



EERC



U N I V E R S I T Y O F
NORTH DAKOTA



Critical Challenges. Practical Solutions.



Energy & Environmental Research Center (EERC)

FIELD STUDY TO DETERMINE THE FEASIBILITY OF DEVELOPING SALT CAVERNS FOR HYDROCARBON STORAGE IN WESTERN NORTH DAKOTA

Contract No. G-054-104

Interim Report, Deliverable 2

December 30, 2022

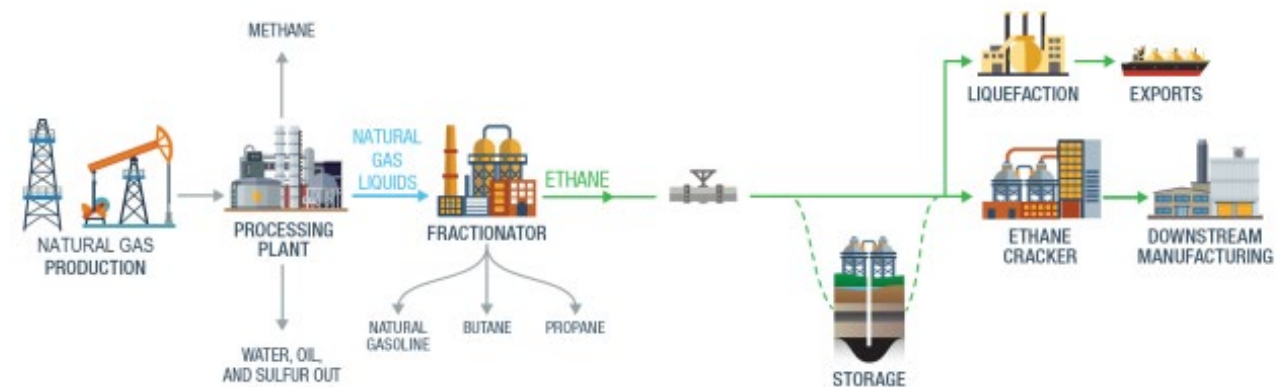
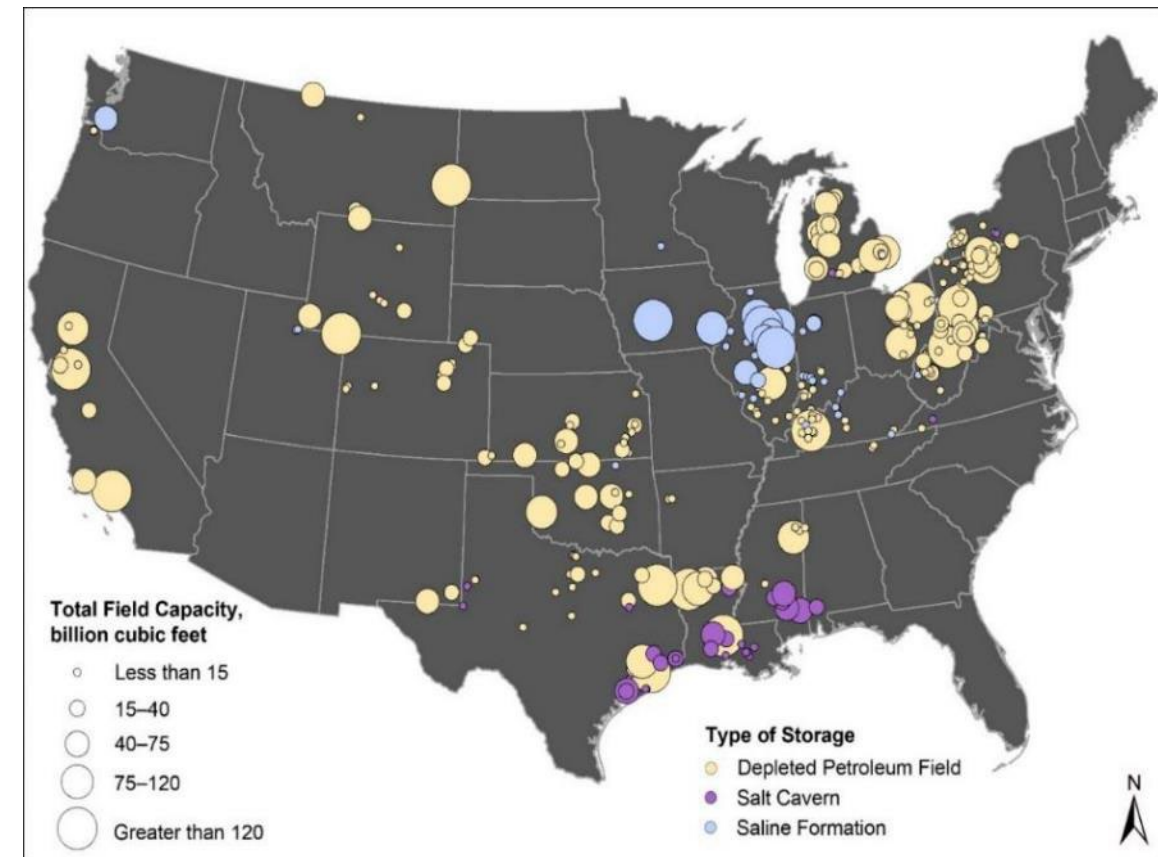
Steve Smith

Assistant Director, Integrated Analytical Solutions

OVERVIEW

GAS STORAGE

- Gas storage is a proven technology that began in 1915.
- Typically, gas storage is used to supplement energy demands associated with seasonal heating needs.
- Over 300 gas storage locations in the United States are active.
- Salt caverns are an integrated element in the petrochemical process.
- NGL (natural gas liquid) hubs are coincident with oil- and gas-producing regions or areas where export capability exists.



NORTH DAKOTA INNOVATION

The U.S. Government is investing billions of dollars into hydrogen research, technology development, and deployment through the bipartisan infrastructure bill.

Salt cavern storage is a necessary operational element!

