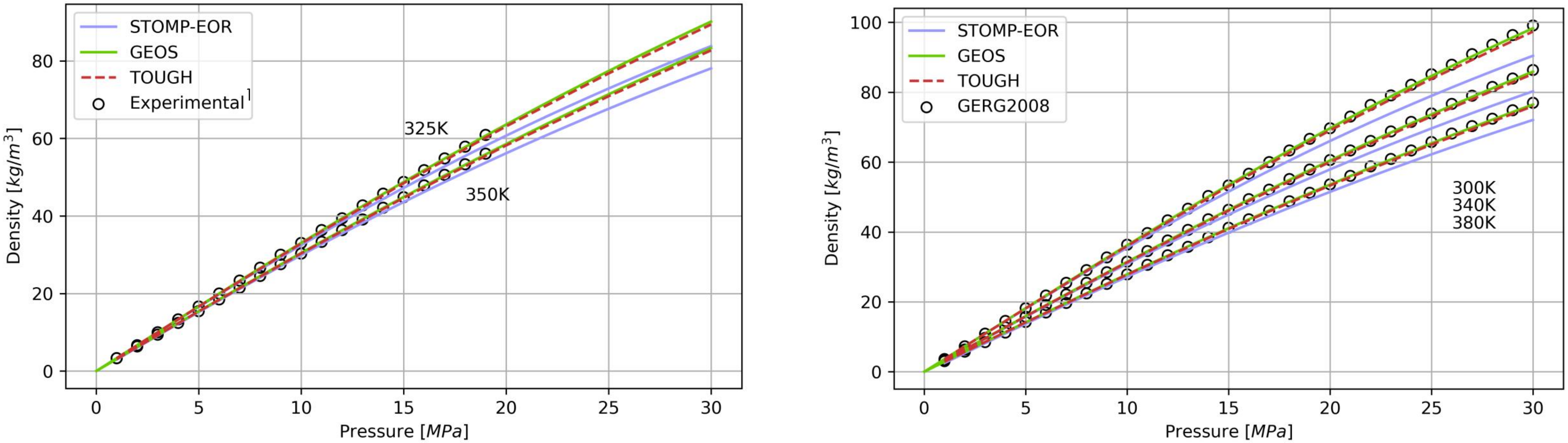
1. Pressure-temperature-volume (PVT) simulations
   - GEOS, STOMP, TOUGH

2. A core-scale, one-dimensional flow problem
   - GEOS, STOMP

3. A three-dimensional reservoir simulation of a hypothetical hydrogen storage system.
   - GEOS

Pressure-temperature-volume simulations

Mass density

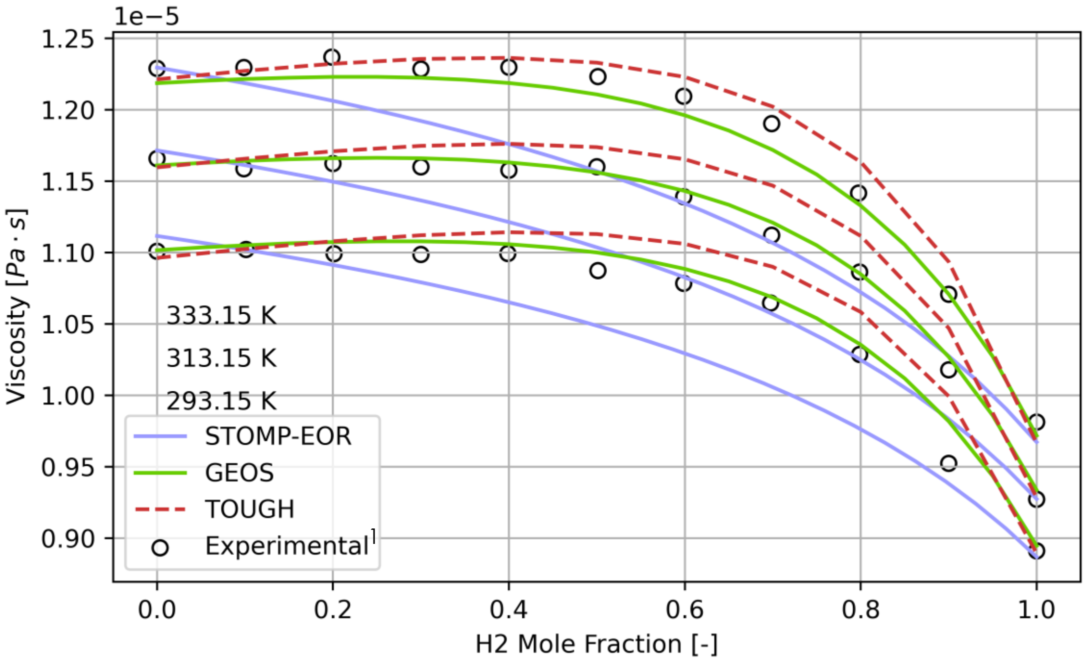


Mass density vs. pressure for a gas blend of 50% H_2 and 50% CH_4 by mole.

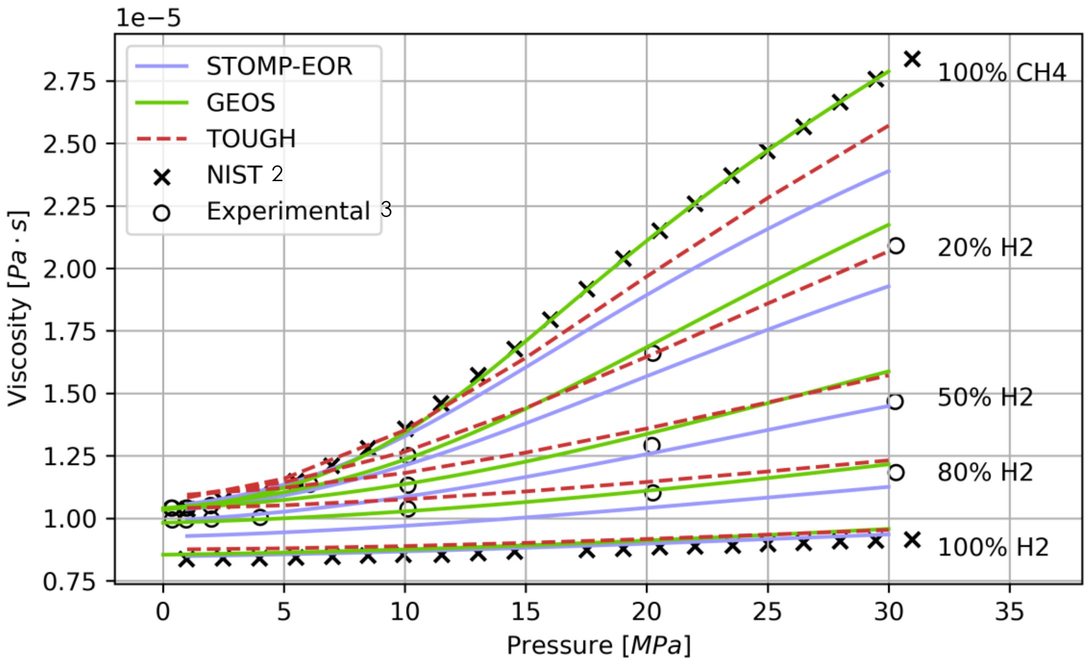
[1] Hernández-Gómez, Tuma, Pérez & Chamorro. (2018). Journal of Chemical & Engineering Data, 63(5).

Pressure-temperature-volume simulations

Viscosity



Gas phase viscosity at atmospheric pressure vs. mole fraction of hydrogen.



Gas phase viscosity at 293.15 K vs. pressure

[1] Kobayashi, Kurokawa & Hirata. (2007). Journal of Thermal Science and Technology, 2(2).
[2] National Institute of Standards and Technology (NIST). (2022). webbook.nist.gov/chemistry/fluid.
[3] Chuang, Chappelear & Kobayashi. (1976). Journal of Chemical and Engineering Data, 21(4).

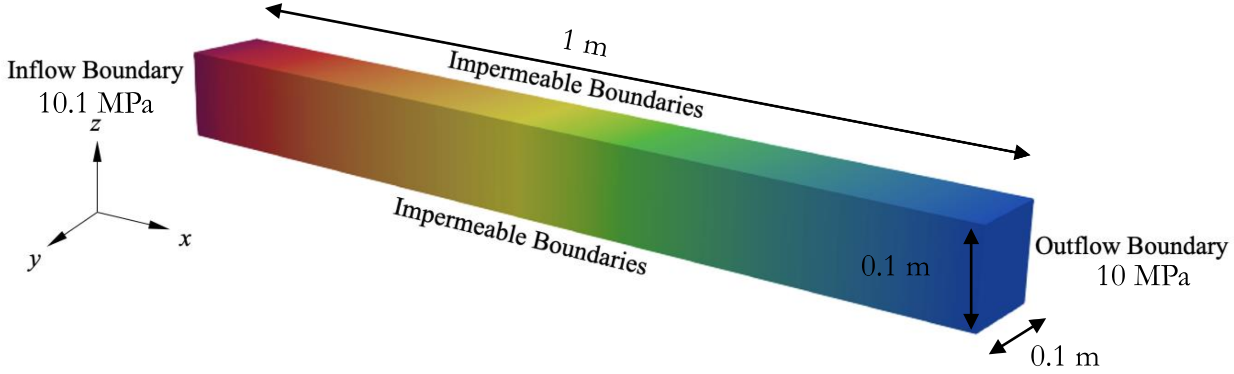
One dimensional flow problem

Set up

- Simulates a hypothetical core flooding experiment.

- Two scenarios:

1. **hydrogen** invading into a core initially saturated with **methane**
2. **hydrogen** invading into a core initially saturated with **water**



Rock Property	Value
Intrinsic permeability (m^2)	$2.0 \cdot 10^{-13}$
Porosity (-)	0.25
Porosity Reference pressure (MPa)	10.0
Matrix compressibility (Pa^{-1})	10^{-10}

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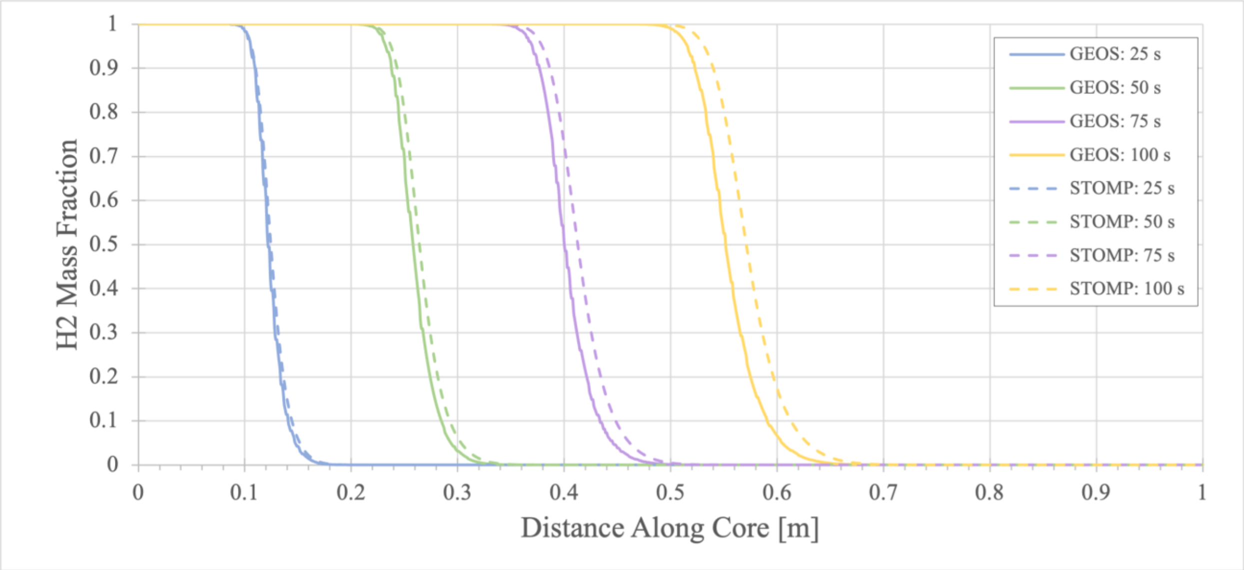
One dimensional flow problem

Results

Hydrogen invading methane



Hydrogen invading water

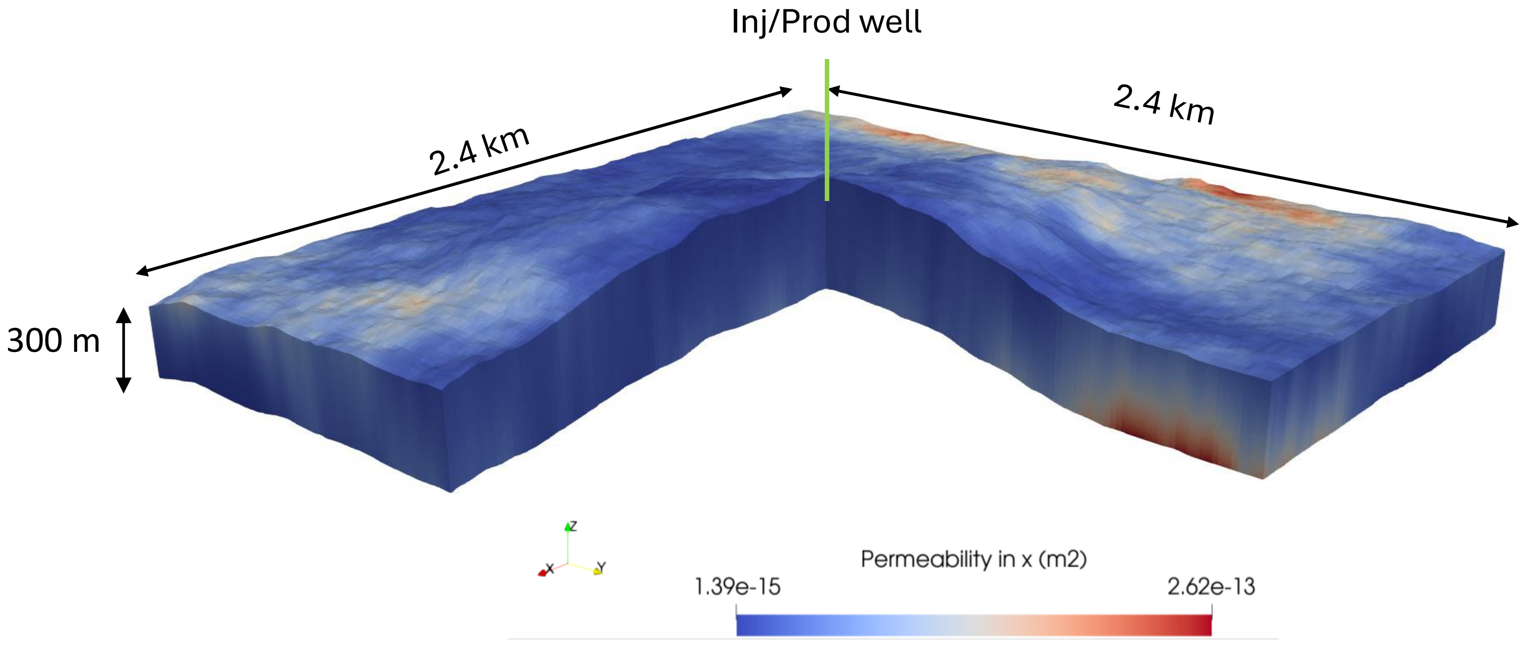
- Investigating reasons for greater mismatch
- That's the point of the code comparison study!

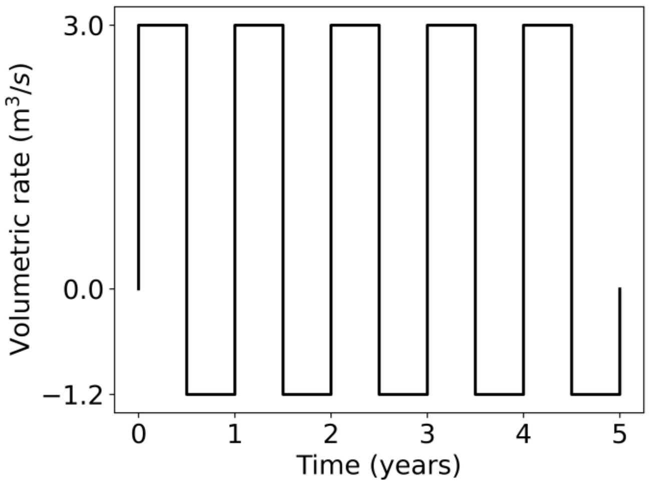
Three dimensional flow problem

Set up

- Simulates injection of pure hydrogen and production of gases from a synthetic domal reservoir.

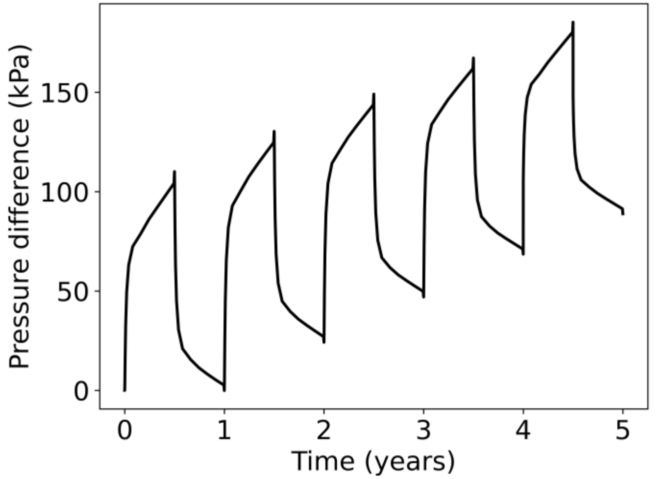
- **Hydrogen** invading reservoir initially saturated with **methane**.

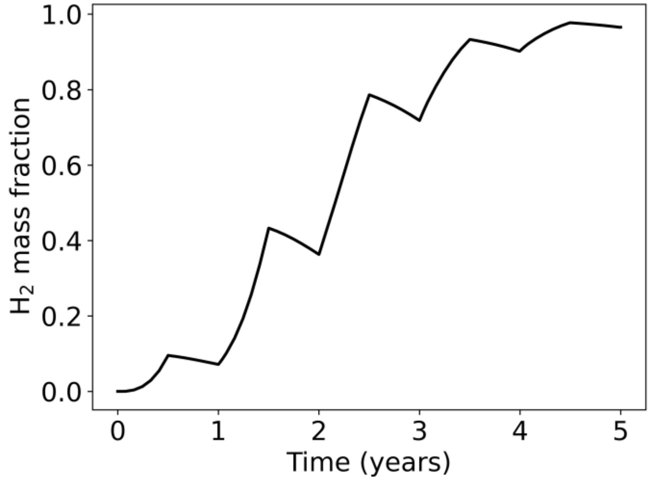


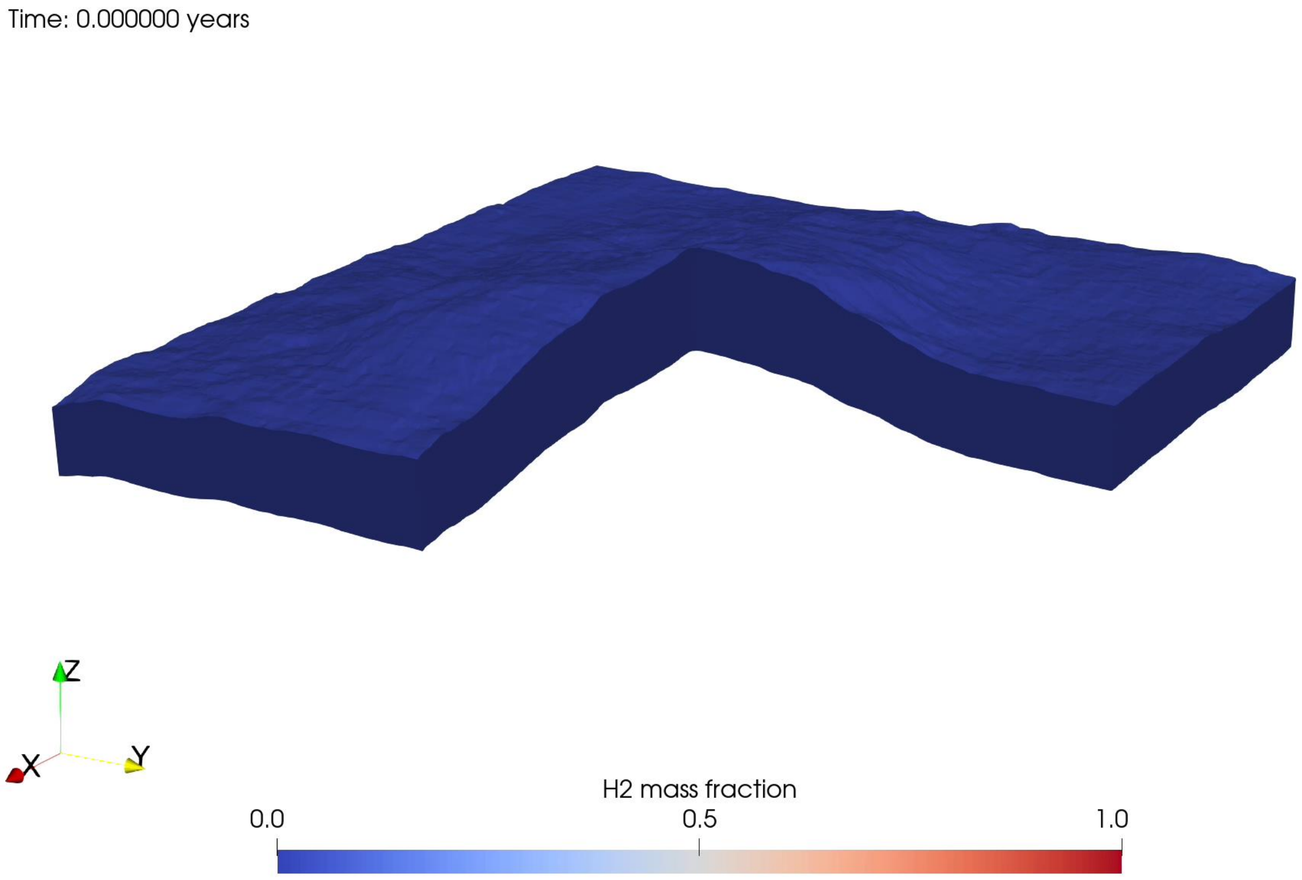


Three-dimensional flow problem

Results







Conclusions

- Good agreement between GEOS, STOMP and TOUGH for **PVT simulations**
    - Mass density
    - Viscosity

- Good agreement between GEOS and STOMP for **one-dimensional flow problem**
    - Hydrogen invading methane
    - Investigating causes for mismatch when hydrogen invades water

- **Next steps**
    - Compare three-dimensional reservoir simulation results with STOMP and TOUGH
    - Add a three-dimensional example with two-phase flow
    - Incorporate other codes and teams in the study

Acknowledgements

- This work was supported by the U.S. Department of Energy, Office of Fossil Energy and Carbon Management through the Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA) project.

Thank You!

Julia Camargo

julia.camargo@pnnl.gov

SHASTA

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Core Flooding Experiments and Simulations

Ryan Haagenson, Lirong Zhong, Seunghwan Baek, Nicolas Huerta, Christopher Bagwell, and Mond Guo

Technical Workshop, April 3rd, 2024

Motivation and Objectives

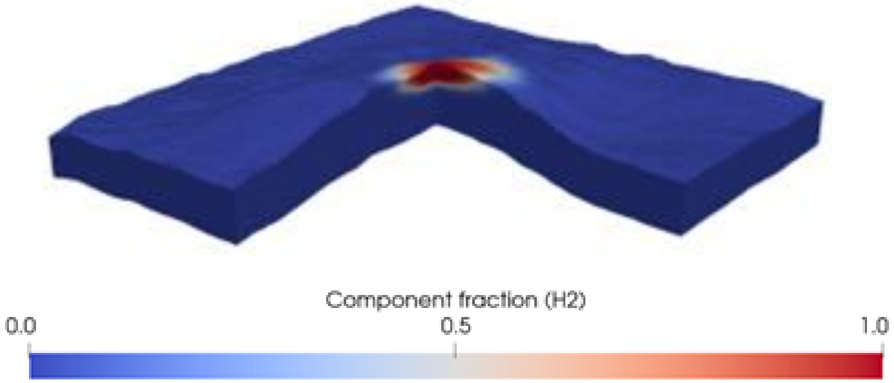
Motivation

Storage sites:

- Working Gas (hydrogen or hydrogen blends)
- Cushion Gas (methane)
- Formation brine

How do these fluids interact in porous medium?

How can we simulate this accurately?

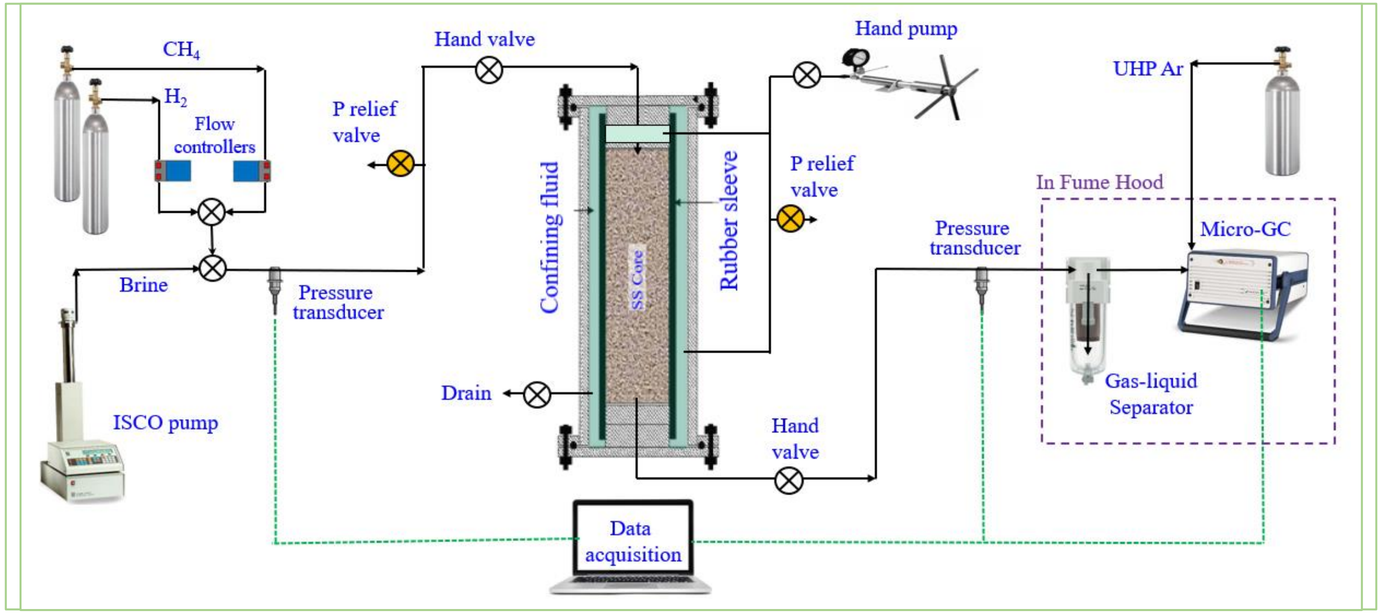


Objectives

- ➢ Perform core flooding experiments with hydrogen (H_2), methane (CH_4), and brine
- ➢ Study flow behavior in sandstone hydrogen storage reservoir
- ➢ Constrain critical parameters for physics-based simulations

Test Setup

Test Setup



CH_4
H_2
Flow controllers
Hand valve
P relief valve
Hand pump
P relief valve
UHP Ar
In Fume Hood
Micro-GC
Pressure transducer
Brine
Pressure transducer
Confining fluid
SS Core
Rubber sleeve
Gas-liquid Separator
Drain
ISCO pump
Hand valve
Data acquisition

Summary of Tests

Test Name	Rock core	Q (mL/m)	CH4 dis. Brine	H2 dis. CH4	CH4 dis. H2	H2 dis. Brine	Flow Hori.	Flow Vert.
Test-01	Berea SS	2.0	x	x			x	
Test-02	Bent. SS	2.0	x	x			x	
Test-03	Berea SS	2.0				x	x	
Test-04	Berea SS	3.0	x	x	x		x	
Test-05	Bent. SS	3.0	x	x	x		x	
Test-06	Berea SS	3.0	x	x	x			x
Test-07	Berea SS	3.0			x	x		x
Test-08	Berea SS	3.0			x	x	x	

Berea SS: *k = 42 mD, φ = 0.18*

Bentheimer SS: *k = 945 mD, φ = 0.24*

Experimental Results

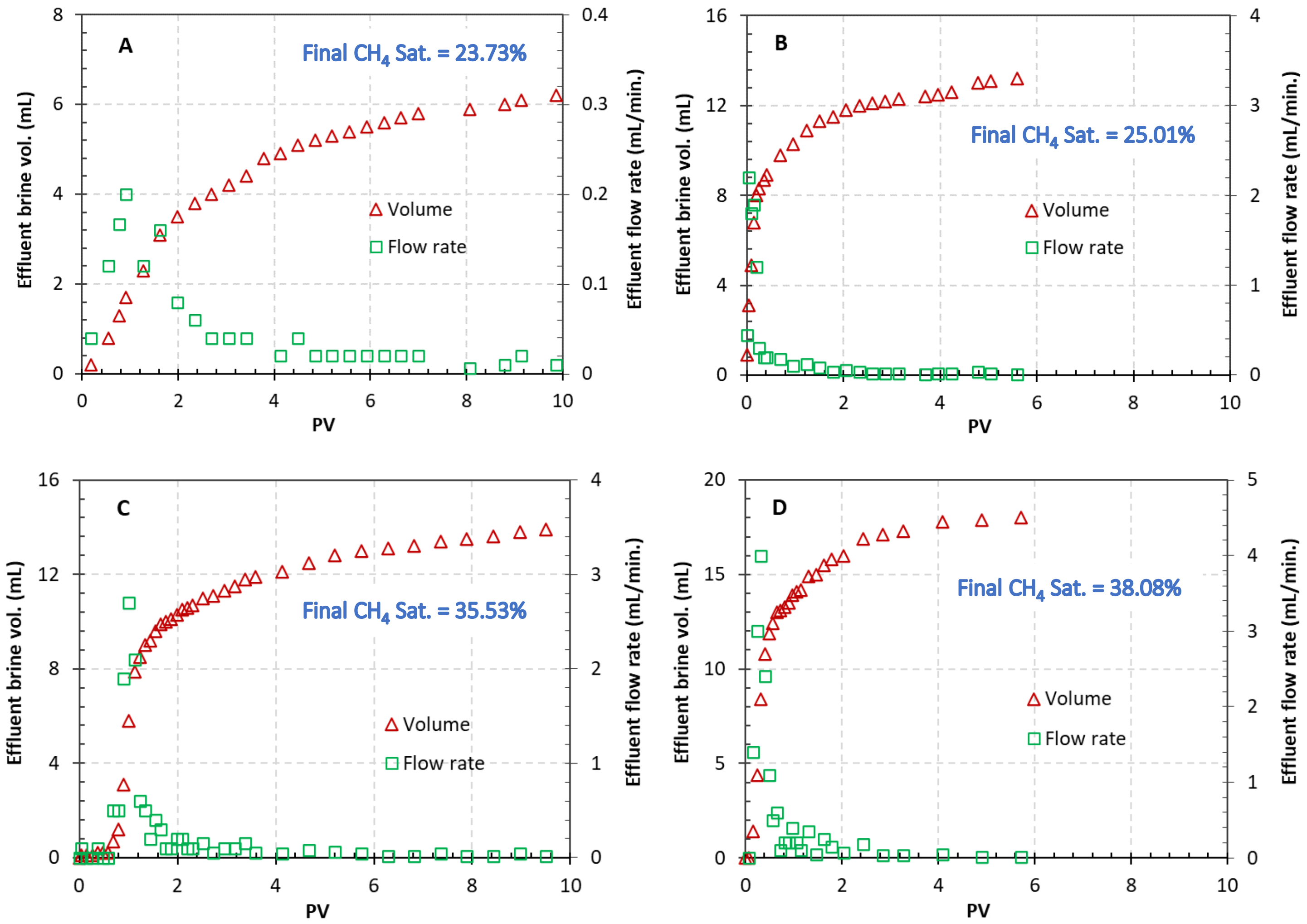
CH4 Displacing Brine

Berea SS

Bentheimer SS

Q = 2.0 mL/m

Q = 3.0 mL/m

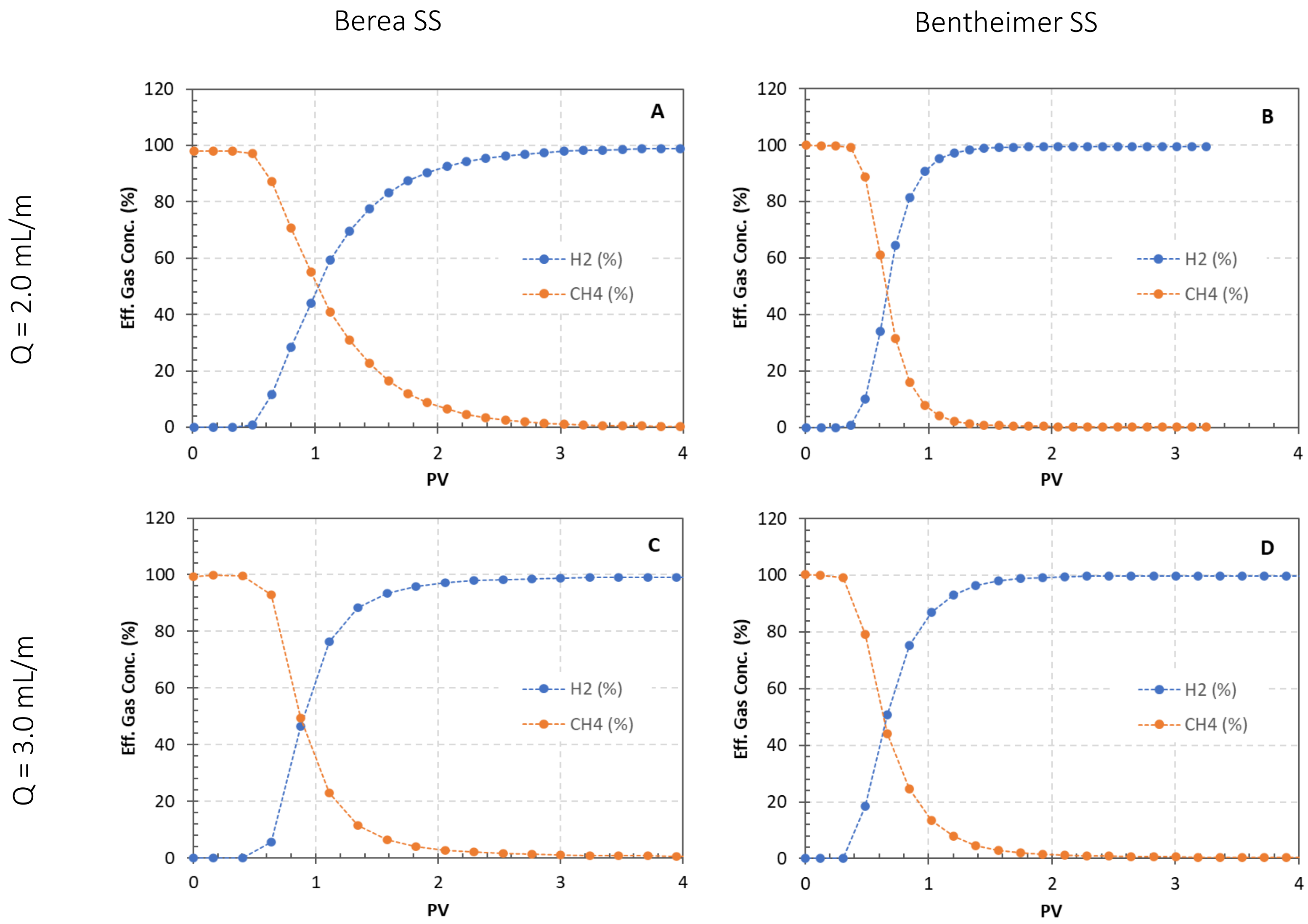


Takeaways:

- ➢ Higher injection rate results in initial methane saturation.
- ➢ At same injection rate, Bentheimer SS shows higher initial methane saturation.

Test 1, 2, 4 & 5

H2 Displacing CH4

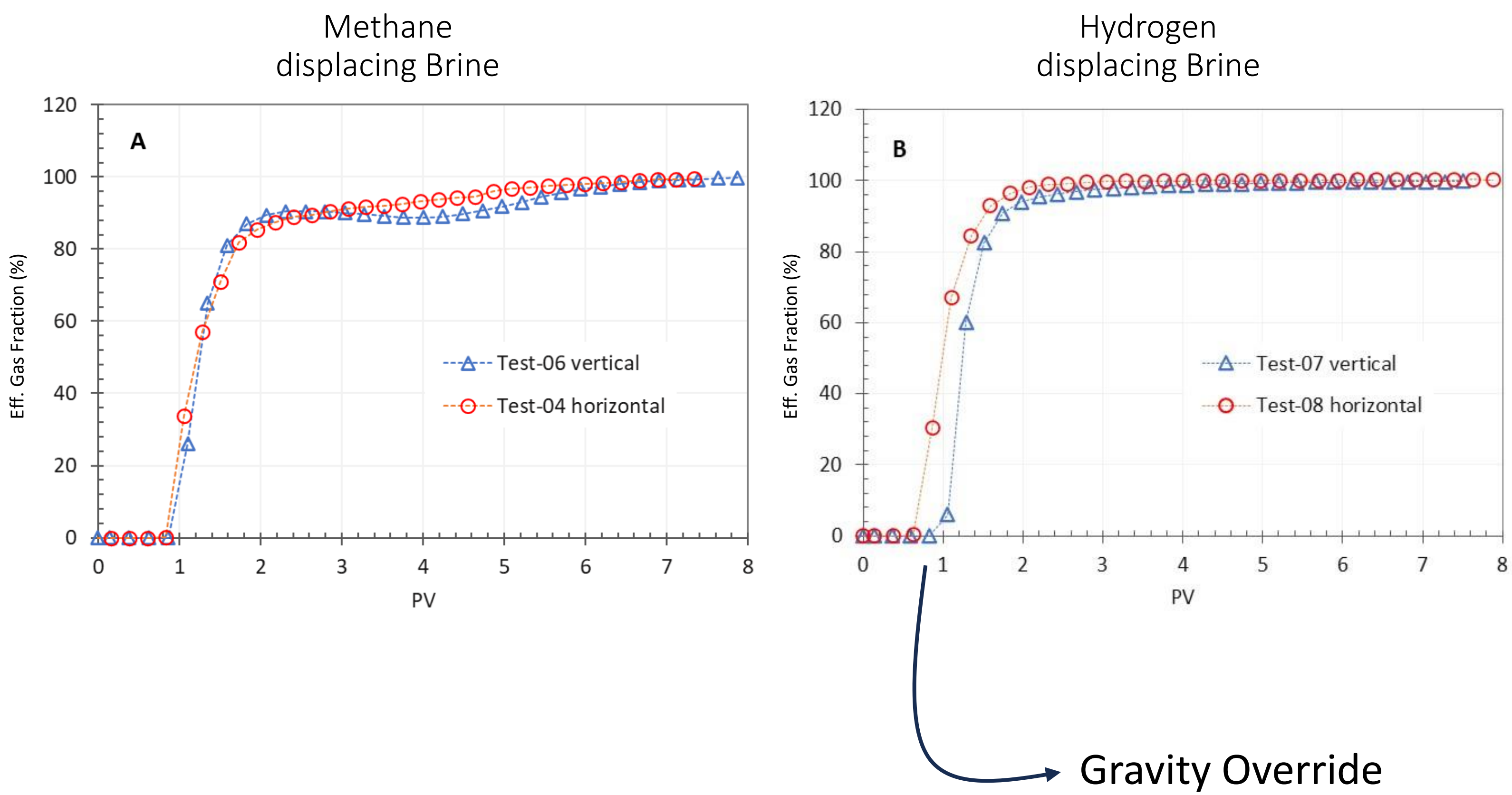


Takeaways:

- Higher injection rates hasten the time of H2 breakthrough.
- Bentheimer SS sees breakthrough of H2 sooner.

Test 1, 2, 4 & 5

Horizontal vs. Vertical Flow



Takeaways:
- Breakthrough occurs sooner in horizontal direction.
- Gas concentrations increase less rapidly in horizontal direction.

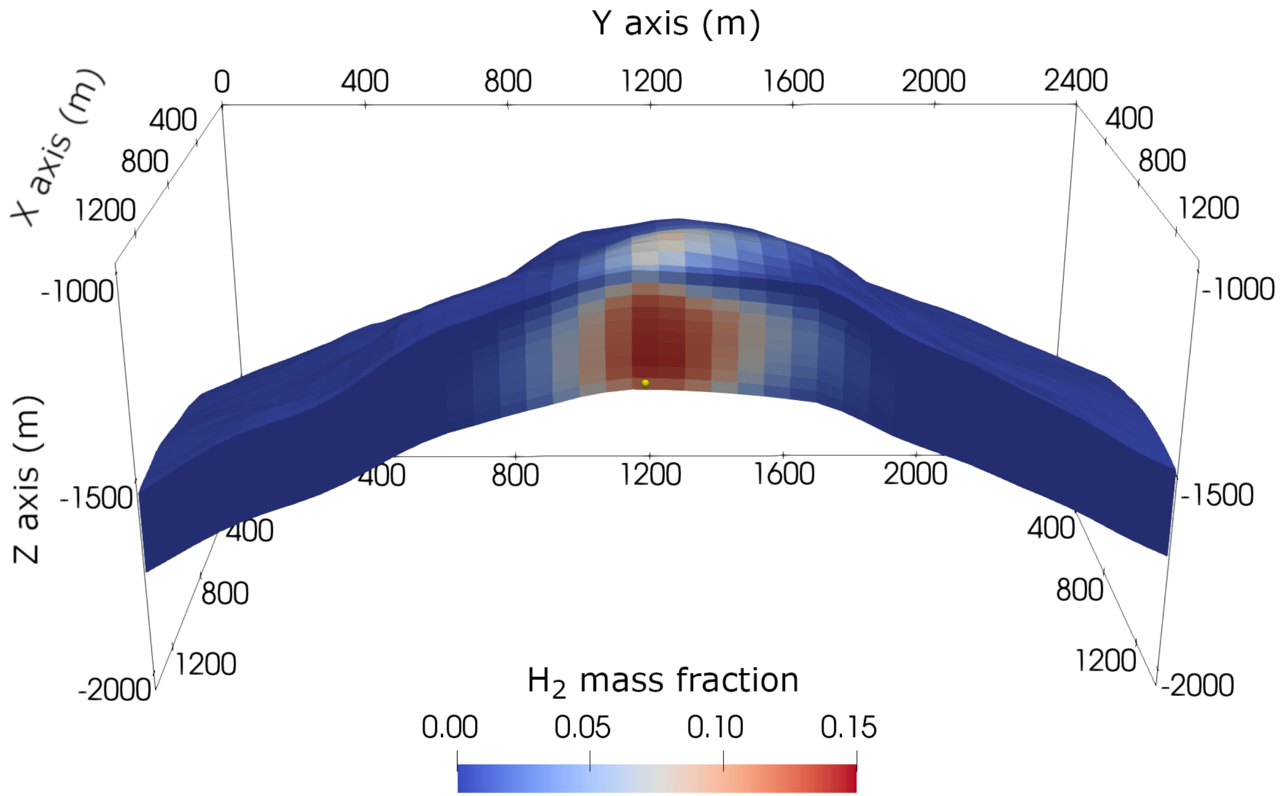
Test 4, 6, 7 & 8

Gravity Override

- Gravity overriding occurs due to high density contrast
- Gas rises, liquid sinks

Gravity Number: $N_g = \frac{\Delta \rho g}{\nabla P}$

Hydrogen	$N_g = 1.58 \cdot 10^{-2}$
Methane	$N_g = 1.43 \cdot 10^{-2}$



Modified from Baek et al. 2021

Simulations

Simulation Setup

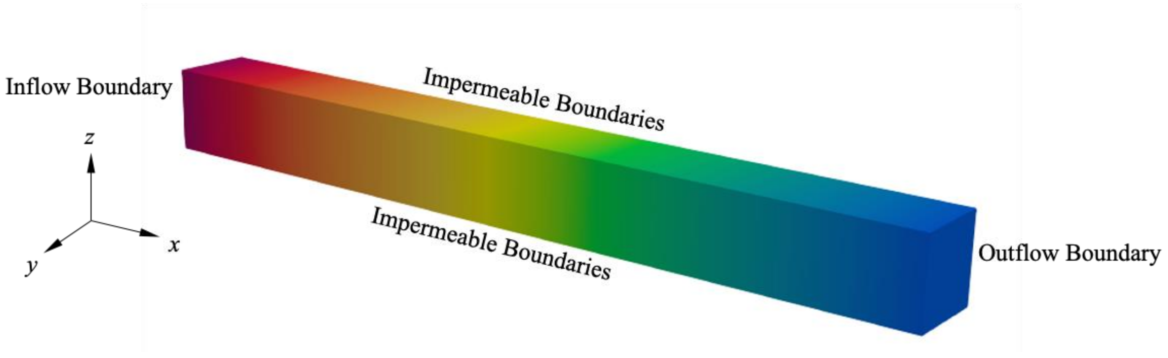
Core Flooding Simulations:

- GEOS
- Constant rate inlet boundary
- Constant pressure outlet boundary
- Impermeable lateral boundaries

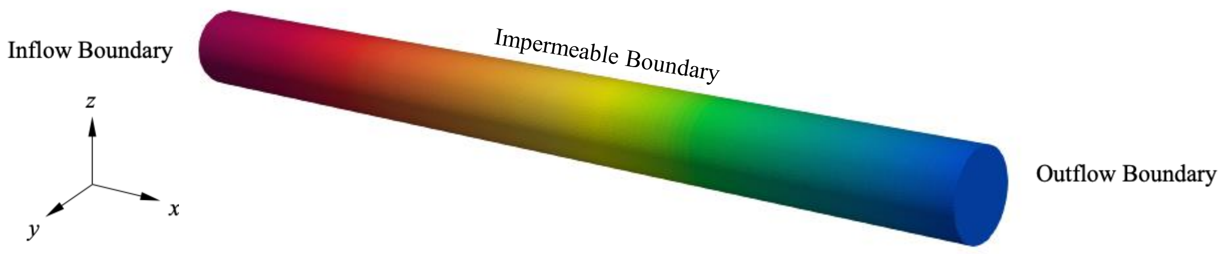
Characterization:

- Rock properties
- Fluid properties
- Capillary pressure model
- Relative permeability model

One-Dimensional



Three-Dimensional

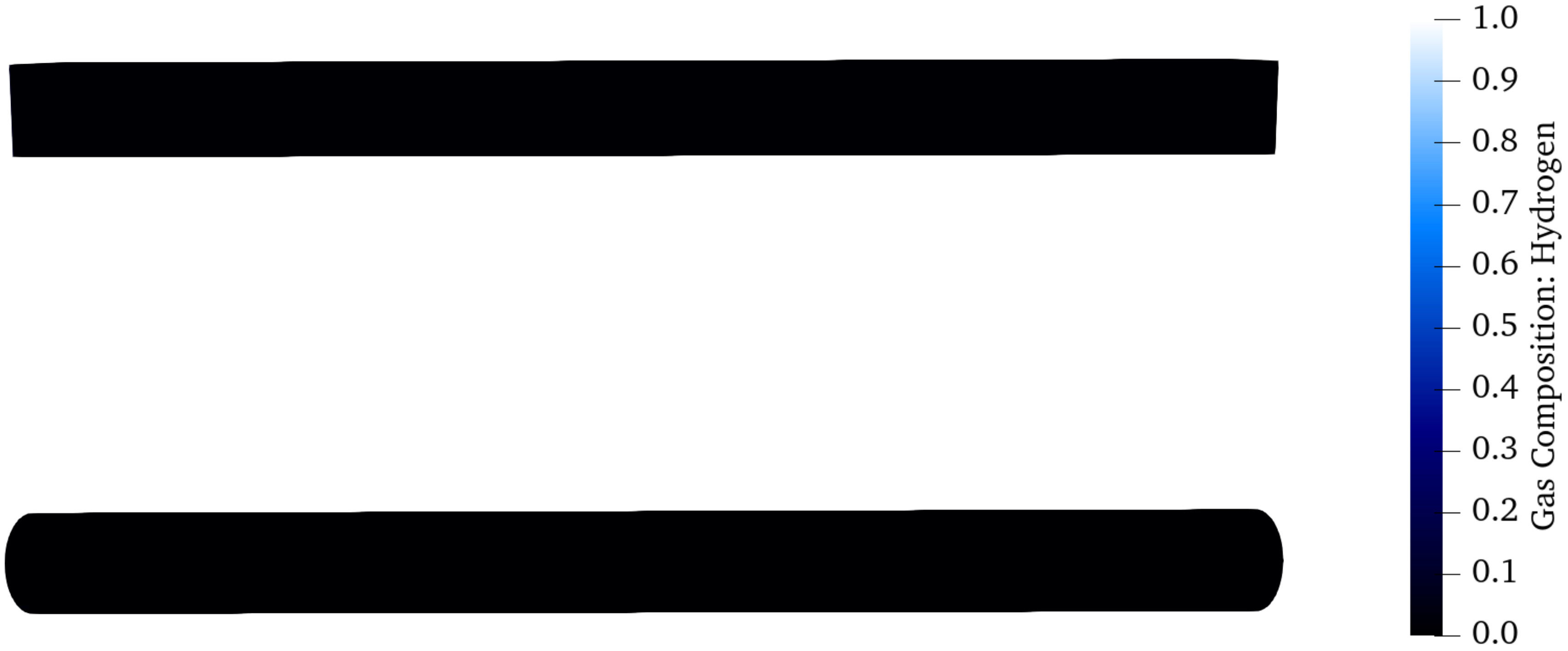


H2 Displacing CH4…

H2 Displacing CH4

One-Dimensional

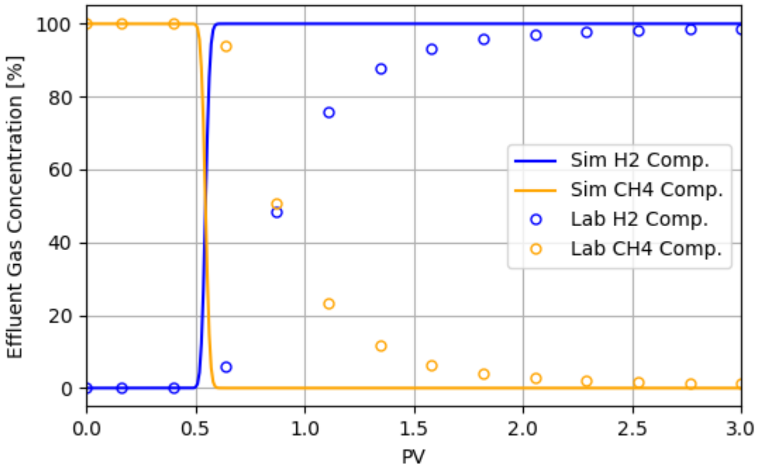
Three-Dimensional



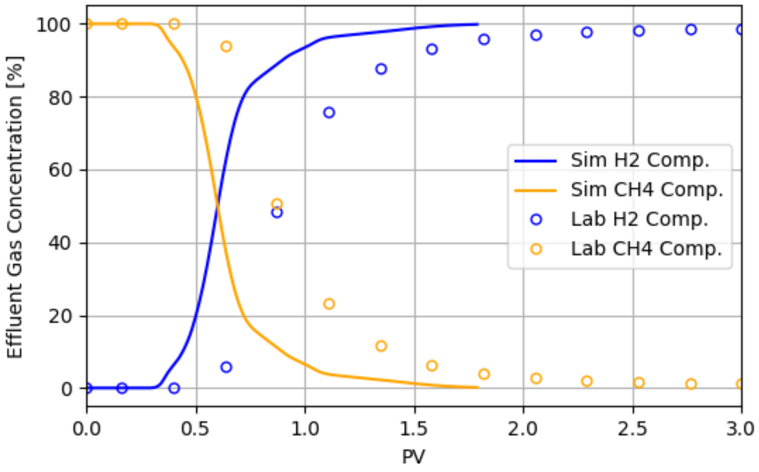
H2 Displacing CH4

Effluent Gas Composition

One-Dimensional



Three-Dimensional



Takeaways:
- Gravity override creates preferential flow path for H2 through core
- Transition to H2 effluent more gradual

More to investigate…

Conclusions

Conclusions

- Performed core flooding experiments: hydrogen (H2), methane (CH4), and brine.
- Higher injection rates or permeability enhances drainage of brine from pore space during gas injection.
- Gravity override a strong driver of advective gas mixing, even at core scale.
- Three-dimensional simulations clearly show gravity override effect.
- More simulations work to be done to improve understanding of flow behavior.

Questions?

References

Baek, S., Bacon, D.H., Huerta, N.J., 2021b. NRAP-Open-IAM Analytical Reservoir Model-Development and Testing. PNNL-31418. Pacific Northwest National Laboratory, Richland, WA. https://doi.org/10.2172/1855765.

SHASTA

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Microbial Characterization of Hydrogen Storage

Presenter: Djuna Gulliver

SHASTA 2024 Technical Workshop, April 3, 2024

People

Pictured (from left to right)

- Ryan Davis - Sandia
- Chuck Smallwood - Sandia
- Djuna Gulliver - NETL
- Kitt Bagwell – PNNL
- Kara Tinker – NETL

Not pictured

- Sierra McDermott – NETL
- Winston E. Anthony - PNNL

Work breakdown

1 **Risk Quantification**

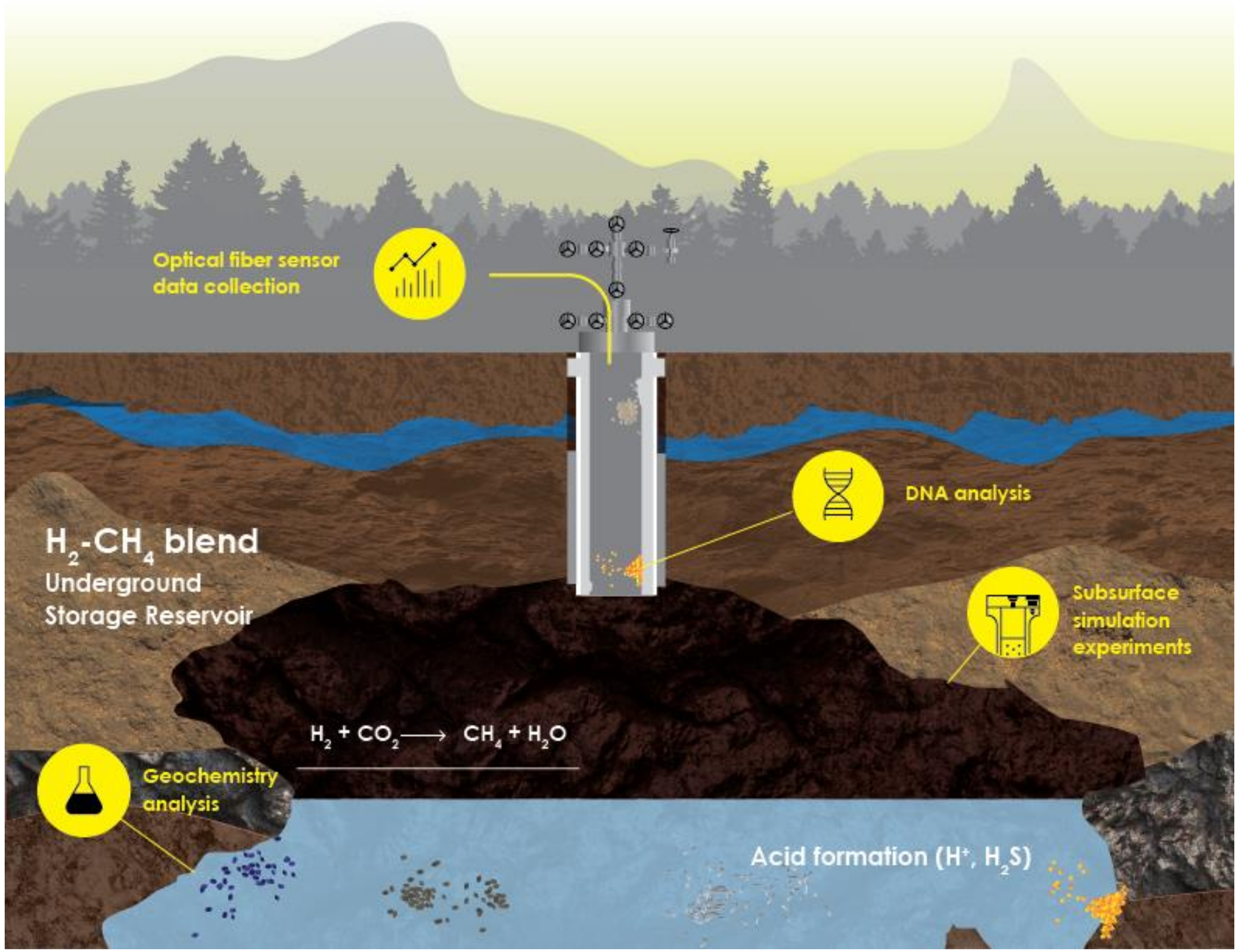
- **State-of-Knowledge and Research Needs Report**
- **Research Capabilities**
  - Reservoir Simulator Upgrades
  - Laboratory Upgrades
- **Fundamental (Applied) Science**
  - Rock-Gas Interactions
  - Flow Characterization & Dynamics
  - Microbial Interactions
  - Well Materials & Components
- **Risk Assessments**
  - Operational Risks
  - Safety Risks
  - Social License to Operate

2 **Enabling Technologies**

- **Software Development**
  - Open-Source Reservoir Simulator
  - Site-Screening Tool
- **Fiber-Optic Sensors**

3 **Stakeholder Engagement**

- **Recommended Practices Document(s)**
- **Techno-Economics and the Business Case**
- **Industry / Stakeholder Interactions**
  - **Case studies**
- **Pilot Study Preparation**



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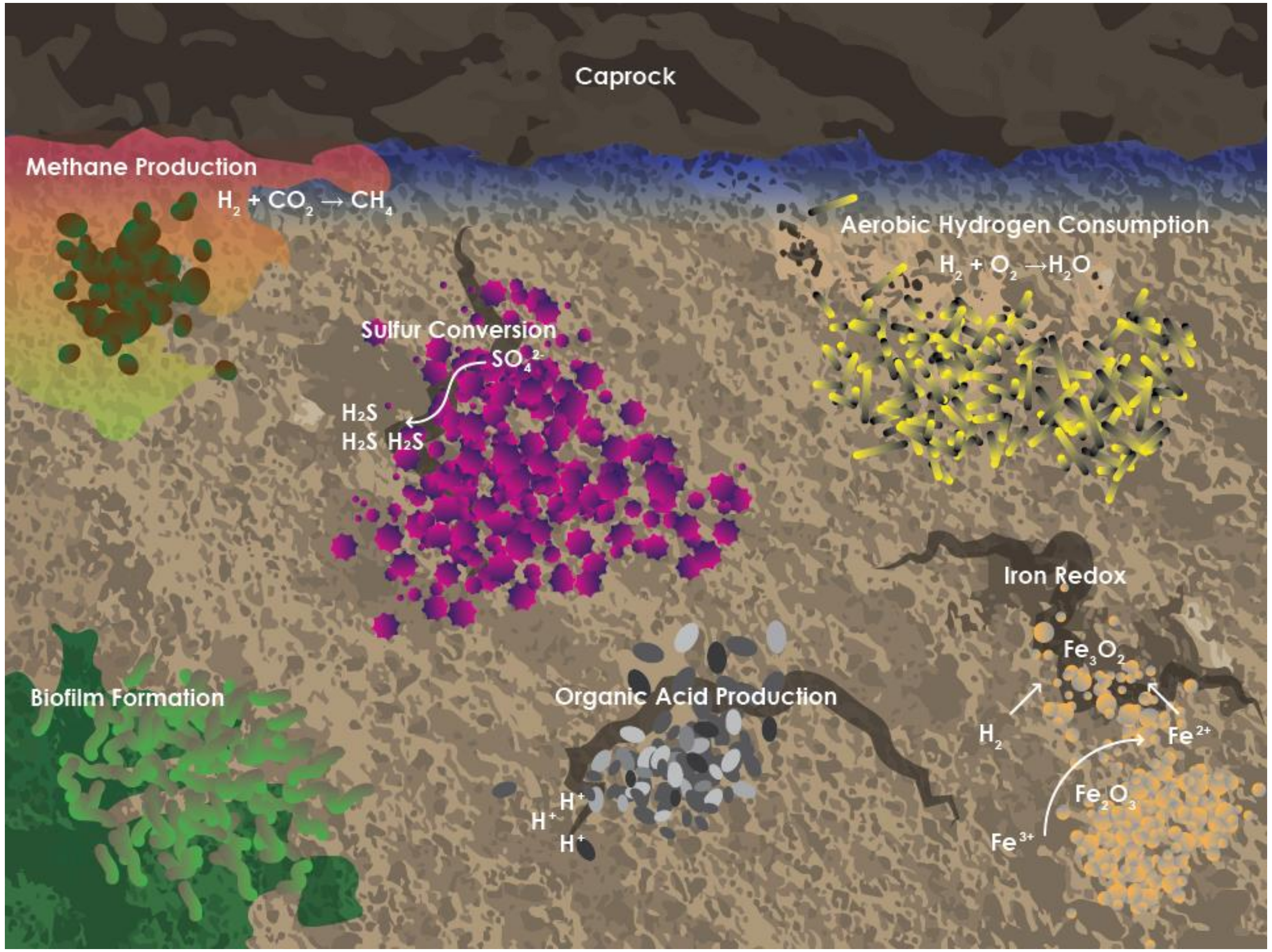
Microbial Interactions

Large-scale hydrogen storage will not be possible without the delineation of expected microbial activity



Microbial activity can affect subsurface energy storage through:

- Methanogenesis
- Hydrogen Sulfide Production
- Acid Production
- Microbiological Corrosion Pathways

Industry has documented microbial impacts on energy storage systems:

- Gaz de France found methanogens consumed 50% of stored hydrogen gas.
- Gaz de France documented challenges from microbially produced H_2S.
- Czech Republic gas storage fields reported consumption of stored H_2 coupled to H_2S production

Before hydrogen can be safely and securely stored in underground reservoirs, the effect of gas injection on the naturally occurring microbial community and the associated change in chemistry needs to be assessed.

Approach

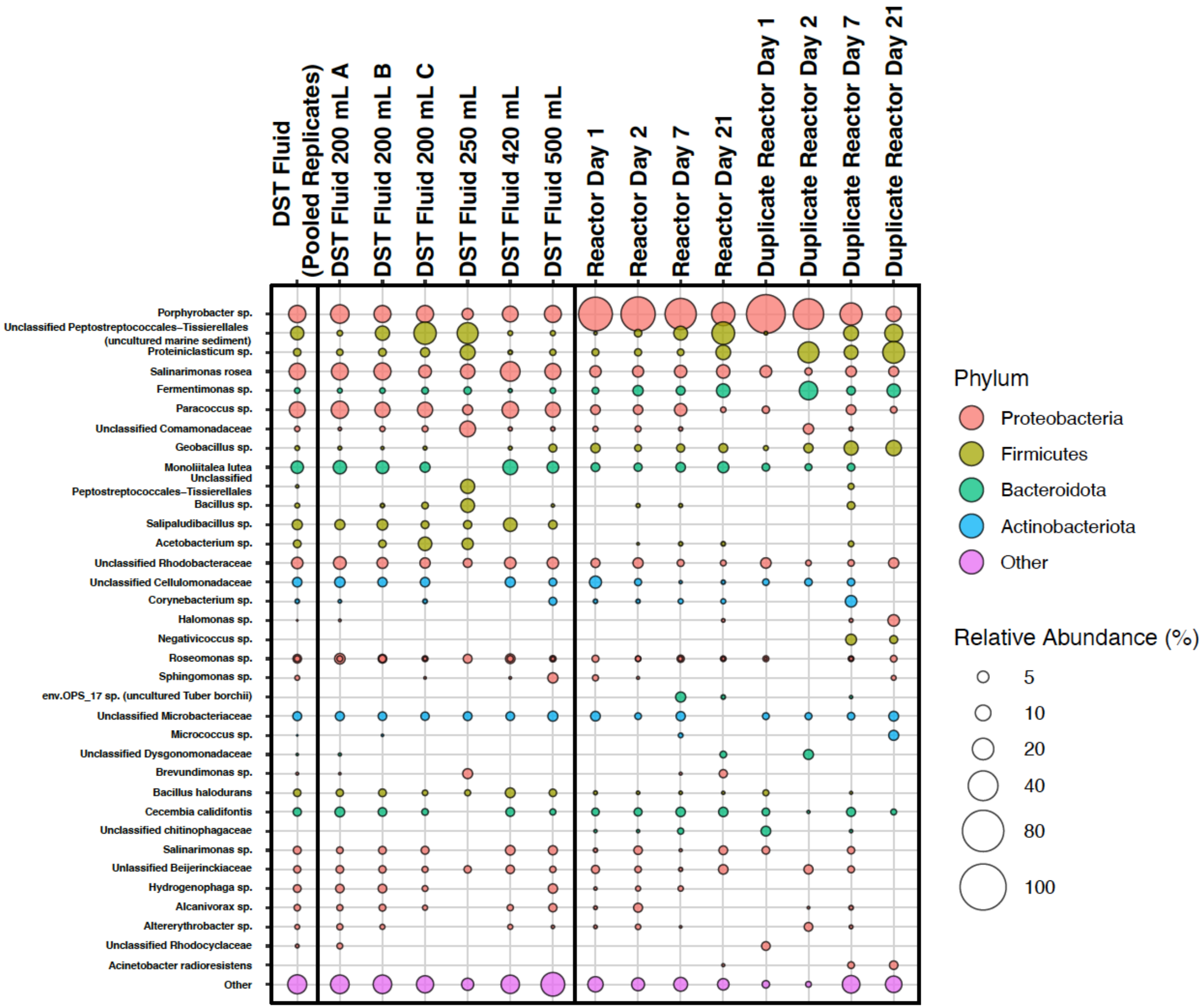
- **Field Sample**
- **Assess baseline geochemistry and microbiology**
- **Simulate various H_2 storage environments**
  - Assess changes in geochemistry, gas content, and microbiology

<u>**Previously presented results from**</u>

- 2021 baseline sites
- Small batch experiments

<u>**Presenting updates on**</u>

- 2023 sample baselines
- Small batch simulation series
- Large batch simulation series with sensors



Baseline - Fluid Chemistry

Date	Sample Name	Gas Analyzer: CH_4 (%)	CO_2 (%)	O_2 (%)	H_2S (ppm)	Balance	YSI Measurements: Temperature (°C)	DO (mg/L)	Sp Conduct (uS/cm)	TDS (mg/L)	pH	Alkalinity mg/L as $CaCO_3$
2/14/23	Site 1 Cubitaner #2	98.7	1	0.2	0	0	18.9	3.3	143,368	93,151	5.97	404
2/14/23	Site 1 Cubitaner #4						19.7	3.12	142,202	92,349	5.91	420
2/13/23	Site 2 Cubitaner #2	80	0.6	19.4	11	0	14.2	4.91	42,031	27,315	5.71	194
2/13/23	Site 2 Cubitaner #3						14.2	4.9	42,584	27,695	5.68	464

Cation/Anion (mg/L)	Ba	Ca	Cl	Fe	K	Li	Mg	Mn	Na	P	SO_4	Sr
Site 1	5.2	1,033	78060	89.4	2,792	0.36	104	4.2	42,966	0.84	195	73.3
Site 1	5.1	1,024	64096	83.4	2,774	0.38	100	4.2	43,592	0.85	191	77.8
Site 2	1.2	250	12144	104.5	2,125	0.90	52	2.7	7,774	0.87	731	5.8
Site 2	1.1	256	12258	103.7	2,139	0.91	54	2.6	7,793	0.96	754	5.7

Organics (mg/L)	Formate	Acetate	Propionate	Butyrate	Succinate	Oxalate
Site 1	27	1,333	326	57	41	2.1
Site 1	27	1,198	257	50	41	2.1
Site 2	8	3,783	843	284	158	4.0
Site 2	8	3,895	853	291	163	4.3

Organic/Inorganic Carbon	Organic Carbon (mg/L)	Inorganic Carbon (mg/L)
Site 1	1045	37.52
Site 1	970.7	38.62
Site 2	2941	42.53
Site 2	3011	55.34

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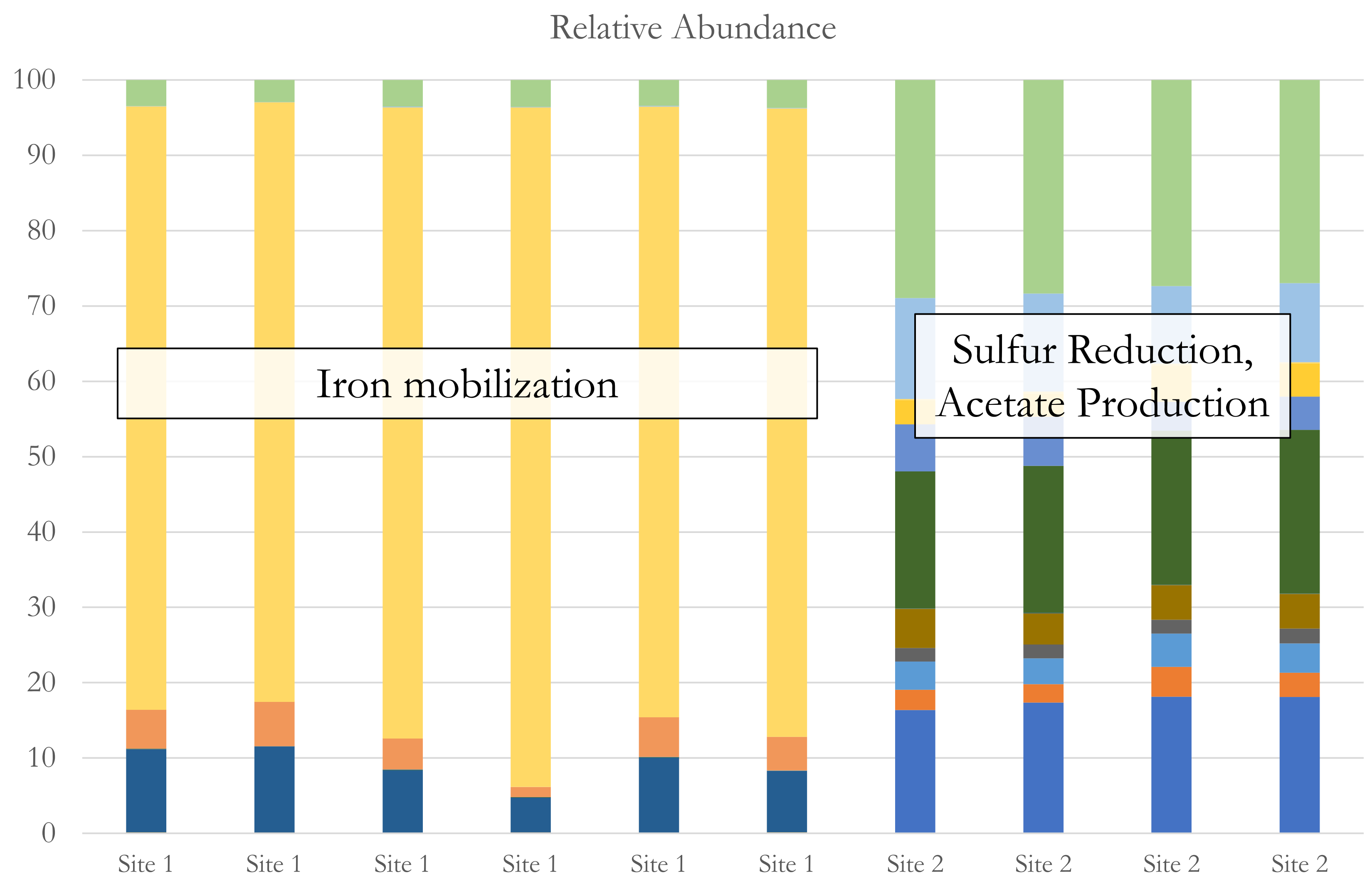
Baseline – Taxonomy

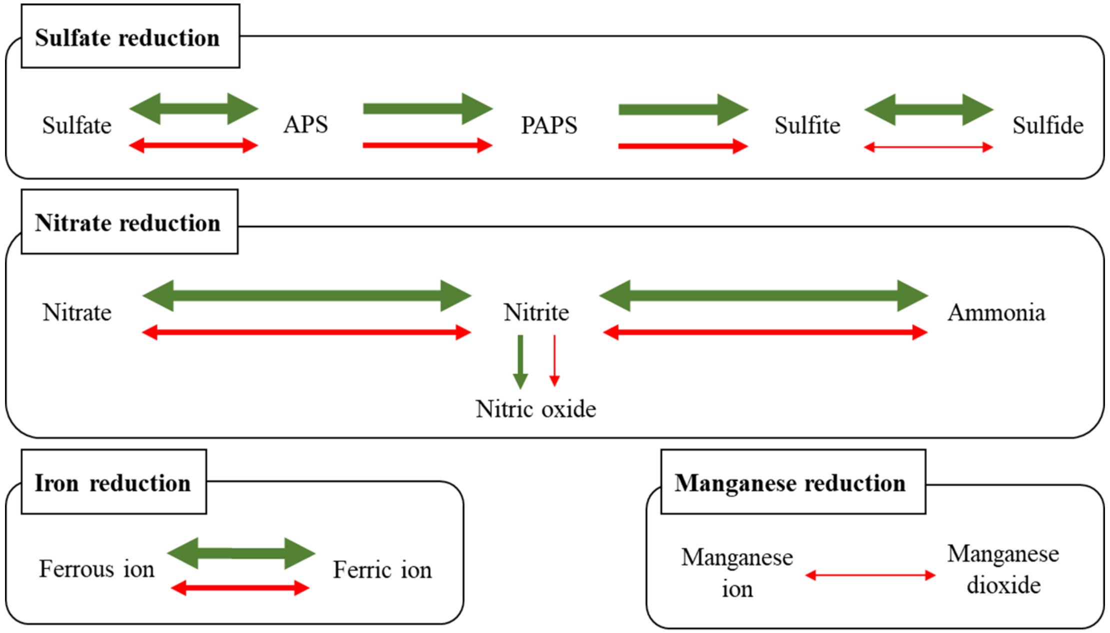


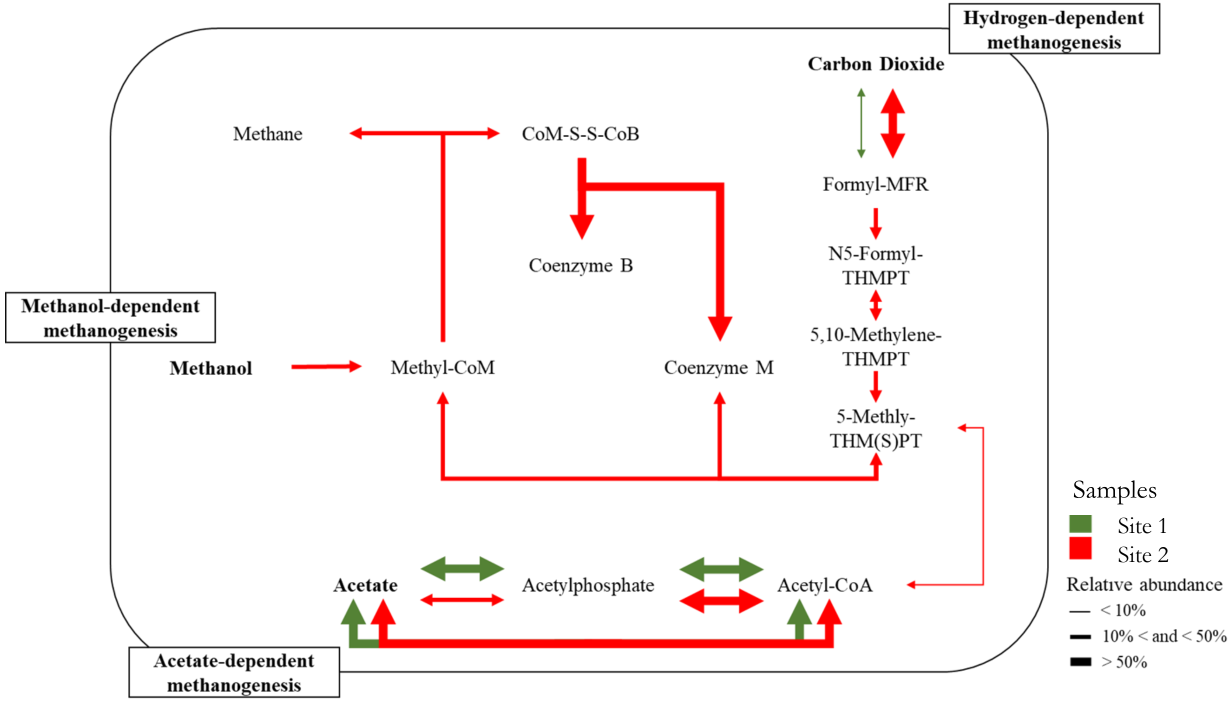
Baseline - Metagenome

Risk Quantification

Potential microbial function, or what reactions the microorganisms have the potential to perform, were assessed for the 2023 samples:

- If subsurface environmental conditions are favorable for methanogens, methane could be produced at site 2 from methanol, carbon dioxide, and acetate.
- The microbiological inorganic compound reduction could be observed at both sites.
- The end products of inorganic compound reductions could have potentially negative structural and environmental impacts.
- The reduction of inorganic compound could be more dominant metabolic pathways at site 1.





H_2 transformation at reservoir conditions

	Biotic Control ($100\% \ CH_4$)	Abiotic Control ($100\% \ CH_4$)	Biotic ($20\% \ H_2$ $80\% \ CH_4$)	Abiotic ($20\% \ H_2$ $80\% \ CH_4$)
1 Day	√	√	√	√
3 Days	√	√	√	√
7 Days	√	√	√	√
3-Day Sterile Blank	√		√	

Sample: Site 2, unfiltered (biotic) or filtered (abiotic)

Pressure: ~1000 psi

Temperature: 80°C

Volume: 500 mL fluid, 500 mL headspace

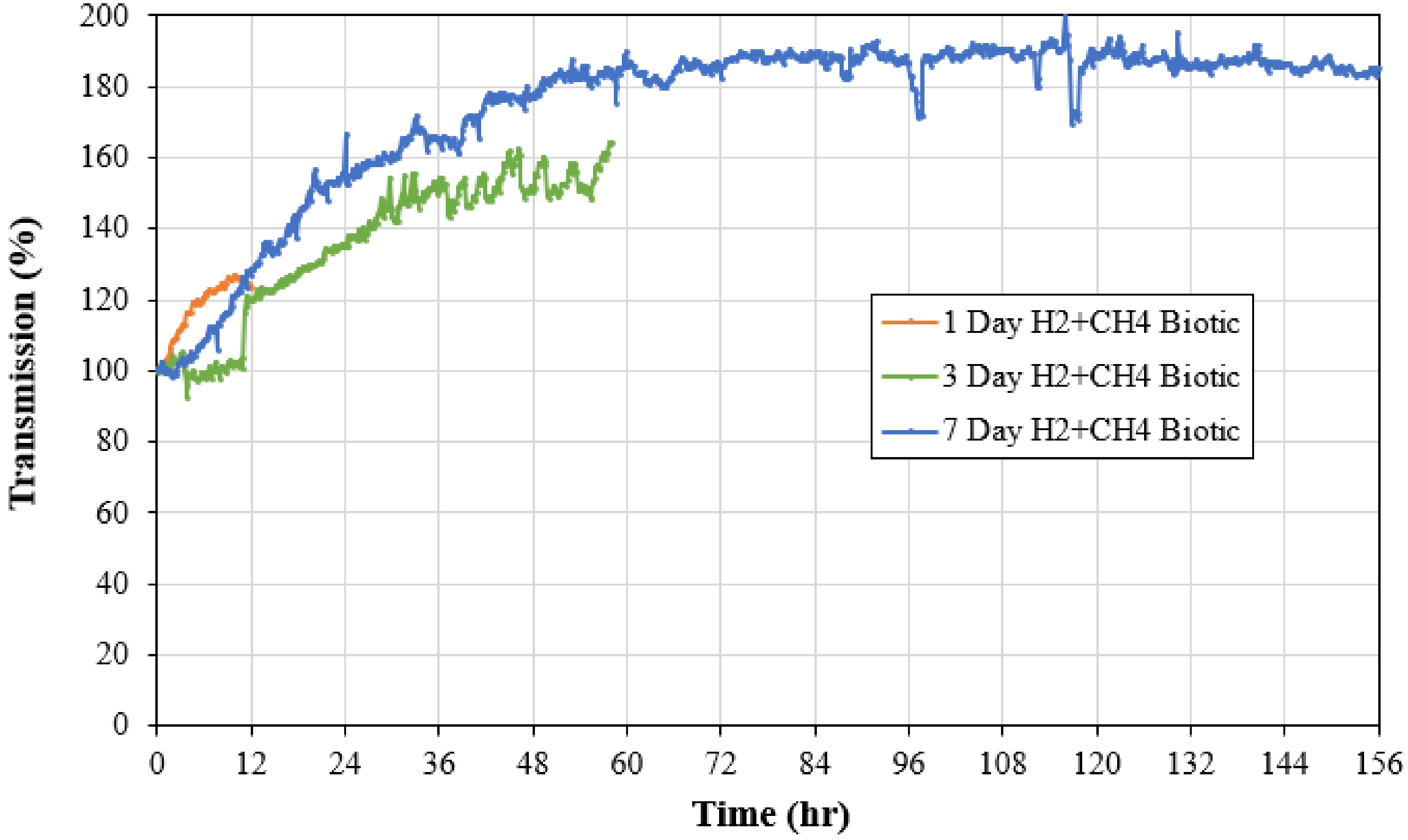
Next Quarter Goals:

- Complete all reactors
- Complete geochemistry and gas analyses
- Analyze sensor data
- Start microbiology analysis

H_2 transformation at reservoir conditions: GC Data

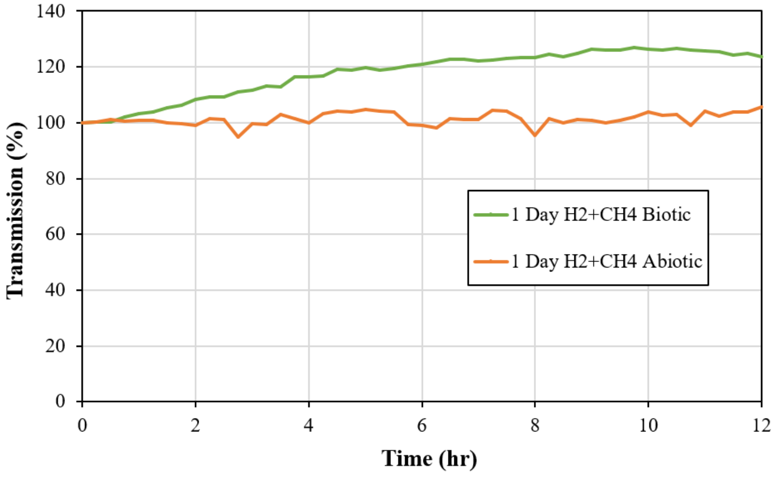
Treatment Length	Reactor	Gas Treatment	% CH_4	% H_2	pH
0 Day	Bottle Control	100% CH_4	100	0	
1 Day	Abiotic	100% CH_4	100	0	5.61
1 Day	Biotic	100% CH_4	100	0	5.61
3 Day	Abiotic	100% CH_4	100	0	5.63
3 Day	Biotic	100% CH_4	100	0	5.58
7 Day	Abiotic	100% CH_4	100	0	5.63
7 Day	Biotic	100% CH_4	100	0	5.58
0 Day	Bottle Control	80% CH_4/20% H_2	85	15	
1 Day	Abiotic	80% CH_4/20% H_2	94	6	5.61
1 Day	Biotic	80% CH_4/20% H_2	91	9	5.60
3 Day	Abiotic	80% CH_4/20% H_2	83	17	5.65
3 Day	Biotic	80% CH_4/20% H_2	93	7	5.58
7 Day	Abiotic	80% CH_4/20% H_2	84	16	5.63
7 Day	Biotic	80% CH_4/20% H_2	86	14	5.58

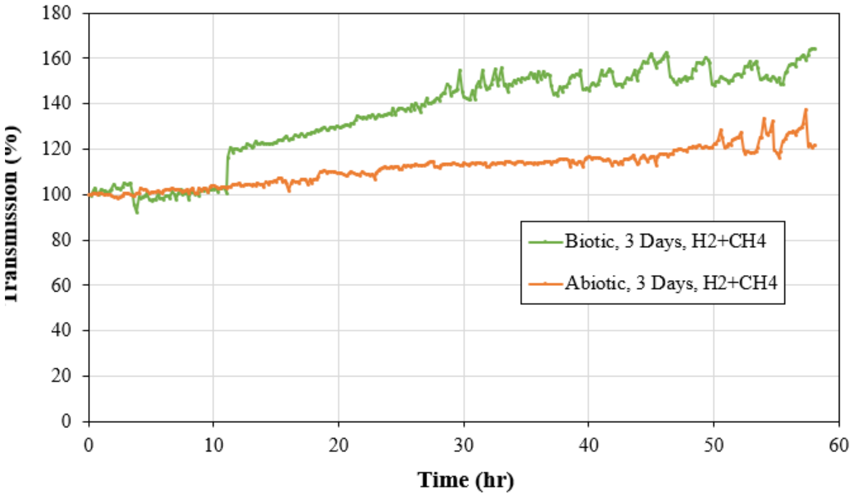
H_2 transformation at reservoir conditions: Sensor Data

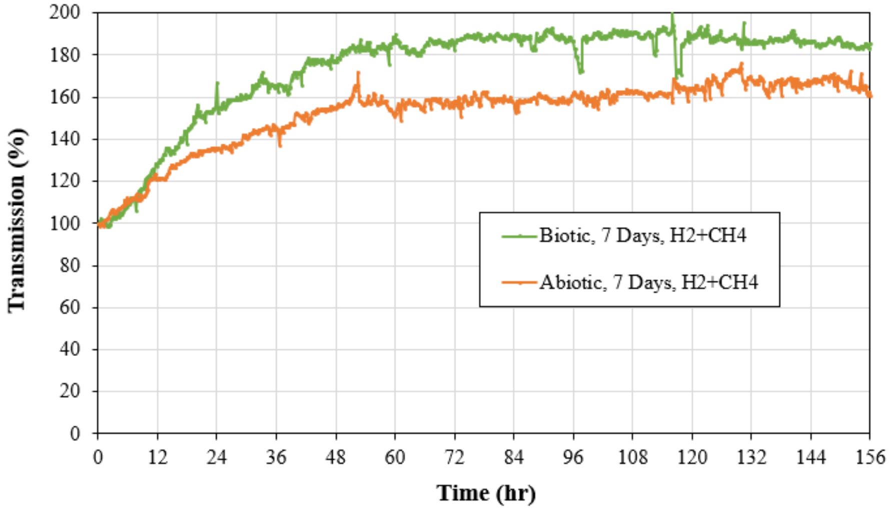


Length	Reactor	Gas Treatment	% CH_4	% H_2
1 Day	Biotic	80% CH_4/20% H_2	91	9
3 Day	Biotic	80% CH_4/20% H_2	93	7
7 Day	Biotic	80% CH_4/20% H_2	86	14

H_2 transformation at reservoir conditions: Sensor Data







Treatment Length	Reactor	Gas Treatment	% CH_4	% H_2	pH
1 Day	Abiotic	80% CH_4/20% H_2	94	6	5.61
1 Day	Biotic	80% CH_4/20% H_2	91	9	5.60
3 Day	Abiotic	80% CH_4/20% H_2	83	17	5.65
3 Day	Biotic	80% CH_4/20% H_2	93	7	5.58
7 Day	Abiotic	80% CH_4/20% H_2	84	16	5.63
7 Day	Biotic	80% CH_4/20% H_2	86	14	5.58

H_2 transformation at reservoir conditions: IC Data

Cation/Anion (mg/L)

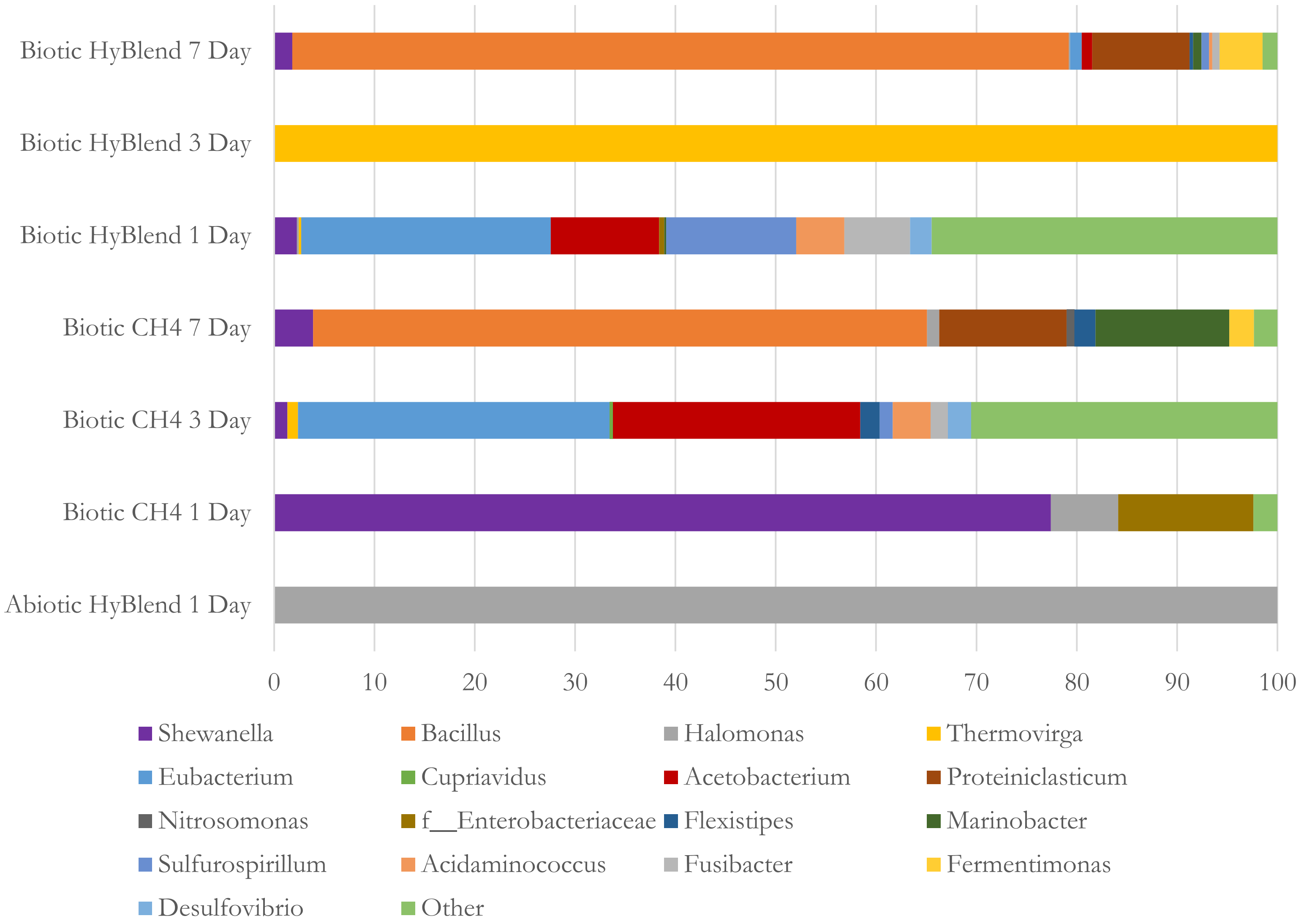
Treatment Length	Reactor	Gas Treatment	**Ba**	**Br**	**Ca**	**Cl**	**F**	**I**	**K**	**Li**	**Mg**	**Na**	**NH_4**	**SO_4**	**Sr**
1 Day	Abiotic	100% CH_4	27.7	123.1	310	13940	6.03	18.79	2508	1.61	57.83	8746	142	788	12.34
1 Day	Biotic	100% CH_4	26.71	101.45	255	11493	5.37	15.62	2087	1.41	46.2	7276	120	650	11.27
3 Day	Abiotic	100% CH_4	30.25	121.38	306	13746	5.77	17.98	2532	1.6	56.96	8805	143	773	12.34
3 Day	Biotic	100% CH_4	61.05	101.69	282	12864	5.65	18.82	2325	1.47	52.03	8169	133	712	11.97
7 Day	Abiotic	100% CH_4	30.85	114.92	306	13041	5.51	17.48	2574	1.62	58.13	8957	147	734	12.49
7 Day	Biotic	100% CH_4	28.16	105.48	283	12038	5.58	15.81	2335	1.51	52.25	8182	134	668	11.91
1 Day	Abiotic	80% CH_4/20% H_2	24.03	72.38	341	11912	4.27	14.55	2712	1.78	69.82	8480	459	639	14.08
1 Day	Biotic	80% CH_4/20% H_2	22.94	72.53	349	11963	4.22	13.11	2749	1.79	70.67	8592	464	645	14.16
3 Day	Abiotic	80% CH_4/20% H_2	24.77	72.16	350	12074	3.74	15.04	2772	1.69	70.27	8672	479	658	14.18
3 Day	Biotic	80% CH_4/20% H_2	22.29	73.1	352	12229	4.09	14.14	2774	1.69	68.5	8670	482	663	14.26
7 Day	Abiotic	80% CH_4/20% H_2	n.a.	75.97	358	12488	4.13	14.51	2817	1.72	69.5	8750	482	688	14.44
7 Day	Biotic	80% CH_4/20% H_2	n.a.	77.44	369	12576	3.95	14.78	2905	1.75	70.73	9012	502	689	14.94

H_2 transformation at reservoir conditions: IC Data

Organics (mg/L)

Treatment Length	Reactor	Gas Treatment	Acetate	Propionate	Formate	Butyrate	Succinate	Oxalate
1 Day	Abiotic	100% CH_4	4416	999	n.a.	333	6.48	9.24
1 Day	Biotic	100% CH_4	3596	823	n.a.	277	n.a.	9.14
3 Day	Abiotic	100% CH_4	4275	974	n.a.	323	7.45	8.74
3 Day	Biotic	100% CH_4	3997	896	13.8	298	30.58	11.64
7 Day	Abiotic	100% CH_4	4063	931	n.a.	310	7.15	8.99
7 Day	Biotic	100% CH_4	3720	849	15.97	284	9.76	10.05
1 Day	Abiotic	80% CH_4/20% H_2	3538	811	29.17	268	4.39	12.29
1 Day	Biotic	80% CH_4/20% H_2	3566	819	29.31	271	4.55	15.46
3 Day	Abiotic	80% CH_4/20% H_2	3639	833	n.a.	268	4.62	14.02
3 Day	Biotic	80% CH_4/20% H_2	3682	845	30.32	275	4.91	15.35
7 Day	Abiotic	80% CH_4/20% H_2	3776	864	31.33	286	4.04	14.45
7 Day	Biotic	80% CH_4/20% H_2	3786	868	31.75	286	4.05	16.02

H_2 transformation at reservoir conditions: Taxonomy Data



Same microorganisms found in the initial sample

- Iron reduction
- Sulfur reduction
- Acetate Production
- High salinity tolerance
- Oil reservoir anaerobic microorganisms

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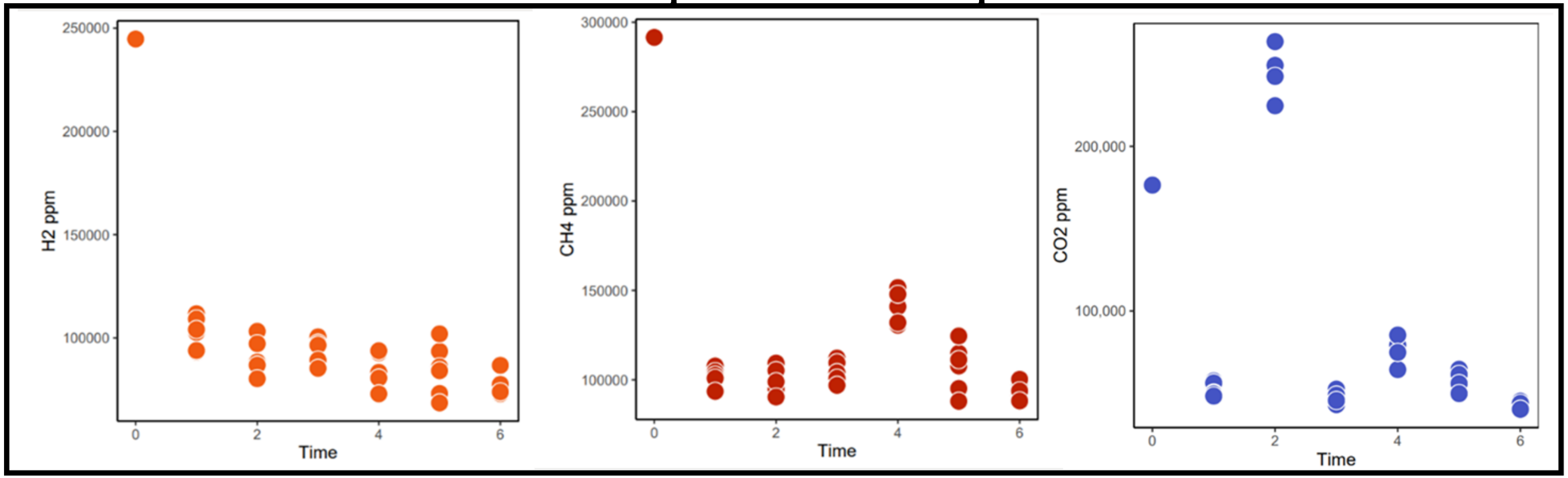
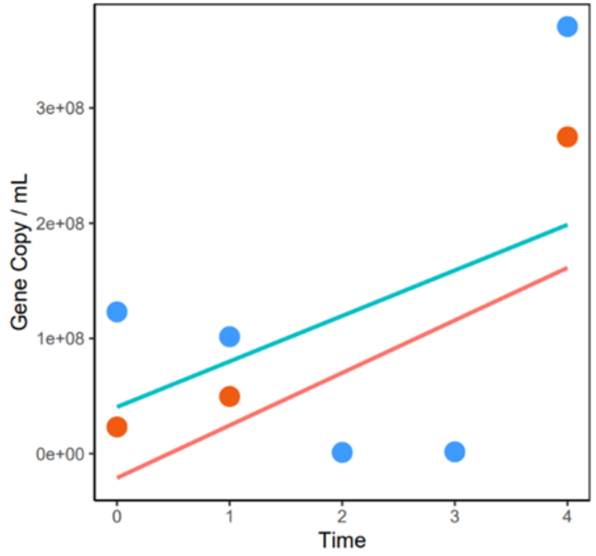
Microbial Interactions

Risk Quantification

Headspace Gas Composition



Microbial Biomass



Completed incubation experiments with Site 2 samples and 40% H_2, 40% CH_4, 20% CO_2

- Lab experiments demonstrate drawdown of gas mixtures. Transformation rates appear to be consistent with published values
- H_2 replete conditions may sustain anaerobic taxa / reaction pathways that would otherwise compete
- Additional samples and experiments are needed to accurately measure reaction kinetics

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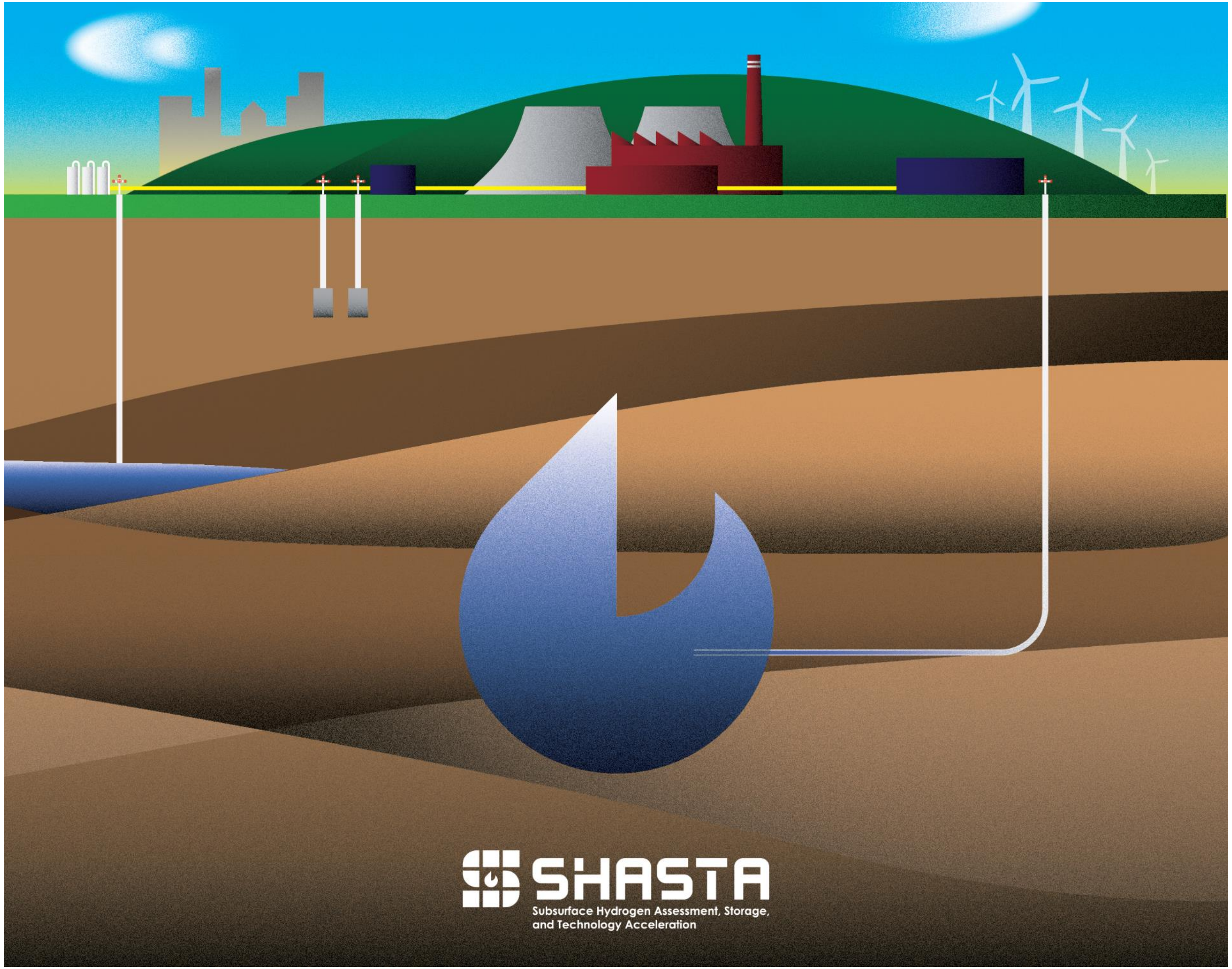
Conclusions

- Sites vary in geochemistry and microbiology
  - Site 1 has a high abundance of metabolic potential to consume hydrogen through iron, nitrate, and sulfate reduction, but potential is present in both
  - Site 2 has a high abundance of metabolic potential to consume hydrogen through methane production
- Initial reactors suggest kinetic rate will be most important during the 1-3 day timeframe

Lessons Learned

- Sterilization methods need to be optimized
- Gas headspace is extremely sensitive to variation
- Replicability will be crucial, and microbiology adds complexity
- Cell preservation methods during sampling will be optimized



Questions?

https://edx.netl.doe.gov/shasta/

Djuna.Gulliver@netl.doe.gov

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Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

H_2 Wettability, Permeability, and Diffusion

Angela Goodman, Deepak Tapriyal, Foad Haeri, Barbara Kutchko, Rick Spaulding Mehrdad Massoudi

National Energy Technology Laboratory

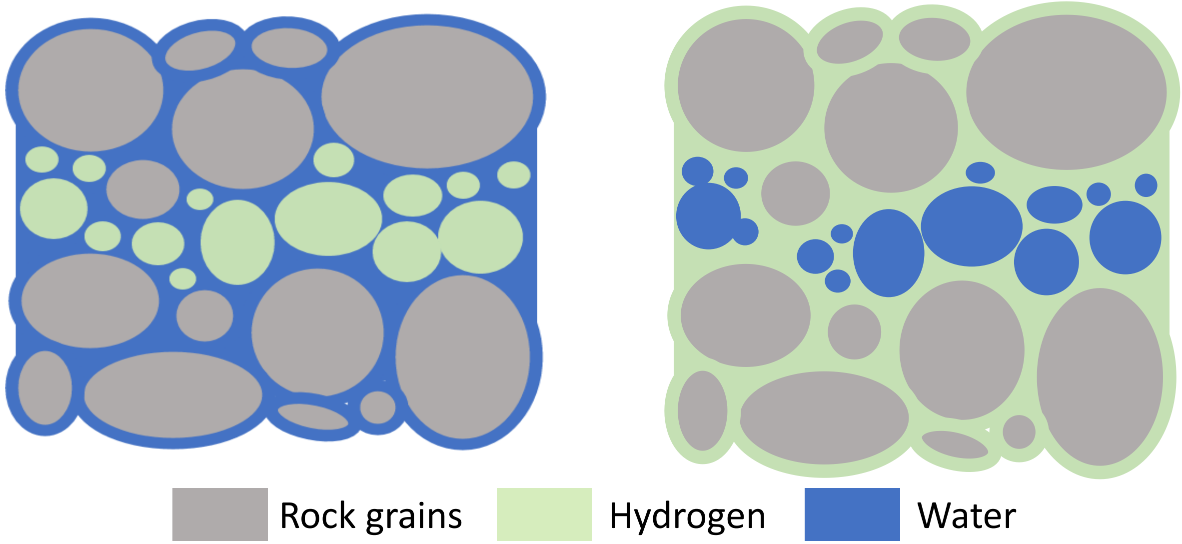
April 3, 2024

Question:

Do rocks become H_2-wet under geologic storage conditions?

(A) <u>Water-wet:</u> Water coats rock grains. H_2 stored temporarily as the non-wetting phase.

(B) <u>H_2-wet:</u> H_2 coats rock grains. H_2 trapped indefinitely.



- [Hydrogen Wettability of Sandstone Reservoirs: Implications for Hydrogen Geo-Storage - Iglauer - 2021 - Geophysical Research Letters - Wiley Online Library]
- [Influence of pressure, temperature and organic surface concentration on hydrogen wettability of caprock; implications for hydrogen geo-storage - ScienceDirect]
- [Hydrogen wettability of quartz substrates exposed to organic acids; Implications for hydrogen geo-storage in sandstone reservoirs - ScienceDirect]

Key Points:

- **Hydrogen storage technology is gaining momentum to reduce emissions to mitigate global warming.**
- **H_2 storage is targeted in depleted gas and oil formations and saline formations (porous rock matrix filled with brine), sealed with a low permeability caprock.**
- **Some studies have examined the wettability of rocks and suggested that H_2 could become wetting under geostorage conditions and negatively impact containment effectiveness.**

Question:

Do rocks become H_2-wet under geologic storage conditions?

Key Points:

- Performed H_2-brine contact angle experiments on shale rocks, sandstone, and cement.
- No change in contact angle temperature (23°C, 45°C and 70°C), pressure (10.3 MPa, 34.5 MPa, and 51.7 MPa), salinity (50,000 ppm), and bubble size (50-2000 μm).

- <u>Reservoir rocks will remain water-wet at geologic H_2 storage conditions</u>

Contact Angle and Wettability

- Contact angle is a measurement of wetting properties of the rock in contact with brine and H_2. It is used as an **indirect method** to estimate the wettability. Factors like surface roughness, heterogeneity within sample, measurement methodology can affect resulting contact angle.
  - If the rock is water wet, the contact angle is less than 90 degrees, P_c is positive, and the pores will retain the buoyant H_2.
  - If the rock is H_2 wet, the contact angle is greater than 90 degrees, P_c is negative, and then H_2 will be imbibed into pores.

- Chalbaud, C.; Robin, M.; Lombard, J. M.; Martin, F.; Egermann, P.; Bertin, H. Interfacial tension measurements and wettability evaluation for geological CO2 storage. Adv. Water Resour. 2009, 32, 98–109.

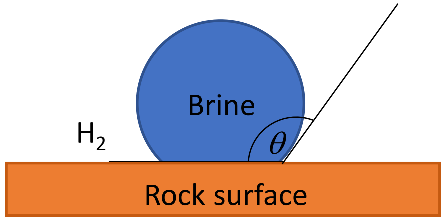
Pc = Capillary entry pressure

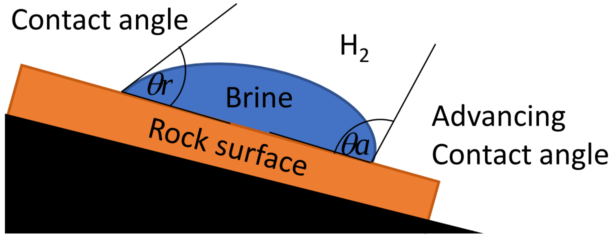
$$P_c = \frac{2\sigma\cos\theta}{r}$$

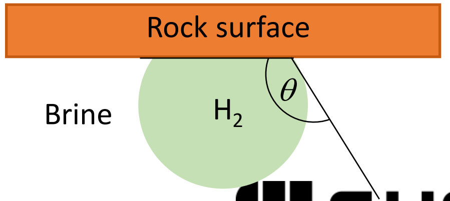
σ = H_2-brine interfacial tension

θ = H_2-brine-rock contact angle

r = pore throat radius





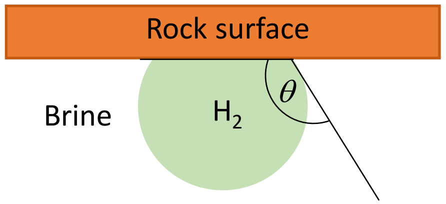


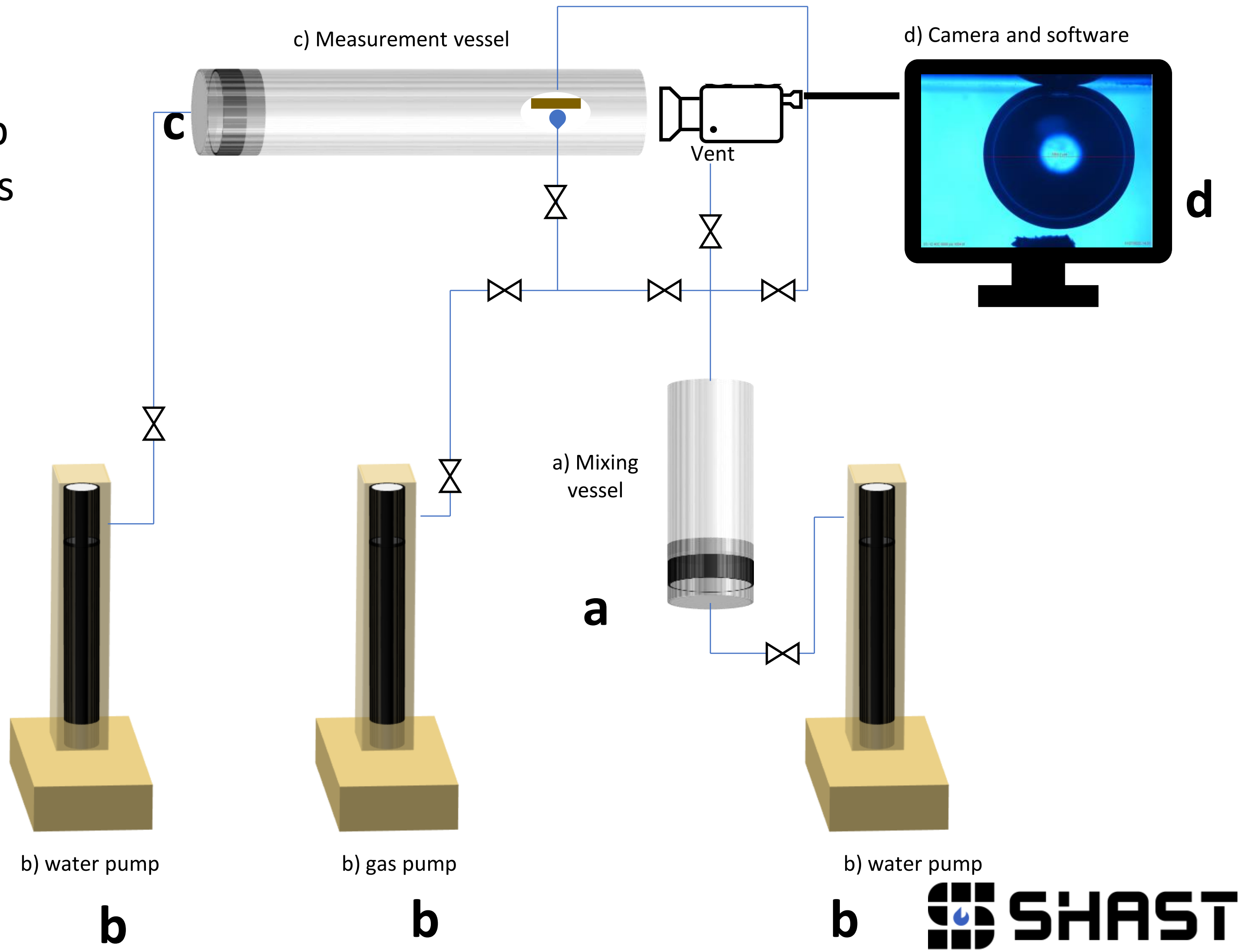
Experimental Set-Up

Customized contact angle measurement setup for high pressure, high temperature conditions

- P_{max}=70 MPa (10,000 psia)
- T_{max}=150 °C

a) Mixing cell
b) Pumping system: water and H_2 pumps
c) Measurement cell
d) Camera and Software.