- North Dakota's leadership has a vision of growth through innovation that precedes this investment.
- North Dakota is committed to investment into energy research, technology, and deployment.
- North Dakota has a demonstrated history of responsibly managing six of the seven topic areas noted in the DOE's Central Region Cluster concept.
- North Dakota has a long-standing commitment to sustainable development.
- North Dakota has Class VI primacy and permitted CCS projects!
- North Dakota has investments into depleted oil and gas and saline formation potential for hydrogen and/or hydrocarbon product storage.
- North Dakota is invested in the development of hydrogen hubs for commercial development opportunities.
- North Dakota is invested in preliminary study for engineered salt cavern and saline potential (2020).

Central Regional Cluster – RFI Response Highlights



Ample wind and moderate solar



Coal resources with CCS



Low-carbon ammonia ammonium nitrate



Saline formations, caverns and depleted oil fields



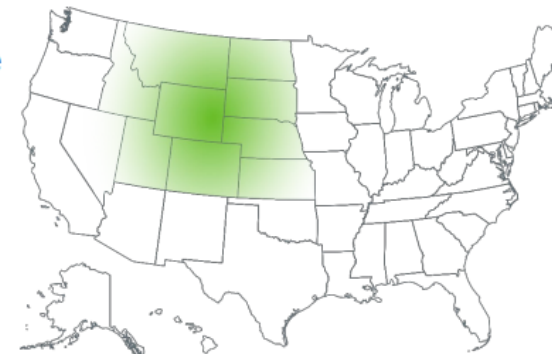
Natural gas resources and infrastructure



Extensive railway infrastructure



Uranium ore for nuclear power



2020 FEASIBILITY STUDY KEY FINDINGS

- The Dunham, Pine, and Opeche salt beds were identified as candidates for salt cavern development and product storage.
- Preliminary simulation results suggest:
 - The development of small caverns is achievable in North Dakota salt beds.
 - The use of multiple caverns was found to be a viable design approach and geomechanically stable.
- Regulations pertaining to the development of salt caverns, mineral ownership, brine handling, and injection are under the purview of three state agencies:
 - NDIC's Geological Survey
 - Department of Mineral Resources – Oil and Gas Division
 - North Dakota Public Service Commission
- Regulations – Several additional factors need consideration if NGLs are to be injected into the subsurface for storage.
 - Leasing of the subsurface salt (i.e., mineral extraction)
 - How to define the extent and volume of the solution-mined cavern
 - Definition of pore space ownership and storage of NGLs
 - Clarity regarding rules governing the use of surface brine storage ponds as part of salt cavern NGL storage facility operations
- Engineering assessments were performed.
 - Evaluated major equipment/components:
 - ◆ Compression
 - ◆ Brine pumps
 - ◆ Surface brine ponds
 - ◆ Electrical needs
 - Additional operational costs including labor, maintenance of surface equipment, and cooling water needs warrant further investigation.

2021 SALT CAVERN STORAGE PROJECT

2021 Legislative Assembly

The Energy & Environmental Research Center (EERC) proposes to directly address the intent of Section 14 of Senate Bill 2014 of the Sixty-Seventh Legislative Assembly of North Dakota, which states: "Pursuant to the continuing appropriation under section 57-51.1-07.3, the industrial commission shall use up to \$9,500,000, or so much of the sum as may be necessary, from the oil and gas research fund to contract with the energy and environmental research center for an underground energy storage study."

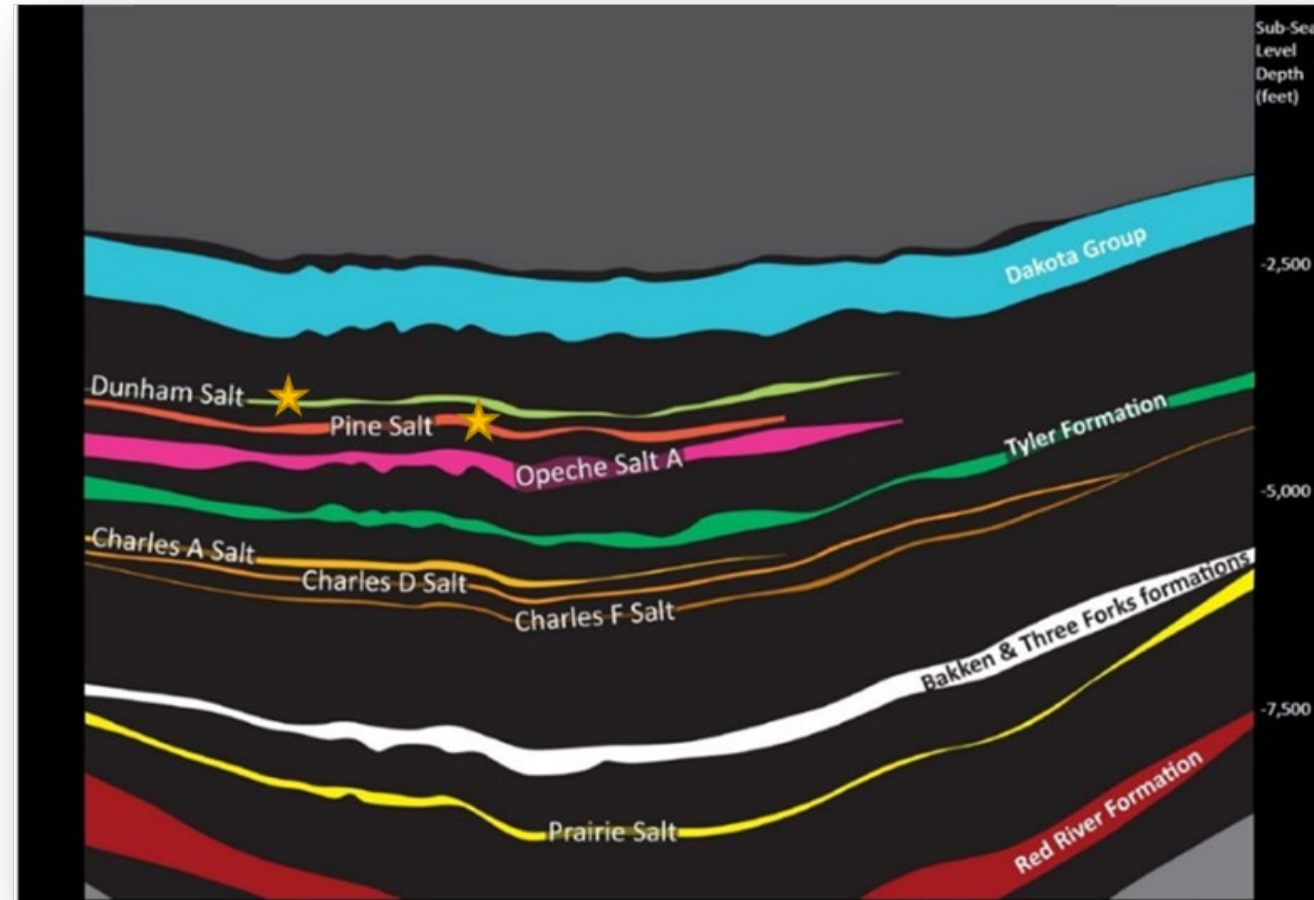
Project Goal: To use field-, laboratory-, and modeling-based efforts to validate the depth, thickness, and geologic/geomechanical suitability of North Dakota salt formations for subsurface gas or liquid storage cavern development.

Anticipated Results:

A final report that includes:

- A summary of the key findings from the site-specific geologic investigation.
- Site-specific cavern design and engineering considerations based on the successful drilling and coring of a well.
- Key lessons learned from active cavern storage projects for future development efforts.
- An implementation plan highlighting the viability of storing hydrocarbon gases and hydrogen in engineered salt caverns.

★ Target formations for core collection (Dunham and Pine)



(extracted and modified from Nesheim and LeFever, 2009).

INDUSTRY ADVISORY BOARD

- Provide advisement and technical project support.
- Are leading experts in transportation, development, and operation of subsurface product storage operations.
- Have met multiple times to discuss site selection, operational, and core collection considerations.

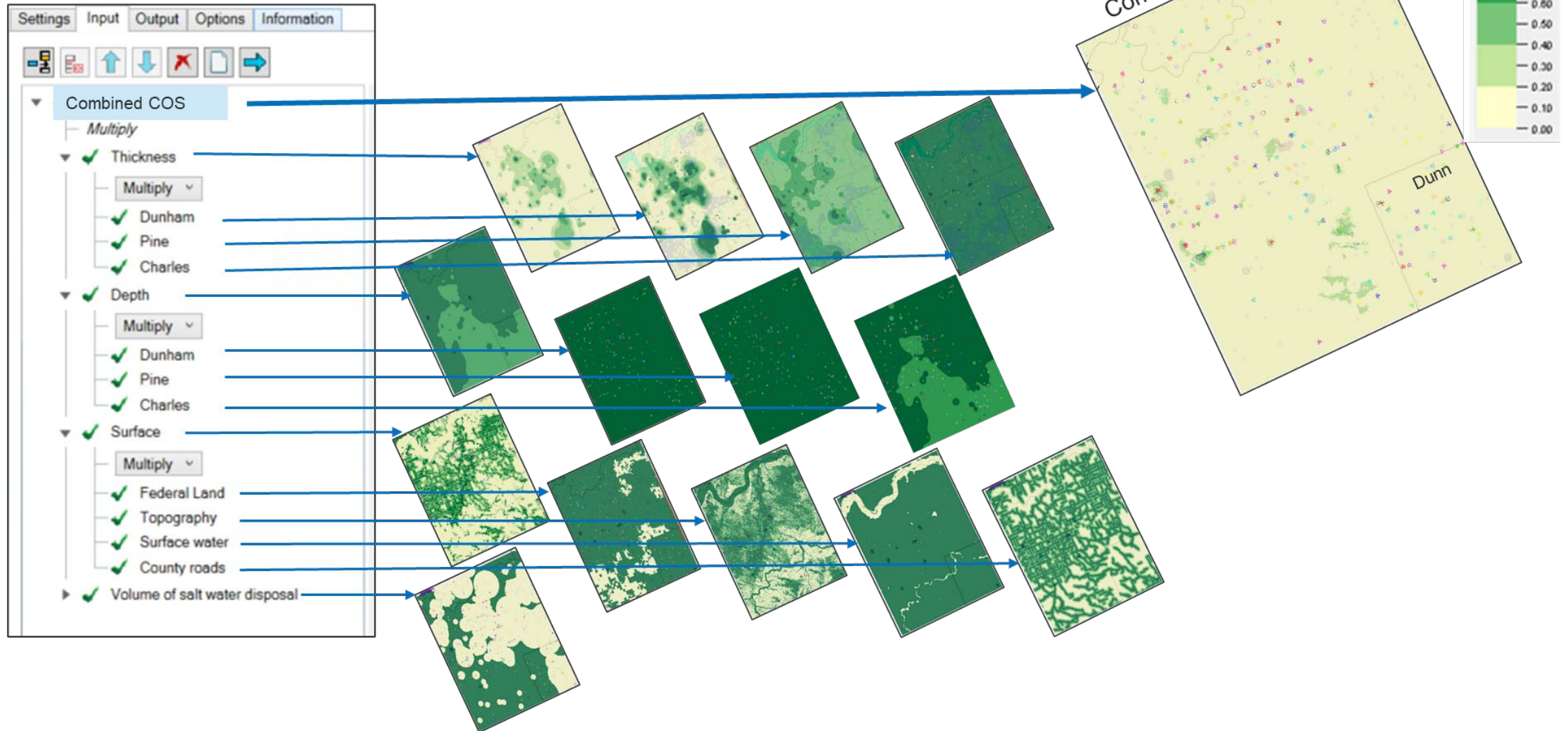


SITE SELECTION

SITE SELECTION AND CHARACTERIZATION

- Characterization was performed to determine the following:
 - Highest likelihood of coring salt formations of interest
 - Thickness of salt at location
 - Proximity to ethane fractionation, pipeline infrastructure, and water resources
 - Potential for future commercial development
 - Timing of pad development and well drilling:
 - ◆ Rig was previously secured and available at the time of drilling.
- Publicly available data were collected and incorporated into a screening tool.
- The tool was used to predict the best chance of success (COS) for encountering the parameters above. The following were used in the characterization:
 - Wireline logs: gamma ray, compressional sonic, resistivity, neutron porosity, bulk density, photoelectric factor
 - Salt formation maps (NDGS)
 - Pipeline infrastructure