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Experimental Materials and Conditions

Samples: Nixon Shale, Class G Cement, Berea Sandstone

Brine: NaCl (50,000 ppm)

Conditions: Temperature: 23°C, 45°C and 70°C

Pressure: 10.3 MPa, 34.5 MPa, and 51.7 MPa (1500 psia, 5000 psia, 7500 psia)

Sample Size: 10 mm x 8 mm.

Measurements: Brine and H_2 are equilibrated overnight at set temperature and pressure
Next day multiple bubbles (50 microns-2000+ microns) are generated for measurements. Each bubble is observed for at least 5 minutes before measurement. Then new bubble is generated.

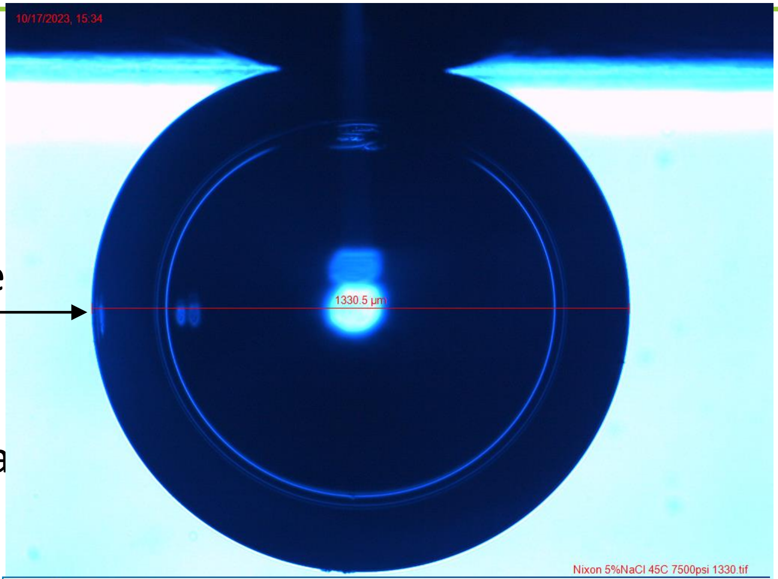
Exposure Time: 3 months exposure

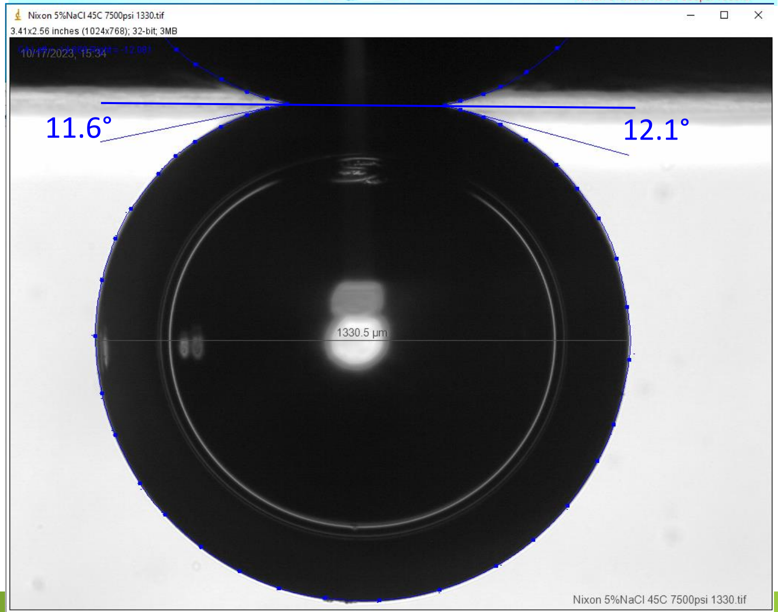
Results: Hydrogen Bubble Generation

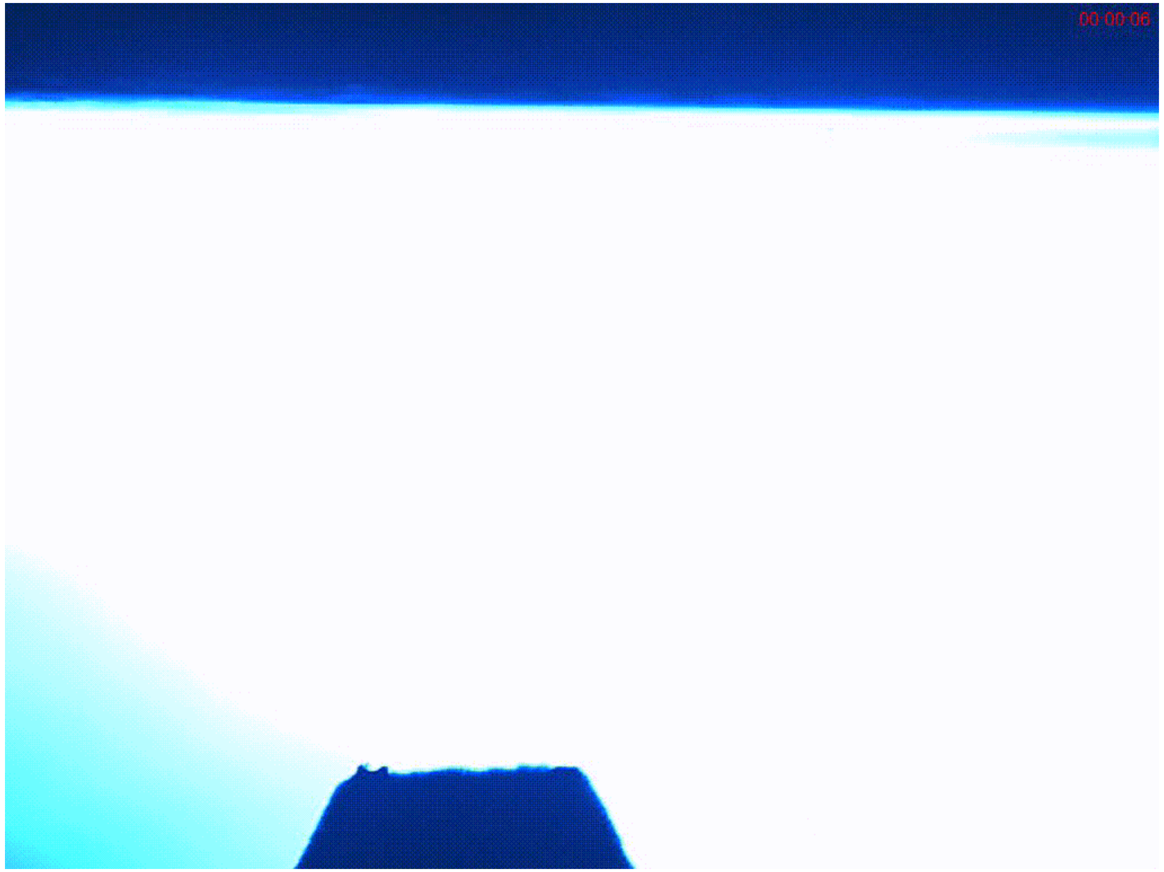
Nixon Shale

H_2 bubble

45°C /7500 psia

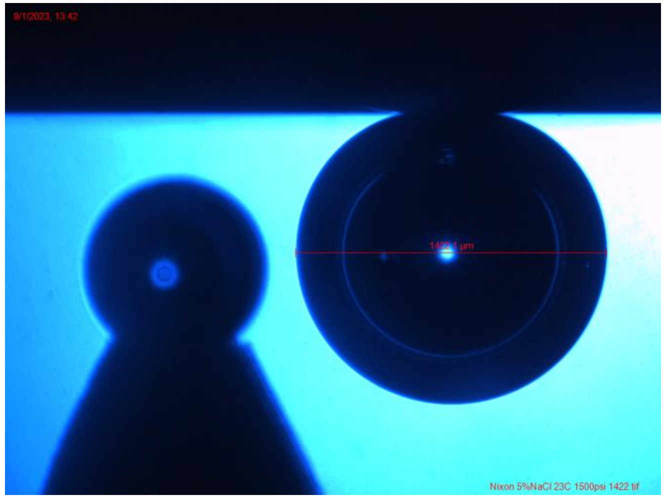


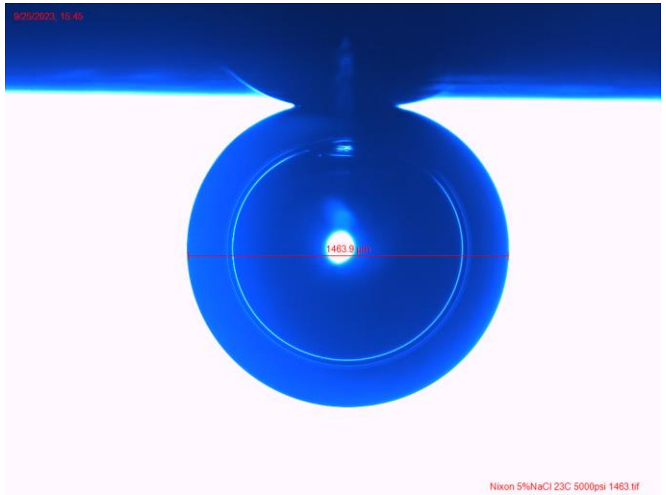


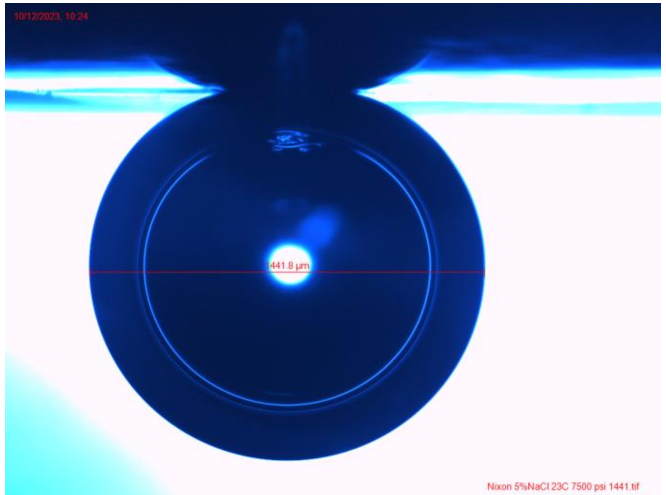


Results: Hydrogen Bubble Generation

Nixon Shale ~1450 micron diameter bubble







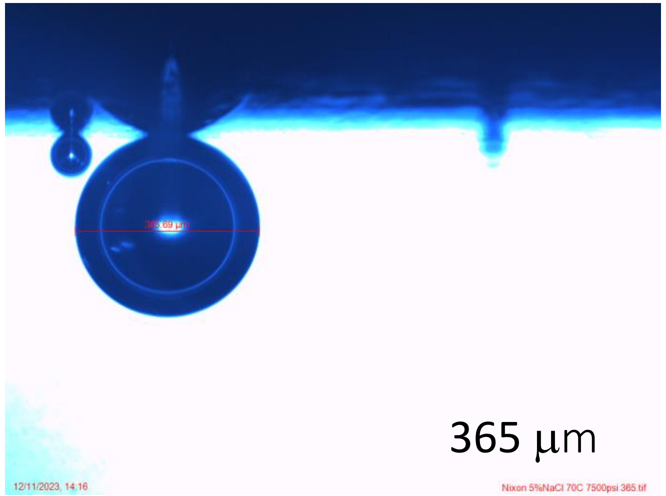
23°C, 1500 psia

23°C, 5000 psia

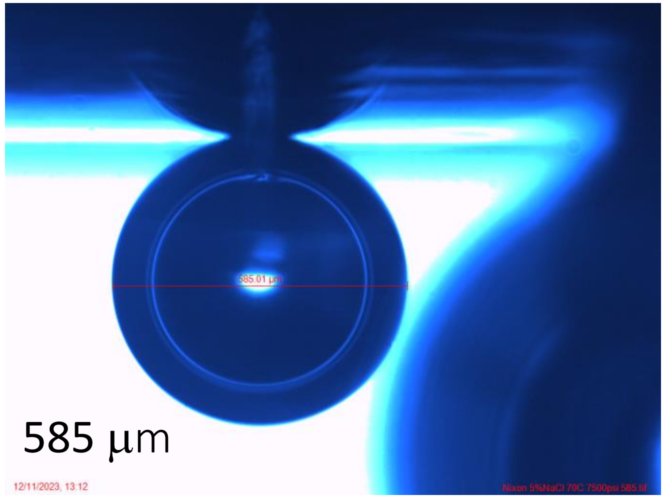
23°C, 7500 psia

Increasing Pressure

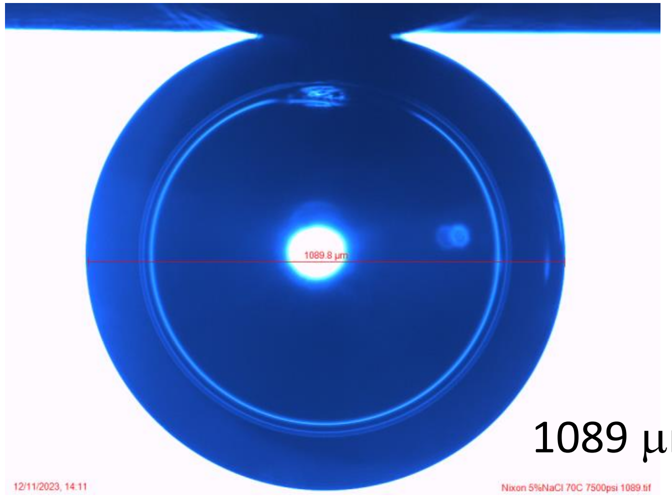
Results: Hydrogen Bubble Generation



365 μm



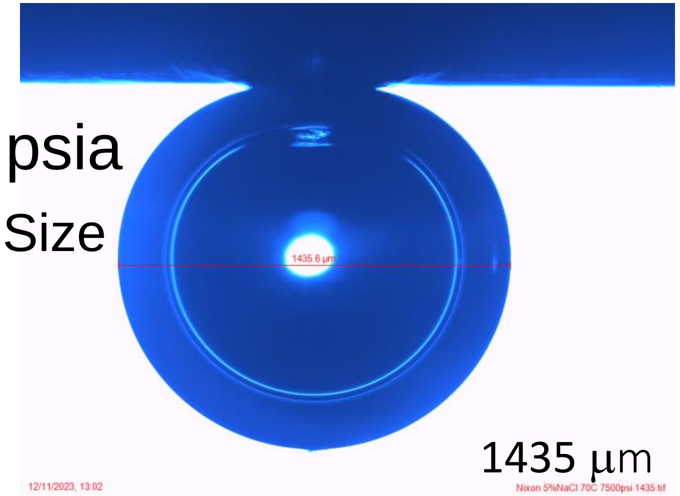
585 μm



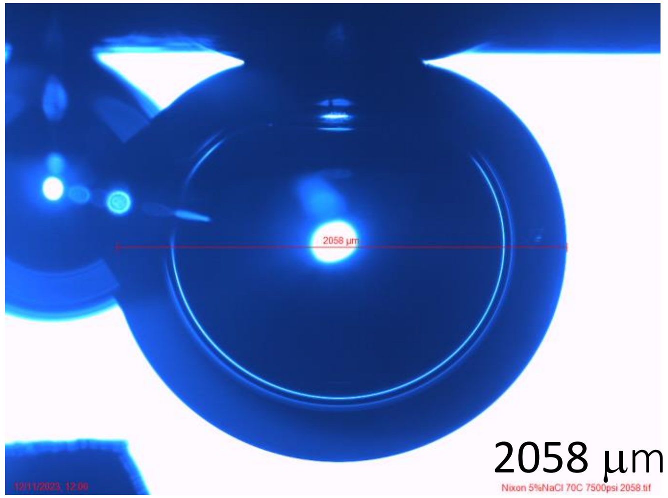
1089 μm

Nixon 70°C, 7500 psia

- Increasing Bubble Size



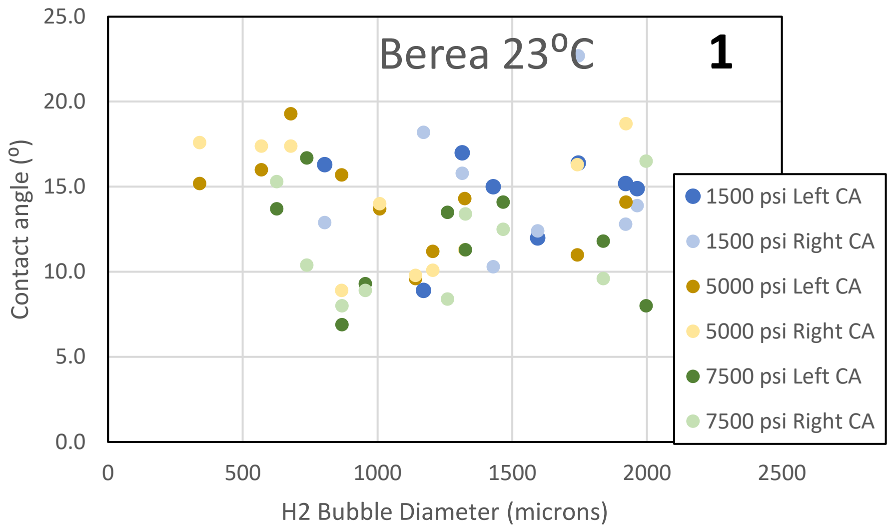
1435 μm

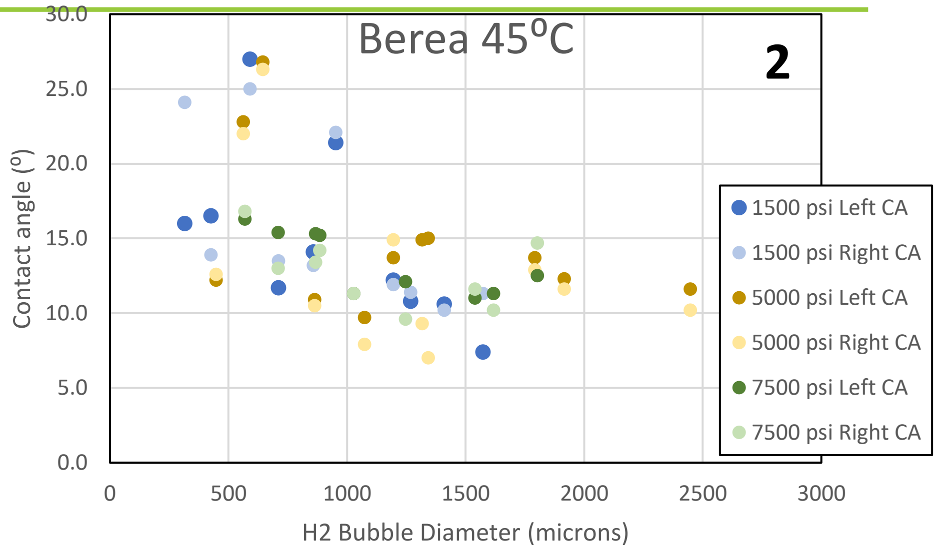


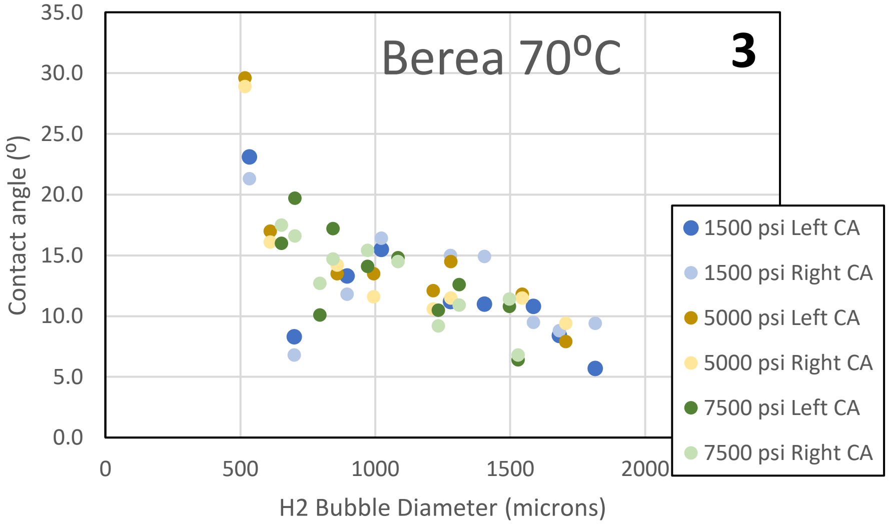
2058 μm

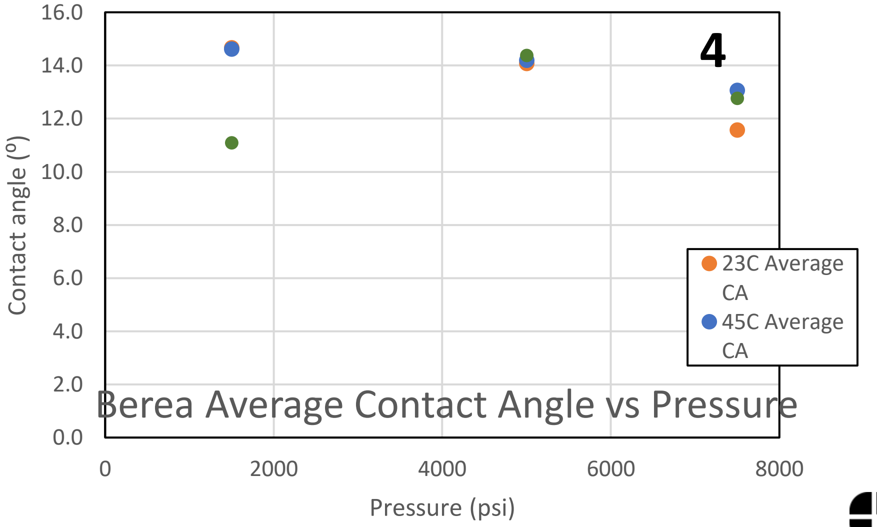
No trend or dependency of contact angle value with mineralogy, temperature, and pressure.

Contact Angle Results



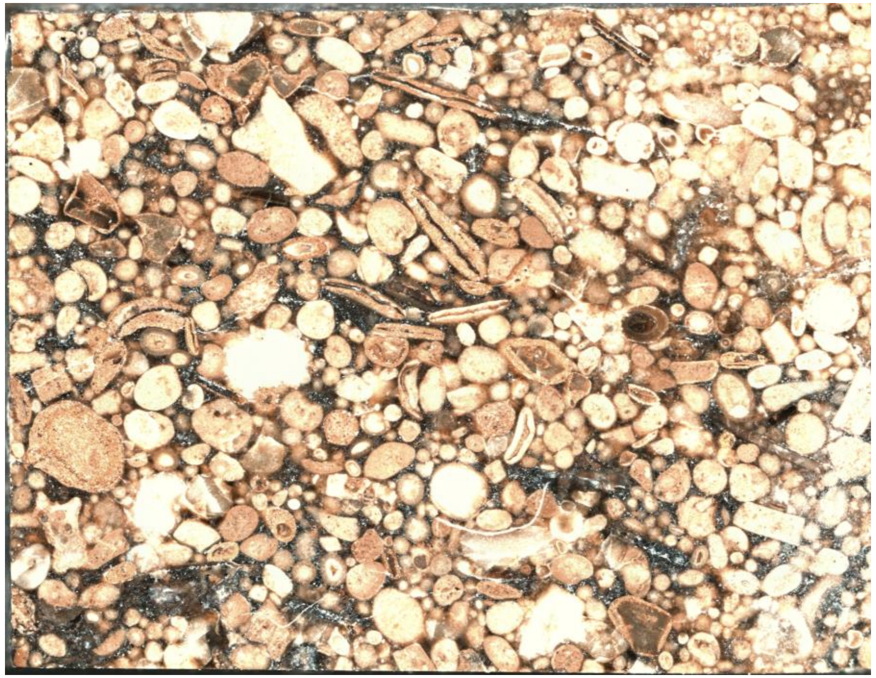






Before and After Wetting Measurements

Nixon Shale:

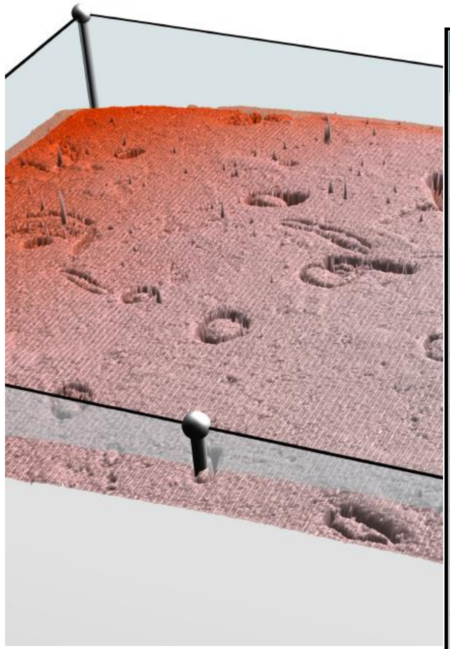


Before

After

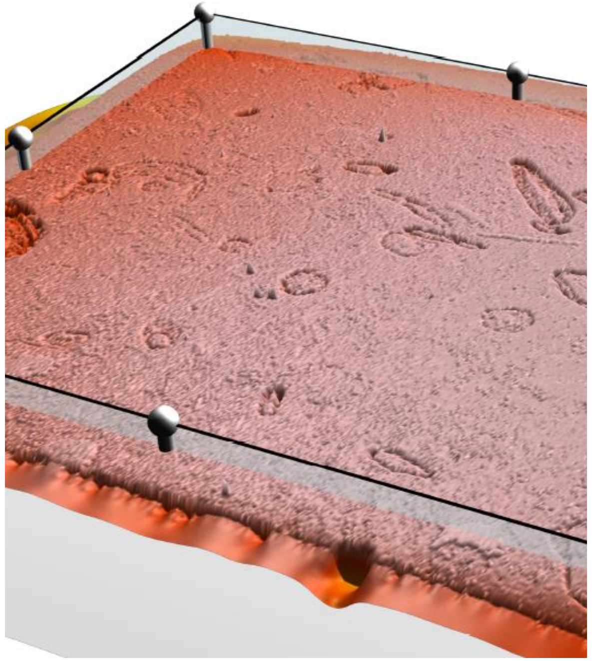
Before and After Wetting Measurements

Nixon Shale: Surface profile



ISO 25178 - Roughness (S-L)		
F: [Workflow] Leveled (LS-plane)		
S-filter (λs): None		
L-filter (λc): Gaussian, 1.2 mm		
Height parameters		
Sq	2.247	µm
Ssk	-6.946	
Sku	76.562	
Sp	14.110	µm
Sv	51.576	µm
Sz	65.685	µm
Sa	0.859	µm

Before



ISO 25178 - Roughness (S-L)		
F: [Workflow] Leveled (LS-plane)		
S-filter (λs): None		
L-filter (λc): Gaussian, 1.2 mm		
Height parameters		
Sq	2.438	µm
Ssk	-5.628	
Sku	75.242	
Sp	39.782	µm
Sv	55.127	µm
Sz	94.910	µm
Sa	1.112	µm

After

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Before and After Wetting Measurements

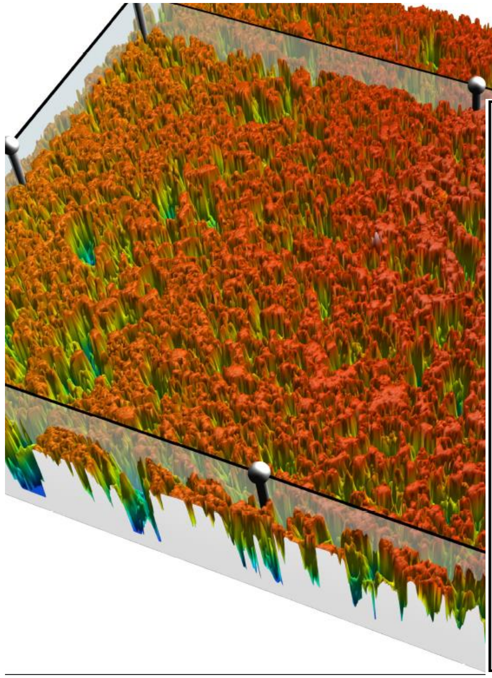
Berea Sandstone

Before

After

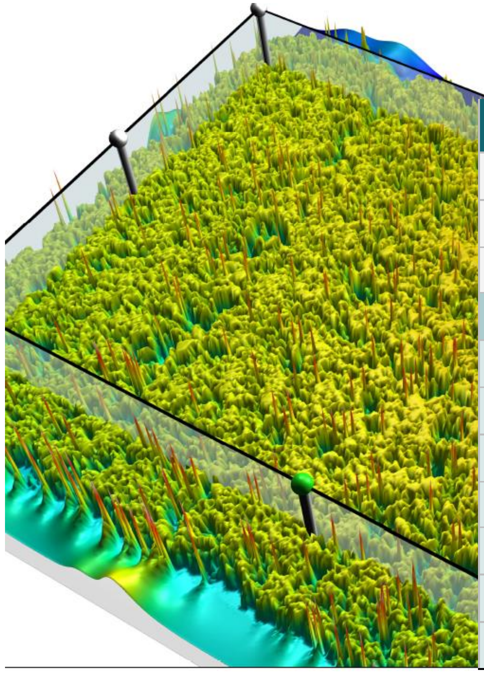
Before and After Wetting Measurements

Berea Sandstone: Surface profile



ISO 25178 - Roughness (S-L)		
F: [Workflow] Leveled (LS-plane)		
S-filter (λs): None		
L-filter (λc): Gaussian, 1.2 mm		
Height parameters		
Sq	25.677	µm
Ssk	-1.340	
Sku	4.787	
Sp	46.928	µm
Sv	129.337	µm
Sz	176.265	µm
Sa	19.962	µm

Before



ISO 25178 - Roughness (S-L)		
F: [Workflow] Leveled (LS-plane)		
S-filter (λs): None		
L-filter (λc): Gaussian, 1.2 mm		
Height parameters		
Sq	23.962	µm
Ssk	-1.196	
Sku	6.619	
Sp	221.046	µm
Sv	151.026	µm
Sz	372.072	µm
Sa	18.166	µm

After

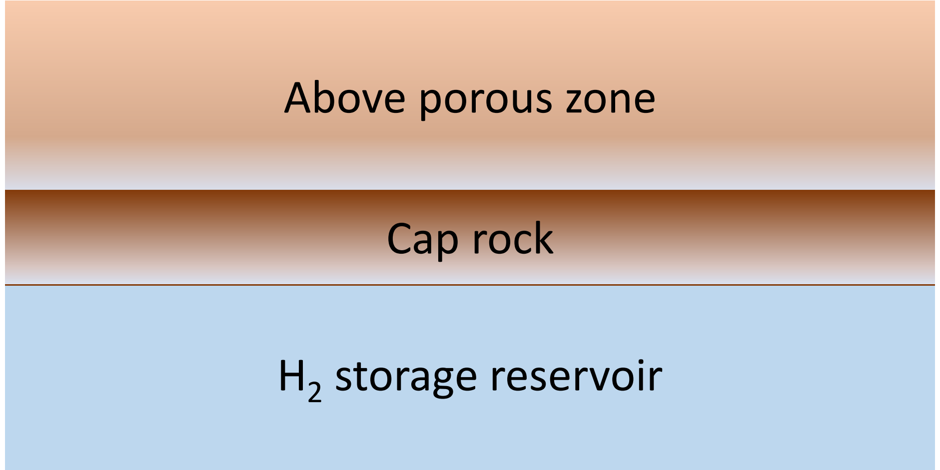
Summary:

Do rocks become H_2-wet under geologic storage conditions?

Key Points:

- Performed H_2-brine contact angle experiments on Nixon Shale, Class G Cement, and Berea Sandstone
- No change in contact angle with Temperature: (23, 45 and 70°C)or Pressure: (10.3, 34.5, and 51.7 Mpa) at salinity (50,000 ppm), and bubble size (5-2000 mm).
- <u>Reservoir rocks remain water-wet at geologic H_2 storage conditions</u>

Hydrogen Flux through the Caprock



Transfer of Hydrogen :

- **Permeability: Viscous flux, based on Darcy law**
- **Diffusion: Based on pore size - Knudson, Transition, Fickian**
- **Diffusion through water saturated rock**

Macropores: > 50 nm : Viscous flux, based on Darcy law

$$\frac{\partial^2 p(x,t)}{\partial x^2} = \frac{c\mu\phi}{k}\frac{\partial p(x,t)}{\partial t} \qquad Q = \frac{kA\Delta P}{\eta L}$$

- Bird et al., [Advances in Chemical Engineering Volume 1](), 1956, Pages 155-239
- Afagwu et al., Energy Reports 7 (2021) 3302–3316

Mesopores: 2-50 nm : Pore flux, mix of Fickian and Knudsen based on mean path length

$$\mathrm{Kn} = \frac{\lambda}{2r} \qquad \lambda = \frac{\mu}{p}\sqrt{\frac{\pi ZRT}{2M}}$$

$$D_p = \begin{cases} D_{Fick} = \dfrac{\lambda}{3}\sqrt{\dfrac{8RT}{\pi M}}, & Kn \leq 0.1 \\ D_{transition} = \dfrac{D_F D_K}{D_F + D_K}, & 0.1 < Kn < 10 \\ D_{Knudsen} = \dfrac{2r}{3}\sqrt{\dfrac{8RT}{\pi M}}, & Kn \geq 10 \end{cases} \qquad \frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

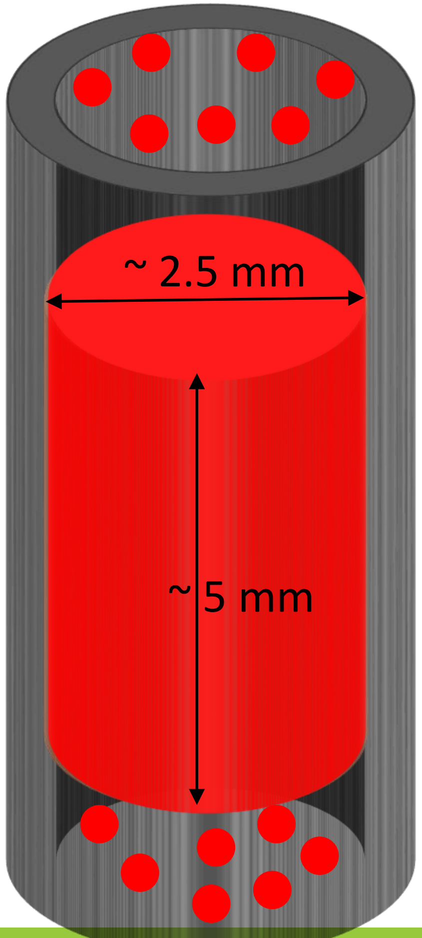
Micropores: < 2 nm : Surface diffusion

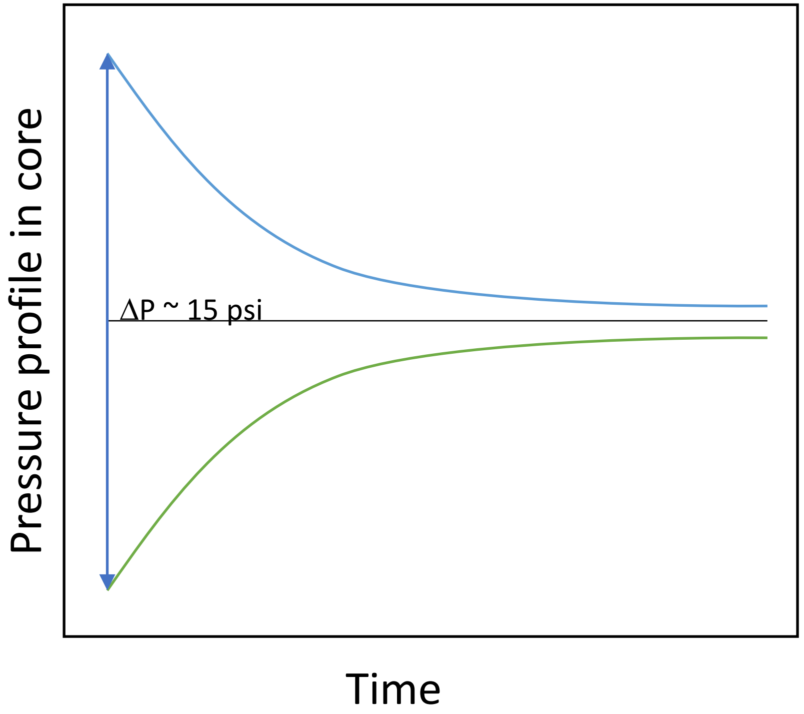
Permeability

Permeability: The measure of the ability of a rock to transmit fluids

Lab Measurement: Core-flooding system: usually used with sandstone
Pulse Decay system: tight samples
Auto – Lab: sonic velocity

Sample	Length	Diameter	Porosity	Pore Volume	H_2 Permeability	CH_4 Permeability
	mm	mm	%	cc	mD	mD
Nix3066.3	5.056	2.53	2.80	0.71	0.01003	0.00682
Nix3066.6	5.019	2.53	2.12	0.53	0.01001	0.00641
Nix3128	5.023	2.53	0.46	0.12	0.01079	0.00743
Eagleford 1	5.140	2.541	4.51	1.17	0.002427	0.00234
Eagleford 2	4.909	2.540	6.33	1.57	0.000407	0.00214
Marcellus 1	3.975	2.531	5.19	1.04	0.000799	0.00071
Marcellus 2	4.652	2.530	4.19	0.98	0.000603	0.00122
Wolfcamp 1	5.055	2.523	1.59	0.40	0.000318	0.00512
Red Willow	7.578	2.502	5.32	1.98	0.001305	0.00023





$$\frac{\partial^2 p(x,t)}{\partial x^2} = \frac{c\mu\phi}{k}\,\frac{\partial p(x,t)}{\partial t}$$

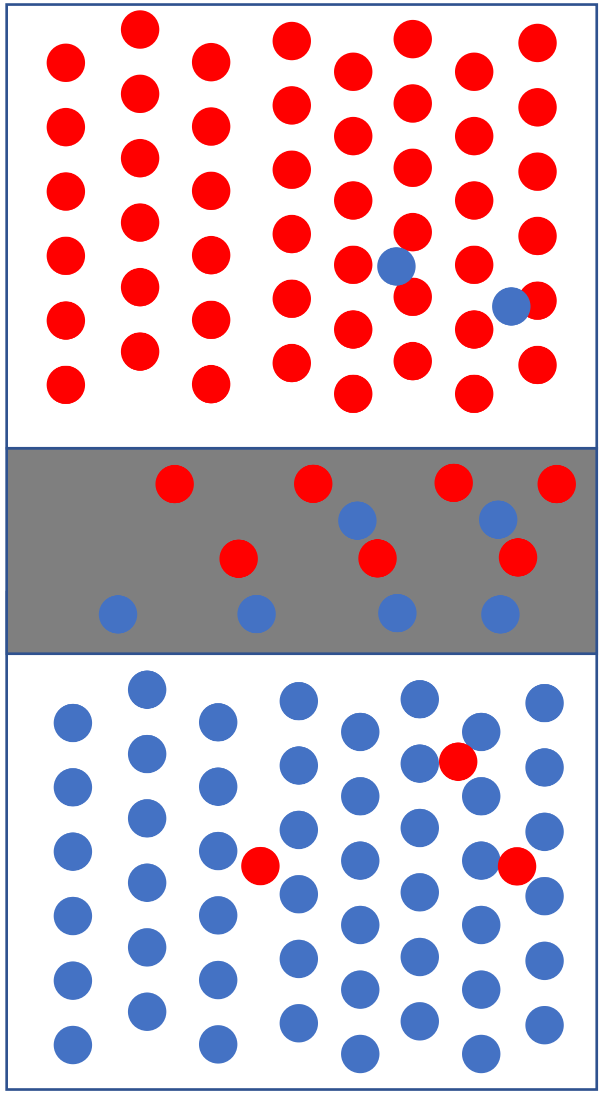
$$\Delta p_D(a,b,t_D) = 2\sum_{m=1}^{\infty} \exp(-t_D\theta_m^2)\cdot \frac{a(b^2+\theta_m^2) - (-1)^m b[(a^2+\theta_m^2)(b^2+\theta_m^2)]^{0.5}}{[\theta_m^4 + \theta_m^2(a+a^2+b+b^2) + ab(a+b+ab)]}$$

Diffusion

Experimental Set-up

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

ΔP = 0



Literature:

- Borello, et al. Energies 2024, 17, 394. https://doi.org/10.3390/en17020394
- Liu, Wang et al. 2022

Diffusion coefficients

- 1×10^{-10} m²/s to 6×10^{-8} m²/s for hydrogen
- 9×10^{-10} m²/s to 2×10^{-8} m²/s for methane

Hydrogen Flux through the Caprock

- ~250 years to reach steady-state diffusive flux through a 10 m thick caprock with 10% porosity

Permeability and Diffusion Summary:

Hydrogen Flux through a Caprock

Key Points:

- Performed H_2 and CH_4 permeability measurements for 10 caprock samples at 50°C and 1200 psi
- Working to measure diffusion of H_2 and CH_4
- Working to estimate leakage rate of H_2 and CH_4 via caprock based on experimental measurements

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Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

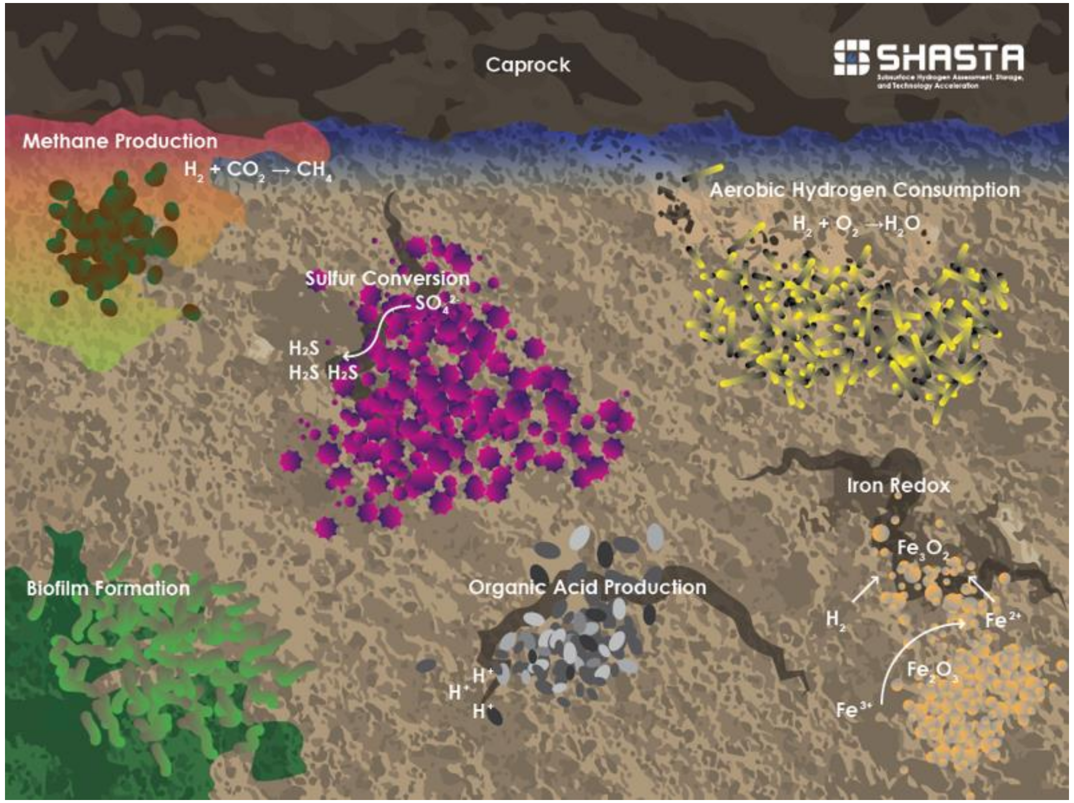
Geochemical impacts of subsurface H_2 storage on reservoir and caprock characteristics

Gabriela Davila, Megan M. Smith, and Joshua A. White

Lawrence Livermore National Laboratory

SHASTA stakeholder meeting, Apr 3rd, 2024

Hydrogen injection causes chemical disequilibria



- Hydrogen loss,
- Production of other gases (e.g. H_2S)
- Mineral dissolution/precipitation reactions, enhanced or reduced injectivity, changes to mechanical rock properties
- Mineral dissolution leading to opening of migration pathways
- Mineral dissolution of reservoir and caprock

Quantify the chemical reactions among H_2, brine, and reservoir/caprock and associated physical changes under hydrogen storage to better understand the long-term stability and deliverability

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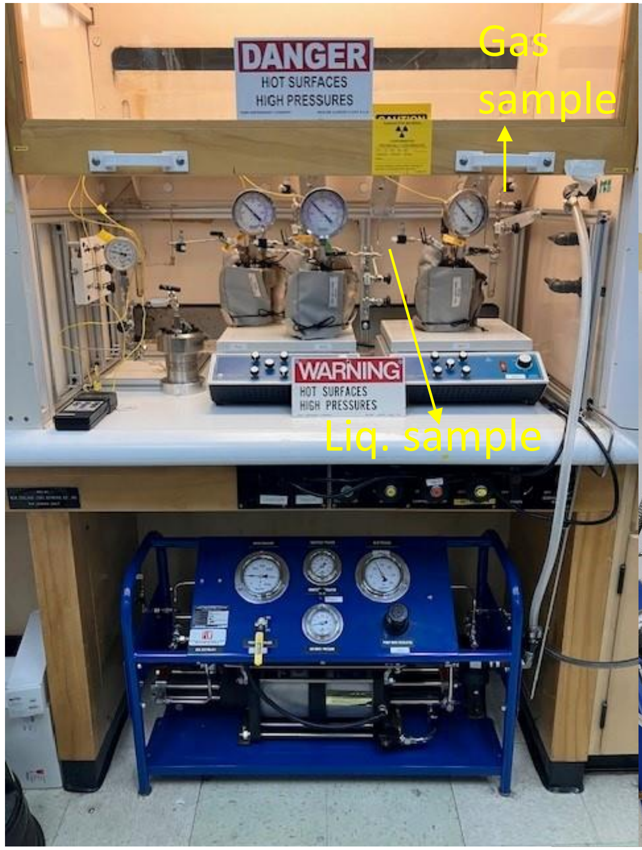
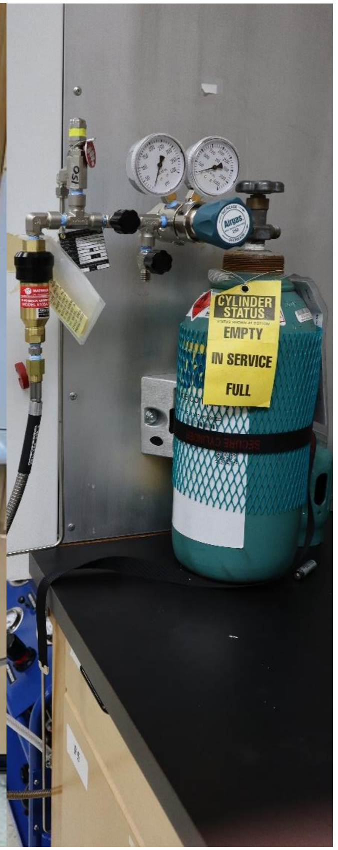
How we experimentally approach this problem:

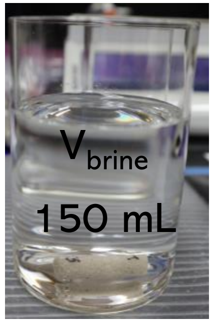
Experimental setup & Conditions → Batch experiments





<u>Initial conditions:</u>

- ❑ Reservoir abiotic conditions (1000psi & 80°C)
- ❑ Low salinity water (3800 mg/L TDS), after Dardor et al. (2022)
- ❑ 150 mLs brine - ~3g rock powder – 150 mLs headspace



stirring
~3g rock

ϕ = 0.75mm

L = 2.5cm
r = 0.8 cm

- ❑ 12 experiments including blanks, duration of 25 ±5 days
- ❑ 10% v/v H_2 blended in N_2
- ❑ Liquid and gas samples periodically collected

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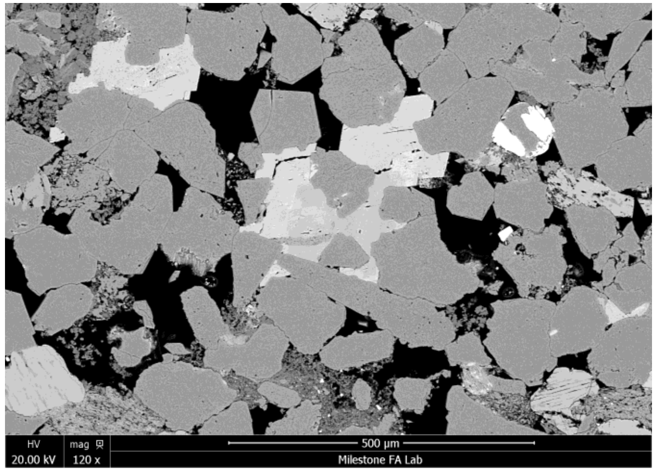
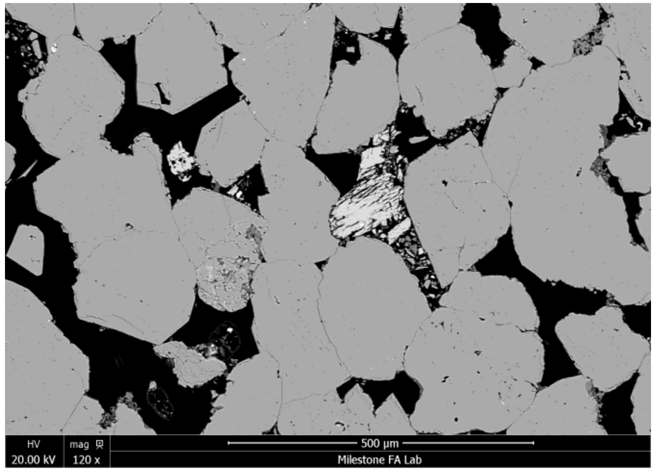
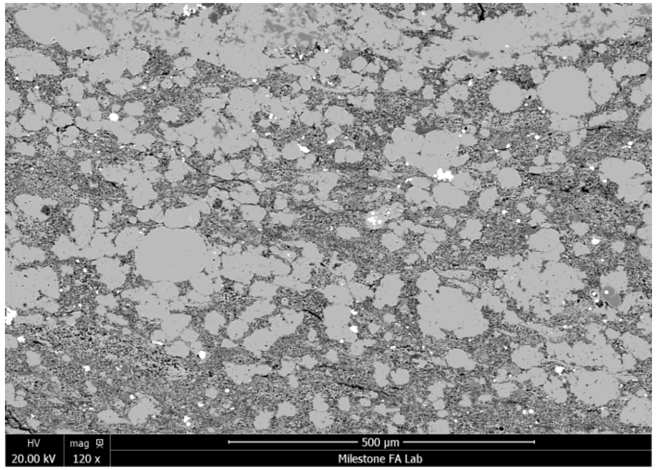
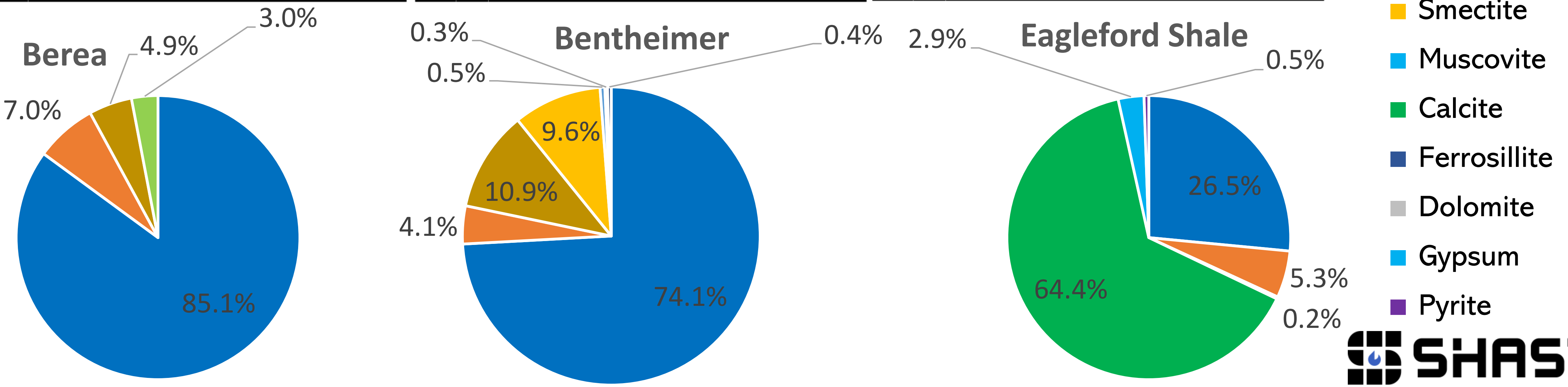
Experimental Materials – Reservoir & Caprock formations

Rock sample characterization → SEM, EDX, XRD/Rietveld analysis









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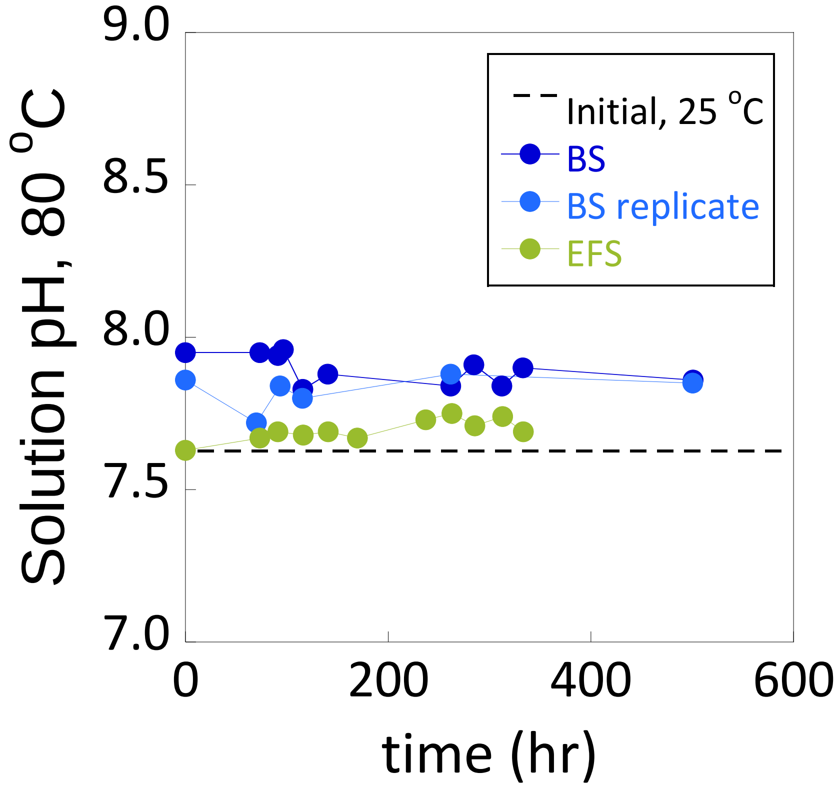
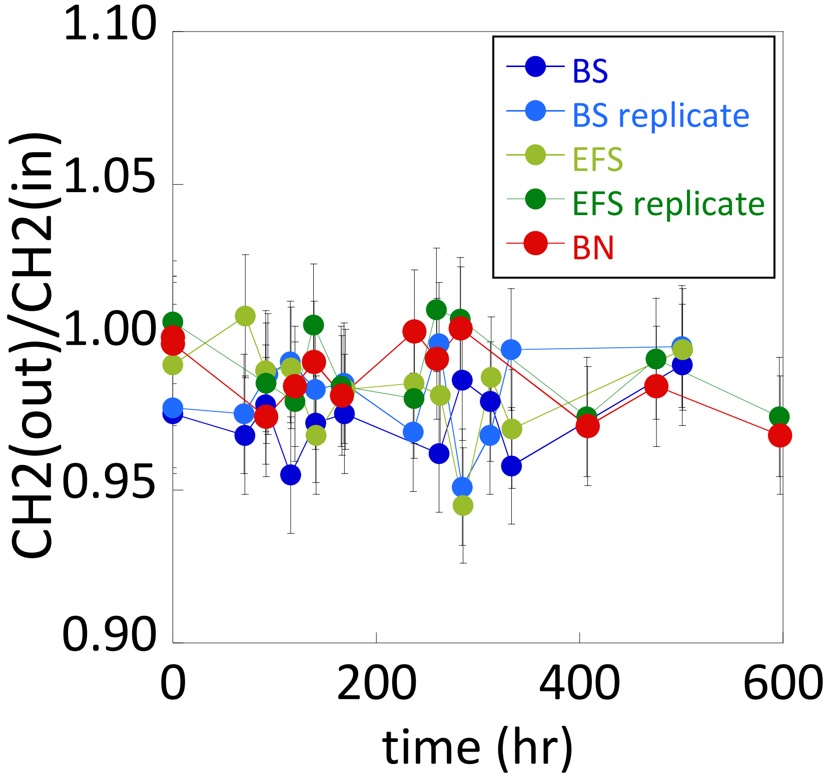
LLNL experiments show slight (<5%) hydrogen loss

Incubator experiments at LLNL are conducted at reservoir pressure & temperature

Pre and post liquid sample and gas sample characterization using pH and Gas Chromatography, respectively.

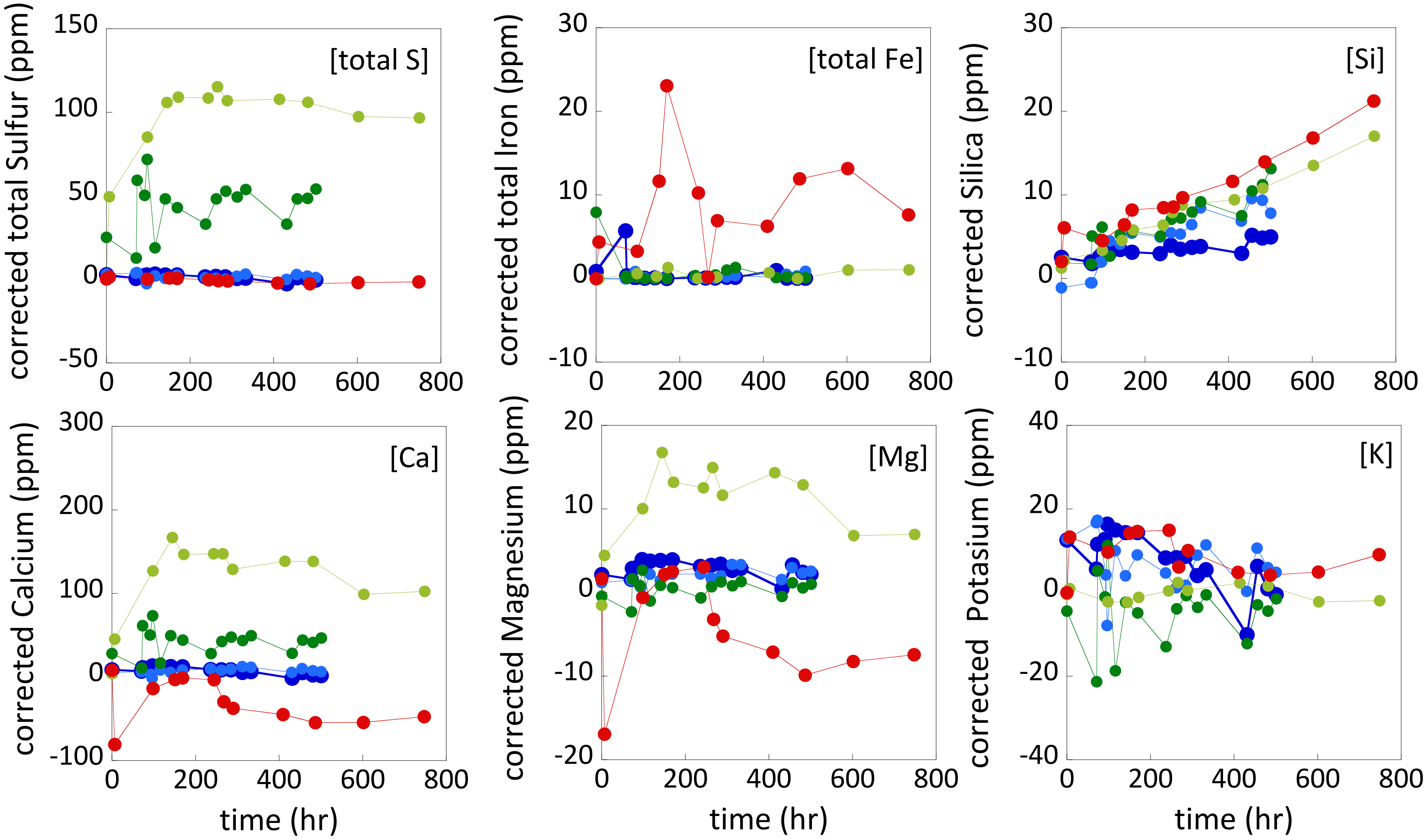




- ❑ Overall slight pH increase.
- ❑ Lower pH values with Eagleford shale.
- ❑ H_2 gas measurement error within 2%.
- ❑ Slight hydrogen loss observed for all cases.

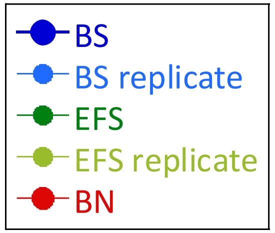
Non-silicate minerals react more readily with hydrogen

Using major and trace element analysis using ICP-MS and IC



corrected concentrations

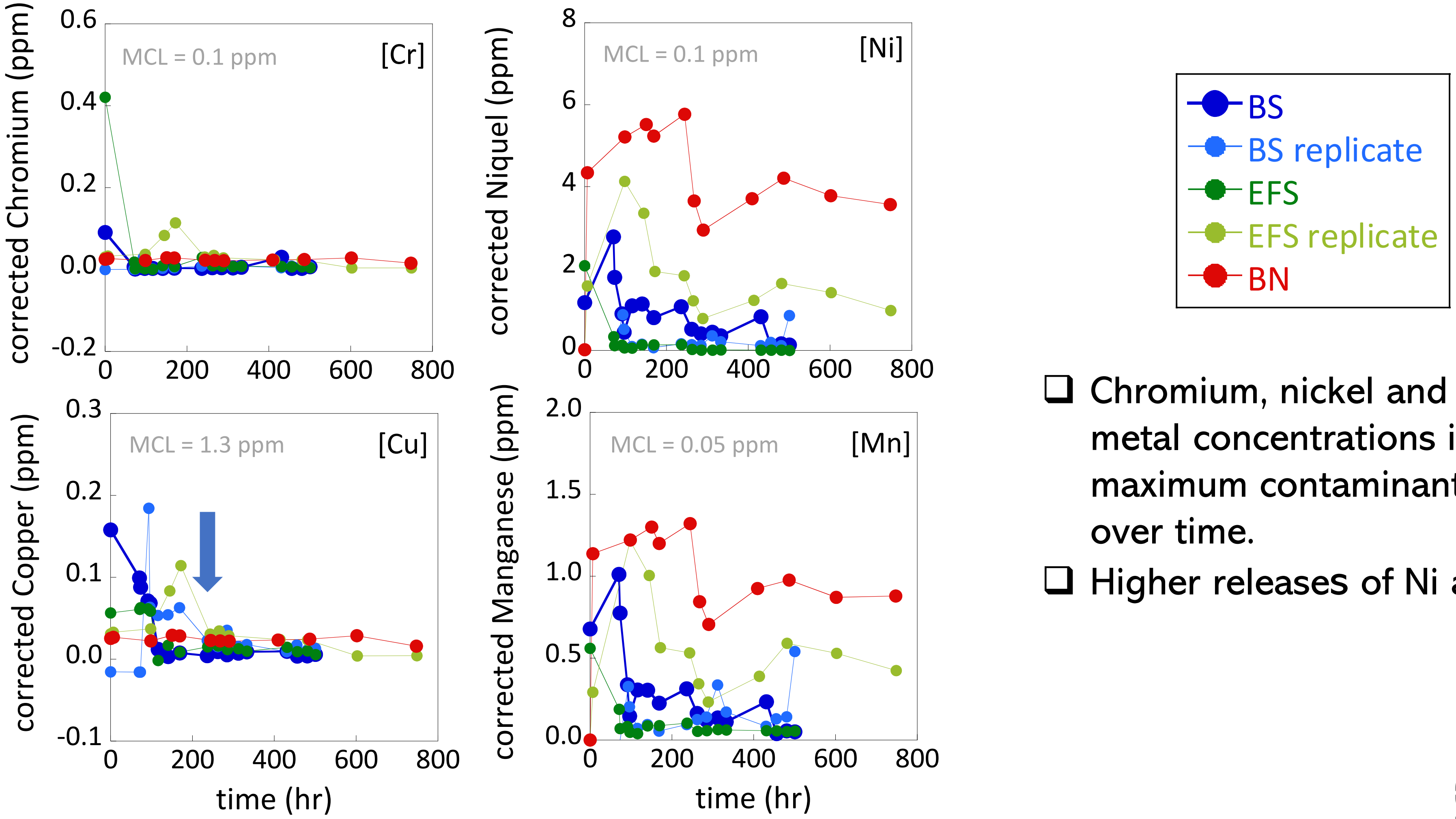
$$C_{corrected} = C_{time\ t} - C_{initial\ solution}$$



- ❑ BS is the least reactive with hydrogen.
- ❑ EFS shows elevated reaction (S, Ca, Mg) as a result of higher volume of non-silicate minerals
- ❑ BN is moderately reactive with high Fe, Si release (clays?).
- ❑ Si gradually increased in all cases.

Trace metal levels are slightly elevated

Using major and trace element analysis using ICP-MS and IC



- Chromium, nickel and manganese metal concentrations increase above maximum contaminant level (MCL) over time.
- Higher releases of Ni and Mn in BN

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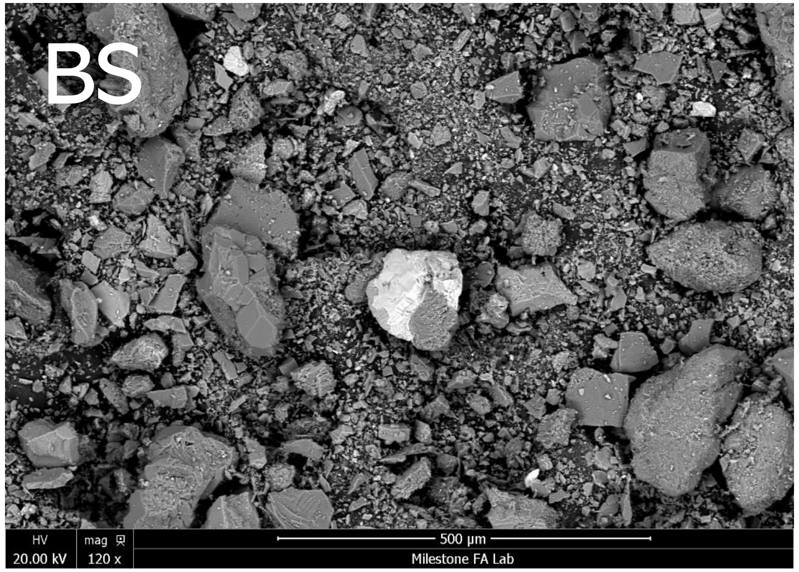
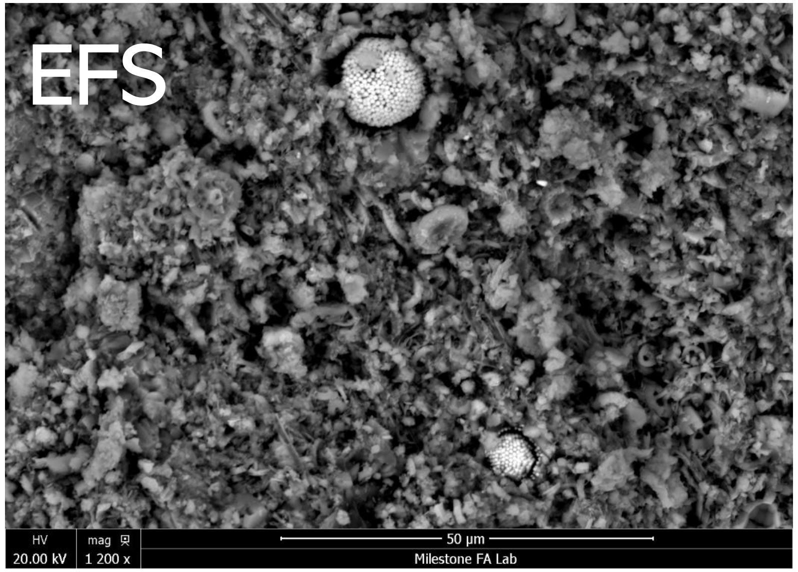
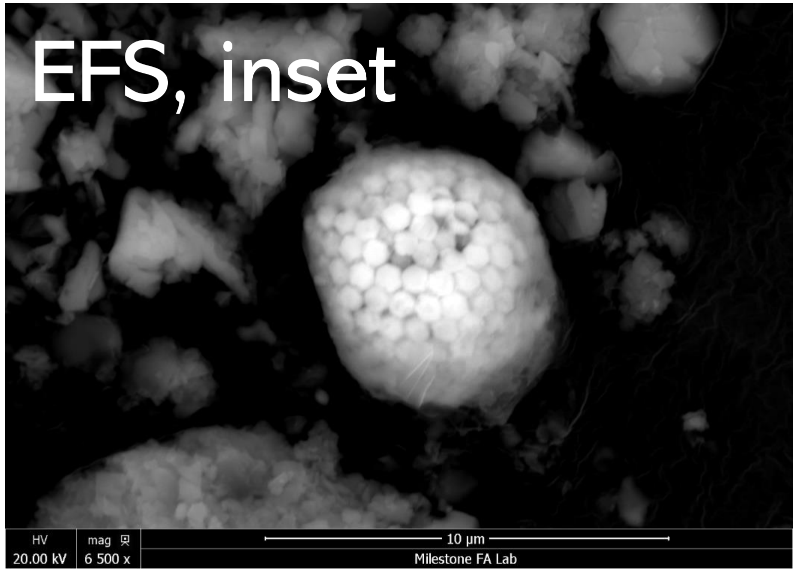
Iron-bearing phases show greatest reactivity

SEM images:





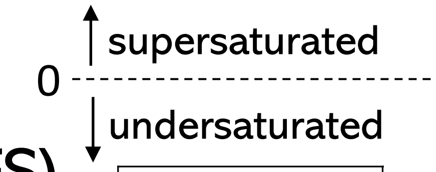


- ❑ Possible new Fe-rich coating (iron oxide?) on Ca-rich groundmass (albite/anorthite?) in BS
- ❑ Newly formed Fe-S phases with framboidal morphology (pyrite?) detected multiple times in reacted EFS

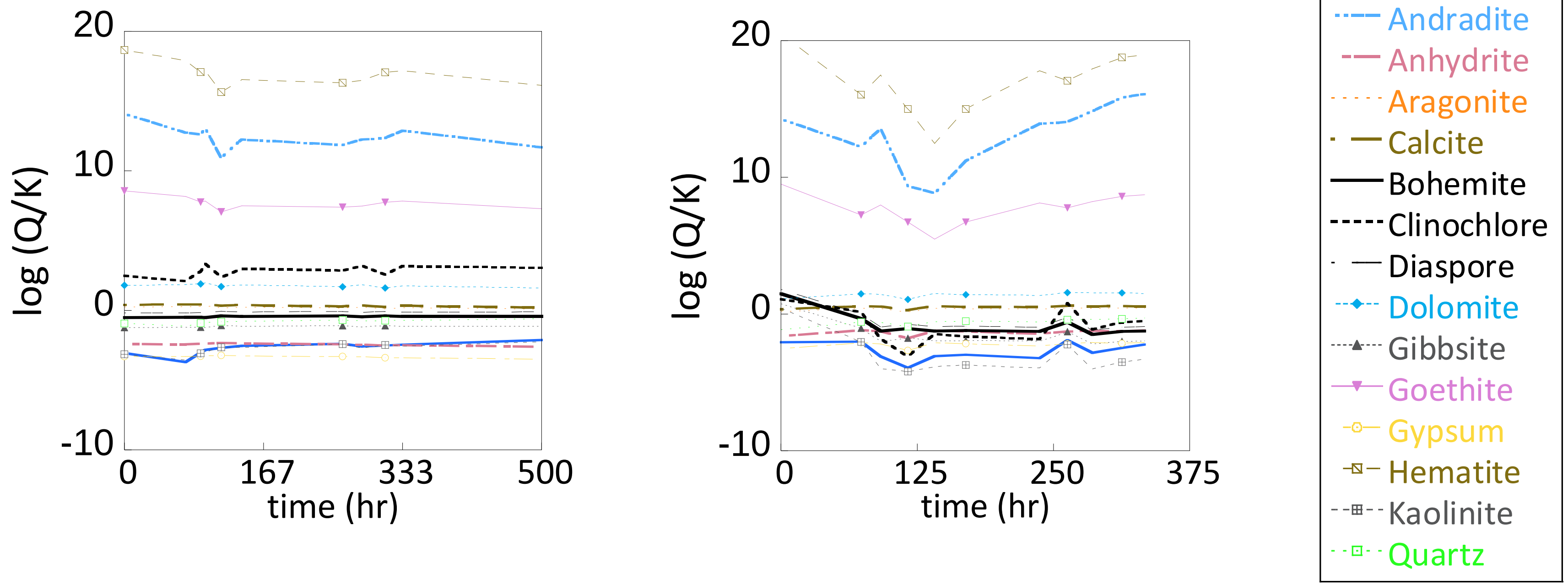
We are still refining redox estimates in models

PHREEQC code/llnl.dat database to track chemical processes from full suite of possible reactions

$$R_m = A_m \sum_{terms} k_{m,T} a_{H+}^{n_{H+}} \left(\prod_i a_i^{\,n_i} \right) \left(\left(\frac{IAP}{K_{eq}} \right)^{m_2} - 1 \right)^{m_1}$$



Berea Sandstone (BS) | Eagleford Shale (EFS)



- ❑ BS data support transformation of primary tectosilicates (77%) to secondary clays during H_2 exposure
- ❑ In EFS, wider variety of minerals are unstable (undersaturated)
- ❑ We will compare these models to hydrogen-free simulations to determine the full impact of hydrogen in these reactions

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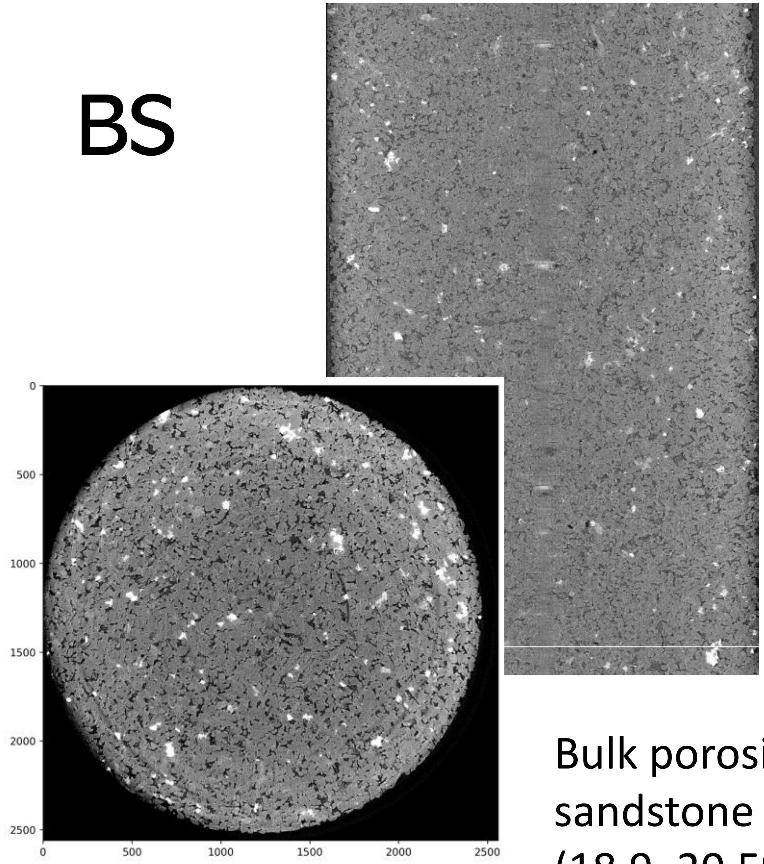
Intact cores reacted with H_2 - bulk porosity unchanged

CT images of pristine and reacted (a) Berea sandstone and (b) Eagleford shale

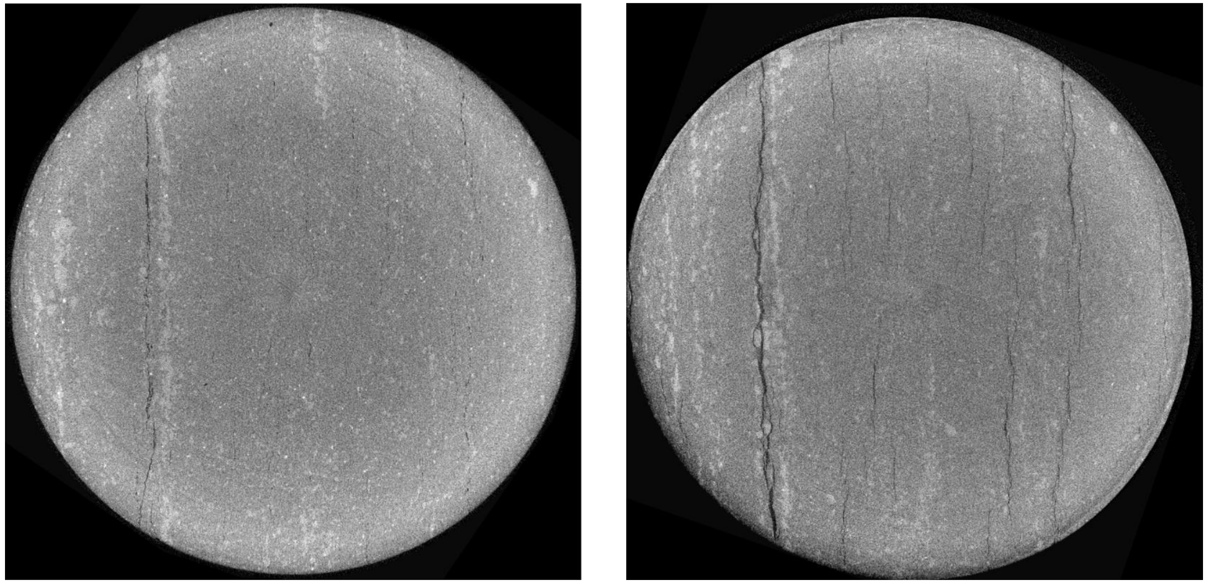
BS



Bulk porosity of Berea sandstone was unchanged (18.9, 20.5%)

EFS

Eagleford porosity is below CT resolution to quantify, but delaminating fractures more apparent after H_2 exposure



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Preliminary conclusions:

The Eagleford shale appears to be more reactive in the presence of elevated H_2 levels, as evidenced by strong release of oxidized sulfur and the presence of newly formed iron sulfide mineral phases. However, a blank (H_2-free) experiment using N_2 is required for validation.

Additional replicate experiments have been performed for all selected rock formations (data analysis ongoing).

The introduction of H_2 does not have an impact on the mineral structure of the Berea sandstone core sample, but slight textural changes (e.g., fracturing) have been detected in addition to increased chemical reactivity for the Eagleford shale reacted core sample.

Saturation state modeling and post-reaction analysis agree that H_2-induced reactivity is low in the Berea sandstone – but the Eagleford shale responded with a greater degree of reaction and changes to rock structure. How much of this is due to purely hydrogen impacts (compared to rock-water reaction)?

Modeling boundary conditions and database selections should be carefully considered.

Thank you!

Gaby Davila
davilaordone1@llnl.gov

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U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

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Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525

H_2 – Cement – Brine Interactions: Impact on Well Integrity

Guangping Xu and Mathew D. Ingraham - Sandia National Laboratories (gxu@sandia.gov)

Barbara G. Kutchko and Richard E. Spaulding - NETL

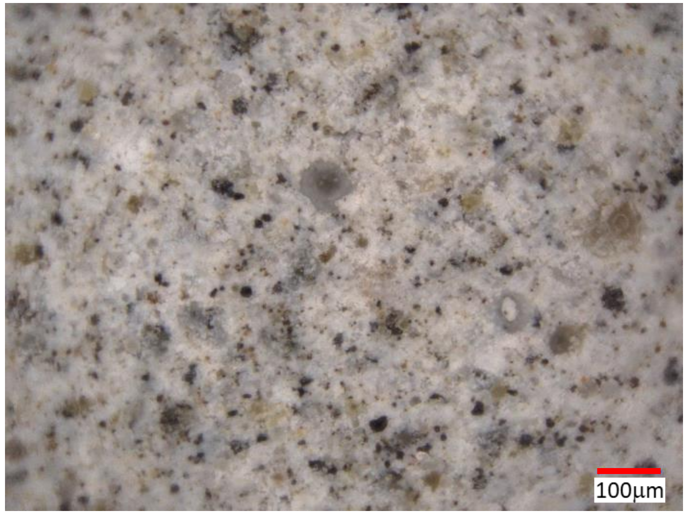
SHASTA stakeholder meeting, Apr 3rd, 2024

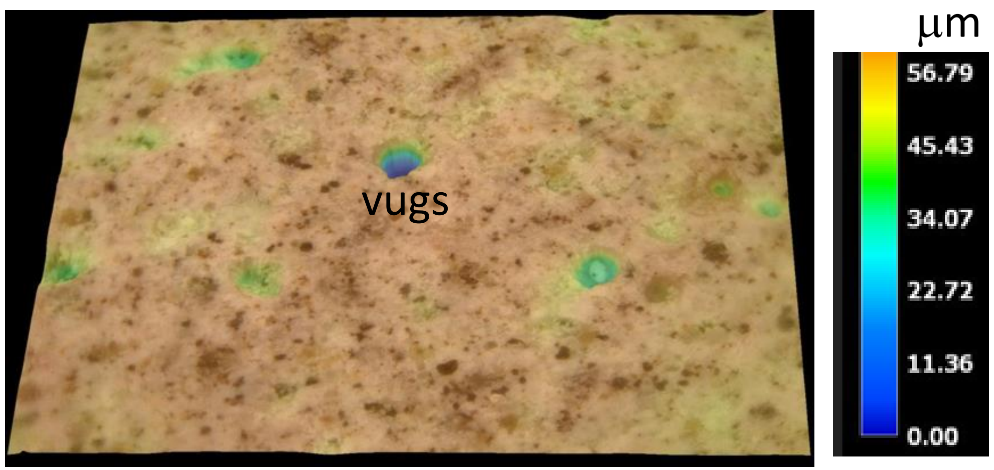
SAND2024-03554PE

Two different type of cements tested: Pozzolana and class H cement

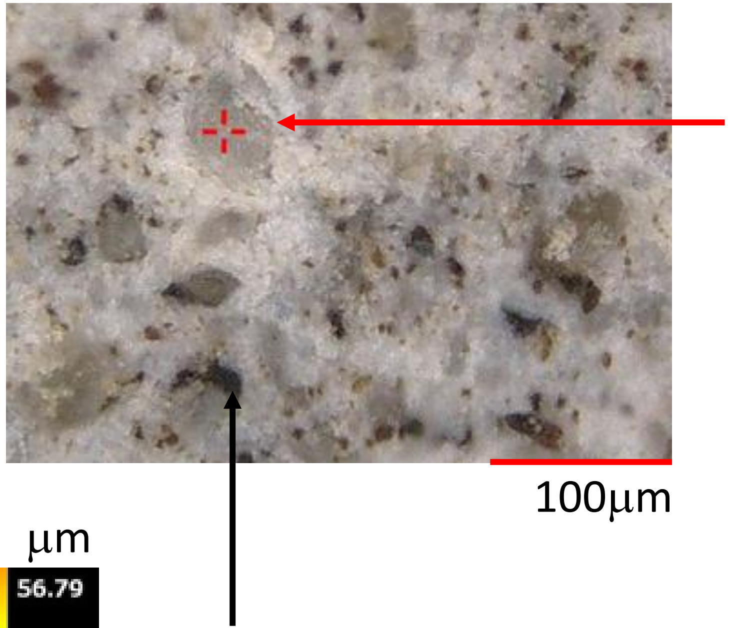
Cement has large vugs (up to 50 μm deep and diameter)

Pozz 35:65   Surface area: 22.1 m^2/g





Class H 0.44 w/c Surface area 6.8 m^2/g



100μm

Fe-bearing black material

O	Ca	Si	H	Fe	Al	Mg
47%	27%	5%	1%	10%	8%	2%

Composition range from pure $Ca(OH)_2$ to iron-bearing

Compositions with drilling down by laser (i.e., cross section)

No.	O	Ca	H	Si	Fe
1	57.2%	40.9%	1.9%		
2	54.9%	42.9%	2.2%		
3		80.5%	2.9%	16.6%	
4		74.2%	0.0%	25.8%	
5		53.3%	0.0%	28.4%	18.3%
6	43.7%	36.1%	0.0%	9.8%	10.4%
7	43.3%	39.0%	0.0%	17.7%	
8		72.9%	0.0%	27.1%	
9		66.2%	0.0%	33.8%	
10		54.7%	0.0%	45.3%	

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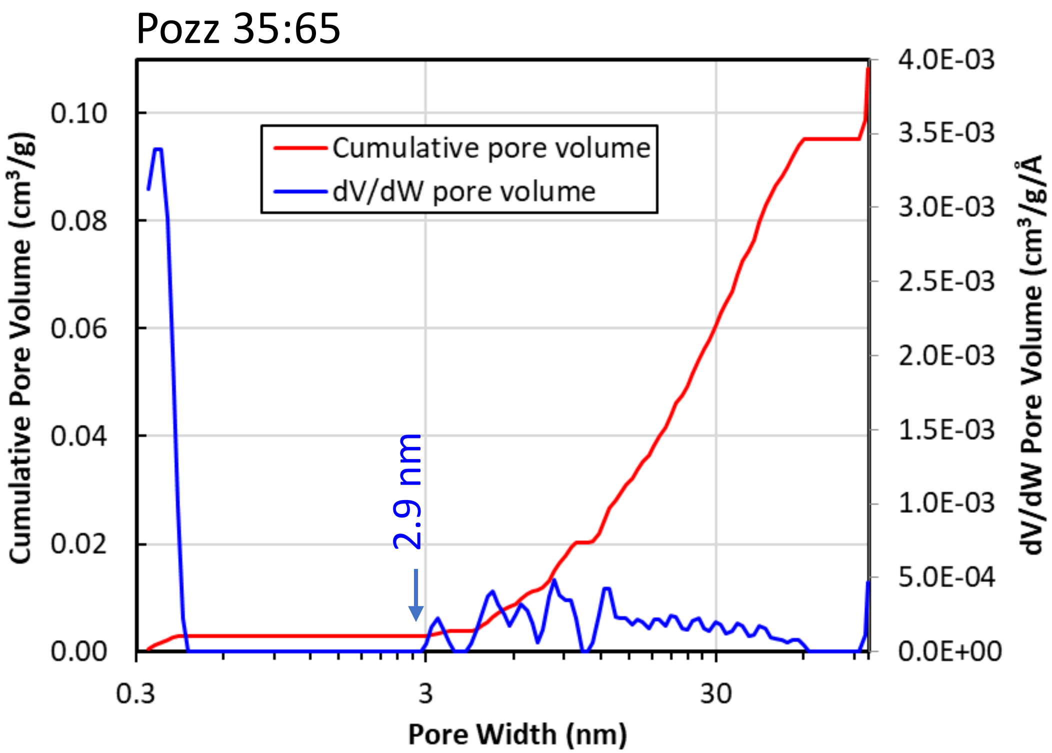
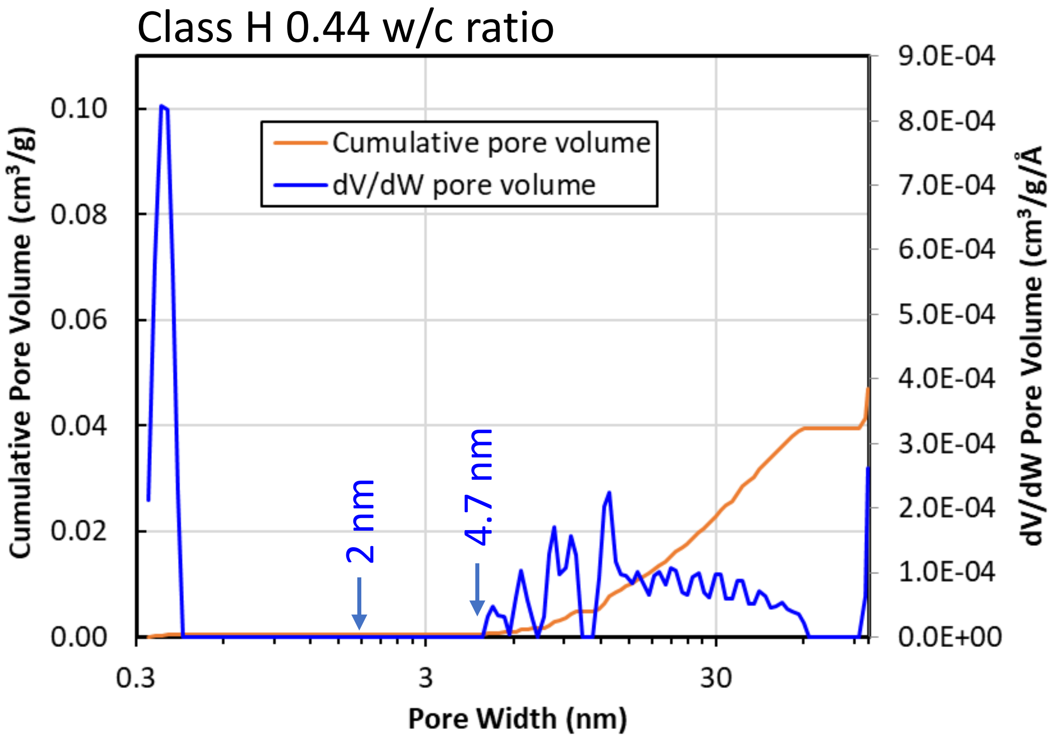
Cement Pore Volume and Pore Size Distributions

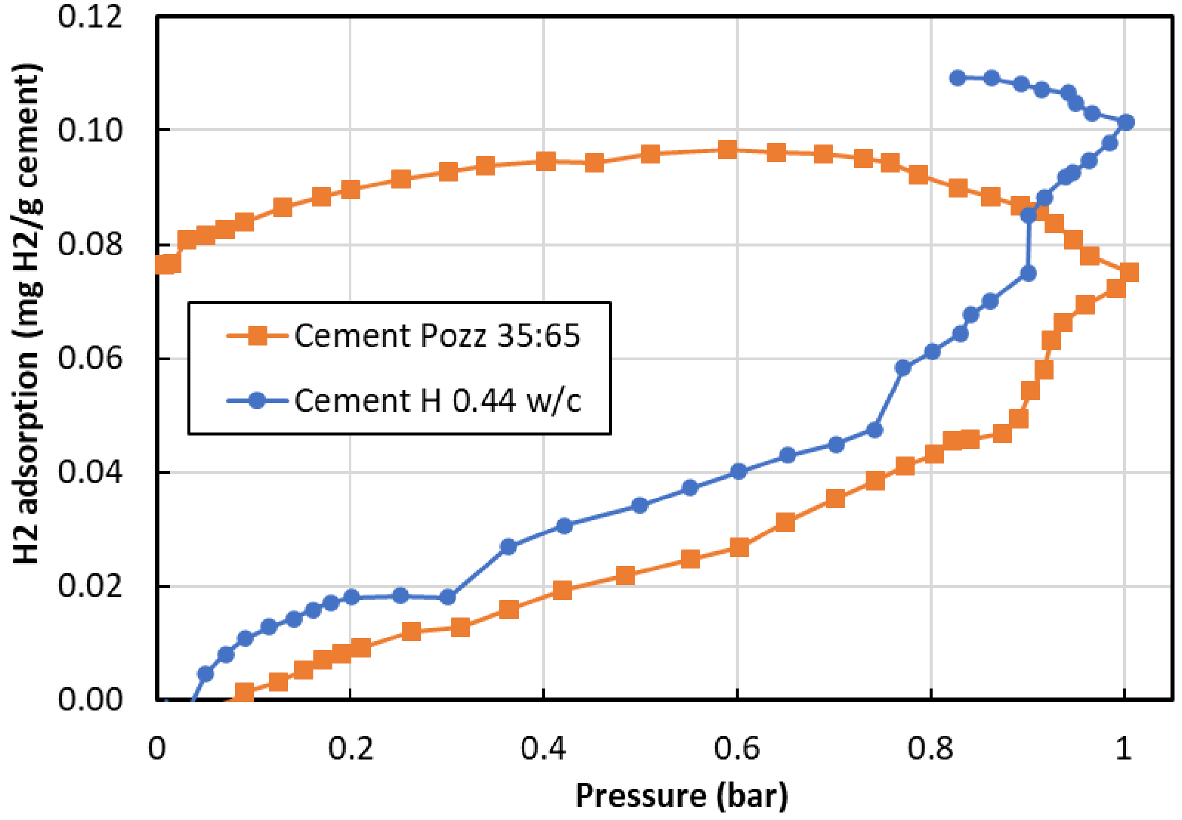




- Pozz cement has higher surface area and high pore volume than class H cement
- Major pores: mesopore, and macropore
- Pozz cement has some micropores whereas class H cement has nearly none (most > 4.7 nm)

Pore size distribution is calculated using DFT based on isotherms of N_2 at 77K and CO_2 at 273K
Only pores < 170 nm were taken into account

H_2 Adsorption in Cement at 0 °C and up to 1 bar



- Pozz cement with higher pore volume adsorbs less H_2 than class H cement
- H_2 adsorption in Pozz: max 110 mg/Kg cement
- H_2 adsorption in Class H: max 99 mg/Kg cement
- Adsorption is relatively small
- In addition, the H_2 contact area with cement is limited in wellbore condition due to low diffusivity/perm

Measurement used long equilibrium interval of 600s and sample was degassed at 60 °C for 2 hours

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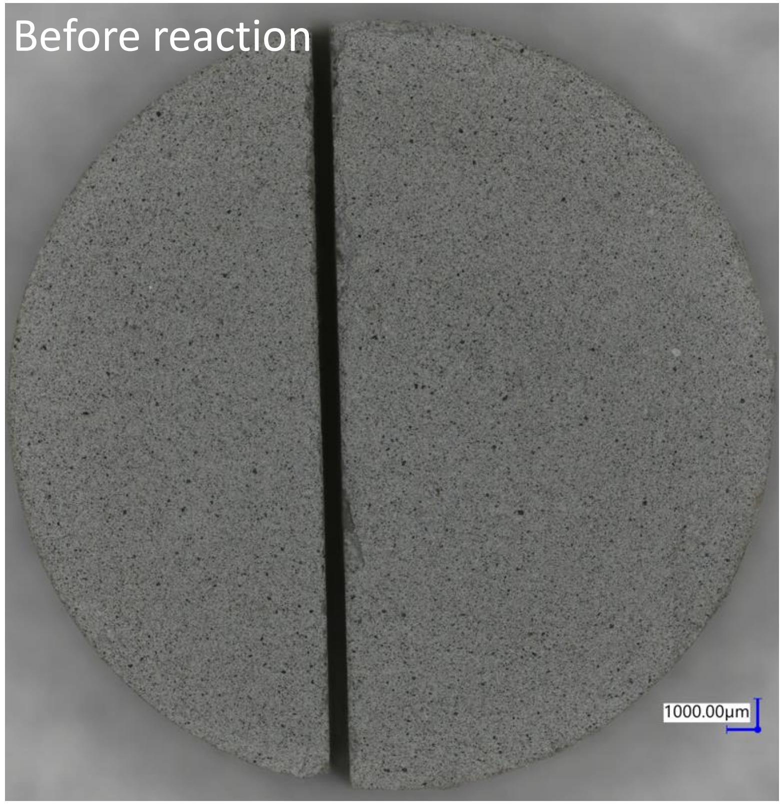
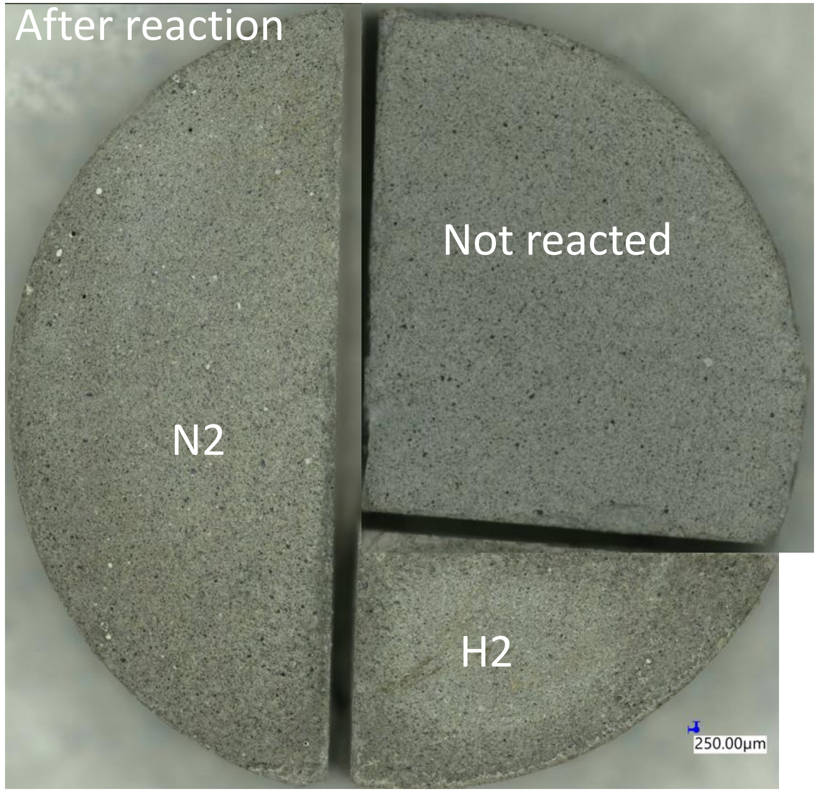
H_2 (and N_2)–Brine–Class H Cement (0.5 w/c) Interaction at 55 °C & 1500 psi





- Minimum amount of cement was dissolved, mostly Ca and K
- Compared to N_2, H_2 reaction seems slightly enhanced (2x more in Ca and K)

	Weight (g)	Brine weight (g)	pressure (psi)	temperature	pH	SO_4 (mmol/g cement)	Ca (mmol/g cement)	Al (mmol/g cement)	K (mmol/g cement)
Chip - Brine - H2	0.62	35.0	1500	~55C	11.39	0.19	0.481	0.017	0.223
Chip - Brine - N2	1.41	35.0	1500	~55C	11.42	0.12	0.193	0.008	0.108

Pure H_2 + saturated synthetic brine reaction one week

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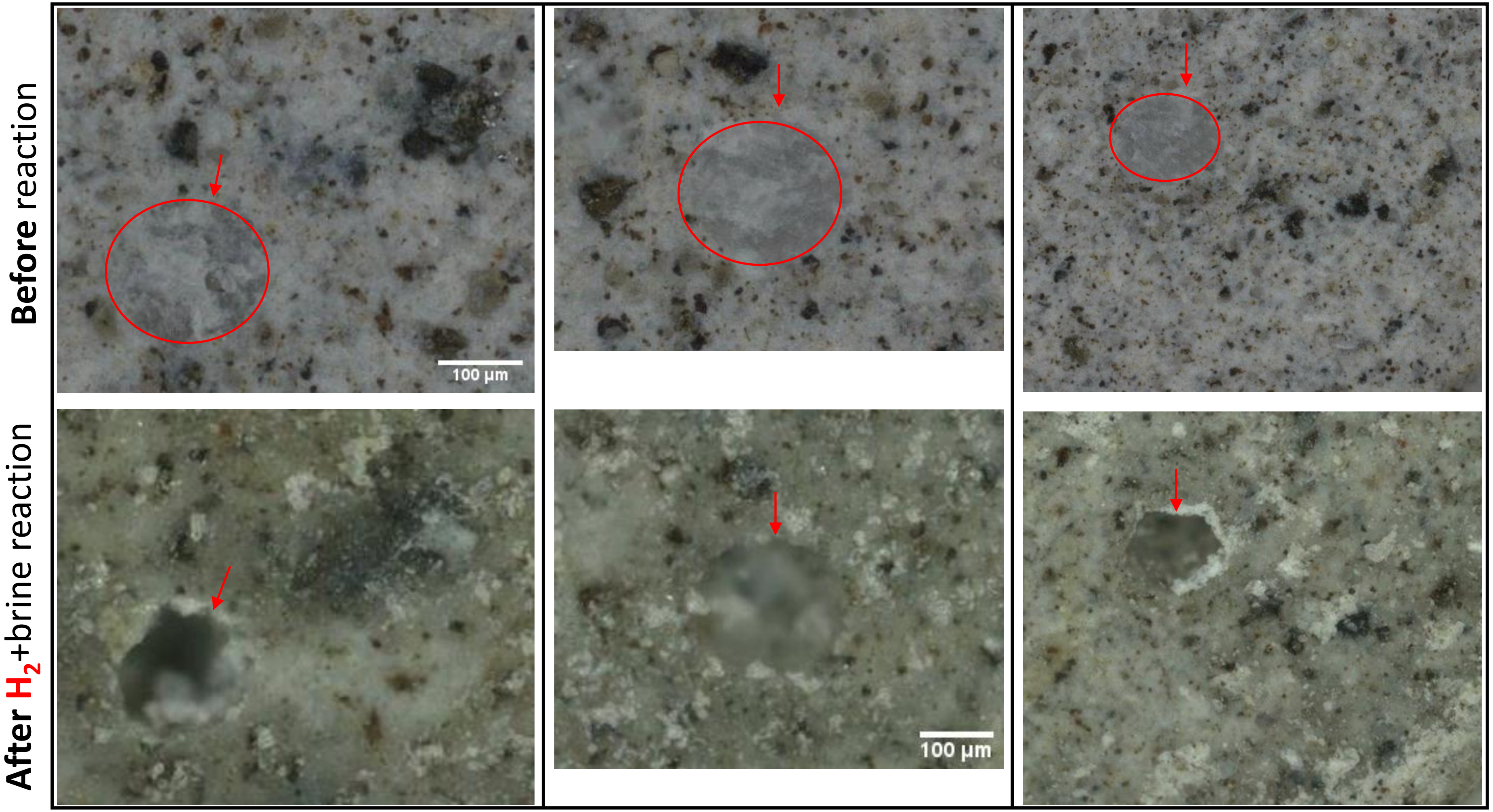
H_2 – Brine – Class H Cement (0.5 w/c) Interaction at 55 °C and 1500 psi

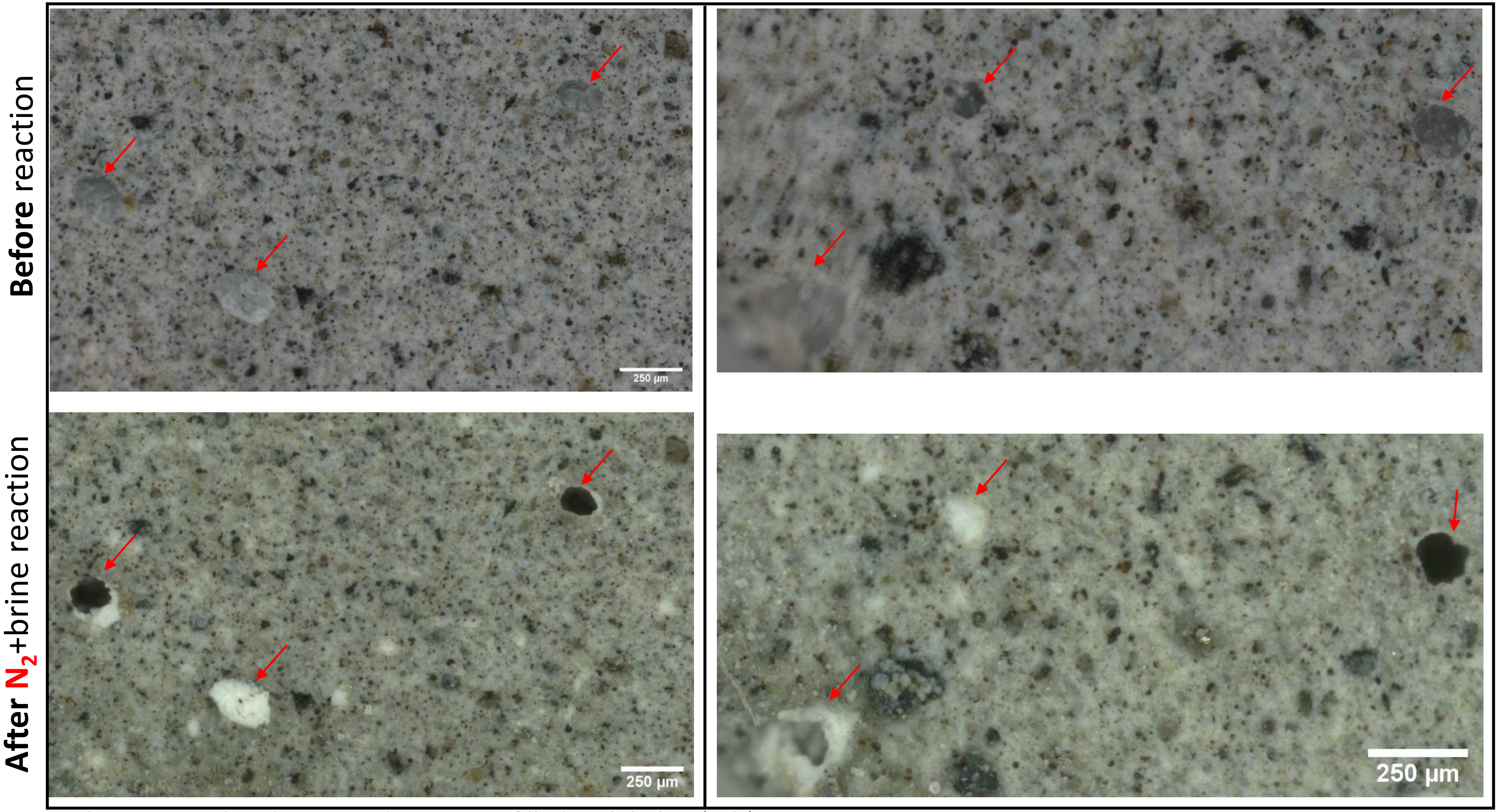


White material in reacted cement is halite (salt)

- Minimum amount of cement was dissolved, mostly Ca and K
- Material in red circles are completely dissolved
- Is this due to H_2?

Pure H_2 + saturated synthetic brine reaction one week

N_2 – Brine – Class H Cement (0.5 w/c) Interaction at 55 °C and 1500 psi



White material in the reacted cement is filled with halite (salt)

- The same type of material is also dissolved in N_2 reaction
- What are the dissolved material?

Pure H_2 + saturated synthetic brine reaction one week

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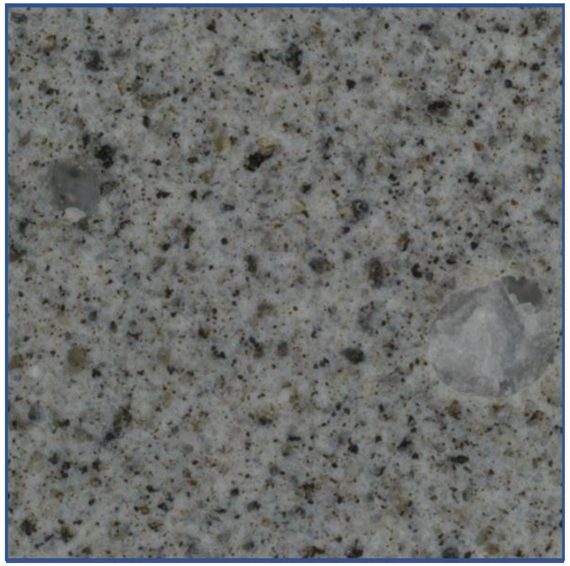
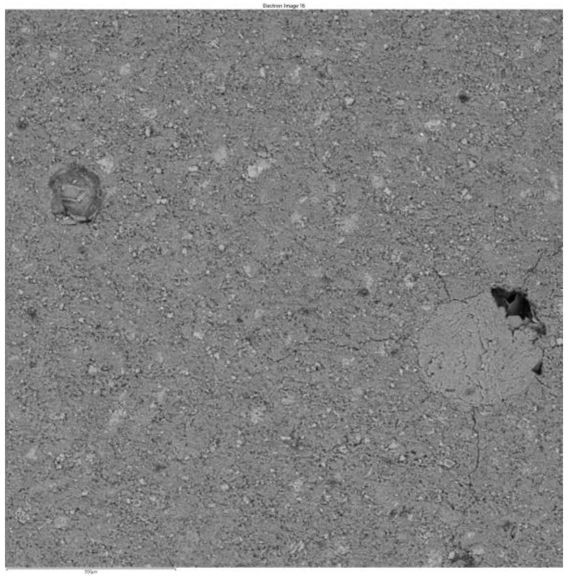
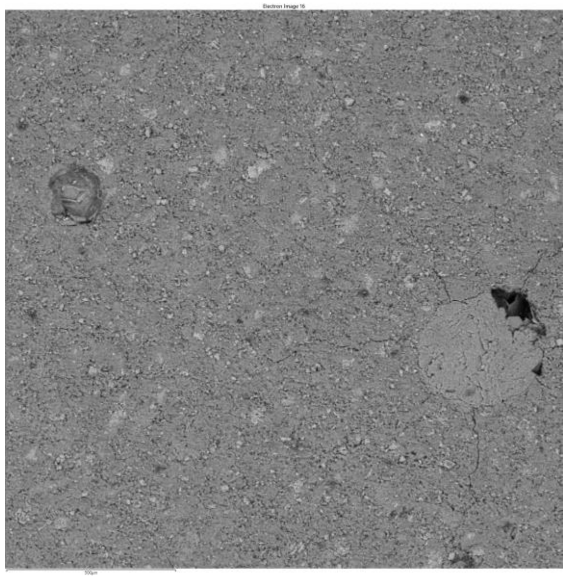
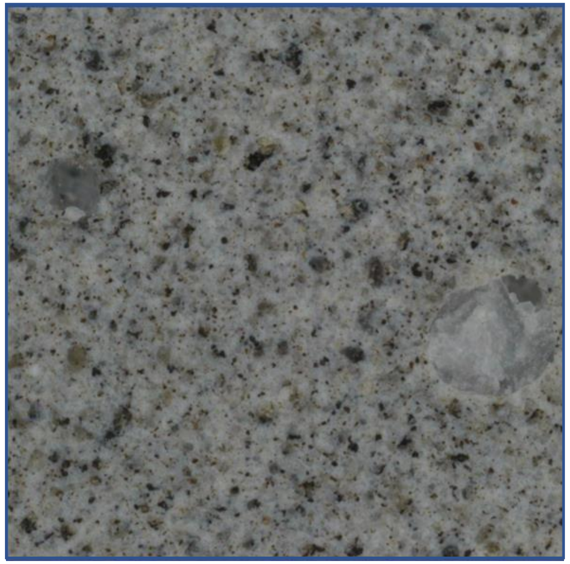
H_2 (and N_2)–Brine–Class H Cement (0.5 w/c) Interaction at 55 °C & 1500 psi





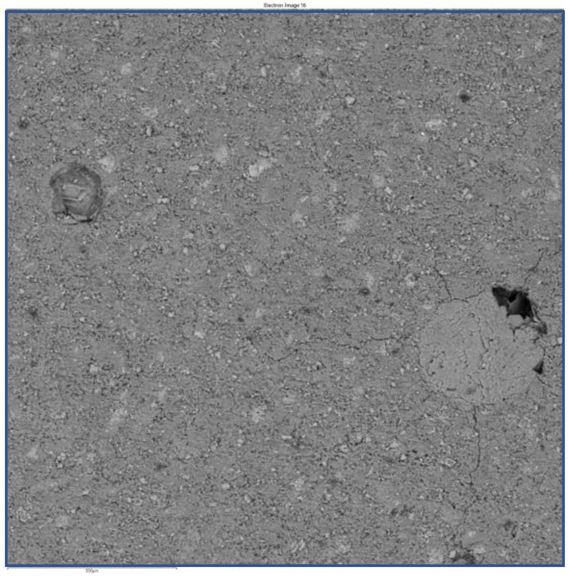




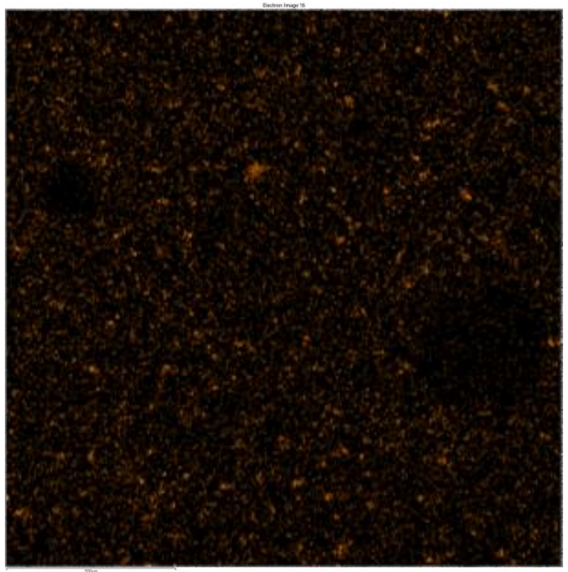
	Weight (g)	Brine weight (g)	pressure (psi)	temperature	pH	SO_4 (mmol/g cement)	Ca (mmol/g cement)	Al (mmol/g cement)	K (mmol/g cement)
Chip - Brine - H2	0.62	35.0	1500	~55C	11.39	0.19	0.481	0.017	0.223
Chip - Brine - N2	1.41	35.0	1500	~55C	11.42	0.12	0.193	0.008	0.108

SHASTA

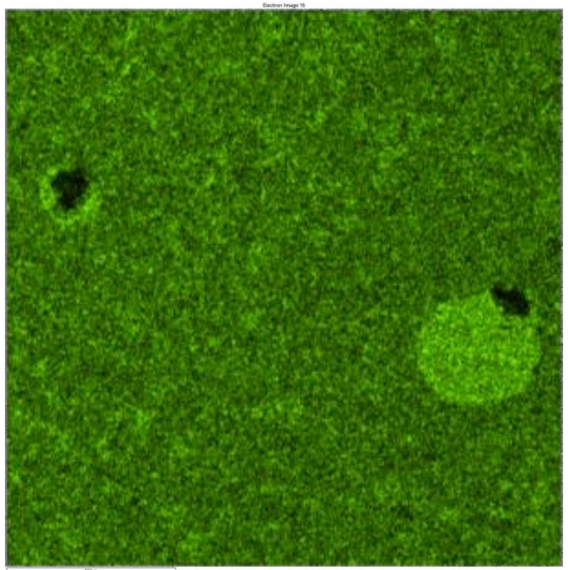
H_2 (and N_2)–Brine–Class H Cement (0.5 w/c) Interaction at 55 °C & 1500 psi



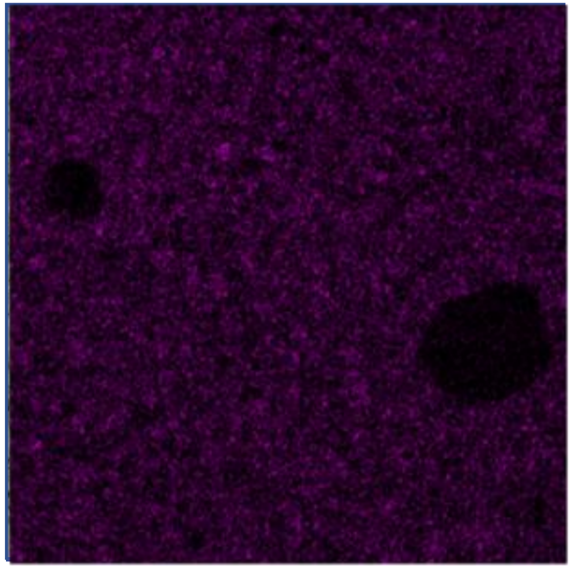
Fe Kα1



Ca Kα1



Si Kα1



The material dissolved is $Ca(OH)_2$

	Weight (g)	Brine weight (g)	pressure (psi)	temperature	pH	SO_4 (mmol/g cement)	Ca (mmol/g cement)	Al (mmol/g cement)	K (mmol/g cement)
Chip - Brine - H2	0.62	35.0	1500	~55C	11.39	0.19	0.481	0.017	0.223
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Summary

- The H_2 adsorption in two different cement samples are very low, less than 100 mg per Kg cement at 0 °C and 1 bar, expected to be even lower at higher temperature.
- When presence of brine, certain mineral, such as $Ca(OH)_2$, in cement can be dissolved but this reaction is not unique to H_2 though slightly enhanced under H_2 compared to N_2.
- It is thus inferred that H_2 will not have any significant damage on well integrity.
- Next steps – are there mechanical strength etc change?