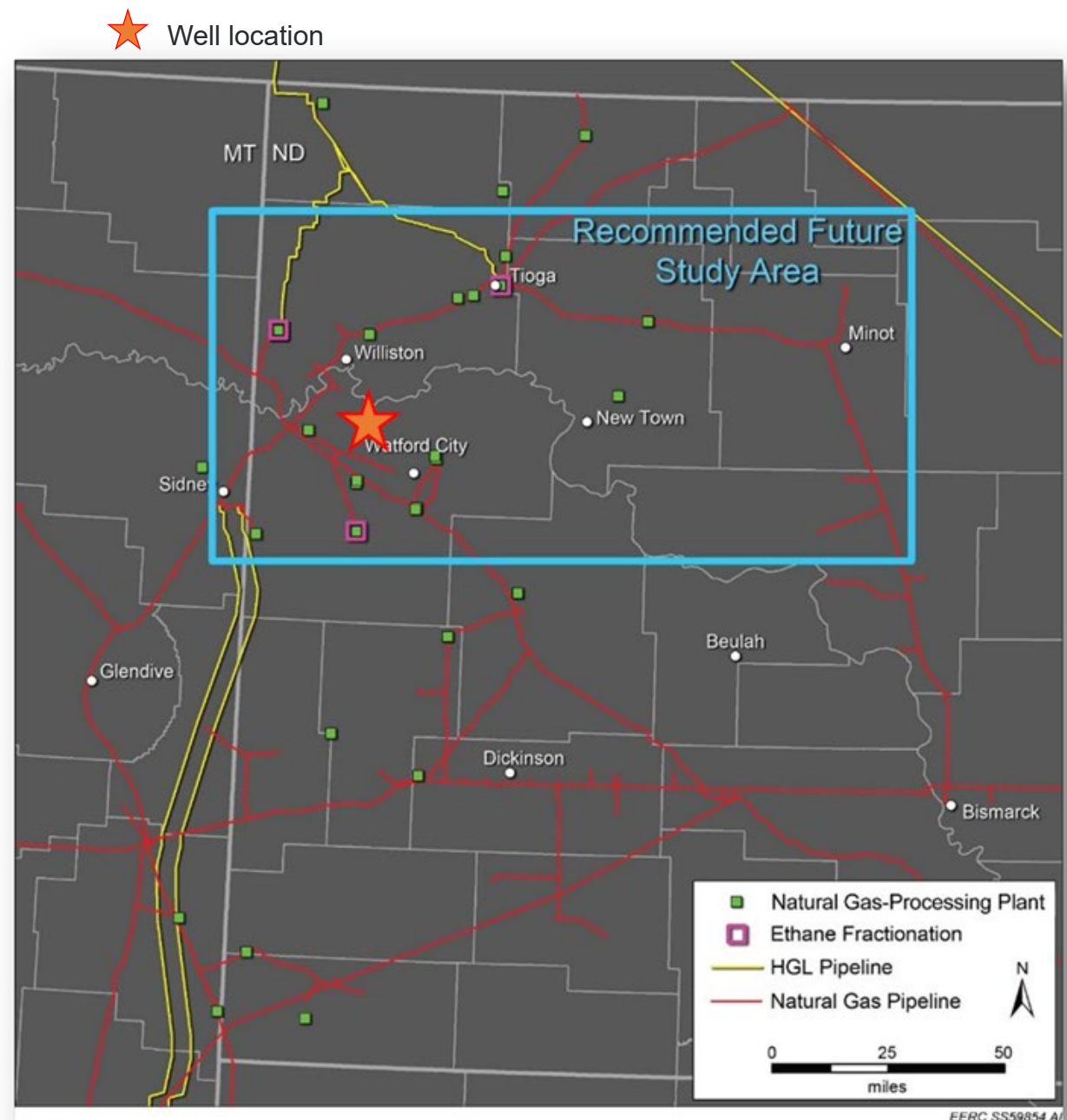
ELEMENTS OF COS MAP



SITE SELECTION

Halite-1 Location

- Ultimately, the EERC partnered with NDIC to identify and select a preexisting well pad for drilling. This decision:
 - Reduced pad development cost.
 - Reduced negotiation timeline with landowners at new sites.
 - Maintained project timeline.
- Halite-1 site is within the recommended study area detailed in the EERC's 2020 feasibility study (OGRP Contract No. G-040-080).
- Halite-1 is proximal to ethane fractionation, pipeline infrastructure, and water resources.

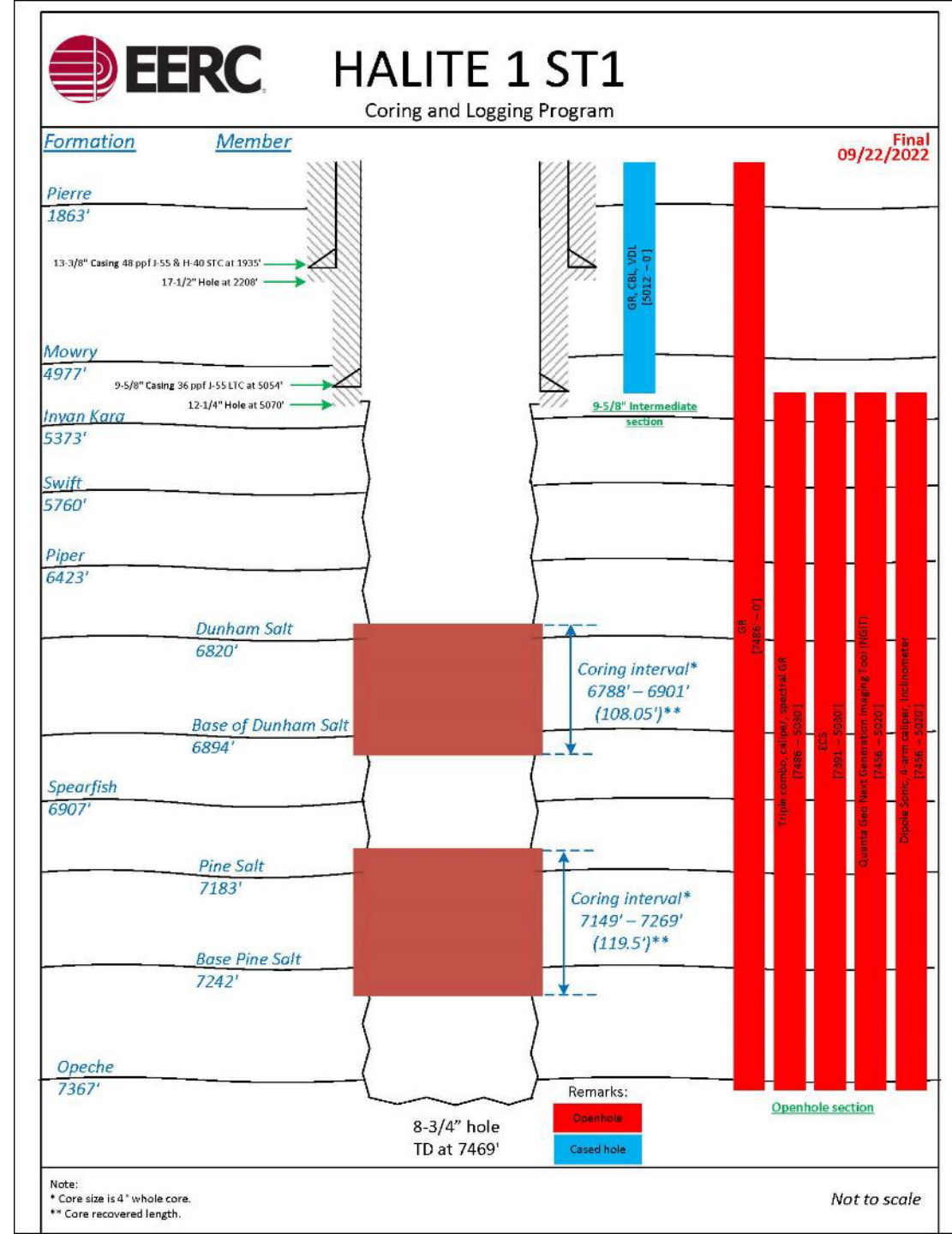


Taken from Smith et al. (2020) study to determine the feasibility of developing salt caverns for hydrocarbon storage in western North Dakota (OGRP Contract No. G-040-080).

WELL DRILLING

DRILLING

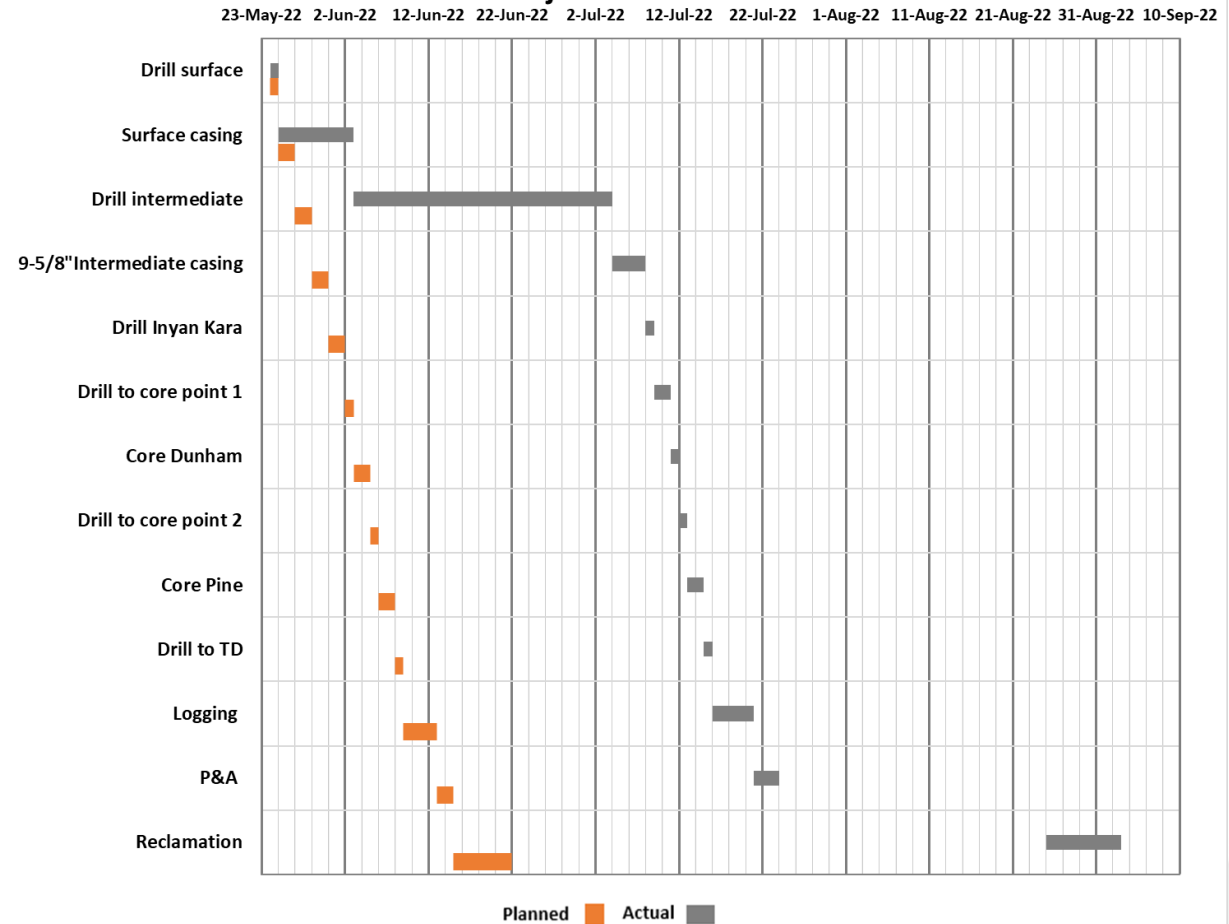
- A significant element of the research was to drill a stratigraphic test well:
 - Collect core from target salt formations.
 - Perform formation tests.
 - Collect a complete set of wireline logs.
- Naset Consulting was selected to operate the well and provide geologic services.
- The EERC and Naset worked together in the planning and drilling operations.
- While drilling, delays were encountered; however, core from the Dunham and Pine Salt was successfully recovered.
 - Results of laboratory testing on core samples will form the basis of geologic and geomechanical modeling of engineered salt caverns.