SHASTA

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Gaseous Hydrogen Embrittlement of Metals for H_2 Storage

Chris San Marchi, Joe Ronevich, Milan Agnani, Fernando D. León-Cázares, Robert W. Wheeler (Livermore CA)

Mathew D. Ingraham (Albuquerque NM)

Sandia National Laboratories

SHASTA – 2024 Technical Workshop

3 April 2024, Pittsburgh PA

SAND2024-04009PE

Hydrogen affects all materials

*Hydrogen embrittlement occurs in **materials** under the influence of **stress** in hydrogen **environments***

Engineering decisions require careful consideration of the operational conditions for the intended service

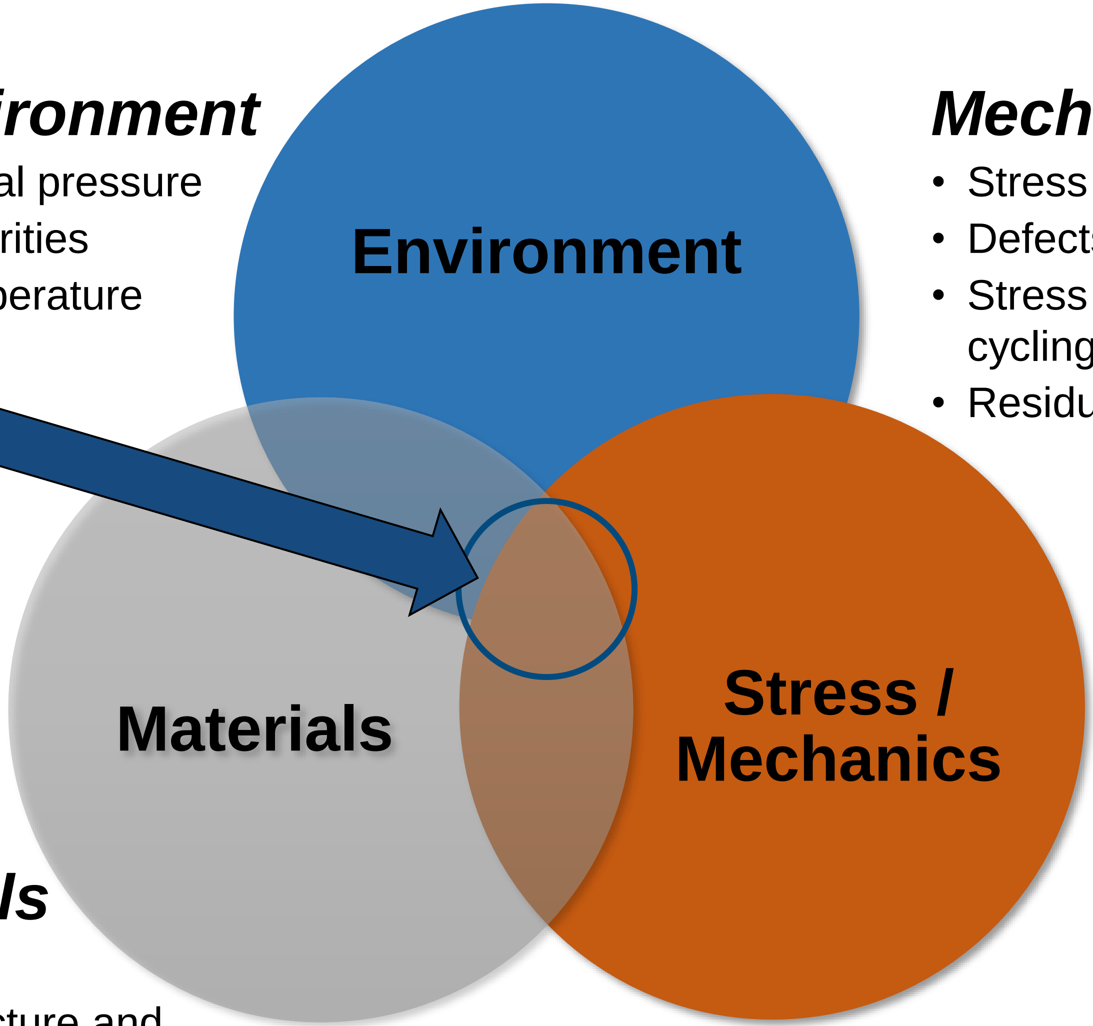
- ***Materials experience substantial degradation*** in hydrogen applications
- ***Design enables accommodation*** of hydrogen-induced degradation

Environment

- Partial pressure
- Impurities
- Temperature

Mechanics

- Stress
- Defects
- Stress (pressure) cycling
- Residual stresses



Materials

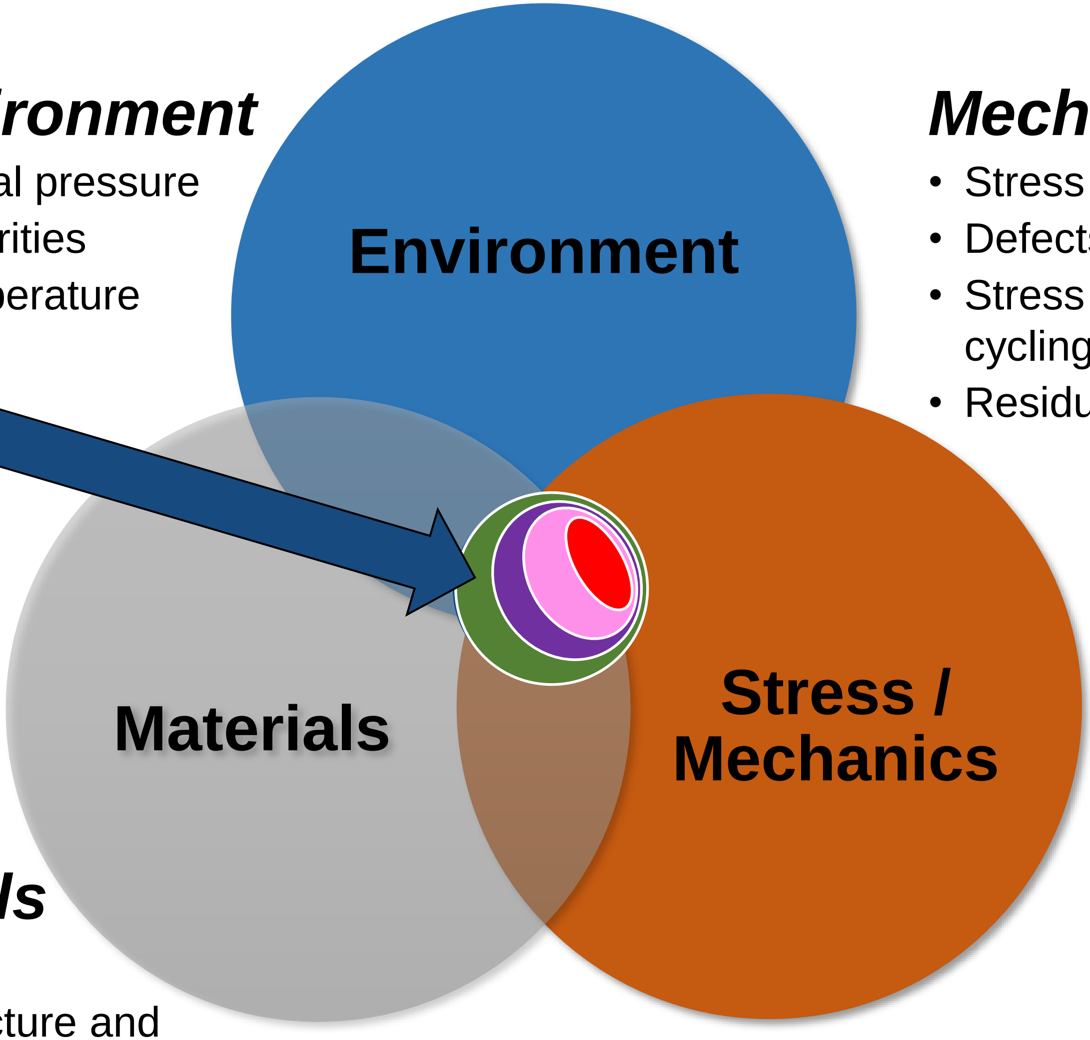
- Strength
- Microstructure and homogeneity

Hydrogen affects all materials

*Hydrogen embrittlement occurs in **materials** under the influence of **stress** in hydrogen **environments***

Engineering decisions require careful consideration of the operational conditions for the intended service

- ***Materials experience substantial degradation*** in hydrogen applications
- ***Design enables accommodation*** of hydrogen-induced degradation



Environment

- Partial pressure
- Impurities
- Temperature

Mechanics

- Stress
- Defects
- Stress (pressure) cycling
- Residual stresses

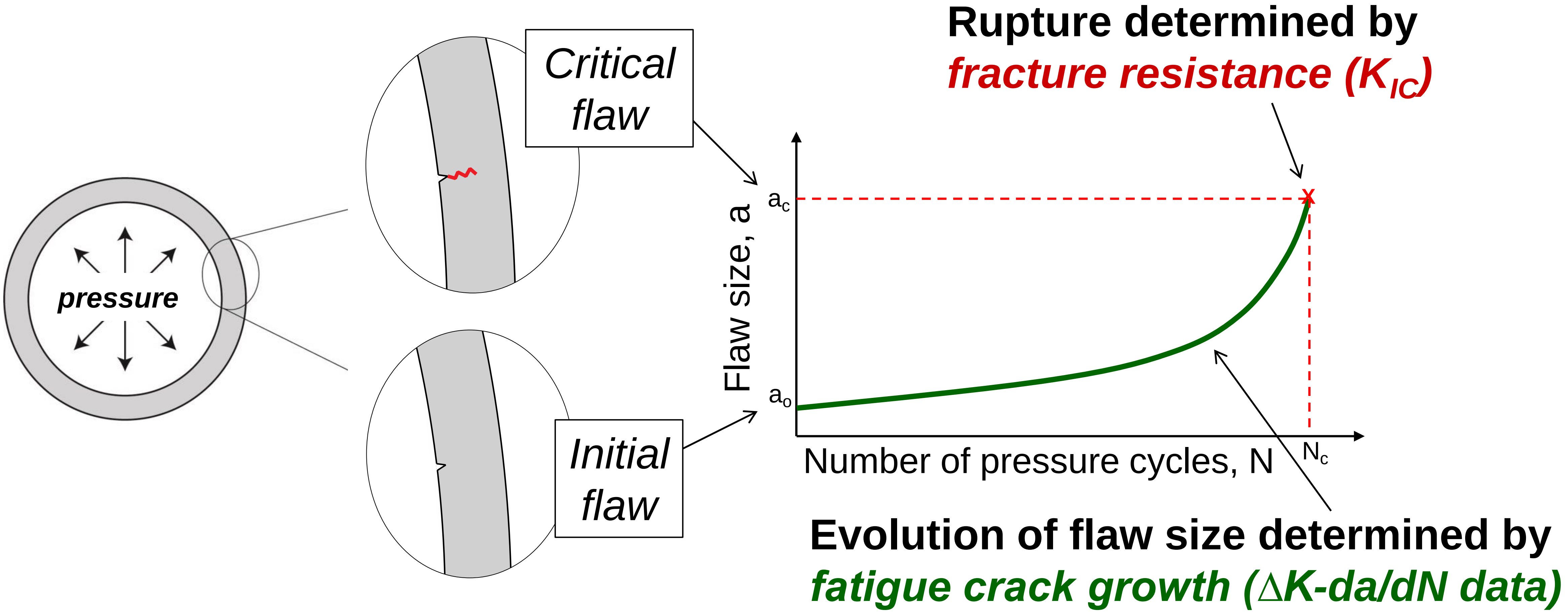
Materials

- Strength
- Microstructure and homogeneity

Diverse range of materials are used in GH2 service

Material	Recommended Condition	Materials performance	Common hydrogen usage	Example alloys
γ stainless steels (solid-solution strengthened)	• Ni > 8 wt% • Minimize magnetic phases • Strain-hardened condition can be acceptable	• Substantial reduction of tensile ductility • Reduction of fatigue life in low-cycle regime	Tubing, fittings, valve bodies, etc	304/304L 316/316L XM-11 XM-19
γ stainless steels (precipitation hardened)	• Avoid overaged condition	• Substantial reduction of fracture toughness (~50 MPa $m^{1/2}$)	Bosses, pressure volumes	A-286
Martensitic stainless steels	• Tensile strength < 900 MPa • use only with extreme caution, especially for high strength conditions	• Fracture toughness < 10 MPa $m^{1/2}$ in high strength conditions • Fatigue crack growth increased by factor of 10 to 100	Valve stems, and sub-assemblies	17-4PH PH13-8Mo 15-5PH
Carbon steels	• Tensile strength < 600 MPa (higher strength conditions may be suitable)	• Fatigue crack growth increased by factor of 10 or more at high ΔK (greater than ~15 MPa $m^{1/2}$)	Line pipe, piping, casing	API 5L (X42-X70) ASTM A516 (API 5CT?)
Low alloy steels (Q&T Cr-Mo & Ni-Cr-Mo steels)	• Tensile strength < 900 MPa	• Fatigue crack growth increased by factor of 10 or more at high ΔK (> 8 MPa $m^{1/2}$)	Transportable gas cylinders, stationary storage (1000 bar)	ASTM A372, ASTM A723 (API 5CT?)
Nickel-based alloys	• Use with caution • Tensile strength < 900 MPa	• Relatively little data available	High-strength, corrosion-resistant components	IN718 IN625
Aluminum alloys	• Avoid tempers susceptible to stress corrosion cracking	• No known effects of gaseous hydrogen	Pressure vessel liners	6061

Fracture mechanics-based testing is the standard



Fitness-for-service methods generally include fracture mechanics to assess structural integrity of large-scale infrastructure

Diversity of application requires broad understanding of ...

- **Mechanics variables**
  - Stresses (cyclic, residual)
  - Rate effects (testing rate, frequency)
- **Environmental variables**
  - Pressure (fugacity)
  - Gas impurities
- **Materials variables**
  - Microstructure
  - Welds and heat-affected zones
  - Strength and hardness

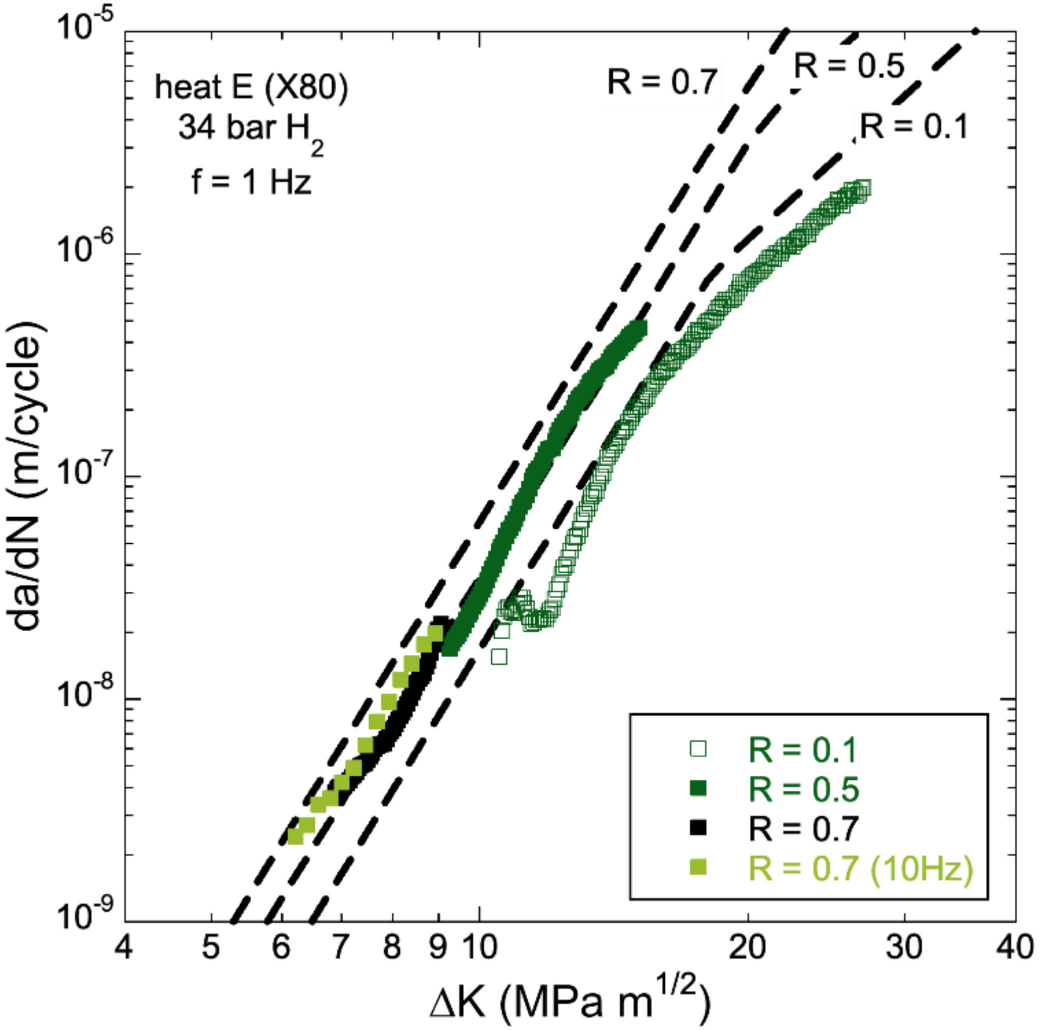
Challenges:

- Effects of hydrogen can depend sensitively on subtle variation in the environment
- Testing hardware is also affected
- Time scales are underappreciated
- Myths and misinformation are common

Consequences:

- *Even experts can get it wrong*
- *Lack of consensus*

Mechanics variables: fatigue stress ratio

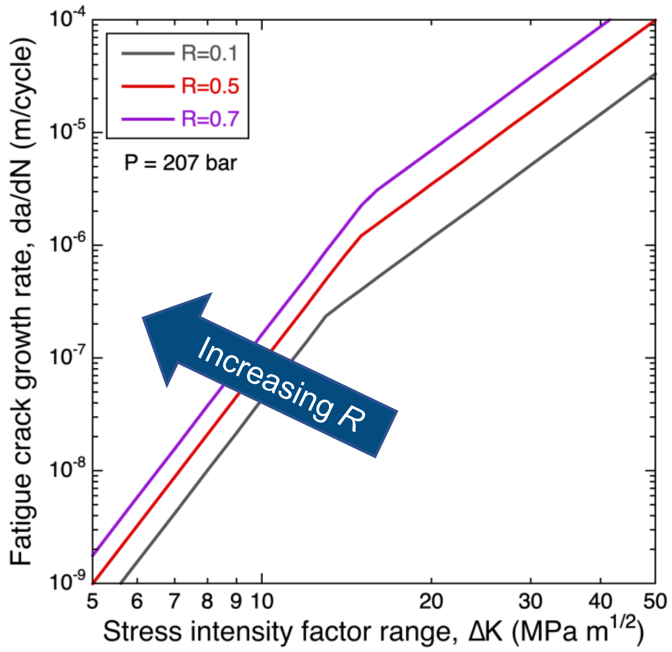


From:
San Marchi et al., PVP2022-84757

- Stress ratio (R) affects fatigue crack growth in gaseous hydrogen
  - Dependence is generally greater than in air

ASME codes have adopted fatigue design curves that account for influence of stress ratio

- Applicable to common pipeline and pressure vessel steels
- See ASME:
  - BPVC VIII.3 CC 2938
  - B31.12 CC 220



After:
San Marchi et al., PVP2019-93907
San Marchi et al., PVP2024-122529

Environmental variables: pressure

Hydrogen permeates in metals as atomic hydrogen

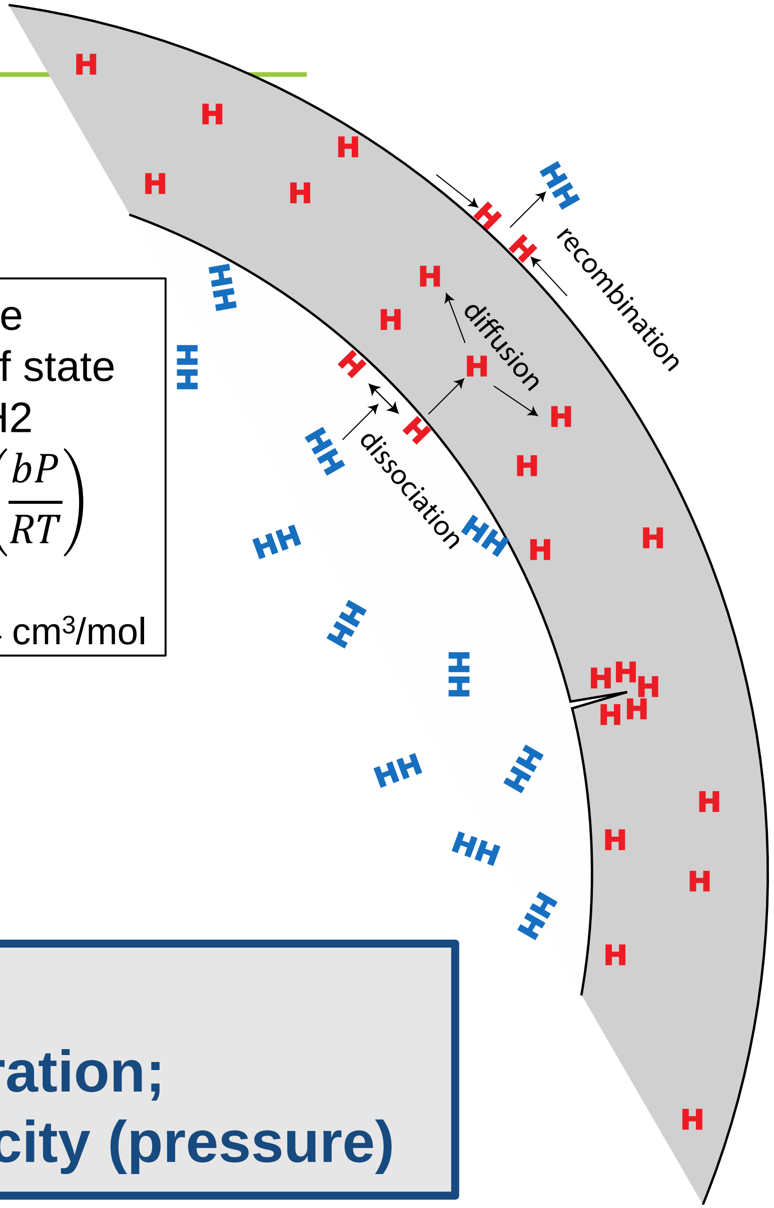
Equilibrium between gas and dissolved hydrogen

$$\frac{1}{2}H_2 \leftrightarrow \underline{H}$$

Simple
equation of state
for GH2

$$\frac{f}{P} = \exp\left(\frac{bP}{RT}\right)$$

b = 15.84 cm^3/mol



General form of Sieverts' Law

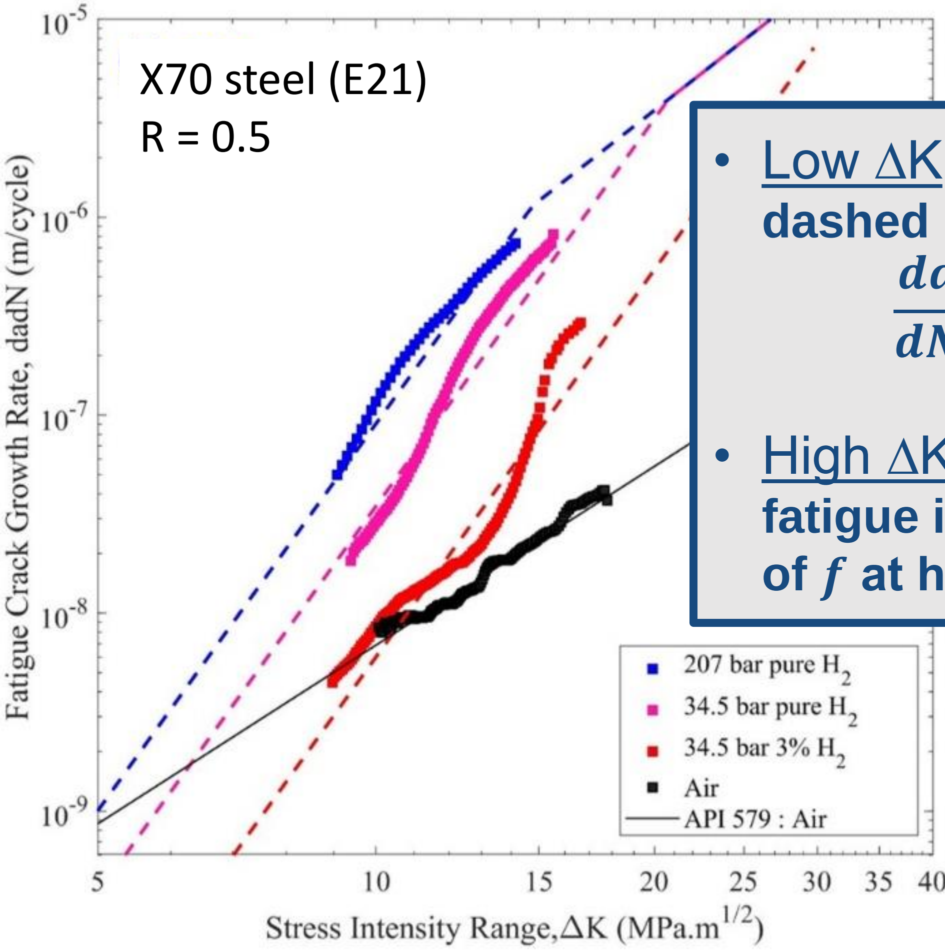
$$c_o = K_m f^{1/2}$$

Hydrogen concentration in metal → c_o ← fugacity (thermodynamic pressure)

Simple phenomenological assumption:
hydrogen effects are proportional to the hydrogen concentration;
therefore, HE should be proportional to square root of fugacity (pressure)

Environmental variables: pressure

Hydrogen-assisted fatigue crack growth

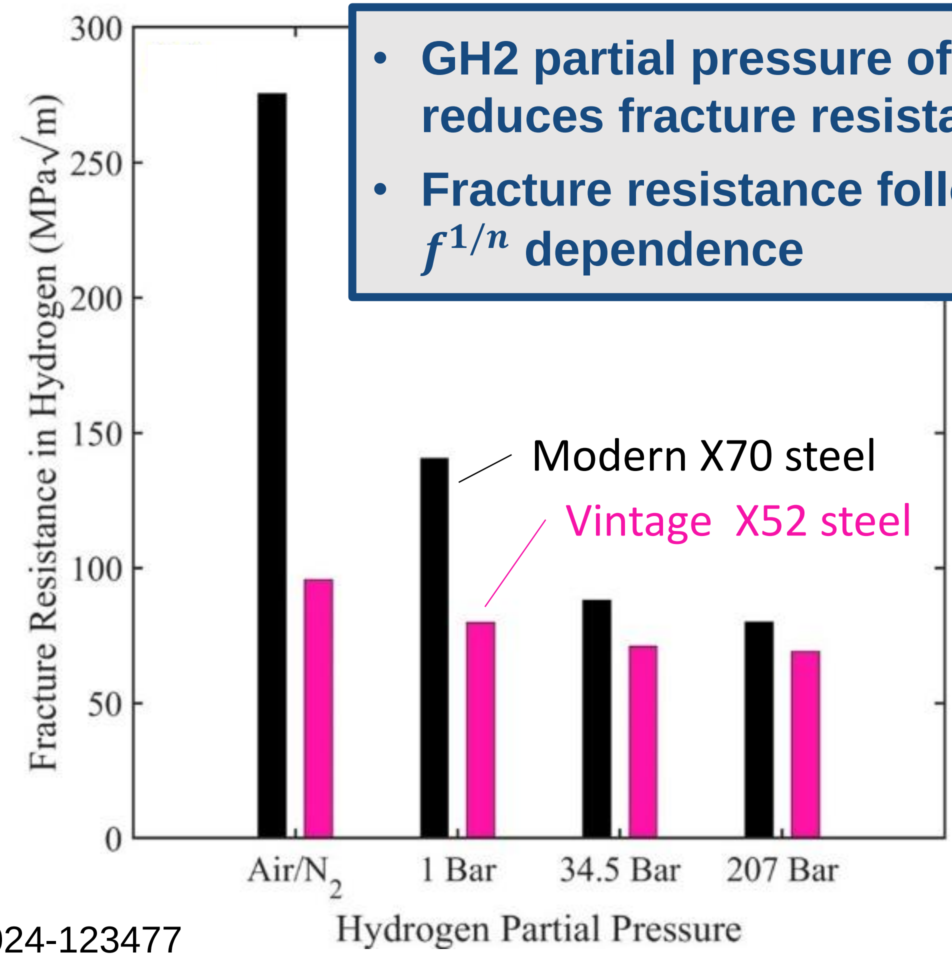


- <u>Low ΔK</u>
  dashed lines represent
  $$\frac{da}{dN} \propto f^{1/2}$$
- <u>High ΔK</u>
  fatigue is independent of f at high ΔK

From:
Agnani et al., PVP2024-123477

Hydrogen-assisted fracture

- **GH2 partial pressure of 1 bar reduces fracture resistance**
- **Fracture resistance follows $f^{1/n}$ dependence**

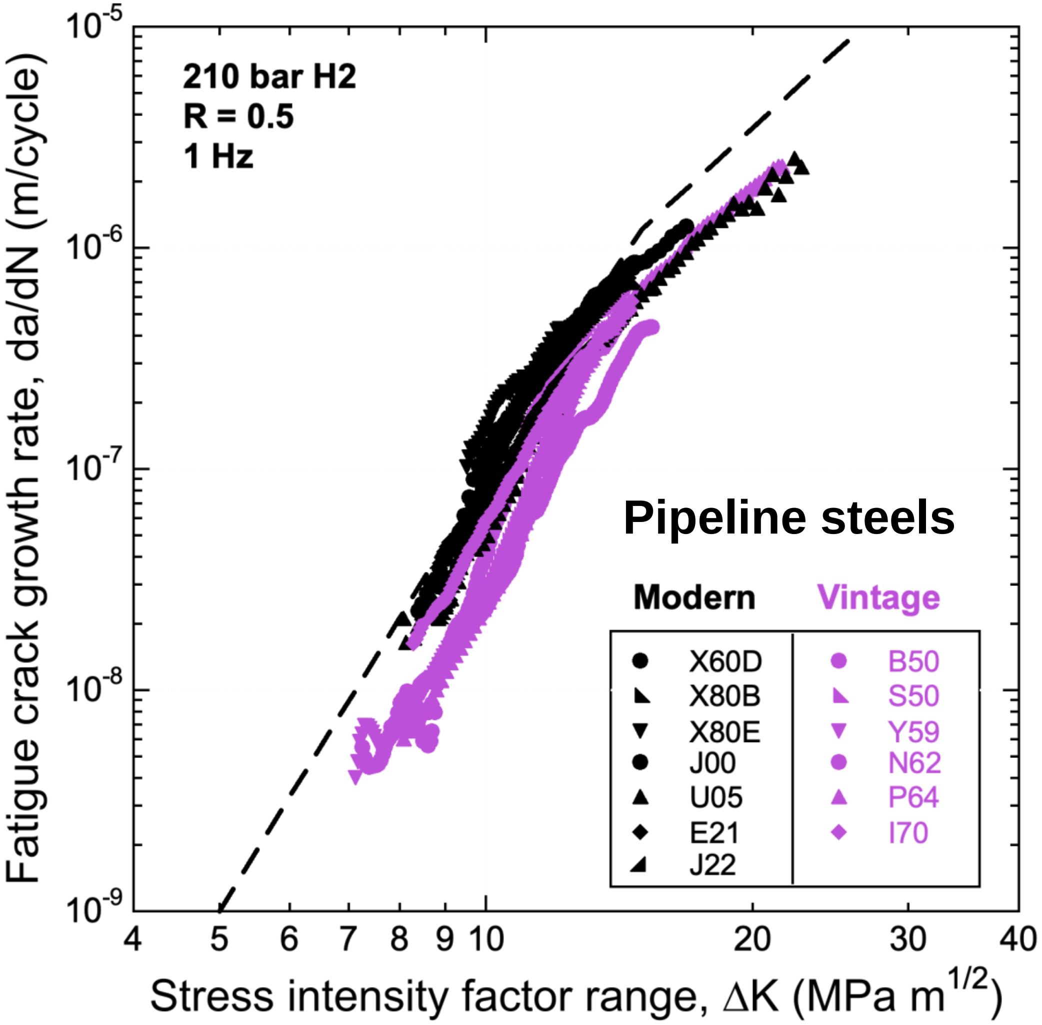


Materials variables: common steels behave similarly

- **Carbon (pipeline) steels**
  - Modern and vintage steels have different metallurgical characteristics
  - Extensive fatigue and fracture data available in GH2 for both modern and vintage steels
  - Pipeline Blending CRADA (a HyBlend™ project)

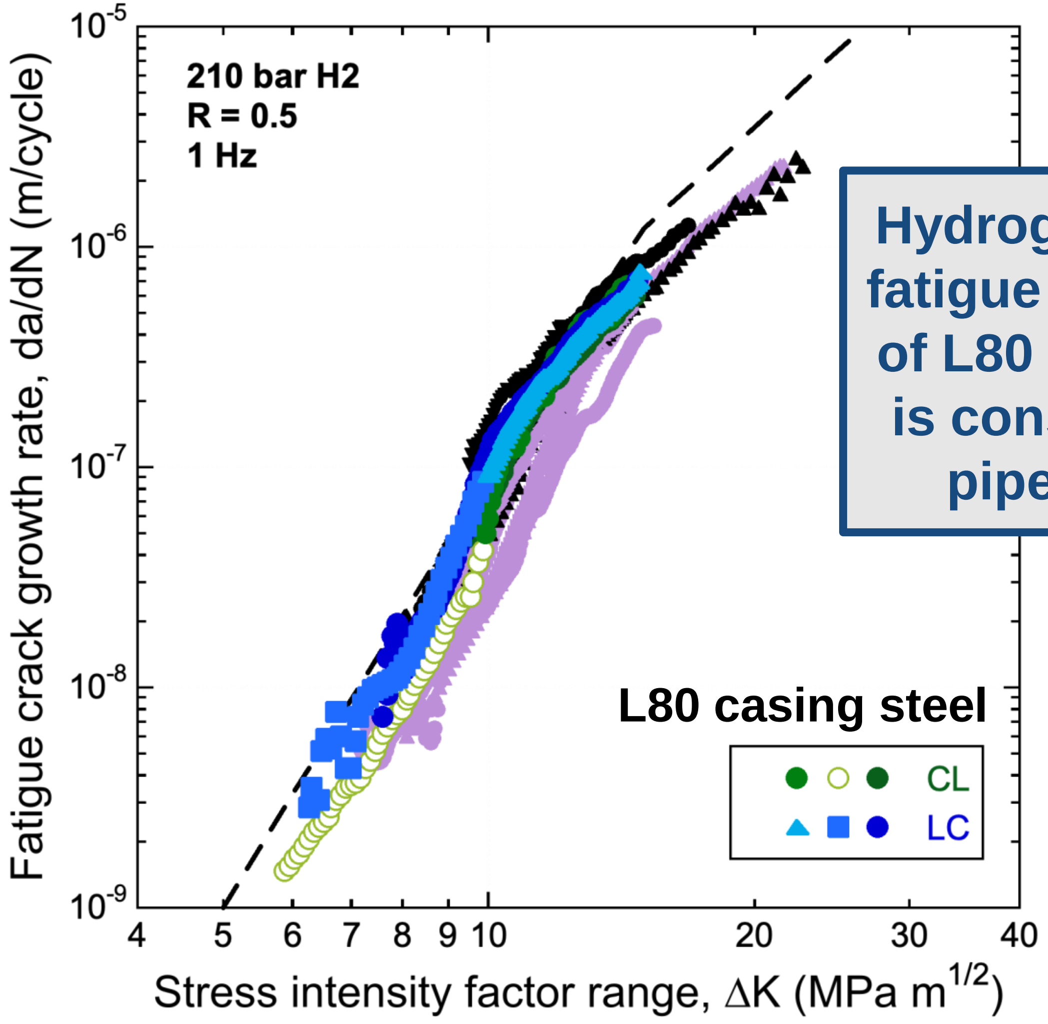
- **Low-alloy (pressure vessel) steels**
  - Cr-Mo and Ni-Cr-Mo quench and tempered steels
  - Extensive fatigue and fracture data available in GH2
  - Hydrogen Materials Compatibility Consortium (H-Mat)

- **High-alloy steels**
  - Less information available for ferritic steels (e.g., Cr- steels and Ni-steels)



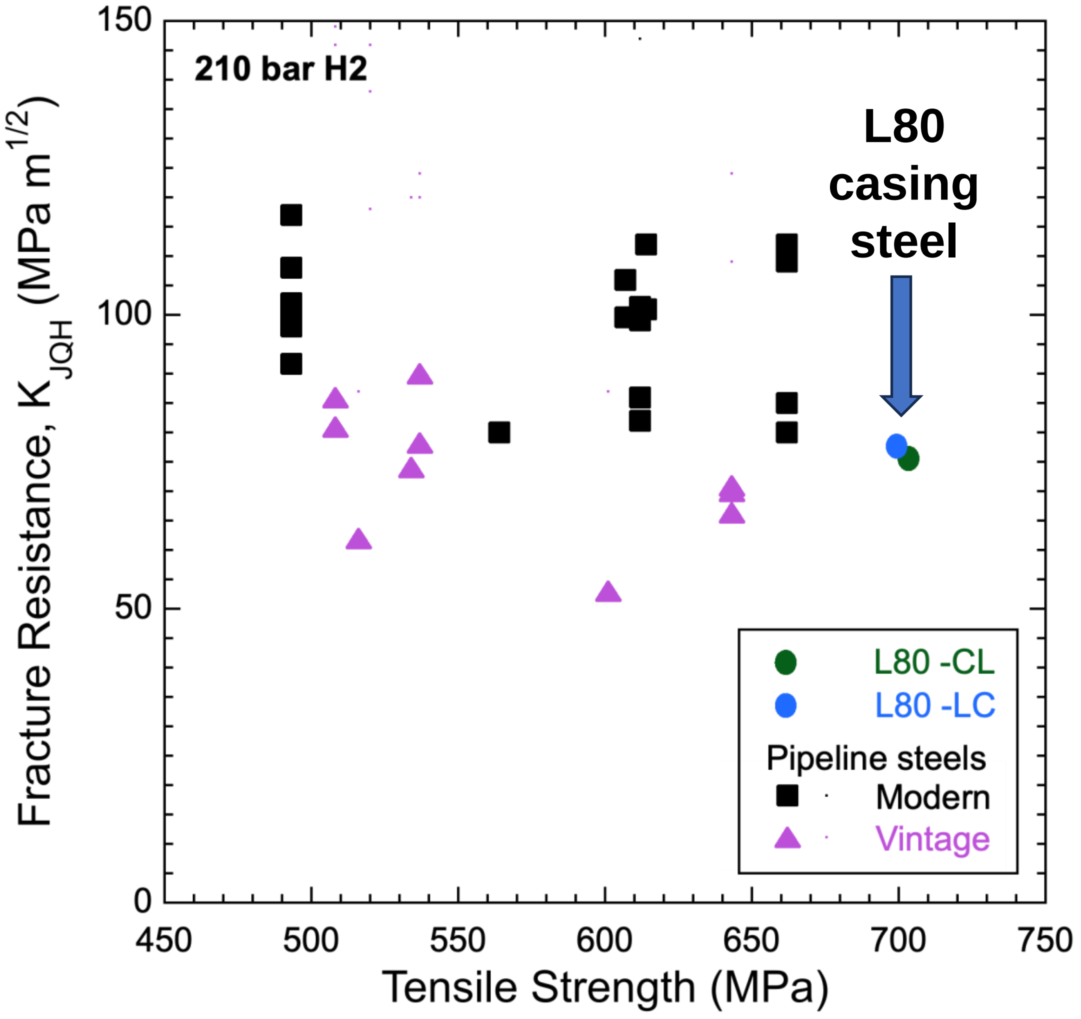
Carbon steel casing (API 5CT L80)

Hydrogen-assisted fatigue crack growth

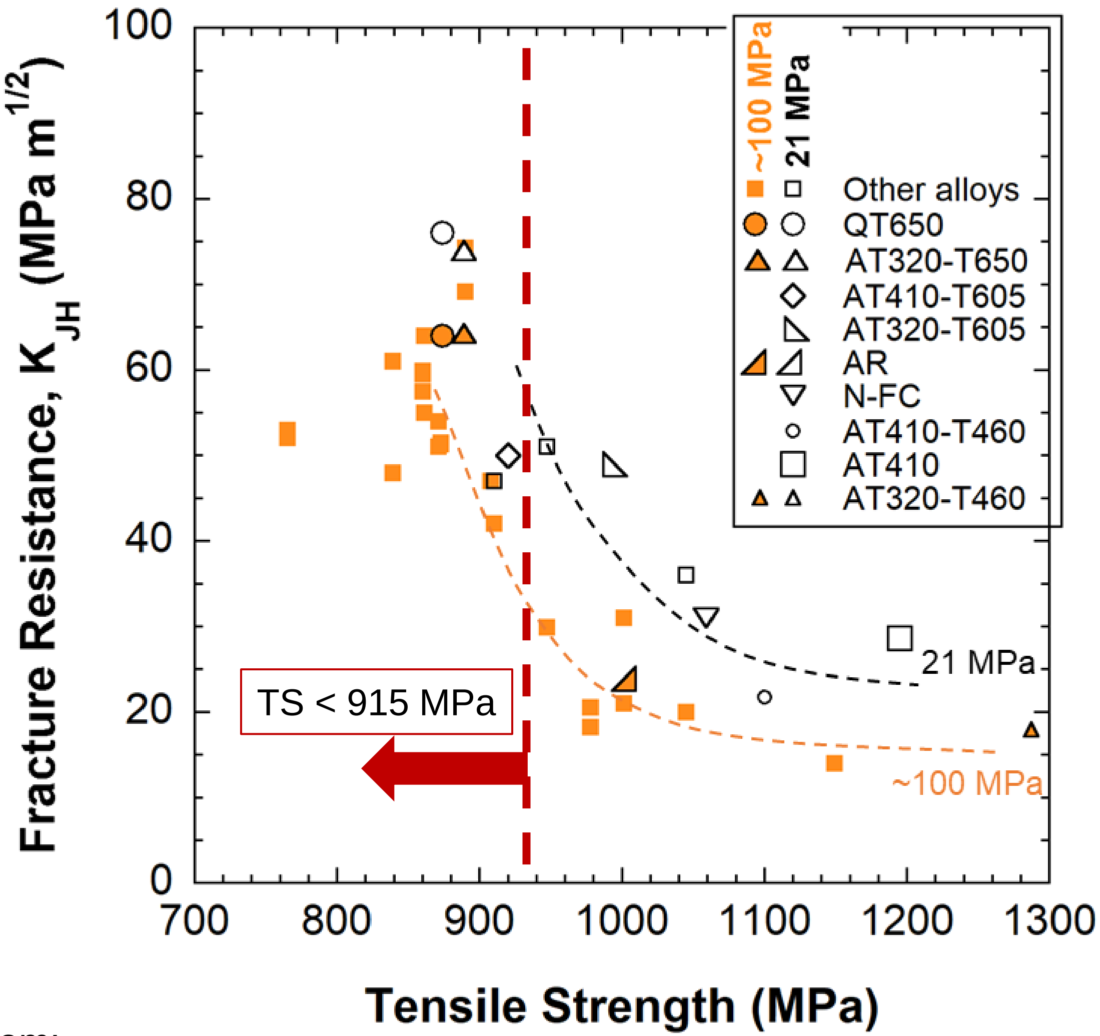


Hydrogen-assisted fatigue and fracture of L80 casing steel is consistent with pipeline steel

Hydrogen-assisted fracture



Low-alloy steels



From:
Ronevich et al., PVP2022-83915

Cr-Mo and Ni-Cr-Mo steels (e.g., P110 steels)

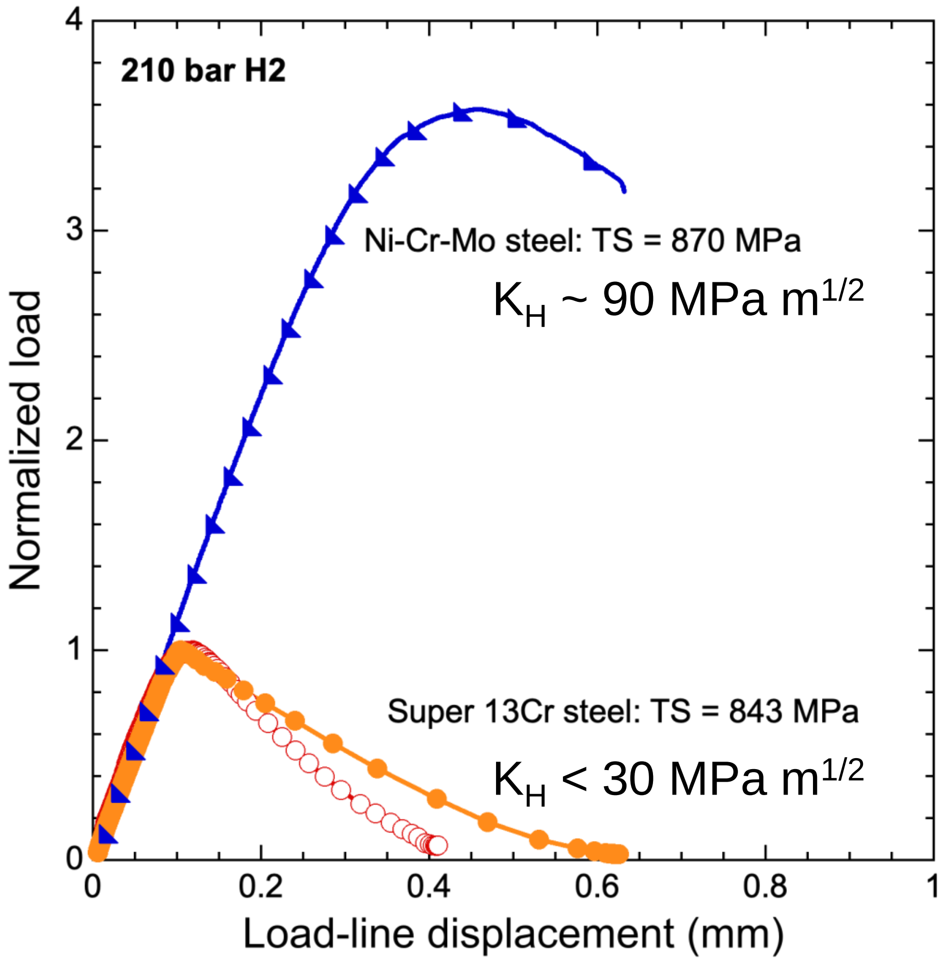
- 41XX and 43XX steels
  - 4130X steel: DOT transportable gas cylinders used for GH2 as well as N_2, He, Ar, etc pressure up to ~410 bar (6,000 psi)
- For high-pressure GH2 service, generally limited to TS < 915 MPa
  - ASME BPVC VII.3 Code Case 2938
  - Fatigue crack growth (not shown) is essentially the same as for pipeline steels

Hydrogen-assisted fatigue and fracture of L80 casing steel is consistent with pipeline steel

High-alloy steels

Many types of high-alloys steels are used in storage systems

- Cr-steels are used for casing –
  quench and tempered martensitic steels
  - 3Cr
  - 9Cr
  - 13Cr
  - Super 13Cr (Ni and Mo additions)
  - These steels are similar to the low-alloy steels but higher alloy content
  - ***Hypothesis***: Cr-steels with tensile strength < 900 MPa should behave similar to low-alloy steels



Hypothesis is wrong: **High Cr-steel is significantly more susceptible to hydrogen-assisted fracture than Q&T Ni-Cr-Mo steels**

Summary

- Hydrogen effects depend *mechanics*, *environmental* and *materials* variables
  - Impact on an application **cannot** be assessed without considering the operational parameters
- Virtually all materials classes are used in gaseous hydrogen environments
  - Material strength is a key parameter for managing hydrogen-assisted fracture
  - *Tensile strength < 900 MPa is a good rule of thumb for most materials* (but may not be sufficient in all cases)
- ASME codes have adopted fatigue design curves for crack growth assessment
- Hydrogen fugacity (not %) determines magnitude of hydrogen effects
  - *Even <1 bar hydrogen partial pressure can affect fatigue and fracture*
- Carbon steels and low-alloys steels have been extensively evaluated in the context of *pipelines* and *pressure vessels* for hydrogen service
- Knowledge gaps exist for high-alloy steels that are relevant to subsurface hydrogen storage

Thank you

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Chris San Marchi
cwsanma@sandia.gov

Joe Ronevich
jaronev@sandia.gov

Additional resources:

- https://h-mat.org/
- https://www.sandia.gov/matlsTechRef/
- https://granta-mi.sandia.gov/
- https://helpr.sandia.gov

Hydrogen Effects on Materials Laboratory
Sandia National Laboratories (Livermore)

Milan Agnani
Rob Wheeler
Fernando Leon-Cazares

Brendan Davis
James McNair
Keri McArthur
Tanner McDonnell

SHASTA

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Wellbore Cement Integrity

Barbara Kutchko, Rick Spaulding, Deepak Tapriyal, Meghan Brandi,
Angela Goodman – National Energy Technology Laboratory
(Barbara.Kutchko@NETL.doe.gov)

U.S. DEPARTMENT OF ENERGY
Fossil Energy and Carbon Management

NATIONAL ENERGY TECHNOLOGY LABORATORY

Pacific Northwest NATIONAL LABORATORY

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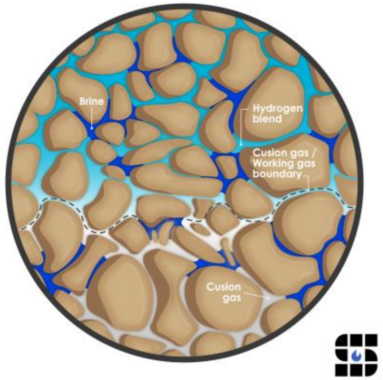
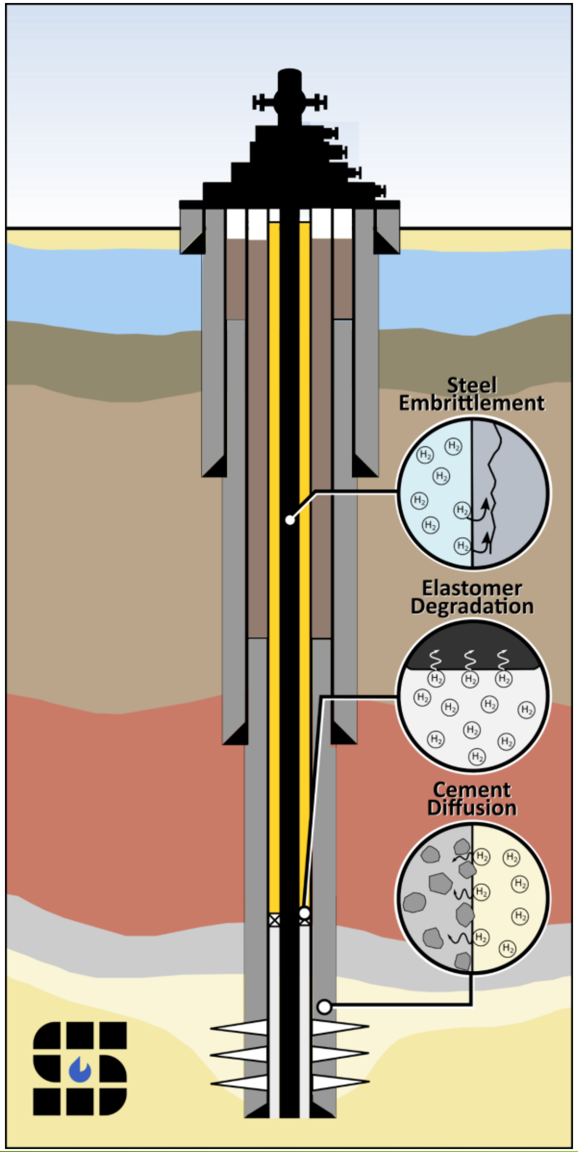


Well Integrity



Well integrity is an important source of risk and liability for UHS

- Well integrity loss has been the source of most leakage events at natural gas storage sites
- H_2 is highly mobile in the subsurface and will potentially leak through faulty wells
- Well integrity must be maintained in injection, monitoring, and legacy wells

Steel embrittlement

- H_2 moves into the atomic structure of steel causing premature cracking and failure
- Commonly used low-carbon steels are susceptible
- Occurs when H_2 concentrations are high

Elastomer degradation

- Damage can result from permeation of H_2 into the material followed by rapid decompression
- Other failure mechanisms may include temperature and chemical degradation, extrusion and nibbling, compression set, wear, and spiral failure

Cement gas/fluid transport

- H_2 is the smallest molecule and has a high diffusivity
- H_2 transport in cement is expected to be more of a challenge than reactivity

Well Integrity - Background

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Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

- The ability to successfully store H_2 underground will depend on the ability of the cement used to line wells to provide zonal isolation and protect the steel casing.
- H_2 has the highest effusion rate of all gases. The heterogeneity of cement make measurements complex and difficult to compare. In porous materials such as cement, permeability and diffusion is impacted by the pore network (porosity Ø, tortuosity τ, constrictivity δ) of the cement matrix.
- The pore network itself is controlled by factors such as water/cement ratio, cement type, additives, particle size (fineness), curing time (age), curing temperature and pressure
- Previous research found that gas permeability (hydrogen flux) decreased with curing time and increased with w/c ratio

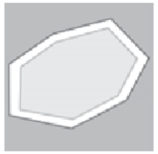
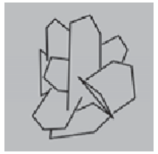
	Size range, diameter/ µm	Description	Trivial names
	100 - 3000	Artificial gas pores generated by hydrogen from aluminium reaction (in some cases foam pores) with expanding crack structure	Air pores, Gas pores, "macro pores"
	5 - 30	Residual pore space of initially water filled volume	Water pores, Inter cluster pores, "micro pores"
	10 - 50	Holes as residuals of dissolved quartz particles, Hollows around residual quartz grains	Quartz grain related pores, "micro pores"
	0.5 - 20	Pore volume between new formed large crystals of tobermorite	Inter particle pores, Tobermorite related pores, "micro pores"
?	0.005 - 1	Pore volume between new formed crystallites of tobermorite and CSH phases	Nano pores, CSH phases related pores, "micro pores"

Figure from Schober 2011 – Classification of porosity in cement

Well Integrity - Approach

Two-fold approach: gas-permeability measurements and batch reactions

1. Gas-permeability of H_2, CH_4, and N_2
2. Batch Reactions: Class H cement exposed to H_2 at underground storage conditions for 3 months - with and without embedded J55 steel
    - Variety of water/cement ratios as well as pozzolan additives
    - 50° C and 1200 psi and submerged in a 1% NaCl fluid

- Analysis/measurements:
    - Pulse Decay Permeameter (PDP)
    - Feature-Relocation Scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS)
    - NER AutoLab: sonic velocity
    - **Pressure differential – both sides; H_2 at 800 psi downstream/upstream – created a differential of about 20 psi**

Pulse Decay Permeameter (PDP-200)

Autoclaves for *in situ* exposure

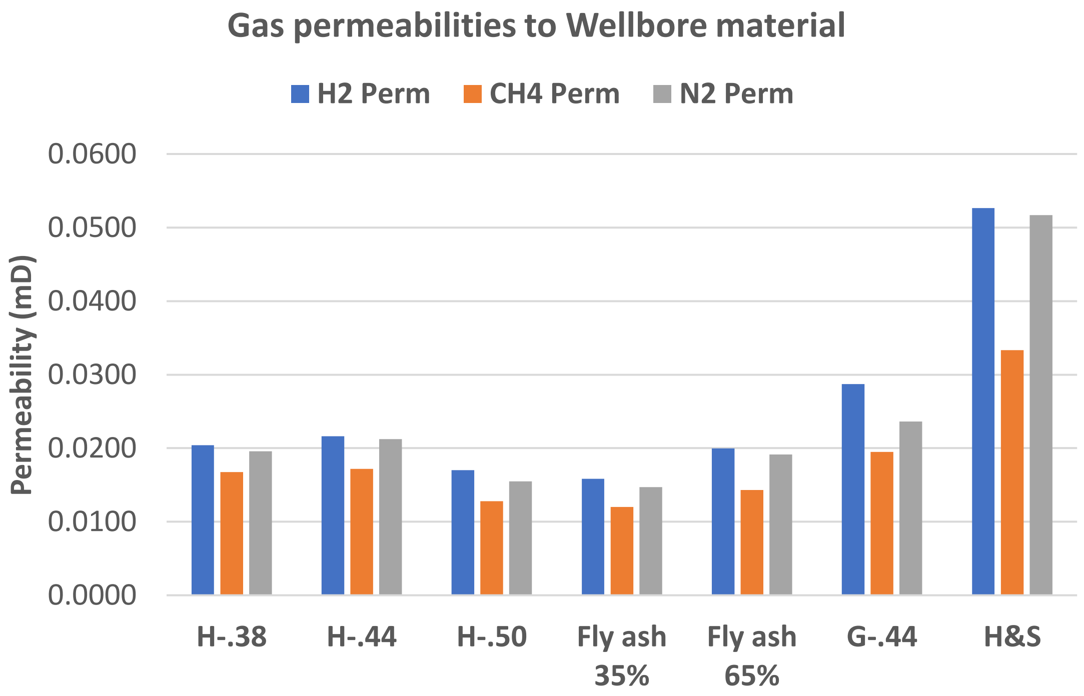
NER AutoLab 1500

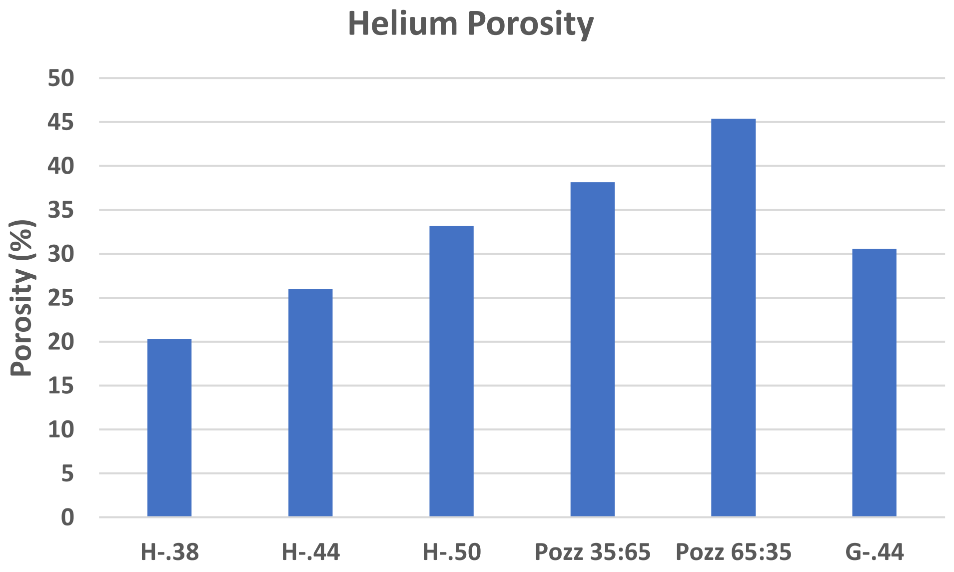
Well Integrity – Gas Permeability

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

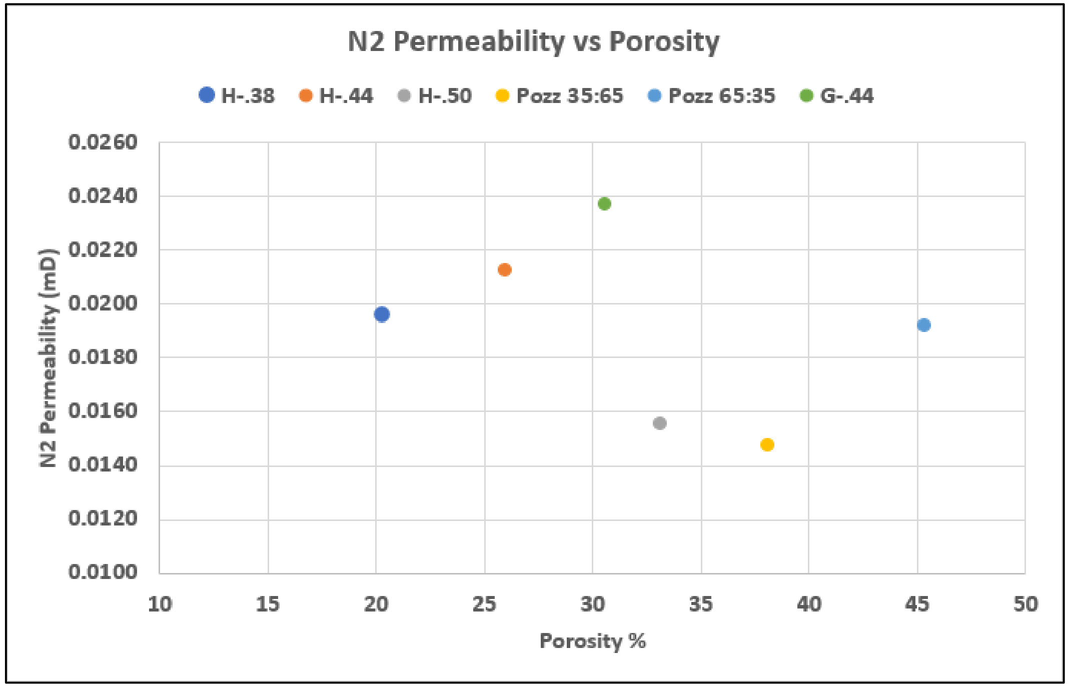
Cement Type	Water/Solids Ratio	Additives	Slurry Density lb/gal (g/cm³)
Class H	0.38		16.6 (2.00)
Class H	0.44		16.0 (1.91)
Class H	0.50		15.4 (1.84)
Class H	0.52	Fly Ash 35%	14.8 (1.76)
Class H	0.56	Fly Ash 65%	13.9 (1.68)
Class G	0.44		15.9 (1.91)

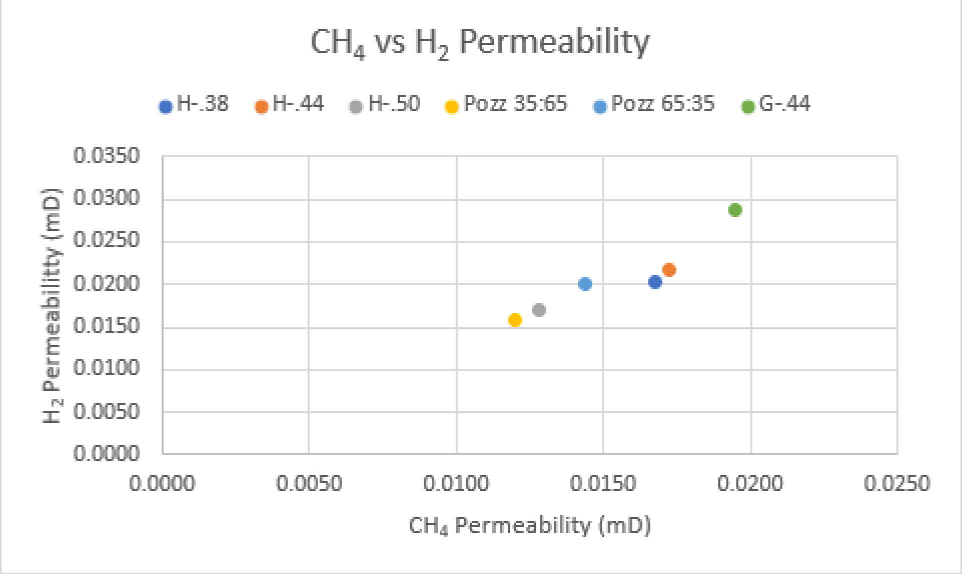
Image of Class H, G, and pozzolan-mixed cement cores

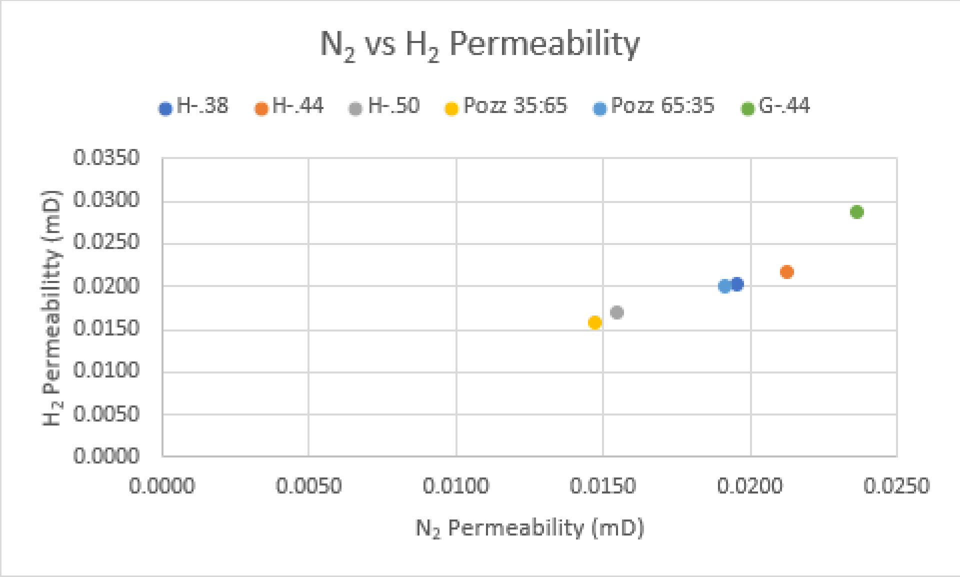




Well Integrity – Gas Permeability



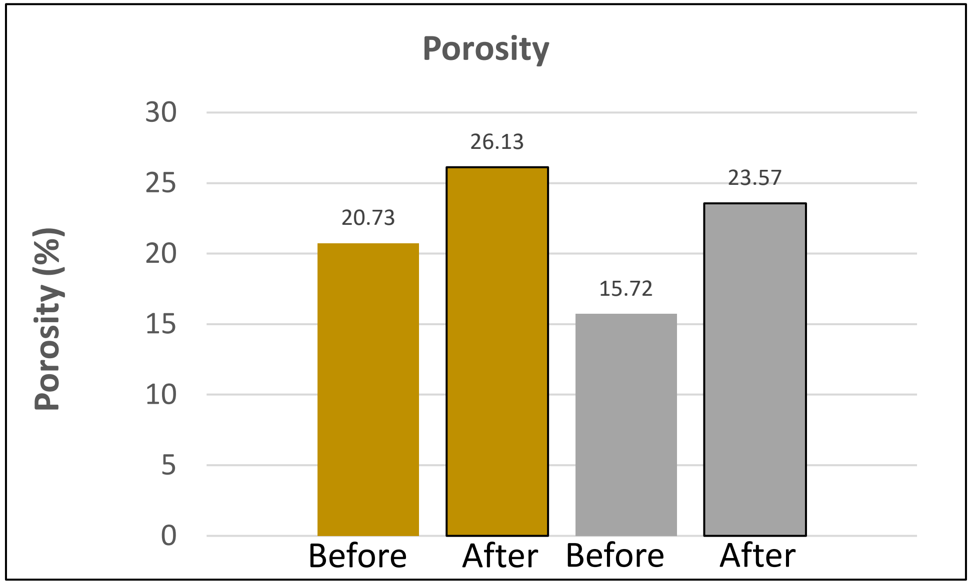


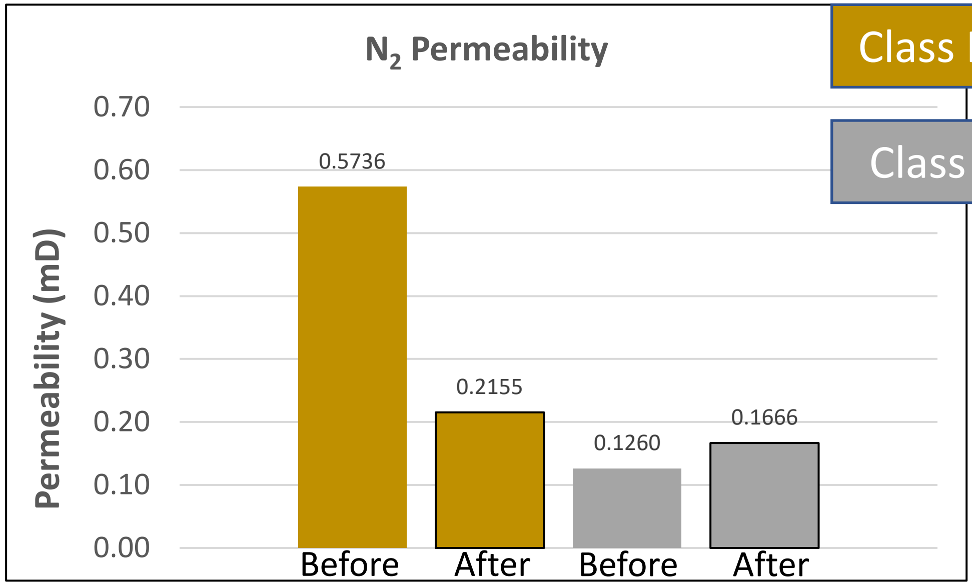


Sample Name	Cement Type	Water/Solids Ratio	Additives	Slurry Density lb/gal (g/cm^3)
H-.38	Class H	0.38		16.6 (2.0)
H-.44	Class H	0.44		16.0 (1.91)
H-.50	Class H	0.50		15.4 (1.84)
Pozz 35:65	Class H	0.52	Fly Ash 35%	14.8 (1.76)
Pozz 65:35	Class H	0.56	Fly Ash 65%	13.9 (1.68)
G-.44	Class G	0.44		15.9 (1.91)

Well Integrity – Batch Reactions

Pre and Post 3 months H_2 Batch exposure @ 1200 psi and 50°C





Class H cement

Class H with steel

Class H Cement
Cement water : 38% (1% NaCl)
Cement water + steel : 38% (DI water)

→

Auto Lab
Poison ratio
Youngs modulus
PDP
-Permeability
SEM-EDS

→

H_2 Exposure
3-month
at
50°C
1200 psi

→

Auto Lab
Poison ratio
Youngs modulus
PDP
-Permeability
SEM-EDS

Well Integrity – Batch Reactions

Class H Cement
Cement water : 38% (1% NaCl)
Cement water + steel : 38% (DI water)

→

Auto Lab
Poison ratio
Youngs modulus
PDP
-Permeability
SEM-EDS

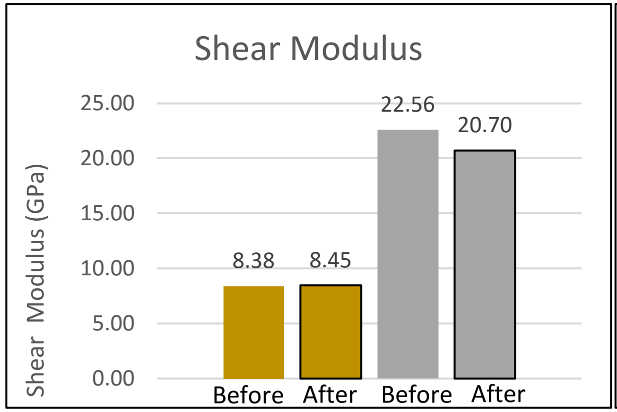
→

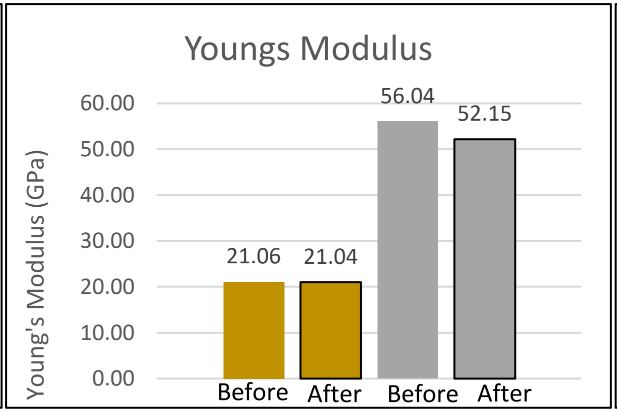
H_2 Exposure
3-month
at
50°C
1200 psi

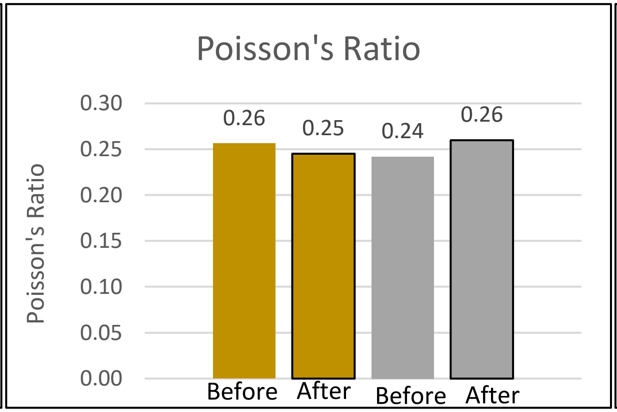
→

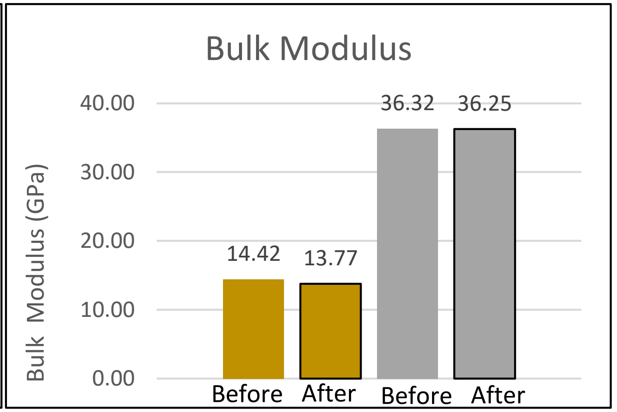
Auto Lab
Poison ratio
Youngs modulus
PDP
-Permeability
SEM-EDS

Class H with steel | Class H cement



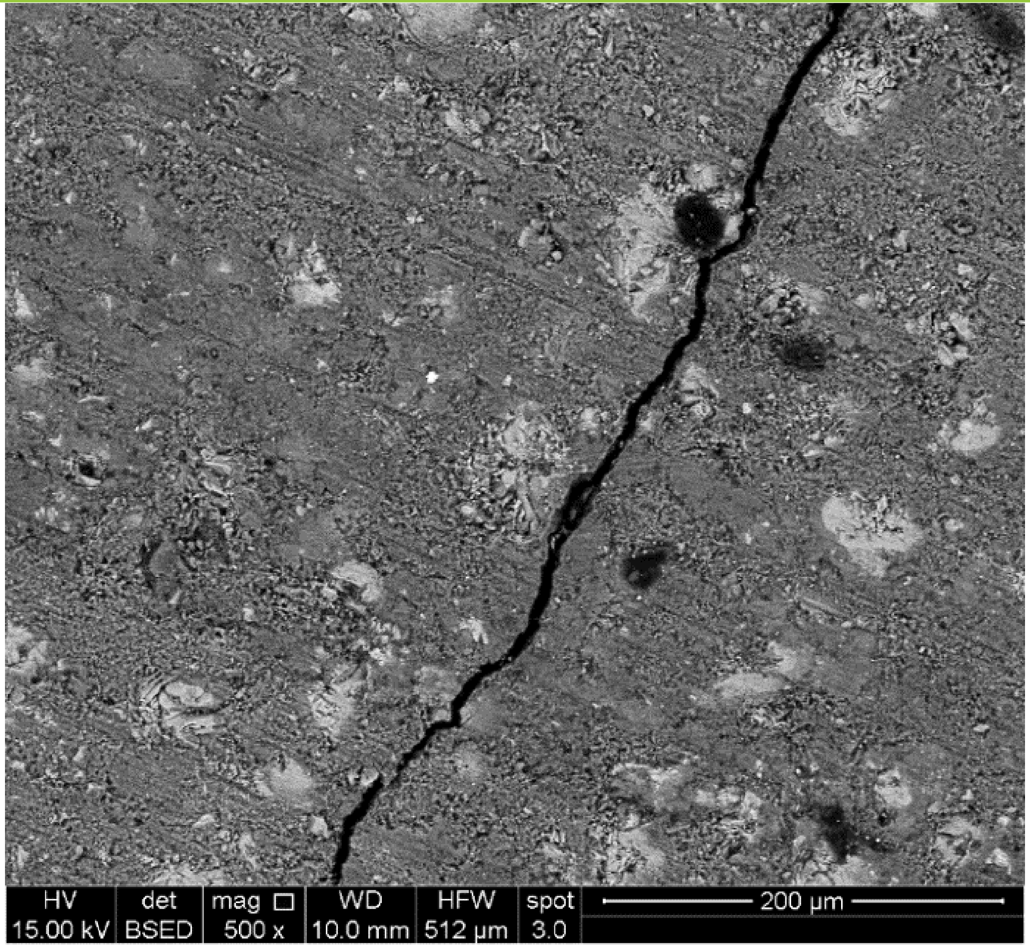




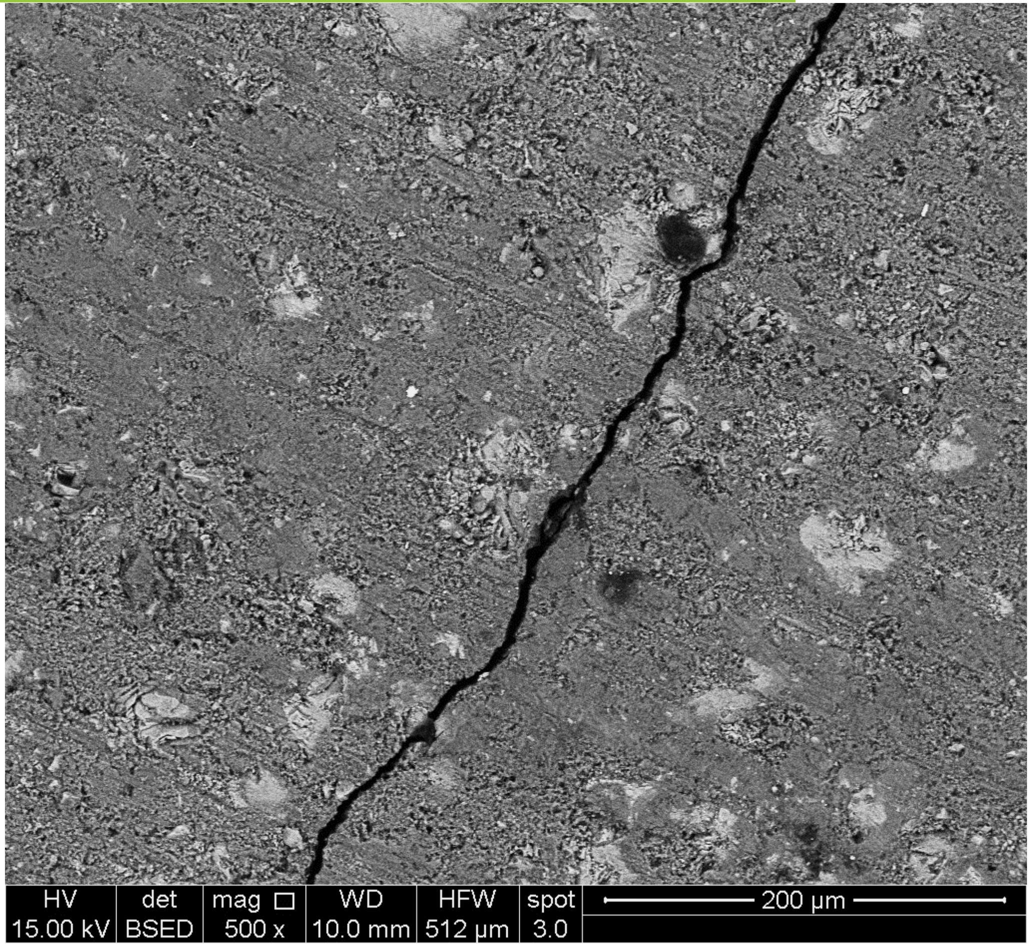


Pre and Post 3 months H_2 Batch exposure @ 1200 psi and 50°C

Well Integrity – Batch Reactions



pre-H_2 exposure



post-H_2 exposure

SEM-BSE (scanning electron microscopy backscattered electron) images of Class H cement before and after 3-month hydrogen exposure at 1200 psi and 50°C. No discernable changes in chemistry or microstructure.

Well Integrity: Summary of Progress and Results

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

- Summary:
  - Measured Class H (neat) cement gas-permeability of H_2, CH_4, and N_2
  - Examined (SEM-EDS and AutoLab) 6 different cement systems – exposure to H_2 at reservoir pressure and temperature
    - Measured porosity, permeability, Young's Modulus Poisson's Ration, Shear Modulus, Bulk Modulus
- Results:
  - Porosity is not a good indicator of gas-permeability
  - Methane and nitrogen gas-permeability measurements may be good proxies for H_2
  - Did not observe changes in the cement chemistry and morphology or significant differences in mechanical properties before and after H_2 exposure
- Future work:
  - Calculate diffusion and potential leakage rates
  - Investigate microbial/cement systems

Optical Fiber Sensor Technologies for Real-time Monitoring of Subsurface Hydrogen Storage

SHASTA
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

PI: Ruishu F. Wright, Ph.D.
Research and Innovation Center (R&IC)
National Energy Technology Laboratory

Research Team: Daejin Kim, Alexander Shumski, Nathan Diemler, Nageswara Lalam.

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration - 2024 Technical Workshop
April 3, 2024, Pittsburgh, PA

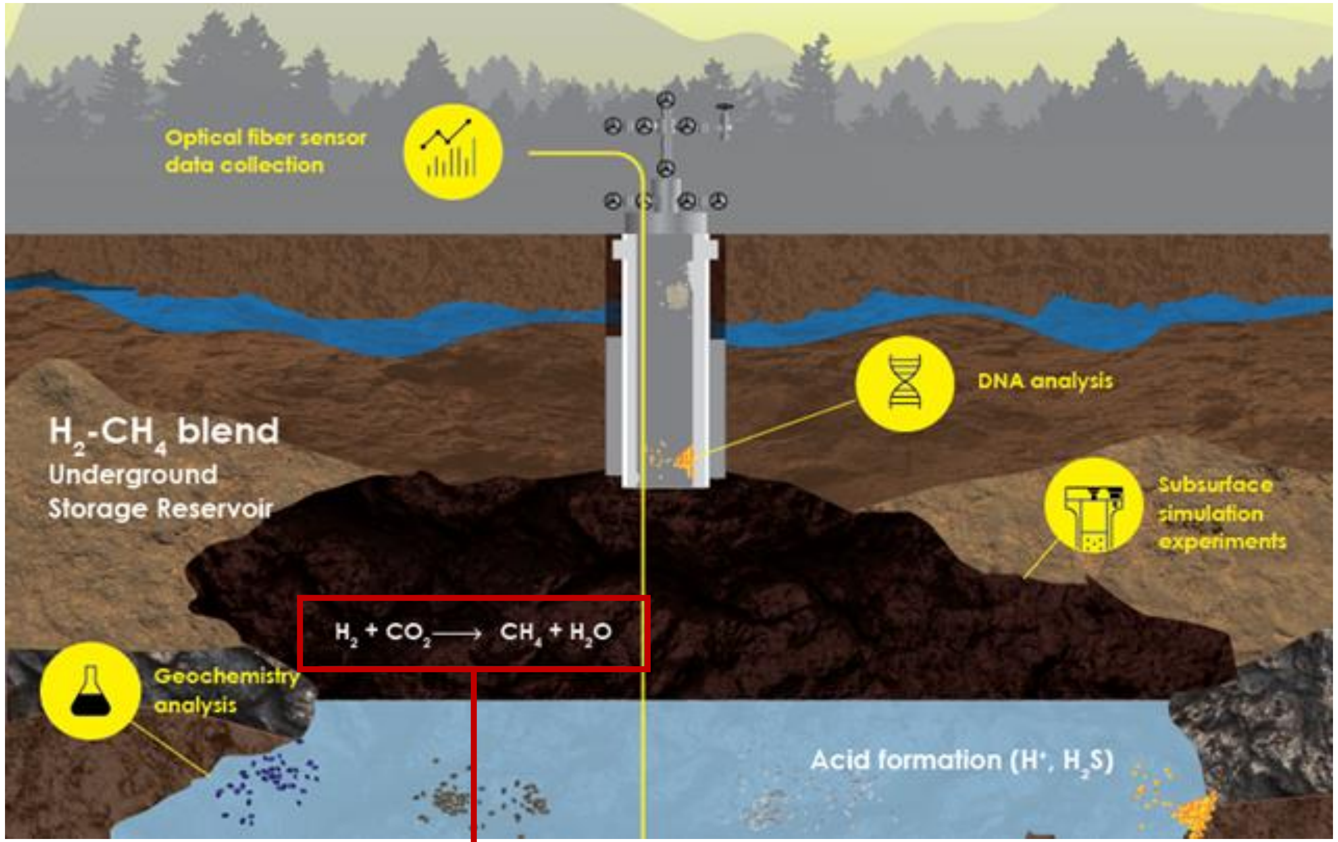
Solutions for Today | Options for Tomorrow

Project Objectives

- In-situ optical fiber sensors for real-time monitoring of **<u>hydrogen, methane, and chemical parameters</u>** at subsurface hydrogen storage conditions

Impact on Subsurface Hydrogen Storage

- Determine microbiological H_2 consumption/depletion and pH change
- Identify well integrity risks
- *Real-time* vs Periodic Sampling
- *In-situ* vs Ex situ

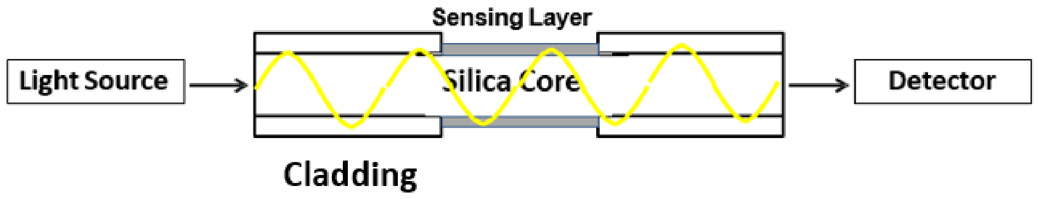


- Microbial conversion of hydrogen in subsurface storage wells
- **Need for real-time monitoring** of gas composition and geochemical conditions.

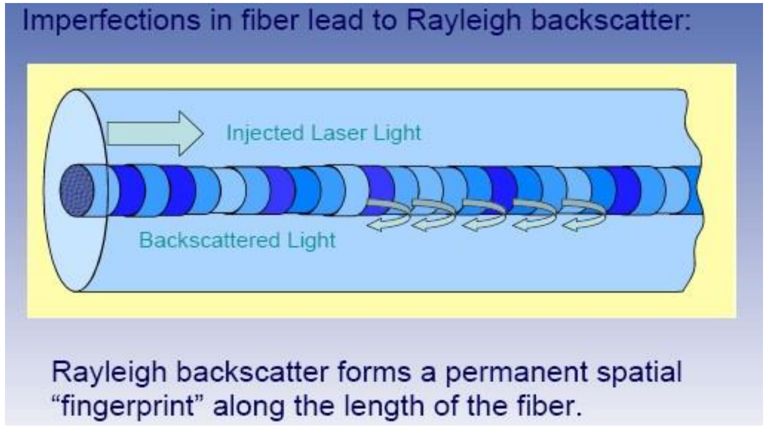
Project Period: 04/2021-04/2024

Approach: Optical Fiber Sensors

Sensing Principle : Evanescent Wave Sensors



Distributed Sensing Capability

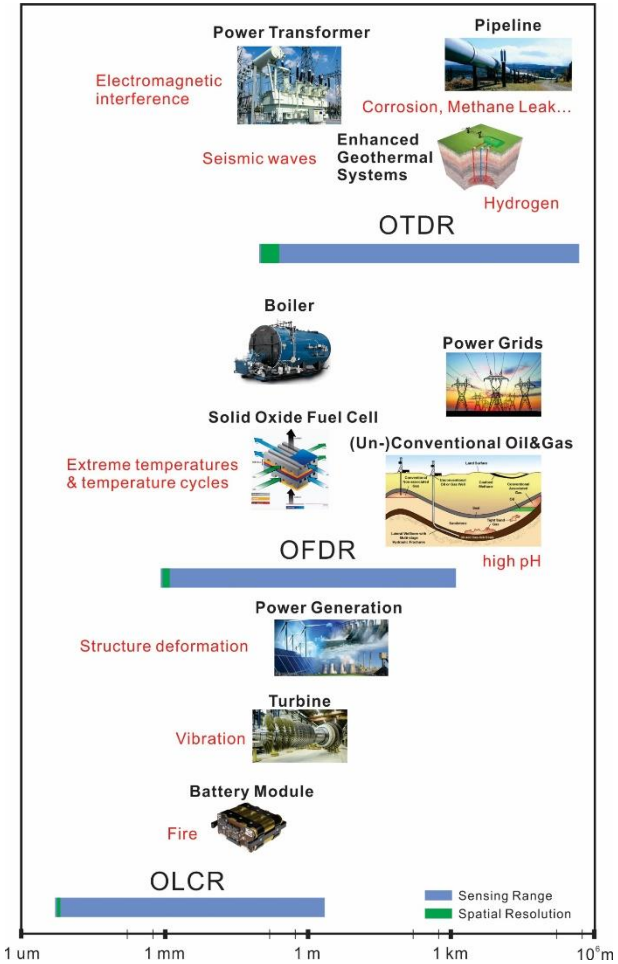


Advantages of Optical Fiber Sensors (OFS)

- **Improved safety** in the presence of flammable gases compared to electrical based sensors
- **Stable** in subsurface harsh environments
- Small size and flexibility
- Long reach, light weight
- Can be **functionalized** for targeted parameters through functional materials
- Compatible with **distributed or multi-parameter** interrogation.

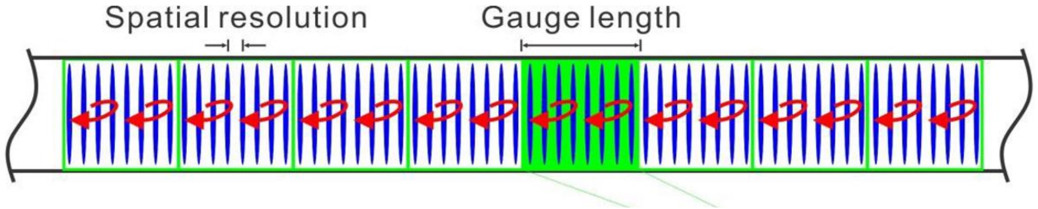
Need functional sensitive materials that enable H_2, CH_4, and geochemical sensing (e.g. pH and corrosion), which are compatible with high pressure high temperature and humid conditions in harsh subsurface conditions.

NETL Capability in Distributed Optical Fiber Interrogator Development

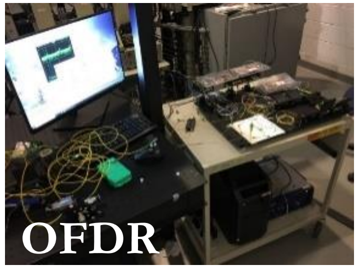


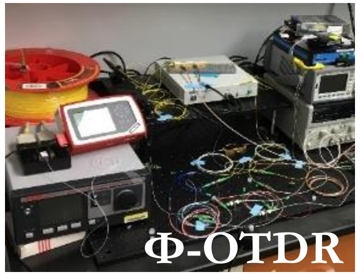
Ref: Lu et al, Appl. Phys. Rev. 6, 041302 (2019)

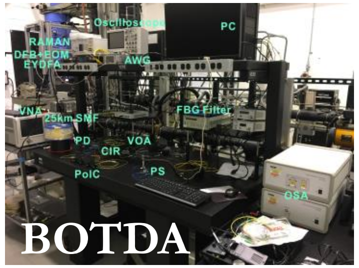
In-House NETL Distributed Optical Fiber Sensor Interrogators



Technology	Sensing Range	Spatial Resolution	Measurement Time	Fiber Type	Sensing Performance
Coherent Rayleigh OFDR	m – km	mm – cm	seconds	SMF	Temperature, strain, vibration, chemical sensing
Coherent Rayleigh OTDR	km	m	seconds	SMF	Acoustic wave, vibration
Brillouin OTDR/BOTDA	> 100 km	cm – m	minutes	SMF	Temperature, strain,







Multiple distributed optical fiber sensing platforms have been developed to enable monitoring of pipelines and wellbores, particularly for structural health monitoring and gas leak detection.

Subsurface Hydrogen Storage Conditions

High-Pressure High-Temperature (HPHT), Humidity, Mixed Gas, and Dissolved Solids

- Stable at ~80°C and ~1000 psi (up to 4000 psi)
- Hydrogen concentration: 5% to 100%
- Capable of surviving mechanical insertion into high pressure wellbore
- Microbially active environments
- pH ranging from ~4 -10
- High humidity environments
- Sensors must be compatible with mixed $CH_4/CO_2/H_2/H_2O$ conditions.

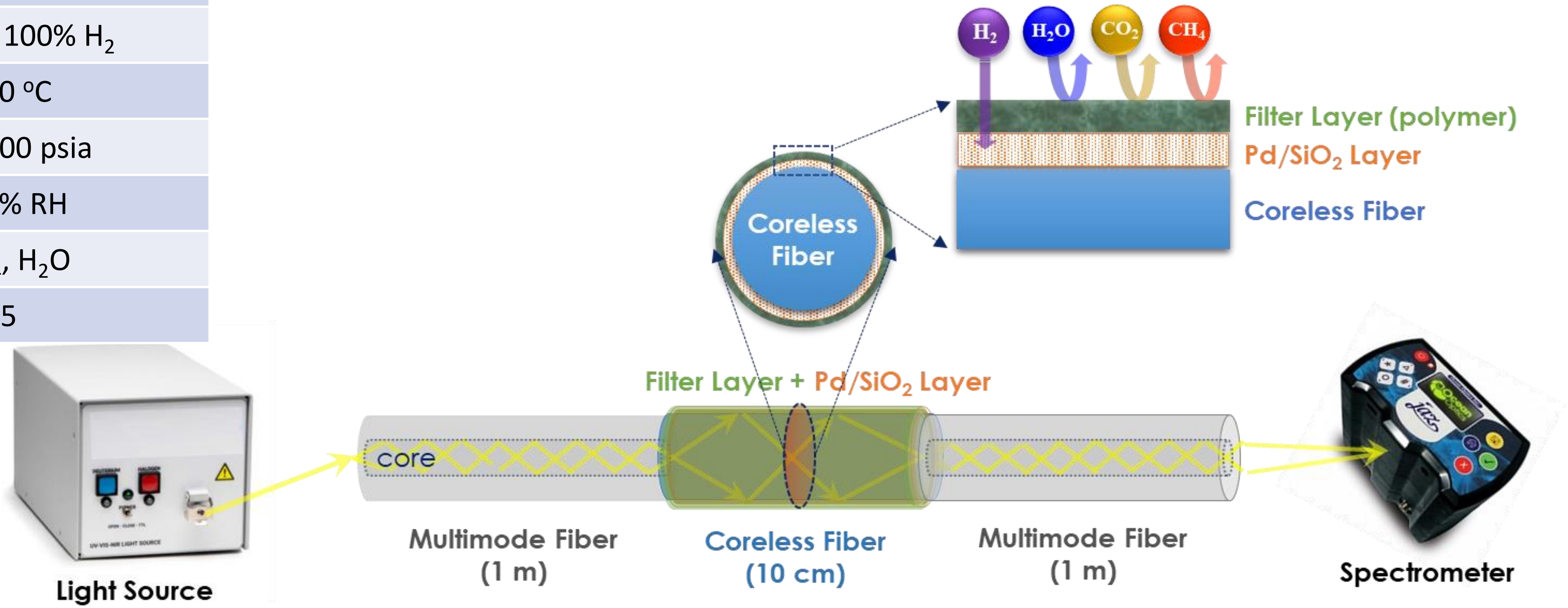
Application	Depth	Average Temperature	Pressure	pH Range	Dissolved Solids	Common Ions
H_2 and H_2/CH_4 Blend Storage	200-2000 m	25-100 °C	5-30 MPa	4-9.5	10,000-70,000 mg/L	Sulfides, CO_2/Carbonate, Cl^-, Na^+, K^+, H_3O^+, Ca^{2+}, Mg^{2+}, Ba^{2+}, Sr^{2+}, $Fe^{II/III}$

(Goodman Hanson et al., 2022; Bérest, 2019;Tarkowski, 2019; Zivar et al., 2021; Muhammed et al., 2022; Pannekens et al., 2019)

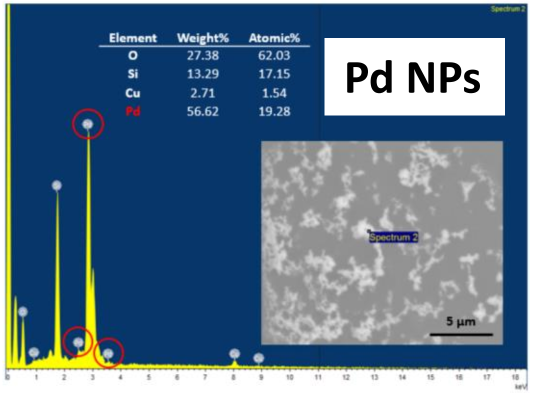
Lack of existing hydrogen sensors compatible with HPHT.

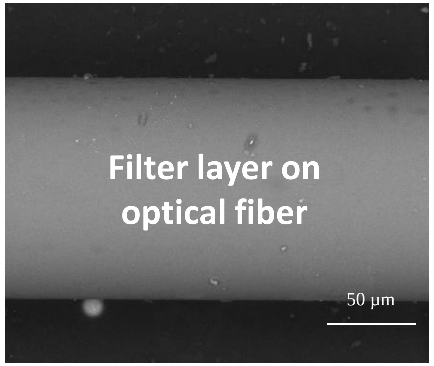
Progress: Optical Fiber H_2 Sensor

Hydrogen Sensor Performance Specifications	
Measurements	Light transmission based
Concentration	100 ppm to 100% H_2
Temperature	20 to 80 °C
Pressure	14.7 to 1000 psia
Humidity	0 to 100% RH
Comparability	CO_2, CH_4, H_2O
Current TRL	4 to 5

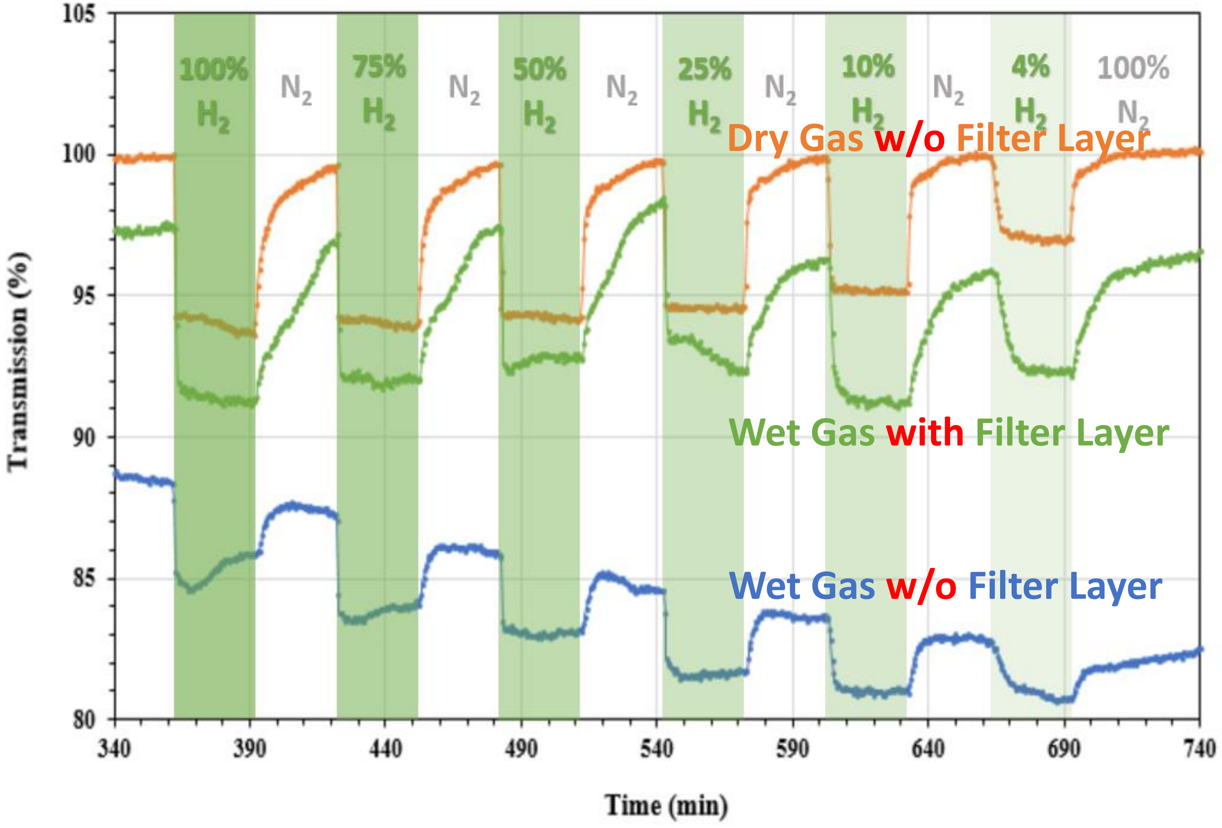


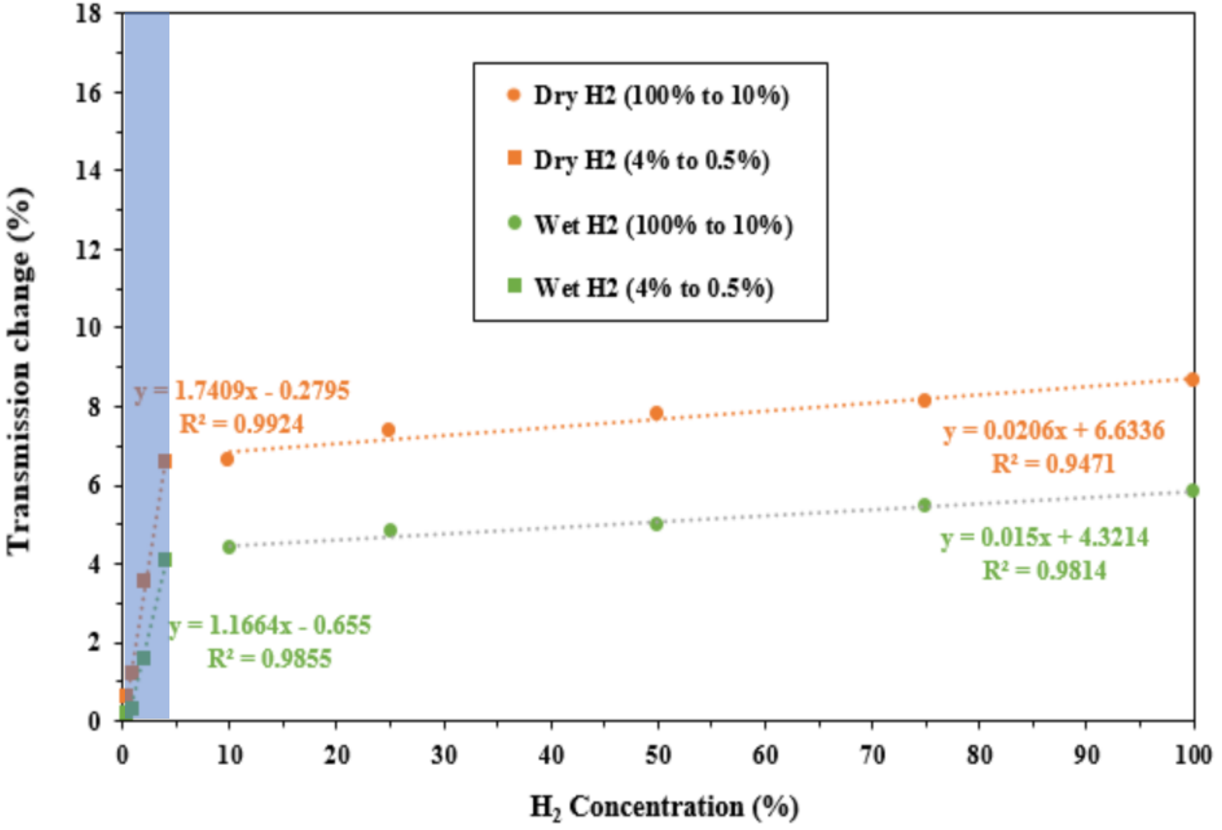
- Pd nanoparticle (NP) incorporated SiO_2 coated optical fiber sensor was developed for H_2 sensing.
- A new filter layer was overcoated on the sensing layer to increase selectivity and mitigate humidity interference.





Optical fiber H_2 sensor under humid conditions





- The new filter layer has significantly mitigated humidity effect on hydrogen sensing.
- H_2 sensing calibration plots under humidity conditions were obtained for a wide range of 0.5% to 100%.

Optical fiber H_2 sensor has no cross-sensitivity to CO_2 and CH_4

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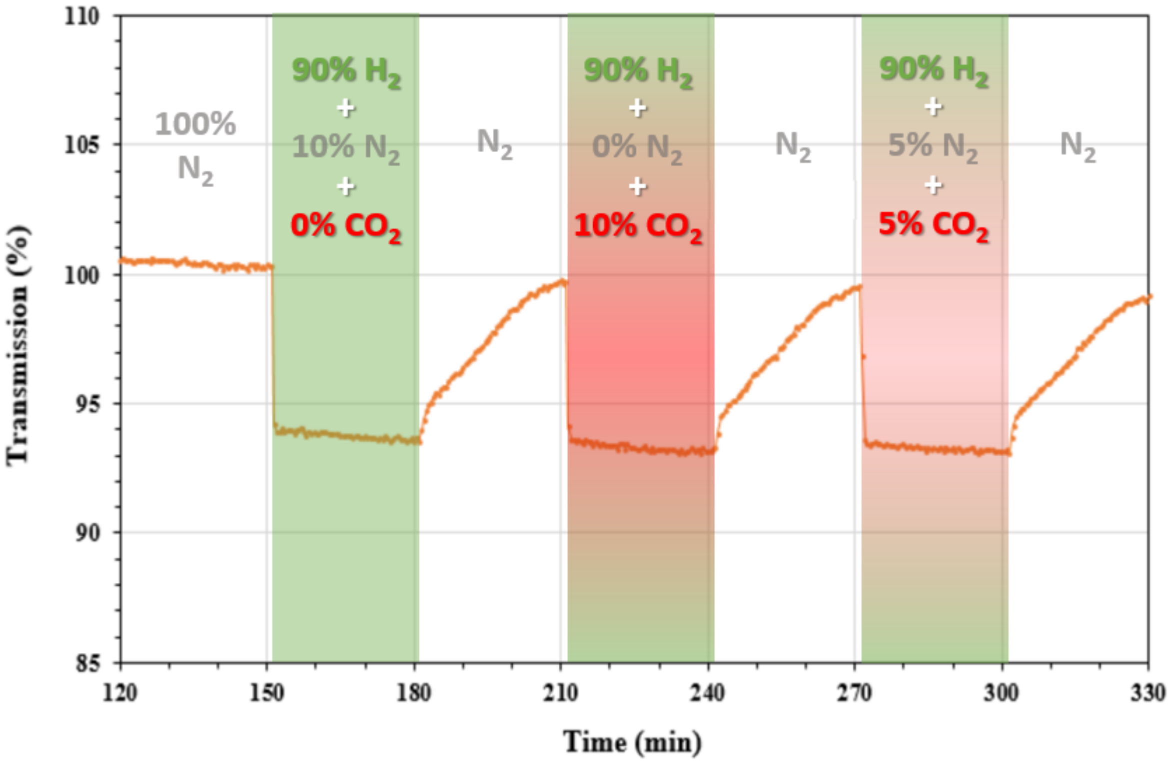
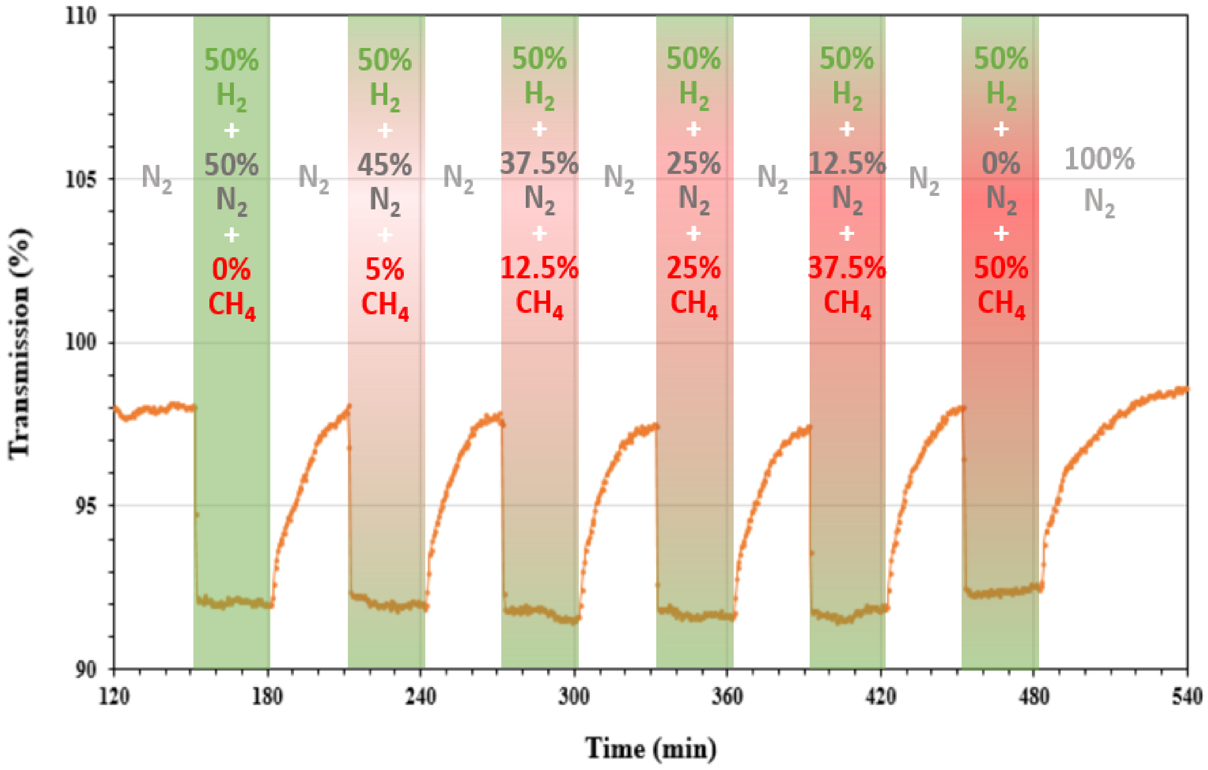
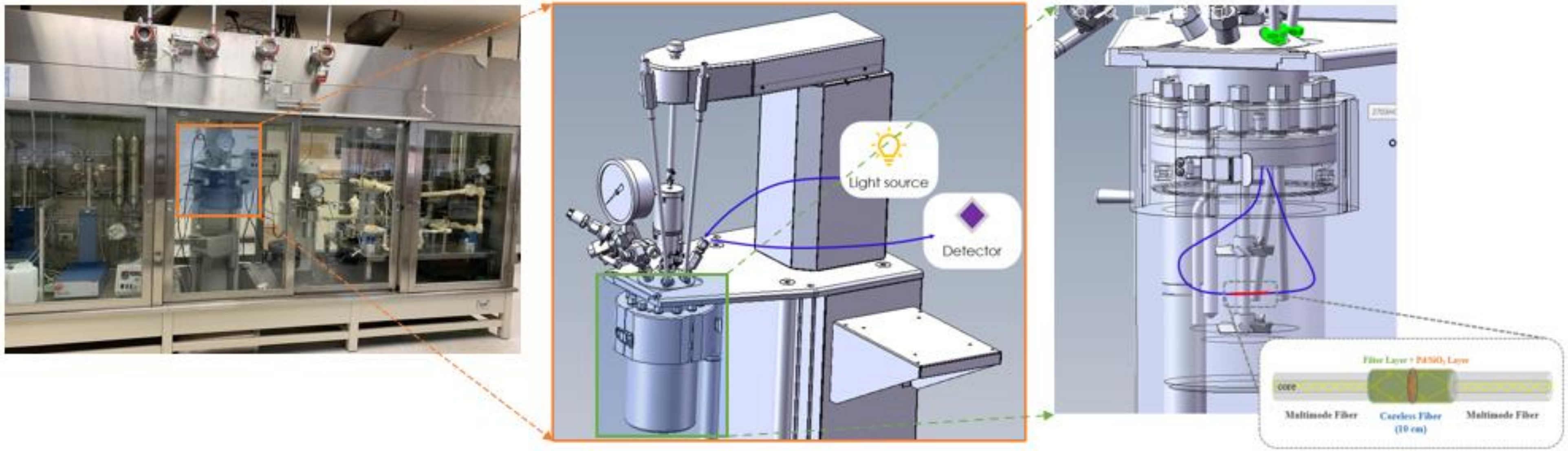




- In order to guarantee a minimum reservoir pressure, the reservoir is filled with a **cushion gas** such as CO_2, N_2, or possibly NG.
- Under 99% relative humidity, the optical fiber H_2 sensor with the filter layer has shown negligible effects from CO_2 or CH_4.