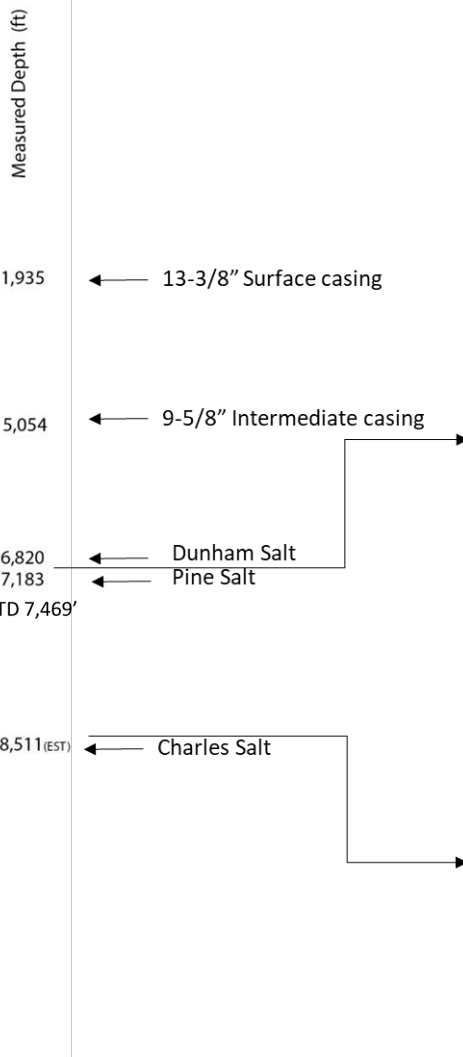
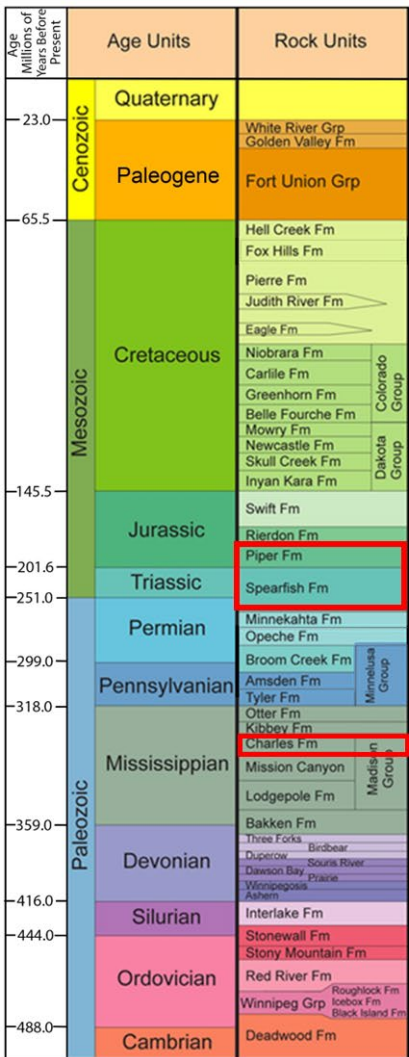
DRILLING SUMMARY

- Drilling initiated May 24, 2022.
- Drilled surface to 2208 ft on May 24.
- Started installing casing May 25.
- Casing parted May 25, causing 1943 ft of casing to remain downhole.
 - Fishing operations needed to retrieve casing.
 - 4 days of rig time to retrieve fish and set surface casing in place at 1935 ft.
 - 3 days waiting on cement for surface.
- Intermediate casing was planned at 6000 ft (below Inyan Kara). While drilling to casing point, fluid losses were encountered on June 4. Most fluid losses were coming from below surface casing shoe:
 - This required additional remediation including setting two cement plugs at surface casing shoe.
 - 12 days spent treating mud with loss circulation material, setting cement plugs, and waiting on cement.
 - Drilling resumed on June 17; bit bounced off plug and started sidetracking the original wellbore.
 - Attempts were made to reenter the original wellbore and were unsuccessful. Received NDIC approval to drill ahead on June 23.
- Drilling and fluid losses continued. 6 days spent trying to heal loss zones.
- Intermediate casing set to 5054 ft on July 3 in Mowry Formation.
- No problems drilling through the Inyan Kara. Drilled to first core point.
- Drilling, coring, and logging were completed July 16.
 - Well was drilled to a total depth of 7469 ft.
- Plug and abandonment (P&A) was not initiated until July 22 because of lack of cement and cement crew availability.
- P&A was completed July 24.
- NDIC site reclamation inspected and approved September 2.

Drilling Timeline



WELL SUMMARY



North Dakota stratigraphic column formations (left) and members (right). (Modified from Murphy et al., 2009).