Sensor Tests in Simulated HPHT wellbore conditions with Microbial Samples

Subsurface Sensor Development Reactor (SSDR)



T: 80 °C; P: ~850-1000 psi.

SSDR capability:

Automation with LabView: Batch and Flow-through Modes;

High-Temperature High-Pressure (HTHP): up to 450 °C, 4500 psi;

Multi-phase: aqueous, gas, supercritical;

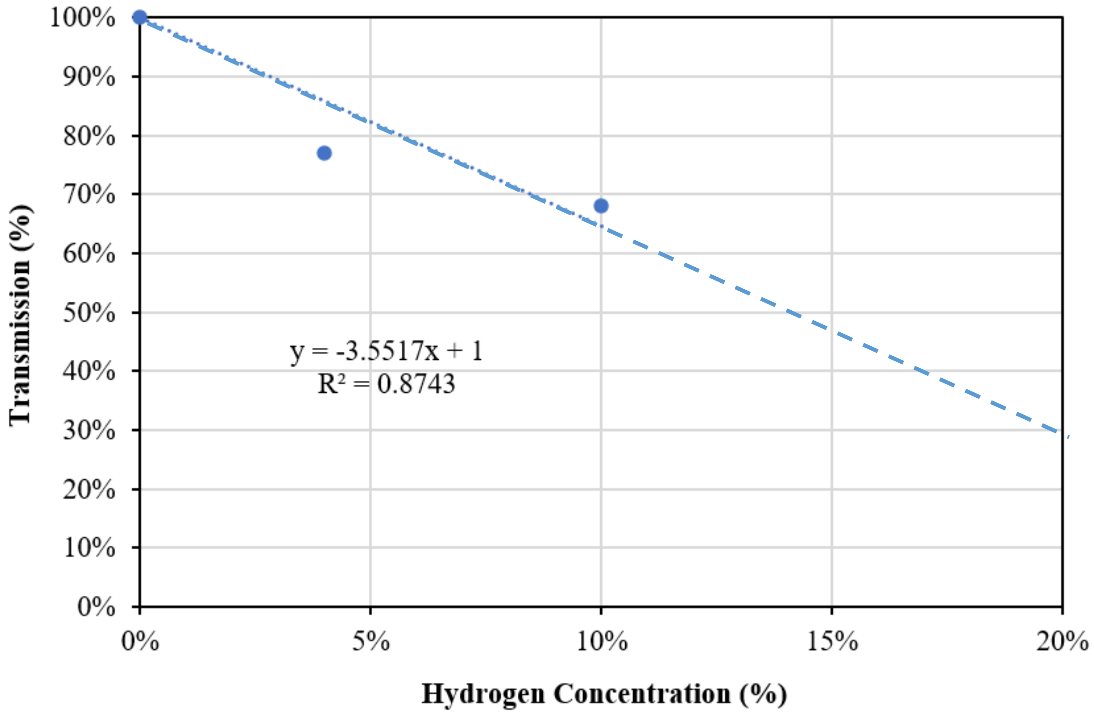
Gas: H_2, CO_2, CH_4, N_2, Air, H_2S.

Type	Liquid Phase	Gas Phase	Days
Control	DI	CH_4 or 80/20 CH_4/H_2	3
Abiotic:CH4	Filtered PDR	CH_4	1,3,7
Biotic: CH4	Unfiltered PDR	CH_4	1,3,7
Abiotic:H2+ CH4	Filtered PDR	80/20 CH_4/H_2	1,3,7
Biotic: H2+ CH4	Unfiltered PDR	80/20 CH_4/H_2	1,3,7

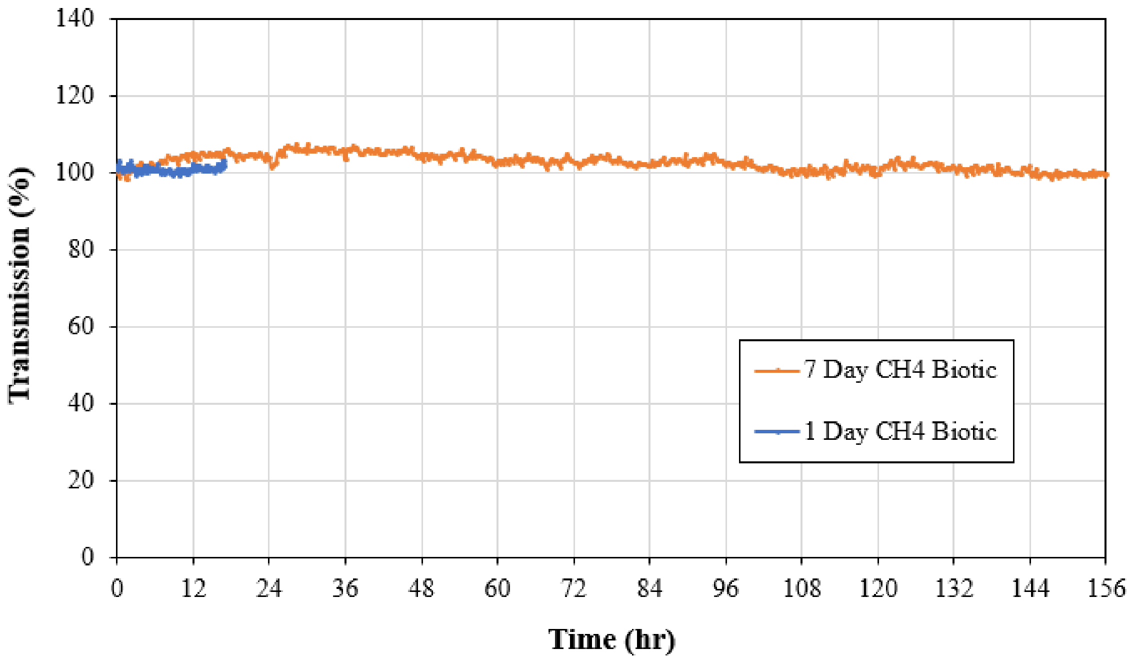
PDR = Playa Del Rey wellbore fluid provided by SoCalGas

Hydrogen Sensing Results in HTHP Microbial Tests

Calibration Plot at 80 °C, 1000 psi



Example: 100% CH4 Biotic condition



- Calibration plot of hydrogen sensor at 80 °C, 1000 psi. More data are needed for wider range calibration.
- Decrease of light transmission indicates increase in hydrogen concentration.
- No hydrogen concentration changes were detected in 100% CH4 biotic conditions.

Real-time Hydrogen Concentration Monitoring

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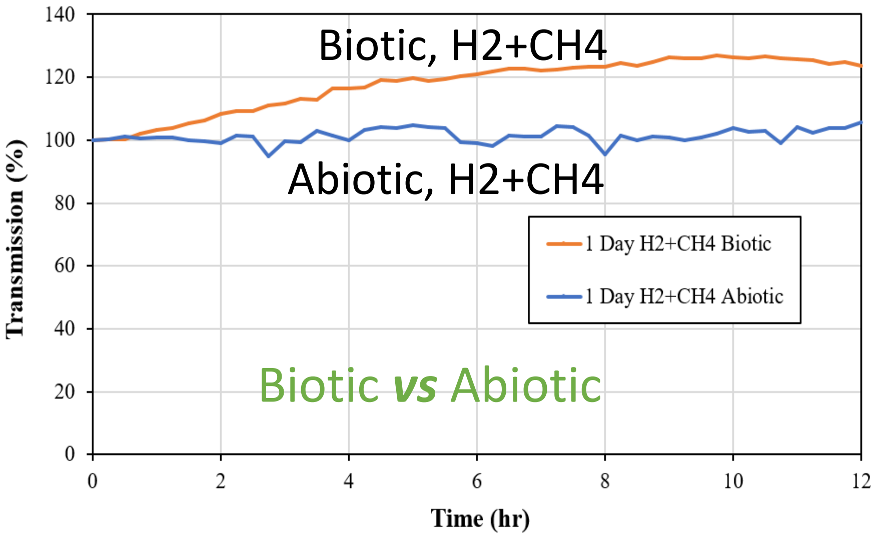
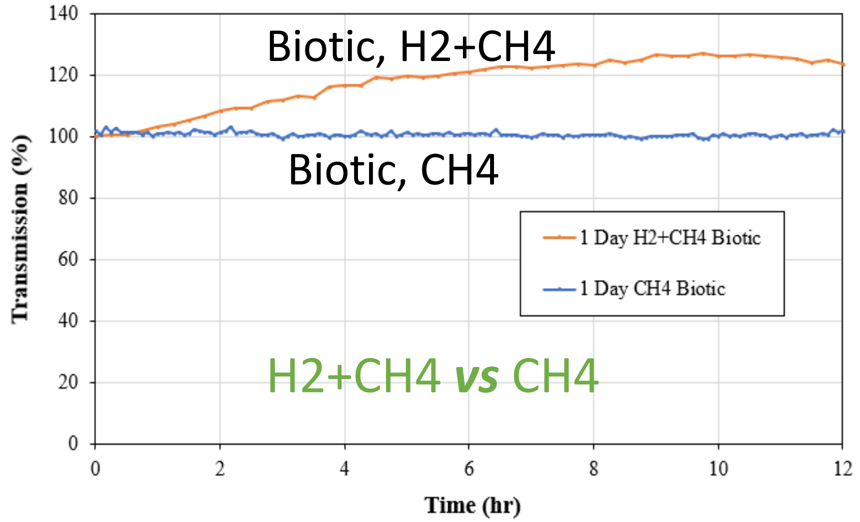
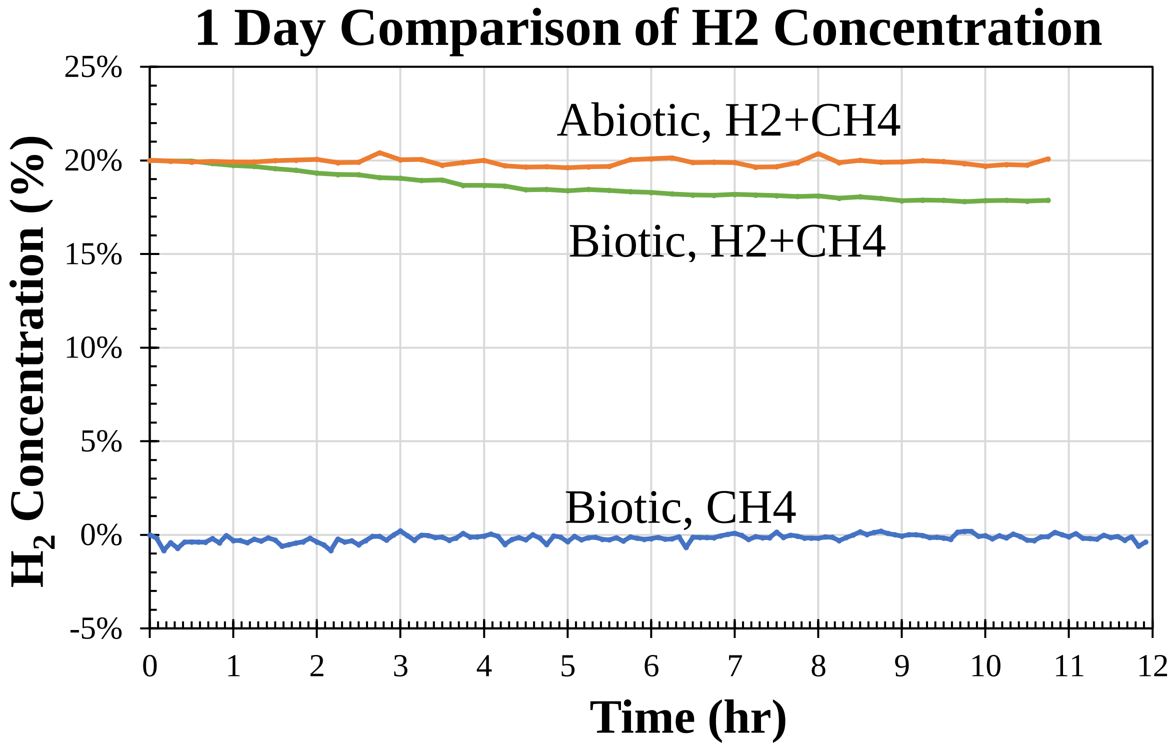
Light Transmission Measurements

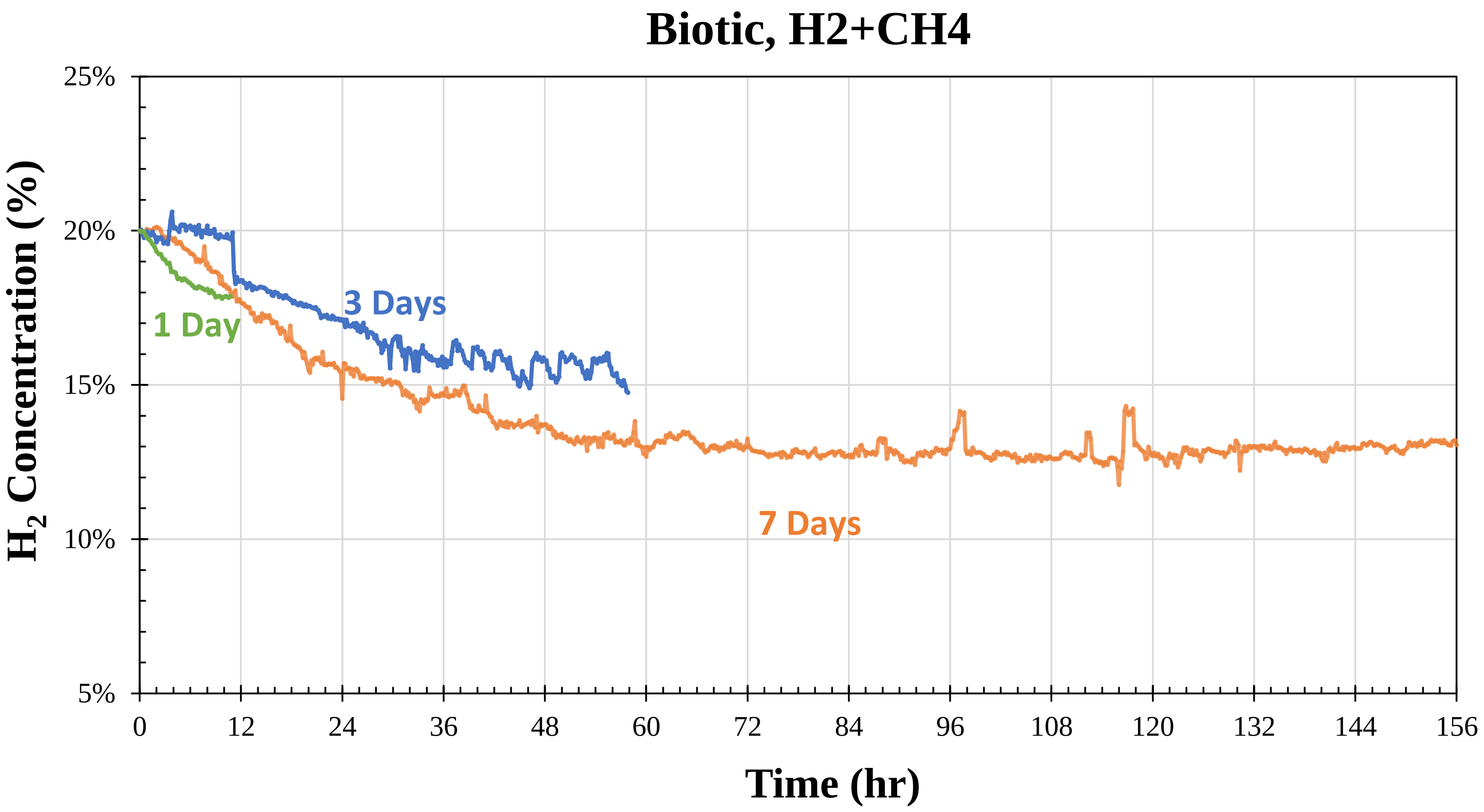






- In biotic conditions, optical fiber hydrogen sensor detected decrease in hydrogen concentration by 2% in 11 hours in H2+CH4 blend.
- The sensor didn't detect hydrogen concentration change in abiotic or pure CH_4 conditions.

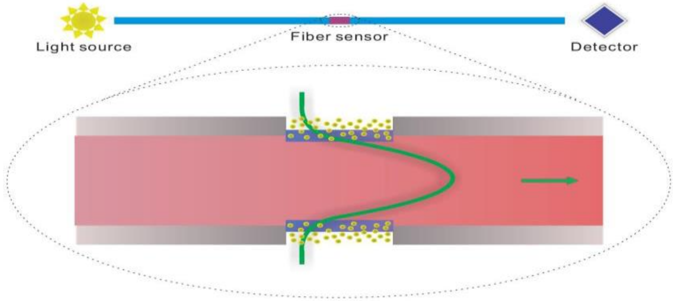
Real-time Hydrogen Concentration Monitoring



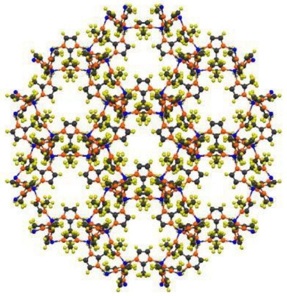
- ➢ The optical fiber H_2 sensor has demonstrated real-time H_2 sensing in simulated subsurface H_2 storage condition with microbes.
- ➢ According to the optical fiber hydrogen sensor, the hydrogen concentration seems to reach a steady state after 48 hours (decrease by 5-7%). The results here can benefit from duplicates to confirm repeatability.

Optical Fiber Methane Sensing

Functional Sensing Layer Integrated Fiber Optic



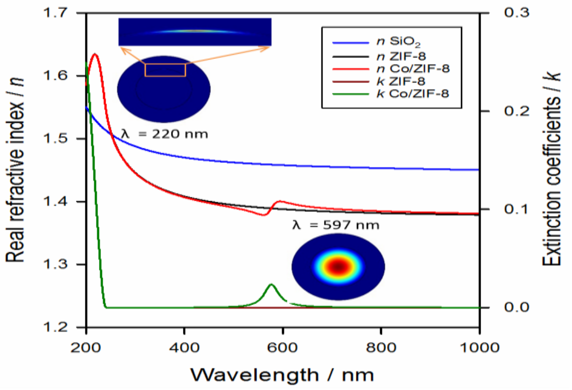
Porous Metal Organic Framework (MOF)



Micro-porous Gas Permeable Polymers

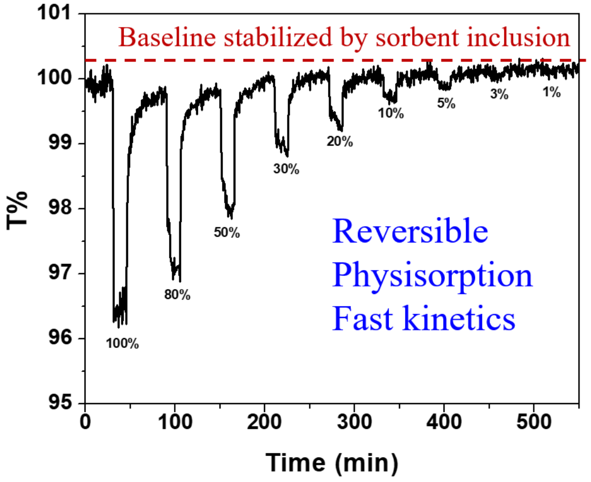
Evanescent Wave Absorption Based Sensors

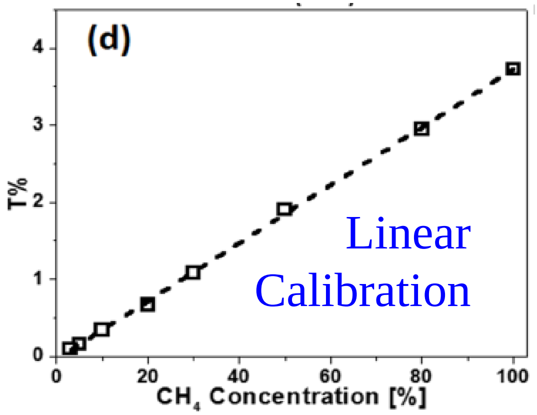
$$I_T(\lambda) = I_0 \exp[-\gamma\alpha(\lambda)CL]$$



Gas adsorption in the sensor coating causes $RI_{(coating)} > RI_{(fiber)}$, inducing optical power changes.

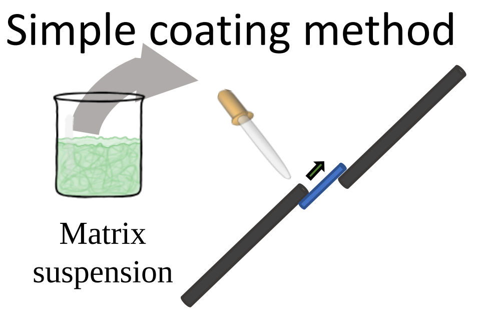
Ref: Kim et al, ACS Sensors, 2018, 3, 386-394.

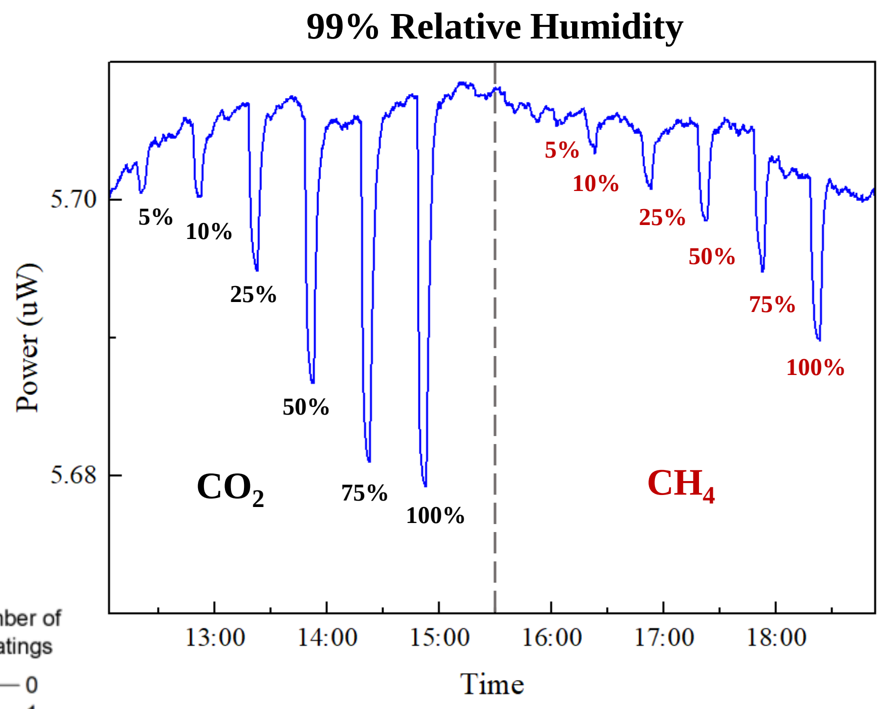


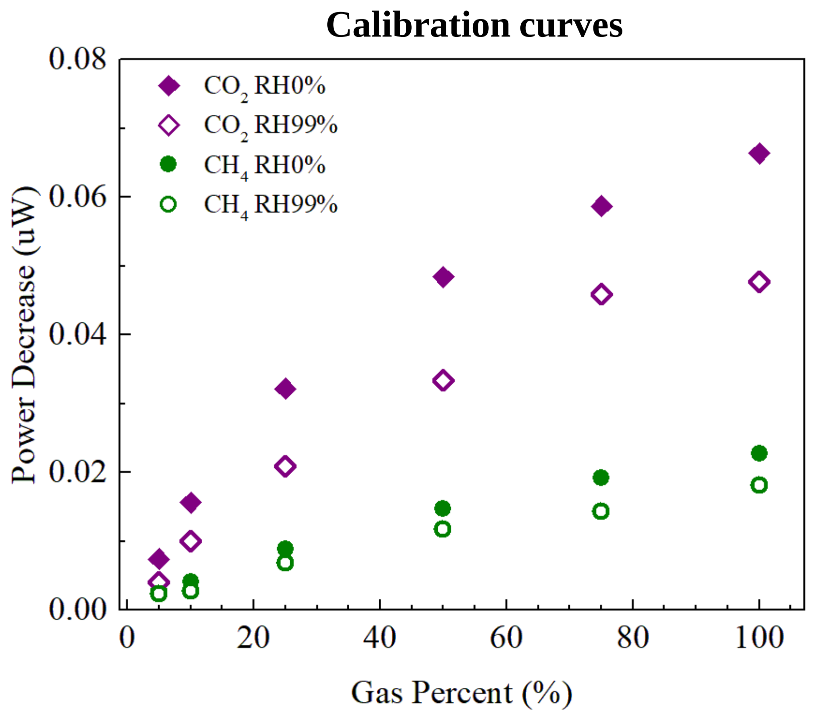


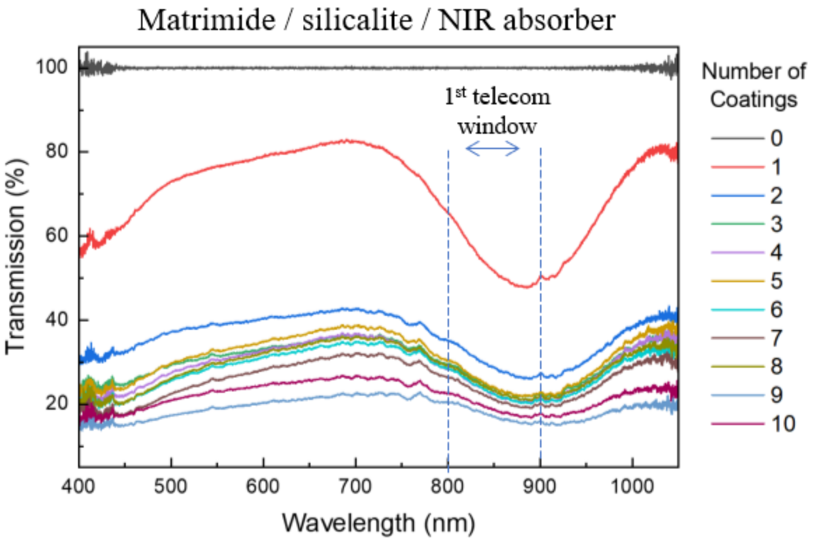
Light Intensity Based Methane Sensing Technology. Integration of Fiber Optic Sensors with Engineered Porous Sensing Layers by Design.

Optical fiber CH_4 sensor under humid conditions







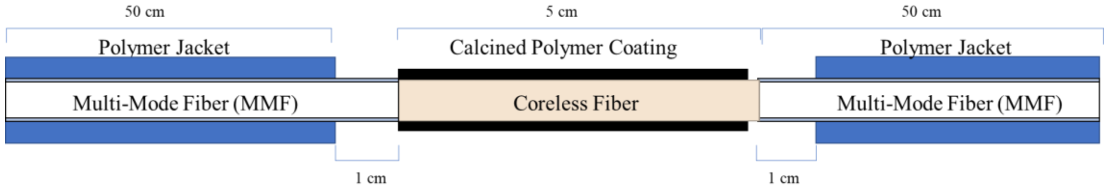


- Successful demonstration of optical fiber methane sensor in humid conditions at 99% relative humidity (RH)
- Tuned the wavelength to NIR range to be readily compatible with commonly used distributed OFS interrogators.
- Fast response time.
- Calibration curve of CO_2 and CH_4 from 5% to 100%.

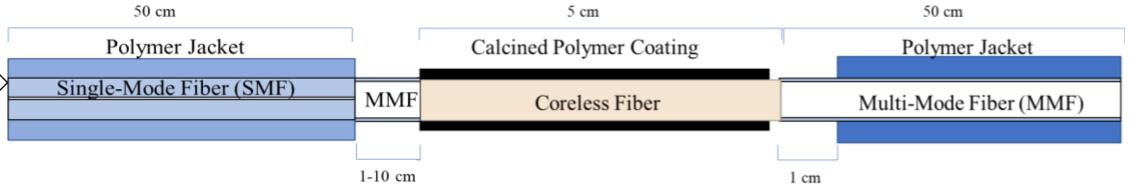
Optical Fiber pH Sensor

pH Sensing Measurements:

Transmission Based Sensor

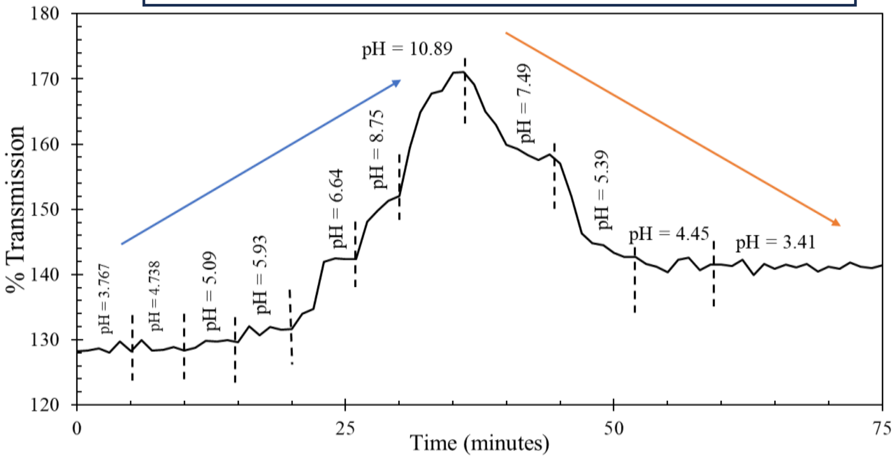


Optical Backscatter Reflectometry Sensor

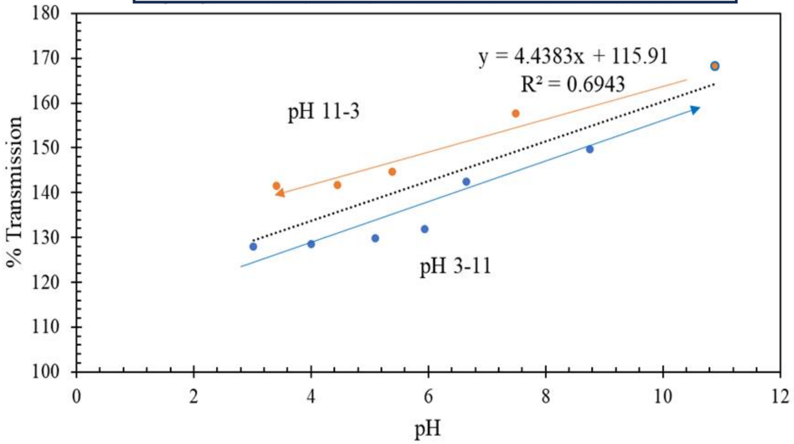


Transmission pH Sensing Results at 20 ^oC and 80 ^oC

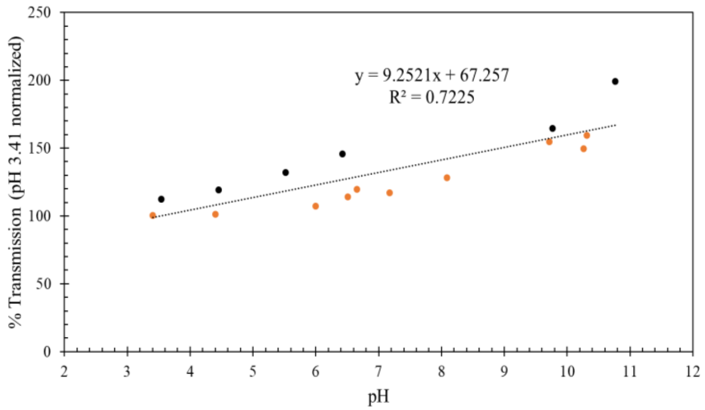
20 ^oC, dynamic pH sensing



20 ^oC pH calibration

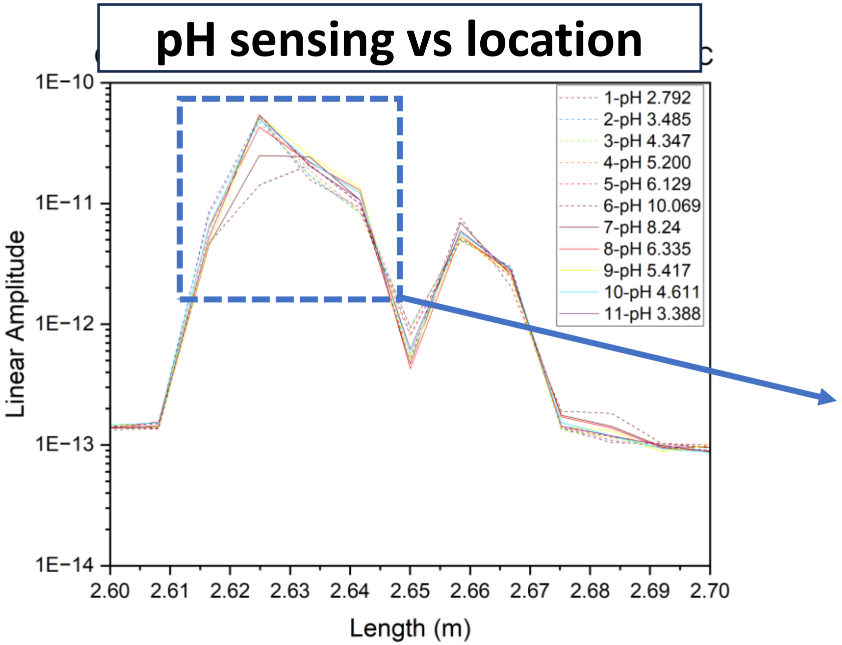


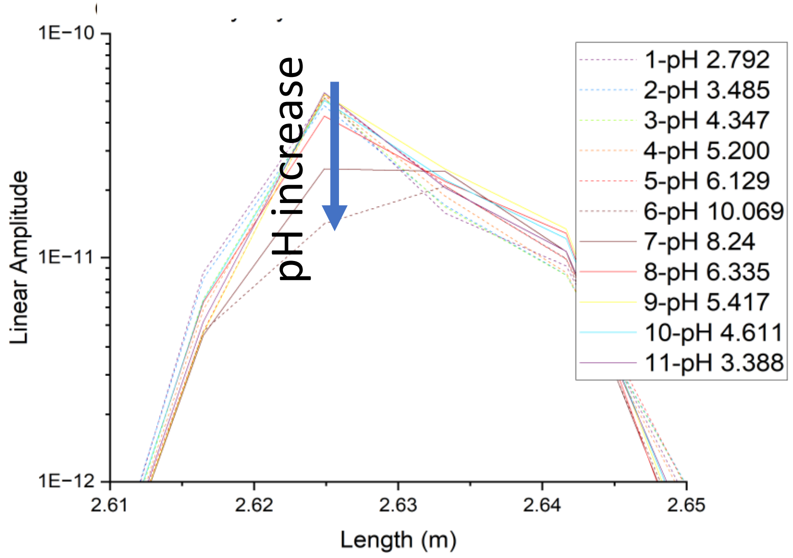
80 ^oC pH calibration



A new pH sensitive layer has showed reversible acid and base responses.

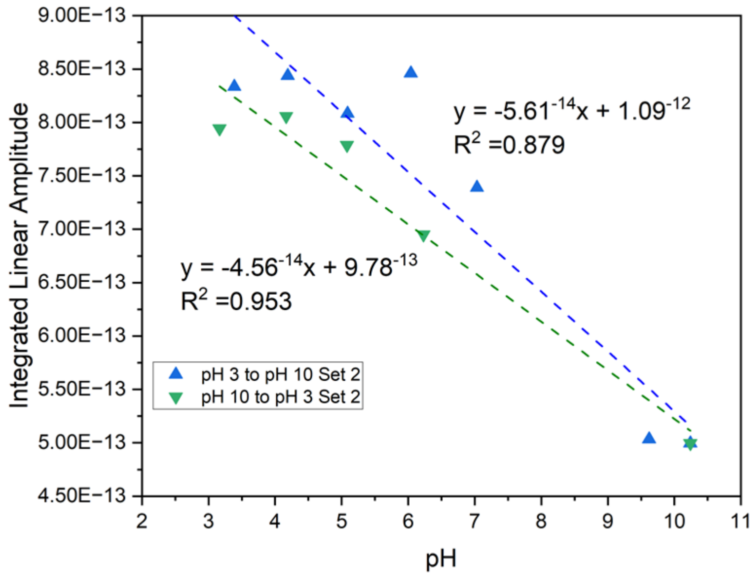
Distributed pH sensor results





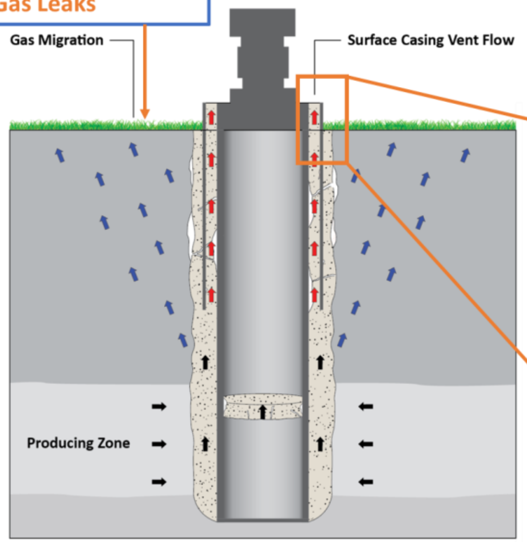
pH Sensor Performance Specifications	
Mechanism	Transmission/Backscattered light
pH Range	2-12
Temperature	20 to 80 ◦C
Pressure	14.7 to 1000 psia
Compatibility	NaCl, Citrate, Carbonate, H_2, CH_4
Current TRL	5 to 6

- Successfully demonstrated distributed pH sensing at 80 ºC and obtained calibration.
- Backscattered light decreases as pH increases, opposite of transmitted light.

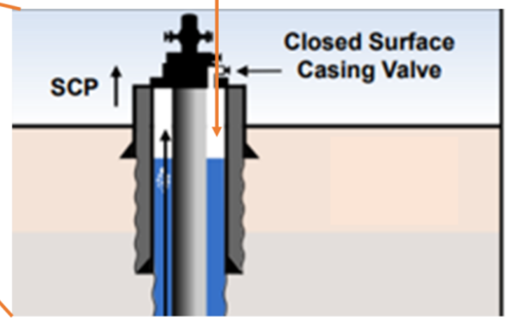


Technology Maturation and Wellbore Deployment Plan

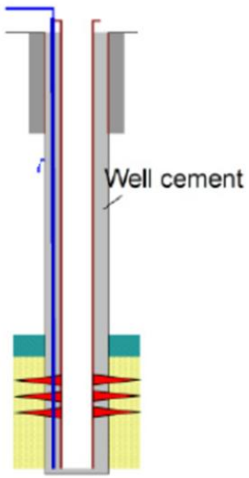
1. Optical Fiber Gas Sensor above the Well Surface to Detect Gas Leaks



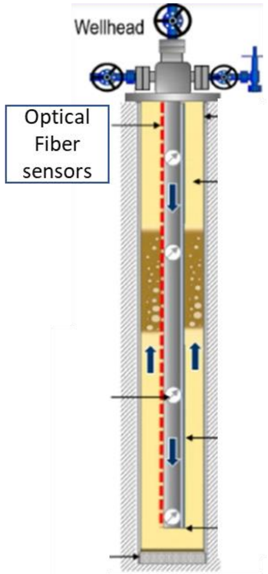
2. Optical Fiber Sensor in Surface Casing Annulus to Monitor Well Integrity and Gas Leaks



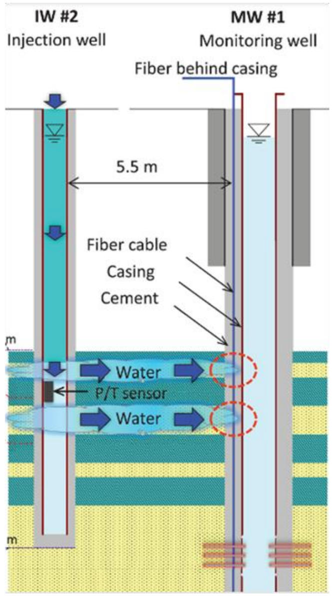
3.1. Optical Fiber Sensor installed in cement / behind the casing



3.2. Optical Fiber Sensor clamped to the injection tubing



3.3. Optical Fiber Sensor installed in the monitoring well



- Sensor Optimization and Ruggedization
- Comprehensive sensor Calibration at HTHP

- Wellbore Deployment Locations and Methods
- Sensor Validation in Test Wellbore with Controlled Conditions

Accomplishments and Future Plans

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➢ Accomplishments

- Pd nanoparticle (NP) incorporated SiO_2 coated optical fiber H_2 sensor was demonstrated for a wide range of hydrogen sensing from 0.5% to 100 %. A new filter layer was developed to increase selectivity and mitigate humidity interference. Negligible cross-sensitivity from common cushion gas CO_2 or CH_4.
- The optical fiber H_2 sensor has demonstrated real-time H_2 sensing in simulated subsurface conditions with microbes (80 ^{o}C, 1000 psi), and detected hydrogen concentration change ***in situ and in real time***.
- Successful demonstration of optical fiber methane sensor in humid conditions at 99% relative humidity.
- Successfully demonstrated a new pH sensing material with reversible acid and alkaline pH sensing, and distributed pH sensing at 80 ^{o}C
- Developed Technology Maturation and Wellbore Deployment Plan.

➢ Future Plans for Sensor Development and Testing

	PHASE I			Proposed PHASE II		
	EY 21	EY 22	EY 23	EY 24	EY 25	EY 26+
SHASTA: Subsurface Storage	Room temperature and ambient pressure	Humid, mixed gas conditions	High pressure, high temperature conditions	Sensor calibration for a wider range. Sensor Packaging	Field demonstration in a Test Well	Pilot-scale Field Demonstration

Publications and Patents

Publications

- D. Kim, K.K. Bullard, A. Shumski, R. Wright, Optical Fiber Sensor with a Hydrophobic Filter Layer for Monitoring Hydrogen under Humid Conditions, ACS Sensors, manuscript draft completed, to be submitted in 2024.
- A presentation and a conference paper: "Calcined Polyethyleneimine Coated Optical Fibers for Distributed pH Monitoring at High Pressures and Temperatures" authored by Shumski, A., Diemler, N., Wright, R. will be presented at SPIE Defense + Commercial Sensing 2024 conference (April 21-25) **SPIE Defense + Commercial Sensing, 13044-20, 2024.**
- A presentation and a conference paper: "Pd Nanoparticles-Enabled Optical Fiber Hydrogen Sensor with a Hydrophobic Filter Layer for Humid Conditions" authored by Kim, D., Bullard, K., Diemler, N., Wright, R. was presented at SPIE Defense + Commercial Sensing 2023 conference (April 30-May 4) and accepted to *Proc. SPIE 12532*, **SPIE Defense + Commercial Sensing, 12532-3, 2023**.
- A presentation and a conference paper: "TiO_2-Coated Optical Fibers for Distributed pH Monitoring at High Pressures and Temperatures" authored by Shumski, A., Diemler, N., Wuenschell, J., Ohodnicki, P., Wright, R. was presented at SPIE Defense + Commercial Sensing 2023 conference (April 30-May 4) and accepted to *Proc. SPIE 12532*, **SPIE Defense + Commercial Sensing, 12532-22, 2023**.
- A presentation and a conference paper: "Physisorbent-Coated Fiber Optic Sensors for Near Ambient Leak Detection of CH_4 and CO_2" authored by Culp, J., Bullard, K., Kim, K., Wright, R. was presented at SPIE Defense + Commercial Sensing 2023 conference (April 30-May 4) and accepted to *Proc. SPIE 12532*, **SPIE Defense + Commercial Sensing, 12532-8, 2023**.
- Invited presentation "Gas Sensors for Energy Infrastructure Monitoring", Presenter: Ruishu Wright, **Pittcon 2023**, Philadelphia, PA, March 2023.
- A poster was given at **2022 AIChE Annual Meeting** (November 13-18, 2022), titled "Pd-nanoparticle enabled optical fiber hydrogen sensor for subsurface storage conditions" authored by D. Kim, N. Diemler, R. Wright, M.P. Buric, P.R. Ohodnicki.
- A presentation and a conference paper: "TiO_2 Coated Optical Fibers for Distributed Real-Time pH Monitoring in Wellbore Conditions" authored by Shumski, A., Diemler, N., Wright, R., Lu, F., Ohodnicki, P. and Su, Y. was presented at SPIE Defense + Commercial Sensing 2022 conference (April 3-7) and accepted to *Proc. SPIE 12105*, **SPIE Defense + Commercial Sensing** (SI22), **12105-21, 2022**.
- A presentation and a conference paper: "Metallic Film-Coated Optical Fiber Sensor for Corrosion Monitoring at High Pressures," authored by Wright, R.F., Diemler, N., Baltrus, J., Ohodnicki, P.R., Jr., Ziomek-Moroz, M., and Buric, M., was presented at **2022 AMPP Annual Conference + Expo**, March 6-10.

Patents

- U.S. Patent issued. 'Low-cost Fiber Optic Sensor Array for Simultaneous Detection of Multiple Parameters,' inventors: C. Sun, P. Lu, R. F. Wright, P.R. Ohodnicki, Jr., Patent Number: US11268984B2, issued on 2022-03-08.
- "Metal Oxides Enabled Fiber Optic pH Sensor for High temperature High pH Subsurface Environments" invented by F. Lu, R. Wright, P. Lu, P. R. Ohodnicki, U.S. Nonprovisional patent application filed, 2022-04-26. Application Number: 17729511.
- Hydrogen Monitoring under High Humidity Conditions Using the Optical Fiber Hydrogen Sensors Coated with a Hydrophobic Filter Layer, D. Kim, A. Shumski, R. Wright, ROI draft completed.

SAND2024-03798C

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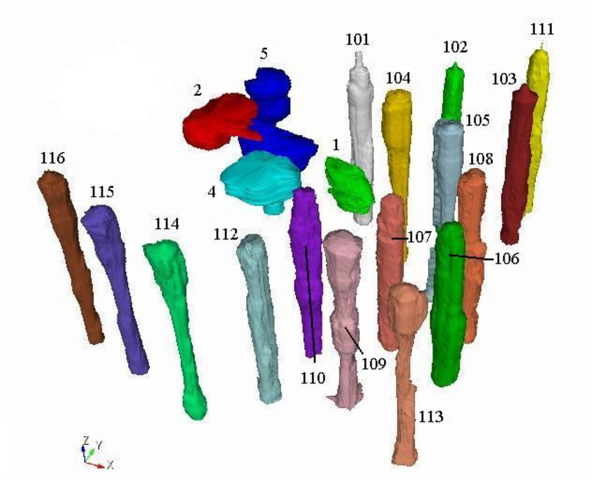
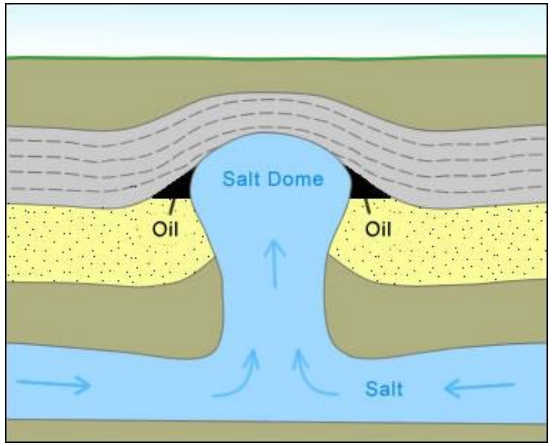
Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Hydrogen Storage in Salt

Mathew Ingraham, Matthew Paul, Barry Roberts – Sandia National Labs

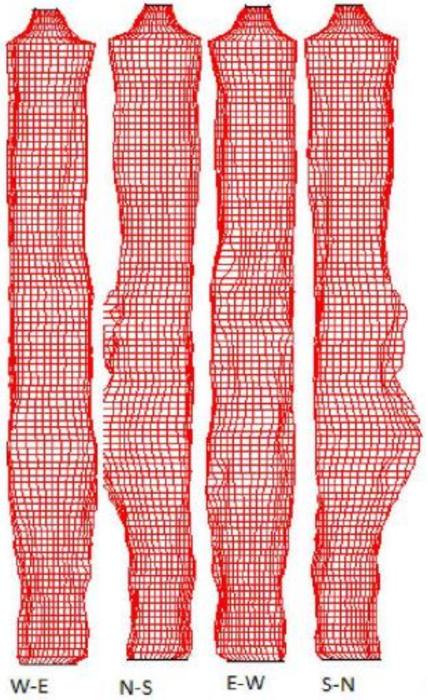
2024 Stakeholder Meeting, April 3, 2024



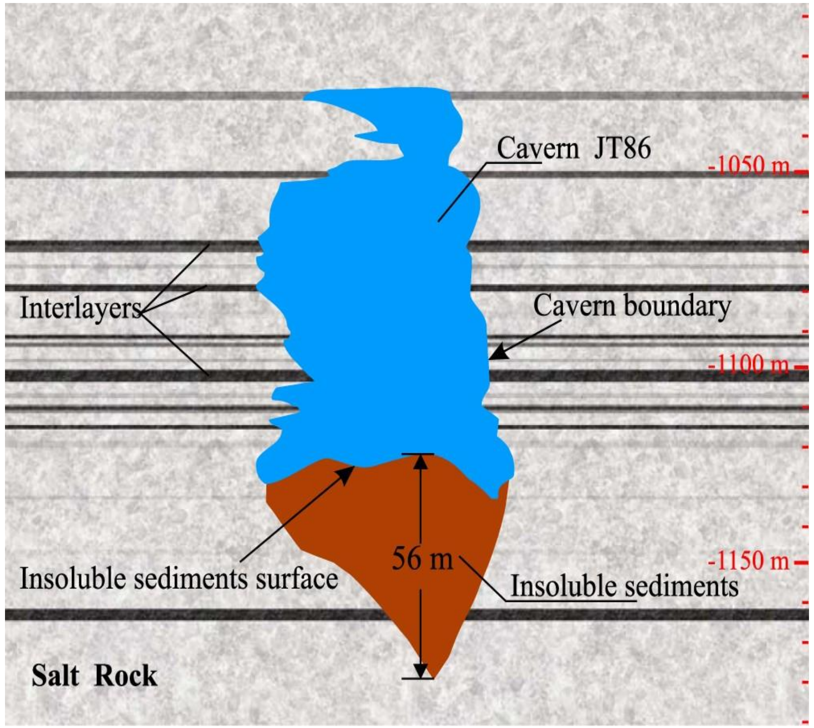


Bedded vs Domal

- Solution mining in domal salts generates much cleaner uniform caverns due to the lack of insoluble interbeds.



Bryan Mound -103 Sonar scans courtesy of S. Sobolik

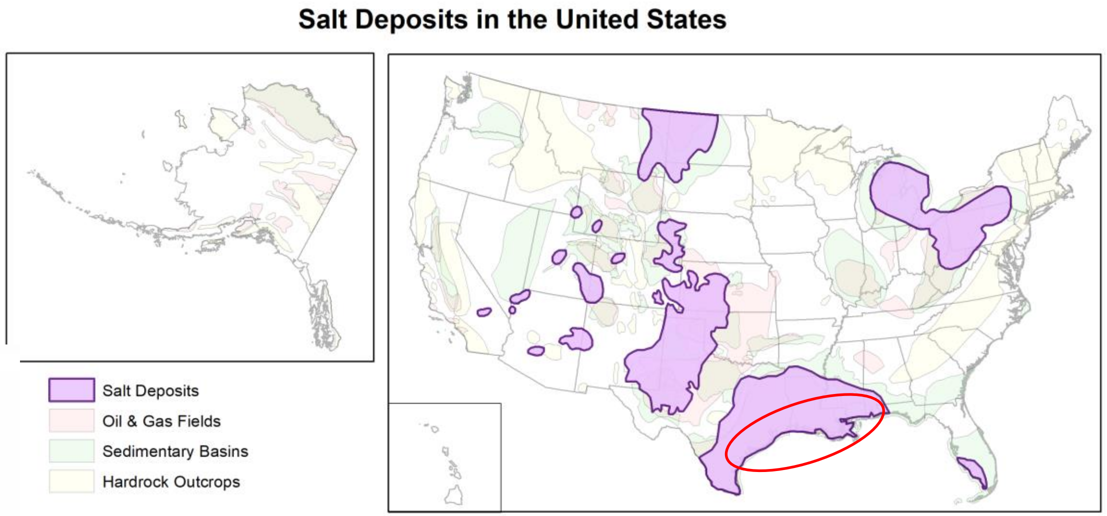


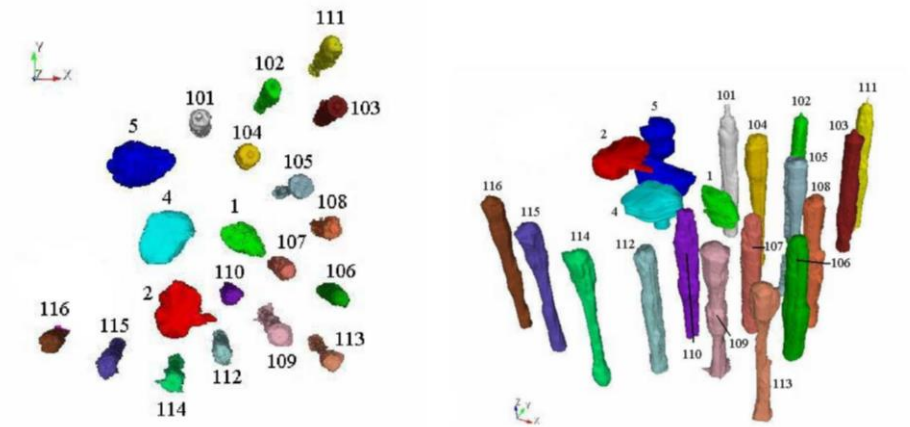
Li, J. et al. (2018). https://doi.org/10.1038/s41598-017-18546-w

Domal Salt

By NASA – Earth Observatory

(Illustration from Los Angeles Department Water and Power)





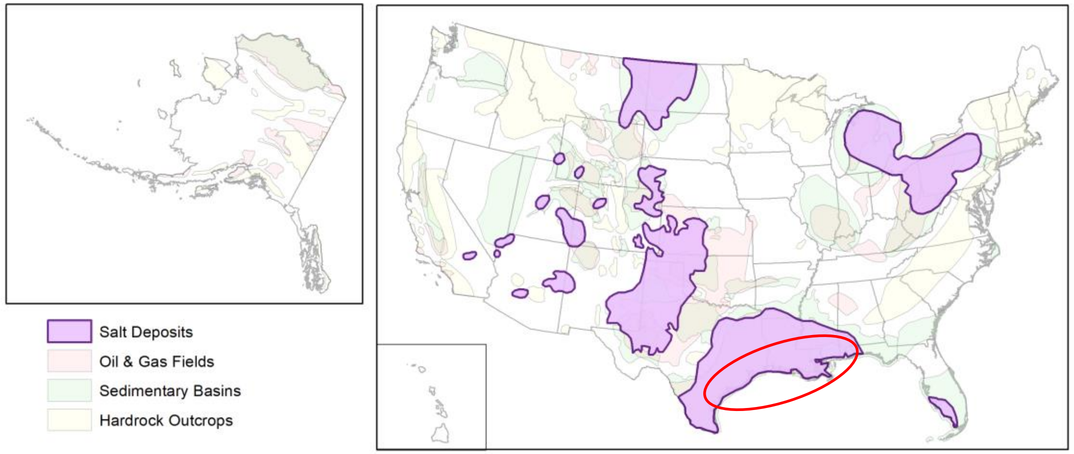
Caverns in Bryan Mound Salt Dome, S. Sobolik

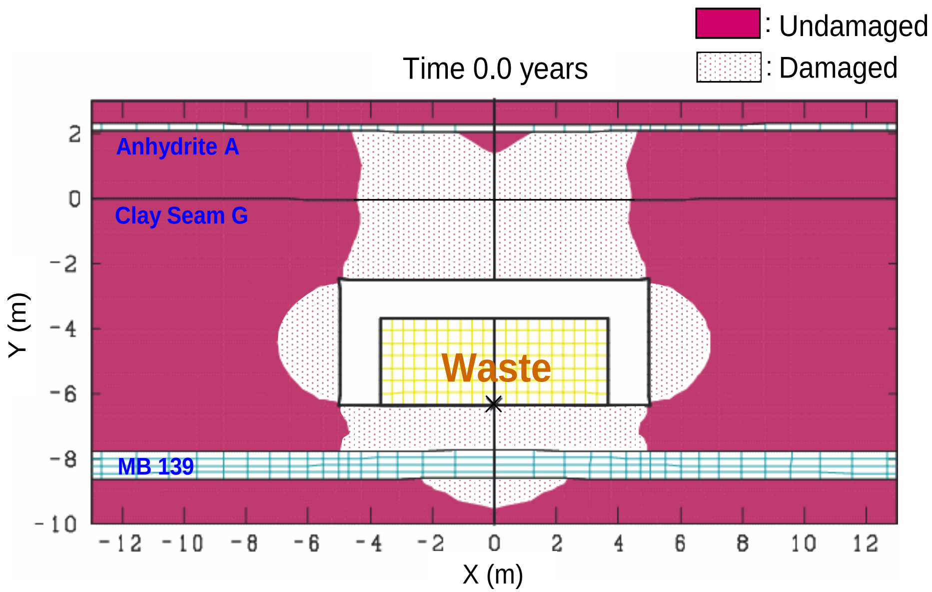
Domal Storage

- Currently 4 Domal H_2 storage locations in the world, 1 UK, 3 US.
- Longest running since 1983
- Privately owned for specific industrial use
- Not setup for deployment of H_2 for power or transportation
- Good track record
- Limited with regards to locations.
- Long term stability, NG and Liquid caverns have been open for 50+ years

Bedded Salt

Salt Deposits in the United States



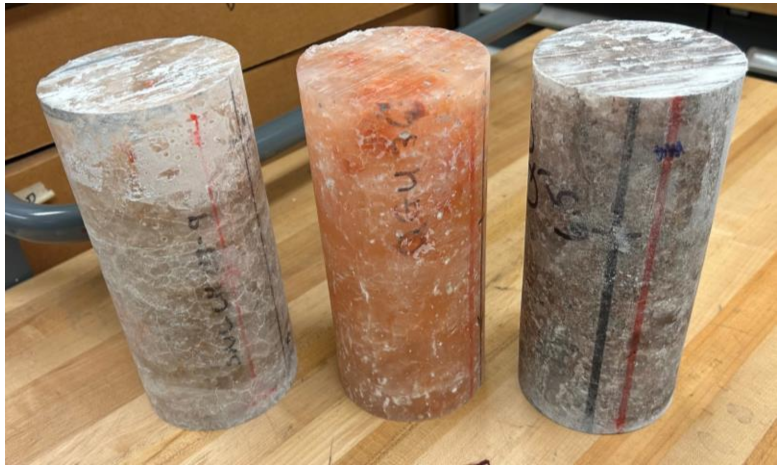


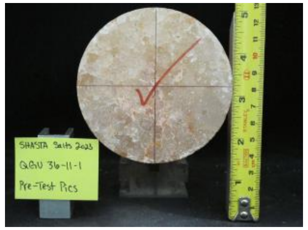
Figures from Herrick et al. 2009

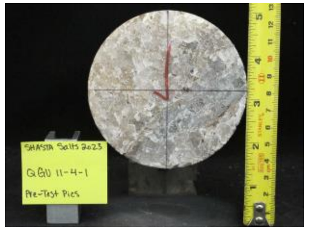
Bedded Storage

- Concerns
  - Cavern Stability
  - Cavern Size/Storage potential
  - Permeability of interbeds
  - Strength of interbeds
  - Relative solubility of interbeds
- Benefits
  - More prevalent
  - Still offers benefits of salt storage, just with some complications
  - Many caverns do exist in bedded salt
  - Significant industrial knowledge on development, but caverns tend to be much smaller than domal salt

Lab Experiments



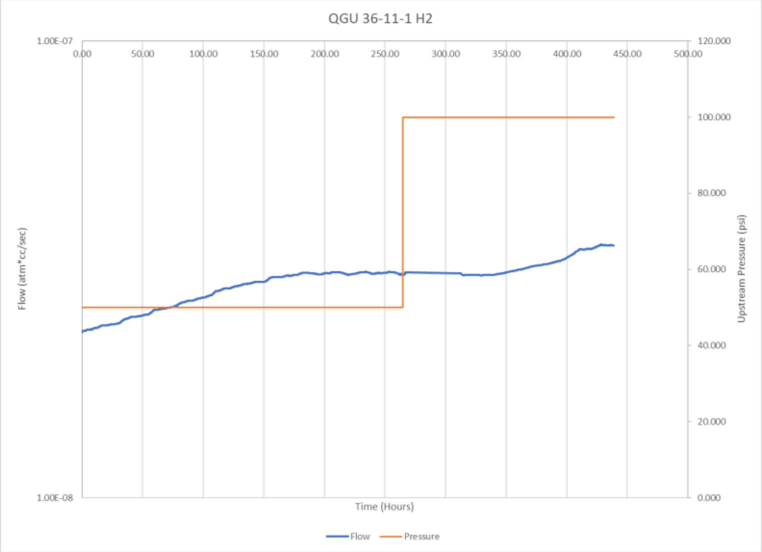




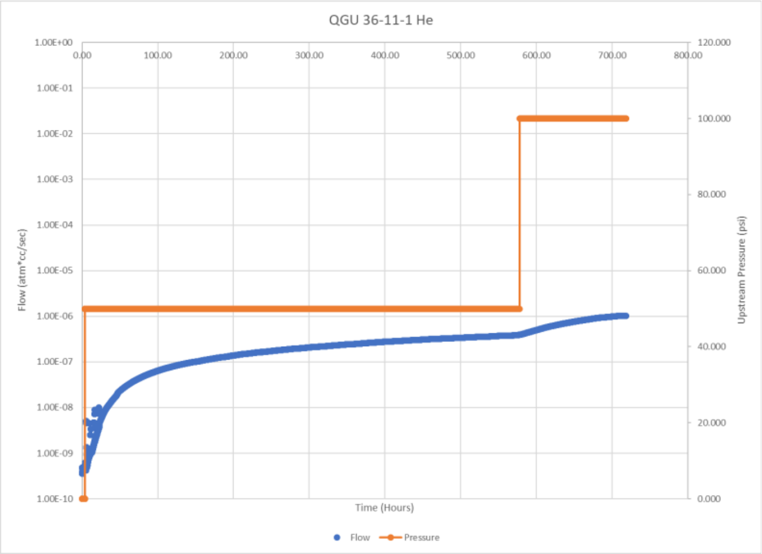
- Clean (95% or more halite)
- Dirty (70% or less halite) selected with clay stringers
- Both tested at 2000 psi confining, 50 degrees C
- He and H2 introduced at 50 psi and 100 psi upstream pressures
- Monitored downstream with leak detector

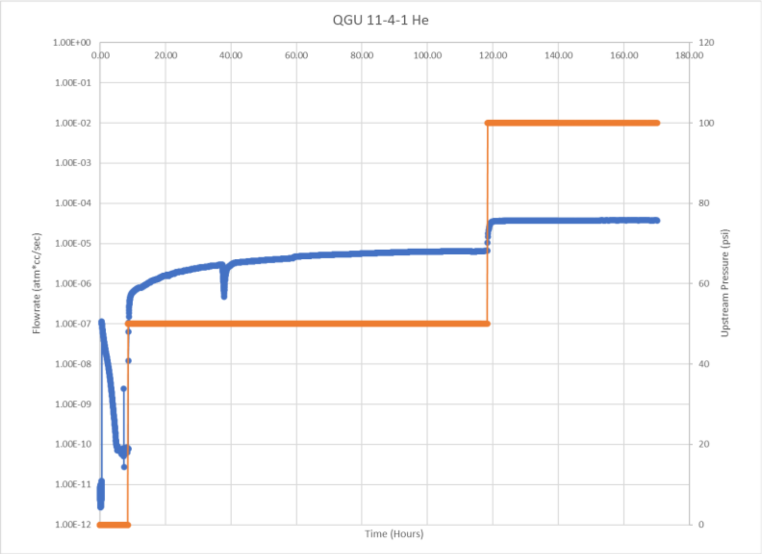
Gas Transport in Salt

- Clean salt
  - Time to reach steady state for He ~300 hours
  - For H2 ~175 Hours
  - Intrinsic perm He (k_∞) – 3.07E-22 m^2
  - Slip correction factor He (b_i) – 1.76E5 Pa
- Dirty Salt
  - Time to reach steady state for He 3.25 hours
  - Intrinsic perm He (k_∞) – 2.34e-20 m^2
  - Slip correction factor He (b_i) - -8.36e4 Pa



$$\dot{N}_i \mu(T) RT \frac{L}{A} = k_\infty \frac{p_{in}^2}{2} + k_\infty b_i p_{in}$$



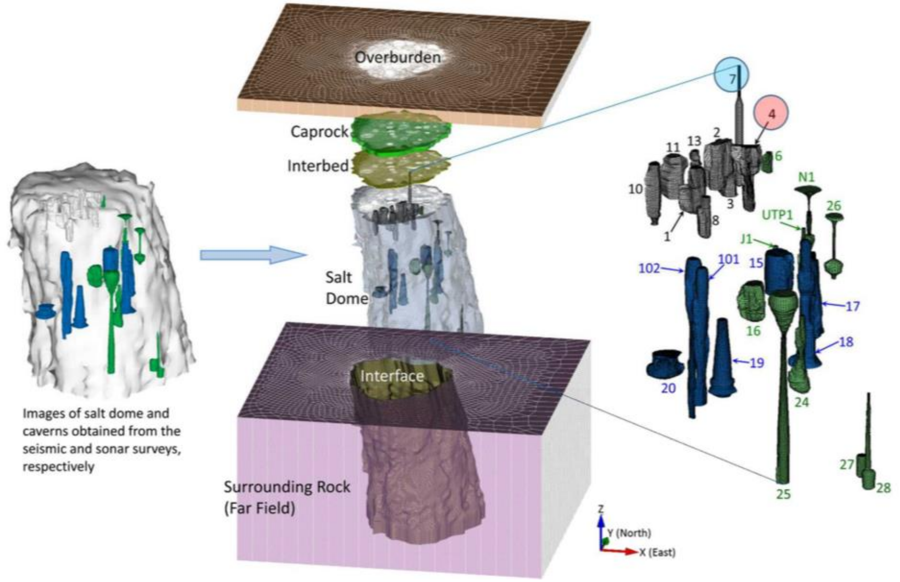


Implications for Storage in Bedded Salts

- Presence of interbeds can cause significant increase in permeability of formation
- Relative permeability of He vs H_2 is different, indicating that He can not be used as a surrogate for H_2 for tight materials like salt.

Conclusions

- Salt remains a highly attractive storage medium for H2
- Cavern storage is nearly ideal, but locations are limited
- Bedded storage is possible, but there are hurdles to overcome
- Effects of interbeds are going to be very important to characterize
- Types/quantity of interbeds may eliminate some locations due to interbed permeability, depending on acceptable loss of stored media.
- Use of surrogate gases needs to be carefully evaluated



Park, B.Y., 2018.

SHASTA

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Recommended Practices for Developing and Operating Subsurface Hydrogen Storage Facilities

Thomas A. Buscheck, Joshua A. White, Lawrence Livermore National Laboratory

Richard A. Schultz, Orion Geomechanics, LLC

Shasta Technical Workshop

Pittsburgh, PA

April 3, 2024

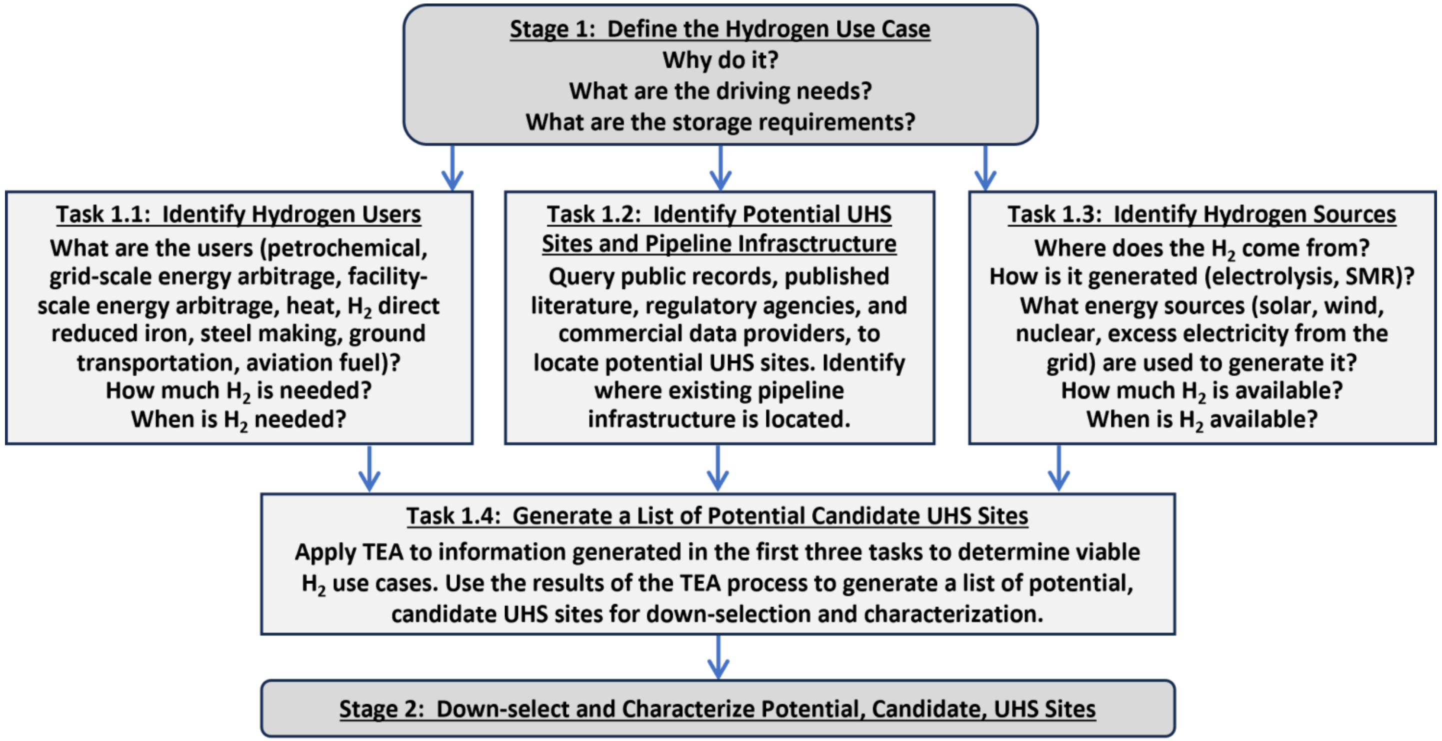
LLNL-PRES-862360

Recommended project-development workflow for UHS facilities

- **The workflow can be broken down to three major stages:**
  - Define the hydrogen use case
  - Rank, down-select, and characterize potential, candidate UHS sites
  - Reservoir design, testing, risk assessment, commissioning, and operations of selected UHS sites
- **A decision-tree process involving multiple tasks is applied within each project stage**
  - where outcomes at decision points determine subsequent actions
  - possibly resulting in multiple iterations before moving onto the next task
- **The goal is to enable UHS facilities to be developed in an efficient and timely manner, while managing project risks.**
- **This workflow is similar to Figure 1 of API Recommended Practice 1171 2nd Edition, Nov 2022: Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs.**

Stage 1: Define the hydrogen use case and UHS storage requirements

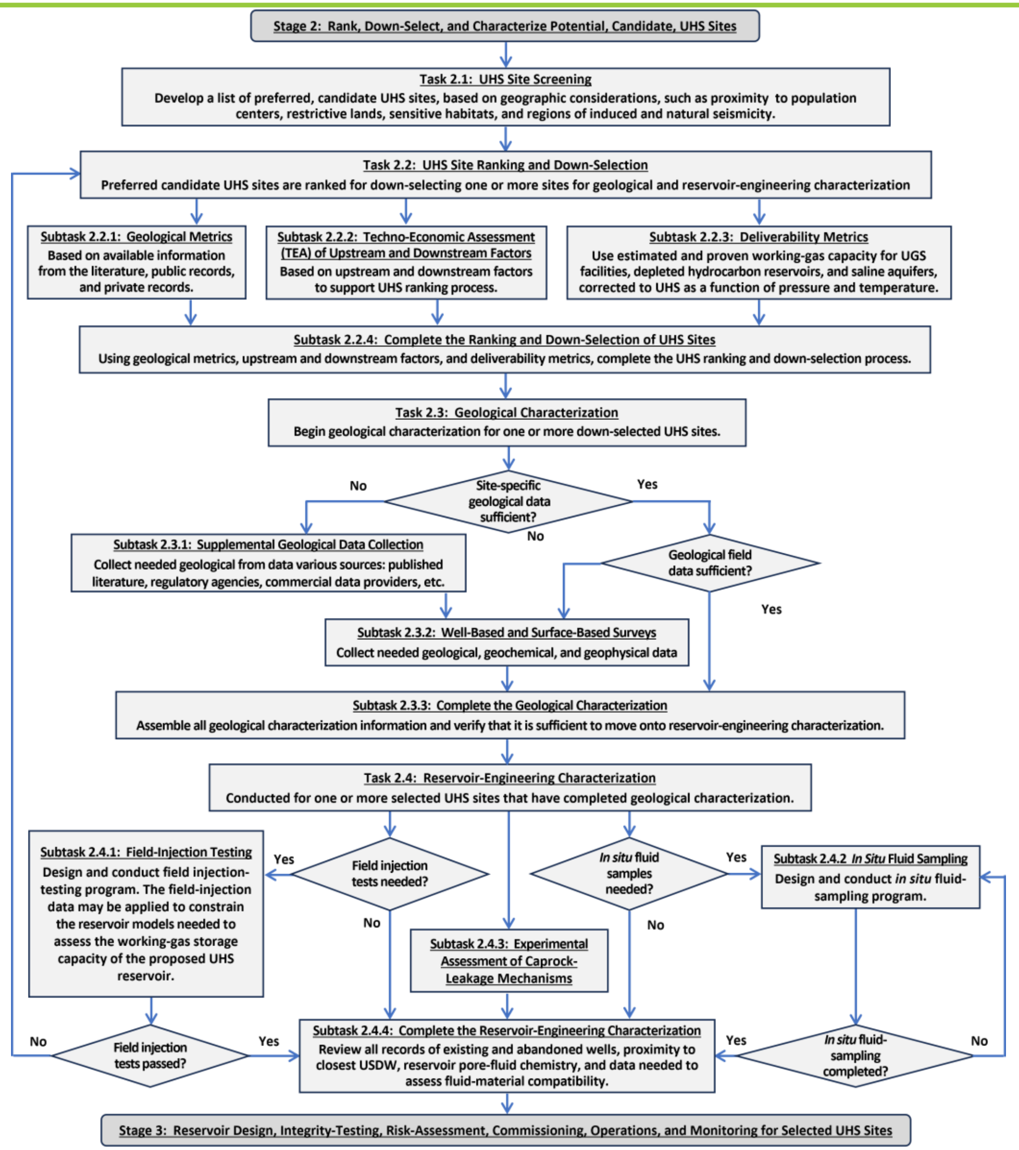
- **Stage 1 involves above-ground considerations that will determine**
  - storage requirements for UHS facilities
  - H_2-pipeline and power-transmission infrastructure needed to connect H_2 sources to UHS facilities to connect UHS facilities to H_2 users
- **Stage 1 will result in a list of potential, candidate UHS sites that will be evaluated in Stage 2.**



Depending on whether Stage 2 identifies UHS sites that meet the storage requirements of the use case, it may be necessary to re-evaluate Stage 1.

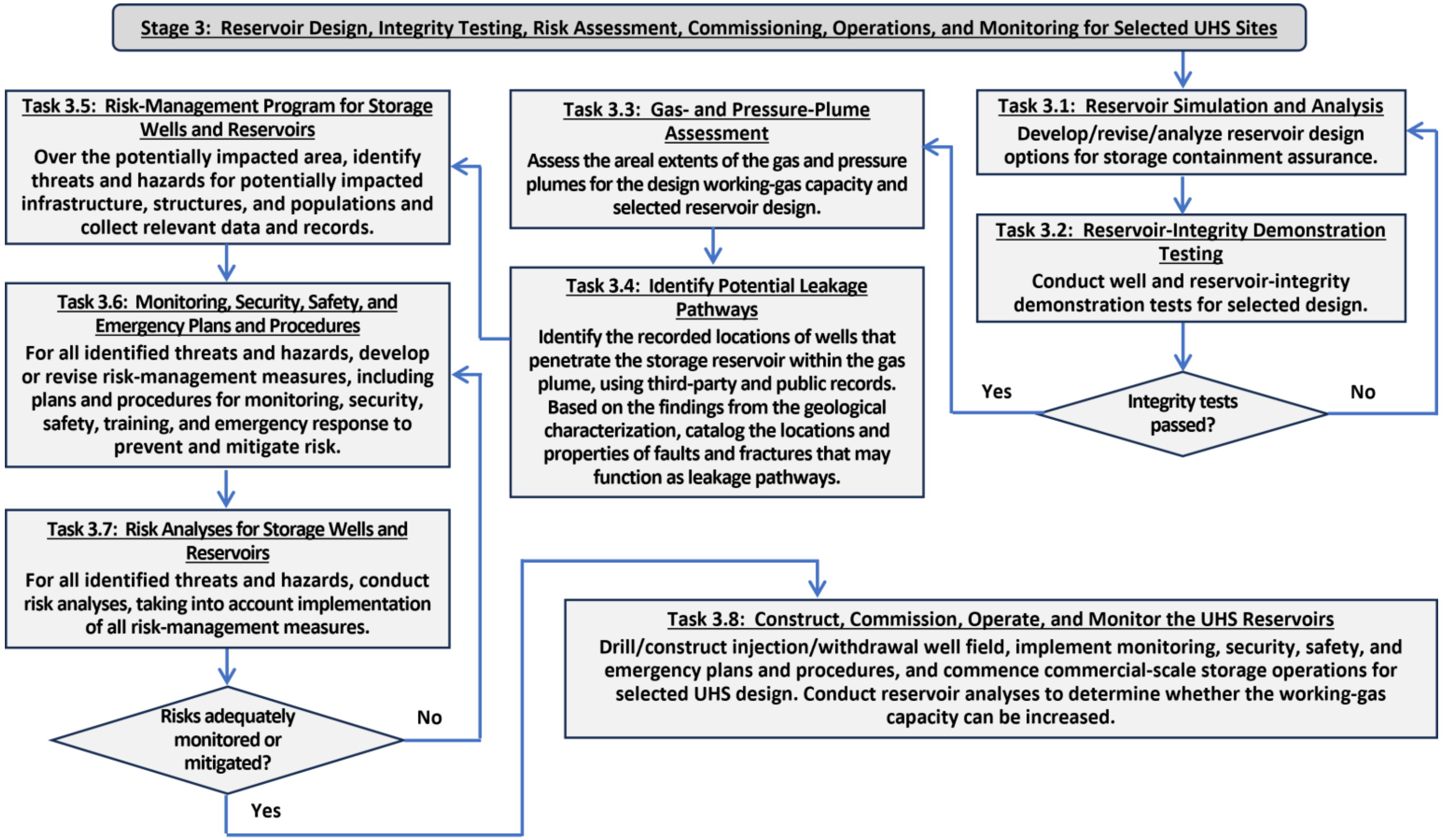
Stage 2: Rank, down-select, and characterize candidate UHS sites

- **Stage 2 consists of three major tasks:**
  - UHS site screening, ranking, and down-selection
  - Geological characterization of down-selected UHS sites
  - Reservoir-engineering characterization of down-selected sites
- **UHS site-ranking and down-selection will consider**
  - geological metrics
  - TEA of upstream and downstream factors
  - deliverability metrics
- **Geological and reservoir-engineering characterization will be more involved for UHS sites with no previous reservoir operations**
- **Stage 2 will result in selected characterized sites being sent to Stage 3.**



Stage 3: Reservoir design, test, risk assessment, and operations

- **Stage 3 consists of 8 tasks, with the first 7 executed in succession**
  - a decision point at the end of the 7th task determines whether the workflow can move to the 8th task.
- **After storage operations commence, additional reservoir analyses and testing can help determine**
  - how to optimize storage operations
  - whether working-gas storing capacity can be increased



Recommended practices for developing and operating subsurface hydrogen storage facilities are likely to evolve with experience.

Thank you!

Evan Frye (DOE FECM)

Timothy Reinhardt (DOE FECM)

Donald Conley (SNL)

Mathew Ingraham (SNL)

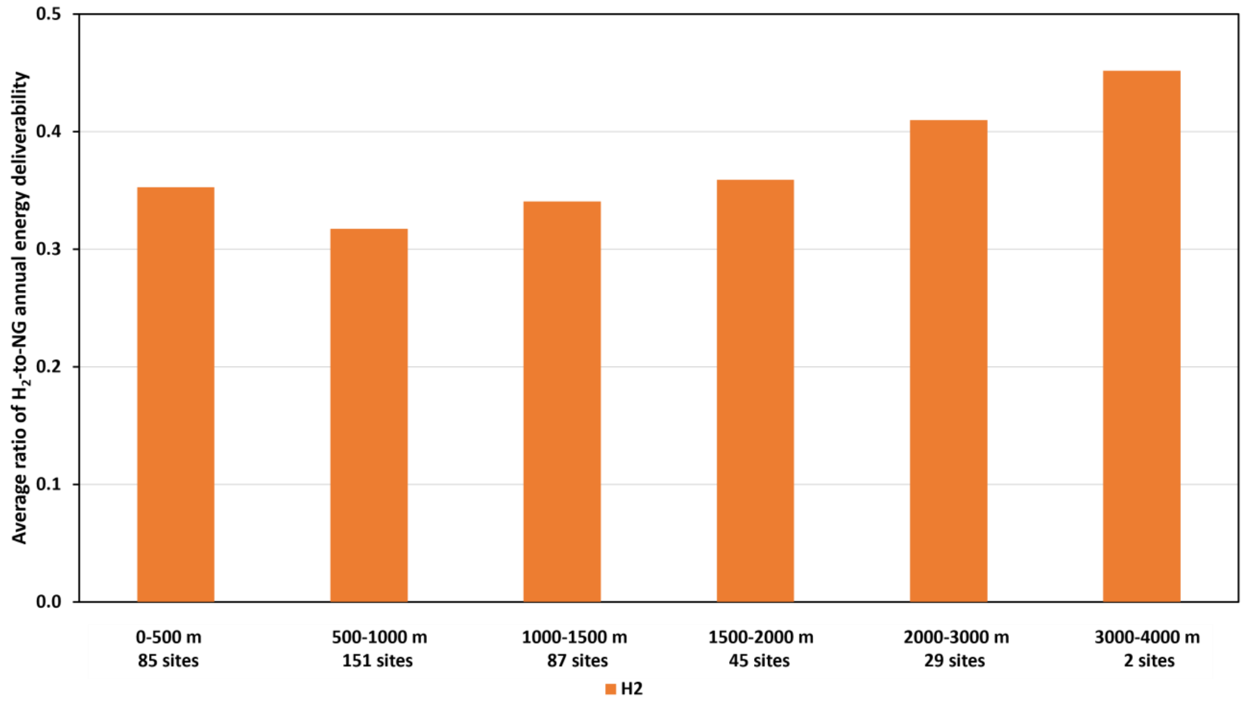
Angela Goodman (NETL)

Joshua A. White (LLNL)

Nicolas Huerta (PNNL)

Backup slides

Dependence of energy deliverability on storage depth



Average ratio of H_2-to-NG annual energy deliverability is shown for the 399 operating UGS facilities in the U.S. (Lackey et al. 2023), broken down by facility storage-depth intervals. The number of sites in each facility storage-depth interval is also shown.

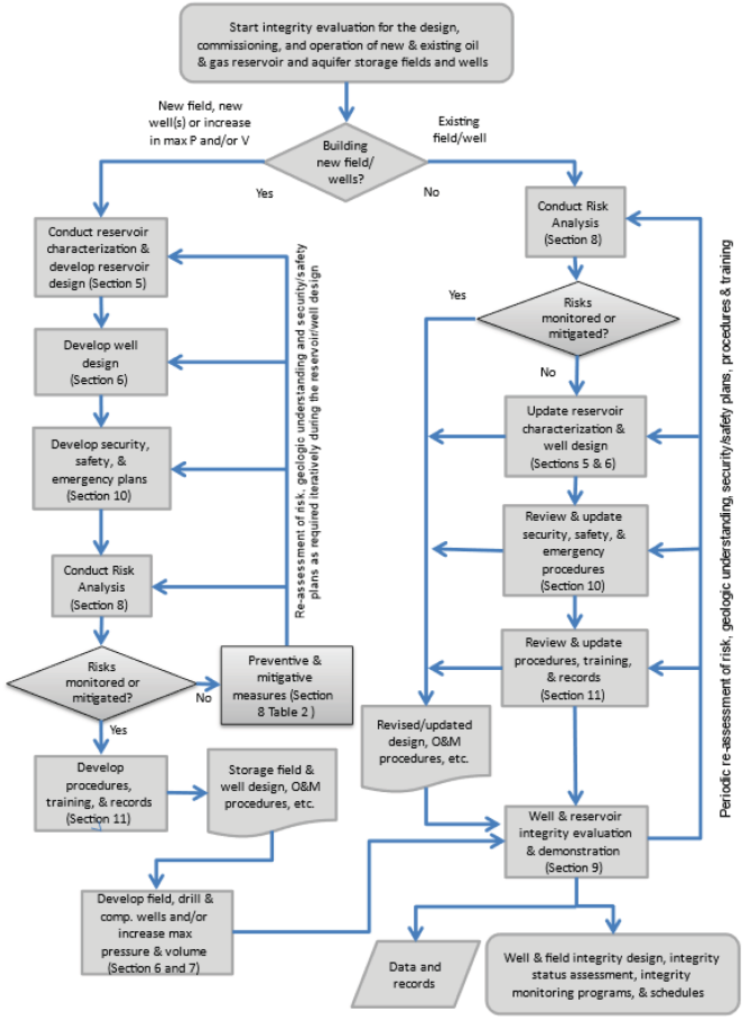


Figure 1—Flowchart of Document Sections

Figure 1 of API Recommended Practice 1171 2nd Edition, Nov 2022: Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs.

SAND2024-03999C

SHASTA

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Hydrogen Field Scale Test Plan

Franek Hasiuk, Mathew Ingraham, Don Conley

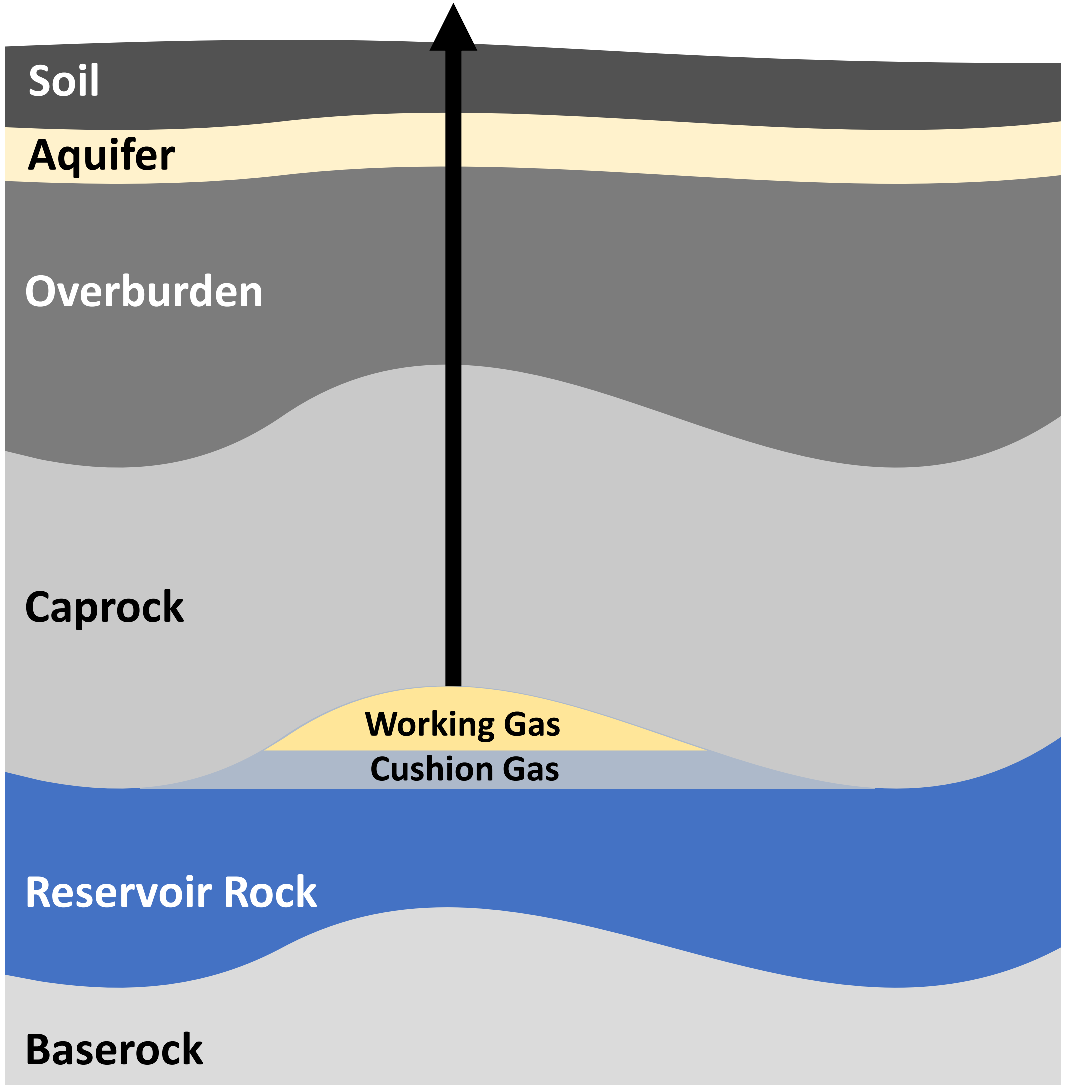
Sandia National Laboratories*

SHASTA Technical Workshop, 03 April 2024

** Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.*

Summary

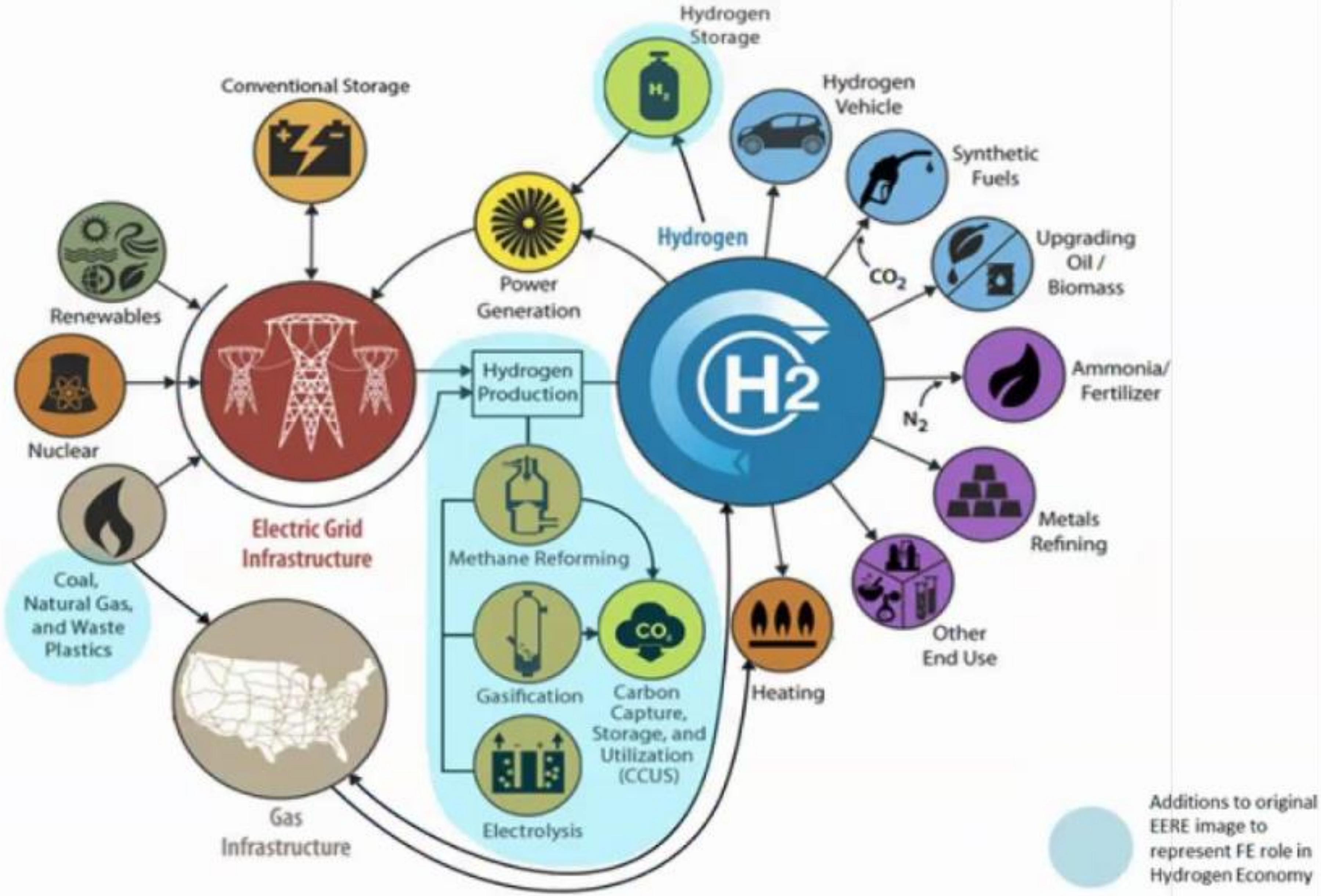
- Hydrogen storage is part of developing a decarbonized hydrogen economy
- Hydrogen reservoir management will evolve from natural gas reservoir management
- Demonstration hydrogen storage projects needed to identify parameters and materials needed to smooth this transition
- A first demonstration could be in a sandstone depleted gas field of similar scale to current gas storage operations



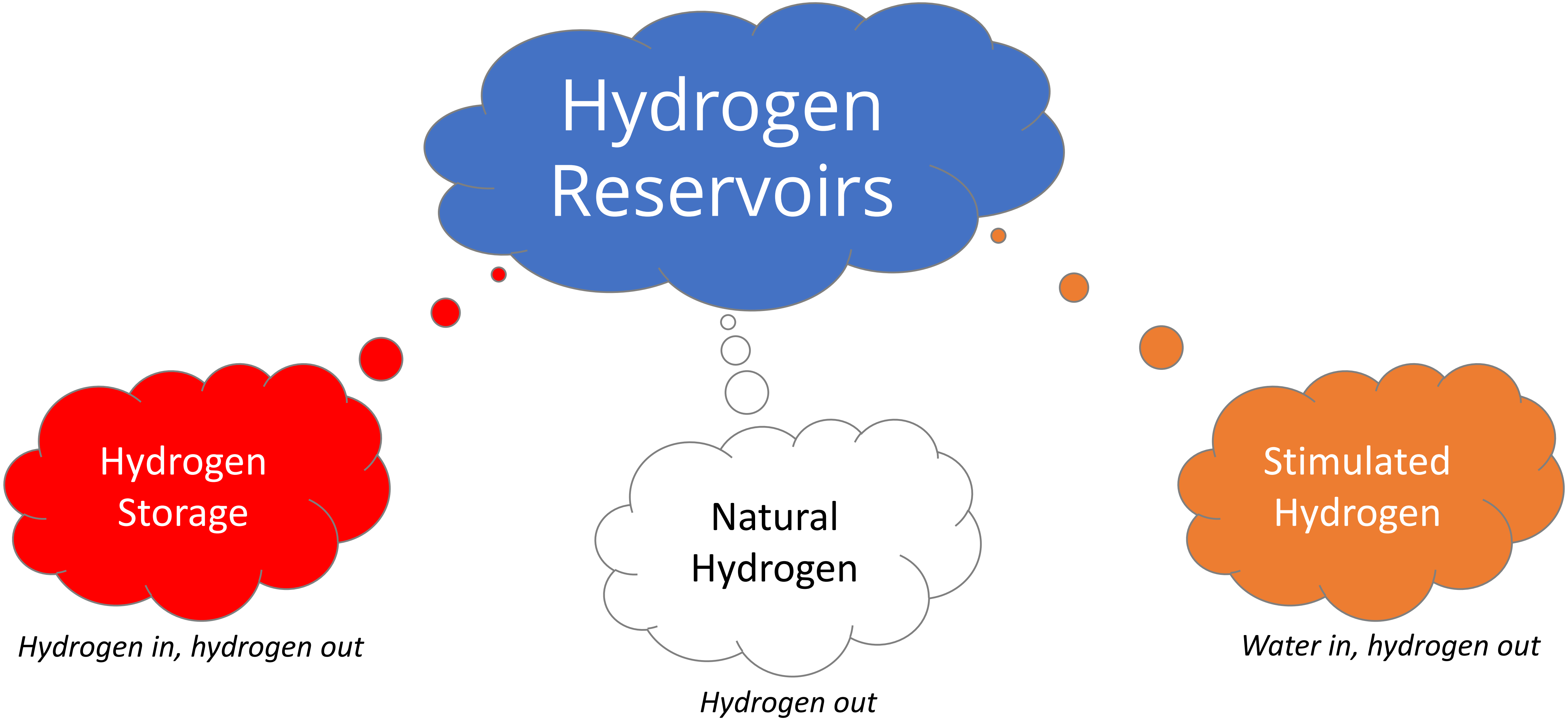
#1 Design Goal: Be Useful

Design a demonstration injection that collects useful data for industry and regulators

Hydrogen

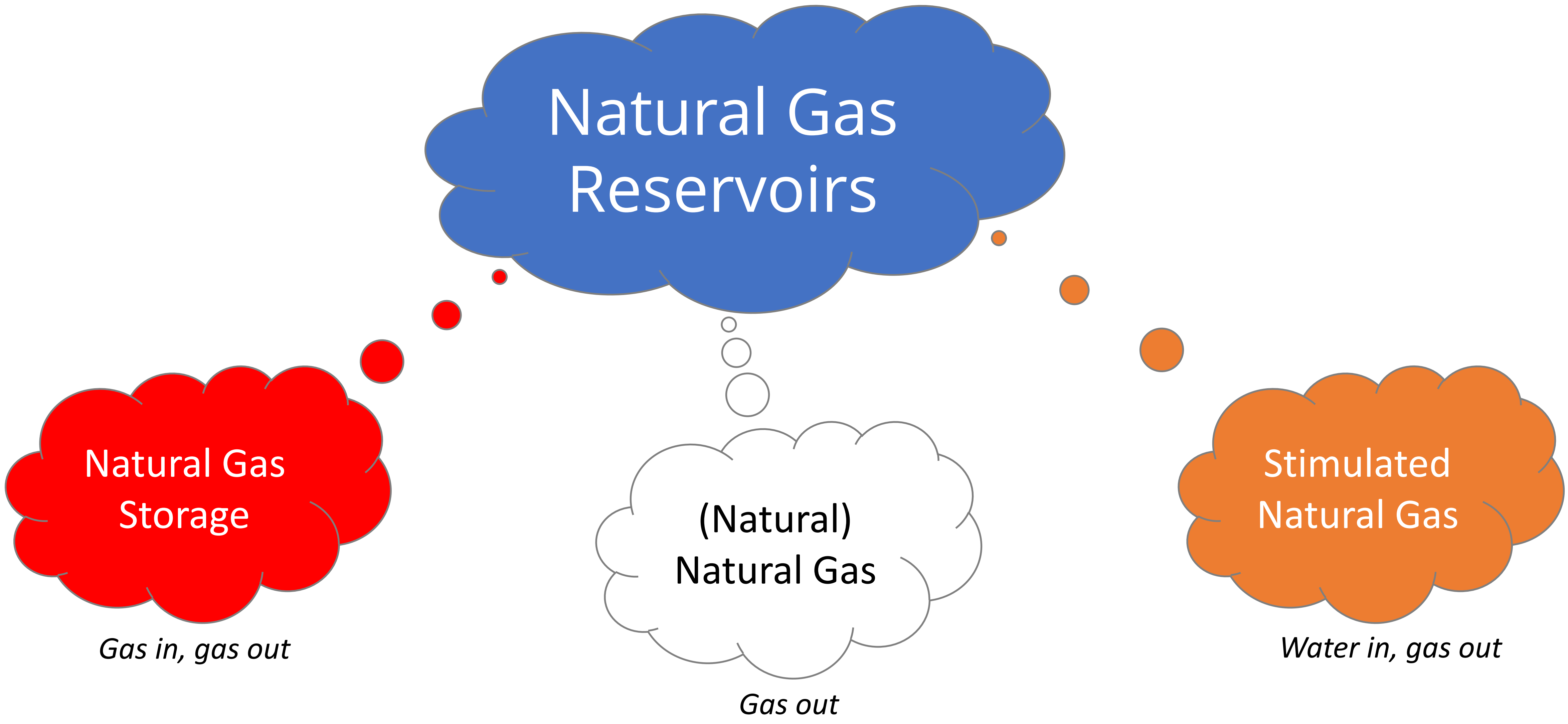

Hydrogen Storage
Conventional Storage
Hydrogen Vehicle
Synthetic Fuels
Hydrogen
Upgrading Oil / Biomass
CO_2
Renewables
Power Generation
Ammonia/ Fertilizer
N_2
Nuclear
Hydrogen Production
H2
Metals Refining
Electric Grid Infrastructure
Methane Reforming
Coal, Natural Gas, and Waste Plastics
CO_2
Other End Use
Gasification
Carbon Capture, Storage, and Utilization (CCUS)
Heating
Electrolysis
Gas Infrastructure
Additions to original EERE image to represent FE role in Hydrogen Economy

Hydrogen reservoir management family



…Natural gas reservoir management family

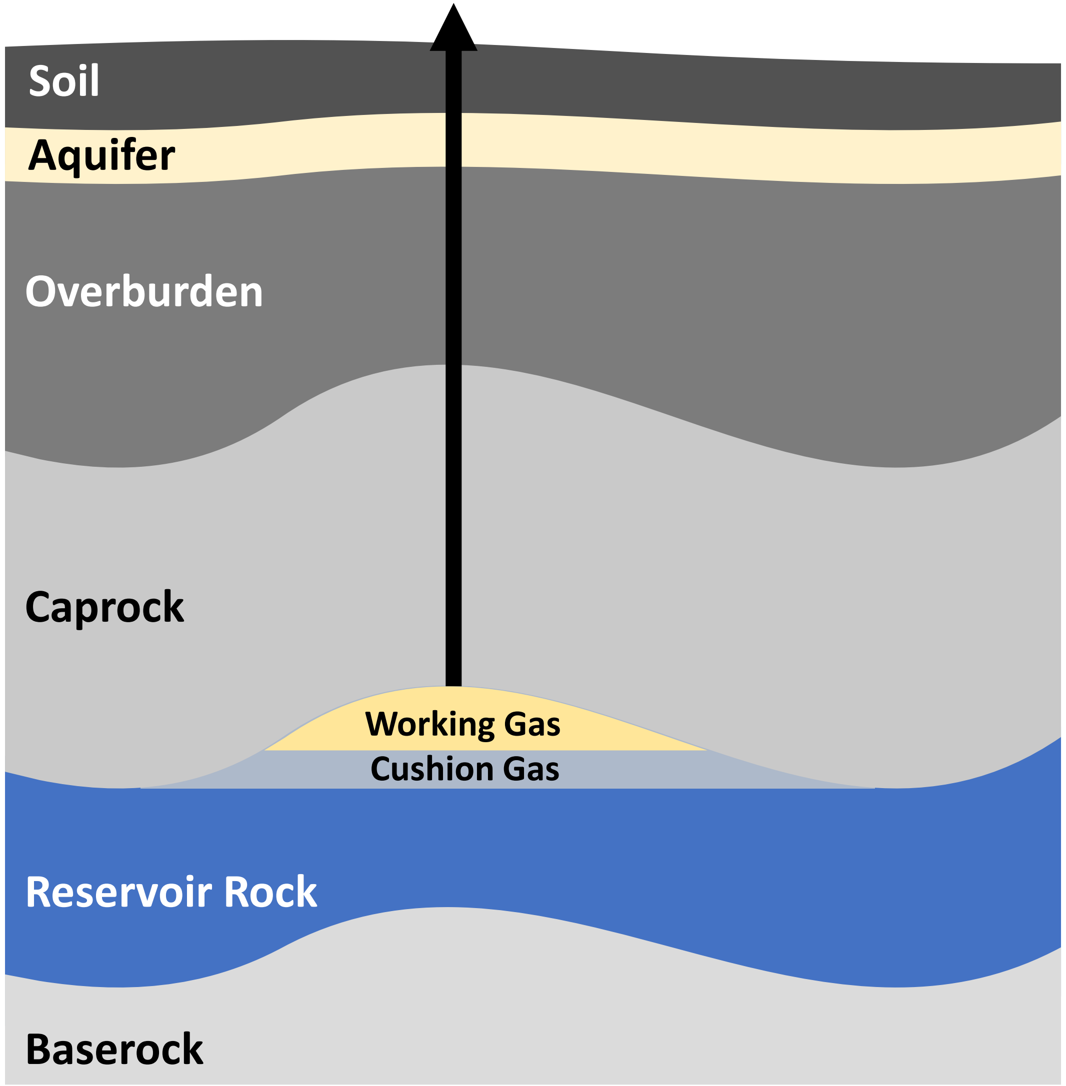
SHASTA



All the presentations today fit together

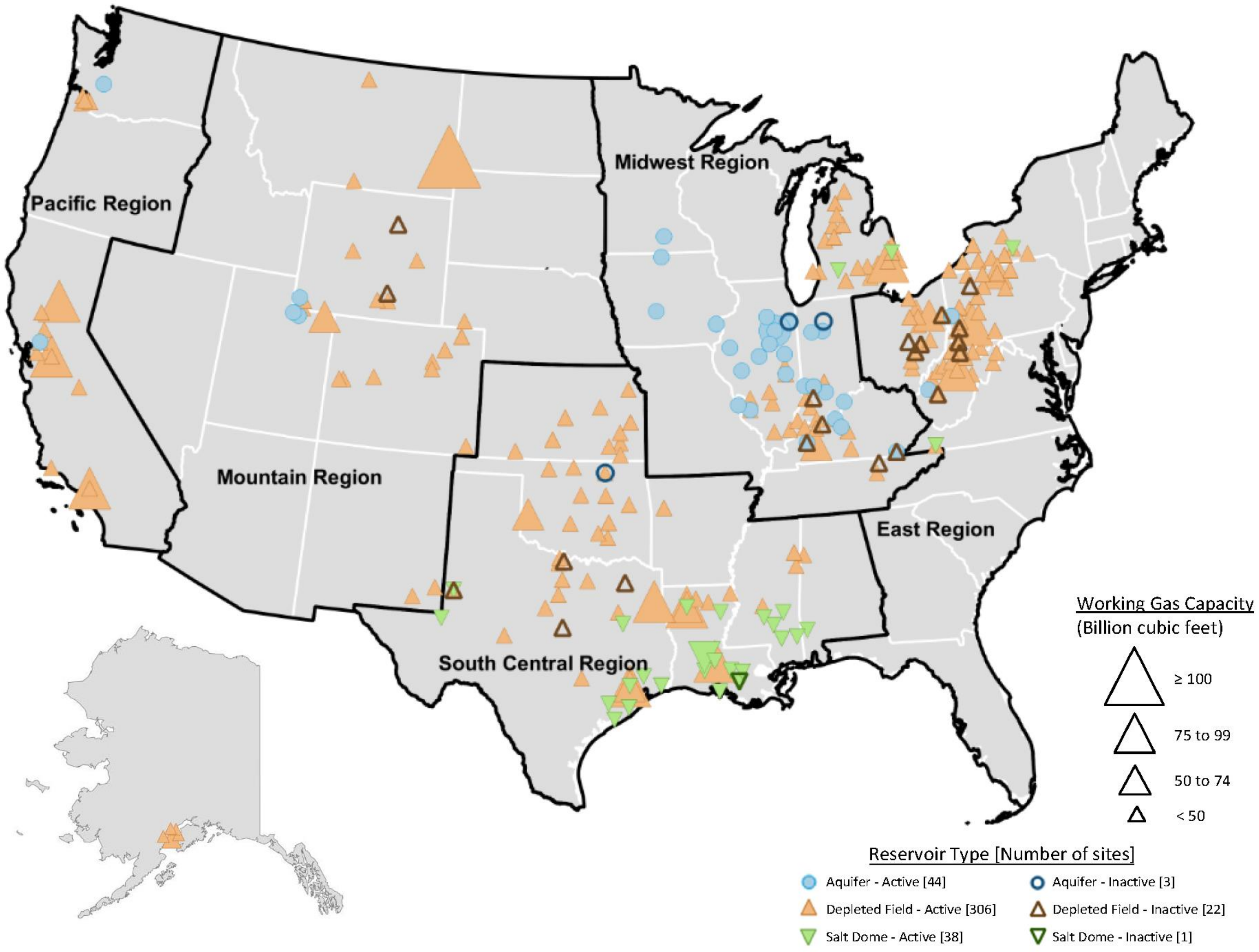
SHASTA

TIME	PRESENTER	ORGANIZATION	TOPIC
8:00 am	Evan Frye/Timothy Reinhart	FECM	Welcome and program comments
8:05 am	Josh White	SHASTA-LLNL	SHASTA Project Overview
8:15 am	Leon Hibbard	SHASTA-PNNL	Regional Case Studies for H_2 Storage
8:35 am	Shruti Mishra/Gerad Freeman	SHASTA-SNL, PNNL	Local and Regional-Scale Technoeconomic Analysis
8:55 am	Julia Camargo	SHASTA-PNNL	Reservoir Simulations and Code Comparison
9:15 am	Ryan Haagenson	SHASTA-PNNL	Core Flooding Experiments and Simulations
9:35 am	Djuna Gulliver	SHASTA-NETL	Microbial Characterization
9:55 am	BREAK		Break
10:15 am	Angela Goodman	SHASTA-NETL	H_2 Wettability, Permeability, and Diffusion
10:35 am	Gaby Davilla/Guanping Xu	SHASTA-LLNL, SNL	Geochemical Impacts of Subsurface H_2 Storage on Reservoir and Caprock Characteristics
10:55 am	Barbara Kutchko	SHASTA-NETL	Well Integrity
11:15 am	Christopher San Marchi	SHASTA-SNL	Gaseous Hydrogen Embrittlement of Metals for H_2 Storage
11:35 am	Ruishu Wright	SHASTA-NETL	Real-time Sensor Technologies for Hydrogen Subsurface Storage
11:55 am	Mathew Ingraham	SHASTA-SNL	Salt Mechanics
12:15 pm	LUNCH		LUNCH
1:15 pm	Melissa Louie/Tom Bushcheck	SHASTA-SNL, LNNL	Risk Mitigation, Operations, and Recommended Practices
1:35 pm	Franek Hasiuk	SHASTA-SNL	H_2 Field Scale Test Plan
1:55 pm	Serge Van Gessel	Task 42	Task 42: IEA TCP
2:15 pm	Todd Deutsch	NREL	An overview of the pipeline blending CRADA - A Hyblend Project
2:35 pm	Carolyn Descoteaux	PRCI	PRCI - Emerging Fuels Institute Update
2:55 pm	Peter Warwick	USGS	Overview of Energy Storage & Hydrogen Research at the U.S. Geological Survey
3:15 pm	BREAK		BREAK
3:30 pm	Ning Lin	GEOH2	Screening and Valuation Frameworks: Paving the Way for Viable Hydrogen Storage Solutions with $Geoh_2$
3:50 pm	Scyller Borglum	WSP	Boots on the Ground: Practical Application for Storing Hydrogen
4:10 pm	Shadi Salahshoor	GTI	Subsurface Storage Technological Advancements & Innovation for Hydrogen: SUSTAIN H_2
4:30 pm	Mohamed Mehana	LANL	Overview of LANL's Underground Hydrogen Storage Projects and Future Outlook
4:50 pm	SHASTA PIs	SHASTA	Wrap-up/Questions
5:00 pm	Adjourn		Adjourn