FORMATION	MEMBER
PIPER	BOWES
	FIREMOON
	TAMPICO
	KLING
	PICARD
	POE
SPEARFISH	DUNHAM
	SAUDE
MINNEKAHTA	PINE
	BELFIELD
OPECHE	
BROOM CREEK	
AMSDEN	
TYLER	ALASKA BENCH
OTTER	
KIBBEY	
CHARLES	

- Dunham Core Recovery**
- 26' cap rock
 - 67' Dunham Salt
 - 15' underlying formation
 - 95.4% recovery
- Pine Core Recovery**
- 29' cap rock
 - 57' Pine Salt
 - 34' underlying formation
 - 99.7% recovery

Dunham Salt Core



Pine Salt Core



DRILLING SUMMARY

Formation Tops and Wireline Logs

HALITE 1 Formation Tops		
KB Elevation (ft) 2024		
Ground Elevation (ft) 1998		
KB Above Ground (ft) 26		
Formation	Depth (ft)	Thickness (ft)
Greenhorn	4546	431
Mowry	4977	396
Inyan Kara	5373	387
Swift	5760	554
Rierdon	6314	109
Piper	6423	484
Dunham Salt Member	6820	74
Base Dunham Salt Member	6894	
Spearfish	6907	428
Pine Salt Member	7183	59
Base Pine Salt Member	7242	
Minnekahta	7335	31
Opeche	7367	

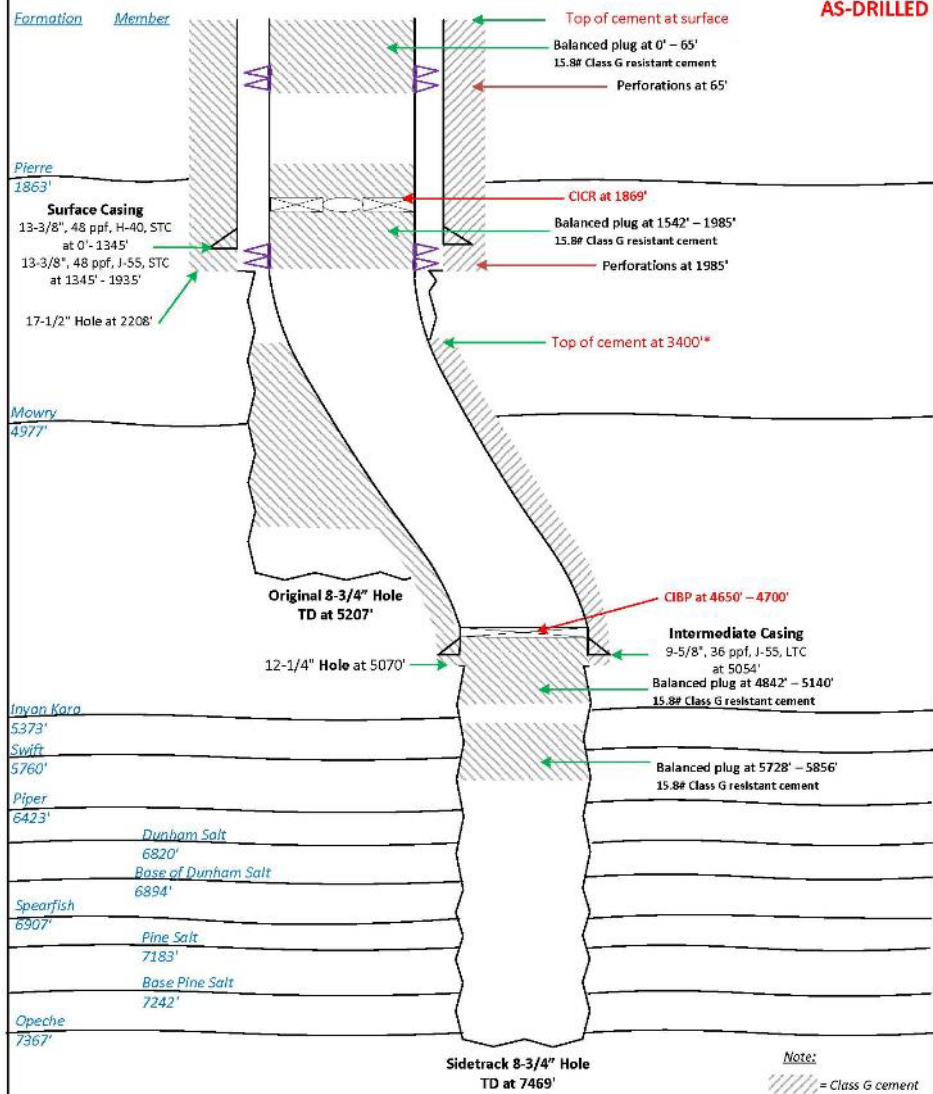
Logs	Collected (Yes/No)	Collected Depth Range (ft)
Triple Combo	Yes	5055-TD
Spectral GR	Yes	5055-TD
Elemental Capture Spectroscopy	Yes	5055-TD
Inclinometer Survey	Yes	5055-TD
Quanta Geo Next-Generation Imaging Tool	Yes	5055-TD
Dipole Sonic with Four-Arm Caliper	Yes	5055-TD
Modular Formation Dynamics Tester	No	N/A
Ultrasonic, Gamma Ray, Cement Bond, Casing Collar Locator, Temperature	Yes	0-5000

HALITE 1 wireline logs. Green is openhole; blue is cased hole.



HALITE 1 ST1

As-Drilled Well Schematic



* 247 bbls of cement has entered and dropped into the original wellbore
 Note: This wellbore schematic was generated according to the well status on July 16, 2022.

Not to scale

Completion Schematic for HALITE 1

Plug No.	Density (ppg)	Top	Bottom	Yield (ft ³ /sx)	Number of Sacks	Water (gal/sx)
1	15.8	5728	5856	1.16	95	5.09
2	15.8	4842	5140	1.16	100	5.09
3	15.8	1542	1985	1.16	160	5.09
4	15.8	0	65	1.16	90	5.09

HALITE 1 P&A Plugs.