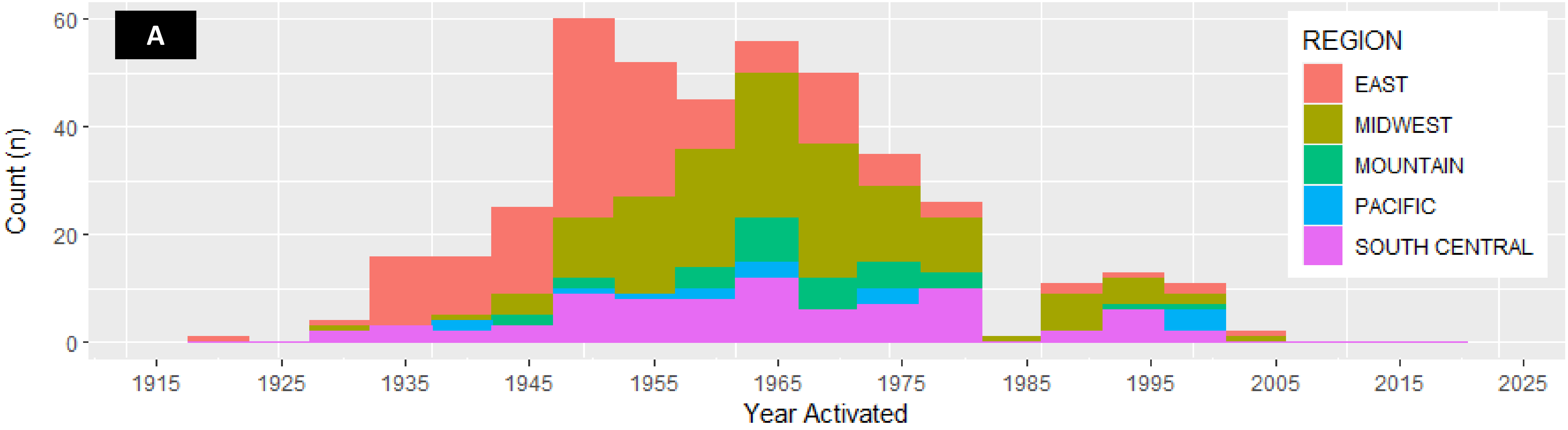
Current gas storage fleet developed over last 100 years

- **Gas storage has been commercial for 100+ years**
- **Gas storage occurring in 30 states**
- **Hydrogen is a different gas, *but not that different***



Current Natural Gas Storage Fleet by Age of Operation

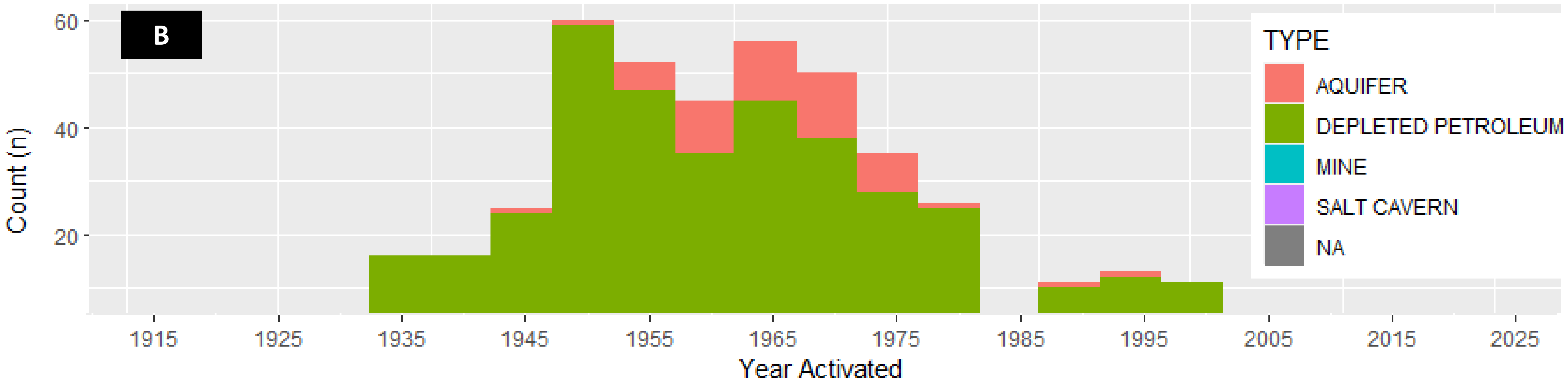
Natural gas storage fields have decades of operational history



Hasiuk et al. (2024)

Current Natural Gas Storage Fleet **by Age of Operation**

But few opened in the last 40 years



Current Natural Gas Storage Fleet by Age of Operation

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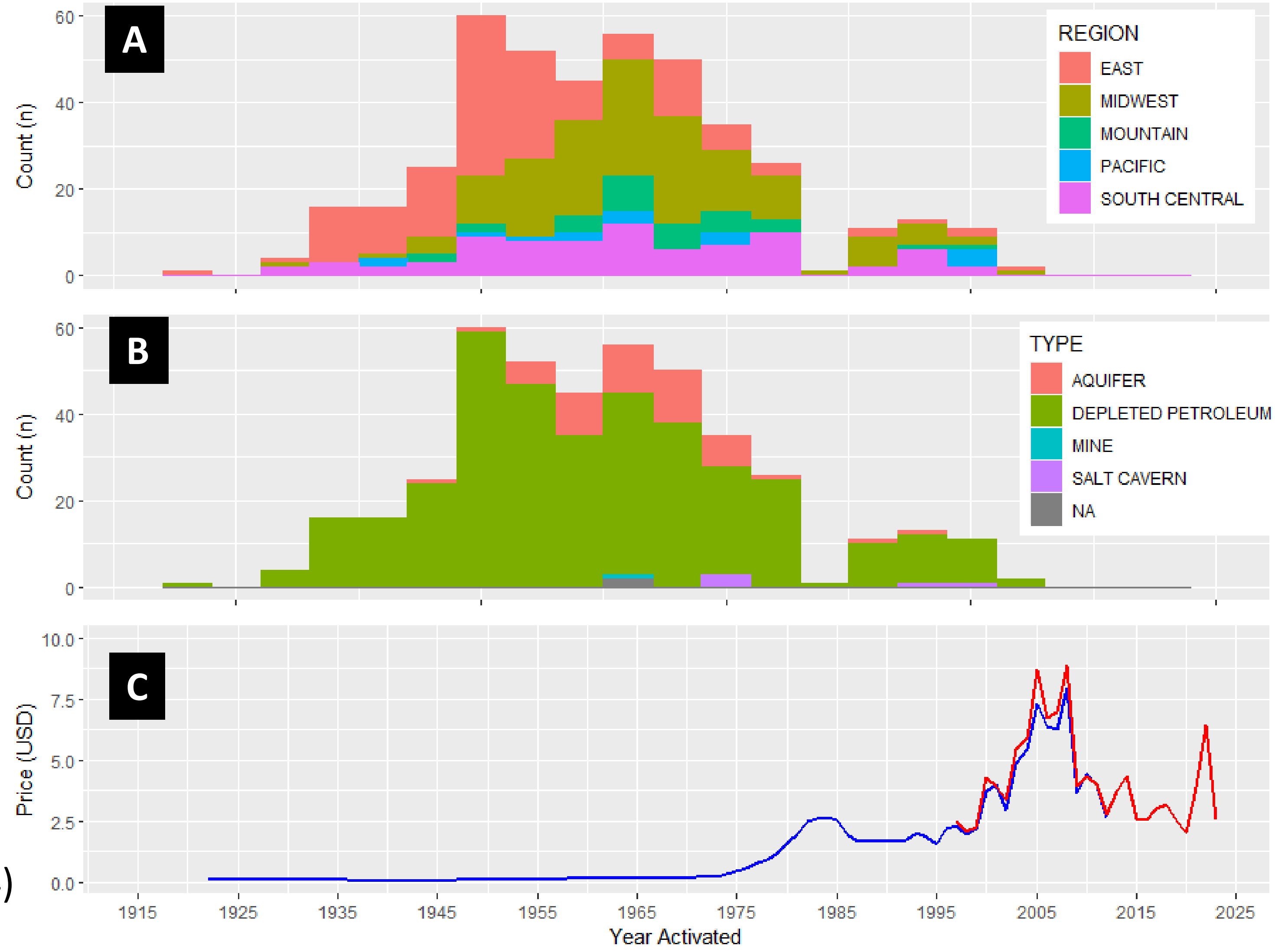
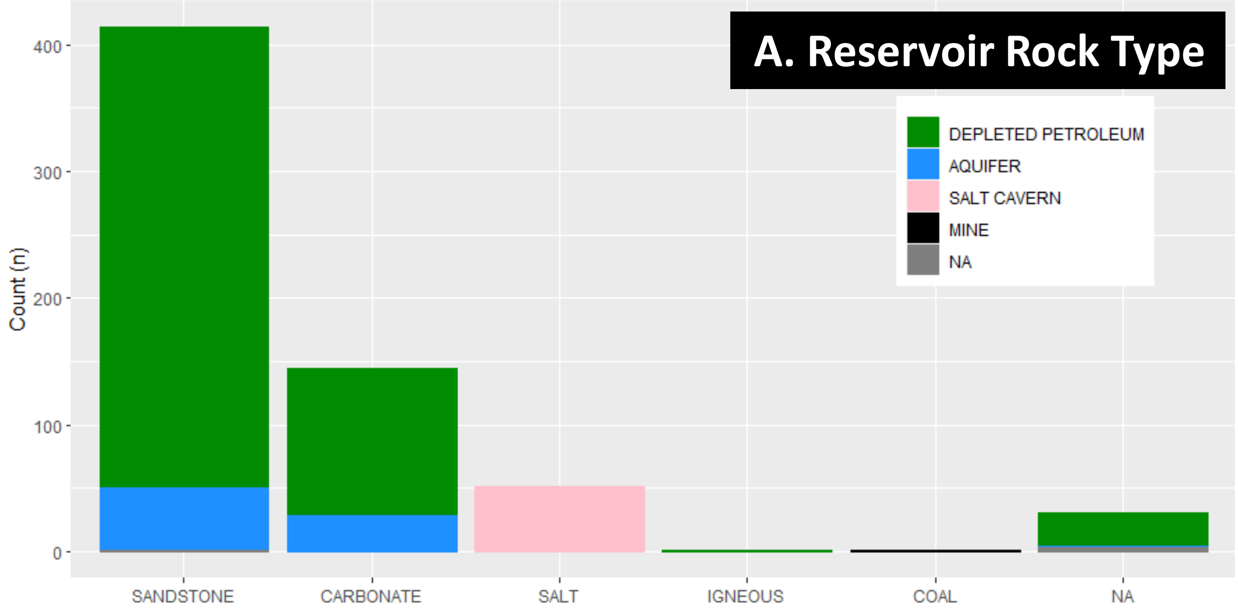
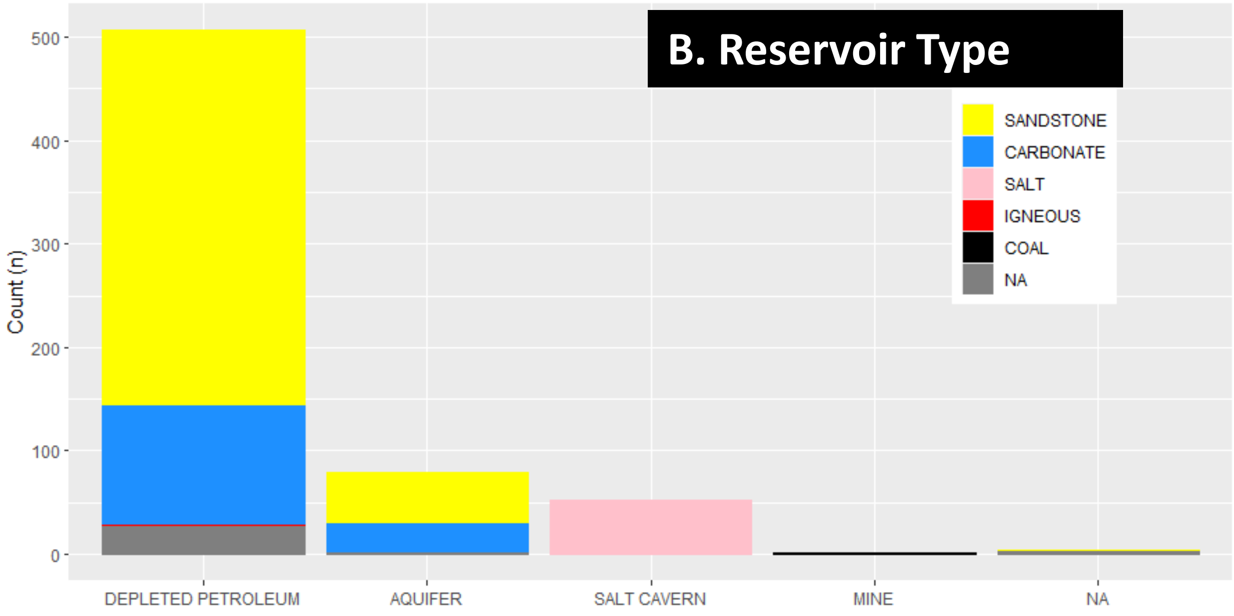


Hasiuk et al. (2024)

Current Natural Gas Storage Fleet by Reservoir Types

Most gas storage reservoirs are sandstone depleted petroleum fields

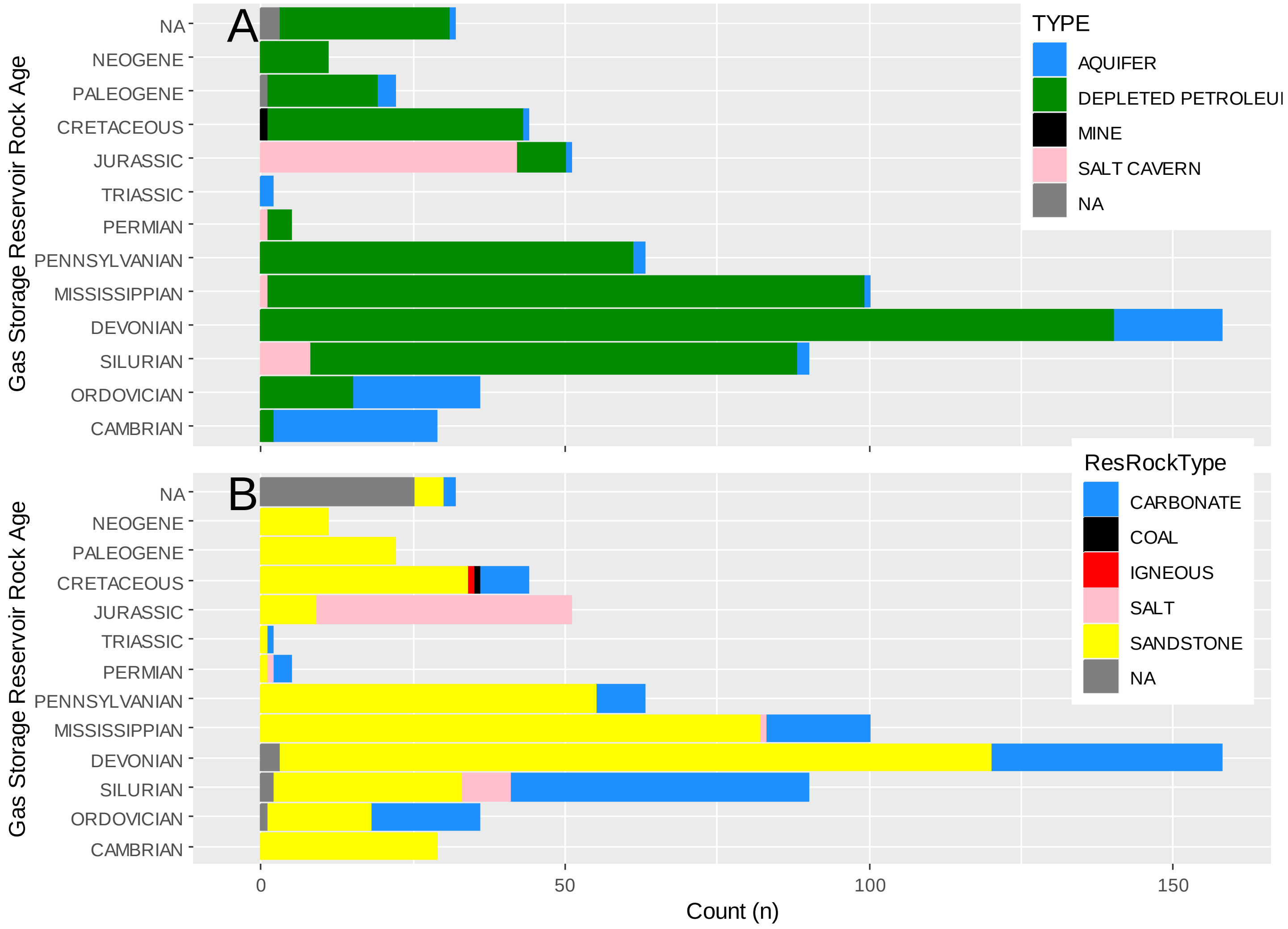




Hasiuk et al. (2024)

Current Natural Gas Storage Fleet by Geologic Age

Gas storage reservoir fleet is dominated by late Paleozoic sandstone reservoirs.



Hasiuk et al. (2024)

Current Natural Gas Storage Fleet by Geologic Age

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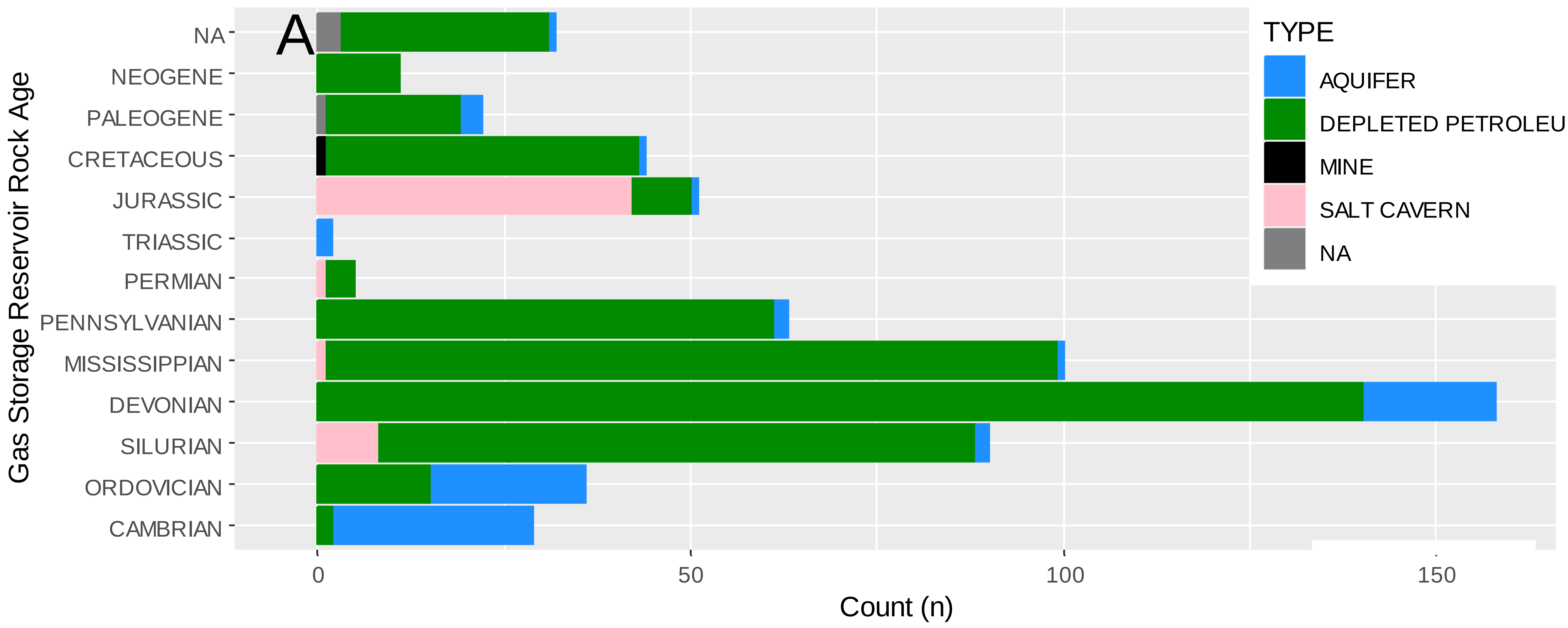

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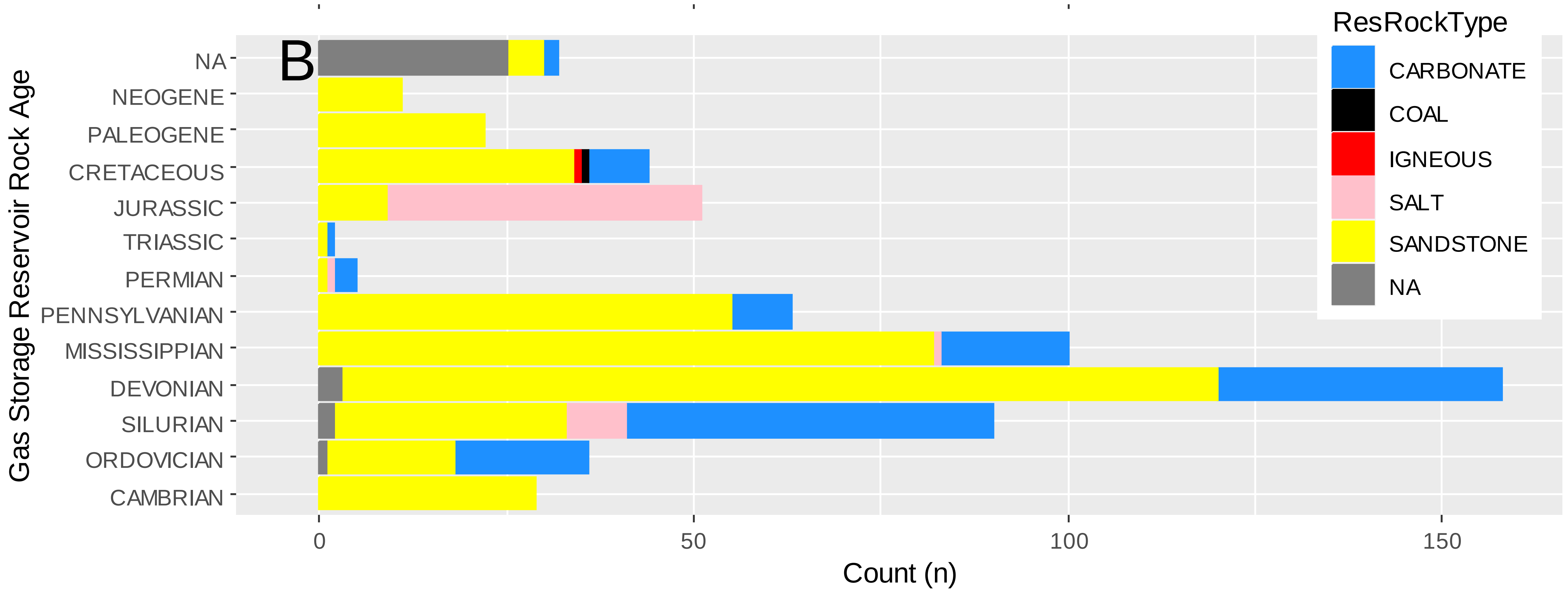
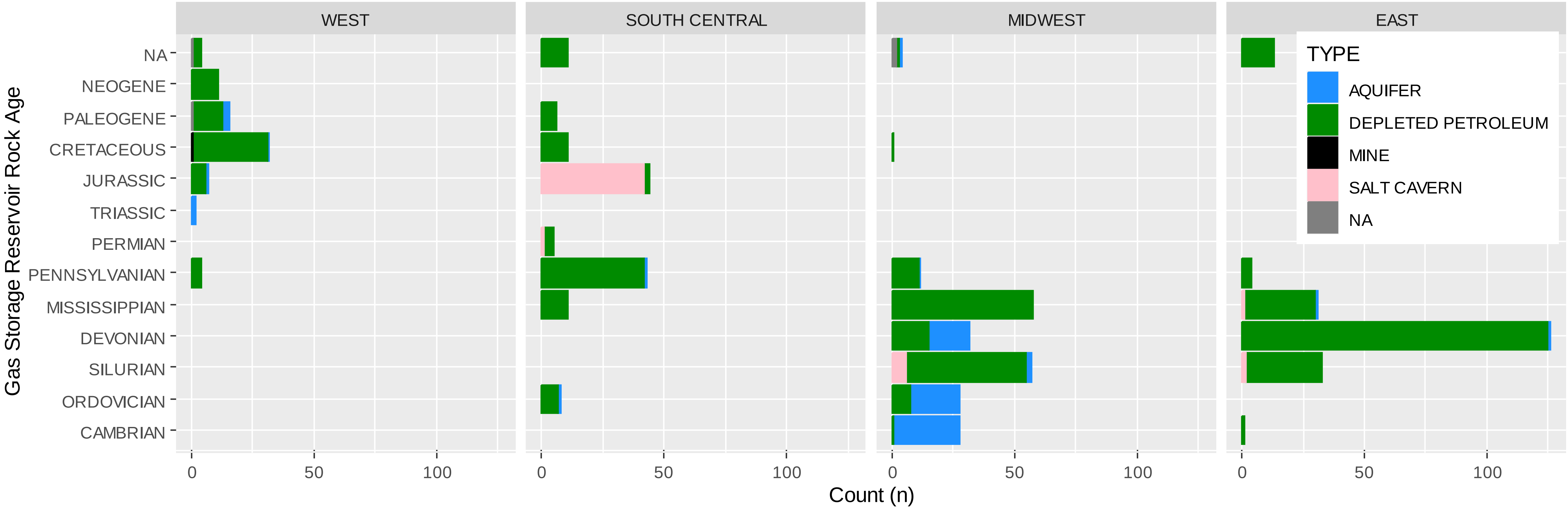


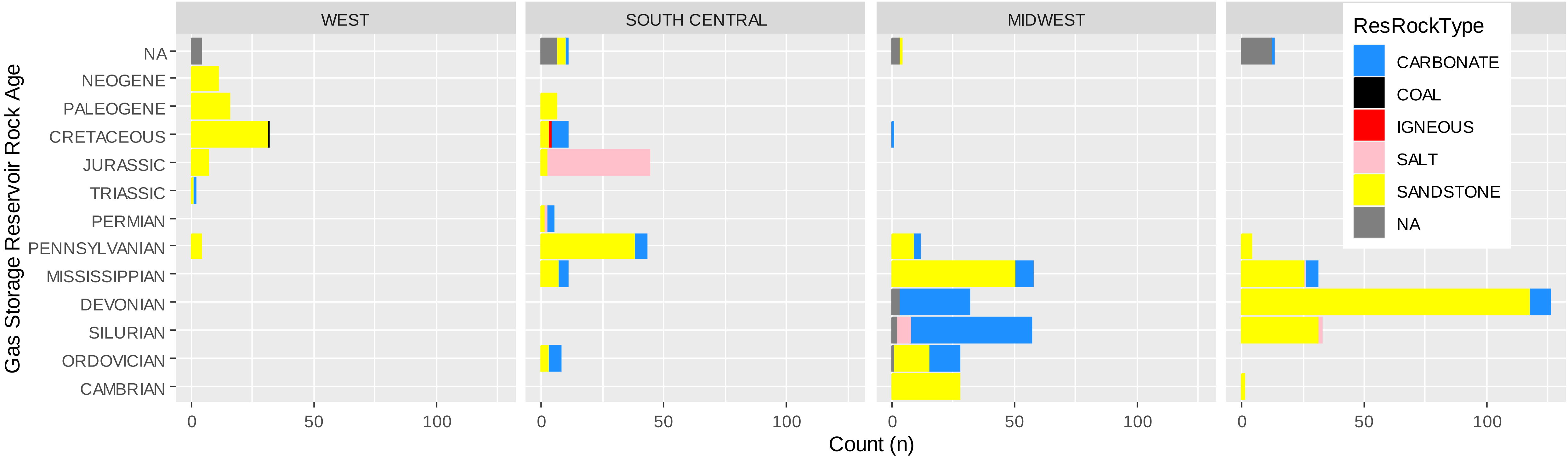
Current Natural Gas Storage Fleet by Geologic Age/Region

Dominant gas storage reservoir lithology is regional



Current Natural Gas Storage Fleet by Geologic Age/Region

Dominant gas storage reservoir lithology is regional



Ten most abundant reservoir combinations

Count	Age	Rock Type	Reservoir Type	Region
116	Devonian	Sandstone	Depleted Petroleum	East
82	Mississippian	Sandstone	Depleted Petroleum	Midwest
53	Pennsylvanian	Sandstone	Depleted Petroleum	South Central
47	Silurian	Carbonate	Depleted Petroleum	Midwest
42	Jurassic	Salt	Salt Cavern	South Central
33	Cretaceous	Sandstone	Depleted Petroleum	West
31	Silurian	Sandstone	Depleted Petroleum	East
27	Cambrian	Sandstone	Aquifer	Midwest
21	Devonian	Carbonate	Depleted Petroleum	Midwest
18	Paleogene	Sandstone	Depleted Petroleum	West

Other design goals 1/2

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- **Use a former depleted natural gas field**
  - Methane is inexpensive and there lots of commercial experience using it as base gas
  - "Blending up" hydrogen (starting at perhaps 10%) when the injection commences and then increase during the demonstration to 100% while watching the behavior of field equipment and reservoir fluids samples from monitoring wells.
- **Newer facility**
  - Biggest concern is the interaction between hydrogen and legacy materials
    - e.g., steel, cement, elastomers
  - Reduces risk of unknown corrosion causing poor performance during the demonstration
- **Field near communities**
  - A pilot near a community will allow effective outreach and engagement programs
- **Long test cycle**
  - Cycle of at least two years
  - Monitor over one full injection-production cycle
  - Flexibility to start the demonstration as soon as possible and potential do a shorter injection-production cycles first
  - Comparable to current natural gas storage facilities

Other design goals 2/2

- **Lower reservoir pressure**
  - Most natural gas storage reservoirs operate between 200-5000 psi
  - 1200 psi would be ideal to save on compression costs and still provide representative reservoir performance data
  - Lower pressure would also reduce the risk to caprock or wellbore
- **Higher deliverability rate**
  - Minimum of 2 MMscf/day minimum
  - 20-100 MMscf/day would be more representative of the current gas storage rates
- **Higher storage volume**
  - 2 BCF of hydrogen over its storage cycle (approximately 6 months at a rate of ~10 MMscf/d)
  - Similar magnitude and rate to current natural gas storage operations
  - Could be curtailed should monitoring suggest concern regarding containment
- **Low sulfur content reservoir**
  - Dissolved sulfate (SO_4) may react with injected hydrogen especially in the presence of certain microbial communities to produce hydrogen sulfide (H_2S)

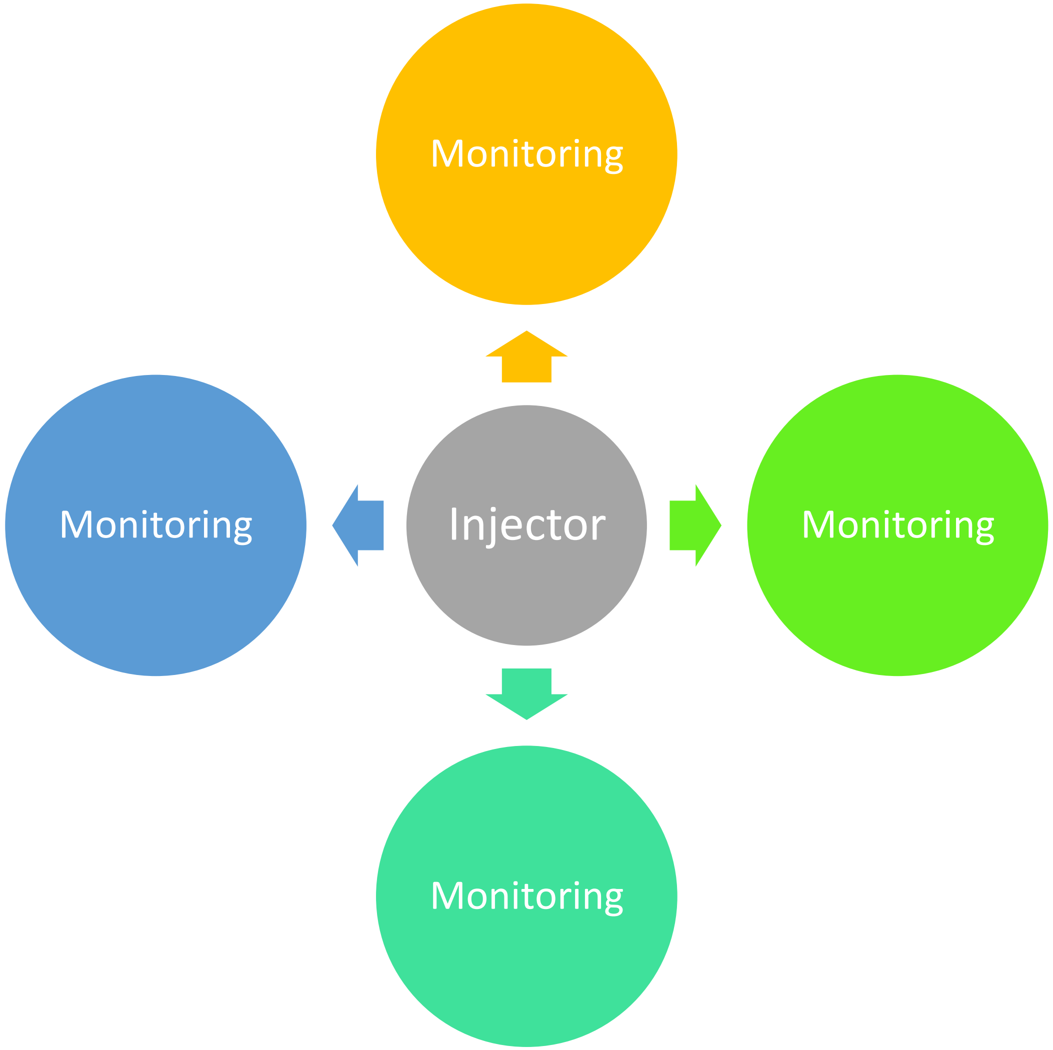
R&D Plan seeks answers to several major questions

- ***What is the geometry of the injected hydrogen bubble?***
- ***How do we account for hydrogen during storage operations?***
- ***How does injected hydrogen interact with reservoir fluids & microbes?***
- ***What is the reactivity of clay minerals in the presence of hydrogen?***
- ***What is the sealability of gas-tight connections?***
- ***What is the appropriate cement to use in well construction?***
- ***How do we monitor for underground leaks?***
- ***How do we monitor for surface leaks?***

Need for a “Field Laboratory”?

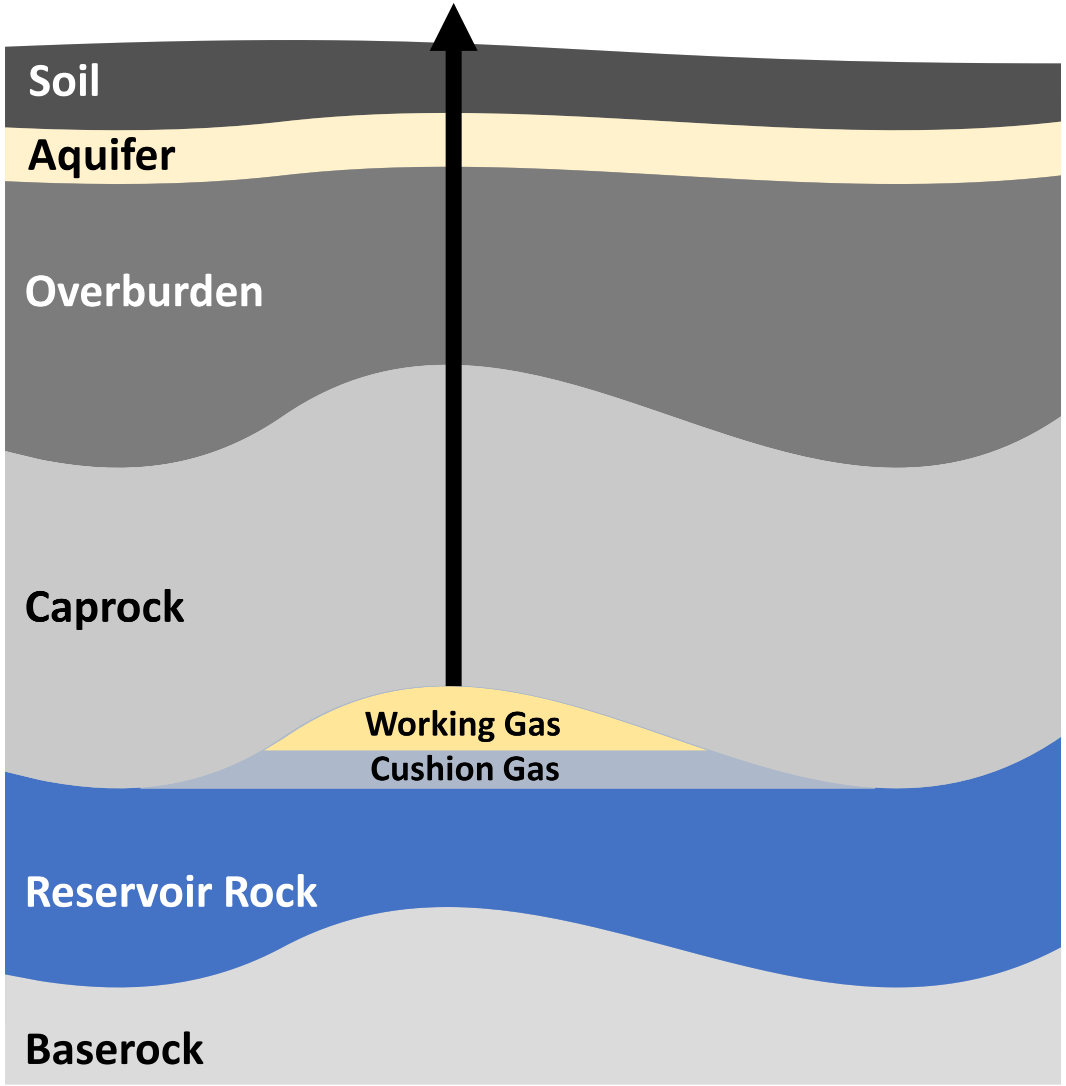
- **Test various construction, production, and monitoring technologies as well as materials could be tested long-term in a field environment.**

- **5-spot well development**
  - One central injector/producer
  - Four monitoring wells located at various distances



Summary

- Hydrogen storage is part of developing a decarbonized hydrogen economy
- Hydrogen reservoir management will evolve from natural gas reservoir management
- Demonstration hydrogen storage projects needed to identify parameters and materials needed to smooth this transition
- A first demonstration could be in a sandstone depleted gas field of similar scale to current gas storage operations



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Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

H_2 (± Brine) Interactions with Minerals and Shale: Impact on Hydrogen Storage Safety and Capacity

Guangping Xu, Mathew D. Ingraham - Sandia National Laboratories (gxu@sandia.gov) and others*

SHASTA stakeholder meeting, Apr 3rd, 2024

* Other contributors include Matt Powell, Sean Dwyer, Jessica Kruichak, Matt Paul, Yifeng Wang, Tuan Ho, Yongliang Xiong and SHASTA leadership team

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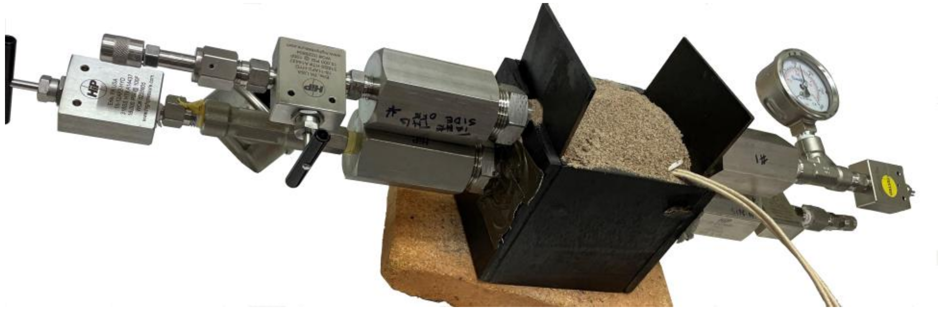
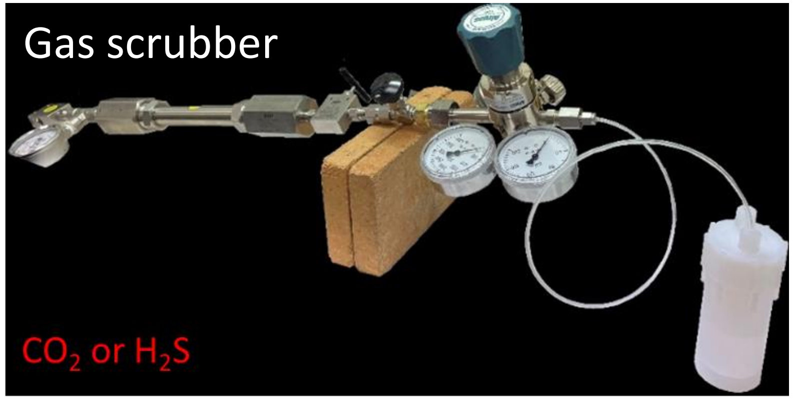
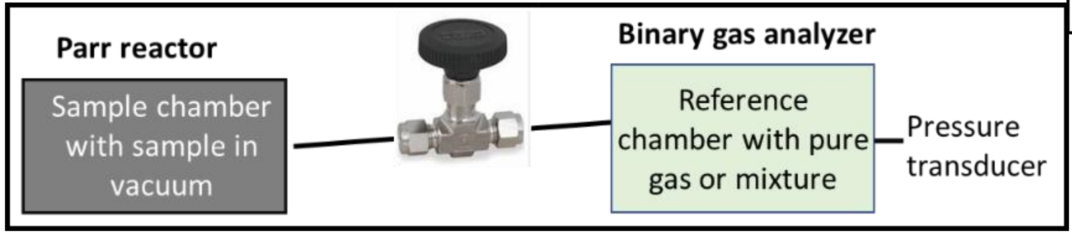
SAND2024-03702PE

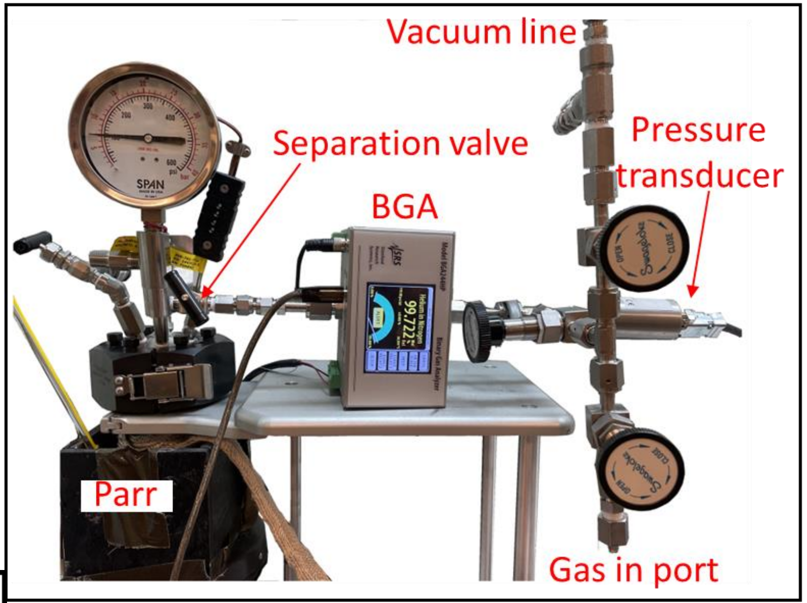
High Pressure Reactors for H_2 ($He/CH_4/N_2$) – Rock Interactions (w or w/o brine)







- Dual reactors to run parallel experiments at same conditions to benchmark
- Ability to run pure hydrogen or mixture with N_2 - CH_4 - CO_2



- Binary Gas Analyzer (BGA) using speed of sound to measure binary gas composition
- Total adsorption can be calculated from the pressure change

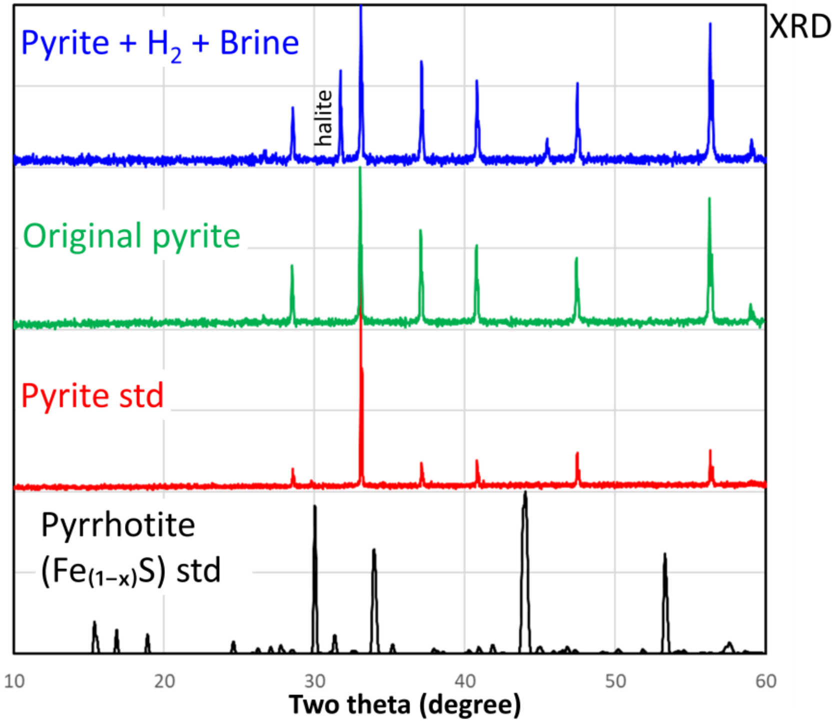
H_2 + Brine with Pyrite

Original pyrite (FeS_2) Reacted pyrite

H_2S can be detected and sulfate in the solution:

$FeS_2 + H_2 + H_2O \rightarrow H_2S + H_2O \rightarrow SO_4^{2-}$

		Pyrite (g)	NaCl (g)	Fe (mmol/Kg)	Sulfate (mmol/Kg)	pH
Pyrite **chips** + H_2 + brine for two weeks at **<u>25°C</u>** and 1200 psi	H2	2.0	25.0	1.11 (0.79)	2.2 (1.57)	4.57
Pyrite **powder** + CH_4 + brine for one week at 55°C and 1500 psi	CH4	2.0	35.0	1.22	0.62	4.57
Pyrite **powder** + N_2 + brine for one week at 55°C and 1500 psi	N2	2.0	35.0	1.19	0.46	4.11
red number in parenthsis - normalized to 35 g solution						



Pyrrhotite does **not** present (or below the detection limit)

Pyrite does dissolve a little at high pressure and temperature, but it is not due to H2 as CH4 and N2 can do the same.

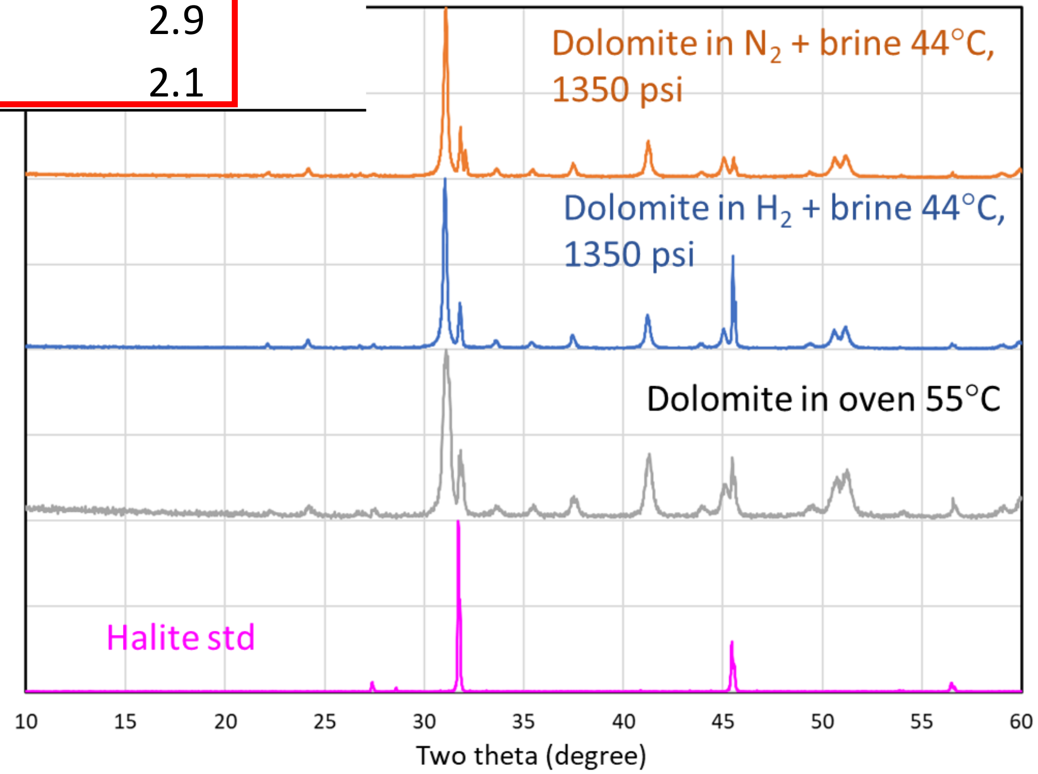
H_2 + Brine with Dolomite Powder for One Week at 1350 psi and 44 °C

	pH	Cl- (mol/Kg)	Na (mol/Kg)	Ca (mmol/Kg)	Mg (mmol/Kg)	Dissolved Inorganic Carbon (mmol/Kg)
Dolomite + N_2 + brine	8	4.1	4.6	1.3	10.2	1.3
Dolomite + H_2 + brine	8.1	4.2	4.2	0.8	6.2	2.9
Dolomite + brine in oven	7.8	4.1	4.1	1.00	4.2	2.1

- Both H_2 and N_2 at pressure do not seem to enhance the solubility of dolomite, $(Ca,Mg)(CO_3)_2$, compared to the oven experiment, ~1.8 – 7.5 mg dissolved per g dolomite.

- There are no mineralogy differences in all three experiments.

XRD



2g powder in 25 g saturated NaCl for one week, mol ratio of Ca/Mg = 1

Sulfate Mineral Reaction with Hydrogen – Phase Transition

$CaSO_4 \cdot 2H_2O$ (gypsum) → $CaSO_4 \cdot 0.5H_2O$ (bassanite) → $CaSO_4$ (anhydrite)

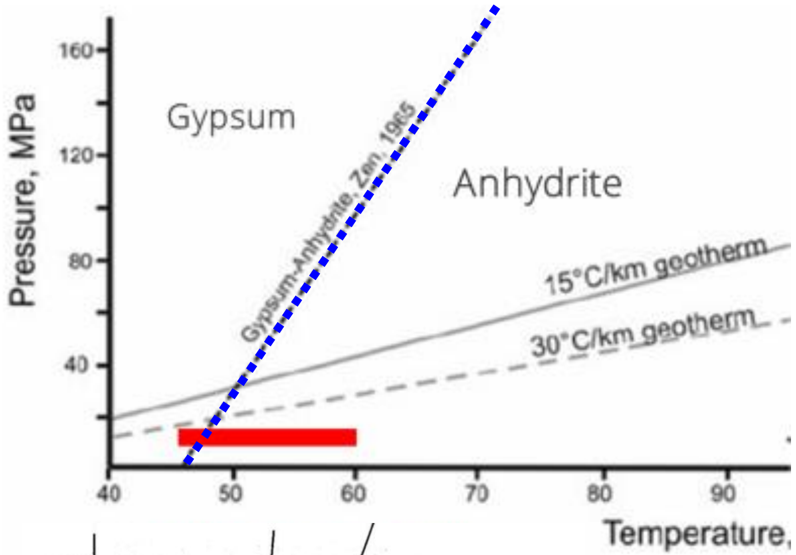
Density: 2.33 g/cm^3 Density: 2.73 g/cm^3 Density: 2.97 g/cm^3

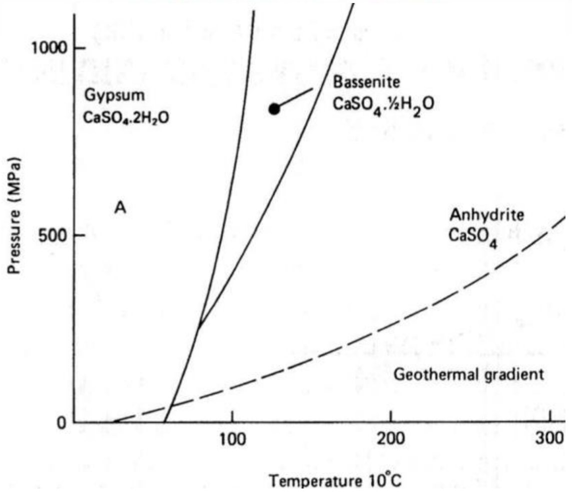
Impact: Phase transitions between gypsum, bassanite and anhydrite will lead to significant volume change (27%) which will cause mechanical property changes.

Exp #	Temperature (°C)	Starting material	Resulting material	Reacting gas	Solution pH	Ca (mmol/Kg H_2O)
21	~44	anhydrite	gypsum, no anhydrite	H2	7.4	38.8
42	~55	anhydrite	anhydrite	H2	7.2	36.3
17	~44	gypsum	gypsum, no anhydrite	H2		42.6
34	~44	gypsum	gypsum, no anhydrite	Helium	6.9	40.4
39	~55	gypsum	bassanite, anhydrite	H2	6.7	59.0
41	~55	gypsum	bassanite, anhydrite	Helium	6.7	63.0
49	~58	gypsum	69% bassanite + 31% anhydrite	N2		54.7
50	~58	gypsum	20% bassanite + 80% anhydrite	H2	6.7	56.9

All reacting pressure are ~ 1400 psi and with saturated brine solution

- There does not seem to be any difference solubility for H_2, Helium and nitrogen.
- Anhydrite solubility is ~ 36-39 mmol/Kg H_2O in H_2, consistent with literature value.





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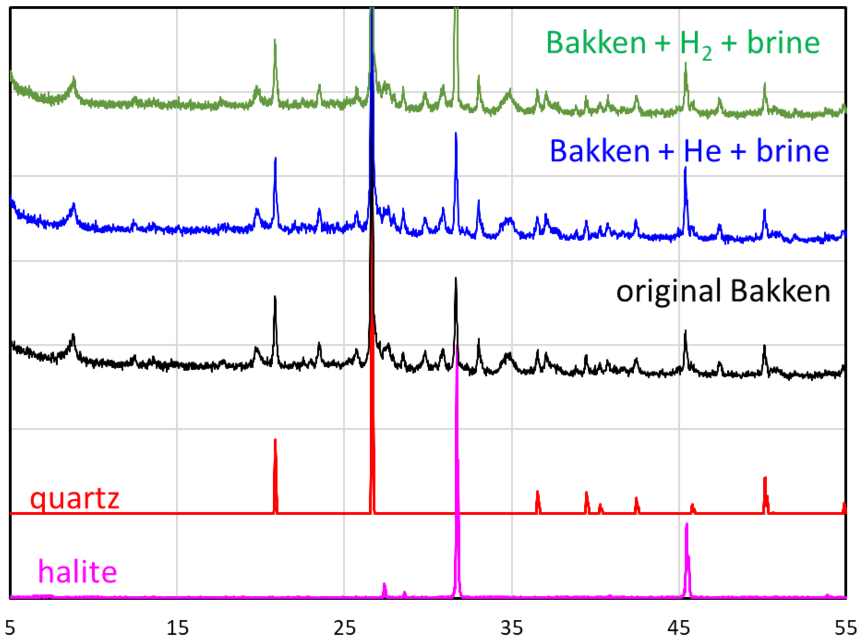
H_2 + Brine with Bakken Shale Powder for One Week at 2000 psi and 55 °C

	Tectosilicates			Phyllosilicates			
Sample Name	Quartz wt %	K-Spar wt %	Plagioclase wt %	Kaolinite wt %	Chlorite wt %	Illite/Mica + Illite/Smectite wt %	Pyrite wt %
Bakken powder	27	14	2	0	3	47	7

	pH	Na (mol/Kg)	Cl (mol/Kg)	SO4 (mmol/Kg)	Fe (mmol/Kg)	Ca (mmol/Kg)	Mg (mmol/Kg)	Al (mmol/Kg)	K (mmol/Kg)
Bakken Shale (He)	7.07	3.61	3.67	0.89	BDL	0.68	0.16	0.18	1.16
Bakken Shale (H2)	7.41	3.47	3.56	0.33	BDL	0.25	0.18	0.19	1.00

- H_2 at pressure does not seem to enhance the solubility of shale compared to He.
- There are no mineralogy differences in all three experiments.

XRD

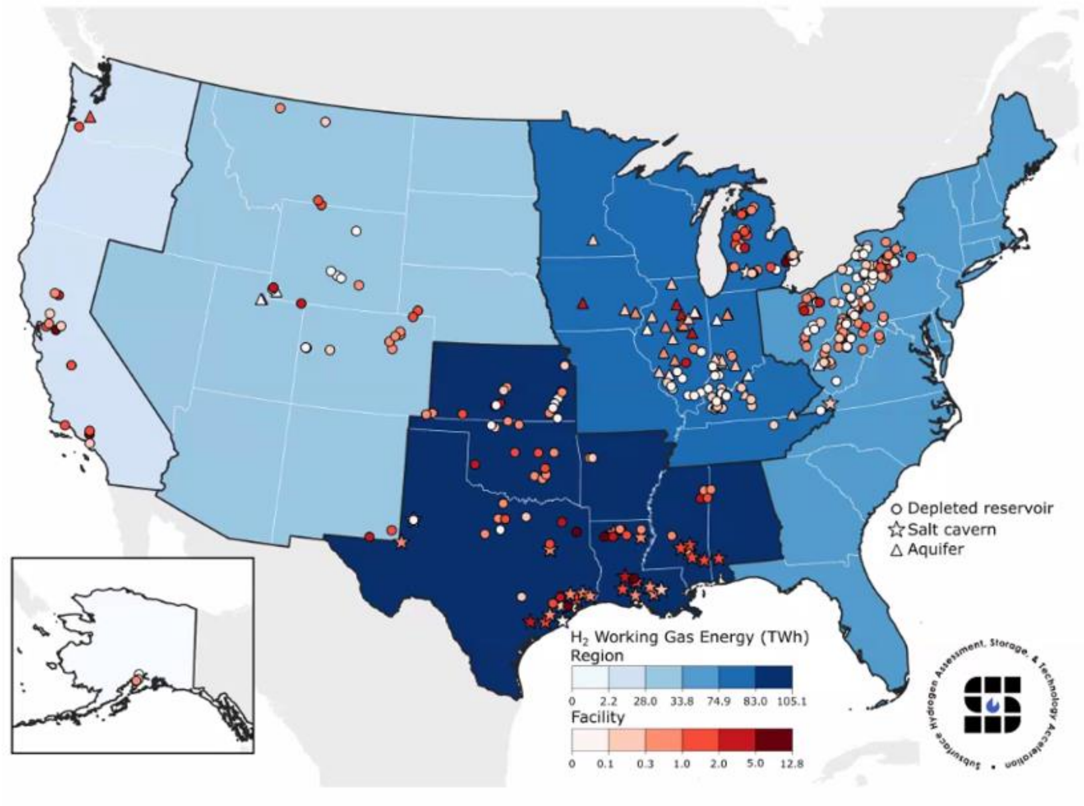


2g powder in 35 g undersaturated NaCl for one week

Depleted O&G Reservoirs (aka shale) have the Most Potential and Geographically Diverse

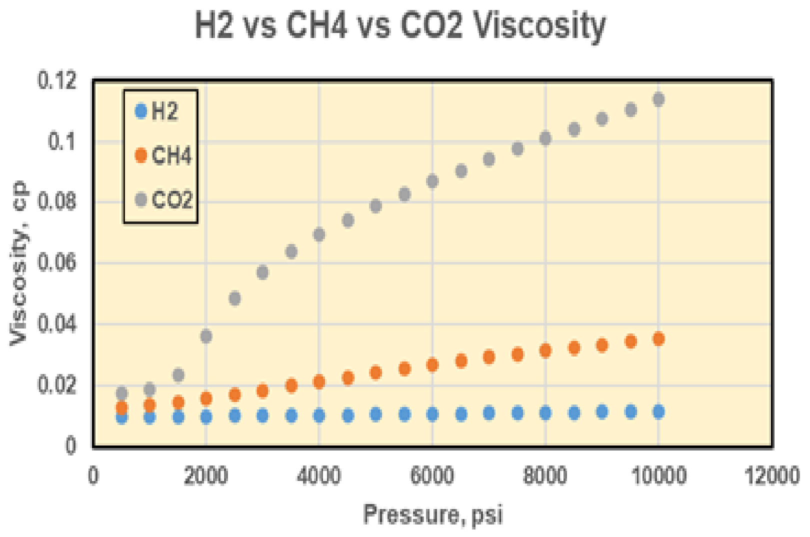
- Storage volume is huge compared to salt cavern and aquifer
- Geographically diverse
- Leverage existing infrastructure and cost effective.
- The levelized costs of hydrogen storage (per Kg of H_2) are (from Chen et al. 2023,doi: 10.1016/j.ijhydene.2022.11.292)
    - $1.15 - depleted gas reservoirs
    - $2.50 - salt caverns
    - $3.27 - saline aquifers

Reservoir type:
- Depleted reservoir: 270.1 TWh
- Aquifer: 27.4 TWh
- Salt Cavern: 29.5 TWh



H_2 Facts: Small Size, Low Reactivity, Low Viscosity and Fast Diffusion

- H_2 is very small (radius 0.289 nm), next to Helium (0.26 nm).
- H_2 has the weakest Van der Waals force (adsorption capability) and similar to Helium which is regarded as non-adsorb gas.
- H_2 viscosity is very low, ~44% of helium, and diffusivity is one order of magnitude higher than CH_4 and CO_2 (Ho et al. 2024)
- H_2 is unreactive compared to diatomic elements such as halogens or oxygen due to the very strong H–H bond.



From Delshad et al. (2021) at 150F.

Delshad, M., Mehrabi, M., Ganjdanesh, R., Eichhubl, P., Umurzakov, Y., Sepehrnoori, K., 2021. Simulations of hydrogen storage in sedimentary geologic formations. GeoGulf Transactions, 71, 45-53.

Previous Studies on H_2 - Shale Interactions

- 0.05% – 0.11% H_2 was adsorbed by clay and 6% of Fe^{3+} was reduced to Fe^{2+} in synthetic clay (Didier et al. 2012)

  ➔ 1 m^3 clay can adsorb 1.20 – 2.64 Kg H_2

- Ho et al. 2024 (DOI: 10.1016/j.ijhydene.2023.11.011)
  - About 10 % of adsorbed H_2 can be lost due to hysteresis in shale from NMR analysis
  - About ~30 % of residual CH_4 can be desorbed upon H_2 injection.

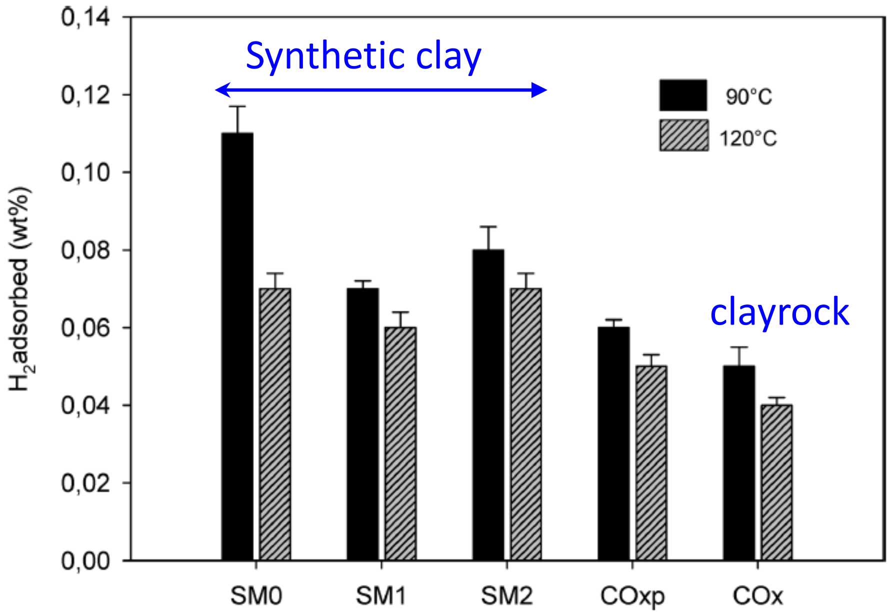


Figure 1. Hydrogen adsorption values on dry synthetic montmorillonites (SM0, SM1, and SM2), Callovo-Oxfordian clayrock (COx), and purified COx (COxp) at T = 90 and 120 °C after 30−45 days under P_{H2} = 0.45 bar. The amount of adsorbed H_2 is calculated from

Didier et al. 2012, dx.doi.org/10.1021/es204583h

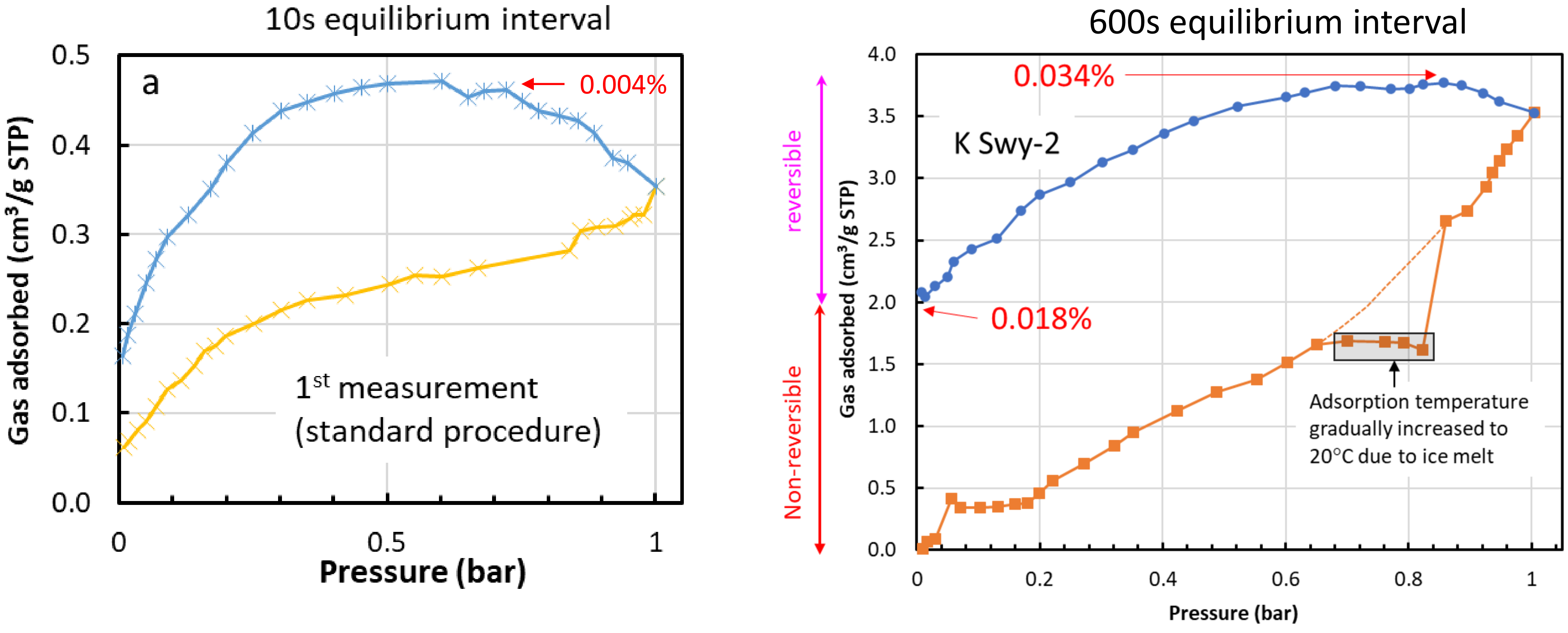
With 0.5 gram powder using 95% Ar + 5% H_2

Low pressure adsorption at 0 °C up to 1 bar

Traditional method: pressure is recorded every 10 seconds and if new pressure is within 5% or 5 torr (whichever is less) of previous pressure, then the system is assumed in equilibrium and moves to next pressure measurement. If the adsorption is very slow, it could be “pseudo equilibrium”.

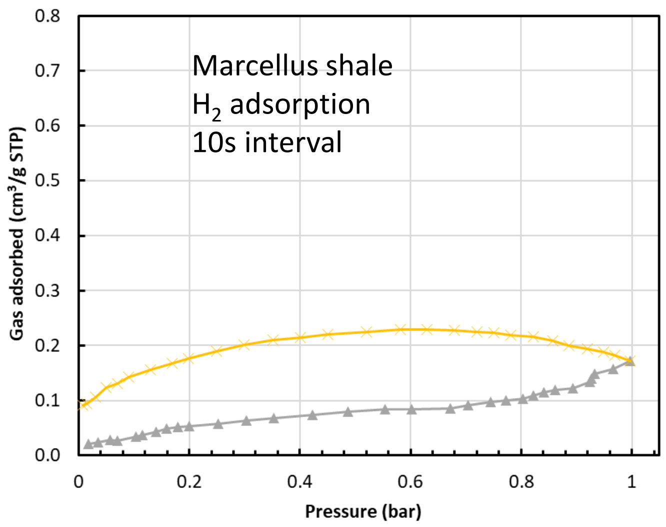
Long equilibrium method: pressure is recorded every 600 seconds and if new pressure is within 3% or 3 torr (whichever is less) of previous pressure, then the system is assumed in equilibrium and moves to next pressure measurement.

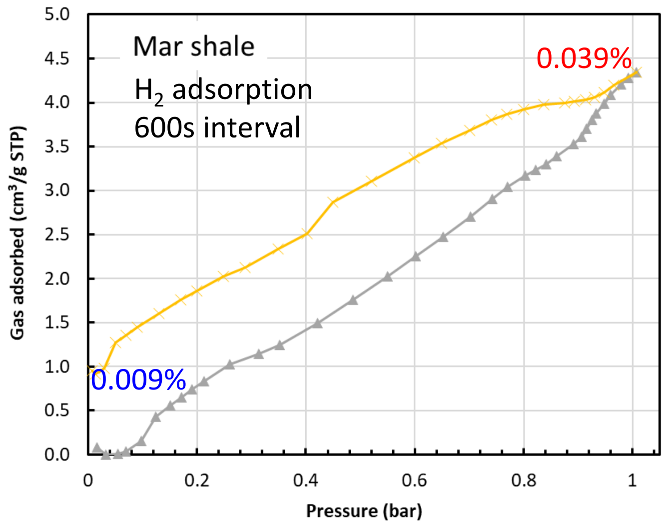
H_2 Adsorption in K-Montmorillonite at 0 °C and Low Pressure (up to 1 bar)

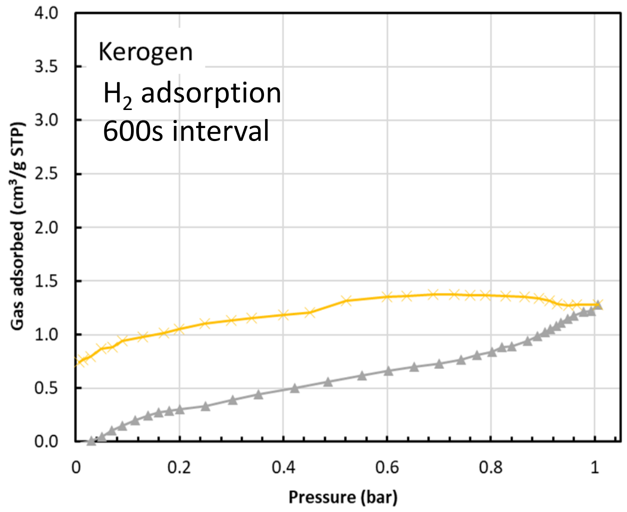


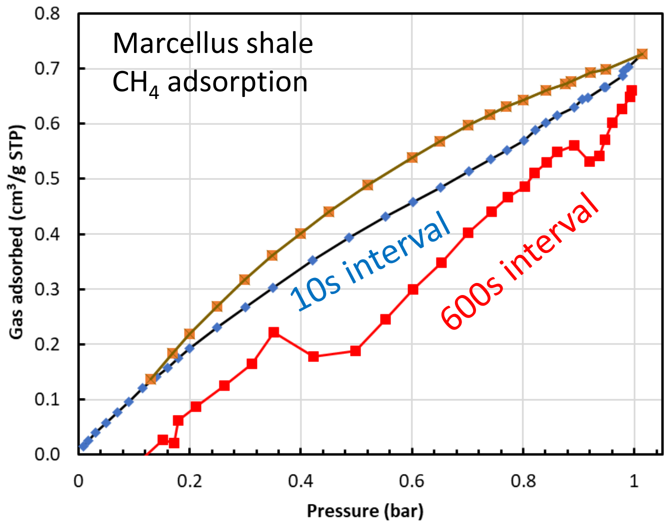
- This confirmed literature data that significant amount of H_2 can be adsorbed by clay and retained in clay
- Hydrogen adsorption is very slow despite perception of H_2: small and fast

H_2 (CH_4) Adsorption in Marcellus Shale and Kerogen isolate at 0 °C and up to 1 bar









- H_2 adsorption in shale is up to 0.039% given enough time, less hydrogen retained compared to clay.
- In contract, CH4 adsorption is fast with less hysteresis, and H_2 can adsorb more than methane in mol content.

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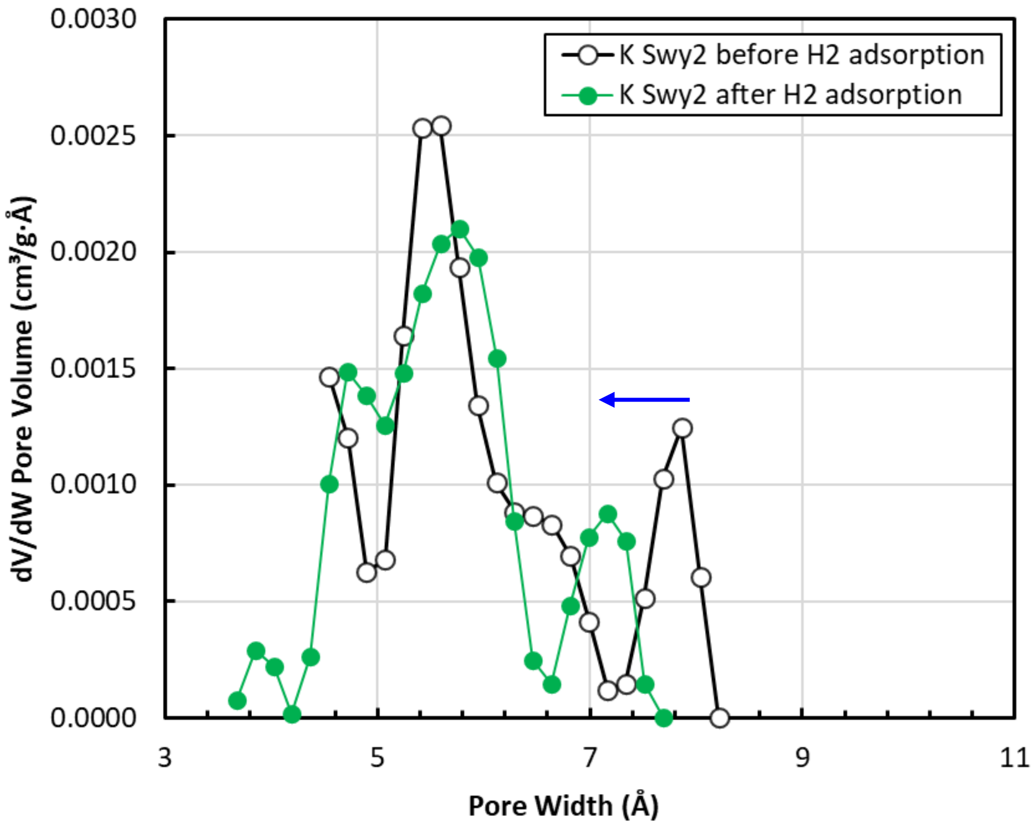
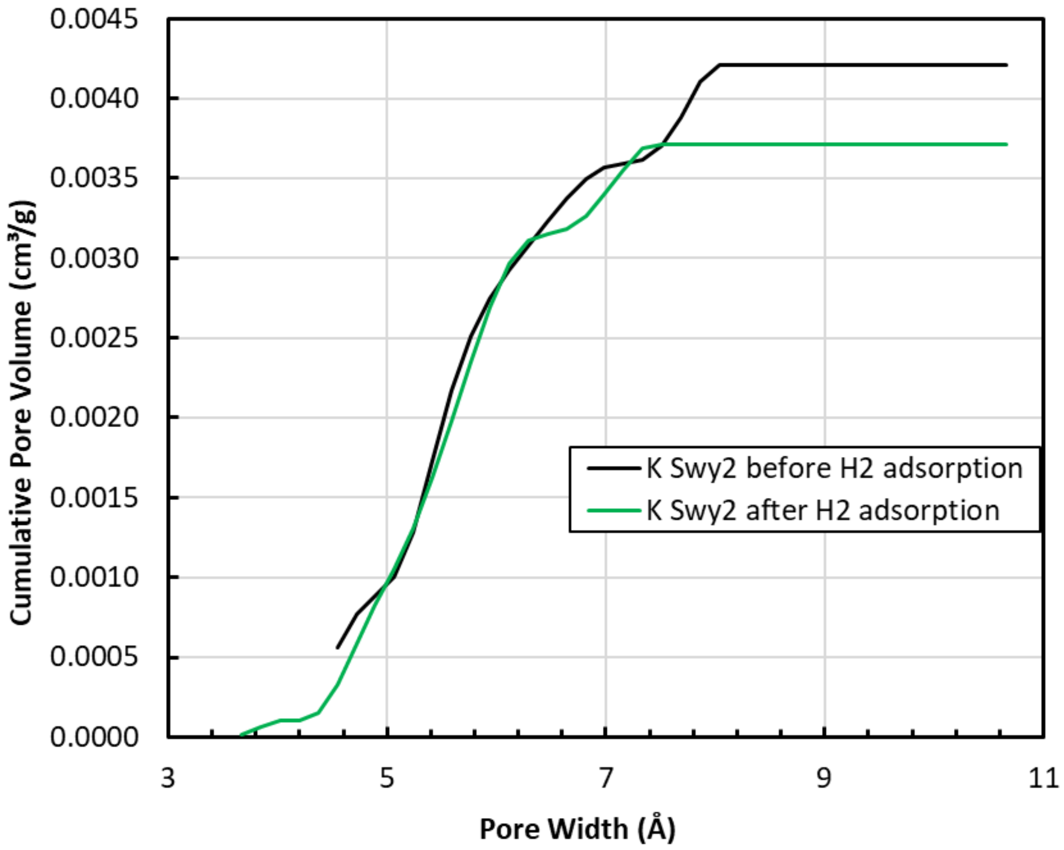
PSD Change in K-Swy2 After H_2 Adsorption at Low Pressure

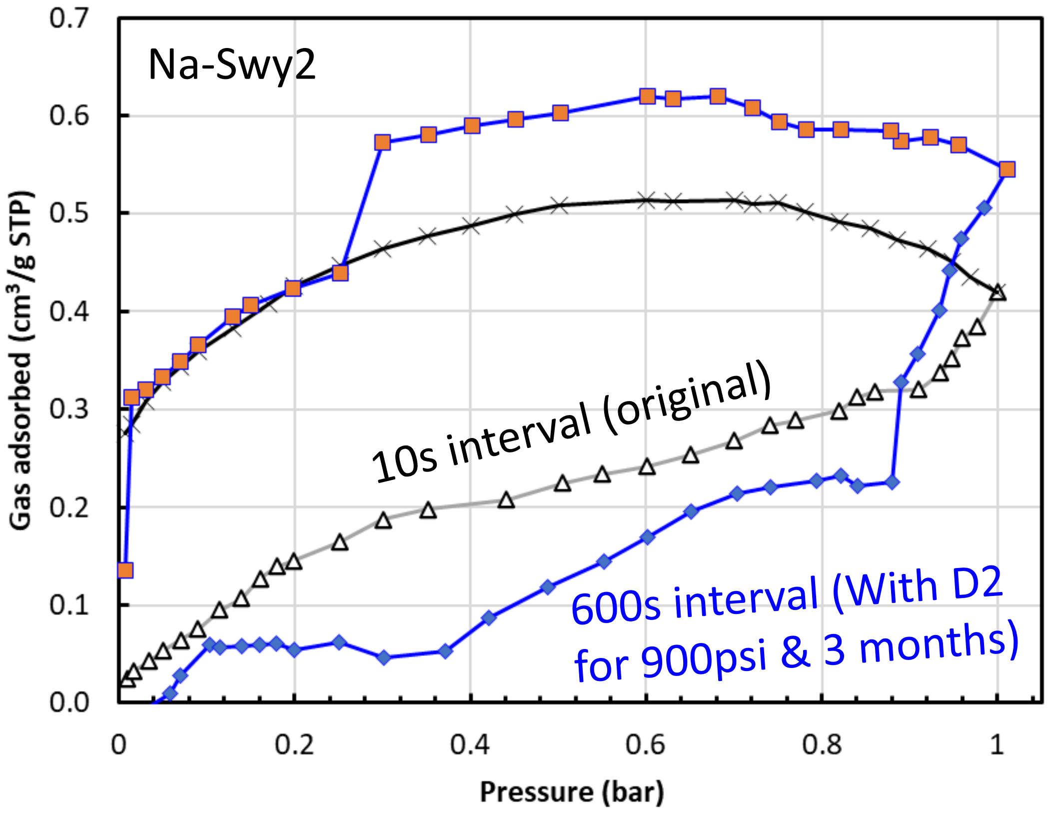


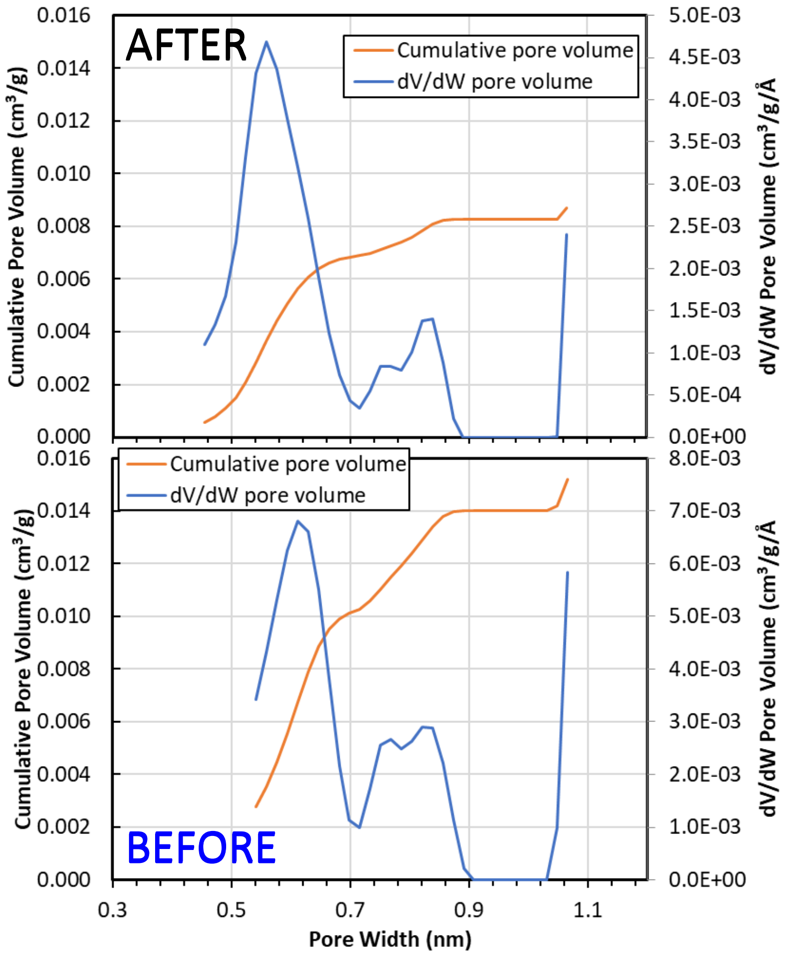


After H_2 adsorption (~6 days), pore size shifts to smaller size and total pore volume decrease

H_2 Adsorption in Na-Swy2 at 0 °C and up to 1 bar after high pressure adsorption

Na-Swy2 powder with D_2 at room temperature and 900 psi for 3 months





After reaction with H_2:

- Adsorption capability decreased significantly
- Pore volume decrease, pore size shifts to smaller

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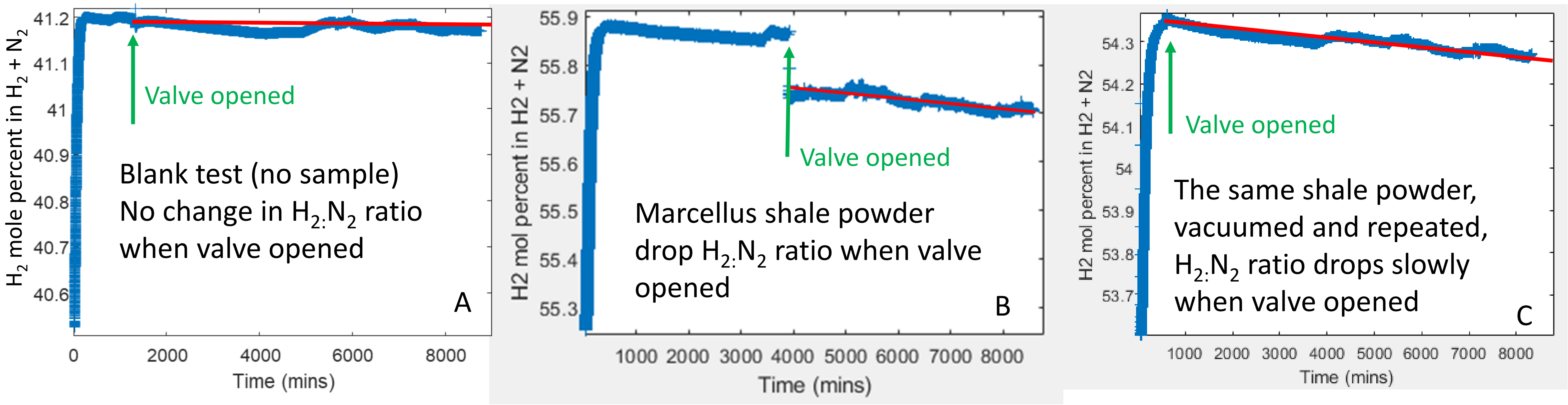
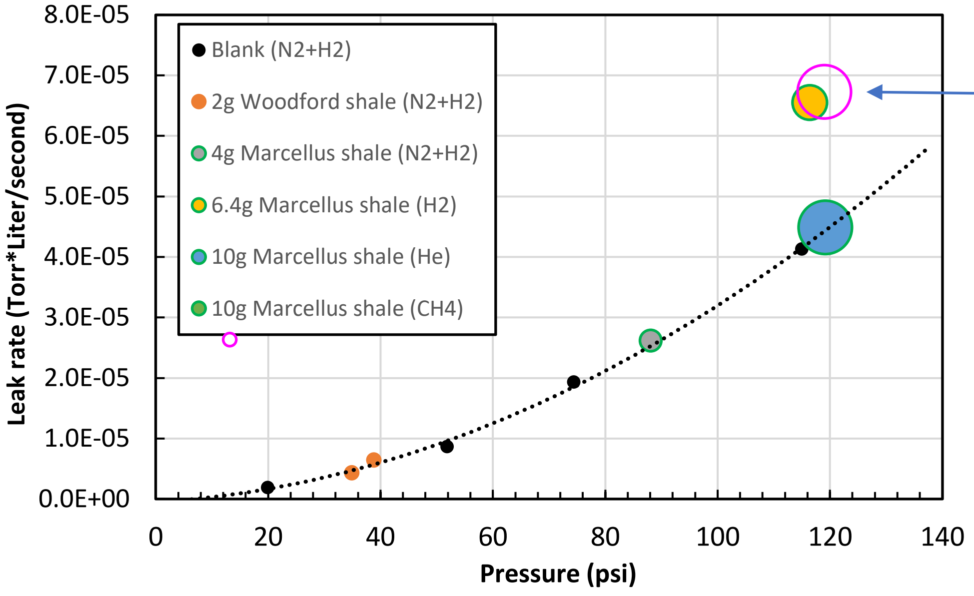
H_2 Adsorption in Cement at 23 °C and ~80-90 psi

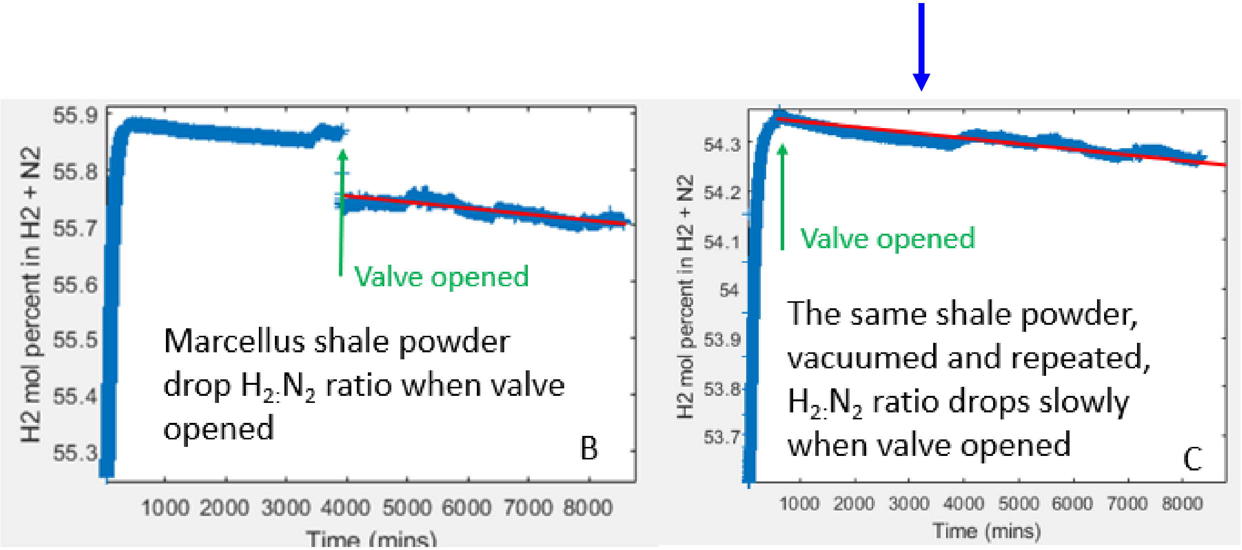


H_2 Adsorption in Cement at 23 °C and ~80-90 psi



0.02% H2 (at 23°C and 120 psi)
0.09% CH4
Mol ratio H_2/CH_4 = 1.76

Arrows: repeat test with same powder



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Summary

- Hydrogen does not seem to enhance the solubility of pyrite, gypsum, anhydrite, dolomite and shale compared to benchmark test with N_2 or He.

- The H_2 adsorption in shale can be significant at low temperature of 0 °C and 1 bar, and nearly 23% can be irreversible, i.e., “permanently“ trapped and loss. Additional CAPEX cost. But the good news is that this is one time cost as the hydrogen adsorption capability decreased after initial adsorption.

- Hydrogen adsorption is very slow compared to methane but has the ability to uptake several times more than methane (in molar) in clay. H2 could desorb CH4 in shale, causing impurities.

- After hydrogen adsorption, the pore microstructure changed: pore volume shrinked and pore size decrease.

- Next Step: examine the mechanical implications due to the changes caused (damaged) by irreversible H2 adsorption

Hydrogen TCP – Task 42

SHASTA Workshop Pittsburg

3 April 2024

Serge van Gessel

Website: https://www.ieahydrogen.org/

Technology Collaboration Programme
by iea

IEA Hydrogen TCP in a nuthsell

33 **Members**

25 Member Countries
+ European Commission
8 Sponsors

40+ **Tasks**

7 Open
40 Finished
≅ **5** in definition

250+ **Experts involved**

In collaborative research on hydrogen and hydrogen technologies

Hydrogen TCP
Underground Storage

Hydrogen TCP Task42 Technology Monitoring Report 2023

https://www.ieahydrogen.org/download/17/task-reports/7067/task42_uhs_technologymonitoringreport.pdf

Hydrogen TCP-Task42: UHS - Subtasks and Research Scope

Leads: *Katriona Edlmann (University of Edinburgh)*
Nicole Dopffel (NORCE)

Subtask A: Geochemical and Microbial Impacts

- Geochemical processes
- Microbial processes
- Hydrogen quality & losses
- Impacts on Integrity & Performance

Lead: *Sam Xie (Curtin University)*

Subtask B: Storage Integrity

- Gas Tightness
- Caprock Integrity
- Reservoir Integrity
- Faults and Fractures

Leads: *Ed Hough (British Geological Survey)*
Gordon Taylor (RPS-Group)

Subtask C: Storage Performance and Screening

- Hydrogen Flow
- Physics ad Thermodynamics
- Hydrogen Recovery
- Cushion Gas Effects

Leads: *Remco Groenenberg (TNO)*
Nicolas Faucompret (Halliburton)

Subtask D: Facilities and Wells

- Well design & materials
- Facility design & engineering
- Operational parameters & limits
- HSE and monitoring

Leads: *Arnaud Reveilere (Geostock)*
Gianluca Grecco (FHA)

Subtask E: Economics and System Integration

- CAPEX & OPEX
- Revenue models
- Energy system services
- Market

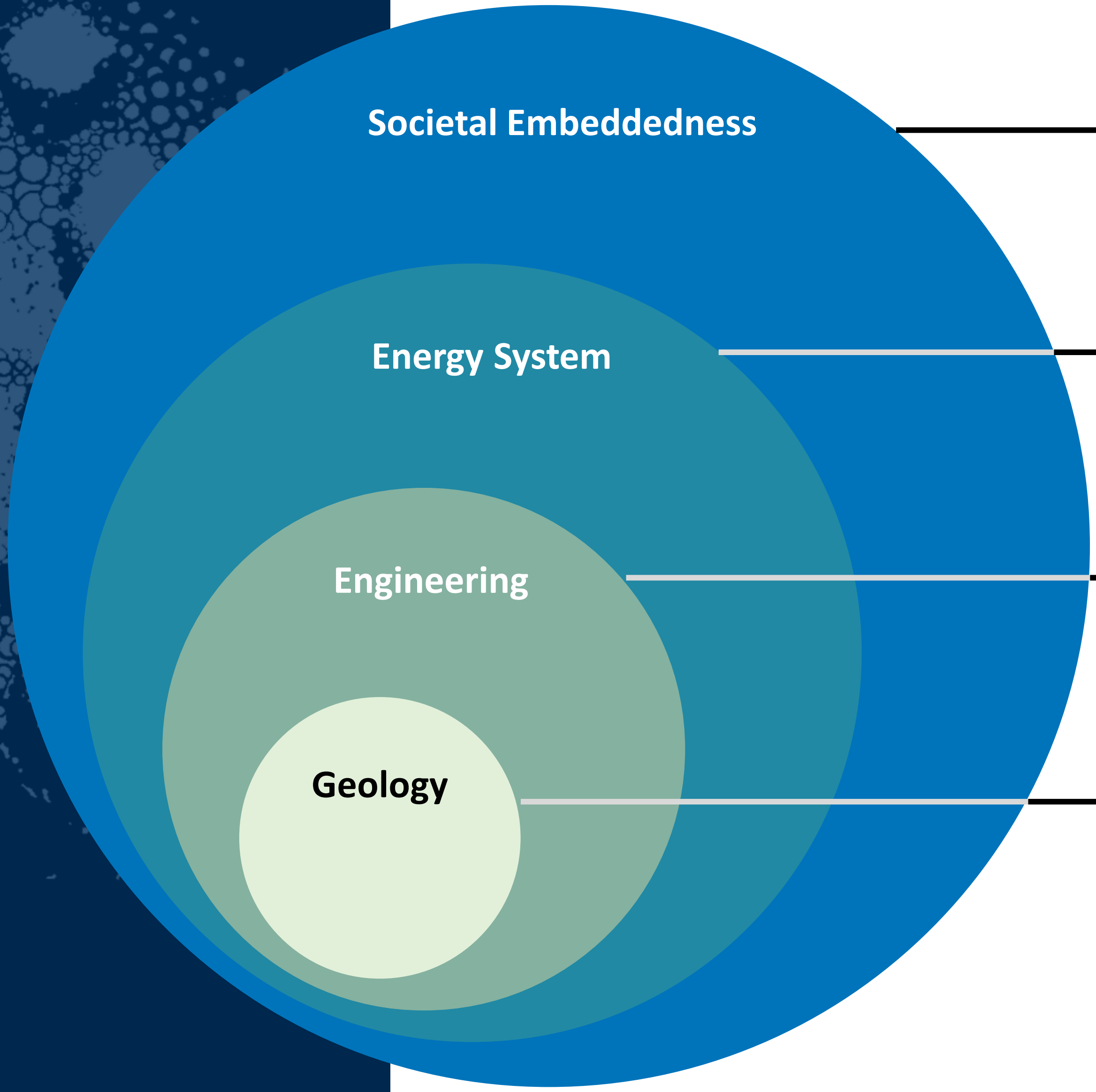
Leads: *Serge van Gessel (TNO)*
Richard Schultz (Orion Geomechanics)

Subtask F: Societal Embeddedness of UHS

- Safety & Environmental impacts
- Stakeholder involvement
- Policy, regulations, planning
- Financial resources, cost/benefit

Hydrogen TCP
Underground Storage

UHS Confidence needs to be build across all domains



Social/environmental impacts and safety
Regulations, norms, standards
Communication and trust
Stakeholders and interactions

CAPEX and OPEX estimates
Impacts on costs
System integration and services
Revenue models, Market

Well materials and designs
Gas treatment
Operations and Safety
Monitoring

Reservoir characteristics
Geochemical and microbial reactions
Storage integrity and geomechanics
Flow performance, migration, recovery
Geological screening

Level of Confidence

1. Identification
2. Modelling
3. Verification
4. Implementation

Some thoughts:

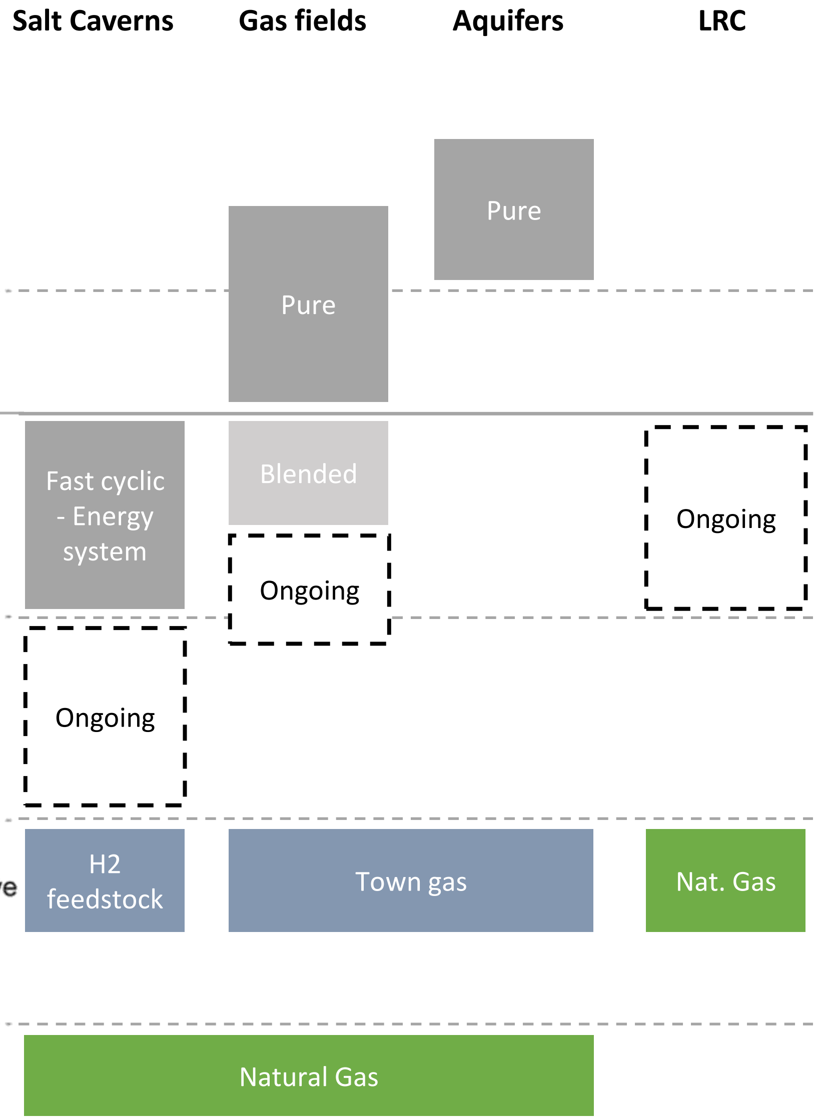
- What KPI's/criteria to use?
- Interdependencies
- Measuring progress
- How to communicate?
- Translate to actions

Hydrogen TCP
Underground Storage

Towards UHS confidence: Estimated Technical Readiness Levels

Long (10+ year) lead times towards commercial; Capacities needed after 2030

CONCEPT	1	**Initial idea** Basic principles have been defined
	2	**Application formulated** Concept and application of solution have been formulated
	3	**Concept needs validation** Solution needs to be prototyped and applied
SMALL PROTOTYPE	4	**Early prototype** Prototype proven in test conditions
LARGE PROTOTYPE	5	**Large prototype** Components proven in conditions to be deployed
	6	**Full prototype at scale** Prototype proven at scale in conditions to be deployed
DEMONSTRATION	7	**Pre-commercial demonstration** Solution working in expected conditions
	8	**First of a kind commercial** Commercial demonstration, full scale deployment in final form
EARLY ADOPTION	9	**Commercial operation in relevant environment** Solution is commercially available, needs evolutionary improvement to stay competitive
	10	**Integration needed at scale** Solution is commercial and competitive but needs further integration efforts
MATURE	11	**Proof of stability reached** Predictable growth

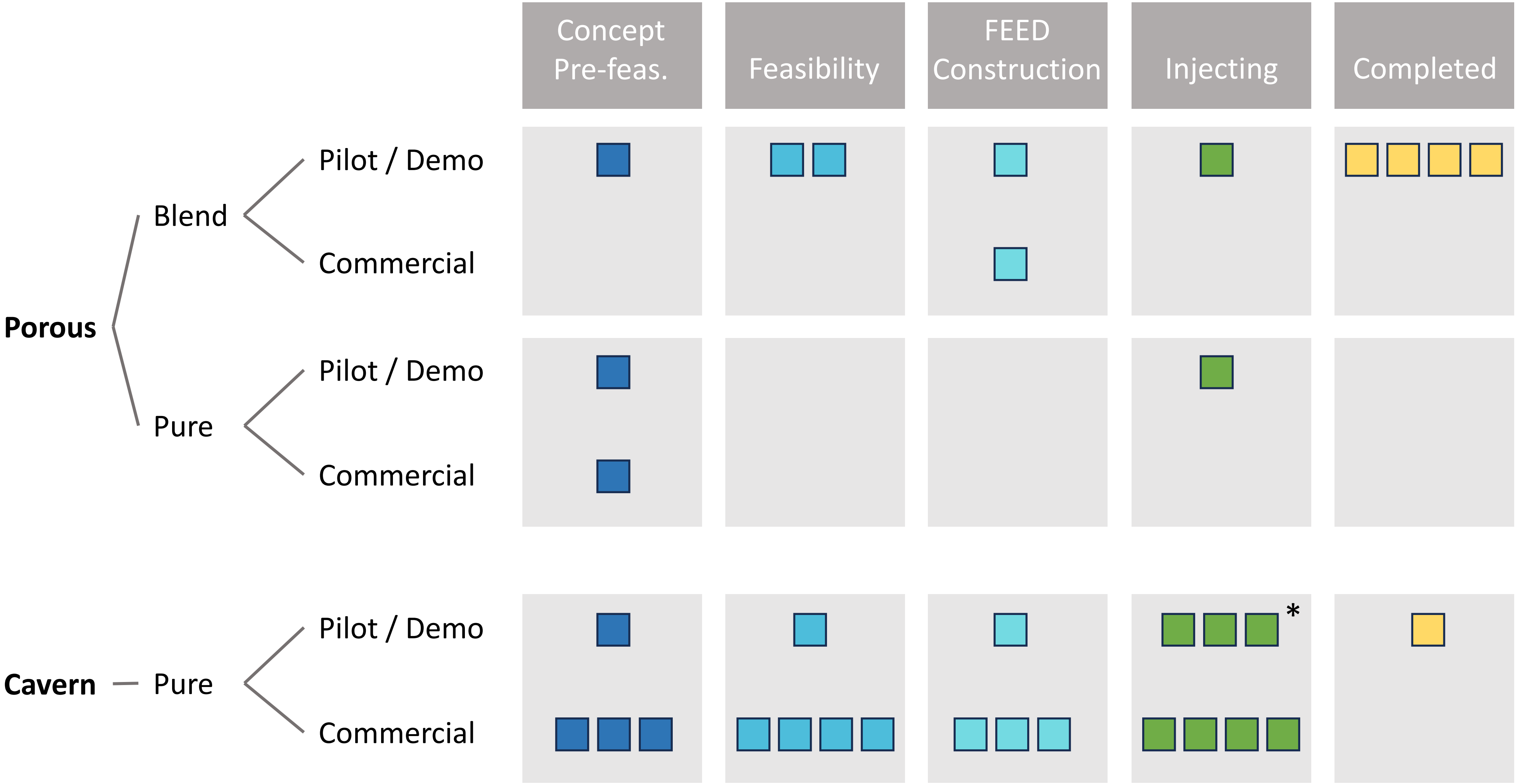


Hydrogen TCP
Underground Storage

Pilots and first commercial projects are under development (Europe and US)

This information is compiled from various public sources on the internet.

The information is provided on an "as is" basis with no guarantees of completeness and accuracy.



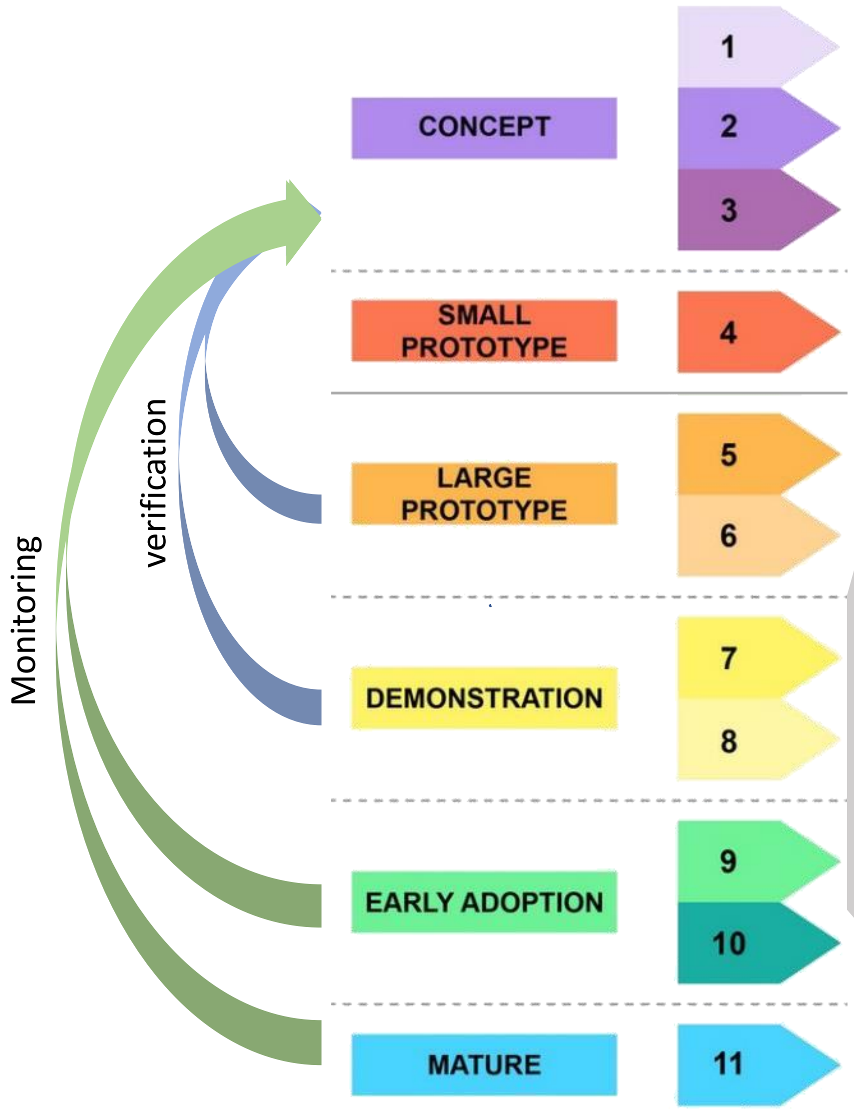
Town gas: Porous: 7 Salt cavern: 2

* One pilot in a lined rock cavern

Projects listed in Hydrogen TCP-Task 42 (2023), "Underground Hydrogen Storage: Technology Monitor Report"

Towards confidence: Technical Readiness Levels

Long (10+ year) lead times towards commercial; Capacities needed after 2030



TRL – Breakdown

- Components with high TRL, e.g. based on UGS, oil/gas operations, cavern development
- What is new for UHS and needs proof of concept/demonstration

Generic TRL vs. Site Specific TRL

- Components that are manufactured
- Components that depend on local geology (exploration, characterization, uncertainties)

Verification & Monitoring

- Feedback: Adapt concepts and models
- How much verification needed before agree on general confidence in TRL?
- What if verification is not published / available?

Hydrogen TCP Underground Storage

Storage of Hydrogen vs. Natural Gas: What are the Differences?

Extensive industry experience in **constructing gas storage facilities** and gas (and oil) storage **and** production **wells**

Differences in design of wells and facilities stem mostly from **differences in characteristics** and **impact** of hydrogen gas vs. **natural gas**.

Molecule size

Hydrogen is a **smaller** and **lighter** molecule than natural gas, has a **higher diffusivity**, and a **lower viscosity**.

Chemical reactivity

Hydrogen is **highly reactive** and other reservoir fluids can enhance negative interactions. It can also **induce microbial activity**, causing a.o. Microbially Induced Corrosion (MIC)

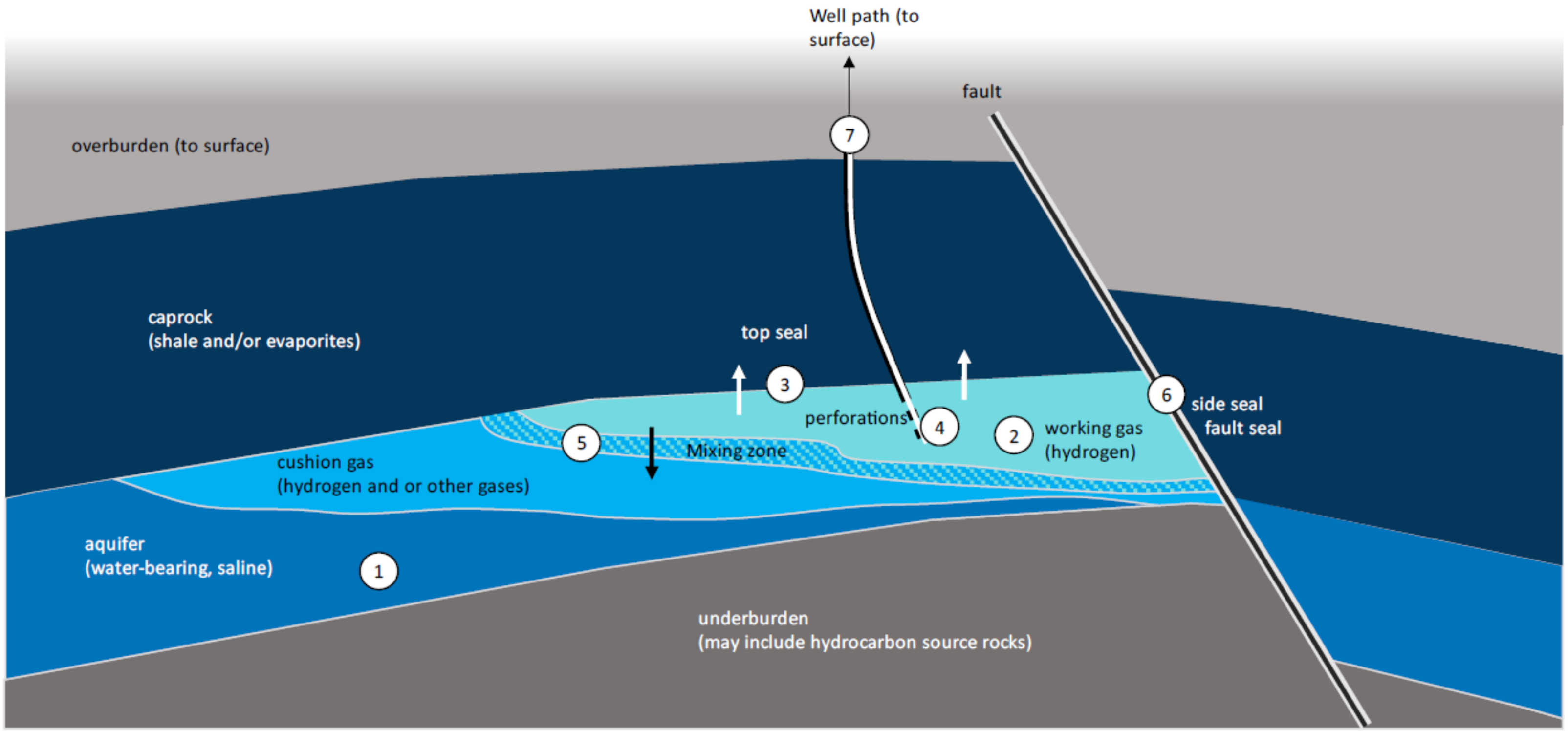
Cycling frequency (?)

Hydrogen stores are expected to inject and extract hydrogen frequently, meaning **more frequent pressure** and **temperature cycling** which can fatigue well components, and the near-well area of the reservoir.

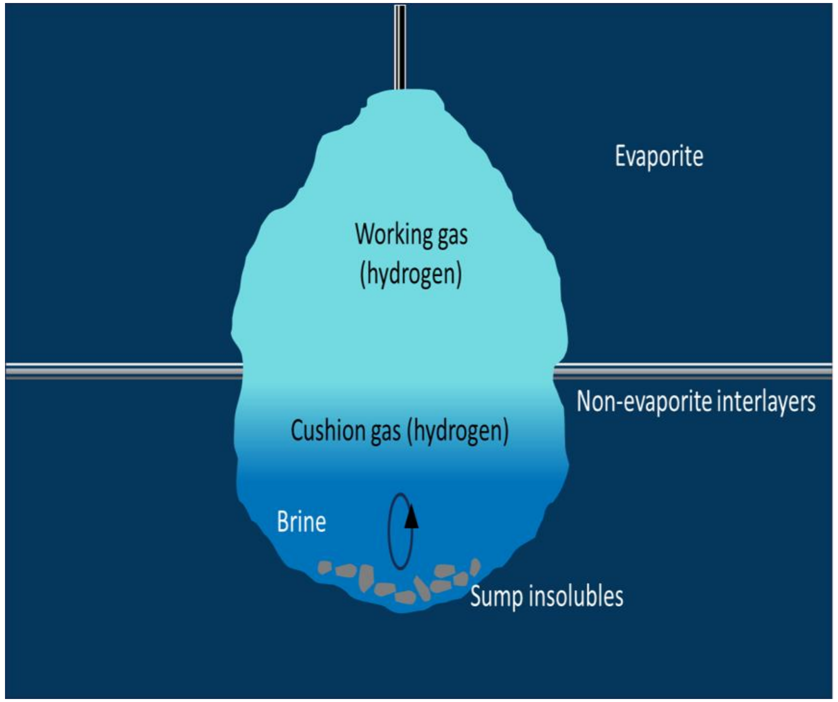
H_2 compatibility

New **materials** and **components** may be required that can withstand long-term operations under extended **exposure** to **hydrogen** or H_2S.

Confidence in understanding and prediction of underground behavior and processes under H_2 storage operations



1. Hydrogen generation (biotic, abiotic)
   Hydraulic drive
2. Hydrogen consumption (biotic, abiotic)
   Dissolution in brine
   Adsorption on clay
   Residual trapping
   Mineral dissolution and precipitation
   Hydrogen contamination
   Souring (H_2S) formation
3. Geomechanical failure
   Subcritical crack growth
   Abiotic and abiotic reactions
   Diffusion, dispersion, permeation
   Capillary pressure
   Buoyancy effects
4. Stress changes
   Subcritical crack growth
   Diffusion, permeation
   Near well thermal effects
   Intergranular clay swelling and shrinkage
   Dehydration
   Microbial influenced corrosion
5. Fingering, channeling
   Gravity override
   Mixing
   Hydrogen consumption (abiotic, biotic)
   Hydrogen contamination
   Residual and capillary trapping
6. Mineral dissolution and precipitation
   leakage, dispersion
   Fault reactivation
7. Cement degradation
   Casing corrosion (biotic, abiotic
   Biofilm, flow assurance



Relevant characteristics and processes are mostly identified

Growing evidence on impacts of geochemical, microbial, geomechanical and thermodynamic impacts

Hydrogen TCP
Underground Storage

Prediction, quantification of processes and impacts

Fully coupled models representative for UHS, interplay of processes

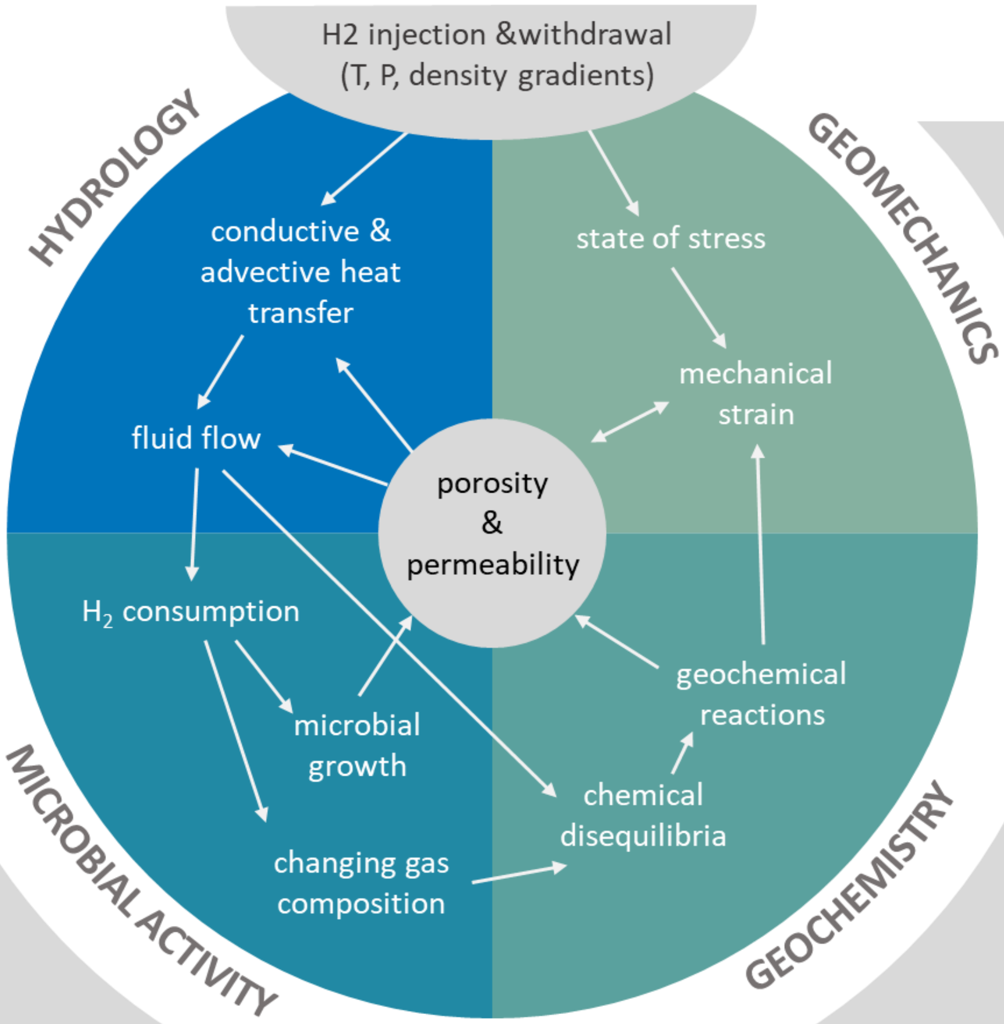
Databases with field and experimental data for model validation

Standardized lab methods, and benchmarked models

Spatial and time-lapse resolution and sensitivity of monitoring

Figure Modified after N. Heinemann et al., Enabling large-scale hydrogen storage in porous media- the scientific challenges. Energy & Environmental Science, vol. 14, p. 853–864, 2021.

Cross-cutting nature of processes and impacts affecting UHS
Technical risks, impacts, mitigation



state of stress
- injection/withdrawal rate
- cycling frequency
- H2 pressure amplitude

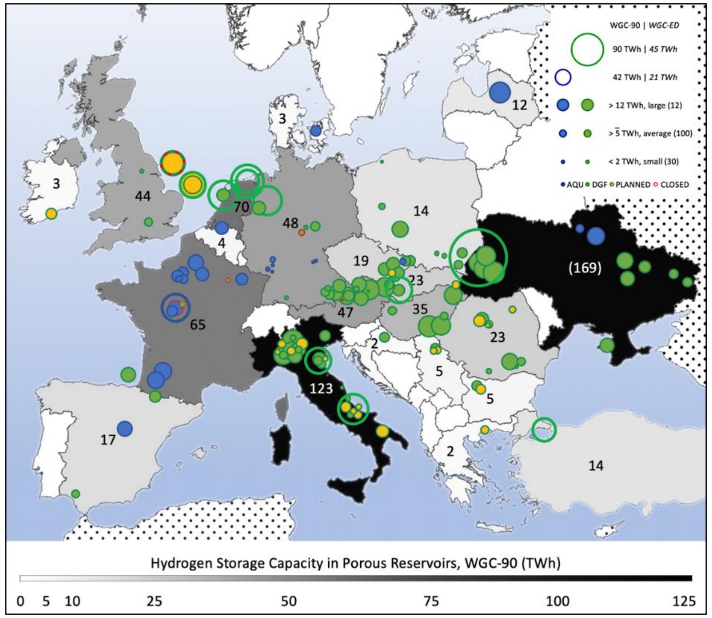
mechanical strain
- subcritical crack growth
- porosity changes
- weakening & strengthening
- sorption (swelling & shrinkage)

geochemical reactions
- soluble minerals
- dissolution & prescipitation
- abiotic redoc reactions
- pH and pE changes
- pore fluid compositional changes (ions, salinity)

microbial growth
- methanogenesis
- aceteogenesis
- SO_4^{2-} reduction
- Fe^{3+} reduction

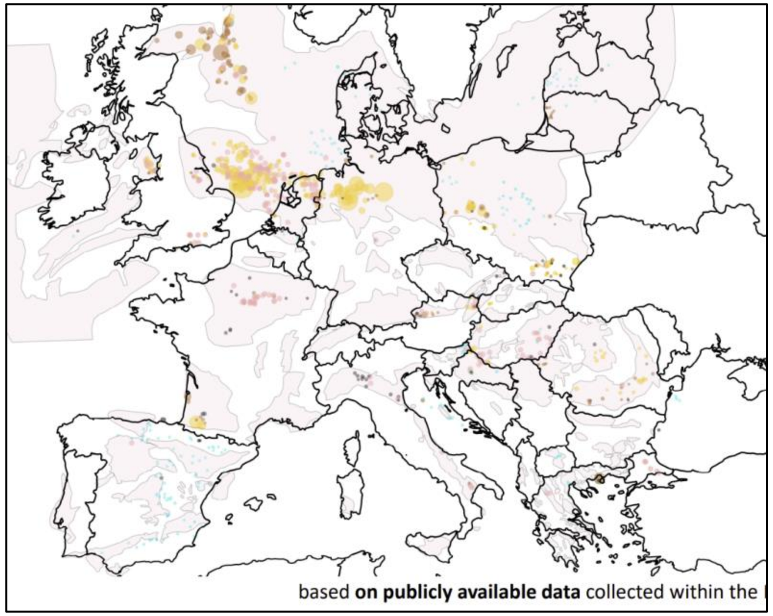
Can we find/determine the optimal geological conditions? To what extent are screening criteria regionally determined?

Existing UGS sites (HyUSPRe)



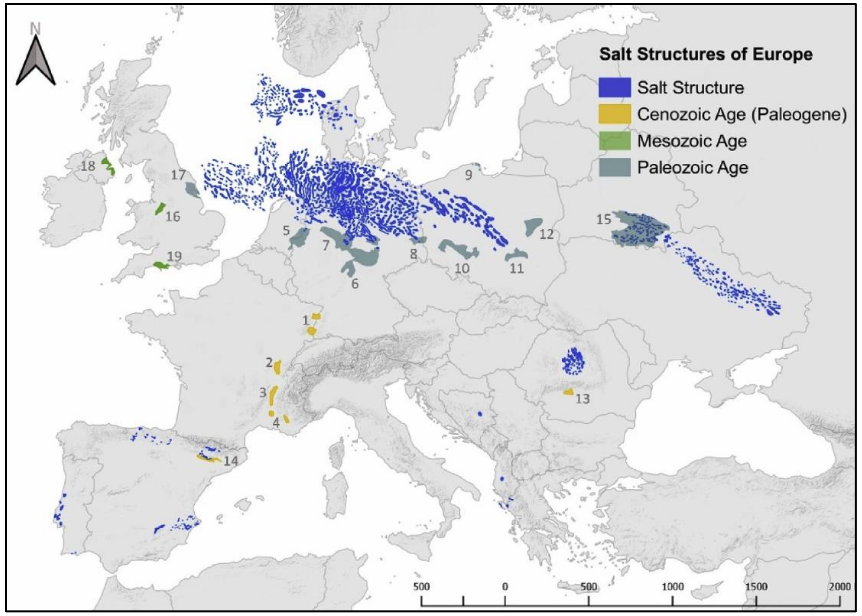
H2020 – HyUSPRe: Cavanagh, AJ, Yousefi, SH, Wilkinson, M & Groenenberg, RM. 2022: Hydrogen storage potential of existing European gas storage sites in depleted gas fields and aquifers.

Porous reservoir traps (Hystories)

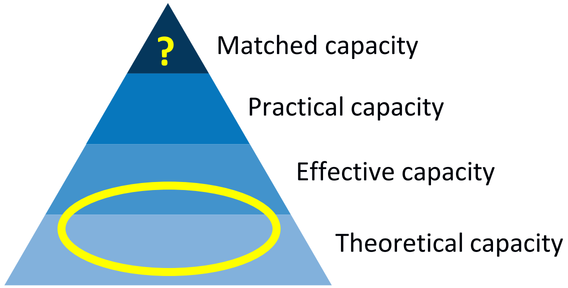


H2020 – HyStories: Ceri Vincent and Yann le Gallo, presented at 15th CO2GeoNet Open Forum, 20 September 2022

Salt caverns (Caglayan)



Caglayan, D.G., Weber, N., Heinrichs, H.U., Linßen, J., Robinius, M., Kukla, P.A., Stolten, D., 2020. Technical potential of salt caverns for hydrogen storage in Europe



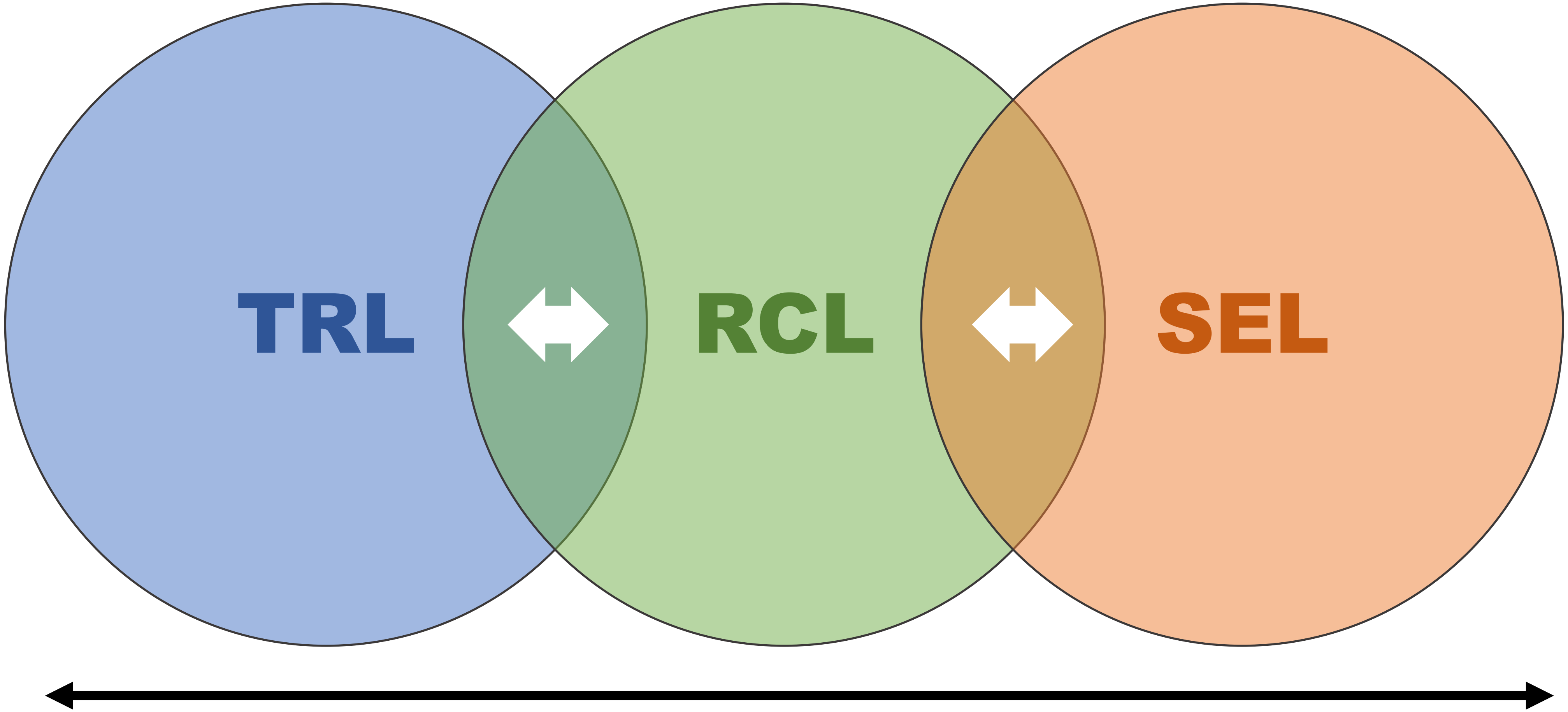
Co-funded by the European Union

Building confidence in UHS

Confidence in screening, system design, operations and commerciality

Confidence in risk identification, reduction, monitoring and mitigation

Confidence in legislation, communication, participation and market



Considers all relevant aspects across the entire life cycle

CONCEPT: RISK CONFIDENCE LEVEL

Technical Readiness Level

TRL 1-3

CONCEPT

TRL 4-6

PROTOTYPE

TRL 7-8

DEMONSTRATION

LEVEL 9+

ADOPTION, COMMERCIAL OPERATION

Risk Confidence Level

LEVEL 1: INDENTIFIED

Identification of all relevant processes and features leading to a possible event
What is the impact?

LEVEL 2: ASSESSED

Modelling and quantification of potential effects, impacts, likelihood, mitigation

LEVEL 3: VERIFIED

processes, monitoring and mitigation measures tested in pilot/demo or oil-gas analogues

LEVEL 4: IMPLEMENTED

Risk is managed/regulated by industry standards and regulations

Societal Embeddedness Level

SEL 1

Social aspects explored

SEL 2

Social aspects assessed

SEL 3

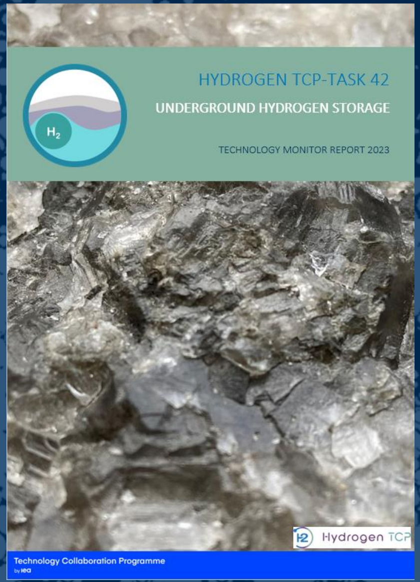
Social aspects demonstrated in full system set-up

SEL 4

Social aspects adopted and proven in societal environment

Hydrogen TCP
Underground Storage

TCP-Task-42 Outlook



Outreach and knowledge sharing

- ❑ Final TCP-Task42 report expected end of 2024
- ❑ UHS Summer school:
  - 3rd edition confirmed as the 8-12th of July 2024 at the University of Edinburgh
  - Intro classes, Main conference, Field trips, Demonstration projects, Geology
  - Enjoy the Scottish traditions
- ❑ Organisation of and participation in Industry and Policy stakeholder events
- ❑ Follow our activities via Newsletters and social media (Linkedin Group)

[Underground Hydrogen Storage Hydrogen TCP Task 42 | Groups | LinkedIn]

References

Hydrogen TCP – Task 42

SHASTA Workshop Pittsburg

3 April 2024

Thank you for your attention

Serge van Gessel

Website: https://www.ieahydrogen.org/

HyBlend
U.S. DEPARTMENT OF ENERGY

An overview of the pipeline blending CRADA - A Hyblend™ Project

Todd G. Deutsch, Kevin Topolski, Zainul Abdin – NREL

Kevin Simmons, PNNL

Chris San Marchi, SNL

Amgad Elgowainy, ANL

SHASTA Technical Workshop

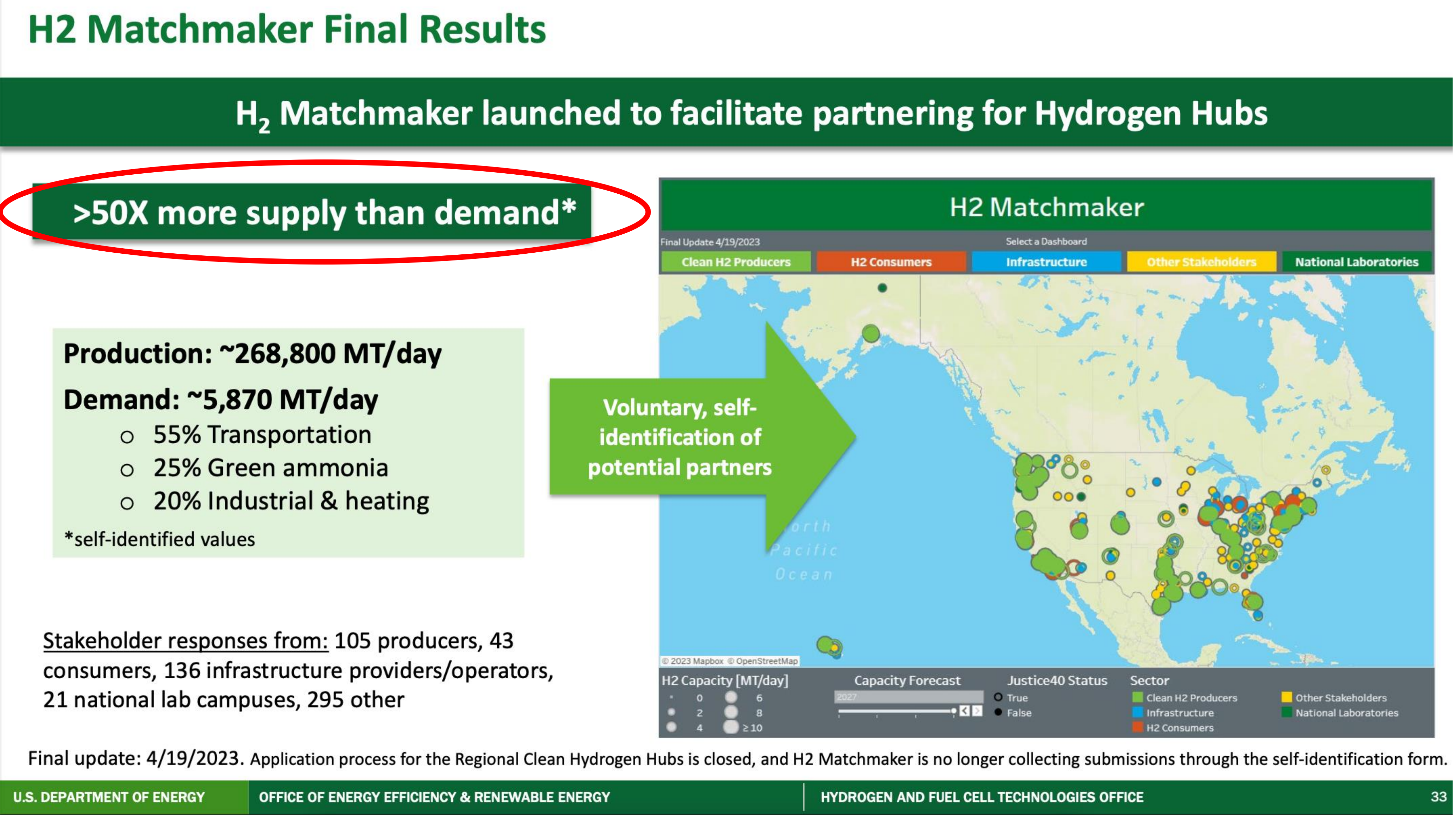
April 3, 2024

Pipeline Blending Benefits

- The U.S. possesses an extensive natural gas pipeline system comprised of **3 million miles**[1] of pipe of which 1.5 million miles[2] is plastic pipe
- Converting networks for hydrogen blending within the U.S. natural gas pipeline system **may offer a low-cost pathway** to distribute green hydrogen
- Blending low-carbon hydrogen into the U.S. natural gas pipeline systems furthers national decarbonization objectives by:
  - Offering a pathway with incremental steps towards cost-efficient pure hydrogen transportation
  - Promoting *early-market access* for hydrogen technology adoption
  - Enabling *short-term carbon emissions reductions* with the potential for long-term emissions reductions for hard-to-decarbonize sectors
  - Potentially providing *lower cost H_2* transport than new-built H_2 pipes or truck delivery
  - Facilitating a *smooth transition* for natural gas workforce into clean energy jobs
  - Utilize existing infrastructure right-of-way to *avoid environmental and social impacts* of developing new energy infrastructure

Ref 1: Celestine, A. D. N., Sulic, M., Wieliczko, M., & Stetson, N. T. (2021). Hydrogen-Based Energy Storage Systems for Large-Scale Data Center Applications. *Sustainability*, *13*(22), 12654.
Ref 2: 2020 Annual Report Data from Gas Distribution, Gas Gathering, Gas Transmission, Hazardous Liquids, Liquefied Natural Gas (LNG), and Underground Natural Gas Storage (UNGS) Facility Operators. USDOT, PHMSA.

Sunita Satyapal's Plenary Talk at DOE Hydrogen & Fuel Cell Technologies Office Annual Merit Review (June 2023)



Blending H_2 into NG network can provide a short-term sink for excess production of clean H_2 until demand for (pure) H_2 catches up.

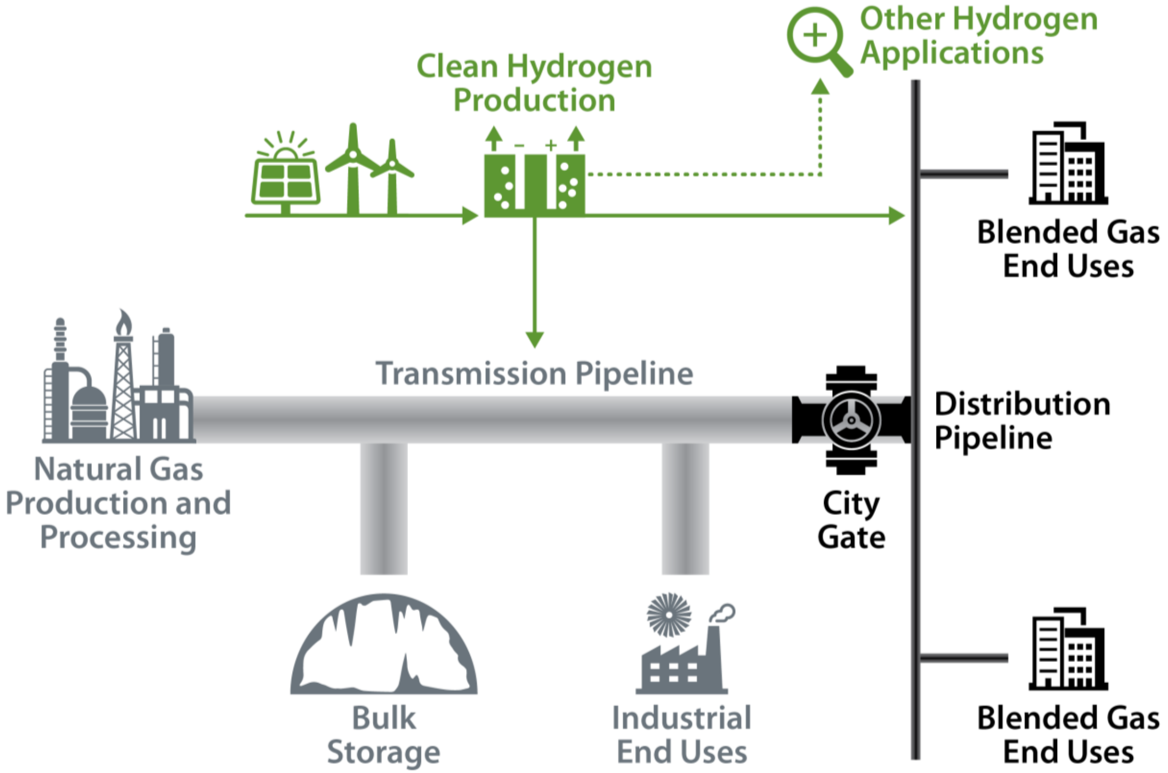
Hydrogen Blending in Natural Gas Pipelines

HyBlend
U.S. DEPARTMENT OF ENERGY

Reducing the Carbon Intensity of the Natural Gas Grid via Hydrogen Blends

Phase I: Two-year, $15MM CRADA Project

- 4 National Labs + 31 partners from industry and academia
- Objectives
  - Pipeline materials compatibility R&D
  - Techno-economic and life-cycle analyses



Key Findings and Outputs

- Metals R&D (SNL)
  - Providing scientific bases and probabilistic tools for structural integrity assessment of H_2 pipelines (HELPR software release date: Fall 2023)
- Polymer R&D (PNNL)
  - Blended gases affect the semicrystalline morphology of high-density polyethylene (HDPE), impacting toughness, pipe stability, and outcome depending on polymer chemistry
- Life-cycle Analysis (ANL)
  - Maintaining energy delivery limits the H_2 blending ratio to ~30%, resulting in ~6% life cycle GHG emissions reduction
- Techno-economic Analysis (NREL)
  - Open-source software providing case-by-case economic analysis of preparing transmission pipelines to blend H_2 (PPCT software release date: Fall 2023)

- **Phase I Summary @ October DOE H2IQ Hour**
  - Results from first CRADA presented at the webinar
  - Recording and slides available (search "H2IQ")

Visit the HyBlend™ Initiative webpage for details and links to tools and publications

Lead Laboratories

ANL
Amgad Elgowainy
Environmental Impact (GREET)

NREL
Mark Chung
Technoeconomic Analysis

H2@SCALE Analysis Leads

SNL
Chris San Marchi
Metallic Material Testing

PNNL
Kevin Simmons
Polymeric Material Testing

Hydrogen Materials Consortium (**H-MAT**)

HyBlend Pipeline CRADA Objectives

Materials R&D

- Develop public **tools** that **assess the risks of blending** to a pipeline system, given the materials in use, age of the system, and blend concentration.
  - The tools will be informed by systematic testing of metal and polymer materials used in pipelines, such as steel and polyethylene, with hydrogen blends.

Technoeconomic Analysis

- Develop a **tool** that evaluates the **opportunities and costs of blending** and of **synthetic natural gas**.
  - The tool will allow for user-defined scenarios of electricity price, pipeline materials, and decarbonization drivers. R&D will assess the impact of hydrogen on durability of pipeline materials, using unique high-pressure test facilities at the H-Mat labs.

Life-cycle Analysis

- **Analyze life-cycle** greenhouse gas and criteria pollutant **emissions of blending** relative to alternative pathways**.**
  - This includes conventional natural gas and synthetic gas pathways, which will be incorporated into GREET®, a public-facing environmental life-cycle analysis model.

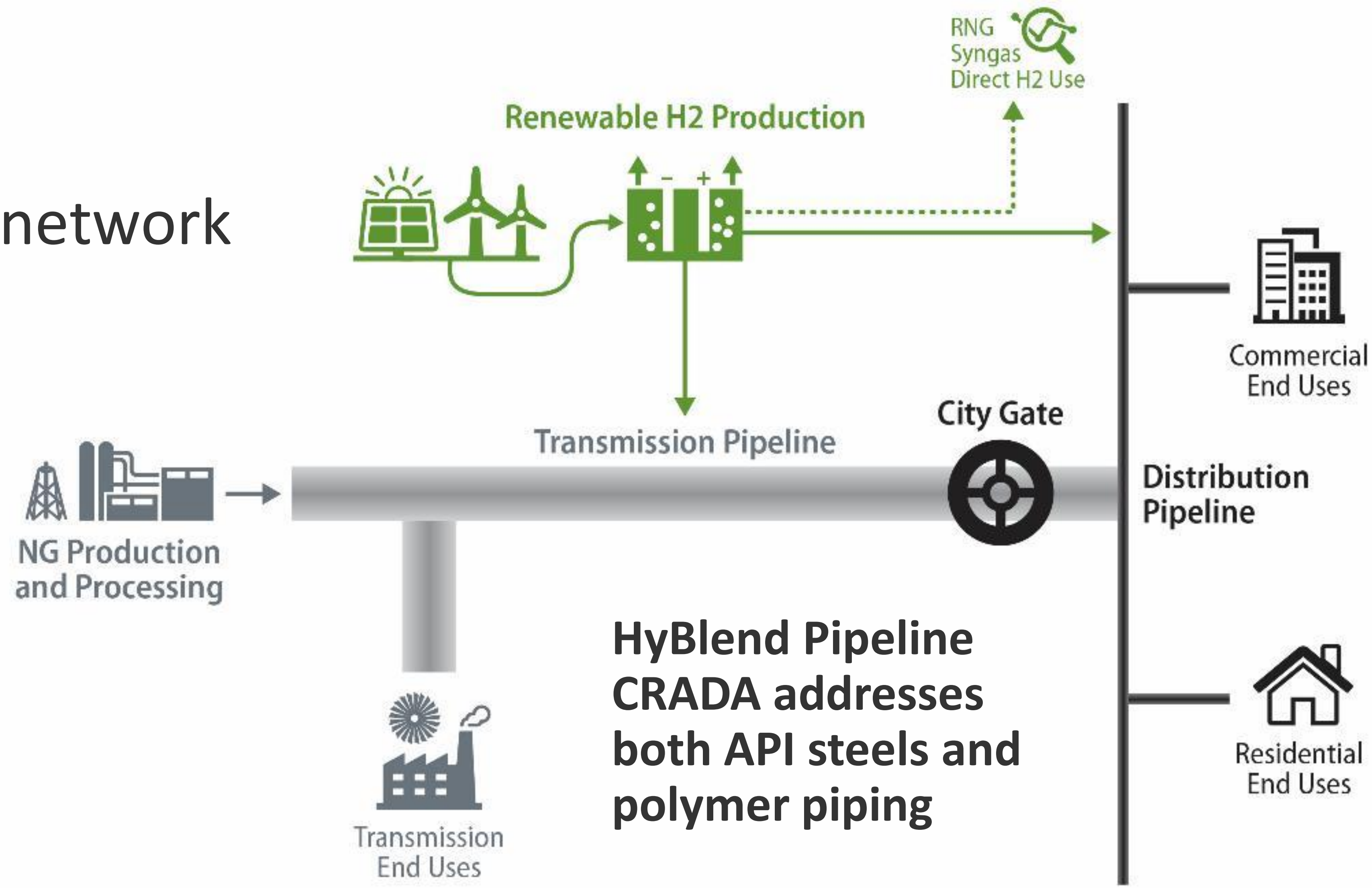
HyBlend Pipeline CRADA: Materials R&D

Transmission

- Mostly steels
- Extensive existing network

Distribution

- Legacy metals
- Extensive polymer networks



HyBlend Pipeline CRADA addresses both API steels and polymer piping

Metals R&D Approach (Sandia National Laboratories): Structural Integrity for Hydrogen Gas Infrastructure

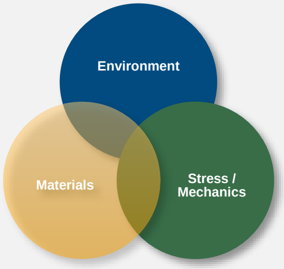
How do we assess structural integrity of infrastructure with hydrogen?

What is the structural risk to NG assets with blended hydrogen?

How do we formulate mechanistic models into predictions?

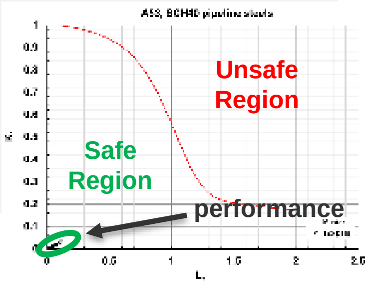
Database of design properties for NG assets with hydrogen

- Assessment of critical parameters determining materials response in hydrogen environments
- Survey of critical materials in ancillary equipment (e.g., pumping stations)
- Evaluation of vintage materials in existing infrastructure



Pipeline Structural Integrity Tool

- Tools to evaluate probability of rupture of NG assets based on Nuclear Regulatory Commission (NRC) framework
- Uncertainty analysis to inform experimental evaluation
- Sensitivity analysis to determine opportunities for system and operational improvements
- Regulations, Codes, and Standards (RCS)-based structural integrity assessment



Physics-based mechanisms of hydrogen embrittlement relevant to NG assets

- Develop deeper understanding of mechanisms of hydrogen embrittlement
- Establish models and framework for implementing physical phenomena into structural integrity tool
- Inform materials selection guidance and establish basis for potential future materials development activity

Guidance on operating conditions

+ partners

Industry-focused probabilistic framework for risk assessment

State-of-the-art characterization

International coordination *facilitates* definition of requirements, *reduces* redundancy, *enhances* rigor, and *improves* breadth of structural integrity tools

Polymers R&D Approach (Pacific Northwest National Laboratory): Hydrogen Effects on Aging of Distribution Infrastructure

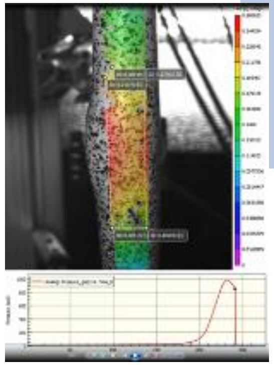
Phase I: Basic Property Characterization
Modulus, yield stress, fracture strength, burst strength, elongation at break, crystallinity, etc

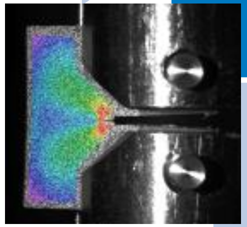
→

Phase II: Life Prediction
Select appropriate life-prediction models and test method for shortened time based on Phase I results and failure mechanism analysis

Inputs from industry & literature survey → **Define test environments**

- Temperature
- Pressure
- H_2 amount
- Defects



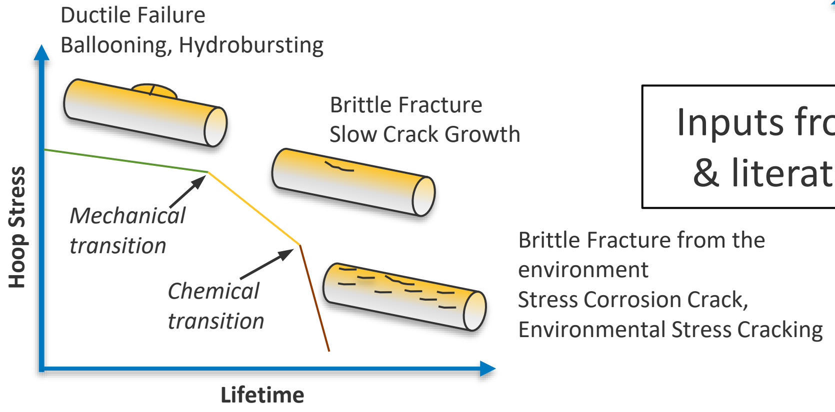


Collect property data

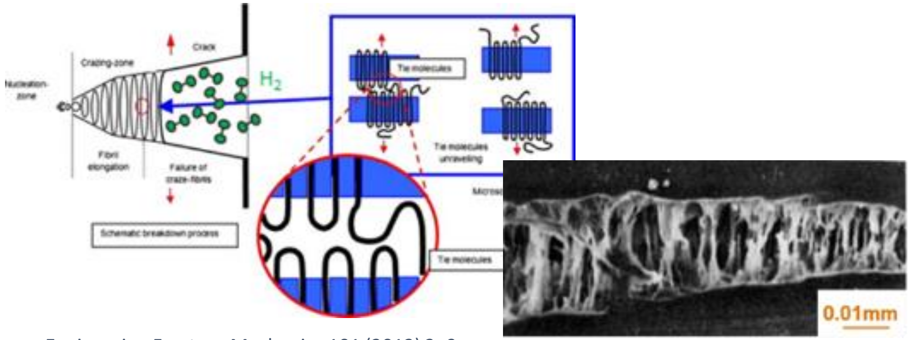
- Tensile dog bones
- SENB/CT Fracture
- Pipe geometry

Evaluate hydrogen effects on properties

- Measure properties with and without hydrogen exposure and characterize failure mechanism



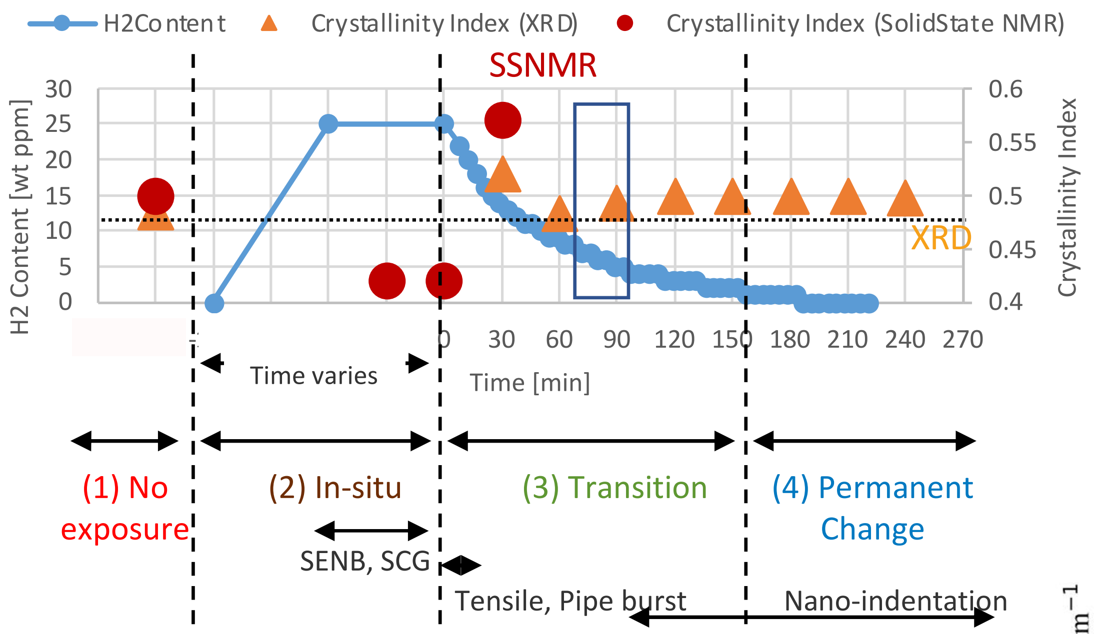
Inputs from industry & literature survey



Engineering Fracture Mechanics 101 (2013) 2–9

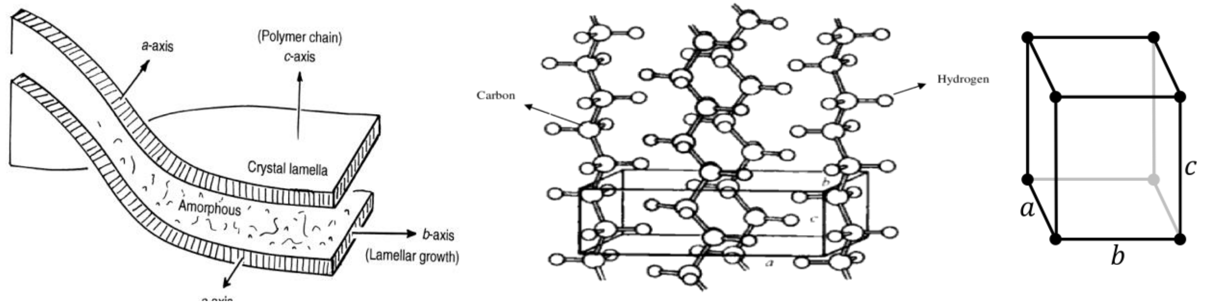
Observed Time Dependence on Polymer Crystallinity

Hydrogen time-dependent effects on crystallinity



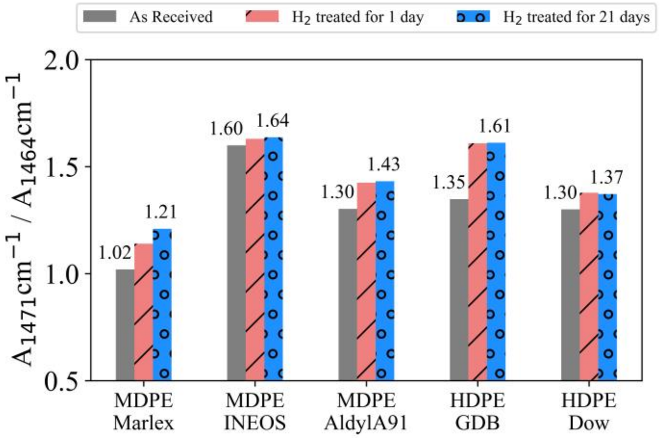
Demonstrates the need for in-situ testing

Orthorhombic PE crystal



- 1471 cm^{-1}: molecular vibrations parallel to the a-axis of crystal lamellae.
- 1464 cm^{-1}: molecular vibrations along the crystal b-axis, i.e., the lamella growth direction.
- *$I_{1378cm-1}/I_{1368cm-1}$: degree of chain entanglement

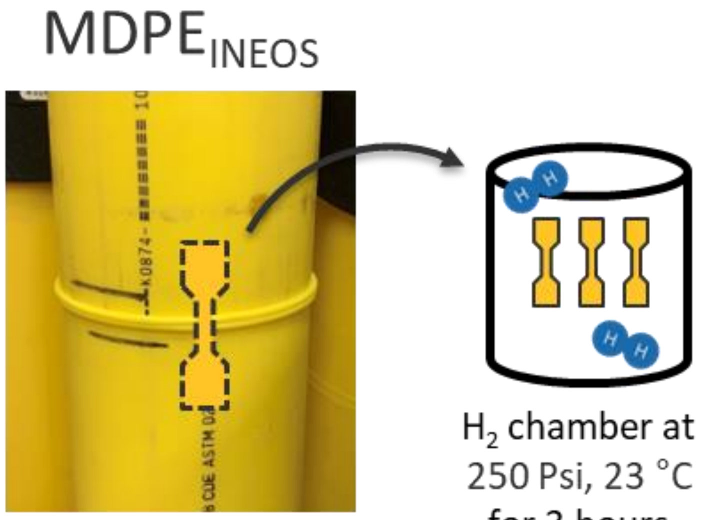
Crystalline Alignment



- Crystalline alignment in all PE pipeline materials increased after the hydrogen exposure.
- The degree of crystalline alignment was insensitive to the exposure time except the MDPE-Marlex.
- Amorphous molecular vibrations (chain entanglement) exhibited mixed behaviors depending on the material.

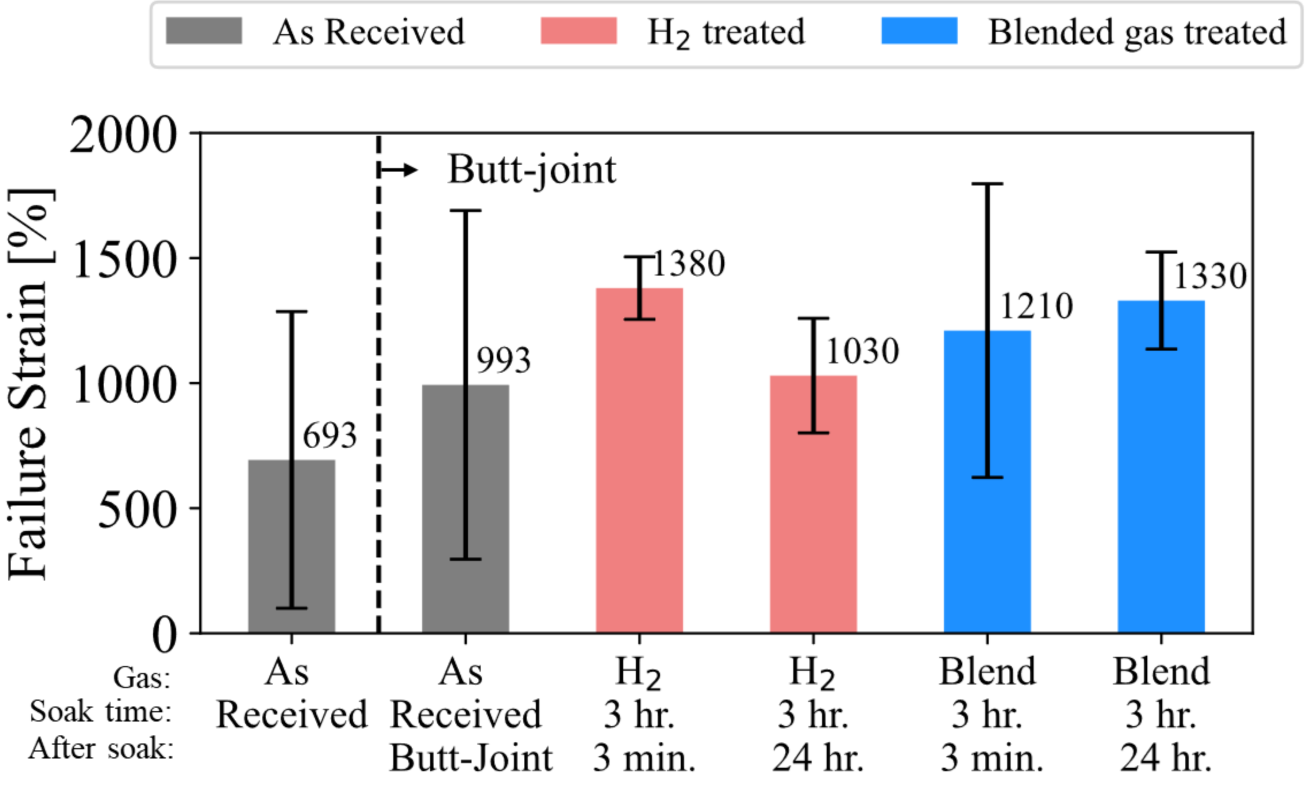
Not All Hydrogen Interactions With Polymers Are Bad

$MDPE_{INEOS}$ @ 250 psi, RT



Butt-fusion joint pipes from SoCalGas

Improved performance of butt-fusion joints after hydrogen and blended gas exposure



The average failure strains are improved and the property variations are reduced.

Materials R&D Summary

- **HyBlend Pipeline CRADA** is multi-lab, stakeholder-driven project
  - Goal of Materials R&D: provide community with **scientific basis to assert safety of piping and pipelines for hydrogen service**
- **Metals R&D**
  - *Preliminary fatigue assessment*: crack growth behavior in hydrogen is bounded and not dependent on alloy or microstructure
  - *Hydrogen-assisted fracture* may be more sensitive to microstructure
- **Polymers R&D**
  - Initial testing shows no change, after initial reduction, in crystallinity or density of MDPE over time in pure hydrogen at constant pressure
    - Previous work did show a hydrogen pressure effect
  - Hydrogen effects on heat fusion joints and effects of defects on the performance of pipe in hydrogen have been identified as gaps

Techno-economic Analysis Approach (NREL)

What upgrades may be required for pipelines? What's the cost?	*What revenue opportunities exist with blending?*	*What are the alternative decarbonization pathways?*

Pipeline Upgrade Cost Model

- Flexible <u>open-source tool</u> to estimate the system cost to blend on a case-by-case basis.
- Captures key NG infrastructure elements (e.g., storage, compressors, piping, materials)
- Use and improve gas network models to understand hydrogen concentration along network and its impact on upgrade costs
- Incorporated materials research from SNL, PNNL to identify and prioritize

Hydrogen Blending Value Model

- <u>Internal tool</u> integrating electrolyzers in power production cost and natural gas network models to estimate the revenue opportunities for hydrogen blending (e.g., sales, grid management, demand response, emissions credits)
- <u>Journal article</u> on use and improve integrated electricity grid and natural gas operational models and hydrogen representation
- Establish metrics for blended system operation

Benchmarking Alternative Pathways

- <u>Internal tool</u> to analyze the economics of alternative pathways to pipeline decarbonization (e.g., estimate USD/tonne-CO_2 avoided cost in collaboration with ANL's LCA modeling)
- <u>Journal article</u> evaluating potential decarbonization pathways including
  - Synthetic natural gas from renewable H_2 + captured CO_2
  - 100% hydrogen pipelines

Materials Research Tasks

Sandia National Laboratories

Pacific Northwest NATIONAL LABORATORY

Building and Improving on NREL Efforts

Southern Company

SoCalGas

A Sempra Energy utility

encoord®

Integrating with LCA Task

Argonne NATIONAL LABORATORY

NREL Transforming ENERGY **Cross-laboratory collaboration *facilitates* learning and *improves* feedback loop** NREL Transforming ENERGY

Note: <u>indicates key deliverable</u>

TEA-Team-Led Literature Review

- NREL TEA team led the drafting and publication of literature review with contributions from SNL and PNNL
- Topics covered
  - H_2 blending on NG properties
  - Transmission/distribution pipe networks
  - Underground storage
  - End-use applications
  - H_2 separation
  - Network design and operation
  - TEA of H_2 blending in NG pipelines
  - Pilot projects and experiences
  - Consensus, disagreement, topics requiring further research

Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology

Kevin Topolski,[1] Evan P. Reznicek,[1] Burcin Cakir Erdener,[2] Chris W. San Marchi,[3] Joseph A. Ronevich,[3] Lisa Fring,[4] Kevin Simmons,[4] Omar Jose Guerra Fernandez,[1] Bri-Mathias Hodge,[1,2] and Mark Chung[1]

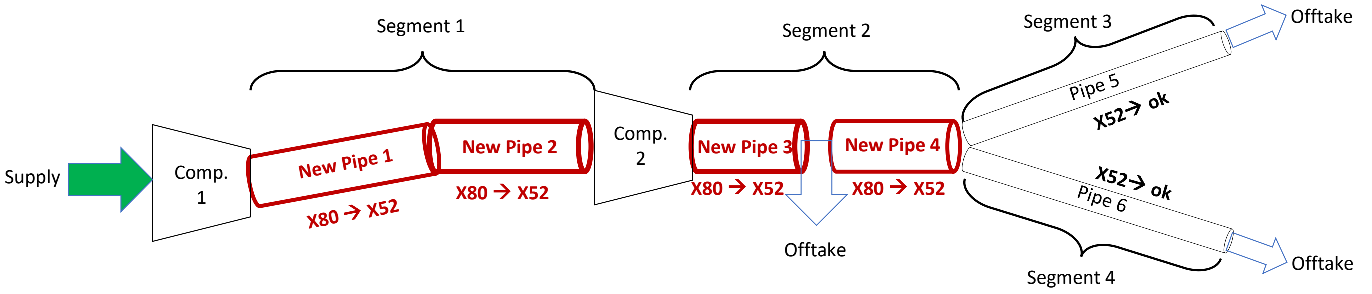
1 National Renewable Energy Laboratory
2 University of Colorado Boulder
3 Sandia National Laboratories
4 Pacific Northwest National Laboratory

Technical Report
NREL/TP-5400-81704
October 2022

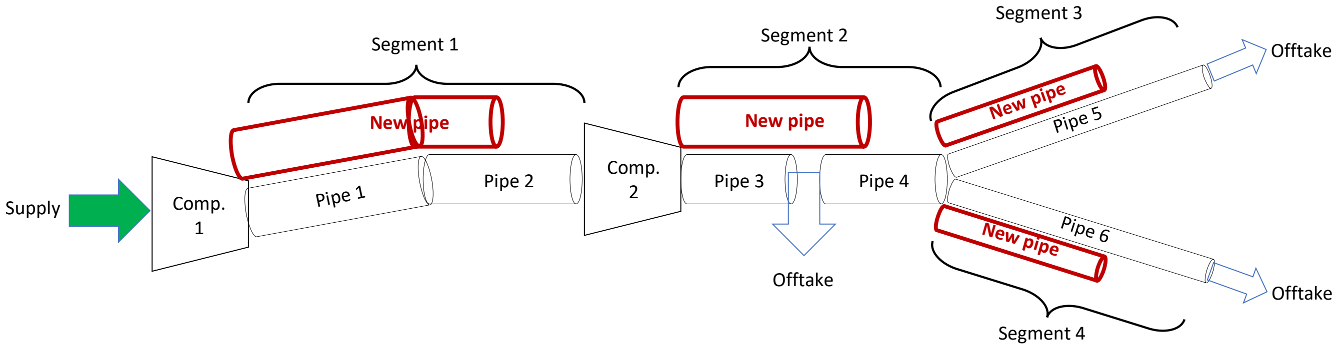
NREL developed a Blending Pipeline Analysis Tool for Hydrogen (BlendPATH) that provides case-by-case techno-economic analyses

- BlendPATH Python tool can answer:
  - What modifications to the pipeline network are necessary to enable blending up to *X*% of hydrogen in pipeline gas and remain compliant with ASME B31.12?
  - What incremental capital investment and operating expense are required to upgrade the natural gas pipeline network for *X*% of hydrogen in pipeline gas in the following scenarios?
    - Direct replacement
    - Parallel looping
    - Additional compressors
- This model targets application at the initial project assessment stage for transmission pipelines
- Intent is to provide the user with an understanding of the <u>most promising opportunities</u> before proceeding with more detailed pipeline inspections based on "probable" economic outcome

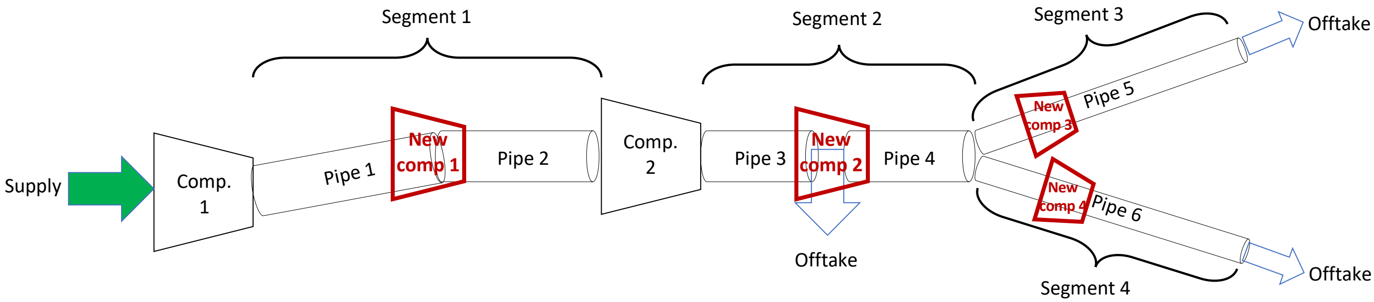
Scenario 1: Directly replace existing pipes that cannot meet required pressure



Scenario 2: Build parallel loops to increase capacity at reduced pressure



Scenario 3: Add compressor stations and operate at reduced pressure



Key activities, findings, outputs from phase I CRADA

HyBlend
U.S. DEPARTMENT OF ENERGY

Materials Compatibility – Metals (Sandia)

- Developed probabilistic fracture mechanics software – HELPR
- Subscale pipe testing to evaluate hydrogen-assisted failure
- Fatigue and fracture testing in gaseous hydrogen

Materials Compatibility – Polymers (Pacific Northwest)

- Discovered time dependence on testing – some polymer pipe properties return to pre-exposure values within a couple hours of removal from hydrogen showing the need for in-situ testing
- Hydrogen has inconsistent impacts on material properties – some had improved performance upon exposure to hydrogen while others had reduced performance, depending on their polymer chemistry

Life-cycle Analysis (ANL)

- Calculated the emission intensity in scenarios that either maintained constant volume or constant energy throughput
- Maintaining energy delivery limits the H_2 blending ratio to ~30%, resulting in ~6% life cycle GHG emissions reduction
- Evaluated TEA and LCA of synthetic natural gas as an alternative to blending

Techno-economic Analysis (NREL)

- Published a literature review summarizing the current state of knowledge on blended gases and hydrogen interaction with pipeline materials
- Developed and released BlendPATH, an open-source software providing case-by-case economic analysis of preparing transmission pipelines to blend H2

Phase I results presented in detail at October DOE H2IQ Hour - Recording and slides available (search “H2IQ”)

Additional needs and future work

- **Safety, Codes and Standards**
  - Qualitative Risk Assessment of Hydrogen Gas Distribution to Residential Sites†
  - Quantitative Risk Assessment of Large-Scale Hydrogen Usage in Industrial Processes†
  - Code and Regulation Guidance on Polymer Pipelines†
  - Gap Analysis on Regulations, Codes and Standards for Distribution System Components and Appliances†
- **Remediation of vintage lines**
  - Coatings
  - Pull through composite liners
  - Repair technologies
- **Components, sub-assemblies and appliances**
  - Materials in wetted components (for valves, stems, springs, burners, compressors, turbines, seals, etc.)

† over targets in HyBlend Phase II proposal

HyBlend Lab Leads and Contributors

Sandia National Laboratories – Metals
- Chris San Marchi (PI)
- Joe Ronevich (fatigue and fracture)
- Remi Dingreville (HELPR)
- Ben Schroeder (HELPR)
- Khalid Hattar (mechanisms)
- Nalini Menon (polymers)
- Rakish Shrestha (post-doc)
- Kathryn Small (post-doc)
- Ryan DeMott (post-doc)
- James McNair (testing)
- Brendan Davis (testing)

Argonne – Life Cycle Analysis
- Amgad Elgowainy (PI)
- Pingping Sun
- Pradeep Vyawahare
- Vincenzo Cappello
- Kyuha Lee

Pacific Northwest National Laboratories – Polymers
- Kevin Simmons (PI)
- Seunghyun (Andy) Ko
- Wenbin Kuang
- Yongsoon Shin
- Kee Sung Han
- Yelin Ni
- Ethan Nickerson
- Yao Qiao

NREL – Technoeconomic Analysis
- Mark Chung (PI)
- Zainul Abdin
- Kevin Topolski
- Evan Reznicek
- Leela Sotsky
- Omar Guerra
- Bri-Mathias Hodge
- Brian Sergi
- Burcin Erdener

- Project Controller
  – Kylie Saddler (NREL)
- Funding
  – DOE HFTO
- CRADA Partners

Hydrogen Blending in Natural Gas Pipelines

HyBlend
U.S. DEPARTMENT OF ENERGY

Seeking Partners to Contribute to a Second Pipeline Blending CRADA

In Planning Stage of Follow-on CRADA (Phase II)

- Same core labs
- 3-year CRADA open to new partners from industry, academia, nonprofits
- $12MM DOE funding*
- Seeking $5.4MM cash cost share
  - Asking partners for minimum $25k/year cash commitment
  - Additional in-kind contributions welcome
- In-person kickoff meeting was held in Los Angeles in December 2023

Benefits of Partnership

- Partners get access to the following:
  - National Lab expertise
  - Data generated by the labs for the CRADA
  - Input on scope of work
  - Monthly project update meetings
  - Quarterly materials meetings
  - Quarterly analysis meetings
  - Lab-generated reports prior to publication
- Partners can advertise they are part of / contributors to HyBlend CRADA

Contact HyBlend_CRADA@nrel.gov for more details

** subject to the availability of appropriated funds, contingent on cost share, not a FOA*

Thank you

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HyBlend
U.S. DEPARTMENT OF ENERGY

HyBlend Contacts

Coordination Team:

Todd Deutsch: Todd.Deutsch@nrel.gov

Kylie Saddler: Kylie.Saddler@nrel.gov

Devinder Mahajan: Devinder.Mahajan@stonybrook.edu

Brian Weeks: bweeks@gti.energy

May Kwan: wkwan@gti.energy

Lab Leads:

Chris San Marchi: cwsanma@sandia.gov

Kevin Simmons: kl.simmons@pnnl.gov

Mark Chung: Mark.Chung@nrel.gov

Amgad Elgowainy: aelgowainy@anl.gov

Pipeline Research Council International

PRCI’s Emerging Fuels Institute (EFI) Update

Carolyn DesCoteaux
PRCI, Sr. Program Manager
SHASTA Workshop
April 3, 2024

PRCI™
LEADING PIPELINE RESEARCH

EFI Vision & Mission Statements

EFI Vision *(the direction that drives us)*

Be the evergreen center for applied strategic research in the rapidly changing emerging fuels space for safe and reliable transmission and storage infrastructure

EFI Mission *(what we are trying to accomplish)*

- ***Reconcile global knowledge into a central clearinghouse***
- ***Prioritize knowledge gaps into funded research focus areas***
- ***Drive adoption of research outcomes into guidance and standards organization documents and inform regulators***

Emerging Fuels Institute - 21 Members

Vanguard (6)

ENBRIDGE

TC Energy

Southern California Gas Company
A Sempra Energy company

Williams

أرامكو السعودية
saudi aramco

ENERGY TRANSFER

Champion (16)

API American Petroleum Institute

bp

PG&E

storengy

GRTgaz

ConocoPhillips

gasunie
crossing borders in energy

OTD Operations Technology Development

ATCO Pipelines

National Fuel

KINDER MORGAN

ExxonMobil

Tenaris

TOTAL

EFI Purpose

Guidance Document

Building Relationships

Industry Standards

Regulations

Clearinghouse

Purpose:

Guide, Influence & Educate Industry!

Leverage through 2026

- **Average Leverage for EFI – 4.4:1**
- **Ratio of Leverage Vanguard - 24:1**
  (based on 6-year participation)
- **Ratio of Leverage Champion - 60:1**
  (based on 6-year participation)

Industry Partners
- DOE
- DNV
- EWI
- Gti
- NPC
- GMRC
- GasUnie
- Solar
- EMPIR
- NREL
- Sandia
- NETL
- PNNL
- LLNL
- PHMSA
- Alberta Innovates

Member Spend
$8.2 MM

Industry Spend
$36 MM

As of Feb 2024

Build a Bridge – Hydrogen State of the Art Gap Study

7 Inspection & Maintenance

15 Integrity

3 Safety

17 Measurement & Analysis

7 Underground Storage

11 Compression

60 Gaps Discovered in the SOTA Report

LEADING PIPELINE RESEARCH

Projects to Close Gaps

4

Inspection & Maintenance

15

Integrity

5

Safety

6

Measurement & Analysis

3

Underground Storage

4

Compression

Total Projects = 38
19 Gaps remaining after these projects are completed
Most projects have an 18 - 24 month timeline.

The EFI Guidance Document

INTEGRITY
- Pipe Material Properties and Fracture Mechanics
- Fitness for Service
- Corrosion
- Seals

SAFETY
- Personal Safety
- Leak Detection

UNDERGROUND STORAGE
- Impacts on Wellbore Integrity
- Column Separation
- Microbial Fouling
- Leak Detection

Pipeline Research Council International
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EFI Guidance Document

Managing H_2/ H_2 Blend Pipelines

INSPECTION & MAINTENANCE
- ILI
- Repair
- Maintenance

NETWORK COMPONENTS
- Blending

MEASUREMENT
- H_2 and H_2 Blend Measurement
- H_2 Blend Gas Quality and Composition
- RNG Quality and Composition

COMPRESSION
- Material Compatibility and Performance
- Fuel Gas
- Physical Properties

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EFI Addressing CO_2 Issues

- Steering Committee comprised of 11 PRCI EFI members
- State of the Art (CO_2 SOTA) gap report completed
- Engaged with PHMSA CO_2 R&D effort
- Aligning with CSA and ASME on standards revisions
- Funding via the EFI and potential external sources
- Project Roadmap being finalized
  - Gaps identified
  - Ongoing project prioritization
  - Guidance Document / recommended practices

LEADING PIPELINE RESEARCH

CO_2 Research Execution

CO_2 Specification	EOS Refinement	CO_2 FM Models	Dispersion/ Safety	Non-Metallics	Guidance/Corrosion/ Social Acceptance
CO_2 Water & Acid Solubility Amid Impurities	Refine EOS in CO_2 Service	Full Scale Fracture Propagation test in gas phase CO_2	CO_2 Dispersion Modeling	Non-metallic compatibility in CO_2 service	Social Acceptance Primer
Guidance on impurity threshold ranges		Effect of CO_2 ductile-brittle fracture initiation			Literature review of CO_2 technical standards
Evaluation of Odorants for CO_2 Service		Guidelines for crack arrest design			ILI Tool Performance in dense phase
		Cracking & Corrosion Fatigue in CO_2 /H_20/CO			Metal loss assessment criteria for CO_2 service
					Corrosive impacts of trace components

6 Research Areas
Mapped to PHMSA Gaps
15 Topics

Next Steps?

- Complete current hydrogen focused research through 2026
- Continue to Engage Industry (ASME, API…)
- Address any remaining gaps
- Guidance Document
- Full-Scale Testing (EFI & EPRG)
- Participation with DOE HyBlend 2
- Address CO_2 Transportation & Sequestration

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Questions?

PRCI

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thank you

PRCI LEADING PIPELINE RESEARCH

Pipeline Research Council International

Carolyn DesCoteaux

PRCI - Sr. Program Manager

cdescoteaux@prci.org

Overview of energy storage and hydrogen research at the U.S. Geological Survey

Peter D. Warwick*, Marc L. Buursink, Sean T. Brennan, Geoffrey S. Ellis, Philip A. Freeman, Joao S. Gallotti, Mathew M. Jones, and Ashton M. Wiens

*Research Geologist, USGS Geology, Energy & Minerals Science Center, and Science Coordinator, USGS Energy Resources Program, pwarwick@usgs.gov

Subsurface Hydrogen Assessment, Storage, and Technology Acceleration - 2024 Technical Workshop
April 3, 2024, Pittsburgh, PA

U.S. Department of the Interior
U.S. Geological Survey

Outline

- Multi-resource assessments at the U.S. Geological Survey (USGS)
- Energy storage resources research and assessments
  - Natural gas
  - Hydrogen
  - Other gases or liquids
- Natural geologic hydrogen resources
- Suggestions for future research
- Summary

USGS

USGS Energy Resource Assessments

Multi-Resource Assessment

Undiscovered Resources

Discovered Resource

Pore Space/ Volumetric

Data compilation

Extraction

Injection

Oil

Gas

Coal

H_2

He

Energy Storage

Chemical

Mechanical

Thermal

CO_2 Storage

Buoyant

Residual

Mineralization

(Modified from Merrill, 2024)

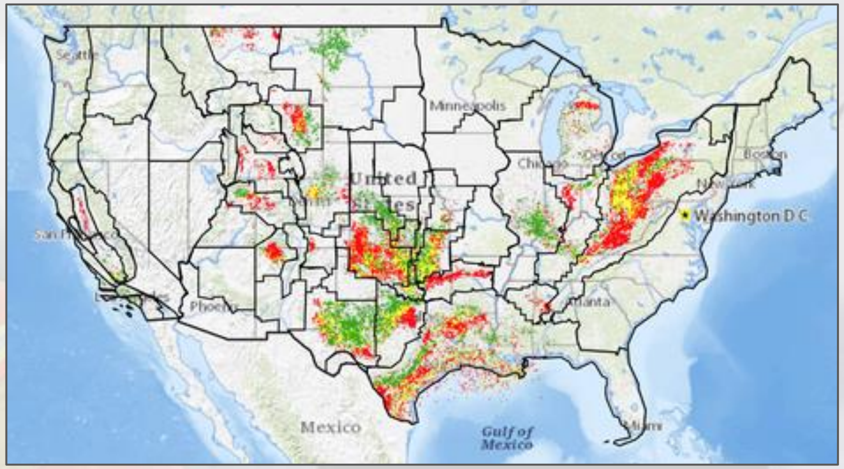
Assessing pore space underground

- USGS regularly assesses geologic energy resources since the 1975 Energy Policy and Conservation Act and CO_2 storage resources since the 2007 Energy Independence and Security Act
    - Undiscovered hydrocarbons (oil & gas)
    - CO_2 sequestration (buoyant and residual trapping)
    - CO_2-EOR (CO_2 retention & oil production)

- Urging from National Academy of Sciences review, State survey proposals, and energy industry conversations

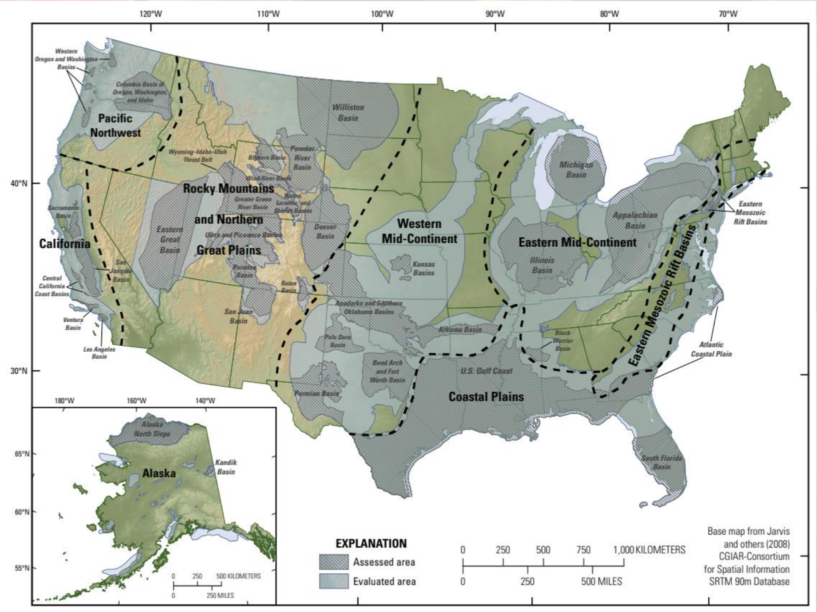
"Assessing the storage potential for various basins in the United States could become a new and strategically important priority for the [Energy Resources Program]." (NASEM, 2018)

Oil & gas resource assessments and wells



(https://www.usgs.gov/centers/central-energy-resources-science-center/science/united-states-assessments-undiscovered-oil)

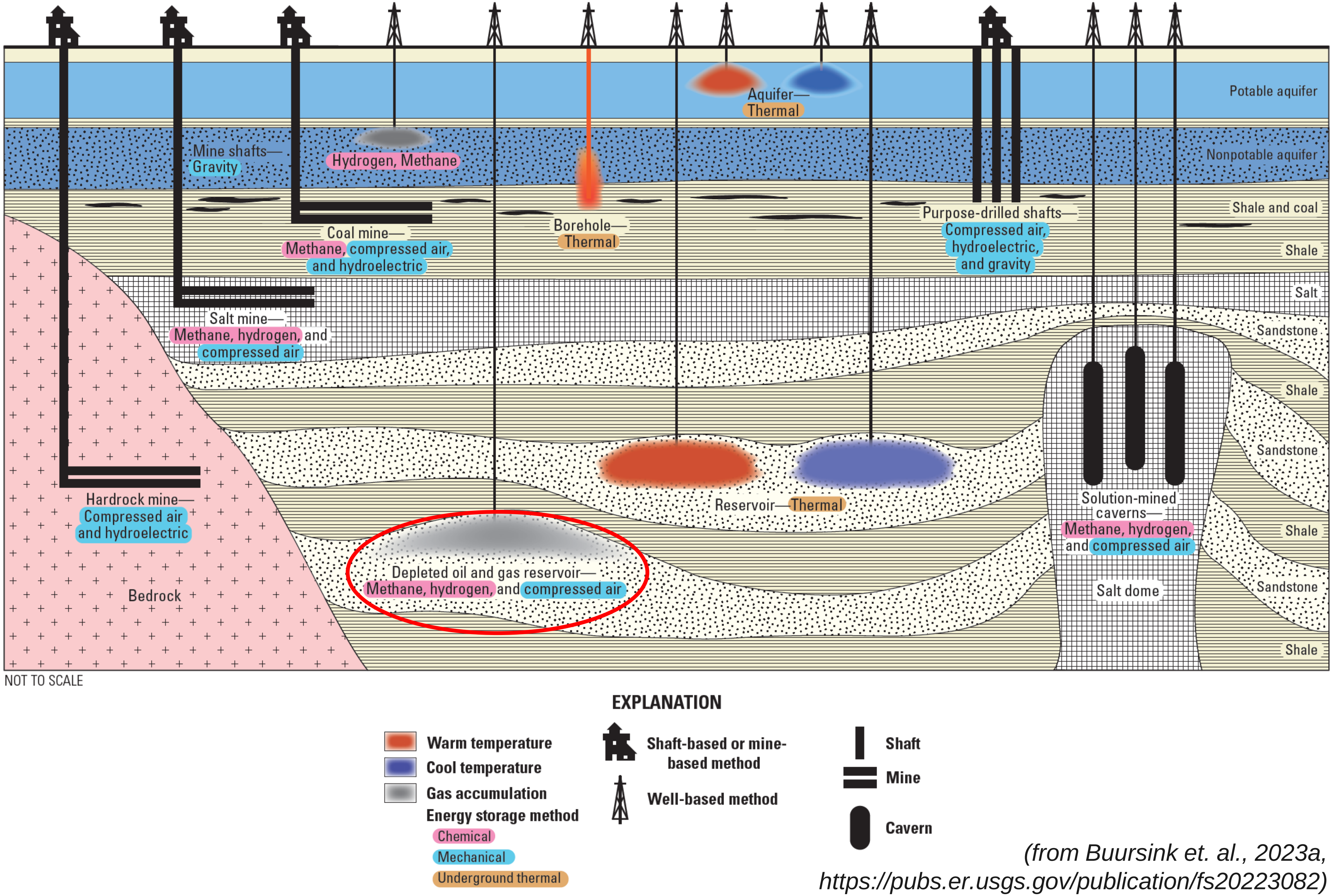
CO_2 sequestration assessment areas



(https://pubs.usgs.gov/fs/2013/3020/)

(Modified from Buursink et al., 2024)

Geologic energy storage methods and settings



(from Buursink et. al., 2023a, https://pubs.er.usgs.gov/publication/fs20223082)

USGS research on assessing gas storage resources

- Working on a new assessment methodology
  - Natural gas storage in depleted gas reservoirs
  - Other types of storage assessments proposed

- Research examples:
  - Identifying amenable depleted hydrocarbon reservoirs (Wind River Basin)
  - Calculating probabilistic gas capacity estimates (Michigan Basin)
  - Modeling potential H_2 reactions (Illinois Basin)

[X, storage possible; —, not applicable]

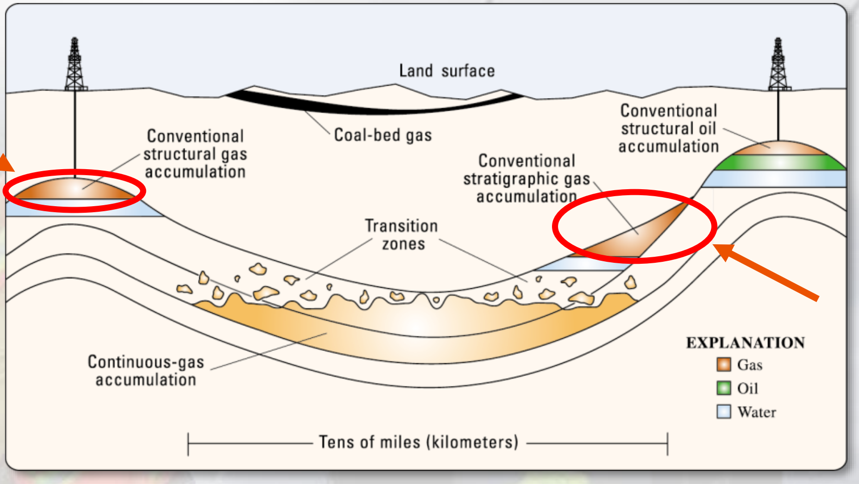
Storage setting	Geologic energy storage method		
	Chemical	Mechanical	Thermal
Depleted gas reservoirs	X	—	X
Solution-mined salt caverns	X	X	—
Non-potable aquifers	X	—	X
Abandoned mines	—	X	X

USGS

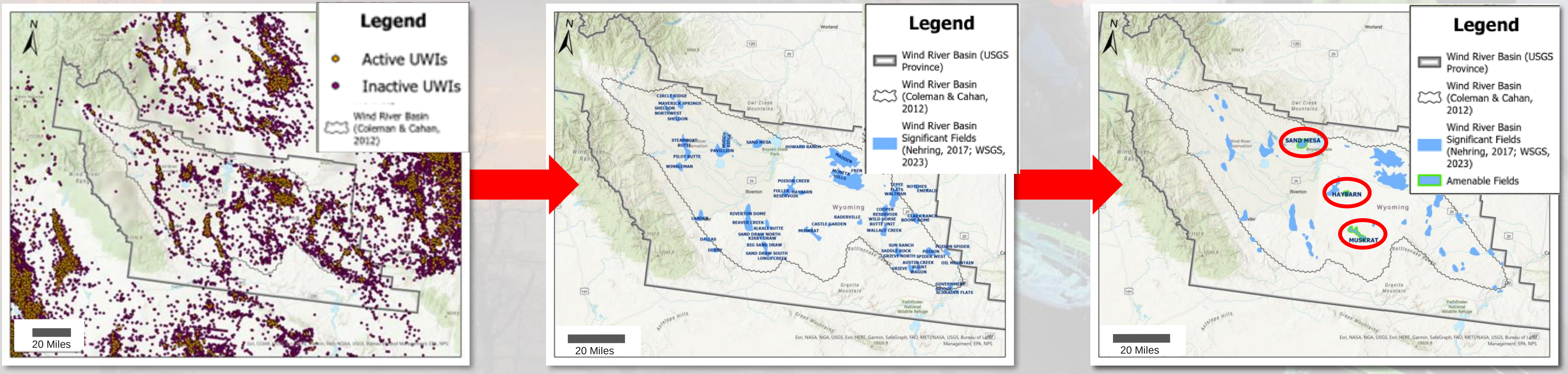
(Modified from Buursink et al., 2023a, 2024)

Hydrocarbon reservoirs – Effectively trapped gas and now depleted

- Reservoir: Persistent gas accumulation (structural trap or stratigraphic traps; red circles and arrows)
    - Significant fields (i.e., 3 BCF) according to nationwide database
- Quantifiable gap in production: Five years
    - Matching producing entity with wells (not necessarily one-to-one)
- Wind River Basin, Wyoming example
    - GIS spatial join – Identified three potential amenable fields



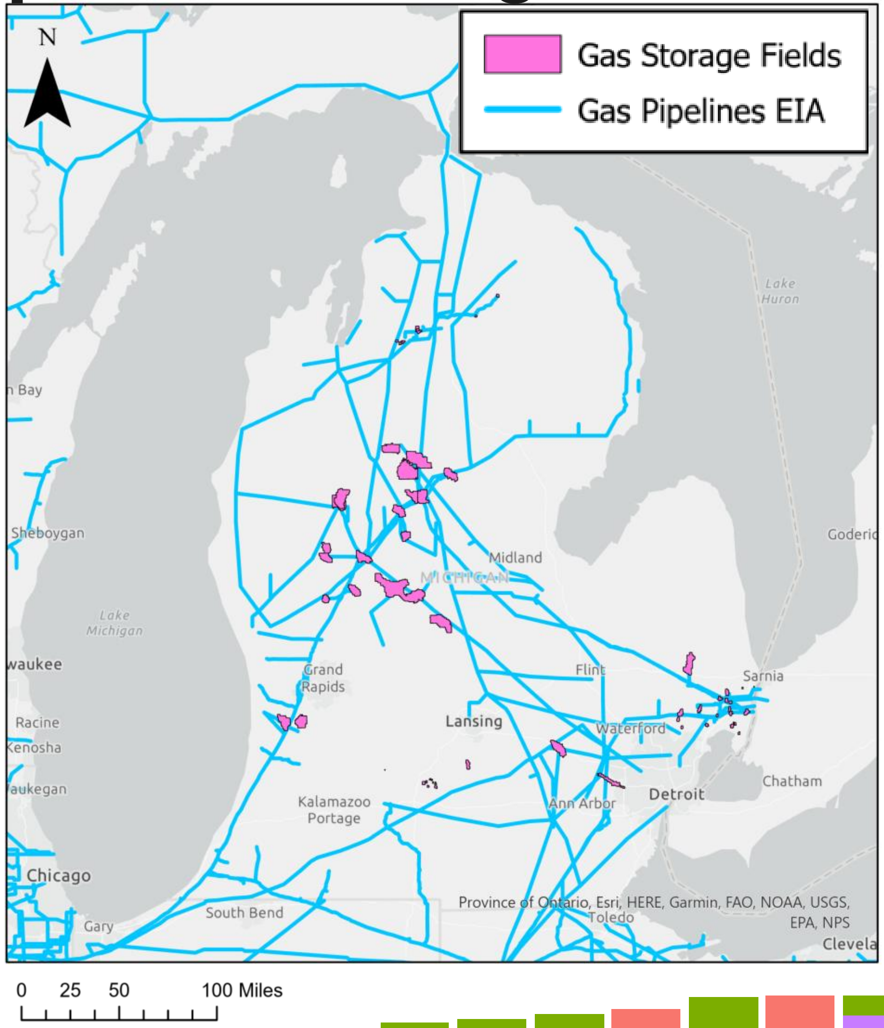
(from https://pubs.er.usgs.gov/publication/fs11301)



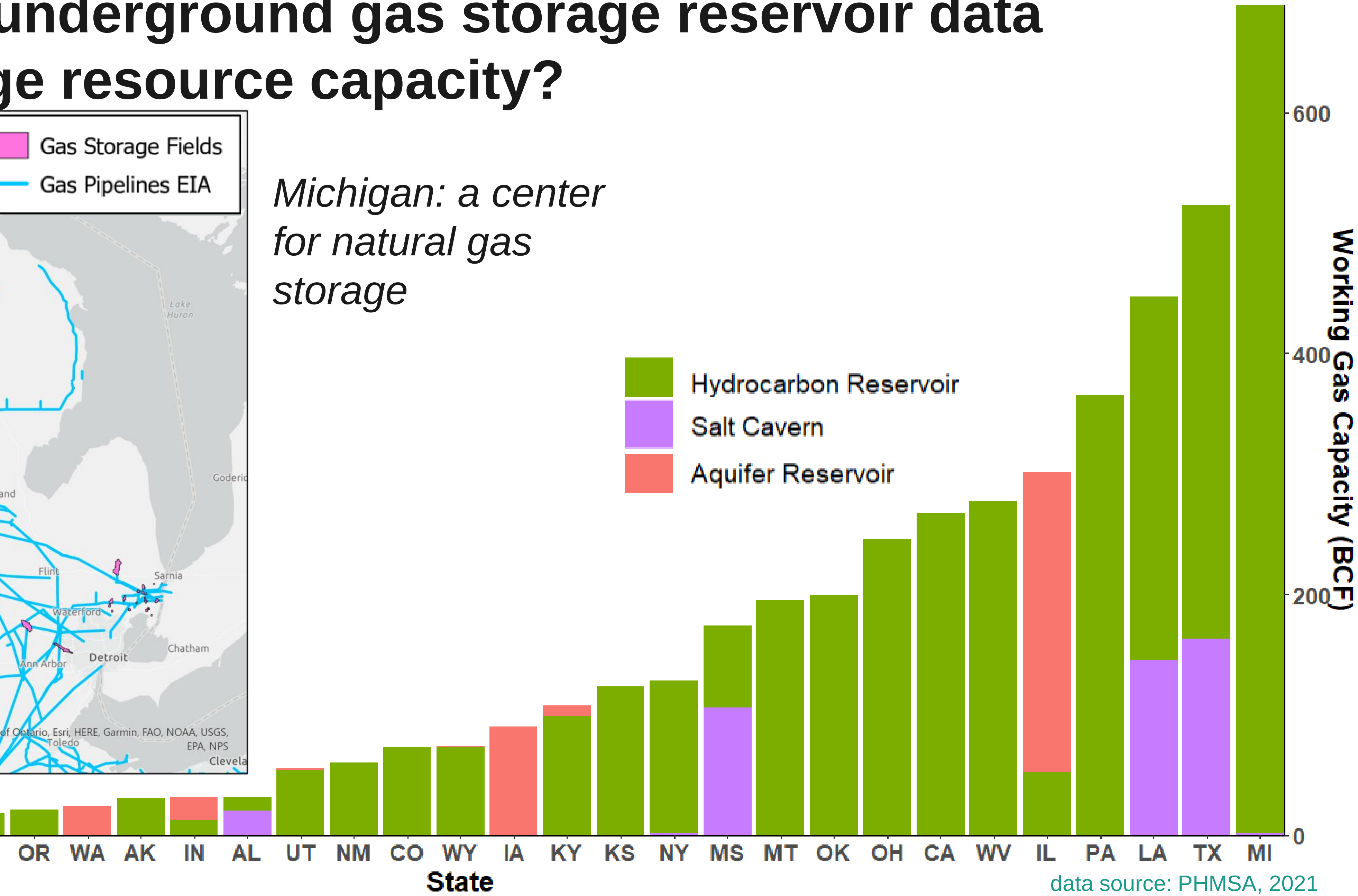
UWIs = Unique well identifiers

(Modified from Buursink et al., 2023b, 2024)

Can existing underground gas storage reservoir data predict storage resource capacity?



Michigan: a center for natural gas storage

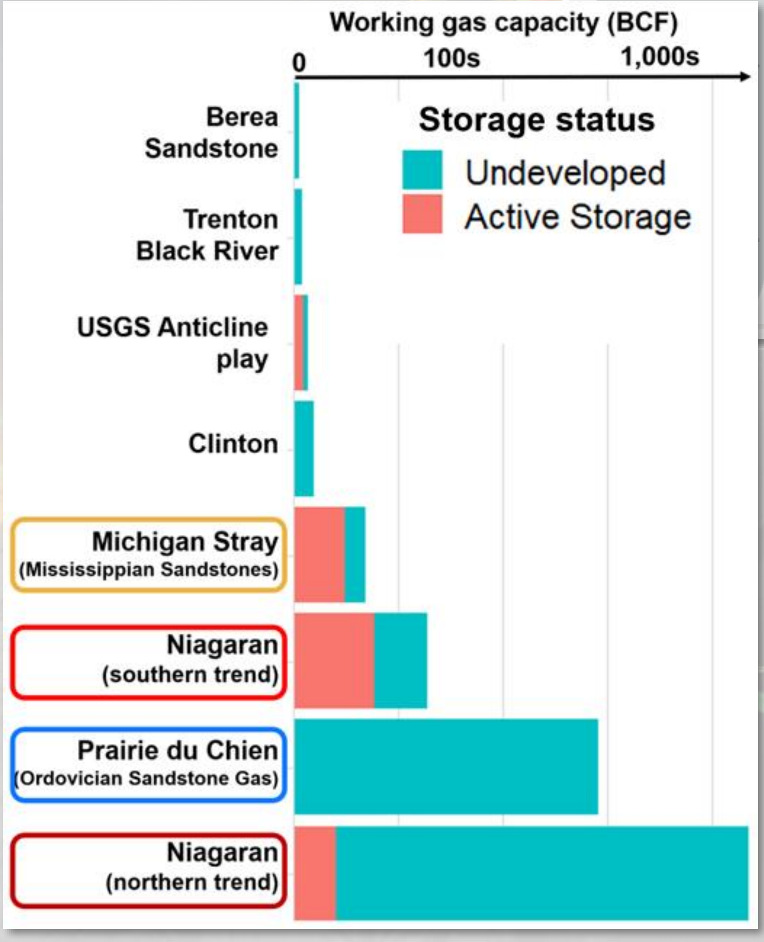


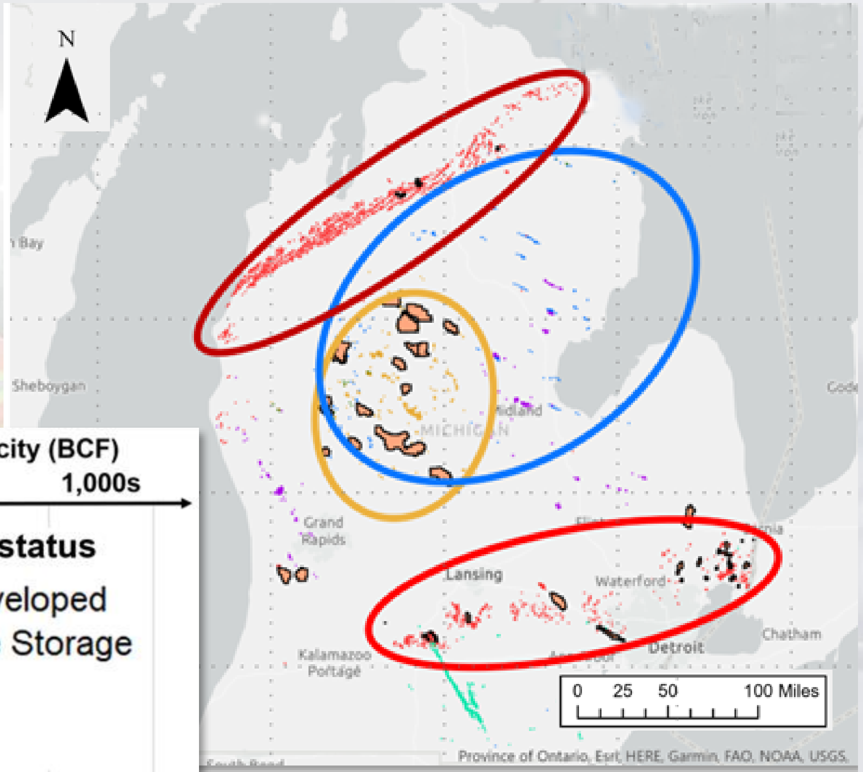
data source: PHMSA, 2021

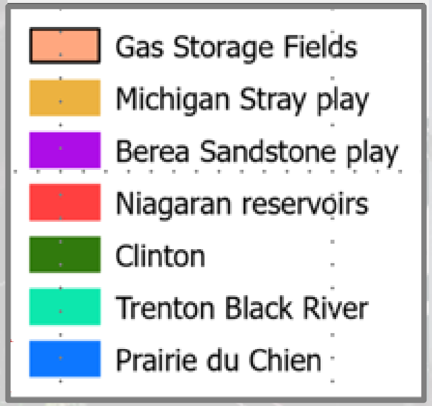
(Modified from Jones et al., 2023)

Gas storage capacity calculations with linear modeling

- Novel method applying three governing equations and respective weighting factors
  - Cumulative gas production
  - Reservoir volume estimates (e.g., OGIP)
  - Pressure-drop method
- Calculations compared to working gas capacity from operating facilities in Michigan
- Method will be applied basin-by-basin pending verification of amenable depleted reservoirs







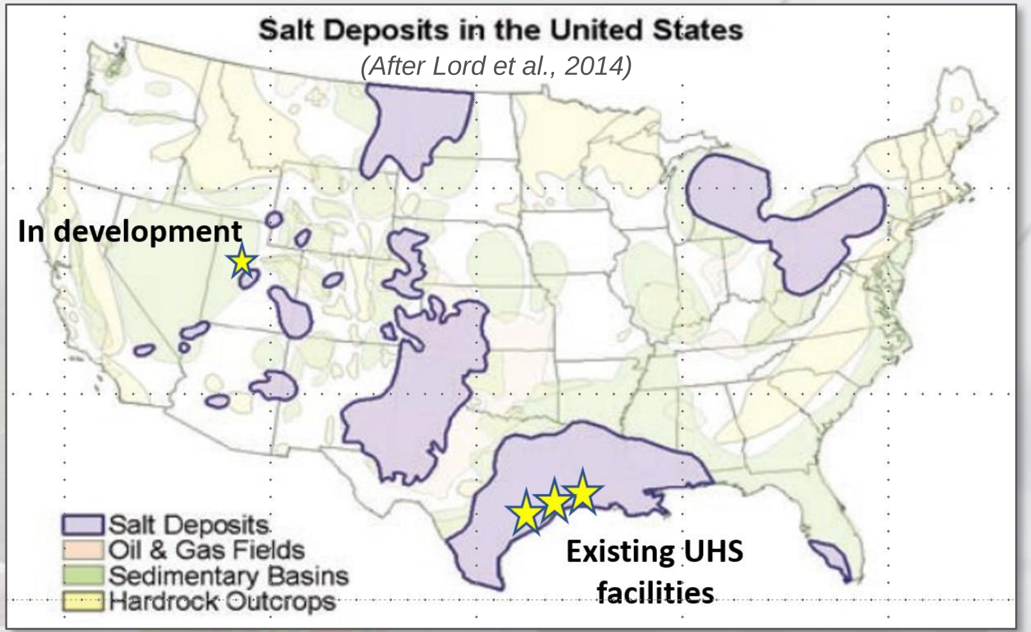
(Modified from Jones, et al., 2023; Buursink et al., 2024)

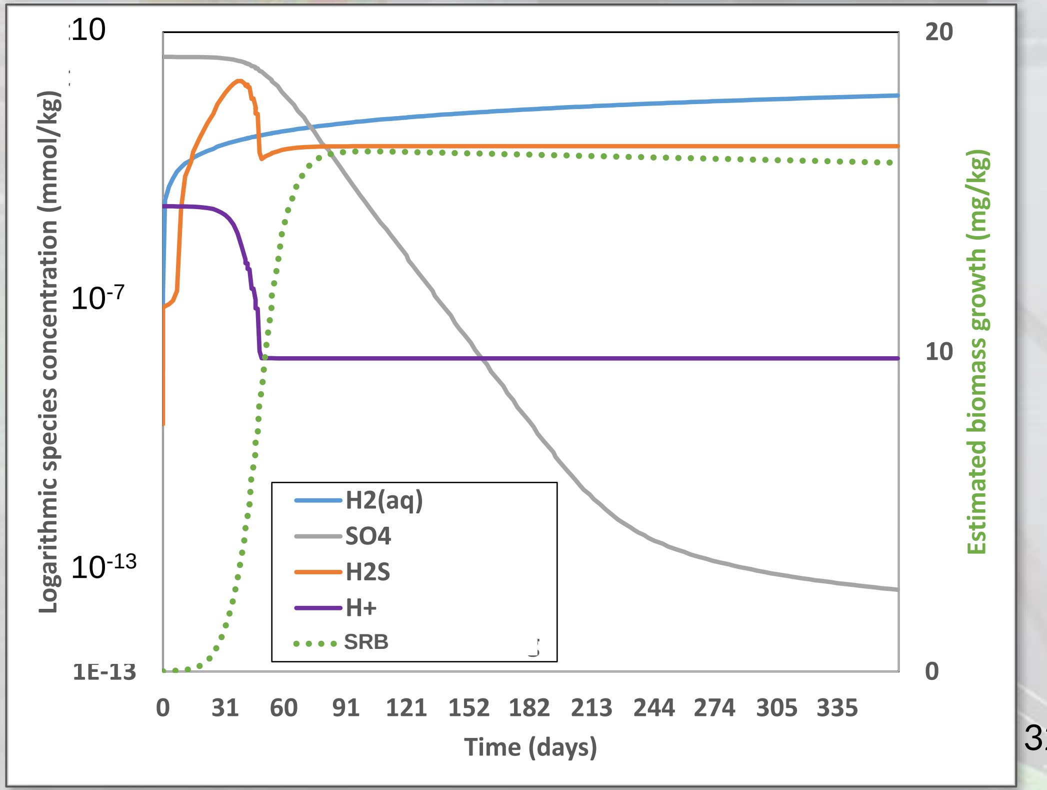
OGIP = Original gas in place

USGS

Modeling underground hydrogen storage (UHS) in porous reservoirs

- Existing and planned commercial UHS facilities in salt caverns in the U.S.
  - Clemens Dome, Moss Bluff and Spindletop, Gulf Coast
  - Advanced Clean Energy Storage (in development) – Delta, UT
- Understanding in-situ H_2 interactions to identify suitable porous storage formations
  - H_2-water-rock reactions (high pressure & temperature) – unlikely
  - H_2-induced microbial reactions – more likely
- Microbial modeling findings (preliminary; Aux Vases Sandstone, Illinois Basin)
  - SO_4 redox begins shortly after H_2 injection
  - Biomass growth of SO_4 reducing bacteria (SRB) peaks in the first months then decays steadily

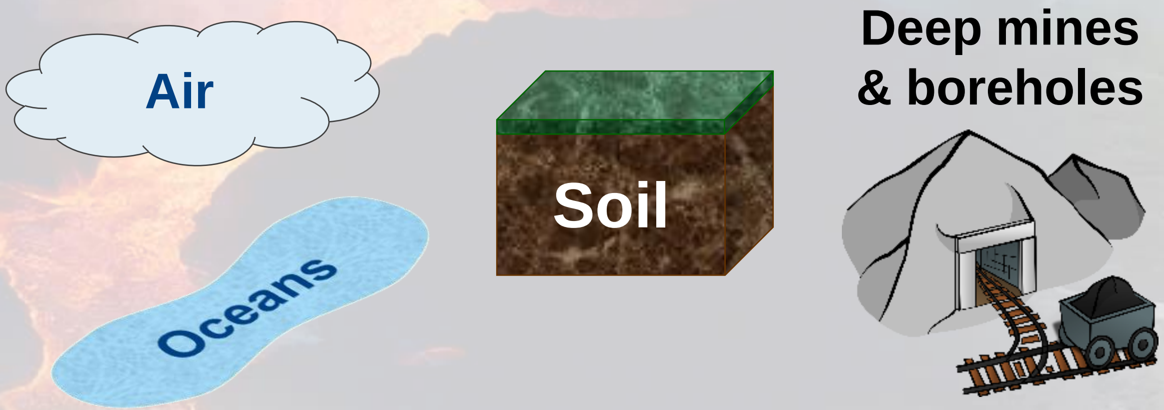


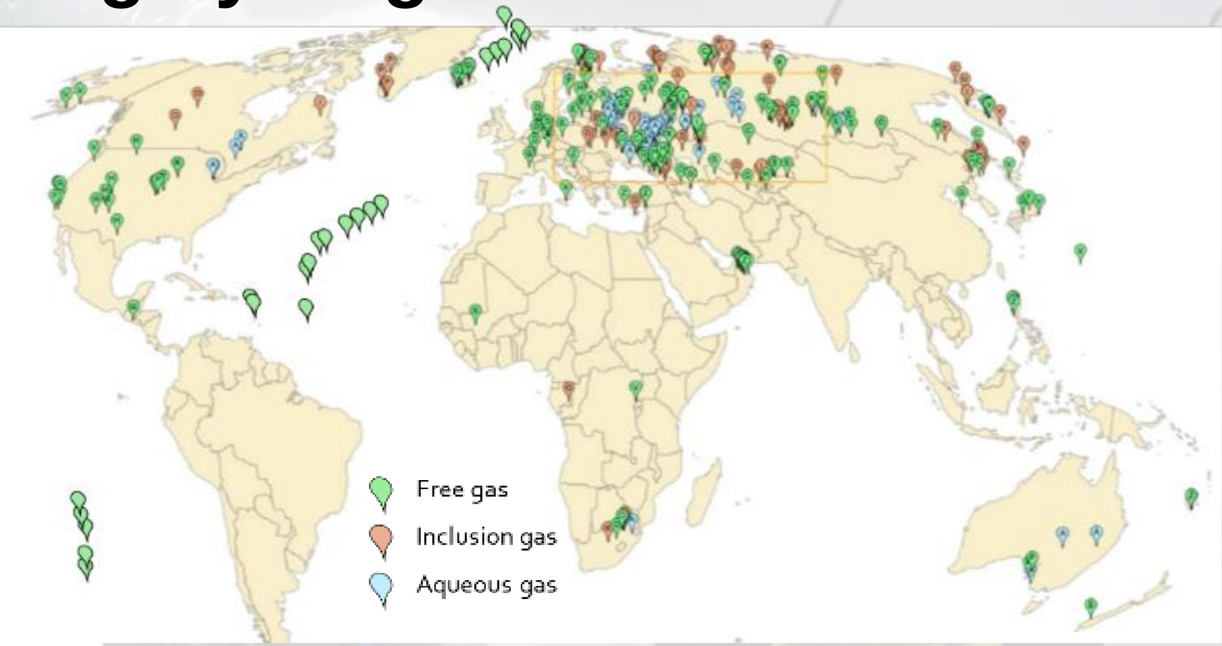


USGS

(Modified from Gallotti et al., 2023; Buursink et al., 2024)

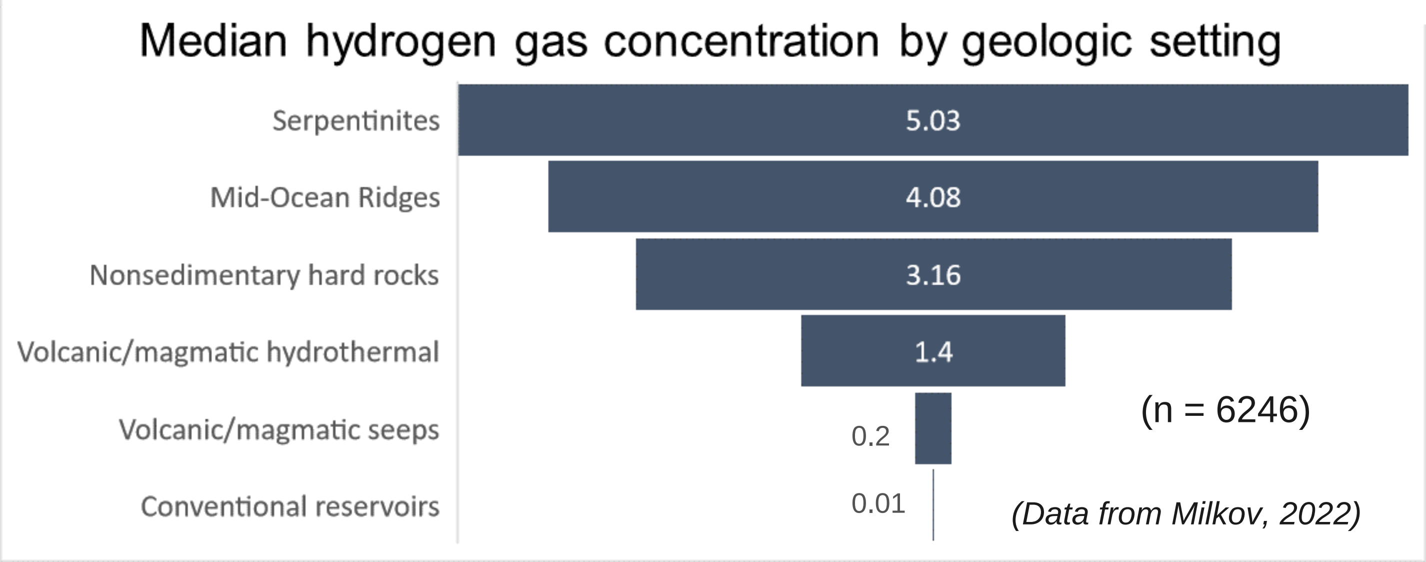
Observations of naturally occurring hydrogen on Earth





Surface observations of hydrogen concentrations >10%

Modified from Zgonnik, 2020 and Prinzhofer & Deville, 2015



High diffusivity and reactivity of hydrogen probably means that accumulations cannot form; however, there are exceptions, for example in Mali (Maiga et al., 2023).

(Modified from Ellis, 2024)

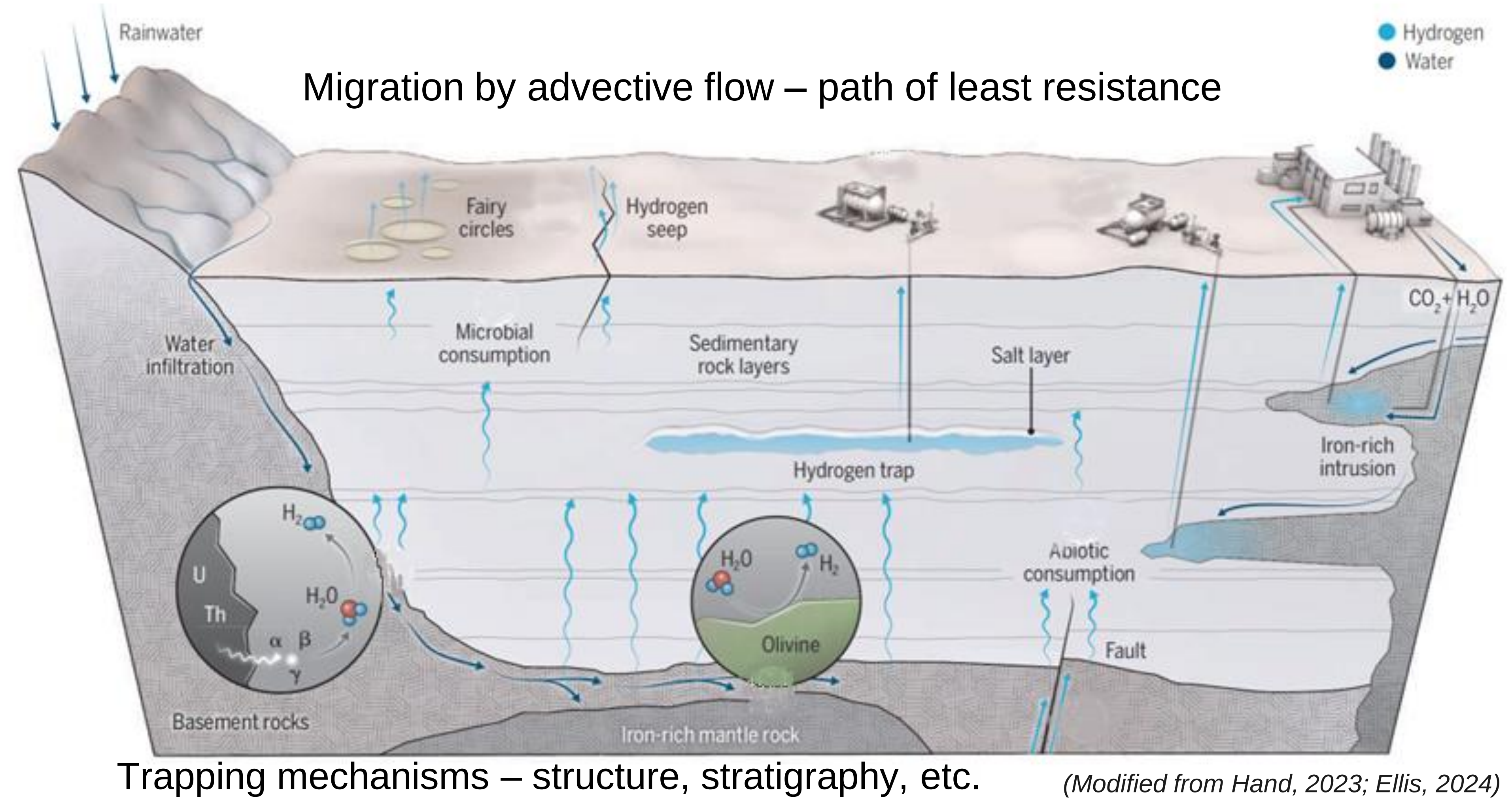
Proposed hydrogen systems

Source rocks – Fe-rich, radiogenic, deep faults

Migration – Hydrogen more mobile and reactive than hydrocarbons

Generation – Hydrogen generated much faster than petroleum

- What can we learn from natural H_2 systems and accumulations that will help with H_2 storage?
- Depleted natural H_2 reservoirs would likely make ideal candidates for underground storage of manufactured H_2.



(Modified from Hand, 2023; Ellis, 2024)

USGS

Research questions to consider

- What are the key barriers for H_2 underground storage?
  - Economics
  - Research is ongoing for non-salt cavern storage of H_2
- What would make a successful [non-salt] field test for storing H_2?
  - Injection of various mixtures of natural gas and H_2 (10% to 90% H_2)
  - Measurable H_2 recovery factors over various storage time durations (months to years)
  - H_2 storage loss estimation due to leakage or chemical/microbial reactions
  - See Hellerschmied et al. (2024, https://doi.org/10.1038/s41560-024-01458-1)
- What are the research/technology gaps?
  - Measurable H_2 recovery factors
  - H_2 storage loss estimation factors

Summary

- Future uses of subsurface may become competitive and require multi-resource and pore-space assessment information
- The USGS is currently **assessing gas storage capacity in amenable depleted hydrocarbon reservoirs** across U.S. basins
- Natural hydrogen accumulations exist in the subsurface
- Research is ongoing to conceptualize the “Hydrogen System”
- What can we learn from natural H_2 systems and accumulations that will help with H_2 storage?

USGS

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Screening and Valuation Frameworks Paving the Way for Viable Hydrogen Storage Solutions with Geoh2

Bureau of Economic Geology

GeoH2

Ning Lin, Ph.D.

Apr 2024

BUREAU OF ECONOMIC GEOLOGY

Bureau of Economic Geology

- **Energy, Environment & Economic Research**
  - $30 million/year budget
  - Established in 1909
  - 2nd largest research unit at UT Austin

- **State Geological Survey of Texas**

Geology

Geophysics

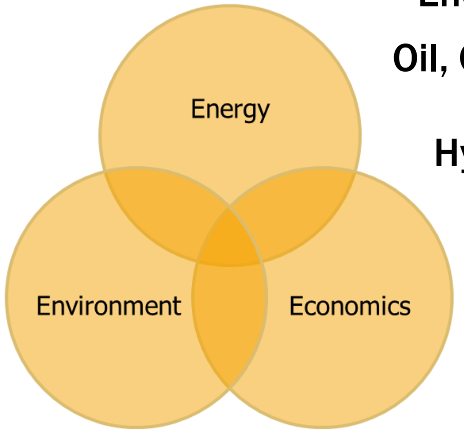
Engineering

Carbon Storage

Seismicity

Water

Minerals



Energy Resources

Oil, Gas, Geothermal

Hydrogen Storage

& Value Chain

Comparative

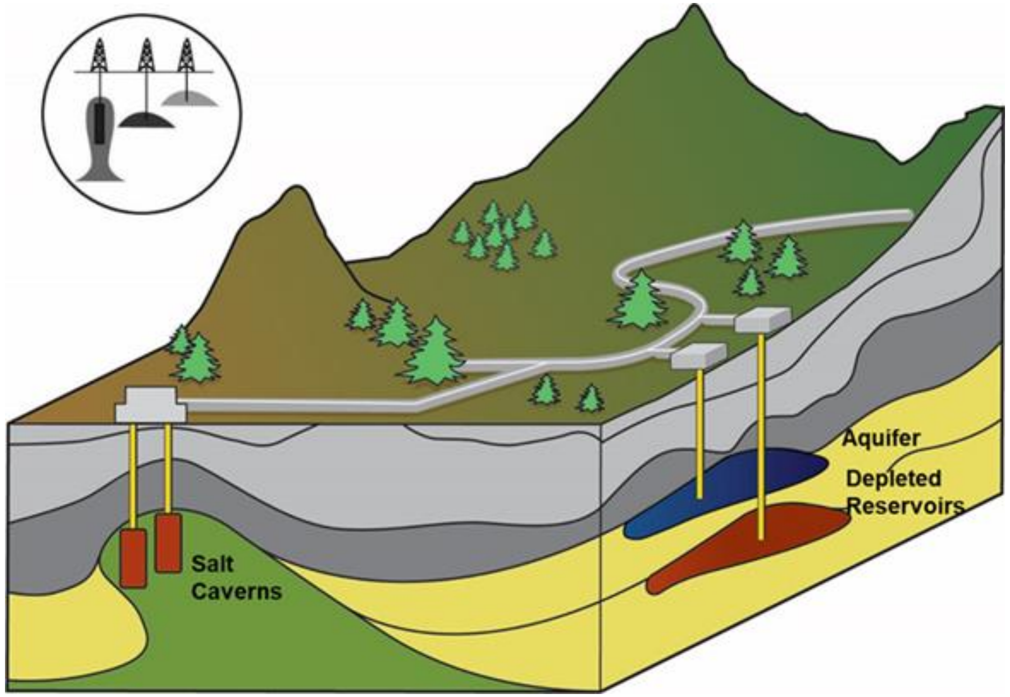
Electricity Options

Bureau of Economic Geology

$GeoH_2$ – Hydrogen Consortium

Conduct geoscience, reservoir engineering, & economic research to facilitate and advance tl development of a hydrogen economy *__at scale__*

- Geological Storage
- Techno-economics and Value Chain Analysis
- In Situ Generation and Novel Concepts



Current Sponsors

Shell, Repsol, bp, SINOPEC Smart Energy Better Life, OMV, PetroChina, equinor, saudi aramco, EDF Environmental Defense Fund – Finding the ways that work, CGG, U.S. Department of Energy, STARR – State of Texas Advanced Oil and Gas Resource Recovery, ExxonMobil, Kinder Morgan – Delivering Energy. Improving Lives., The University of Texas at Austin Center for Subsurface Energy and the Environment, Cockrell School of Engineering

$GeoH_2$ Research

Geological Storage

Focus:

- Reservoir Characterization and Flow Modeling
- Risk Assessment, Field Testing and Monitoring Design

Goals:

- Understand Geologic Reservoirs and H_2 Subsurface Behavior
- Develop Technology and Workflows to Inform Best Practices

Economic Analysis

- Techno-economics
- Value Chain Analyses
- Market Assessment

- Assess Value Chains Linking Supply-Transportation-Storage-Usage for Market Scenarios
- Calibrated Storage Screening Tool

Novel Concepts

- In Situ Generation
- Flow & Dispersion Phenomena
- Native Hydrogen Occurrence

- Evaluate the Potential for In Situ Generated and Natural Hydrogen
- Conduct Exploratory Research on High Impact Opportunities

BUREAU OF ECONOMIC GEOLOGY

$GeoH_2$

Team $GeoH_2$

Reservoir Characterization, Geology, Geochemistry, Geophysics, Petrophysics, Geomechanics, Reservoir Engineering, Energy Economics


JP Nicot


Ning Lin


Seyyed Hosseini


Peter Eichhubl


Lorena Moscardelli

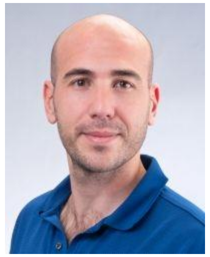

Larry Lake


Mojdeh Delshad


Ian Duncan


Tongwei Zhang


Jay Kipper


Leo Ruiz Maraggi


Shuvajit Bhattacharya


Toti Larson


Mark Shuster


Sobhan Razm


Ander Martinez-Donate


Reza Ershadnia

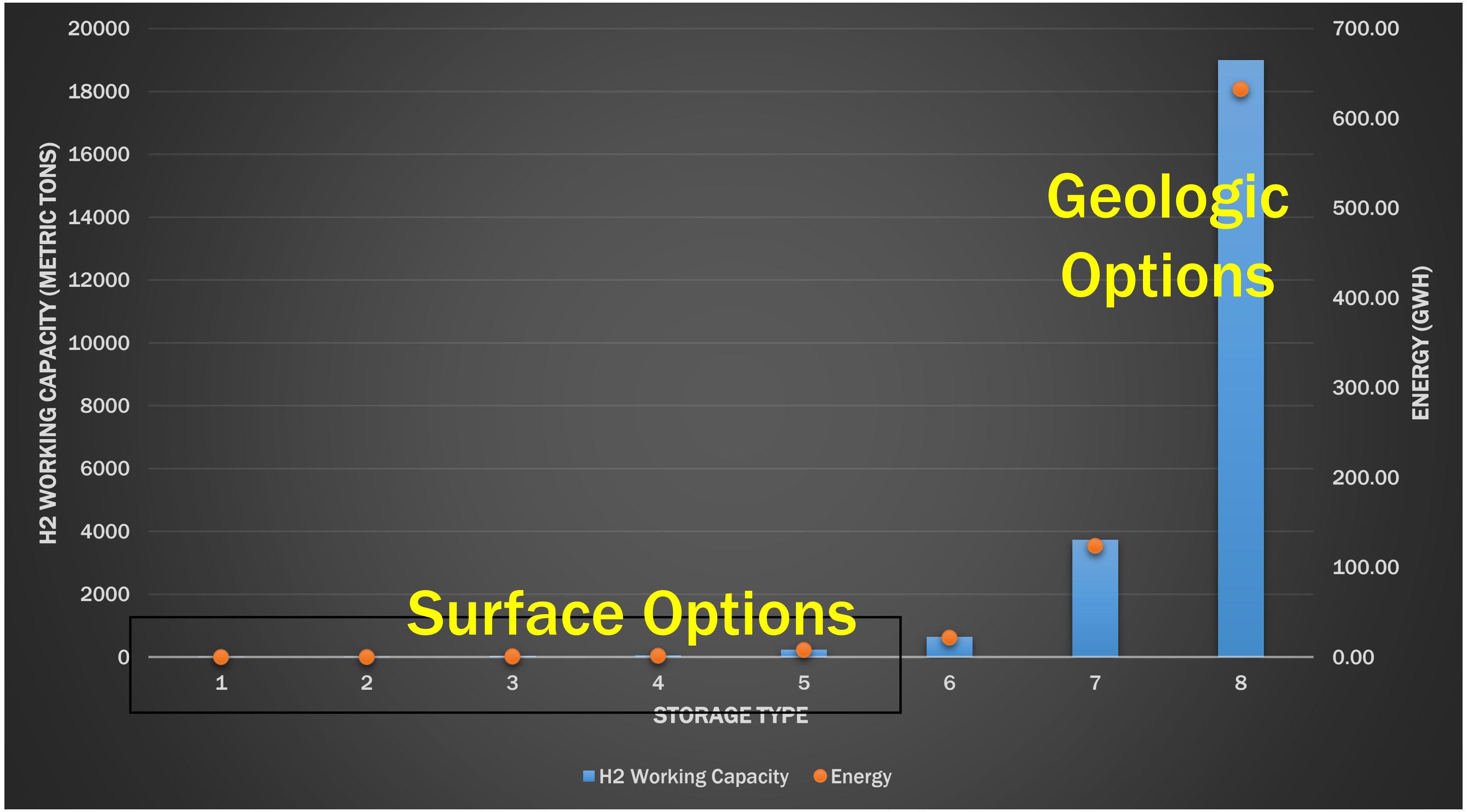

Nur Schuba


Xiaoqiang Li


Ali Cherif


Kamy Sepehrnoori

Indicative H_2 Storage Options by Unit Capacity



- How much storage do we need for hydrogen?
- How does that differ for UGS for natural gas in terms of operation requirements from the market?
- How does hydrogen storage quantify its value proposition in the value chain?

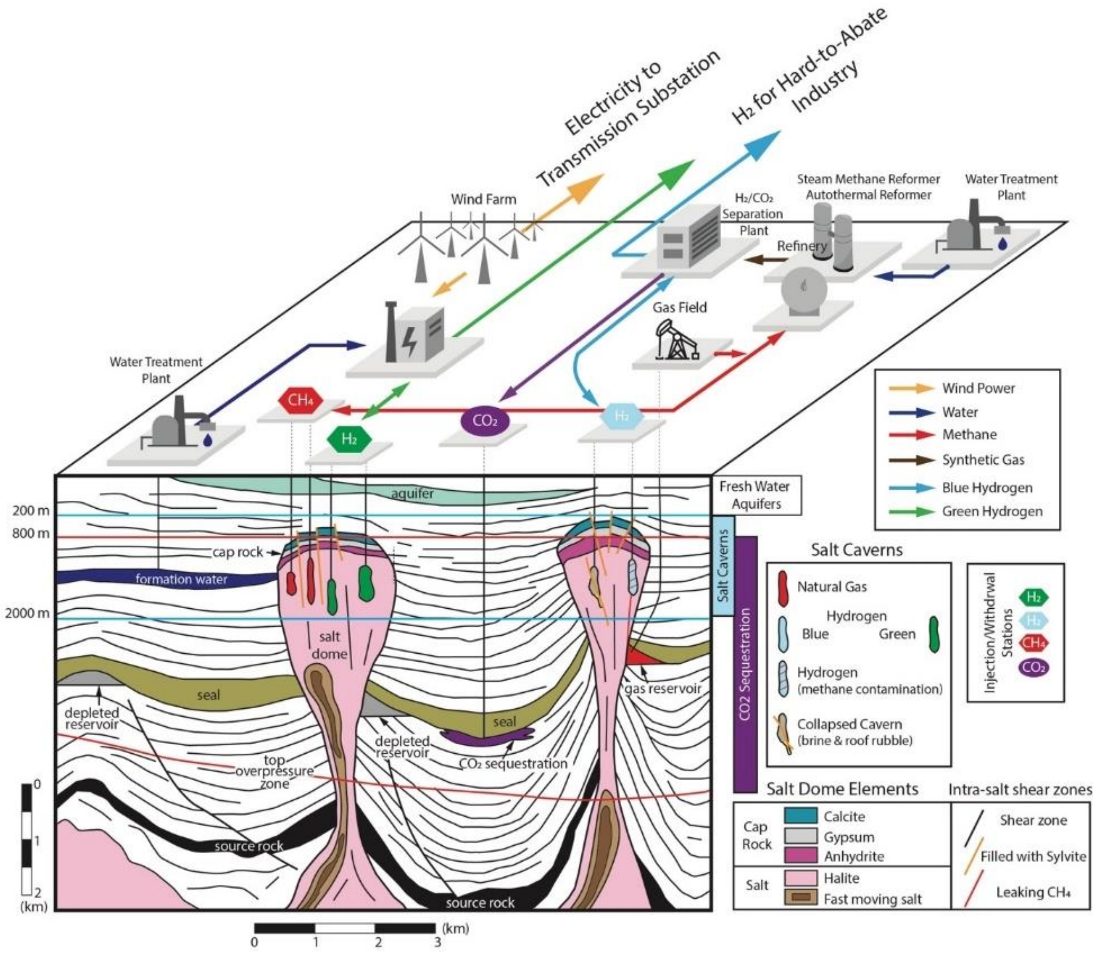
Data from Ahluwalia et al, 2019

Bureau of Economic Geology

GeoH2

Screening and Valuation Framework for Hydrogen Storage

- Geological assessment
- Engineering estimates
- Economic valuation and value chain pathway



Ruiz-Maraggi and Moscardelli (2023) Modeling H2 storage capacities, injection and withdrawal cycles in salt caverns: Introducing the GeoH2 salt storage and cycling app: Int. Jour. of Hydrogen, 48, 26921-26936

https://www.beg.utexas.edu/research/programs/starr/salt-storage-cycling

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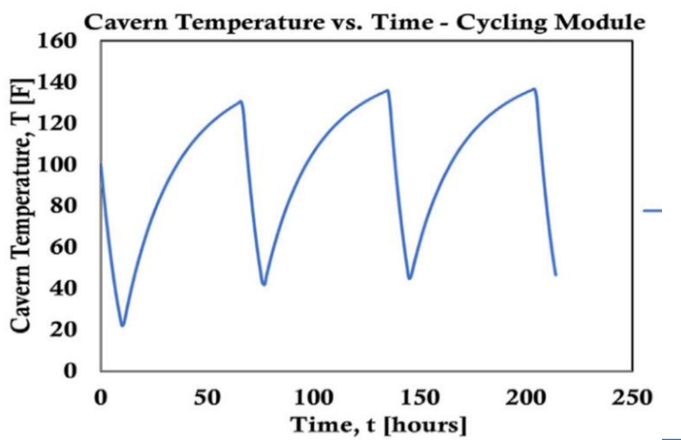
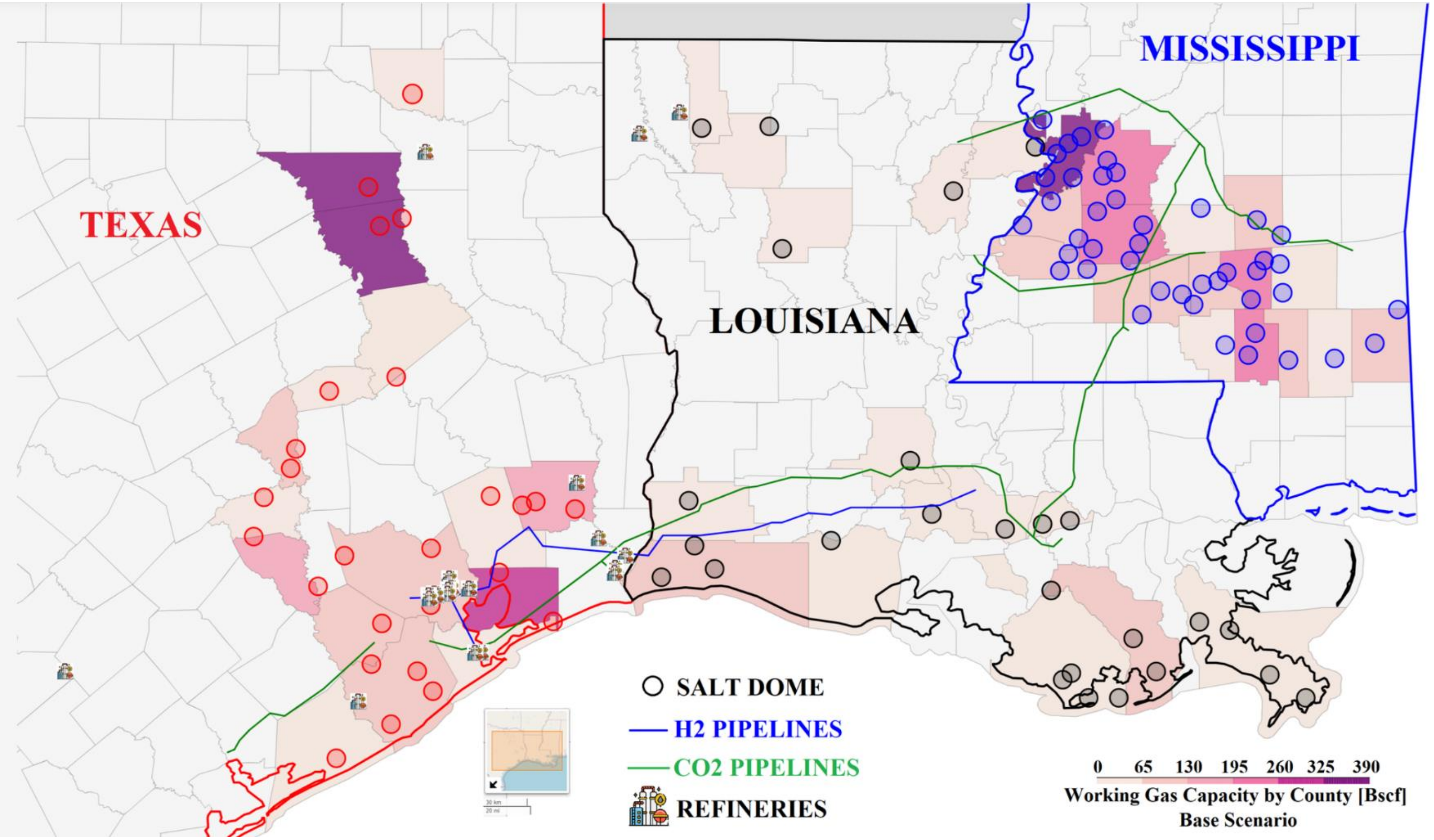
Assessing H_2 Salt Storage Capacity

- GeoH2 Salt Storage and Cycling App
  - Thermodynamic simulator to assess technical potential of H2 storage, injection, withdrawal, and cycling operations in salt caverns

GeoH2 App / H2 Storage and Cycling in Salt Caverns





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https://www.beg.utexas.edu/research/programs/starr/salt-storage-cycling

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Active Research on Salt Domes

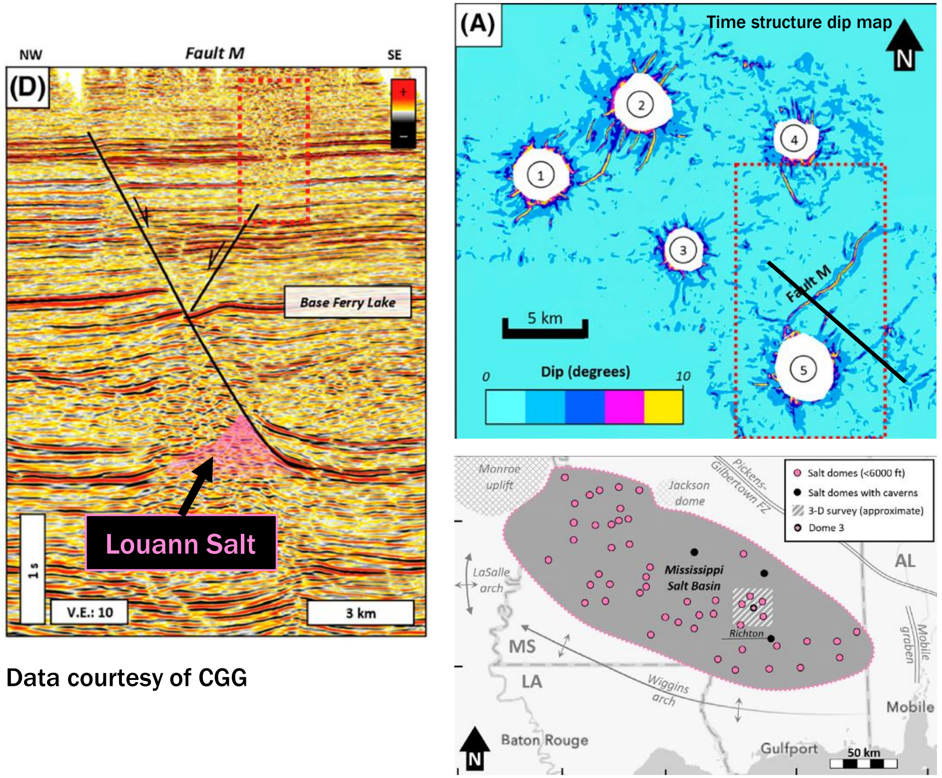
Subsurface storage in the Mississippi Salt Basin domes: Considerations for the emerging hydrogen economy

C. Nur Schuba and Lorena Moscardelli (2022)

AAPG Bulletin, v.107, no 11

Salt Domes

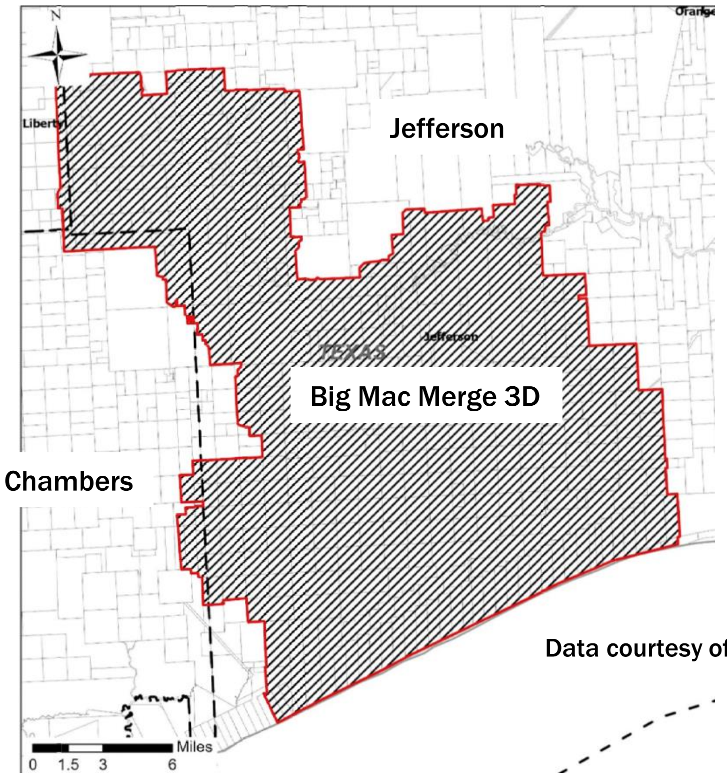
1. Kola
2. Don't
3. Eminence
4. Centerville
5. Moselle



Data courtesy of CGG

Currently working on Big Mac 3D Merge

Evaluating synergies between CCS and H_2 storage



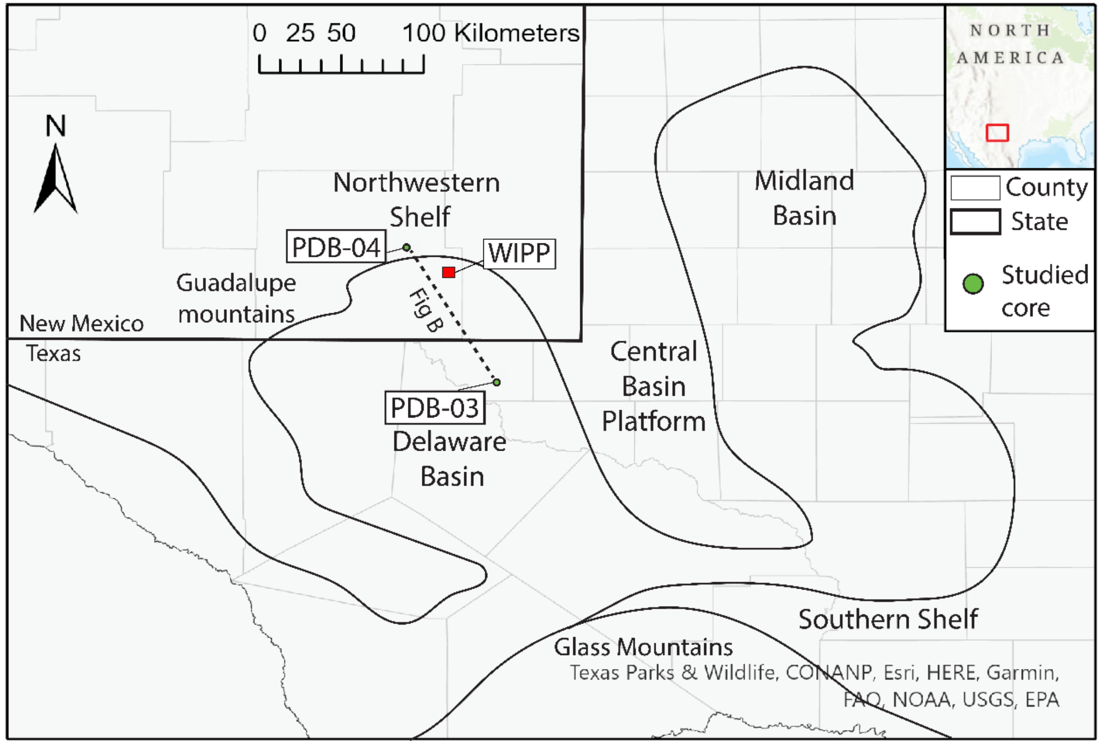
Data courtesy of SEI

Bureau of Economic Geology

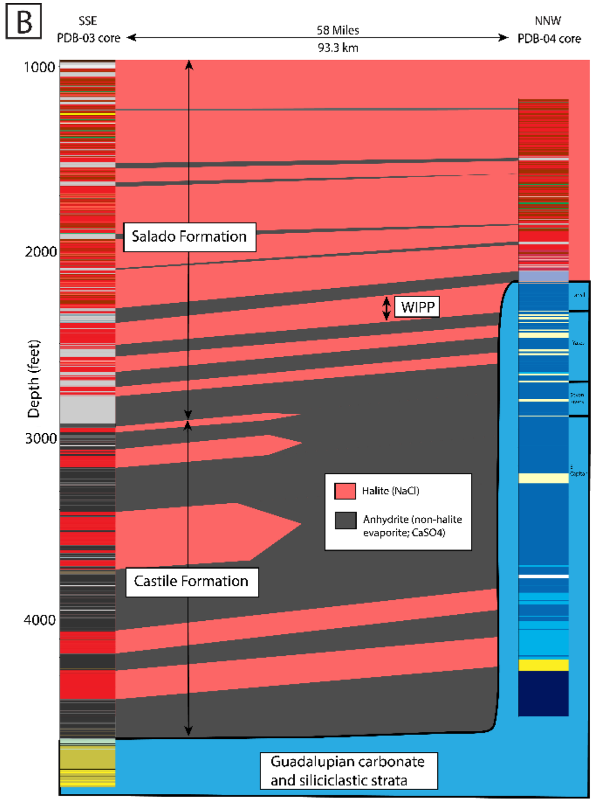
Permian Basin Core Research and Coverage

More than 4,000’ of well-preserved continuous core within the evaporitic sequence of the Permian Basin (Castile and Salado) in one well

A



B



Martinez-Doñate et al. (2023) Geological and geochemical characterization of salt-bearing sequences for hydrogen storage in the Delaware Basin (West Texas): GET EAGE Extended Abstract, Paris, France

We have entire coverage (continuous core)

Bureau of Economic Geology

Not All Salt is the Same

BEG has extensive (1000s of feet) collection of salt cores available for research covering both the Gulf Coast region of the U.S. and the Permian Basin in West Texas / Active research ongoing

(contact: Dr. Lorena Moscardelli) $GeoH_2$

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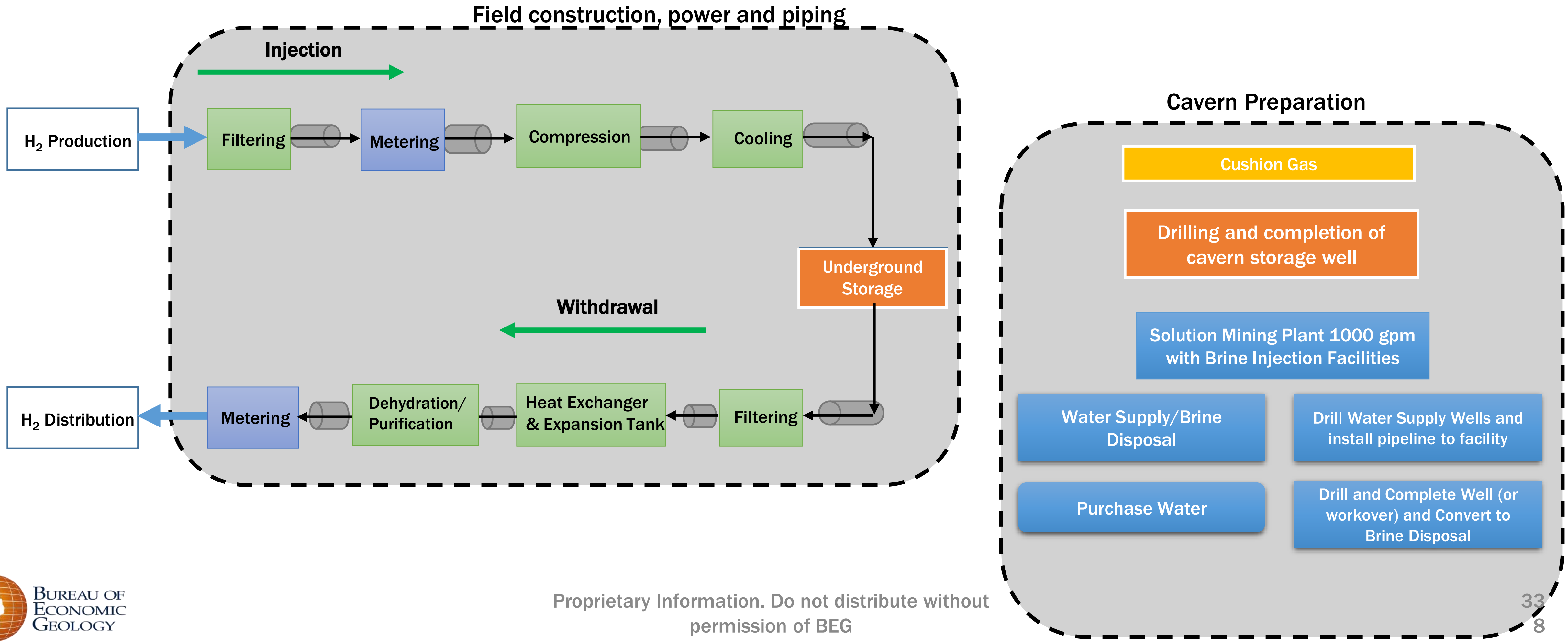
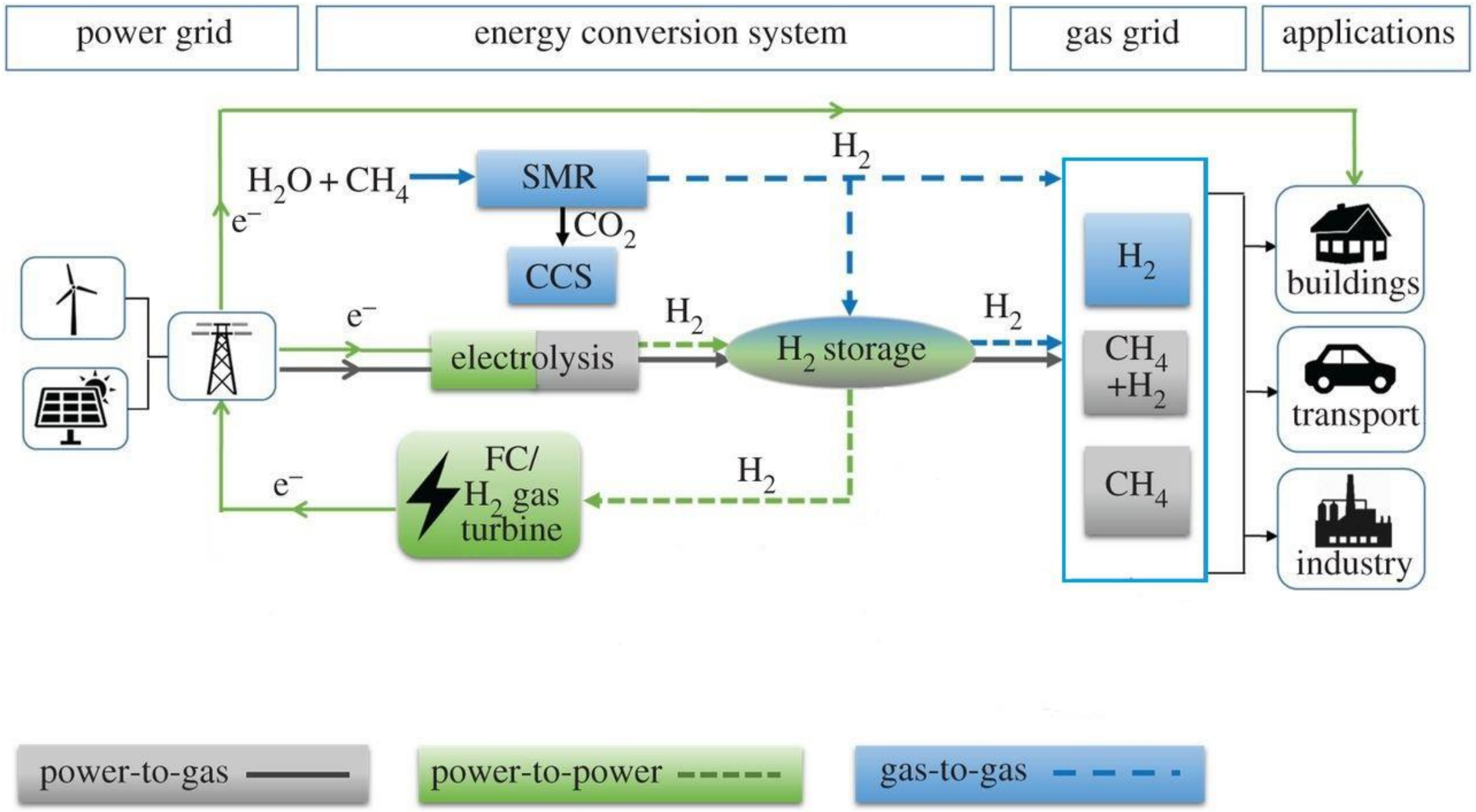
Defining Scope of A Hydrogen Storage Asset



Market Pathway With Geological Hydrogen Storage

- Geological underground storage of hydrogen could receive hydrogen from different production routes.
- Gas storage here serves two purposes:
  - Provide ratable and responsive supplies of hydrogen for end markets
  - Intermittent supply of hydrogen from renewable resources



Lin et al. (2024) Market-based asset valuation of hydrogen geological storage: Int. Jour. Of Hydrogen, 49, 114-129
https://www.sciencedirect.com/science/article/pii/S0360319923034894?via%3Dihub

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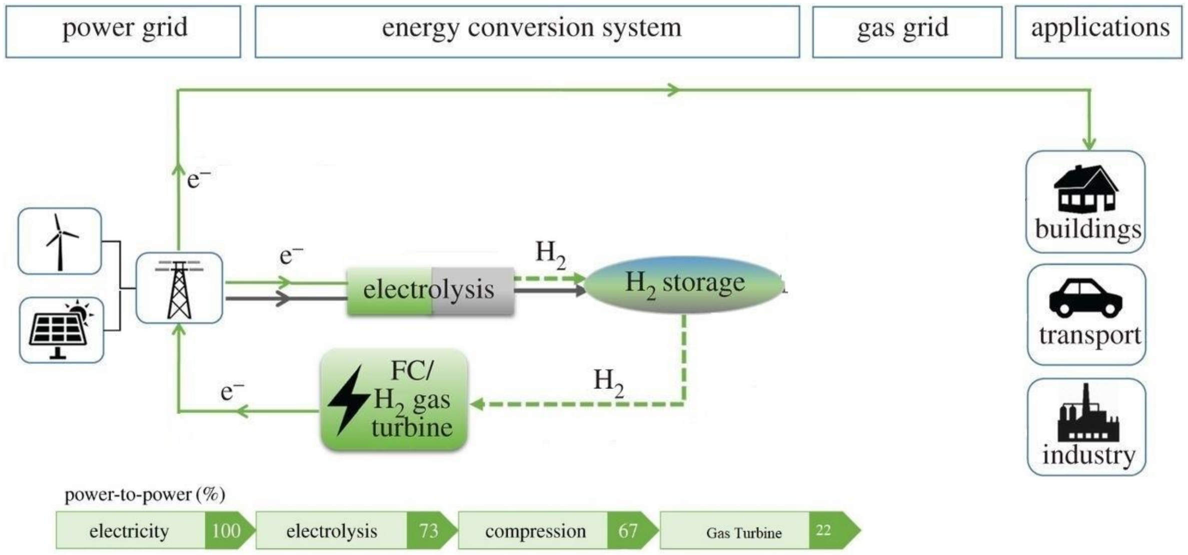
Site B – Multi-turn single well storage

- A 80 MW wind farm in the SPP market of West Texas
- A 21 MW electrolyzer, which produces H2 when the electricity price is sufficiently low **(<$36/Mwh, including production tax credit $25/Mwh)**
- The wind farm's capacity factor is 25%, while the electrolyzer load factor is 50-65%, depending on the season.
- Adding salt storage to the facility to store hydrogen and then convert it back to electricity through a simple gas turbine (65 MW) when the market condition is profitable.

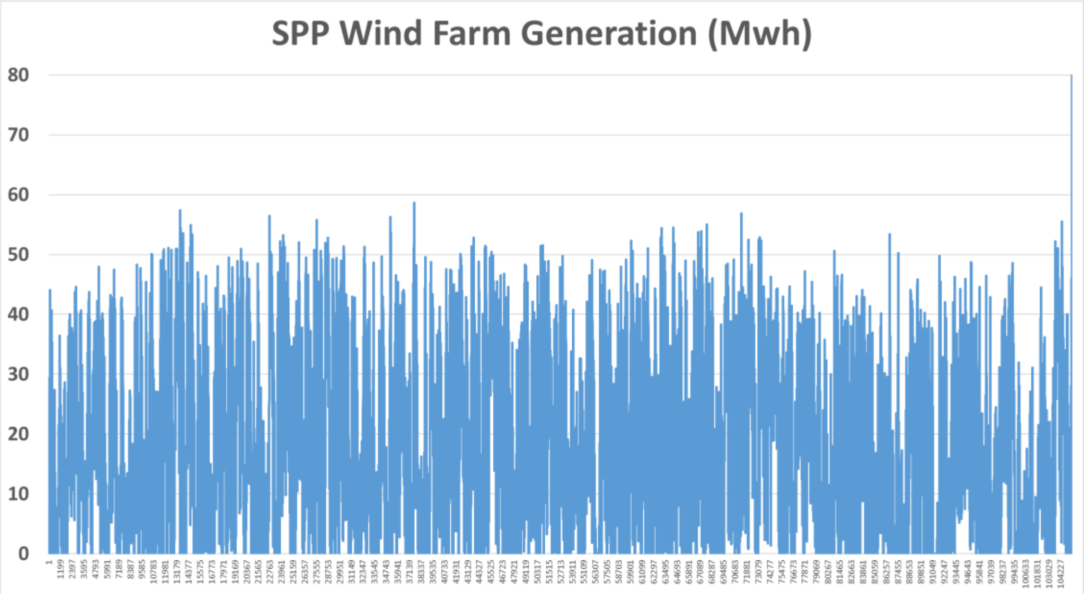
*Reference on wind farm simulation from Dr. X. Feng, M. Lewis from H2@Scale project at UT Austin

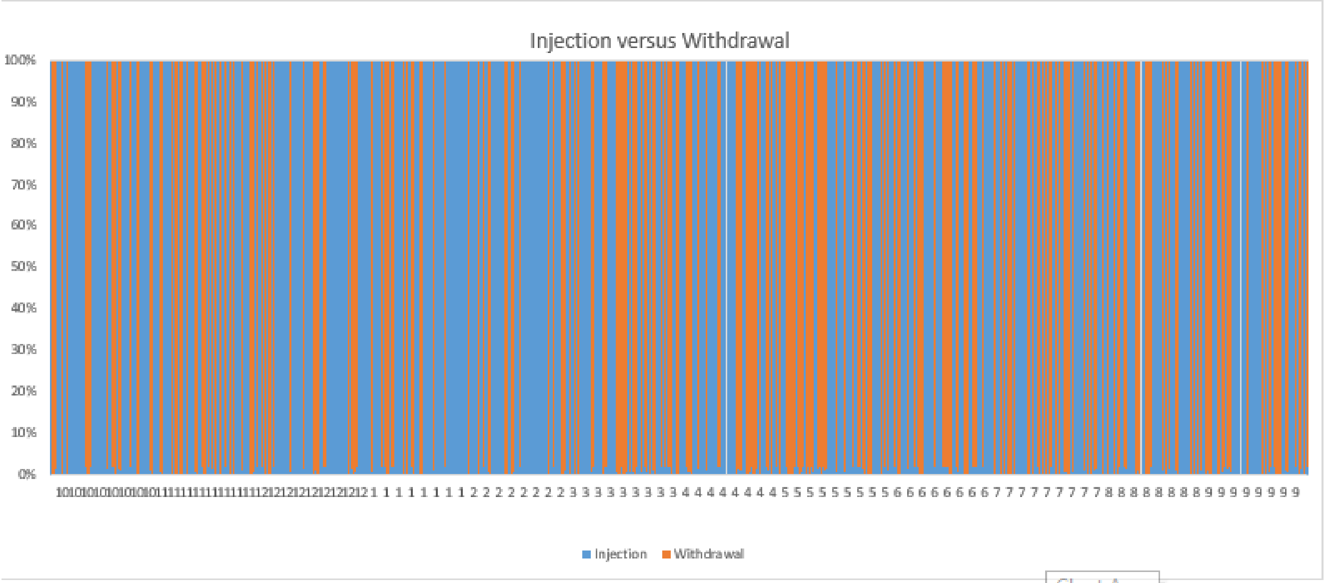


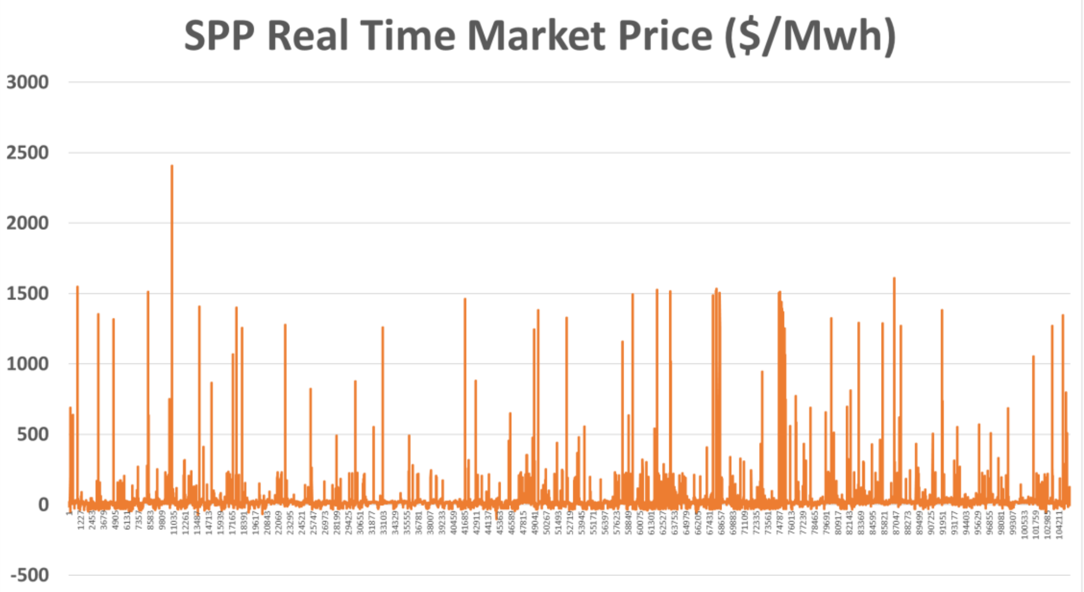
The step conversion efficiencies for the hydrogen supply pathways being considered. Percentage is compounded efficiency at the segment, assuming 2% loss in storage and 30% efficiency for simple cycle gas turbine, takes 80-100% hydrogen

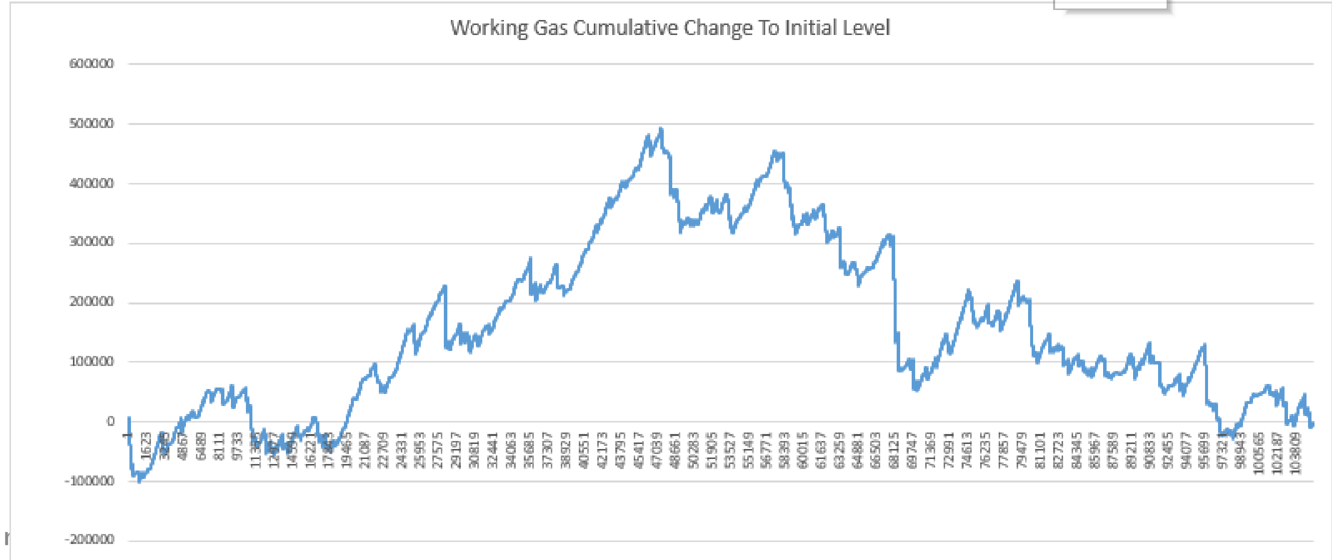
It's designed to turn the energy generated by the wind farm into a dependable asset that can be tapped into as needed.

Site B – Market Simulation



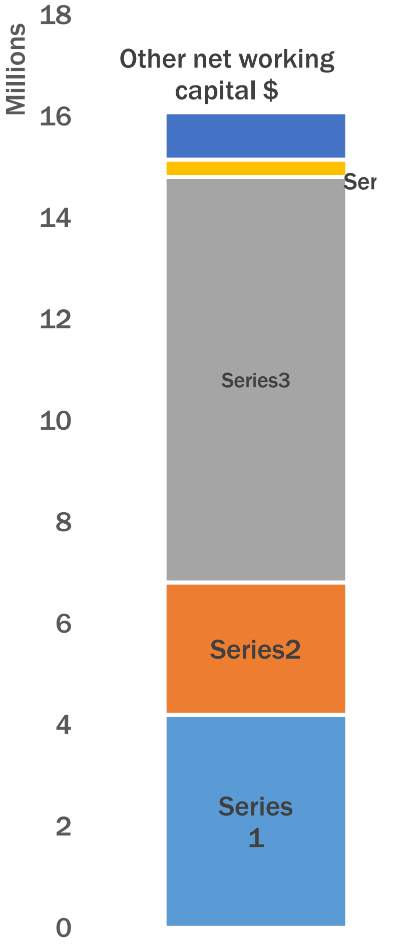




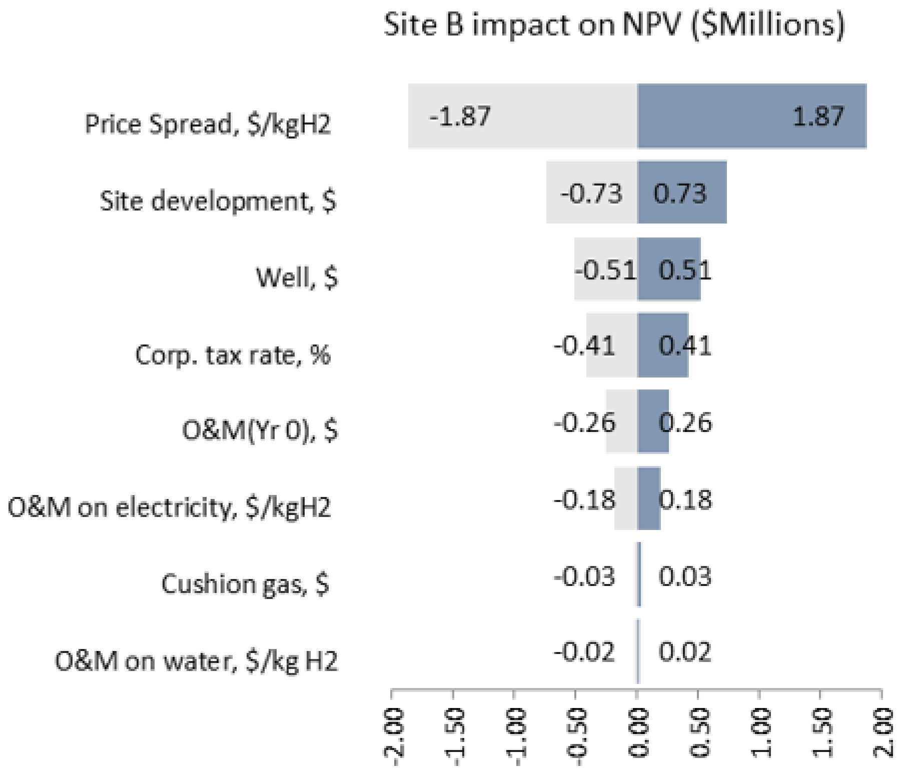


Site B Results – Costs and Commercial Viability

- Working gas: 250MMSCF; 3.5 Turns/Year
- Injection capacity: 415.6 kg/hr (4.14 MMSCF/D), withdrawal capacity 5323.2 kg/hr (53 MMSCF/d)
- Annual Hydrogen: 876MMSCF (2100 Tons)
- Capital cost:
  - Initial capex investment, including cushion gas: $15.9 million
  - Given the spreads of off-peak to peak electricity, the hydrogen value spread can provide 17% IRR.
  - The breakeven cost of hydrogen storage is $1.21/kg



+/- 10%



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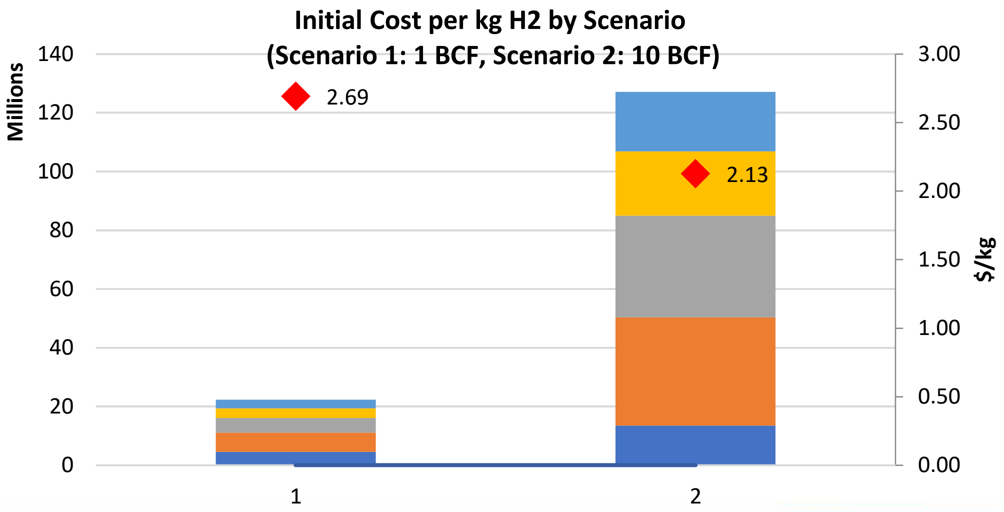
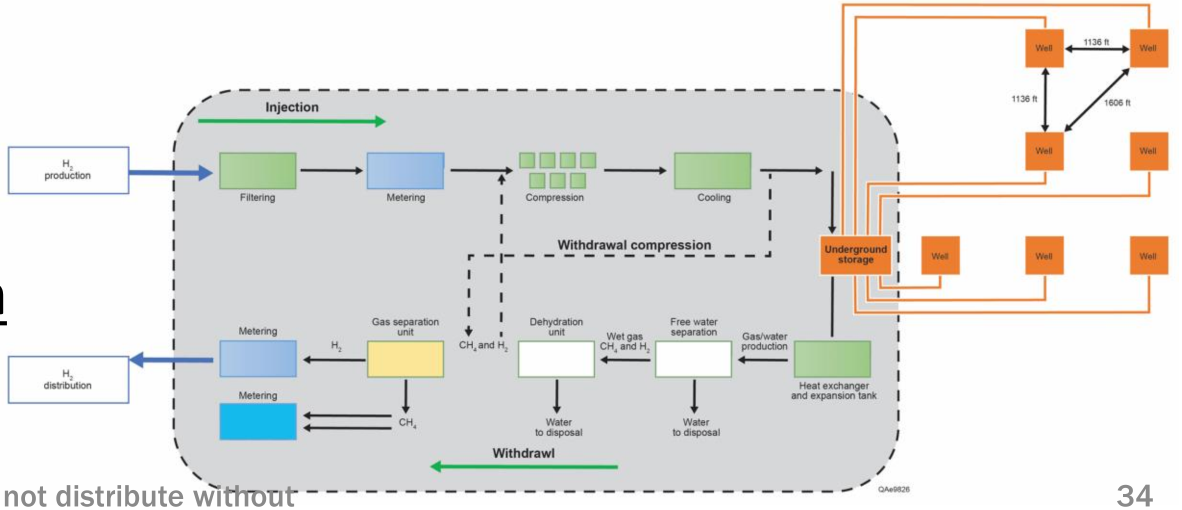
Techno-Economics and Valuation of Hydrogen Geological Storage in Depleted Reservoirs – Lin and Xu (2024)

- 10 bcf 2 cycle 7 well scenario:
  - CAPEX with cushion gas – 125+ million.
  - Base scenario – with a price spread of \$1.0/kg between injection and withdrawal, IRR = 23%, and breakeven cost of storage less than \$1.0/kg.
- Screening is the key:
  - The <u>**initial cushion gas**</u> is <u>**not**</u> key cost concern, while <u>**higher loss of H2**</u> in initial years can be a key factor for reservoir screening.
  - <u>**Number of wells drilled and compression**</u> are the two most expensive factors in capital costs.





Ongoing Research Directions

- Evaluate viable commercial **geological storage opportunities** in the early investment phase
- Develop **contracting and operation strategy** based on route-to-market analysis.
- **Web-based screening and cost tool** HyFive will be available to sponsors in June 2024.

Salt cavern storage valuation

(Jun 2022)

"Market-Based Asset Valuation of Hydrogen Geological Storage", article accepted for publication, International Journal of Hydrogen Energy, 2023

Proprietary TEA and Valuation Model

HyFive Model (Feb 2023)

Depleted reservoir storage for hydrogen – Phase 1, presenting 1.5 bcf scenario techno-economics

(Jul 2023)

Depleted reservoir storage for hydrogen – Phase 2, presenting 10 bcf scenario techno-economics and economic valuation

(Oct 2023)

Screening framework for storage project using HyFive Model (Oct 2023)

Web-based HyFive launch (June 2024)

Bureau of Economic Geology

Sandia National Laboratories

SHASTA Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Risk Assessment Frameworks for Underground Hydrogen Storage Facility Leaks

Melissa Louie and Brian Ehrhart

April 3, 2024
SHASTA Technical Workshop
Pittsburgh, PA

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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SAND2024-02924PE

Regulations, Codes, and Standards Landscape for UHS Risk

Publishing Authority	Document Number	Document Name	Year Last Updated	Guidance
CISA	6 CFR 27	Chemical Facility Antiterrorism Standards (CFATS)	2023	Reporting requirements for large-scale H_2 storage [Expired as of July 2023]
OSHA	29 CFR 1910.103	Hazardous Materials: Hydrogen	2007	Setback distances for aboveground H_2 systems
	29 CFR 1910.119	Process Safety Management of Highly Hazardous Chemicals	2013	Process safety management requirements for Category 1 flammable gases
PHMSA	49 CFR 192.12	Underground Natural Gas Storage Facilities (UNGSFs)	2020	Requirements for UNGSFs including risk management and compliance with API RP 1170 and 1171
API	RP 1170	Design and Operation of Solution-mined Salt Caverns Used for Natural Gas Storage	2022	Practices for salt cavern UNGSFs including siting, geomechanical evaluation, well design, monitoring, risk assessment
	RP 1171	Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs	2022	Practices for depleted reservoir UNGSFs including siting, geomechanical evaluation, well design, monitoring, risk assessment
NFPA	NFPA 2	Hydrogen Technologies Code	2023	Setback distances for aboveground and underground H_2 containers

Regulations for **"natural gas"** (49 CFR 192.12, AP RP 1170 and 1171) may be **generic** enough to apply to hydrogen as written.

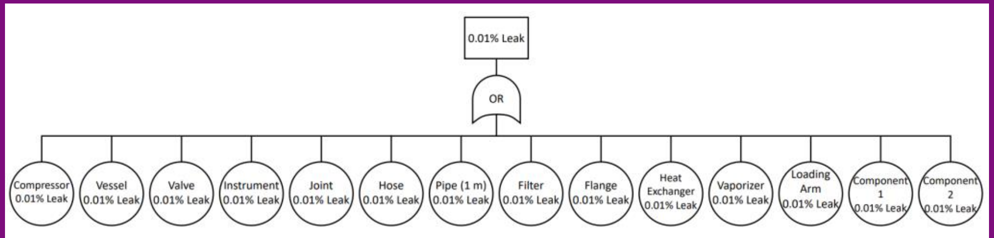
Regulations for **hydrogen** (29 CFR 1910.103, NFPA 2) **do not currently apply to subsurface storage**.

Quantitative Risk Assessment Methodology

H_2 Facility or Wellhead

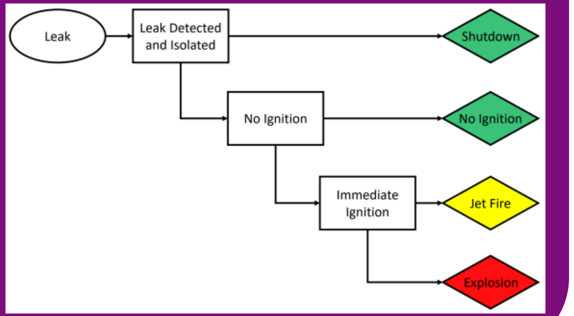
Leak Frequency Analysis

- Component counts
- Leak size data



Physical Response Analysis

- Heat flux (jet flame models)
- Overpressure (explosion models)



Consequence Analysis

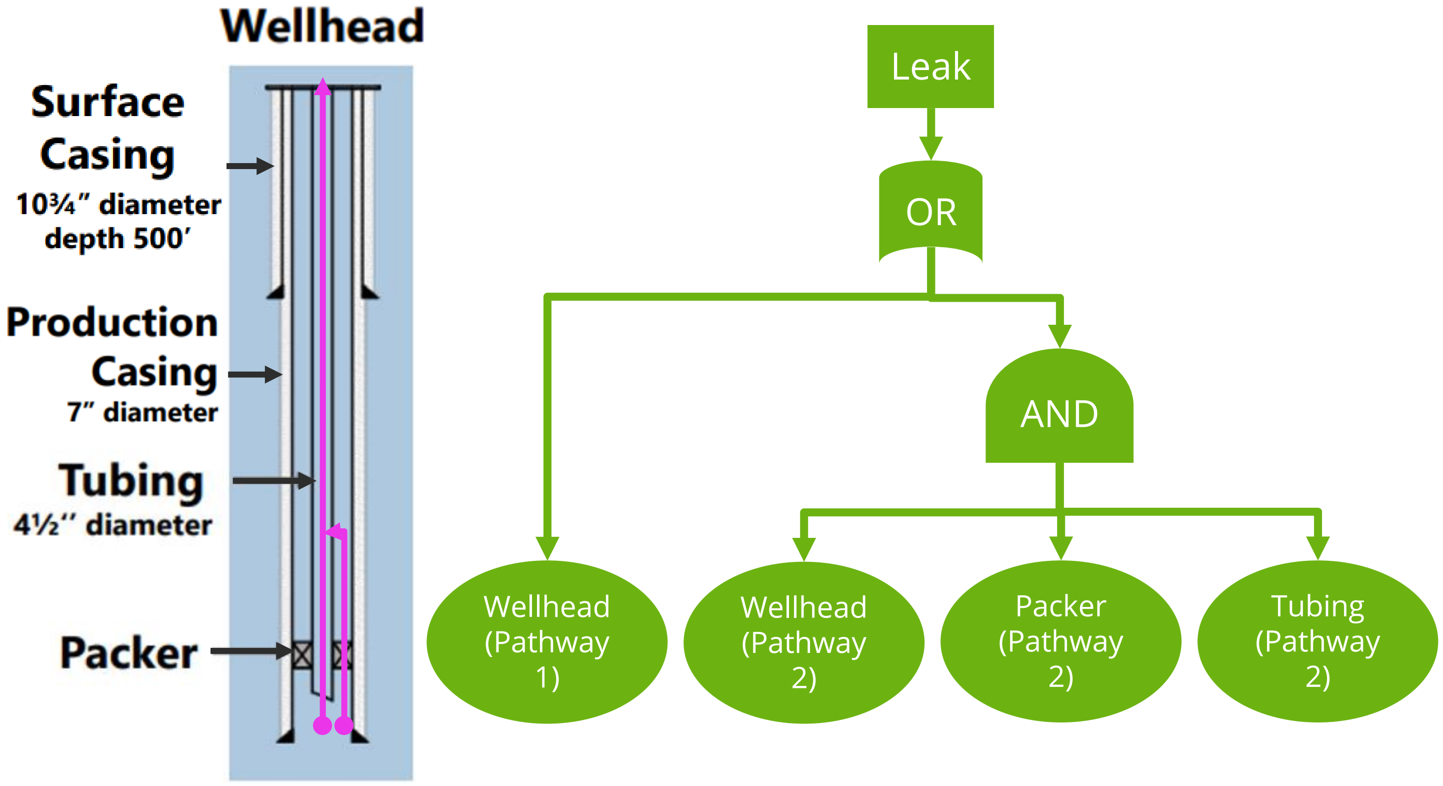
- Probit models
- Ignition probabilities

Individual Risk Analysis

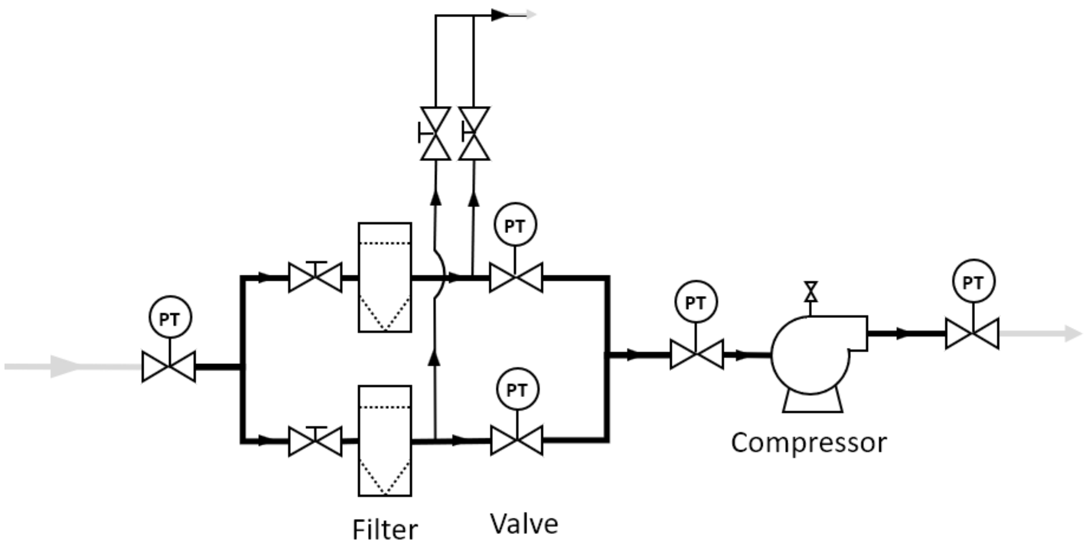
- Annual frequency of fatality

B. Ehrhart, E. Hecht, and B. Schroeder, "Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 5.1 Technical Reference Manual," Sandia National Laboratories, SAND2023-14224, Dec. 2023, https://energy.sandia.gov/download/62976/

Generic System Configurations and Leak Pathways/Sources



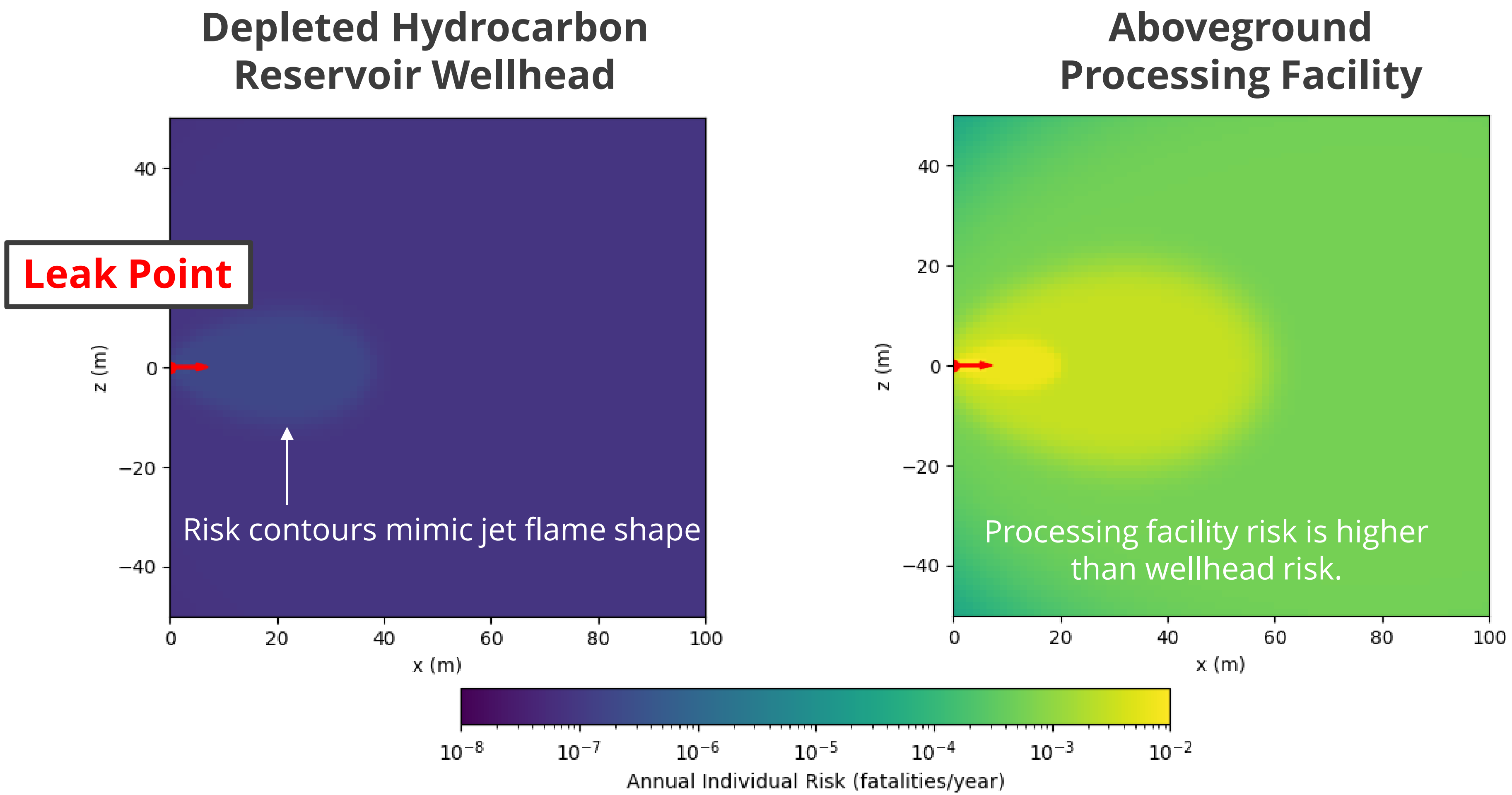
Wellhead configuration and fault tree for an example depleted hydrocarbon reservoir



Aboveground processing facility P&ID

M. Stephens, "Applying the New PHMSA Guidelines contained in Risk Assessment and Treatment of Wells," C-FER Technologies Webinar - Part 2, 2020.

Contour plots show main contributors to individual risk.



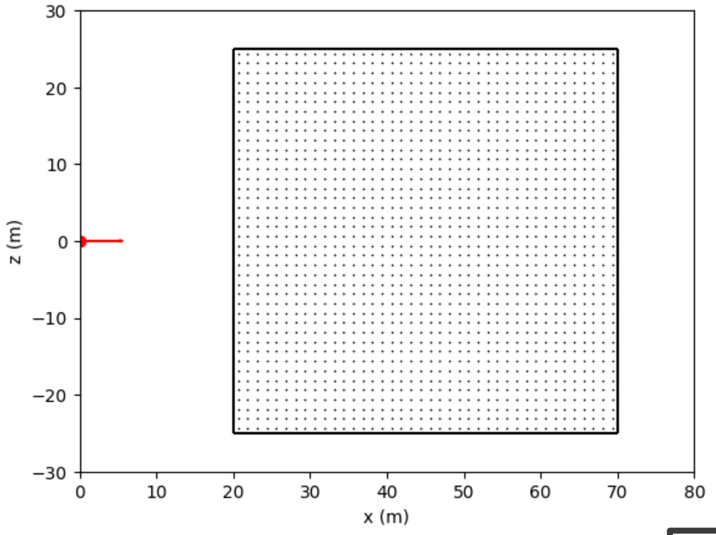
Thermal effects dominate overall risk compared to overpressure effects.

The **aboveground processing facility dominates overall risk** compared to the wellhead.*

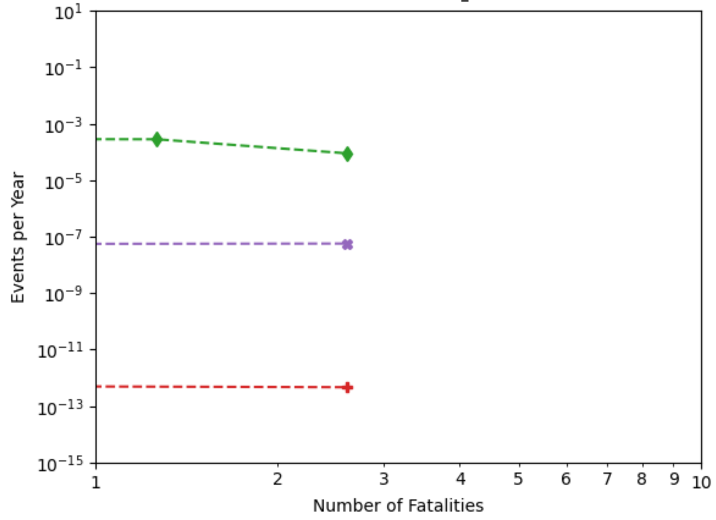
* Based on leak frequencies derived from available data (not specific to hydrogen)

F-N curves highlight potential sources of leaks and need for hydrogen-specific data.

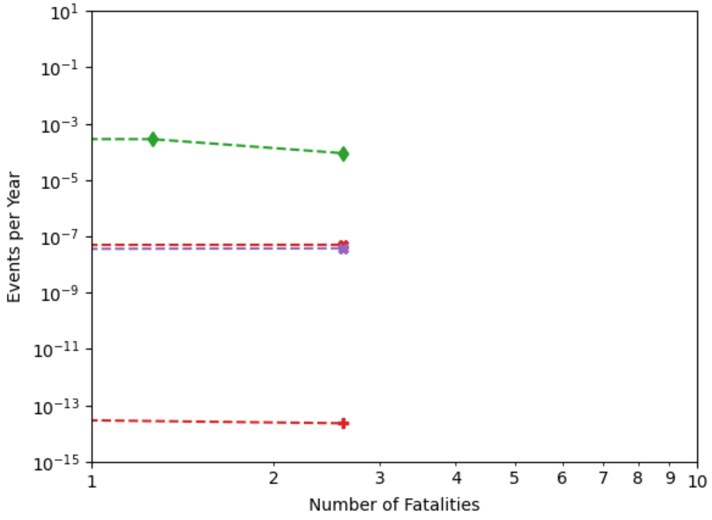
Area of Interest



Depleted Hydrocarbon Reservoir/Aquifer*



Salt Cavern*



Processing Facility — Wellhead Operations — Wellhead Entry
--- Jet Fire ····· Overpressure
♦ Processing Facility Component ✖ Wellhead Through Casing ✚ Wellhead Through Tubing

The processing facility is the source of the most leaks.**

The **wellhead leaks more during entry than normal operations** in the reservoir configuration.**

The **wellhead through casing pathway leaks more** than the wellhead through tubing pathway in the salt cavern configuration.**

* Based on greatest county population density of 2700 people per square mile
** Based on leak frequencies derived from available data (not specific to hydrogen)

Interpreting and Applying Risk Assessment Results

Example Result	Potential Applications
Certain components/pathways have high leak frequencies	Implement rigorous monitoring, repair, maintenance protocols for those components
Certain components (ex. DHSV) decrease risk	Include safety components in wellhead design
Higher Mach flame speeds cause higher overpressure risk	Limit obstructions and confinement in/near system
Ambient temperature affects heat flux risk	Account for ambient temperatures when designing placement and orientation of components within system

Thank You!

Evan Frye (DOE FECM)

Timothy Reinhardt (DOE FECM)

Mathew Ingraham (Sandia)

Franek Hasiuk (Sandia)

Donald Conley (Sandia)

Angela Goodman (NETL)

Joshua White (LLNL)

Nicolas Huerta (PNNL)

Questions?

Melissa Louie
mlouie@sandia.gov

Backup Slides

Backup Slides: Data

Data Sources

Wellhead [1]

- PHMSA Project DTPH56-17-RA-00002
  - Oil and gas data, including:
    - Canadian Association of Petroleum Producers (CAPP)
    - U.K. Health and Safety Executive (HSE)
    - International Association of Oil & Gas Producers (IOGP)

Aboveground Processing Facility [2]

- HyRAM+ defaults
  - Derived from oil and gas data, including:
    - U.K. HSE
    - IOGP
    - Analyses by Pacific Northwest National Laboratory (PNNL), Idaho National Engineering Laboratory (INEL), Sandia National Laboratory

Leak frequencies for hydrogen piping and instrumentation are currently **highly uncertain**.

Increasing availability of hydrogen-specific data can improve the accuracy of risk assessment results.

[1] M. Stephens, “Applying the New PHMSA Guidelines contained in Risk Assessment and Treatment of Wells,” presented at the C-FER Technologies Webinar - Part 2, Nov. 17, 2020.

[2] Brooks, Dusty, Glover, Austin, and Ehrhart, Brian D. 2022. "Compressed Natural Gas Component Leak Frequency Estimation". United States. https://doi.org/10.2172/1892133. https://www.osti.gov/servlets/purl/1892133.

Ignition Probabilities

Hydrogen Release Rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability
<0.125	0.008	0.004
0.125-6.25	0.053	0.027
>6.25	0.230	0.120

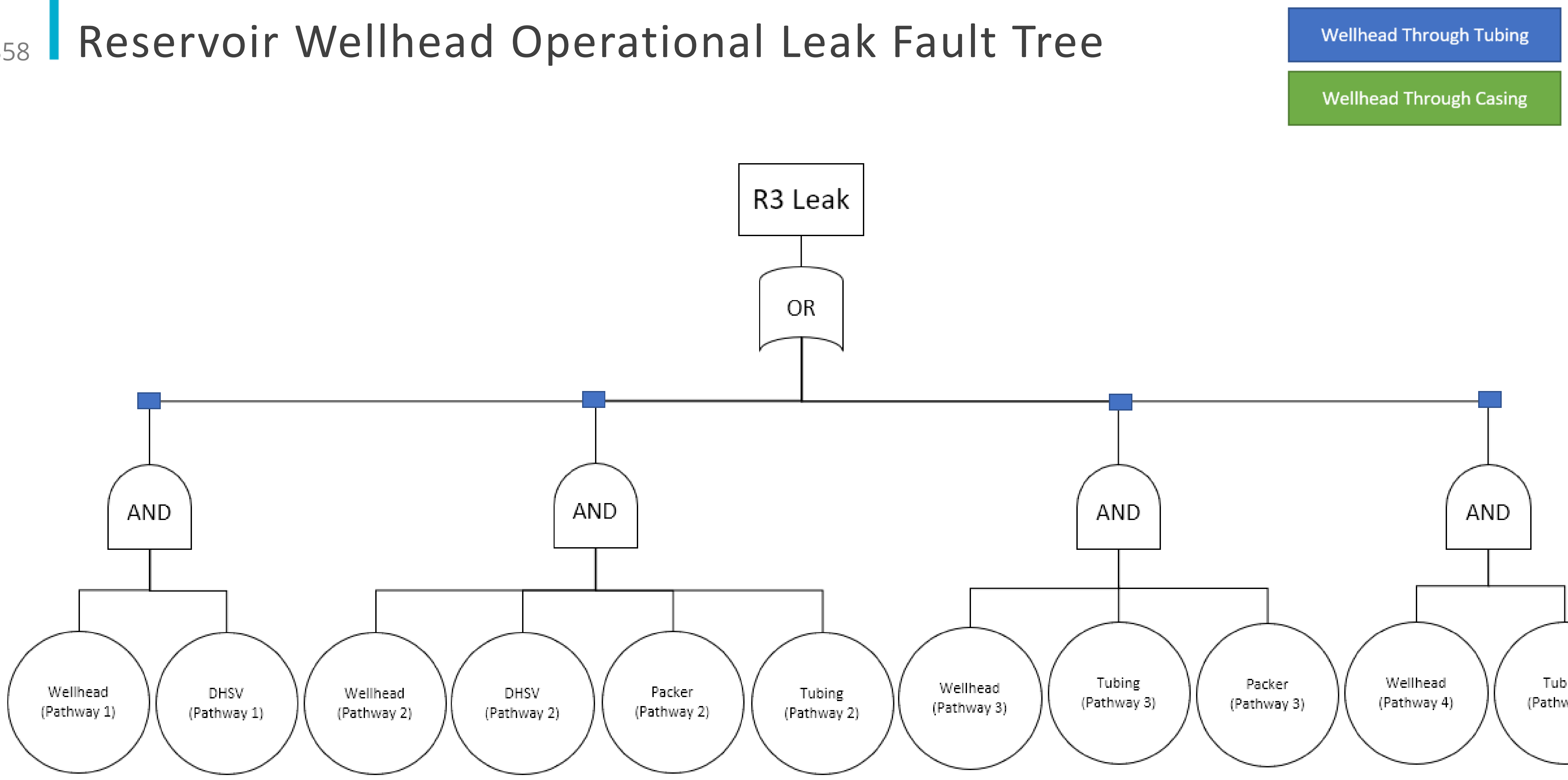
Brian D. Ehrhart, Ethan S. Hecht, Benjamin B. Schroeder, Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+), Sandia National Laboratories, Version 5.1, December 2023, https://energy.sandia.gov/download/62976/.

Wellhead Component Operational Leak Frequencies

Wellhead Component	Failure Frequency (per Year)
Surface Casing	8.00E-06
Production Casing (above surface casing shoe)	8.00E-06
Intermediate Casing (above surface casing shoe)	8.00E-06
Production Casing (below surface casing shoe)	7.20E-05
Intermediate Casing (below surface casing shoe)	7.20E-05
Wellhead Assembly	5.40E-05
Tubing	2.30E-05
Packer	2.90E-03
DHSV	2.00E-05

M. Stephens, “Applying the New PHMSA Guidelines contained in Risk Assessment and Treatment of Wells,” presented at the C-FER Technologies Webinar - Part 2, Nov. 17, 2020.

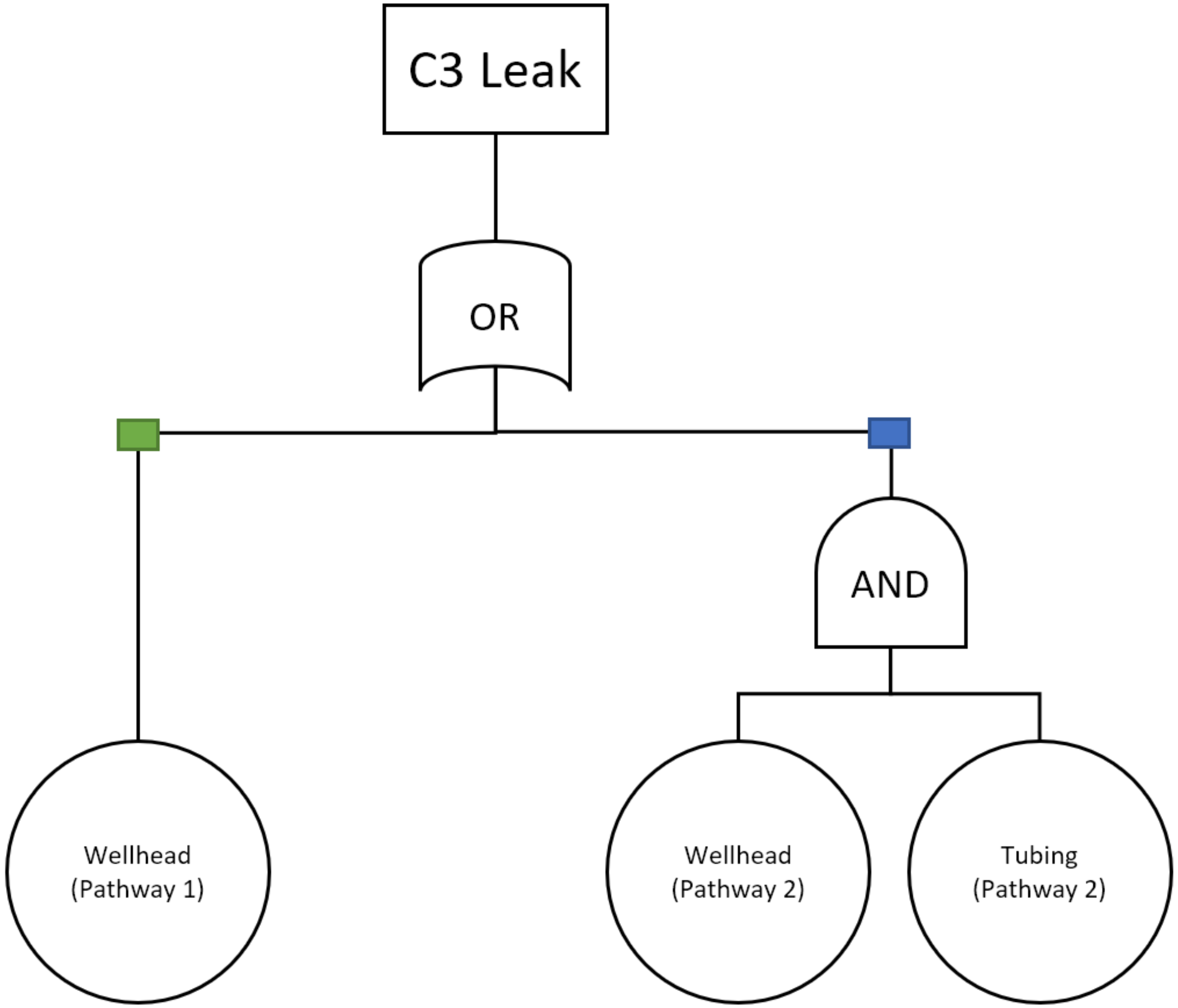
Reservoir Wellhead Operational Leak Fault Tree



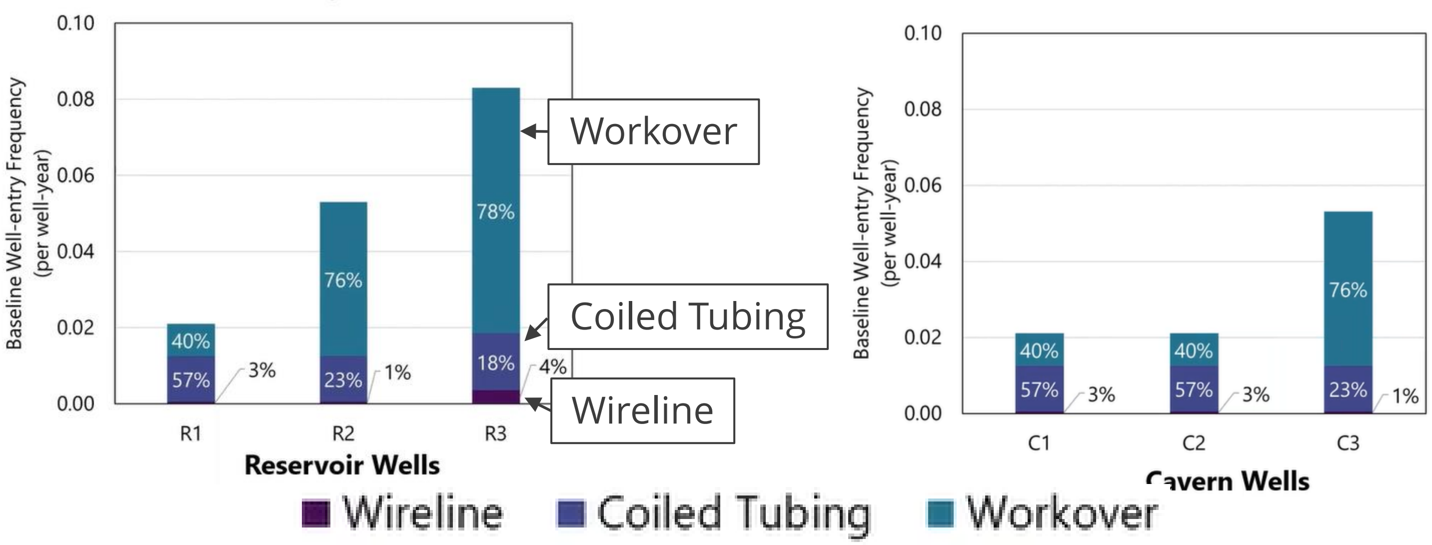
Cavern Wellhead Operational Leak Fault Tree

Wellhead Through Tubing

Wellhead Through Casing



Wellhead Entry Failure Frequencies



Well Entry Type	Failure Rate per Entry
Workover	2.0E-04
Coiled Tubing	5.5E-05
Wireline	4.5E-06

Leak Size	Percentage of Well Entry Leaks
Small	9%
Large	73%
Rupture	18%

Well Configuration	Annual Well Entries	Annual Well Entry Failures								
		Workover			Coiled Tubing			Wireline		
		Small	Large	Rupture	Small	Large	Rupture	Small	Large	Rupture
R1	0.021	1.5E-07	1.2E-06	3.0E-07	5.9E-08	4.8E-07	1.2E-07	2.6E-10	2.1E-09	5.1E-10
R2	0.0529	7.2E-07	5.9E-06	1.4E-06	6.0E-08	4.9E-07	1.2E-07	2.1E-10	1.7E-09	4.3E-10
R3	0.0831	1.2E-06	9.5E-06	2.3E-06	7.4E-08	6.0E-07	1.5E-07	1.3E-09	1.1E-08	2.7E-09
C1	0.021	1.5E-07	1.2E-06	3.0E-07	5.9E-08	4.8E-07	1.2E-07	2.6E-10	2.1E-09	5.1E-10
C2	0.021	1.5E-07	1.2E-06	3.0E-07	5.9E-08	4.8E-07	1.2E-07	2.6E-10	2.1E-09	5.1E-10
C3	0.053	7.3E-07	5.9E-06	1.5E-06	6.0E-08	4.9E-07	1.2E-07	2.1E-10	1.7E-09	4.3E-10

M. Stephens, "Applying the New PHMSA Guidelines contained in Risk Assessment and Treatment of Wells," presented at the C-FER Technologies Webinar - Part 2, Nov. 17, 2020.

Processing Facility Leak Frequencies

Component	Leak Size (Percentage of Pipe Area)				
	0.01%	0.1%	1%	10%	100%
Filter	2.97E-03	9.98E-04	3.35E-04	1.17E-04	3.72E-05
Compressor	9.97E-02	1.70E-02	4.57E-03	1.52E-04	1.46E-05
Valve	2.87E-03	5.86E-04	5.44E-05	2.47E-05	4.82E-06
Instrument	6.24E-04	1.95E-04	1.12E-04	1.00E-04	3.68E-05
Joint	3.50E-05	4.69E-06	7.86E-06	7.53E-06	6.40E-06
Pipe	8.02E-06	3.70E-06	9.56E-07	4.61E-07	1.47E-07

Brian D. Ehrhart, Ethan S. Hecht, Benjamin B. Schroeder, Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+), Sandia National Laboratories, Version 5.1, December 2023, https://energy.sandia.gov/download/62976/.

Leak Sizes

Facility	Leaking Component	Leaking Component Diameter (mm)	Leak Diameter (mm)		Percentage of Component Area
Wellhead	Wellhead through Tubing	114	Small	1	0.01
			Large	11	1
			Rupture	110	93
	Wellhead through Casing (Production, Intermediate, or Surface)	178, 273, 273	Small	2	0.01, <0.01, <0.01
			Large	18	1, 0.4, 0.4
			Rupture	180	100, 43, 43
Processing Facility	Any	180	Very Small	1.8	0.01
			Minor	5.7	0.1
			Medium	18	1
			Major	56.9	10
			Rupture	180	100

M. Stephens, "Applying the New PHMSA Guidelines contained in Risk Assessment and Treatment of Wells," presented at the C-FER Technologies Webinar - Part 2, Nov. 17, 2020.

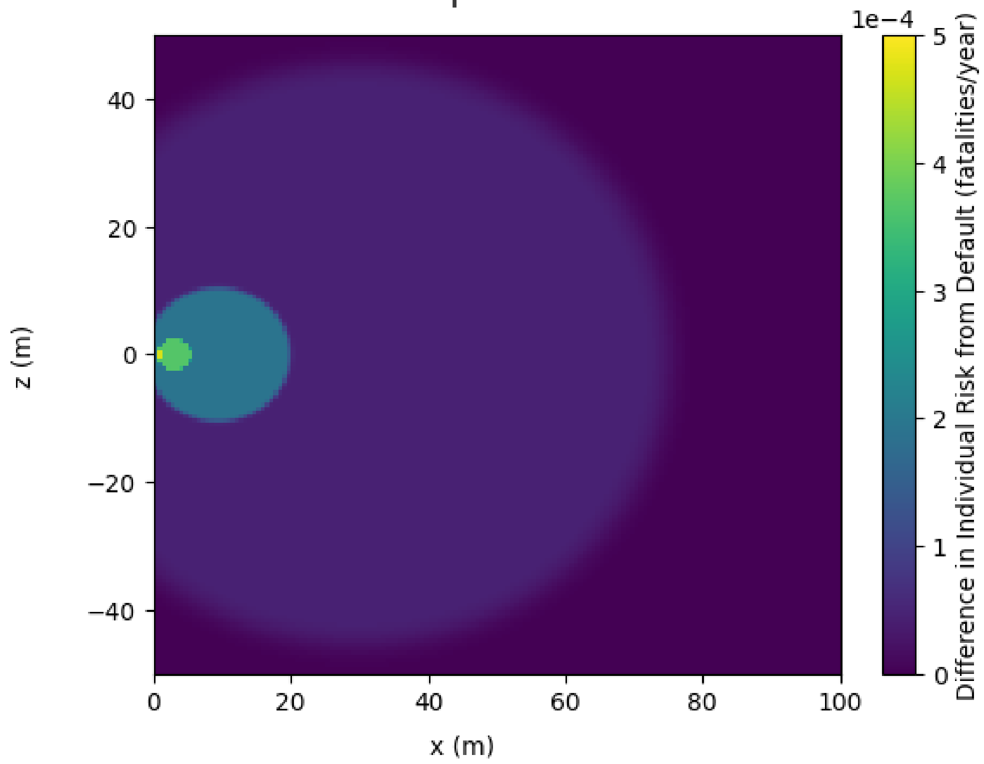
Brian D. Ehrhart, Ethan S. Hecht, Benjamin B. Schroeder, Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+), Sandia National Laboratories, Version 5.1, December 2023, https://energy.sandia.gov/download/62976/.

Backup Slides: Results

Sensitivity of Risk to Mach Flame Speed

Reservoir Configuration

Difference in individual risk between Mach flame speed of 5.2 and 0.35

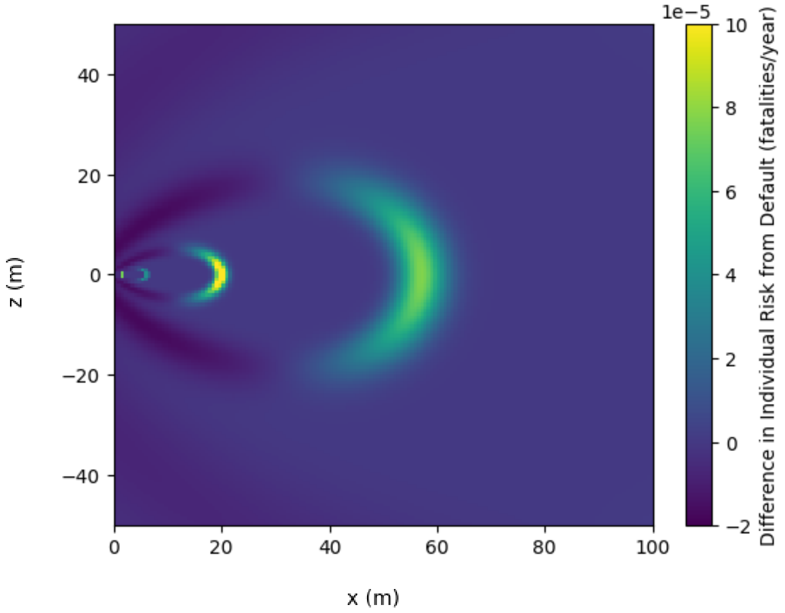


Increasing the **Mach flame speed** increases **overpressure risk**.

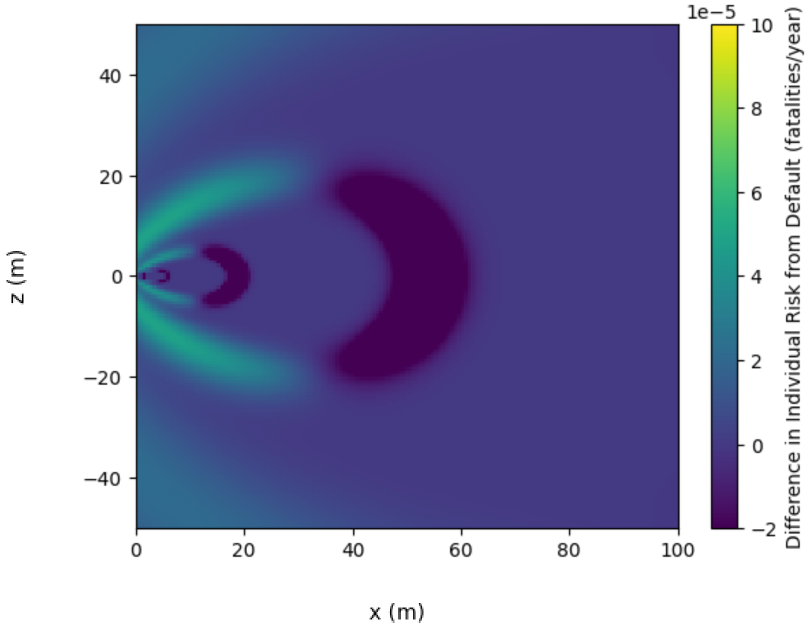
Sensitivity of Risk to Ambient Temperature

Reservoir Configuration

Difference in individual risk between higher temp and room temp



Difference in individual risk between higher temp and room temp

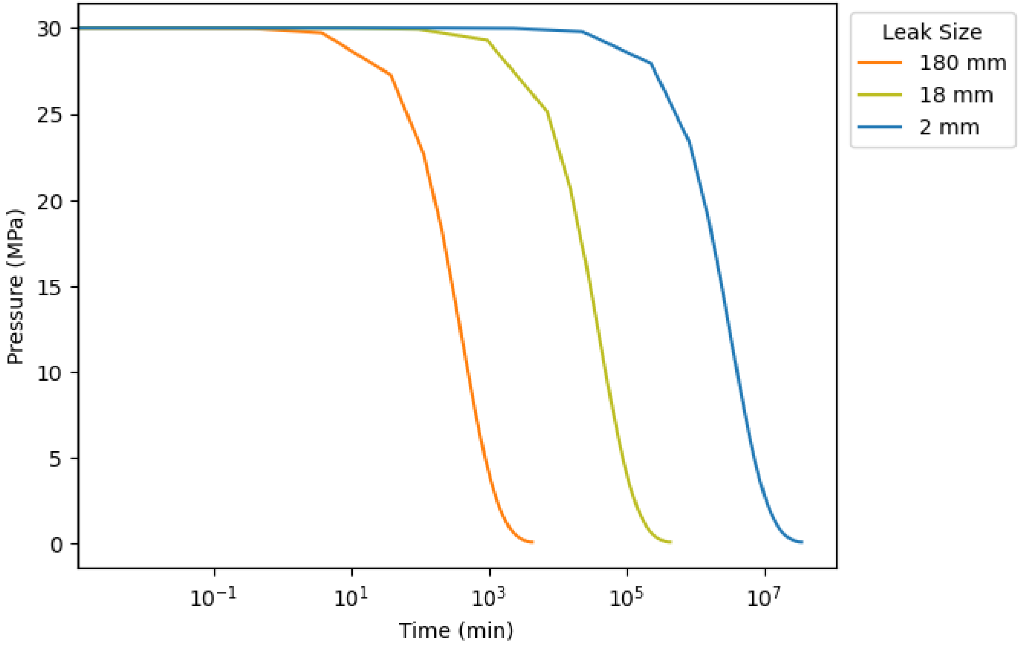


Higher ambient temperatures lead to slightly **longer and narrower** heat flux profiles.

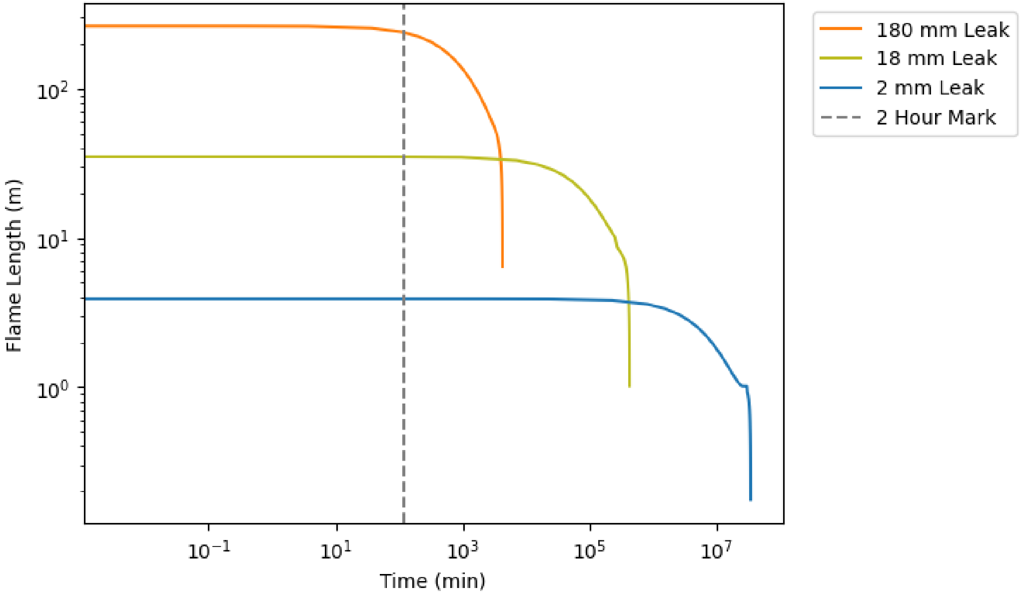
Lower ambient temperatures lead to slightly **shorter and wider** heat flux profiles.

Leak durations can affect damage to infrastructure.

Pressure Considerations*



Jet Fire Considerations*



- **Leak detection**
  - Pressure indicates leaks, product loss
- **Well integrity**
  - Well can lose structural integrity at low pressures

- **Large leaks** have **far-reaching** jet flames (spatial)
  - Can damage infrastructure that is farther away
- **Large stored quantities** have **long-lasting** jet flames (temporal)
  - Can cause greater damage to infrastructure in affected area

* Using a 900,000 m^3 reservoir volume

[1] Jeffrey LaChance, Andrei Tchouvelev, Angunn Engebo, Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure, International Journal of Hydrogen Energy, Volume 36, Issue 3, 2011, https://doi.org/10.1016/j.ijhydene.2010.03.139.

Summary of Findings

Leak Frequency Data

Hydrogen-specific leak frequency data is needed.

Risk Metrics of Interest

Individual and **societal** risk can be considered in UHS design and regulation.

Variables of Interest

Wellhead configuration, **Mach flame speed**, and **ambient temperature** may affect risk.

Temporal Effects of Leaks

It may be helpful to consider **temporal effects** of leaks for UHS.

Risk Tradeoffs

Risk mitigation is a balance of **safety**, **cost**, **time**, **feasibility**, and **efficacy.**

A **quantitative risk threshold** can help regulators and owner-operators understand the relative importance of risks.

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solutions that transform

SUSTAIN H2
SUbsurface Storage Technological Advancements & INnovation for Hydrogen

Shadi Salahshoor, PhD

Senior Program Manager, GTI Energy

SHASTA Technical Workshop - April 2024

The need for expanded hydrogen storage

GTI ENERGY

Large-scale low-cost storage solutions will be critical to implementing a hydrogen economy

Long-duration Energy Storage

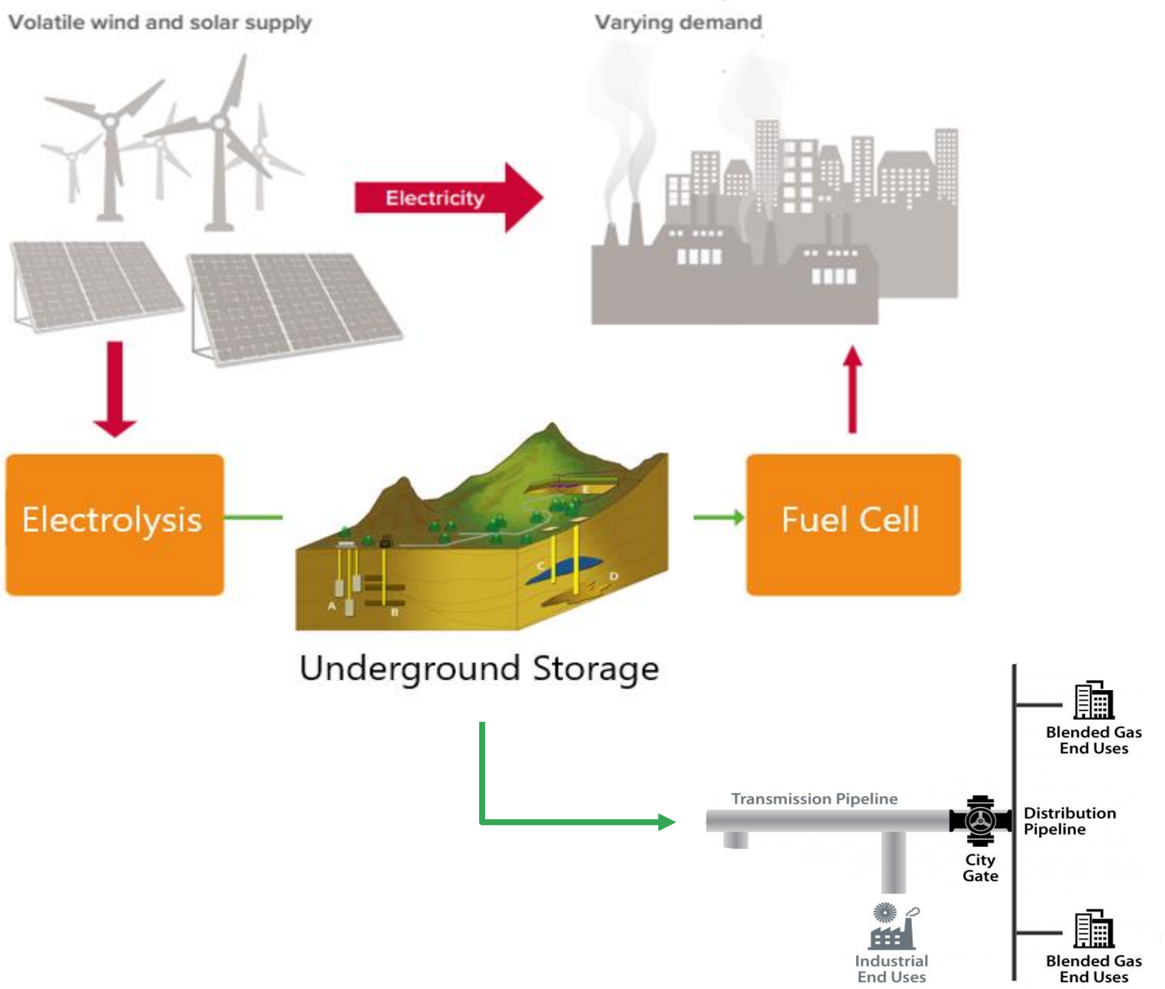
– Comparable to developing storage opportunitie for natural gas storage, thus expediting the potential for hydrogen's widespread adoption

Renewable Energy Integration

– Opportunity to store surplus energy during peric of excess generation.

Resource Optimization

– Minimizing infrastructure development costs and environmental impact.



Storage: Infrastructure Resiliency Component

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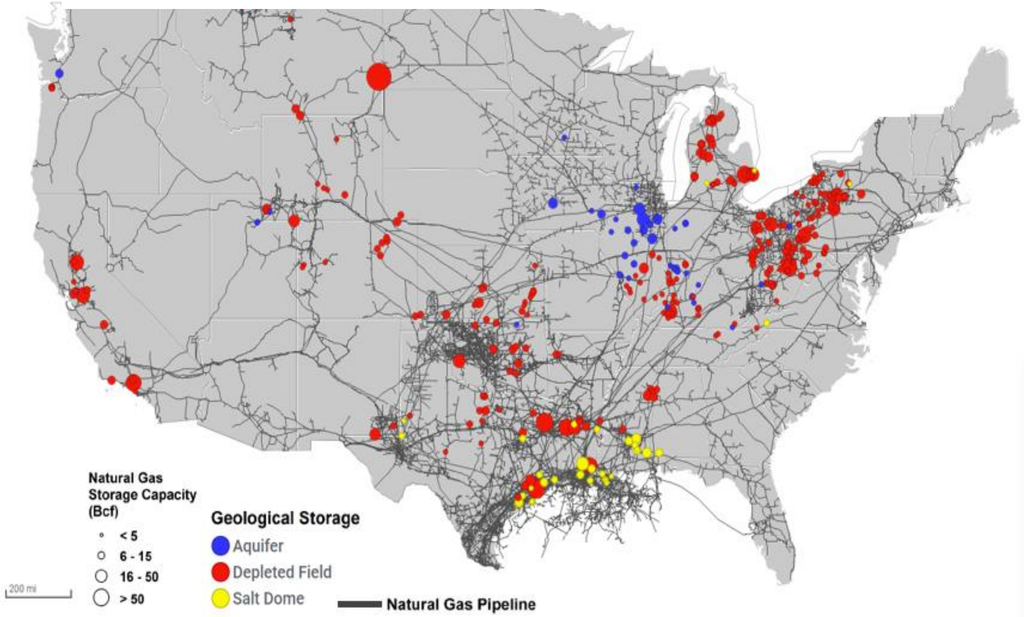
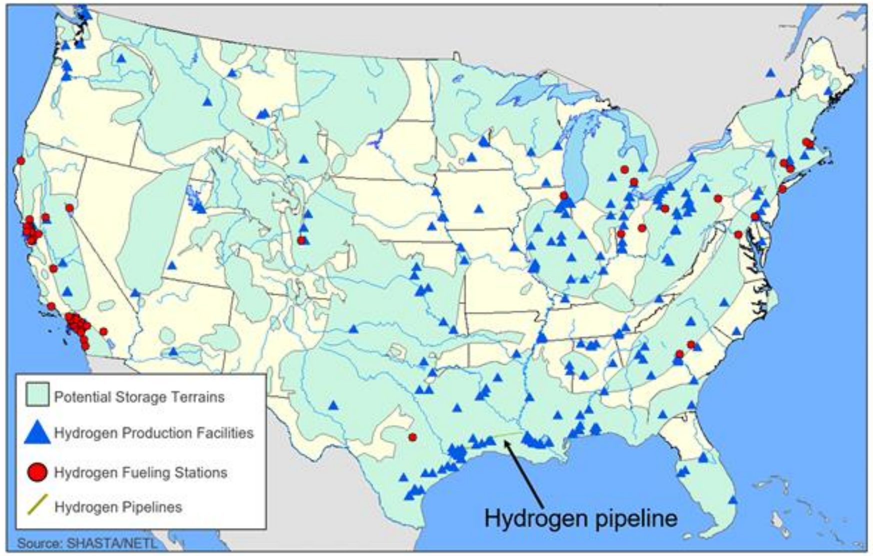
Natural Gas Experience



Today: 4.8 Tcf of underground storage capacity across 412 active facilities

- **20% of winter consumption**
- **Provides economic and price flexibility**

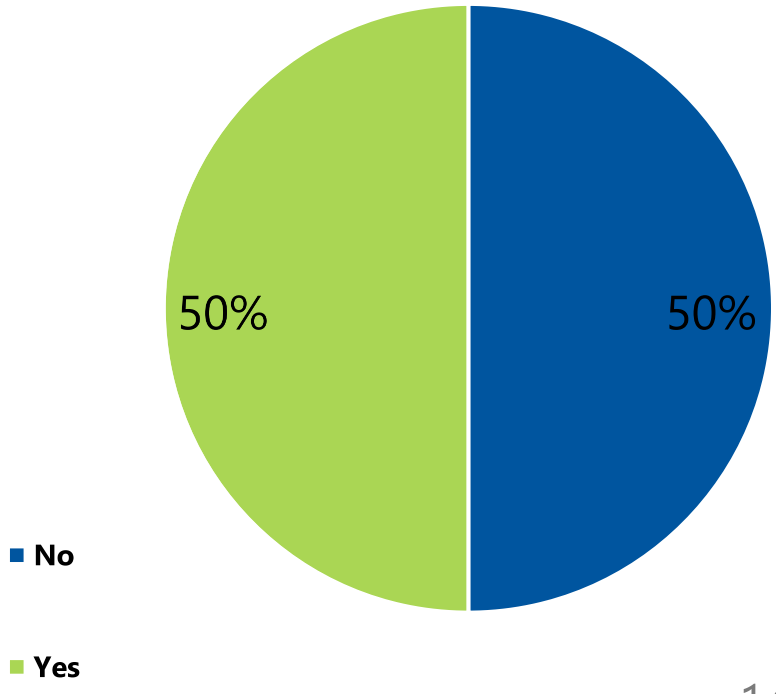


Locations of potential hydrogen storage systems in the United States and distance to existing hydrogen production and distribution infrastructure. Source: https://edx.netl.doe.gov/shasta/

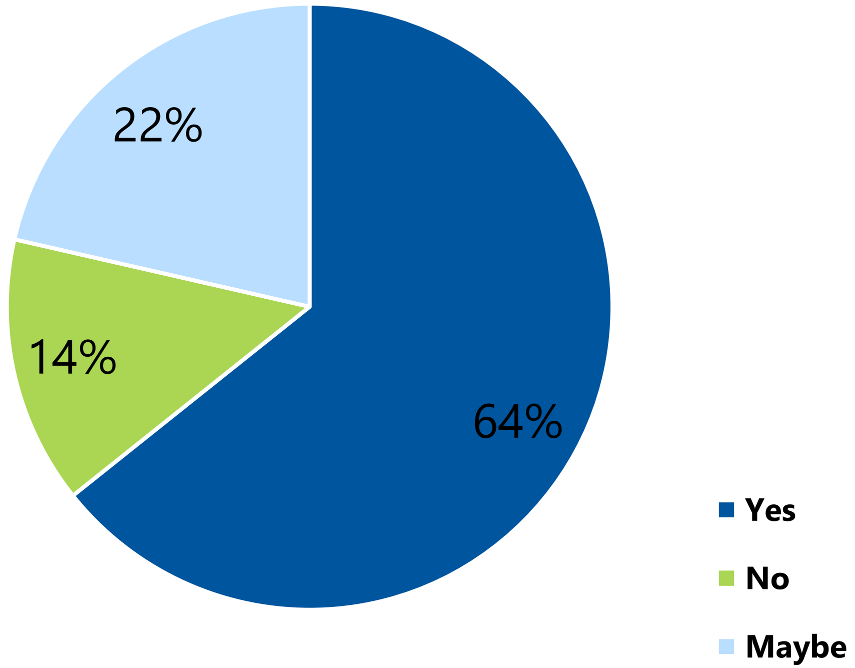
Evaluate potential pathways for large-scale underground H2 storage

GTI Energy asked for information regarding the opportunities and needs for underground hydrogen storage to develop the basis and criteria to design and execute field pilot tests of subsurface hydrogen storage in porous media formations.

Current or planned activities on hydrogen storage



Interested in research/experimentation or pilot field testing



14 companies responded.

Addressing the Challenge

GTI ENERGY

- Market Assessment & Economics
- Recommended practices
- Capabilities establishment
- **<u>Field demonstrations</u>**

- Fundamental R&D
- Data and Studies

SUSTAIN H2 Objectives

GTI ENERGY

Accelerate the deployment of safe & cost-effective long-term underground hydrogen storage through a combination of scientific expertise, market insights, field experience, & industry collaboration.

Vision

- **Engage diverse stakeholders** to coordinate cross-collaborative R&D
- **Address key technical challenges** to resolve critical uncertainties
- **Facilitate data collection, sharing, and analysis** to guide site selection
- **Complete national and regional techno-economic assessments**
- **Accelerate field deployment** by engaging all stakeholders and reducing remaining uncertainties

Underground Hydrogen Storage Timeline

GTI ENERGY

U.S. DEPARTMENT OF ENERGY | Fossil Energy and Carbon Management

2021
Fundamental H2 Storage R&D Initiated

2023
Characterize high-potential subsurface H2 storage reservoirs

Scale up of Fundamental Technologies for Prototype Demonstration

2027
Initial Regional H2 Storage Demonstration

SUSTAIN H_2

2023
Program Inception

Q1 2024
Stakeholder Engagement

2024- 2025

- Geo-Engineering
- Technology & Operation
- Market & Economics
- System Integration
- Policy & Social Impacts
- Community Engagement

2025+
Field Development Planning

Field Pilots

Technical Scope

- Conduct coordinated R&D to tackle key questions, narrowing the existing knowledge gap.
- Technologies needed and operational information for implementation of a field pilot
- Pathways for retrofitting underground natural gas storage facilities
- Site screening workflow/guideline by structuring collected data and information

Geo-Engineering	Technology & Operations	Market Assessment & Economics	System Integration	Policy & Social Impacts
Technical De-risking	**Operational De-risking**	**Economic De-risking** **Business Concept**	**Infrastructure De-risking** **Hydrogen Value Chain**	**Legal and Regulatory Frameworks**

Current Partners and Supporters

GTI ENERGY

U.S. DEPARTMENT OF ENERGY

PHMSA

OTD
Operations
Technology
Development

ATMOS energy

Washington Gas

ENBRIDGE

Nicor Gas

NW Natural

Black Hills Corporation

PEOPLES GAS
We Keep Life Moving

SOUTHWEST GAS

ONEOK

Pacific Northwest
NATIONAL LABORATORY

UNIVERSITY OF ILLINOIS
URBANA-CHAMPAIGN

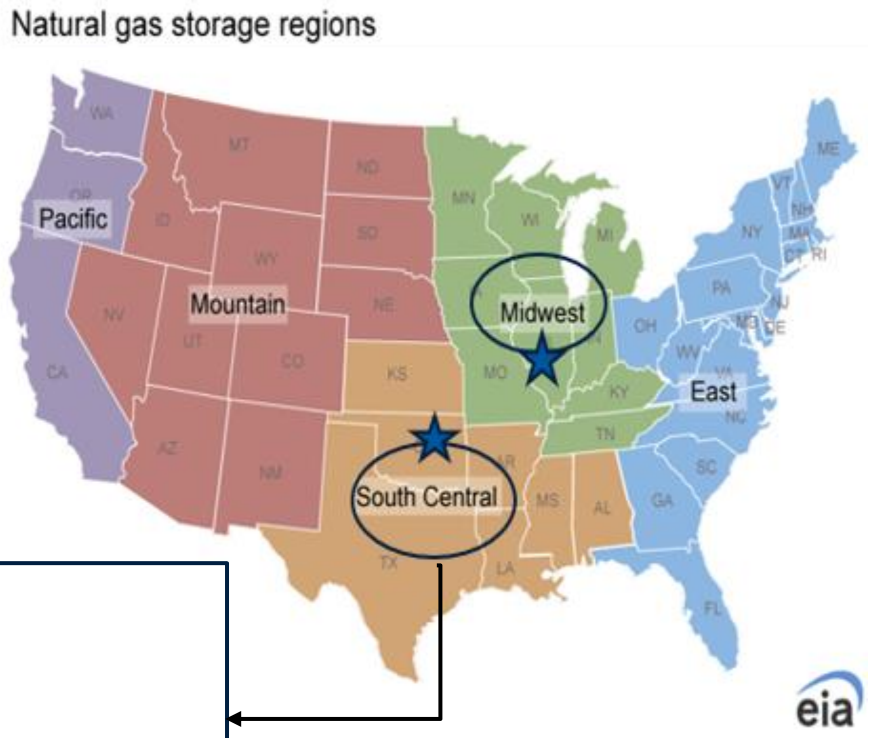
ILLINOIS
Illinois State Geological Survey
PRAIRIE RESEARCH INSTITUTE

OKLAHOMA GEOLOGICAL SURVEY
1908

Progress Up-to-Date

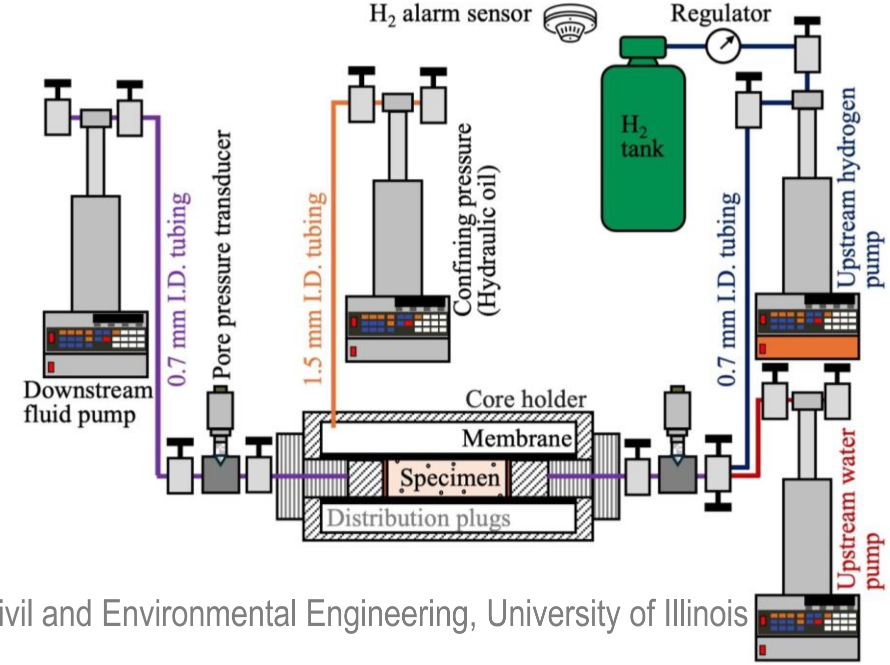
In Progress:

- ➢*Microbial Analysis*
- ➢*H2 Injection Experiments*
- ➢*Geological and Reservoir Modeling*
- ➢*Market Assessment and Techno-economic Assessment (TEA)*

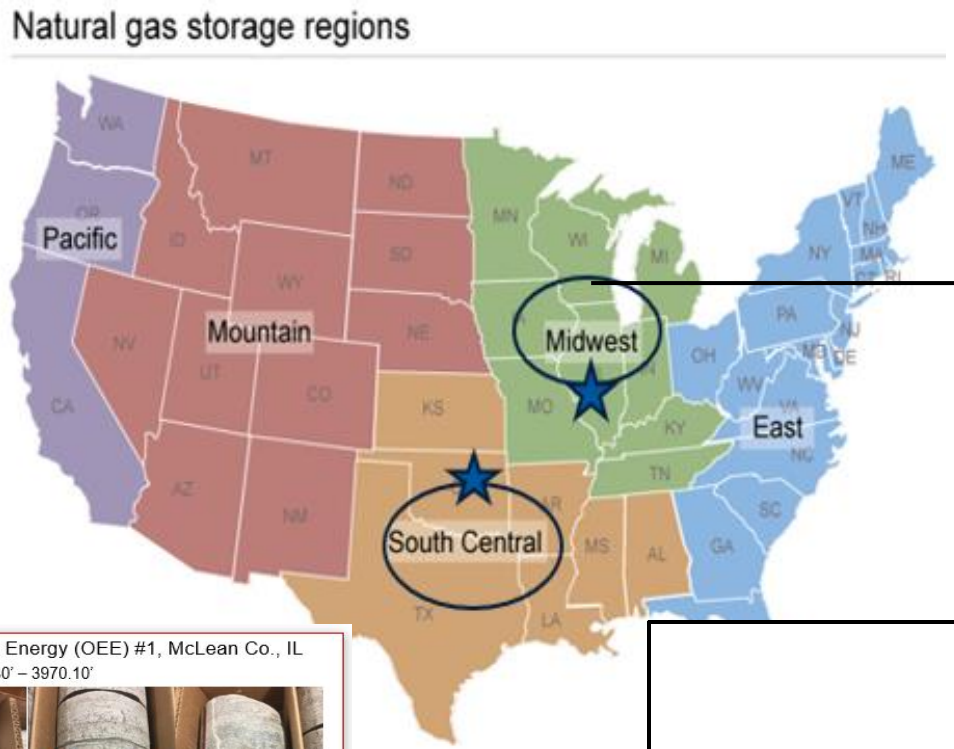


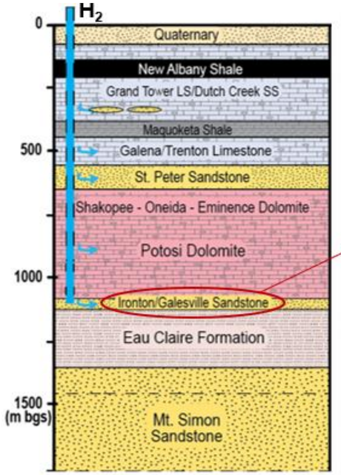
Progress Up-to-Date

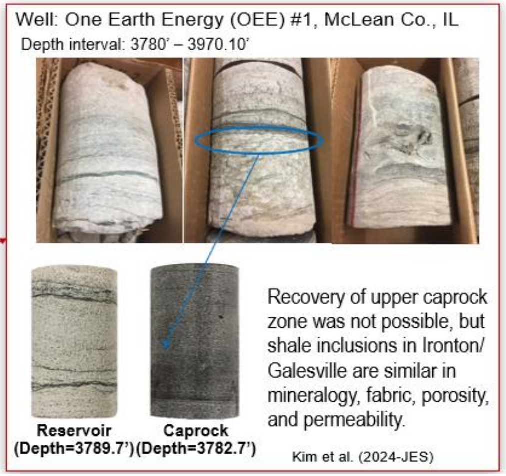
GTI ENERGY



Civil and Environmental Engineering, University of Illinois







PHMSA

GTI ENERGY

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

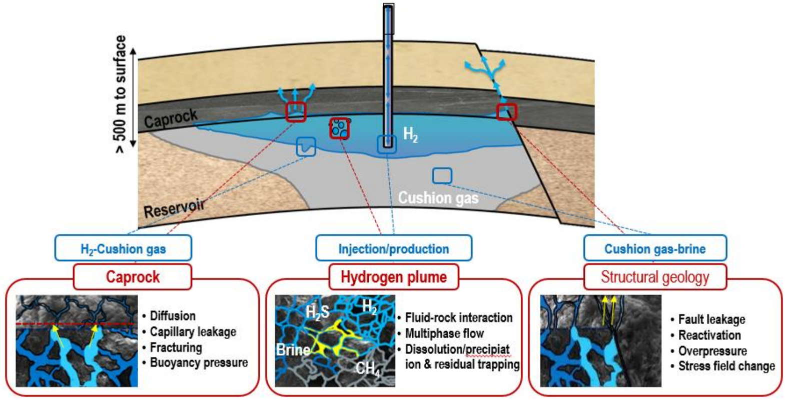
ILLINOIS Illinois State Geological Survey PRAIRIE RESEARCH INSTITUTE

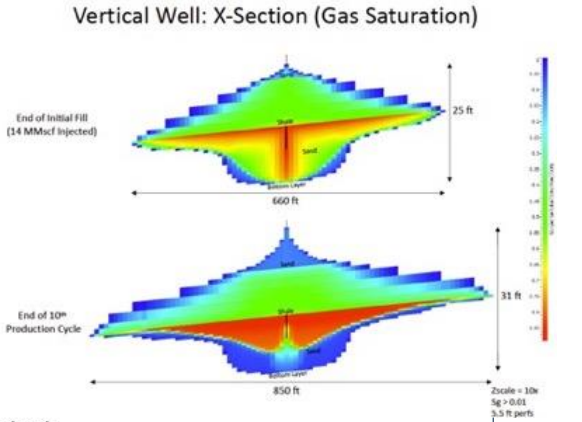
OTD Operations Technology Development

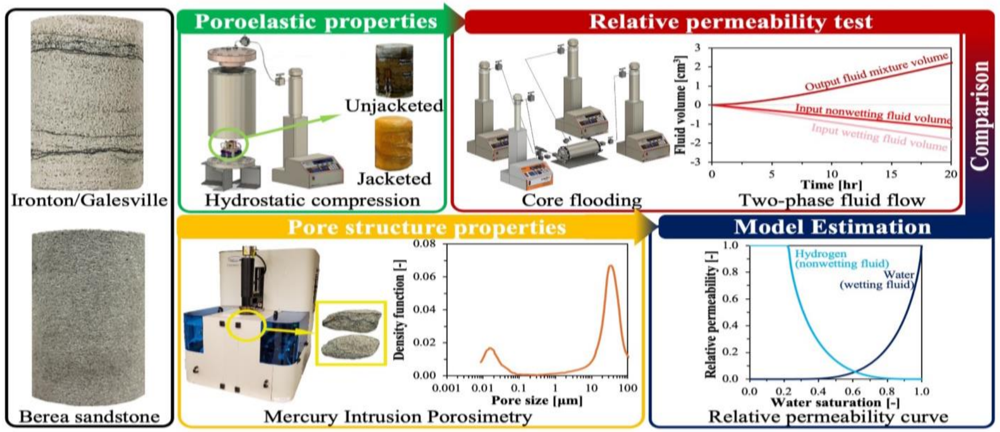
Progress Up-to-Date

- Experiments and models to understand:
  - ➢ *Hydrogen movement*
  - ➢ *Storage integrity and stability*
  - ➢ *Interactions of different elements within the storage system*

- Upcoming:
  - ➢ *Infrastructure needs and economics evaluations*
  - ➢ *Operational framework*
  - ➢ *Develop evaluation approaches for commercial-scale developments*







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ILLINOIS
Illinois State Geological Survey
PRAIRIE RESEARCH INSTITUTE
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Path Ahead…

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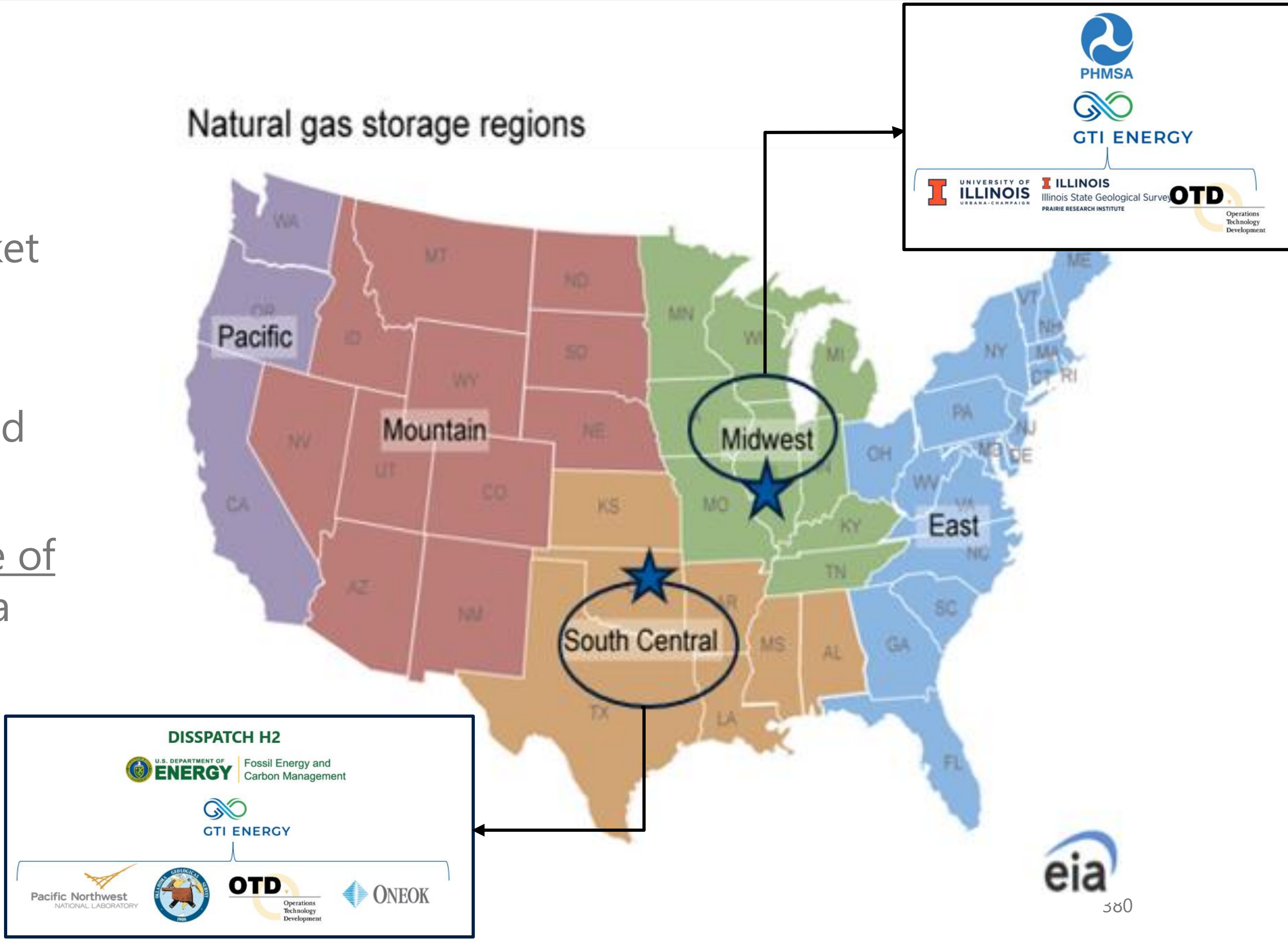
- <u>Holistic region-specific approach</u>, harnessing the unique geological characteristics and hydrogen market variations
- <u>Facilitate the preparation for pilot project(s)</u> by optimizing testing and ensuring scalability and efficiency
- <u>Leveraging the collective expertise of industry and research partners </u>in a unified framework to foster practicality.



Industry Partnerships

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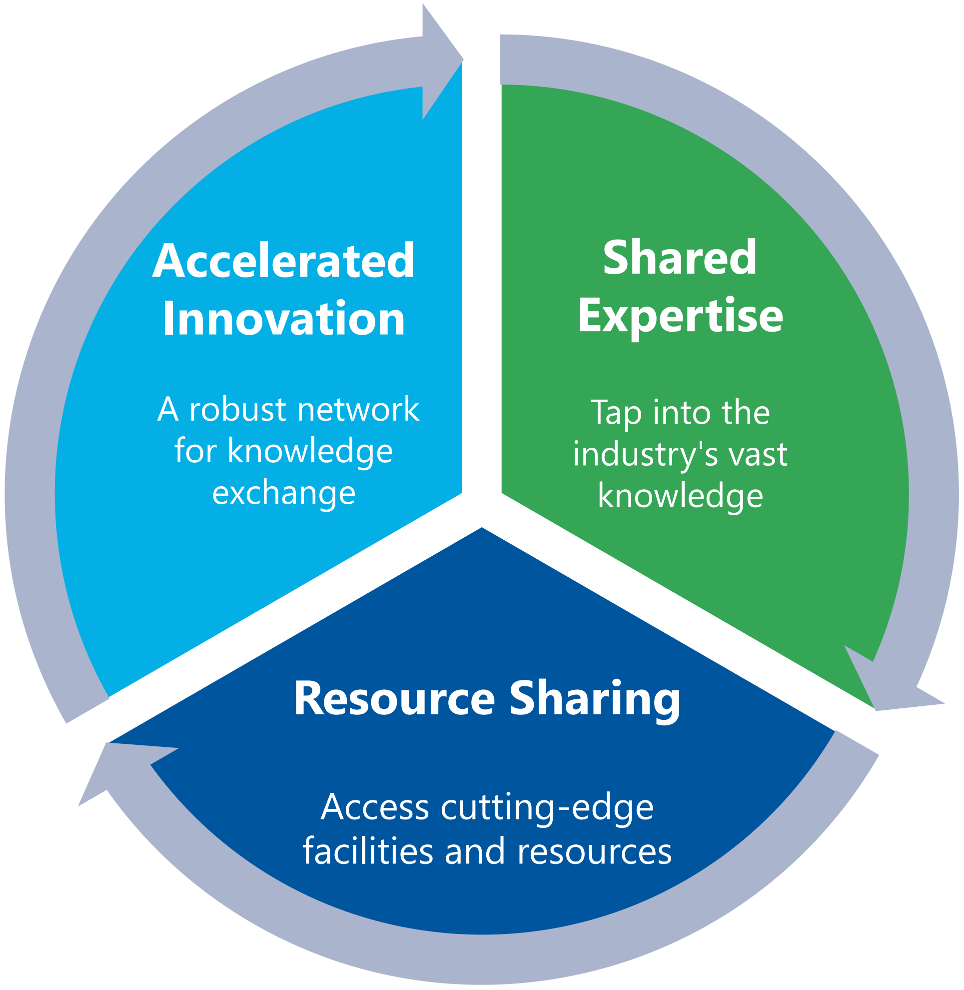
Timeline: 2 years

Participation Opportunity

- Industry partners to join technical teams
  - Input and technical advice
  - **Samples and data to their respective region(s)**

- Regular meetings, workshops, and virtual conferences
  - Communication, knowledge-sharing, and progress updates



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solutions that transform

GTI Energy develops innovative solutions that transform lives, economies, and the environment

ssalahshoor@gti.energy

Phone: +1 847-768-0979

Overview of LANL's Underground Hydrogen Storage (UHS) Projects and Future Outlook

Mohamed Mehana
Energy and Natural Resources Security Group
Los Alamos National Lab

April 3rd, 2024

LA-UR-24-22951

Acknowledgment

Fangxuan Chen, Joseph Heimerl, Mohamed Malki, Shaowen Mao, Martin Ma, Bailian Chen, Neala Creasy, Daniel Eldridge, Thom Rahn, Jolante van Wijk, Chelsea Neil, Michael Gross, Gaoxue Wang, Bijay K C, Luke Frash, Siddharth Babu, Prakash Purswani, Ruyi Zheng, Tim German, Amber Zandanel, Robert Currier, Yun Yang, Eric Guiltinan, Siqin Yu, Ruyi Zheng, Lawrence Boampong, Qinjun Kang

LANL-Technology, Evaluation, and Demonstration Program
LANL-LDRD Mission Foundation Research Program
LANL-LDRD Directed Research Program

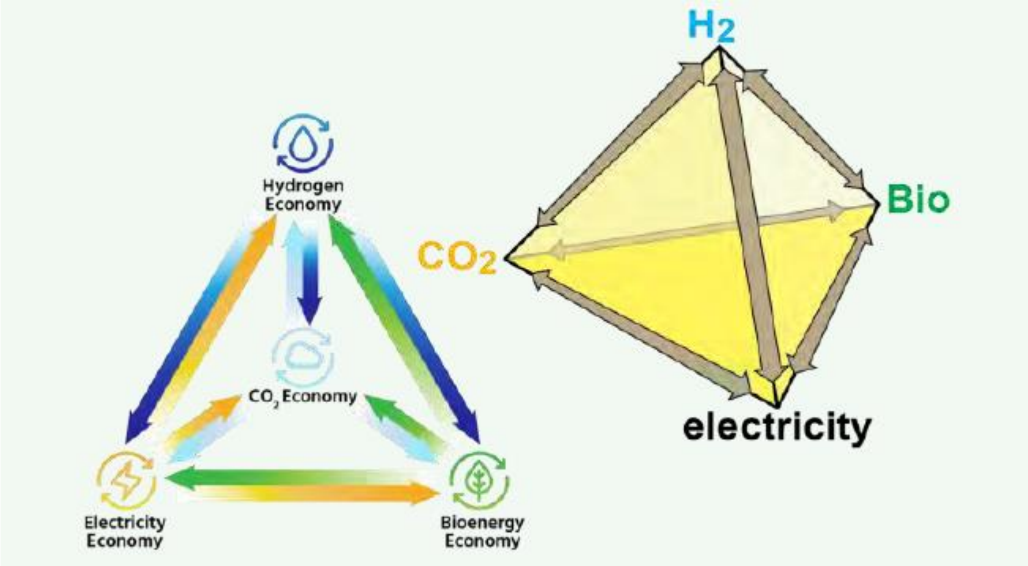
Hydrogen Storage Projects at Los Alamos

- Resource Assessment and Techno-economic analysis of UHS in the Intermountain West region. PI: Mohamed Mehana
- A Multi-Scale Investigation of Hydrogen Geologic Storage: Transport, Reactivity, and Caprock Integrity. PI: Michael Gross
- Risk-informed Assessment of Hydrogen Storage, Production, and Infrastructure. PI: Mohamed Mehana
- Reducing Underground Hydrogen Storage Risks with Improved Seismic Monitoring. PI: Neala Creasy
- Hydrogen Isotope Toolkit for Loss Assessment During Geologic Hydrogen Storage. PI: Thom Rahn
- Hydrogen Storage in Salt Caverns in the Permian Basin: Seal Integrity Evaluation. LANL PI: Eric Guiltinan

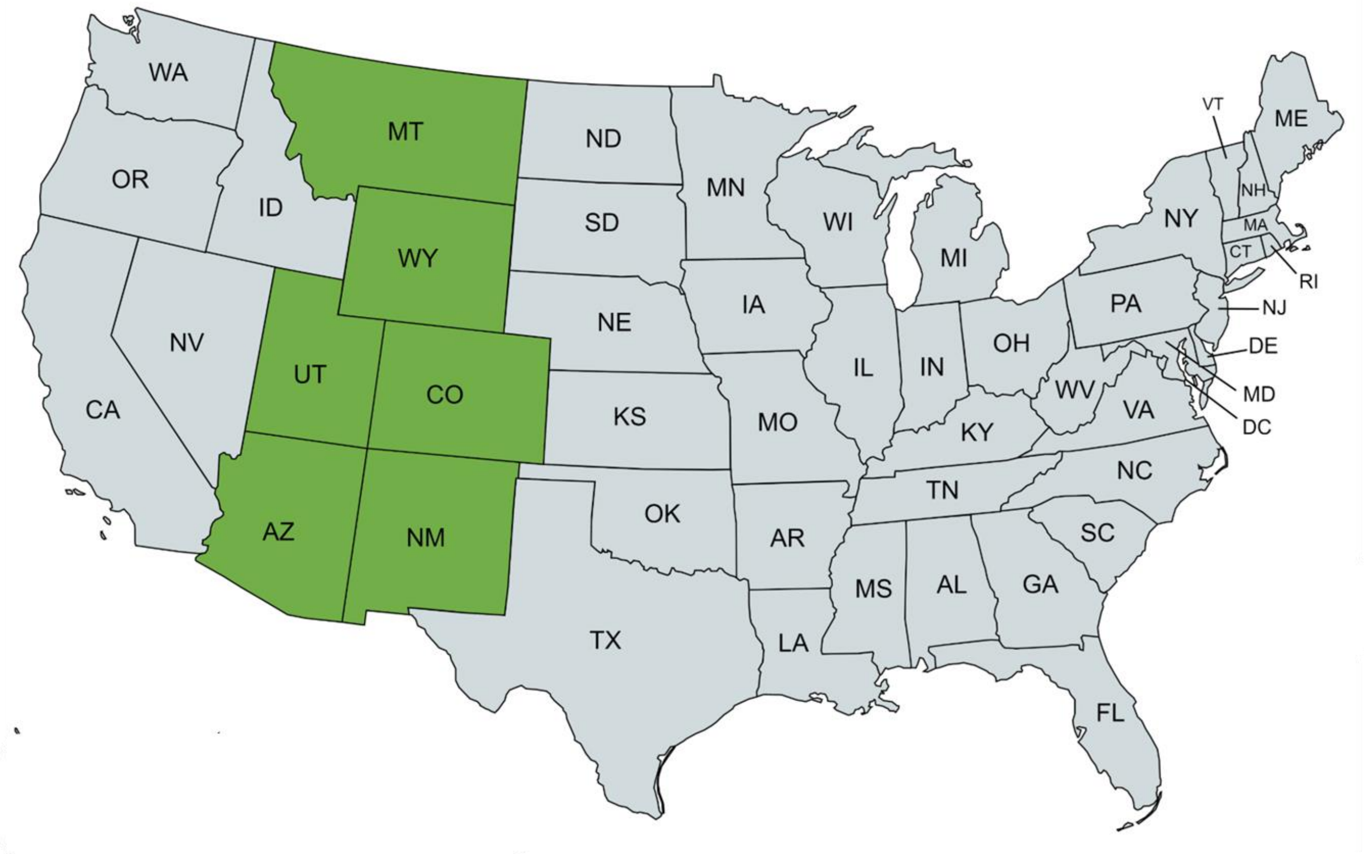
Resource Assessment and Techno-economic analysis of UHS in the intermountain west region

Multiple Technologies and Multiple (*Symbiotic*) Economies

- Carbon capture, utilization, transport, and storage
- Clean hydrogen
- Bioenergy
- Low-carbon electricity

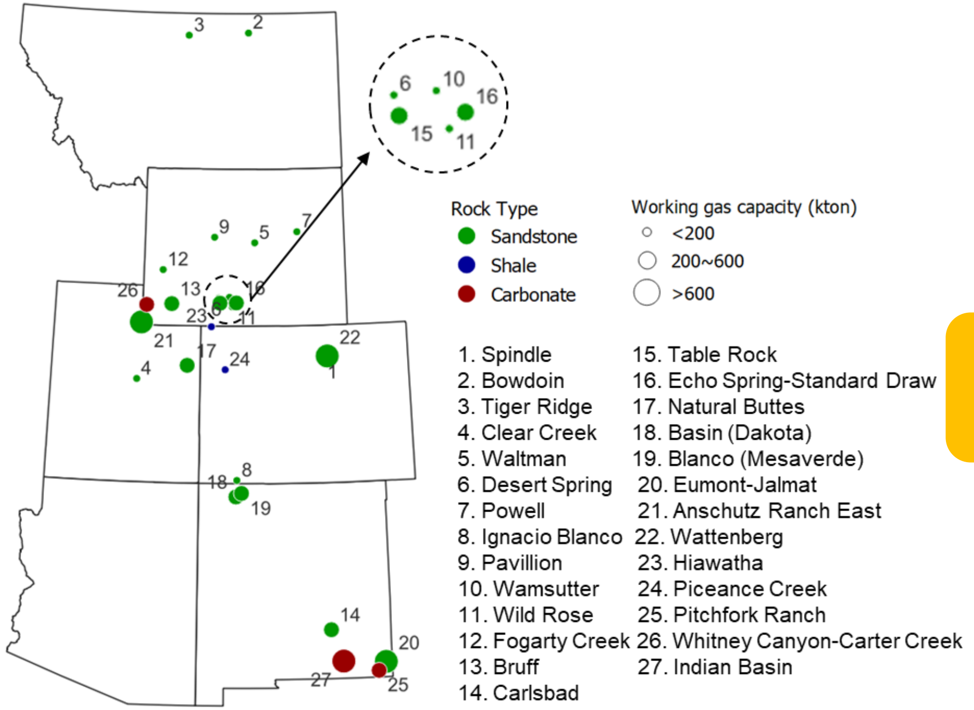


Visit iwest.org for more detail and archived material from workshops or email iwest@lanl.gov

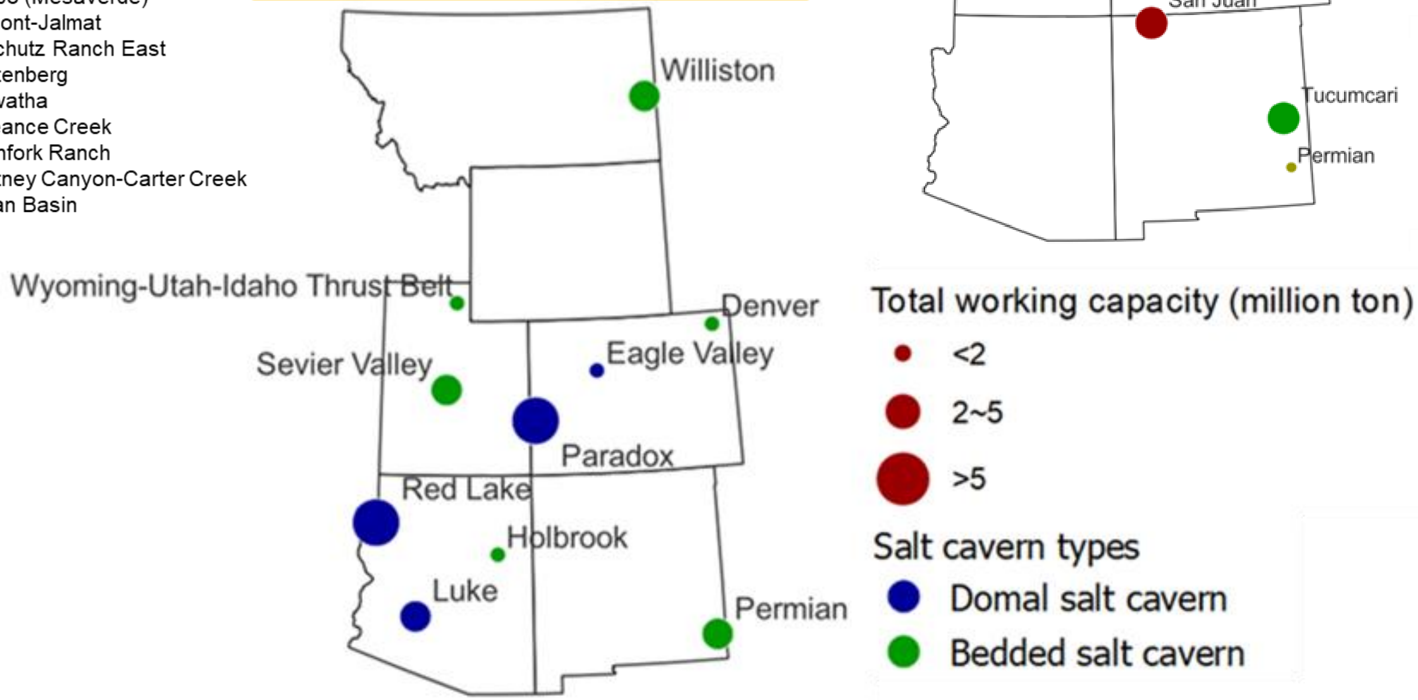


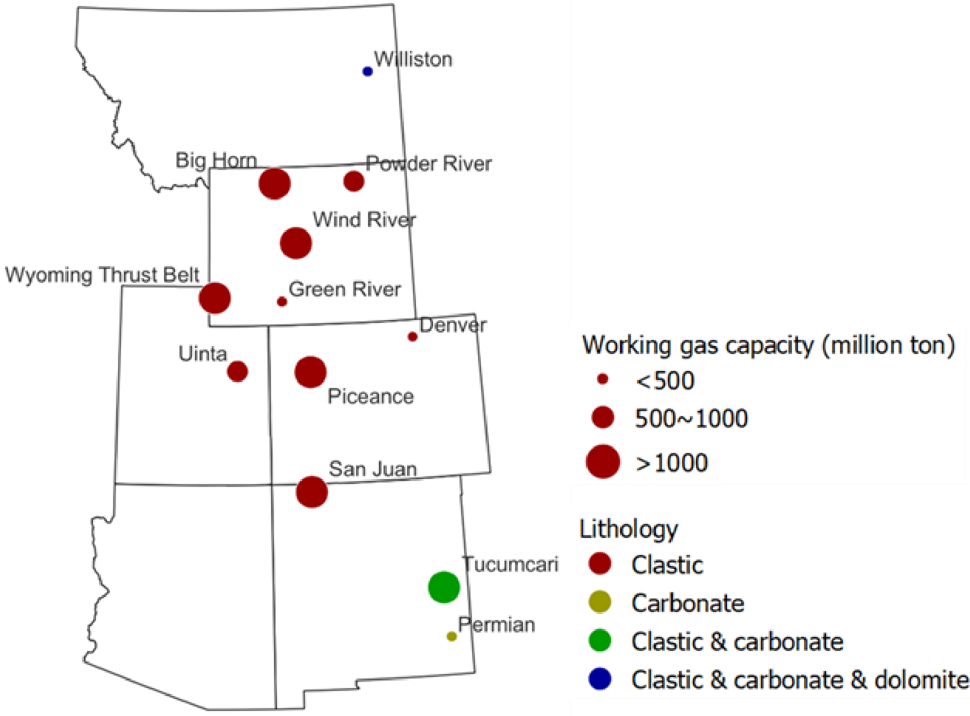
H_2 geologic storage capacity and cost

Saline Aquifers
Storage cost: 3.2 $/kg_H$_2$



Salt Caverns
Storage cost: 2.3 $/kg_H$_2$

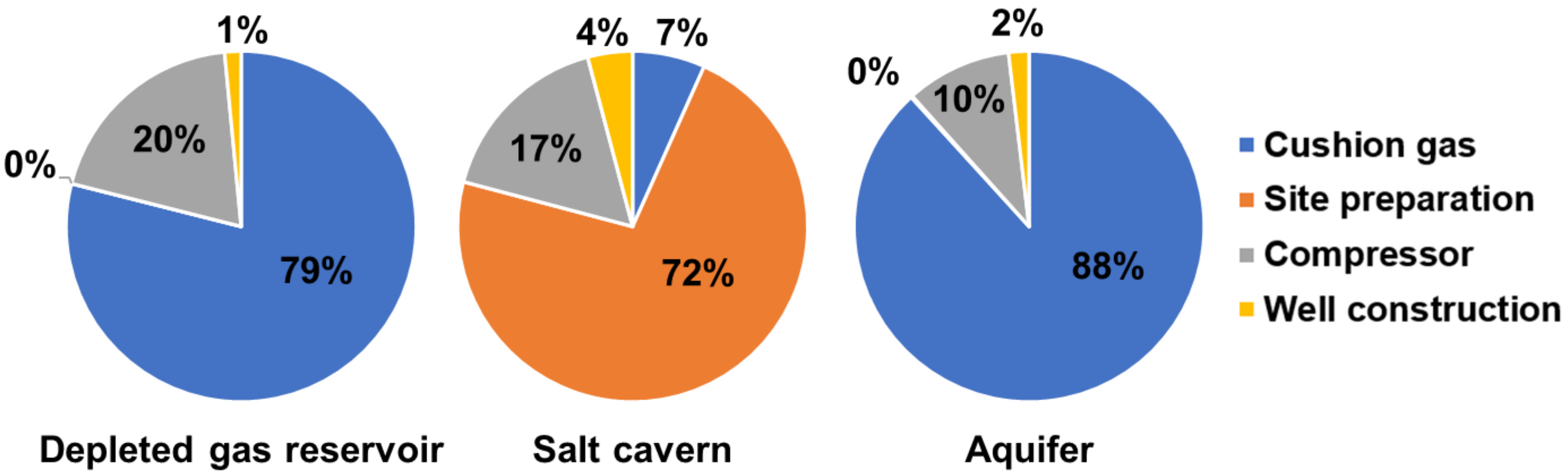




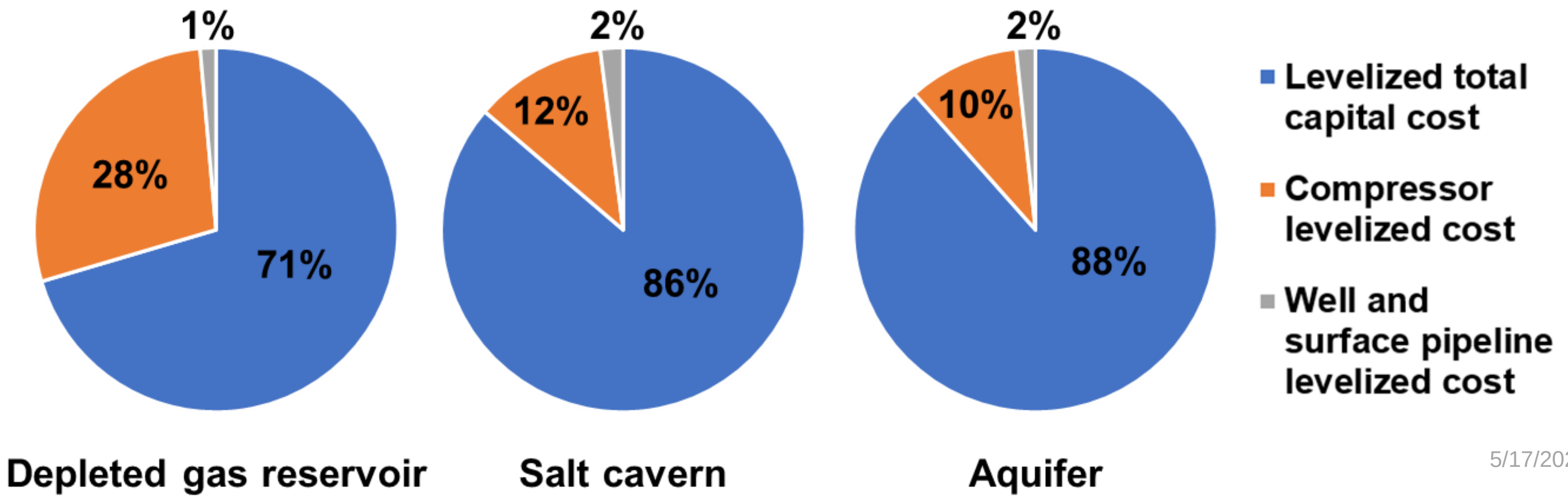
Depleted Gas reservoirs
Storage cost: 1.1 $/kg_H$_2$

H_2 Storage: Cost breakdown

Capital cost

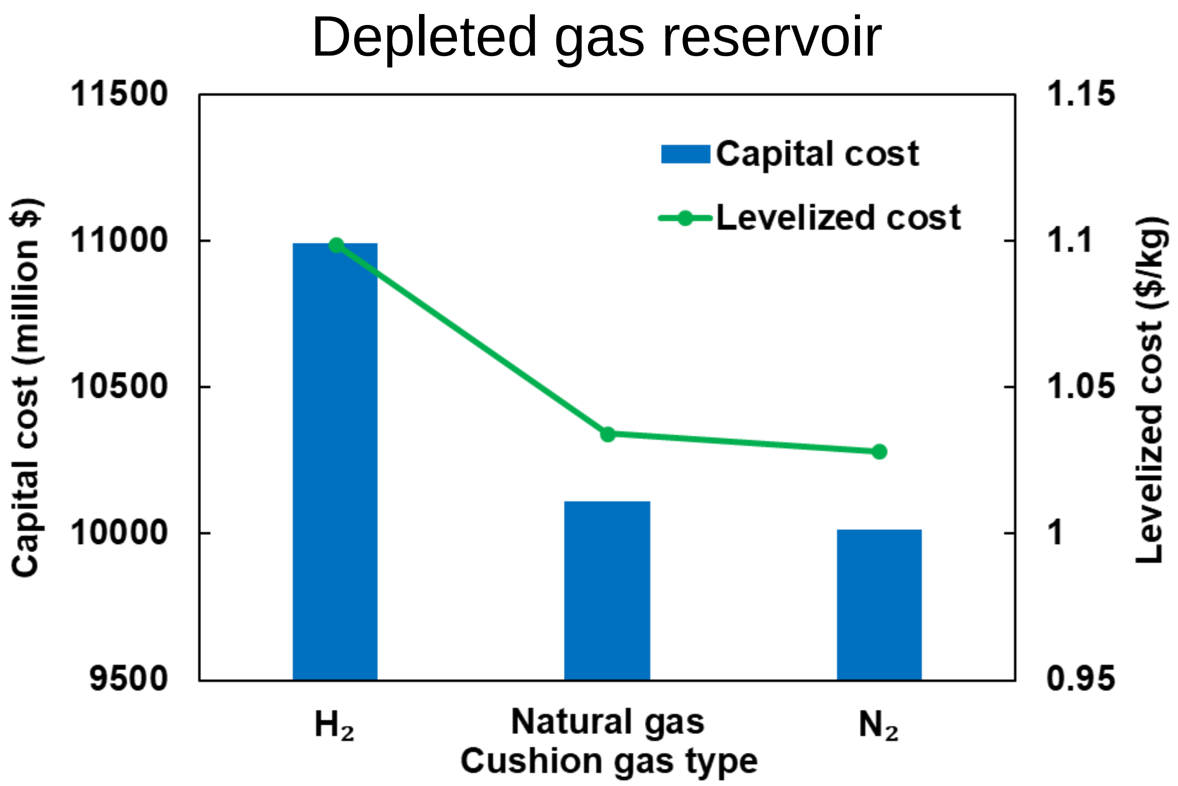


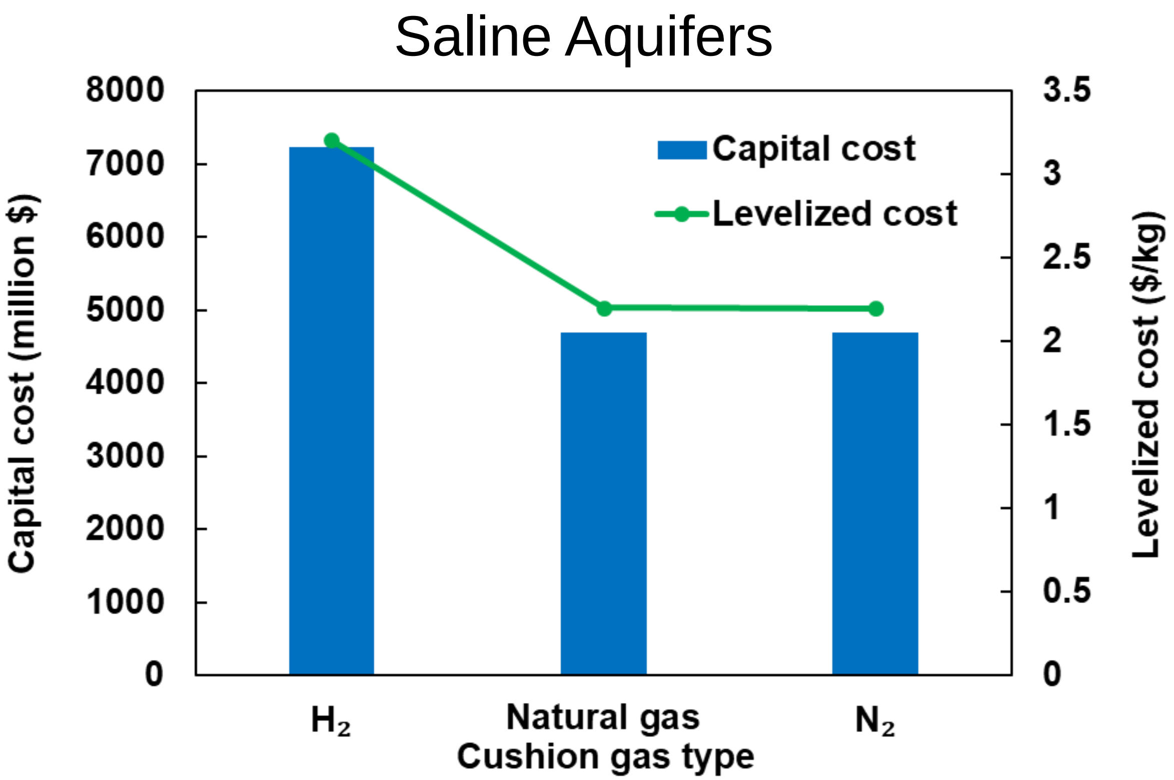
Levelized cost



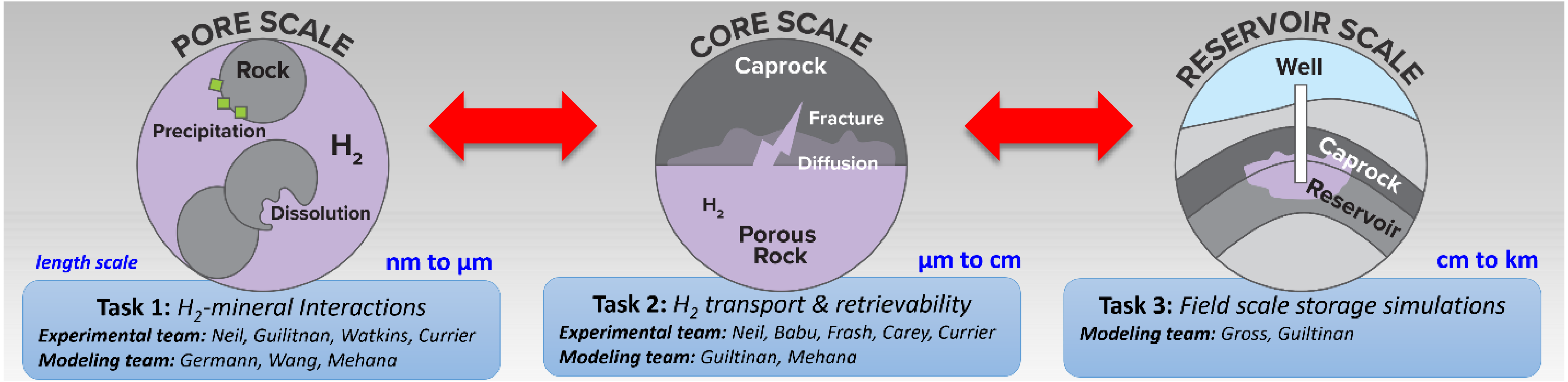
H_2 Storage cost optimization: effect of cushion gas type

H_2: \$5/kg, natural gas: \$0.2553/kg, N_2: \$0.1826/kg, purification cost: \$2/kg H_2.





A Multi-Scale Investigation of Hydrogen Geologic Storage: Transport, Reactivity and Caprock Integrity.



Objective #1: *Assess the rate, extent, and mechanism of H_2–mineral interactions and their influence on H_2 recoverability, contamination, and transport during geologic storage.*

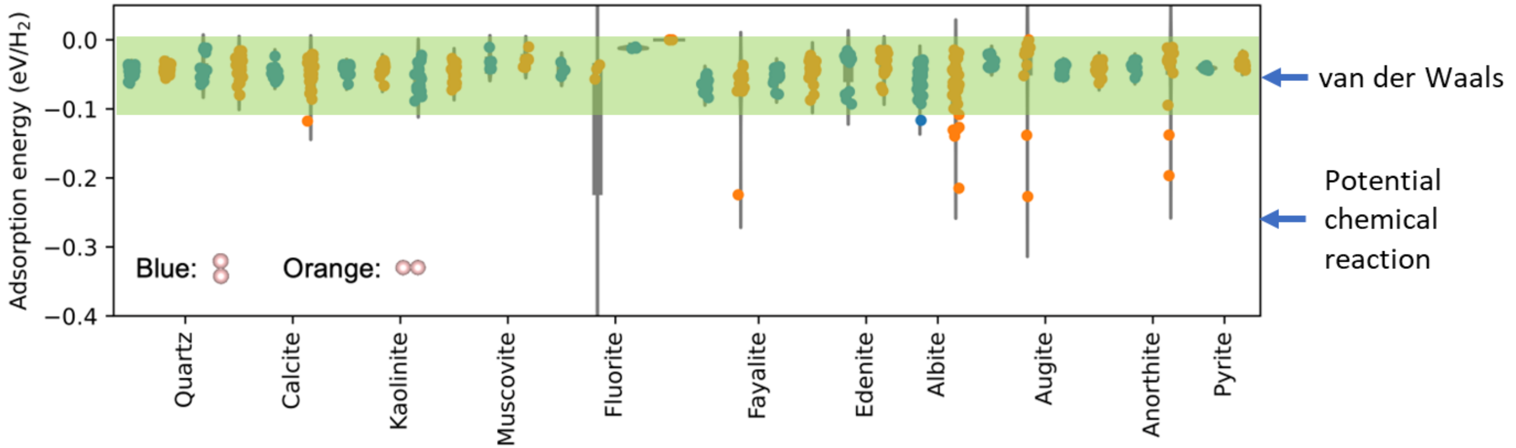
Objective #2: *Evaluate H_2 transport properties within storage reservoir rocks and caprocks.*

Objective #3: *Determine the feasibility of H_2 geologic storage in porous reservoir rocks such as depleted oil and gas fields and saline aquifers and identify site characteristics that promote efficient storage.*

*<*excludes microbial activity>*

H_2 – mineral interactions

- Results from *Ab initio* simulations (DFT) for physical interaction of H_2 with minerals:

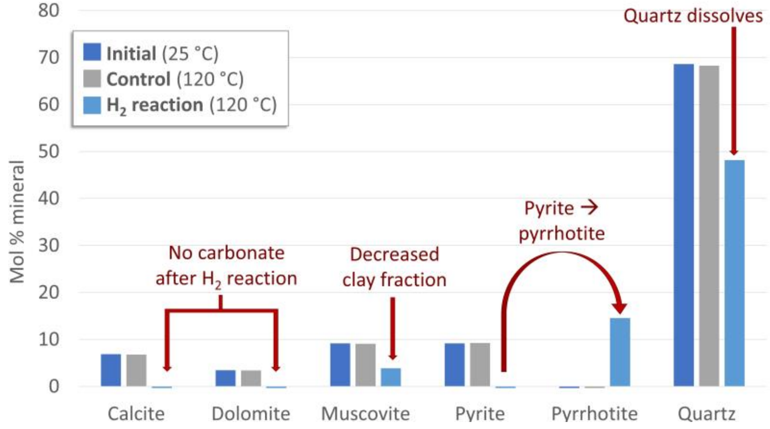


Lower risk for chemical reactions

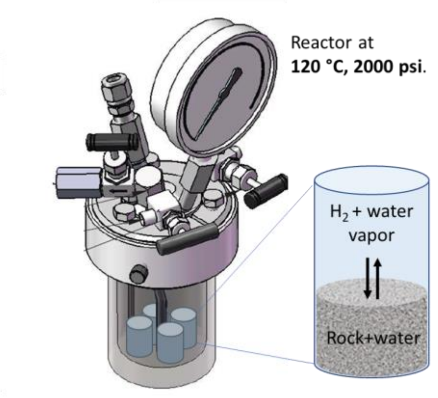
Higher risk for chemical reactions and produced gas purity

- Reactivity Experiments:

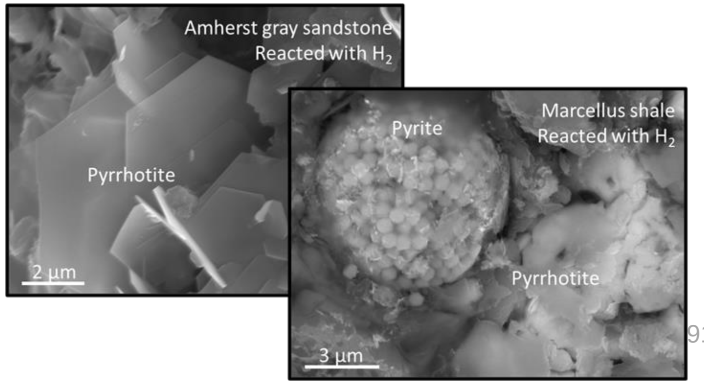
Equilibrium model (120 °C, 14 MPa H_2)



Experimental results (120 °C, 14 MPa H_2)

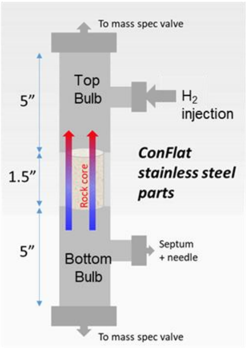


Scoping batch experiments suggest rate-limited alteration at reservoir timescales and pyrite transformation after 30 days

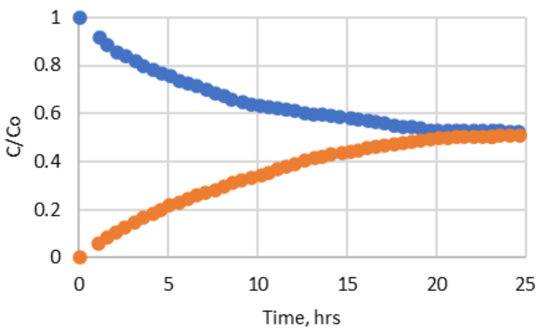


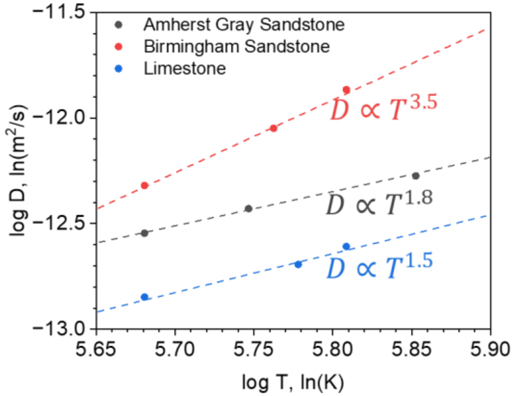
H_2 transport properties

- **H_2 Diffusion coefficients measured in reservoir and caprock**:



Eagle Ford Shale

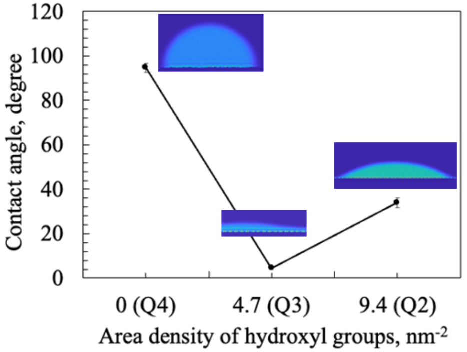




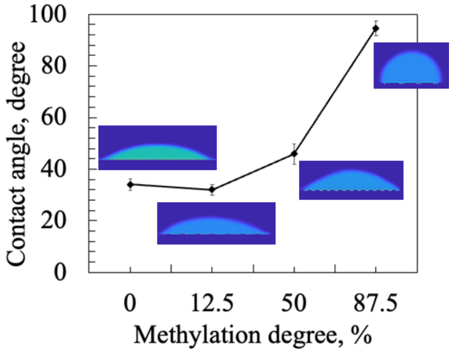
Implications for:
Plume migration in reservoirs
Leakage through caprock

- **MD Simulations unravel factors controlling wettability in the hydrogen-water-quartz system**:

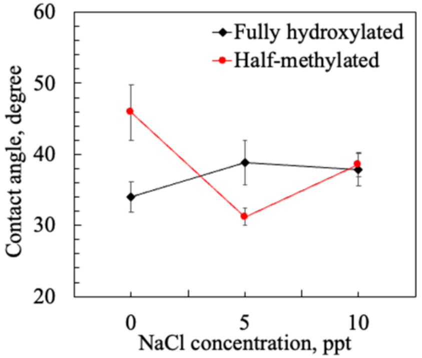
Hydroxyl Groups



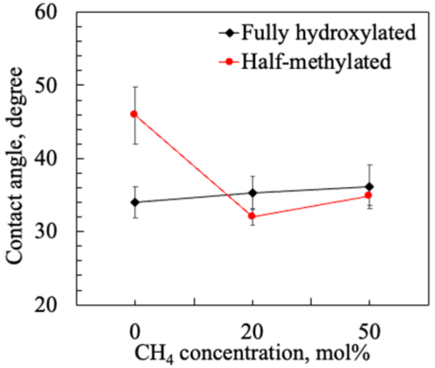
Organic Ligands



Salinity



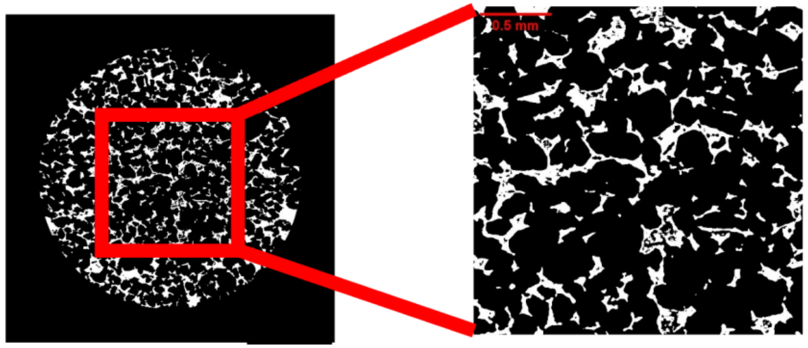
Cushion Gas

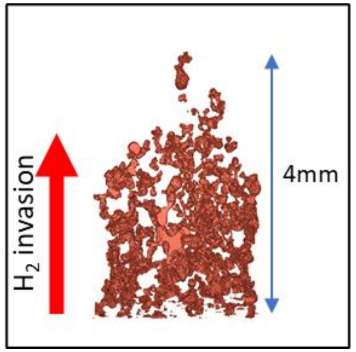


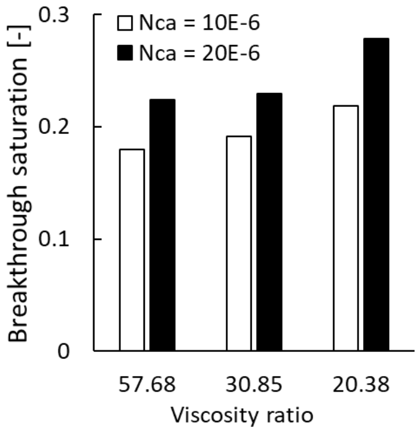
Implications for:
Reservoir transport
Caprock sealing

H_2 transport properties (cont)

➢ **LBM Pore scale modeling**:

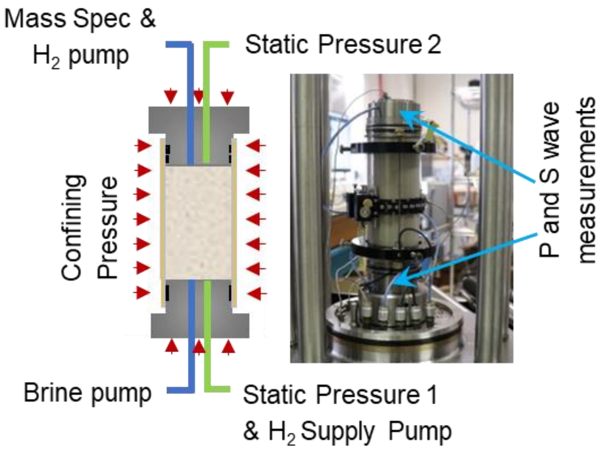


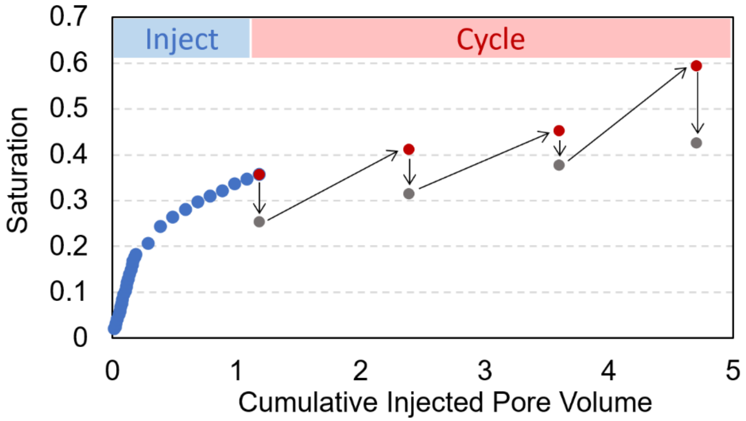




- Dynamics of H_2 displacement are sensitive to flow and field conditions.
- Displacement efficiency increases with increasing Ca (injection rate) and decreasing water/ H_2 viscosity ratio.

➢ **Core flood experiments**:



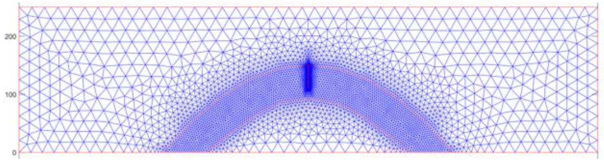


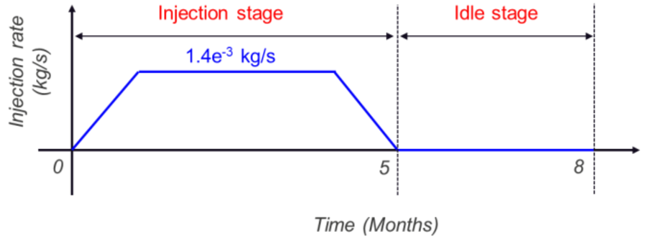
- Injection rate affects H_2 saturation at first breakthrough (10% to 20%)
- Produced gas concentration was H_2 rich but contaminated with water and trace methane
- Water evaporation into H_2 should achieve higher peak saturation but will precipitate salts in the rock pores.

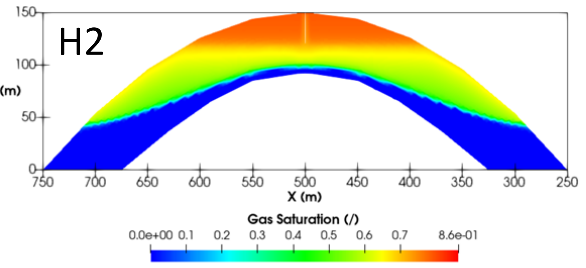
Feasibility of H_2 geologic storage

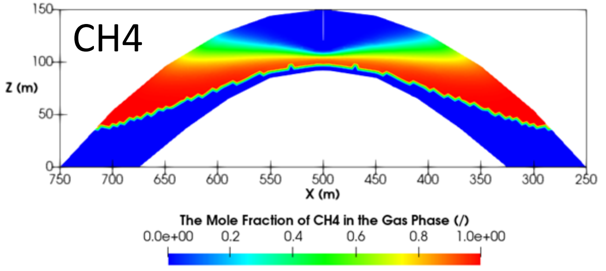
- **Reservoir simulations and leak detection**:

Conceptual Anticline

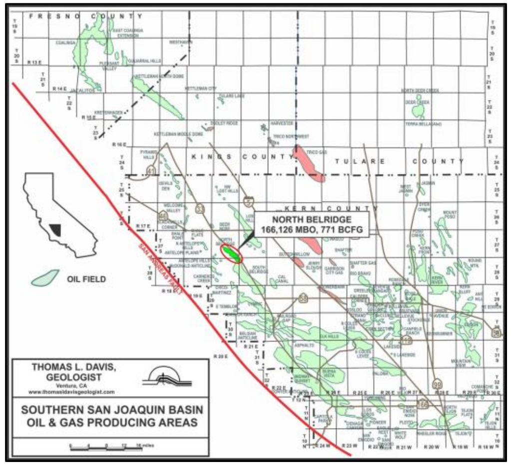


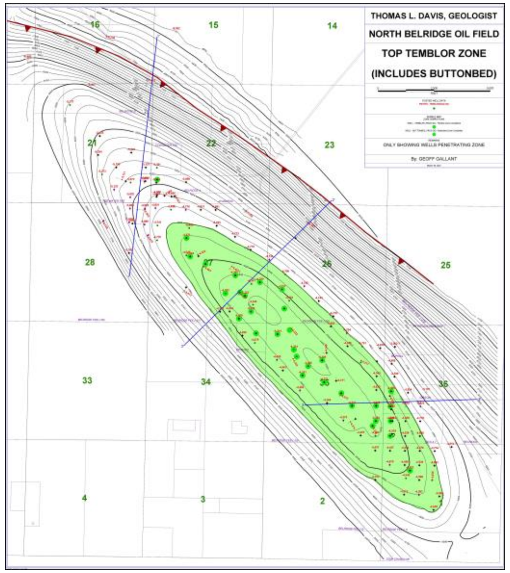


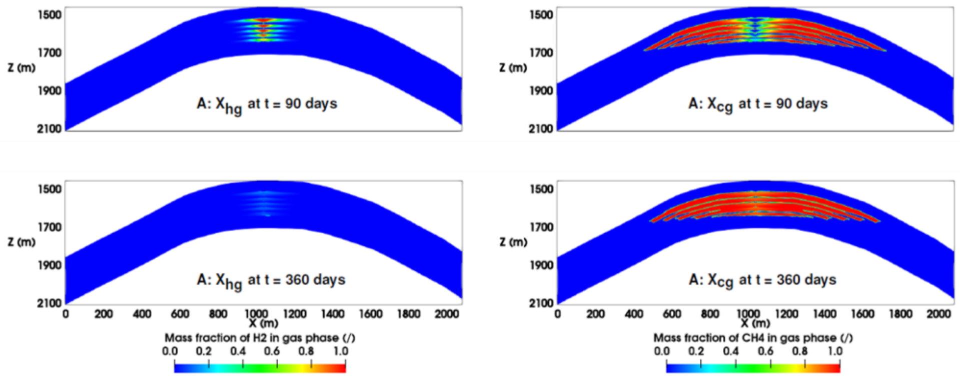


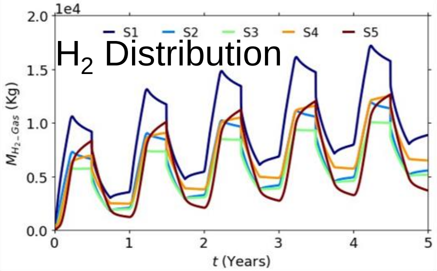


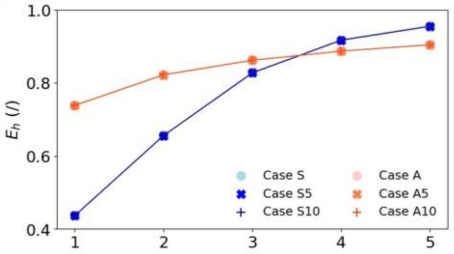
North Belridge (California) Field Study











H_2 Withdrawal Efficiency

- Production efficiency and H_2 purity improve with time.
- Contact with interlayered shales reduces H_2 purity.
- Elevated pressure risks with single layer sandstone injection.

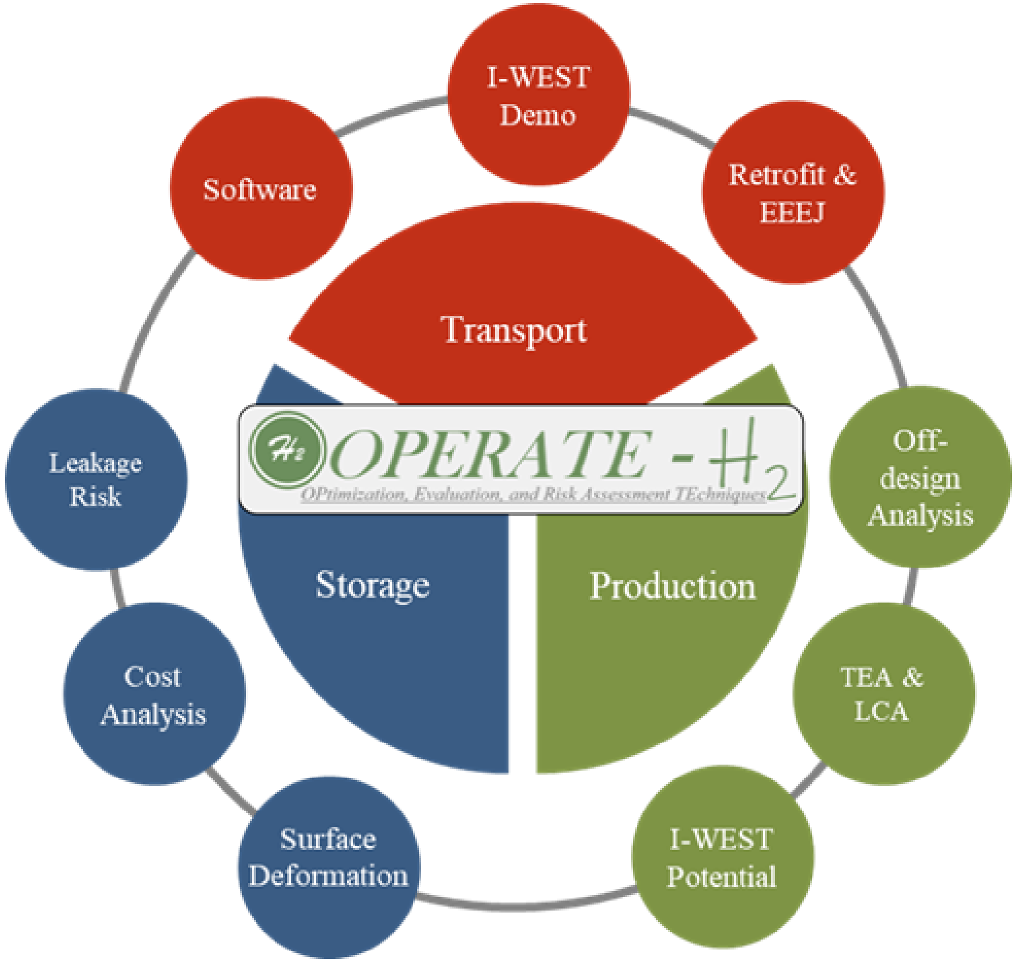
NATIONAL LABORATORY

Risk-informed Assessment of Hydrogen Storage, Production, and Infrastructure.

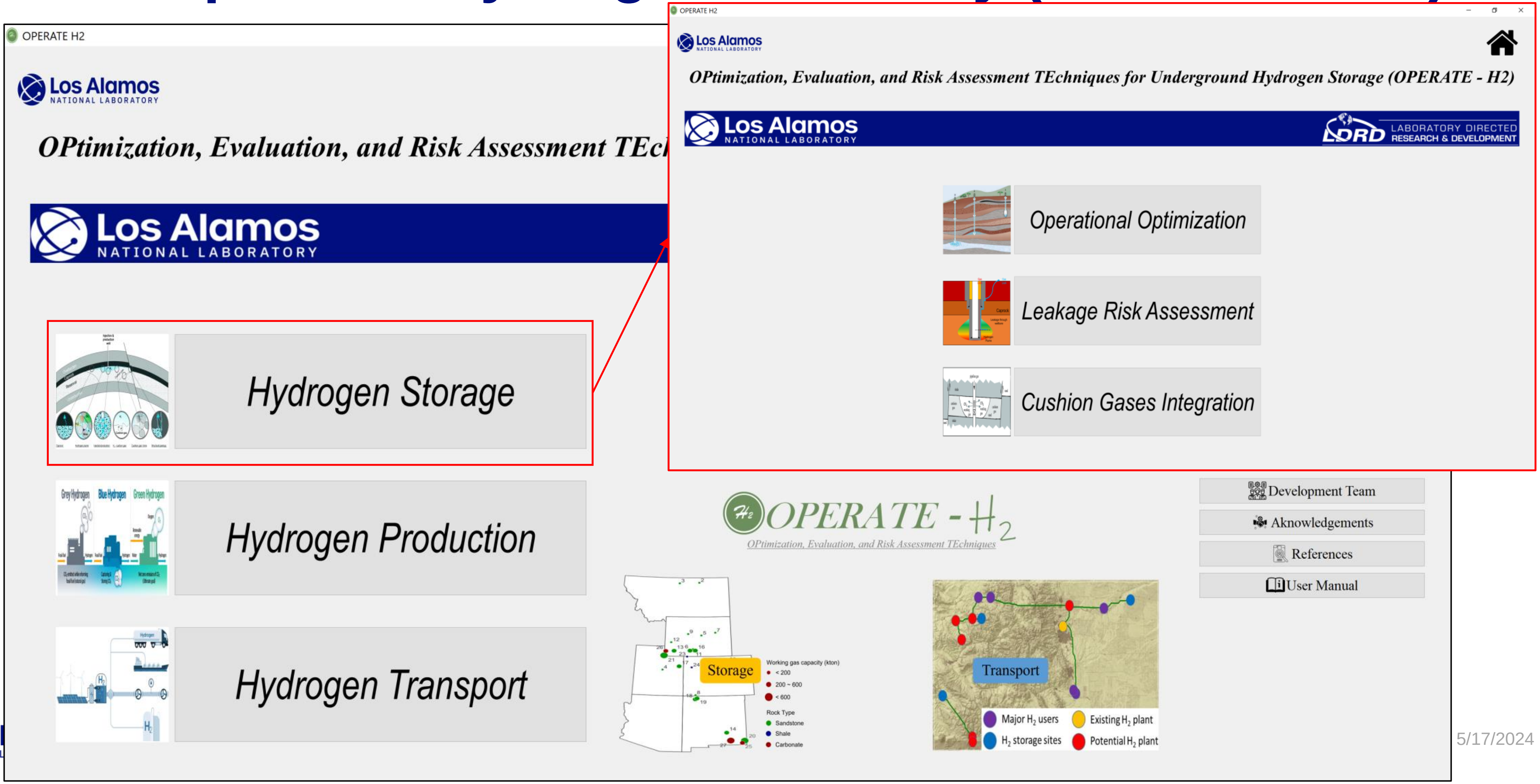
Objective: Extend the capability of our risk-informed storage assessment and optimization toolsets to include H_2 geologic storage and utilize them for the roadmap design for an H_2 economy.

Approach: Leverage our extensive experience with CO_2 sequestration where we develop and integrate multi-fidelity techniques and machine learning.

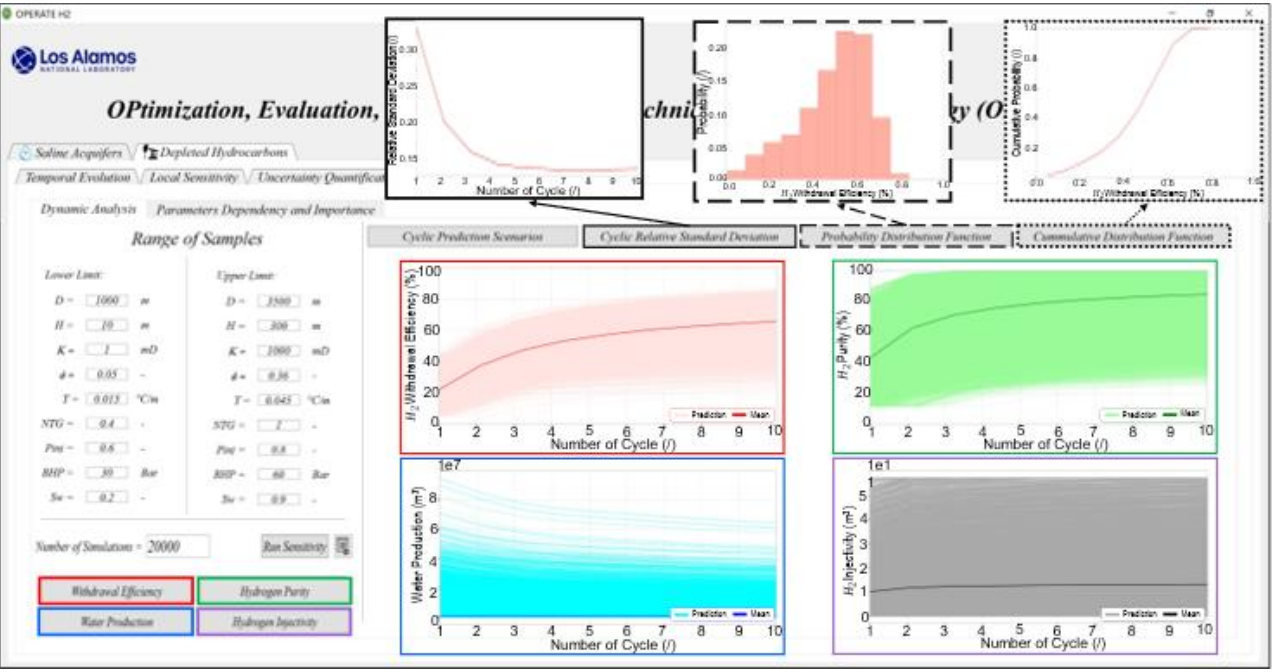
Outcome: Comprehensive toolset to holistically design and optimize a future H_2 economy

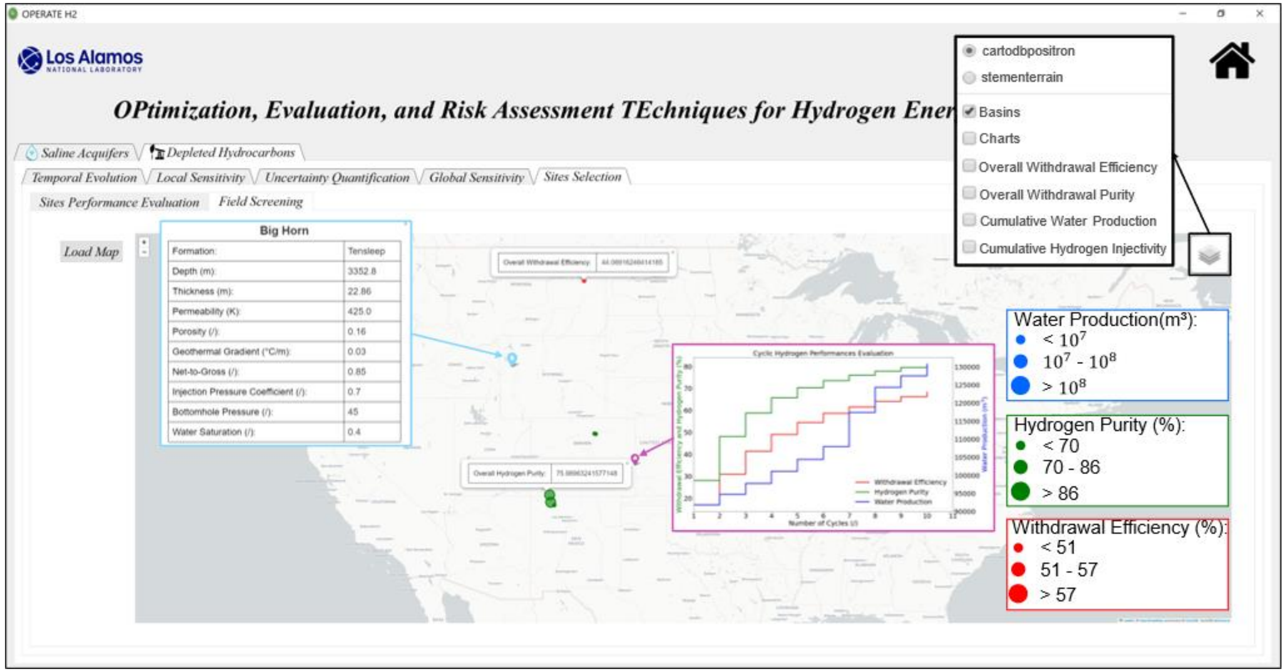


Optimization, Evaluation, and Risk Assessment Techniques for Hydrogen Economy (OPERATE-H2)



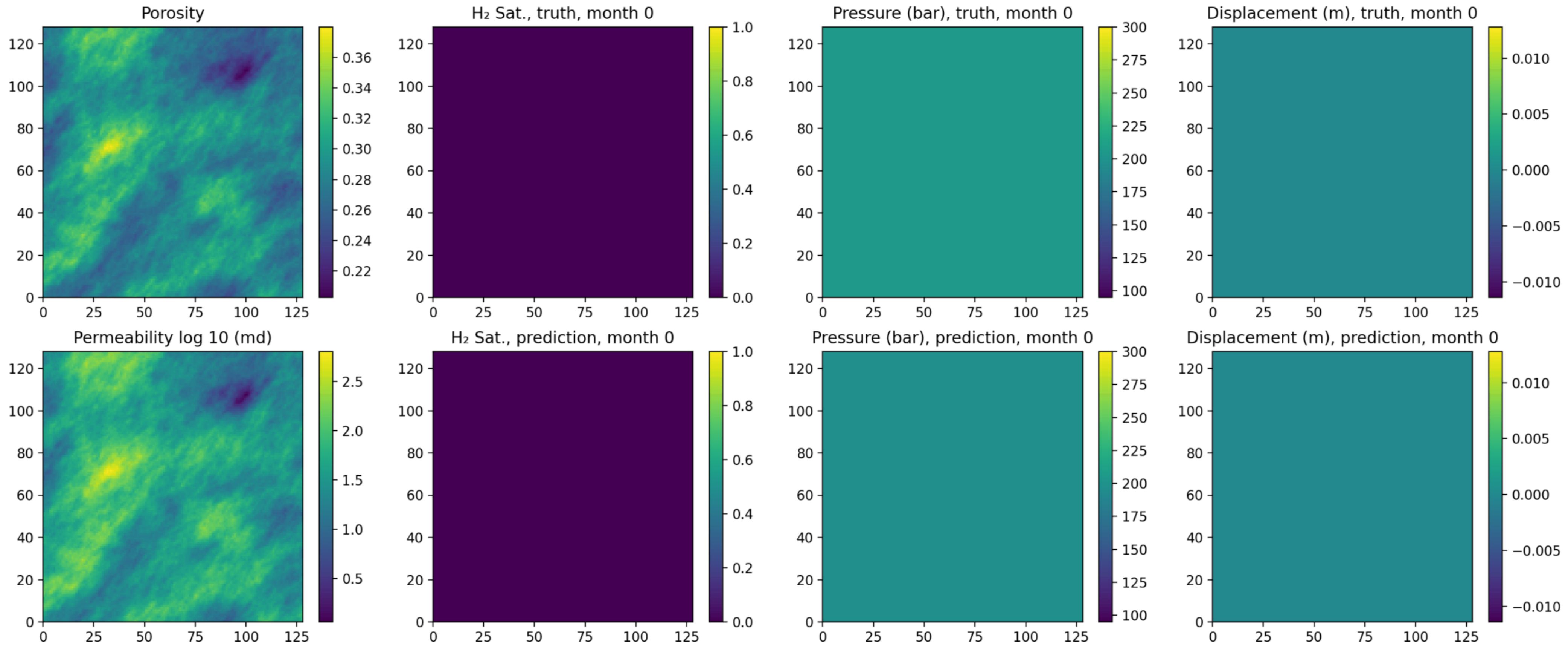
OPERATE-H2: Uncertainty quantification and field Screening





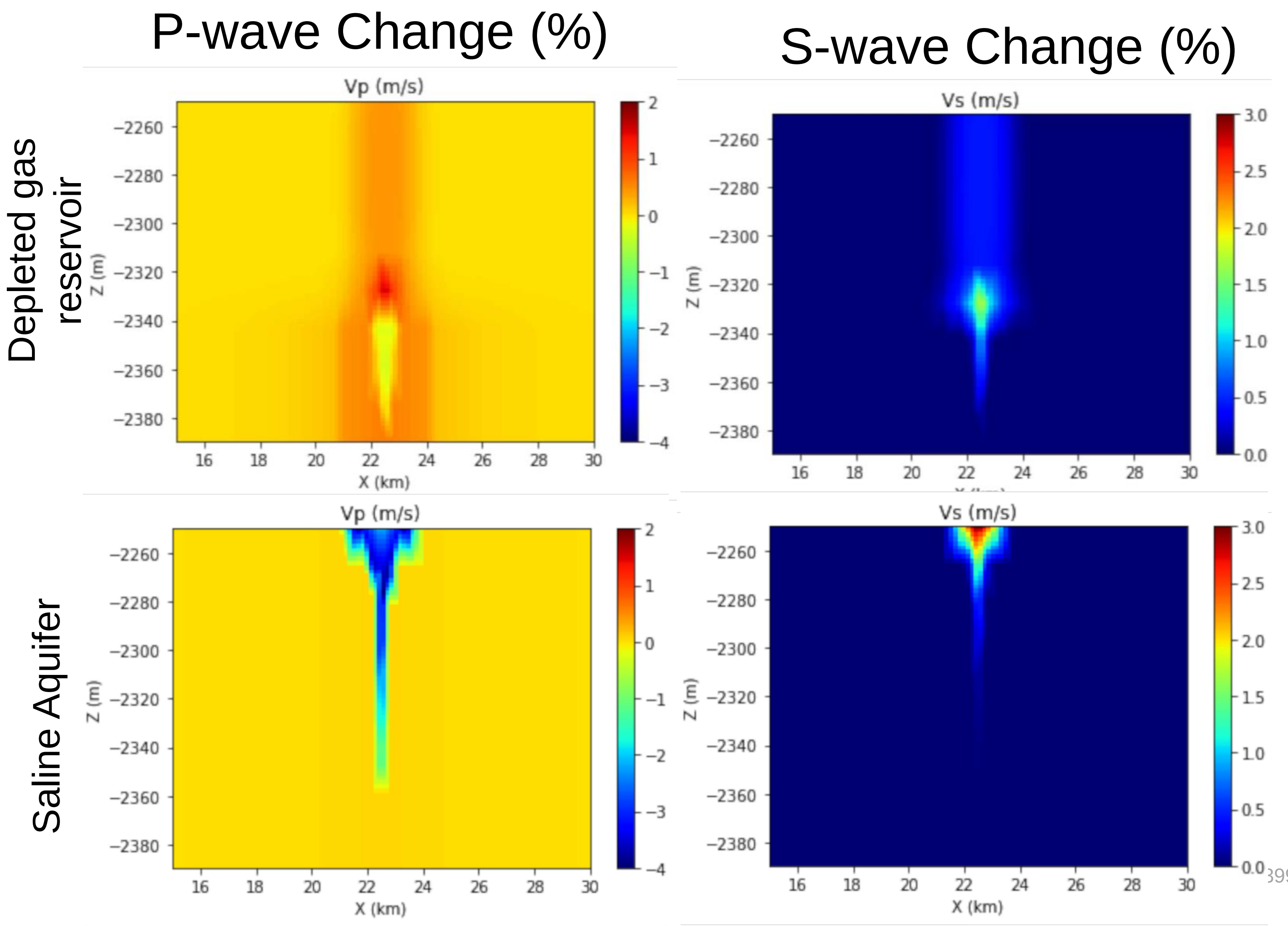
New Features

- Plume predictions
- Leakage assessment
- Microbial risk assessment
- Cushion gas optimization
- Geomechanics risk
- Cap rock integrity

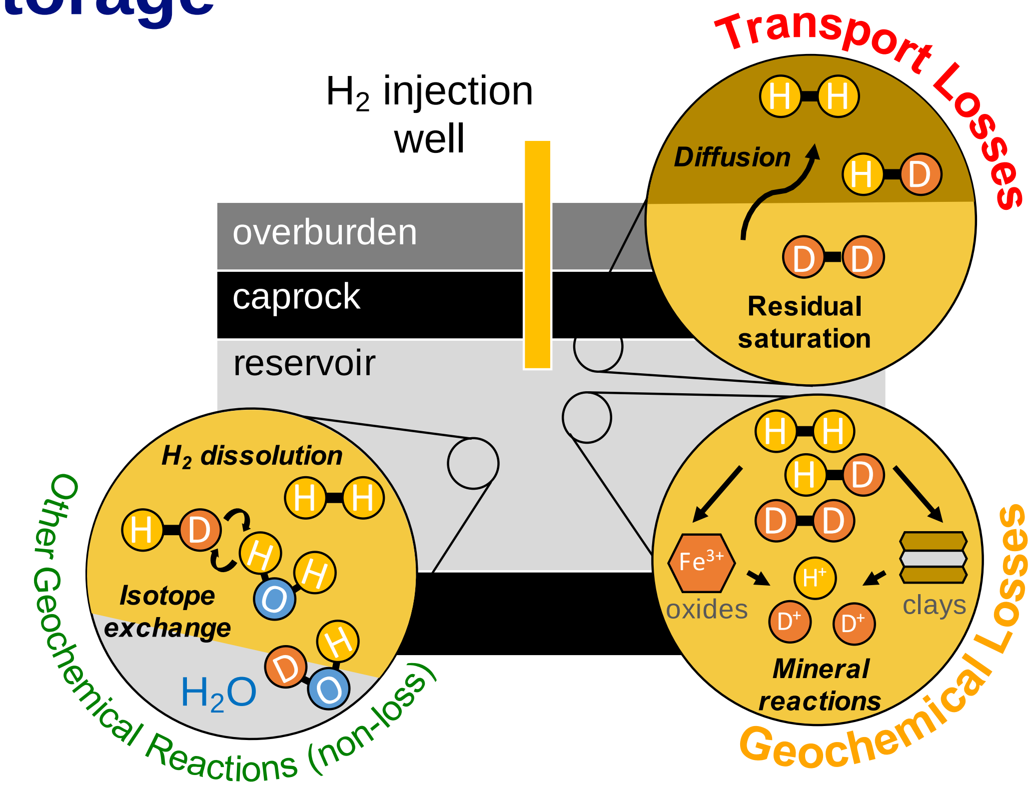


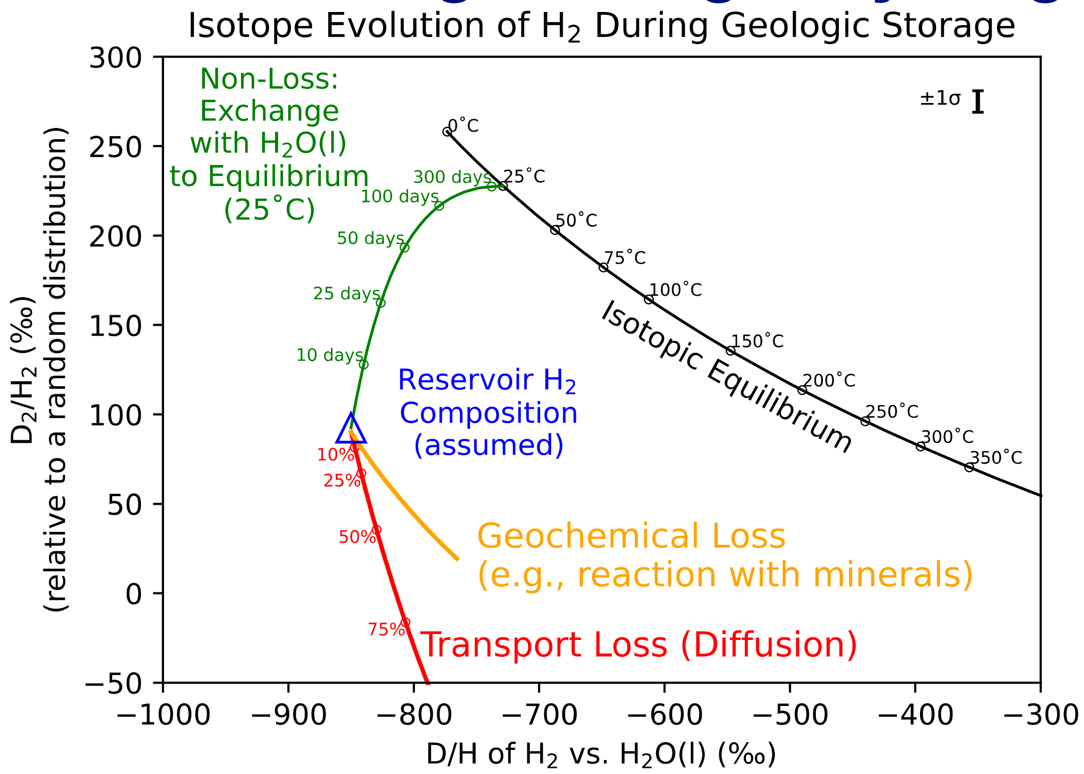
Seismic Modeling of Hydrogen Storage

- **Objective:** Extend the capability of our seismic monitoring toolsets for underground hydrogen (H_2) storage
- LANL has developed seismic monitoring tools for geologic carbon storage, geothermal, etc.
- Currently, no seismic monitoring plan for underground hydrogen storage (UHS)

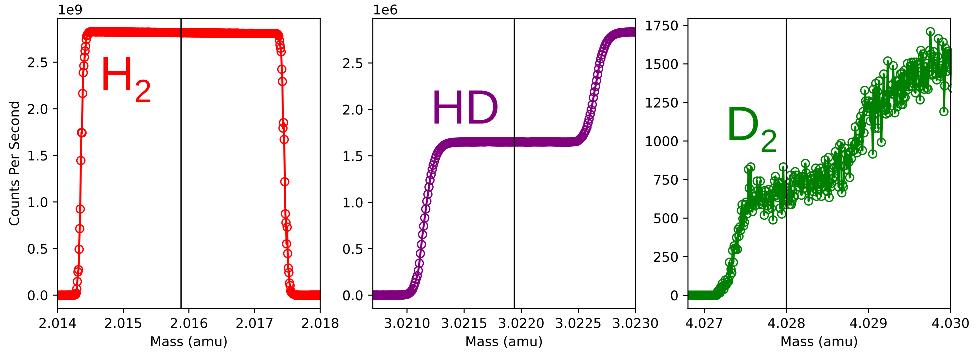


Stable Isotope Toolkit for Loss Assessment During Geologic Hydrogen Storage





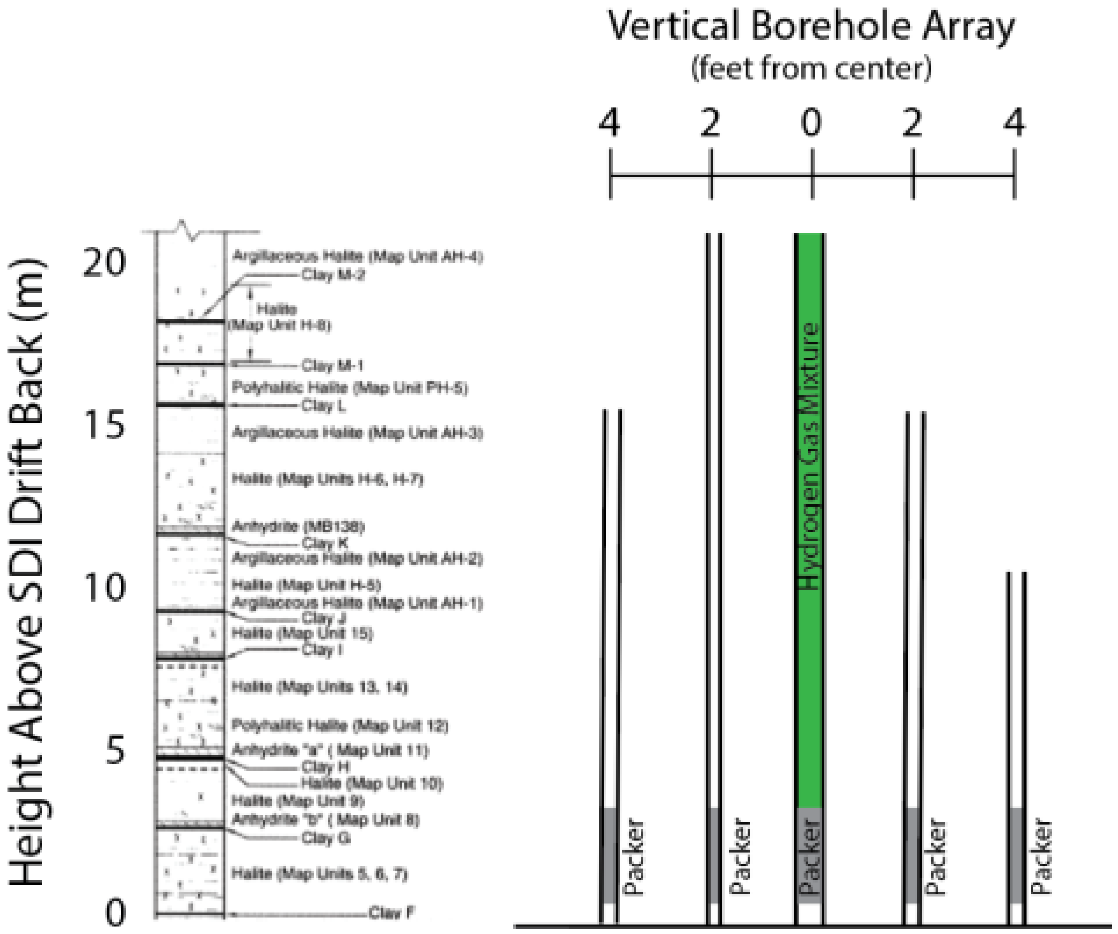
Isotopic Molecules of Hydrogen on LANL's Ultra HR-IRMS



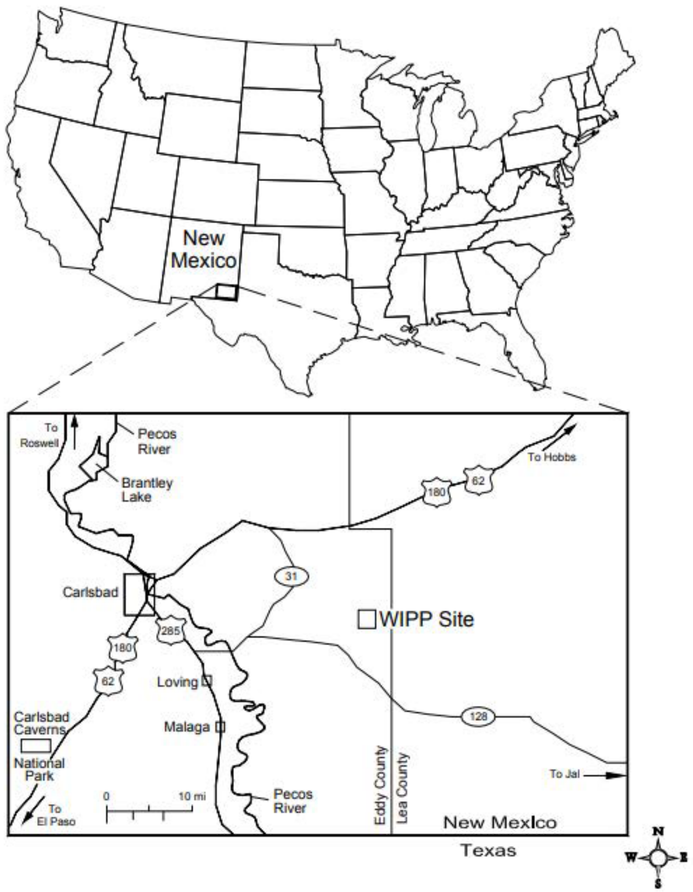
Note:
H = protium = ^{1}H (*~99.98% of natural hydrogen*)
D = deuterium = ^{2}H (*~0.02% of natural hydrogen*)
Data Sources:
Cartoon: Chelsea Neil (EES-16) & Daniel Eldridge (EES-14)
Scans on Ultra HR-IRMS: Daniel Eldridge (EES-14)
Isotope models: Daniel Eldridge (EES-14)
H_2-H_2O system experimental isotope constraints: Pester et al. (2018) *GCA*

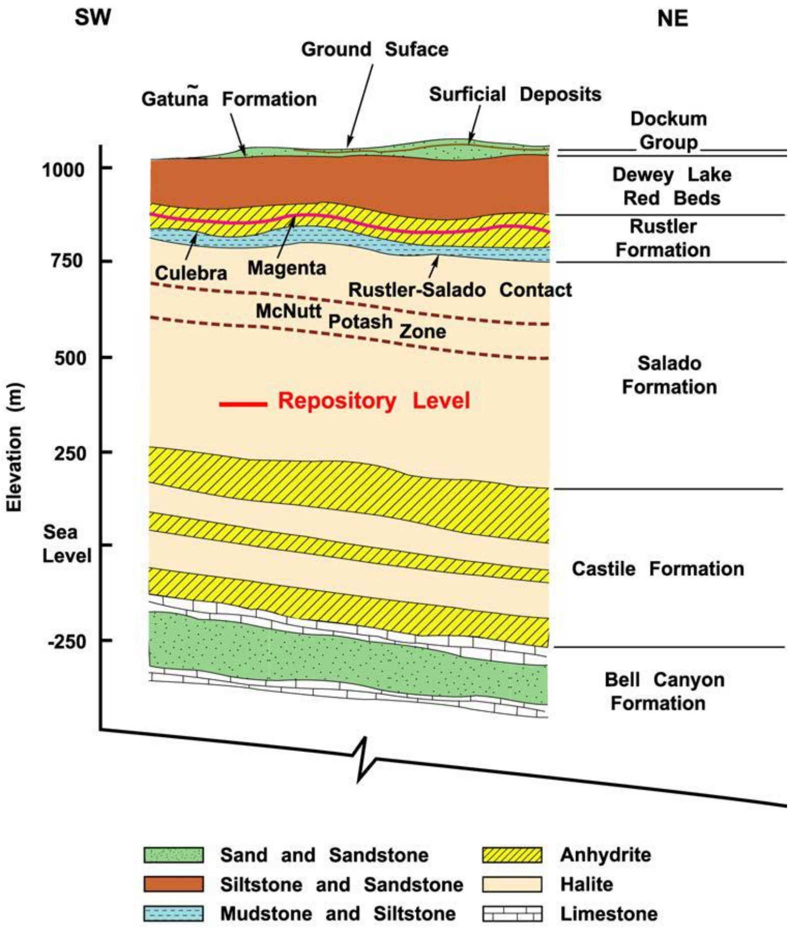
Bedded Salt Hydrogen Storage

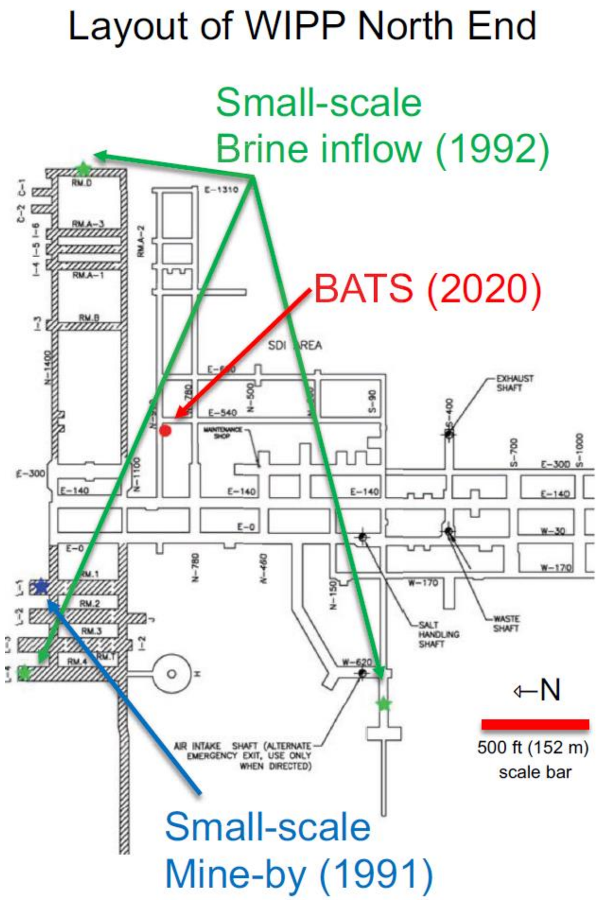
- Focused on characterizing bedded salt for hydrogen storage
- Collaboration between UT and LANL
- Includes small scale experiment at WIPP with boreholes drilled vertically into the back (the ceiling) to cross units.
- Laboratory experiments being conducted on salt cores
- Poster being presented by Nicolas Espinoza tonight



Bedded Salt Hydrogen Storage





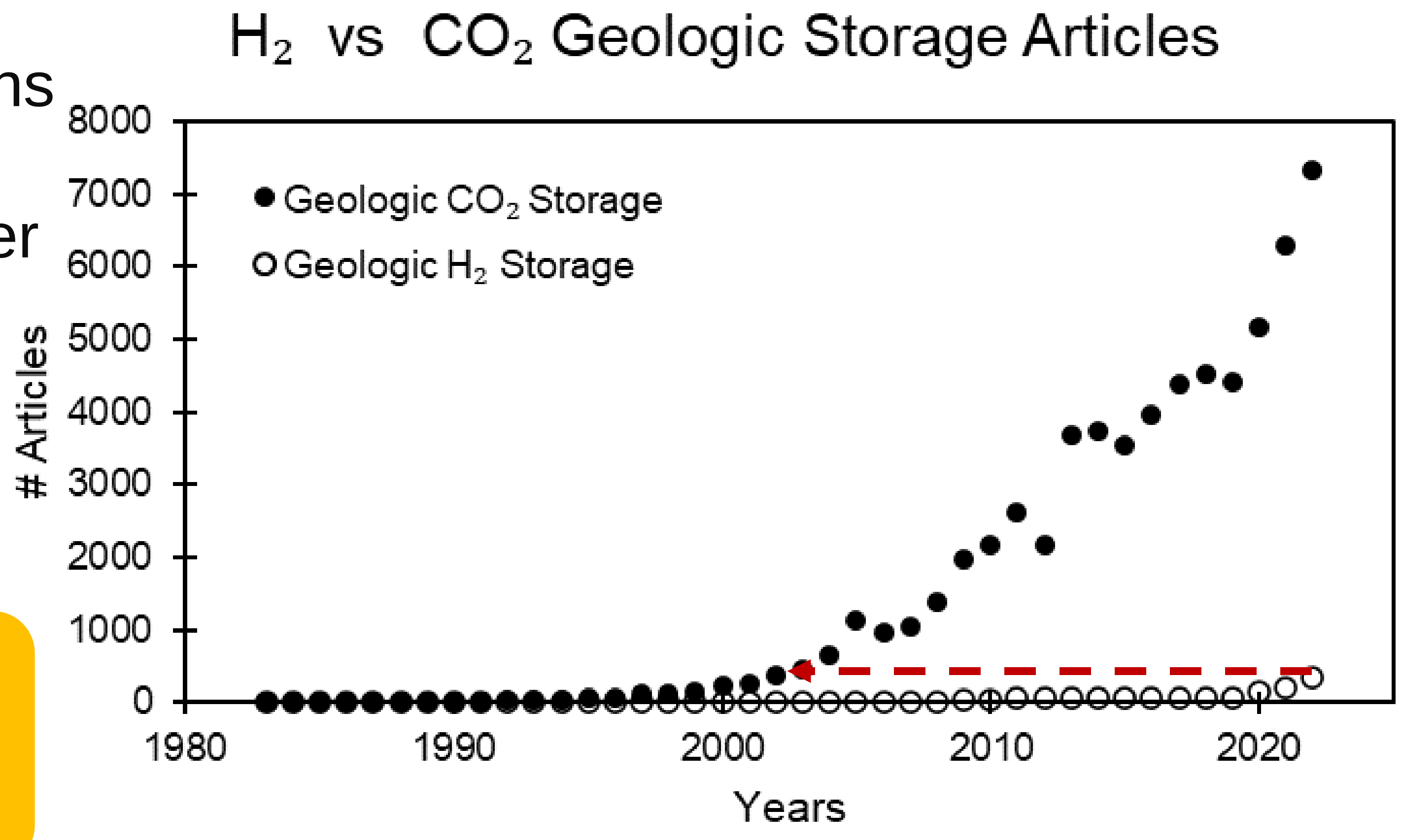


Strategic Hydrogen Reserves for a Growing Clean Energy Economy

- **Need:** In a growing market for clean hydrogen, early adopters face uncertainties in managing commercial needs.
- **Challenge:** The challenges in ramping up a clean hydrogen economy include logistical uncertainties and the classic "chicken-or-egg" problem.
- **Solution:** Strategic Hydrogen Reserves, backed by the Federal government, offer a solution to ensure market reliability and facilitate the rapid development of a clean hydrogen economy.

Where we are today and what do we need?

- The first international demonstrations of large-scale capture, utilization, and storage of CO_2 was the Sleipner CCS project in 1996
- Geologic H_2 Storage Lags Behind CO_2 Storage by 20 Years



Limit silos and support coordinated research efforts with all hands on deck.

Thank You!!

Mzm@lanl.gov

Strategic Hydrogen Reserves for a Growing Clean Energy Economy

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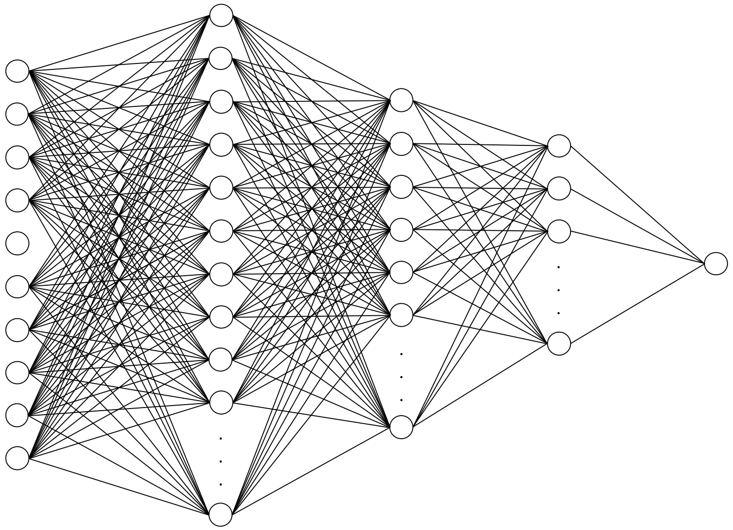
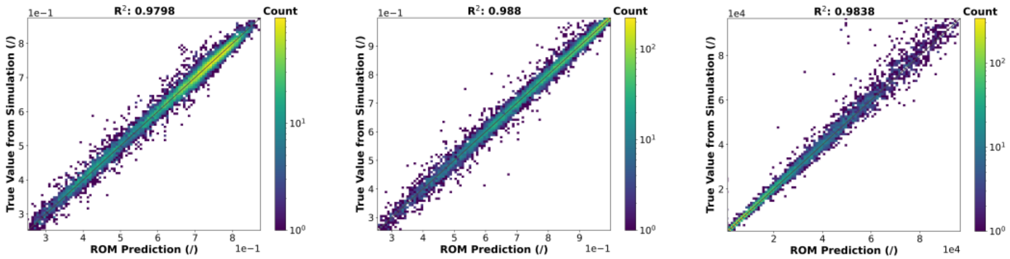
Reduced-Order Models (ROMs)

Uncertain Parameters

- Reservoir Depth
- Thickness
- Permeability
- Porosity
- Geothermal Gradient
- Net-to-Gross Ratio
- Injection Pressure Coefficient
- Production Pressure
- Initial Water Saturation

Artificial Neural Network (ANNs)





Objectives of Interest

Depleted Gas Reservoirs

- H_2 Withdrawal Efficiency
- Produced H_2 Purity
- Produced Gas Water Ratio

Saline Aquifers

- H_2 Withdrawal Efficiency
- Produced Gas Water Ratio

Disclaimer

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