Casing Cap Marking the Conclusion of HALITE 1.



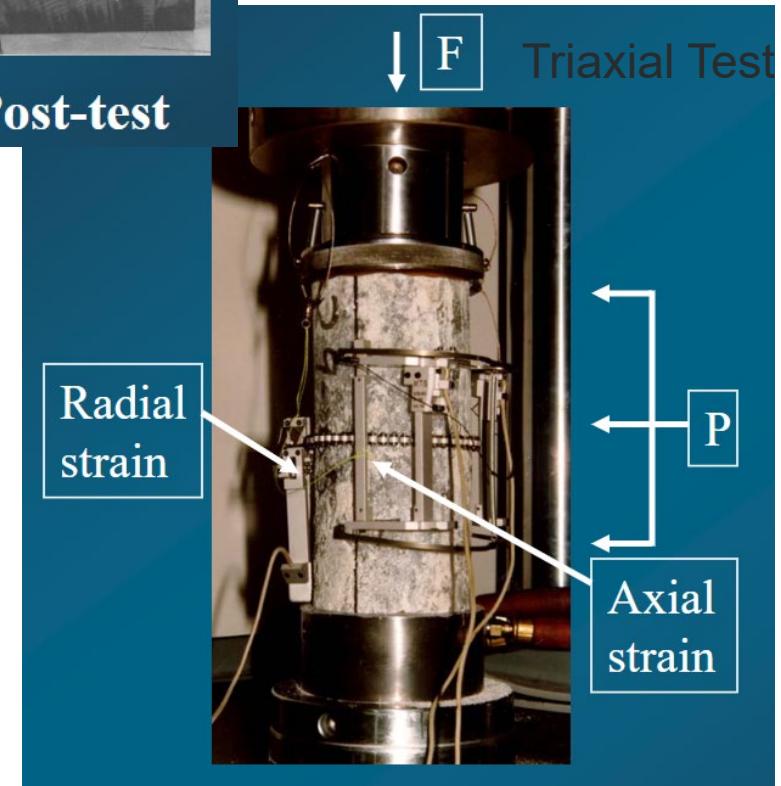
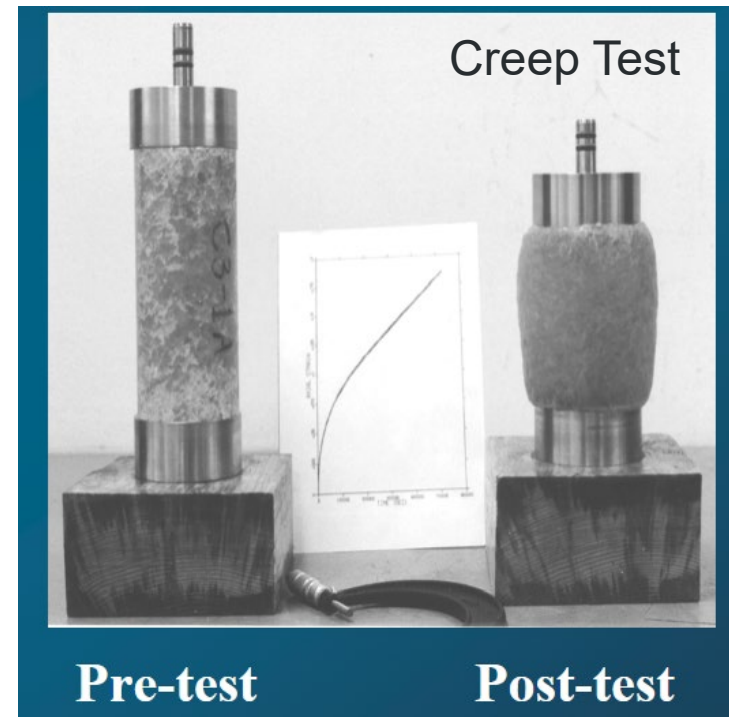
HALITE 1 Wellsite Reclamation.

CORE TESTING

CORE TESTING

- Work performed by RESPEC, Rapid City, SD
- Performed on core collected from:
 - Overlying sealing formations.
 - Dunham and Pine Salts.
 - Underlying adjacent formations.
- Core was transported from the Halite 1 site directly to Rapid City to begin processing and testing.
- Work complete includes:
 - Core processing – description, core preparation and boxing, core gamma ray, and photography.
 - Core testing
 - Insoluble mineral determination
 - Geomechanical creep testing to determine salt cavern stability.
 - Geomechanical triaxial tests.
- Work in progress:
 - Porosity and permeability
 - Direct shear testing

Core testing will inform geologic and geomechanical modeling, needed to evaluate the feasibility of salt cavern development within the respective salt formations



Photos from RESPEC

CORE TESTING RESULTS

Dunham Salt Member

- Cored interval (45' out of 60') shows high halite concentrations
 - A benefit for development and stability of engineered salt caverns.
- Individual salt (small to medium size) grains are at a size that has proven success in existing commercial operations.
- Overlying formations are tight and have thickness that will promote cavern roof stability.

6815'



6818'

Piper FM, Poe Member (siltstone, mudstone, anhydrite). This directly overlies the Dunham Member Salt

6860'



6863'

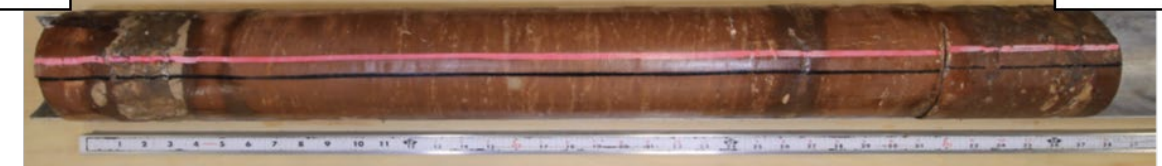
6887'



6890'

Dunham Member Salt (Halite)

6899'



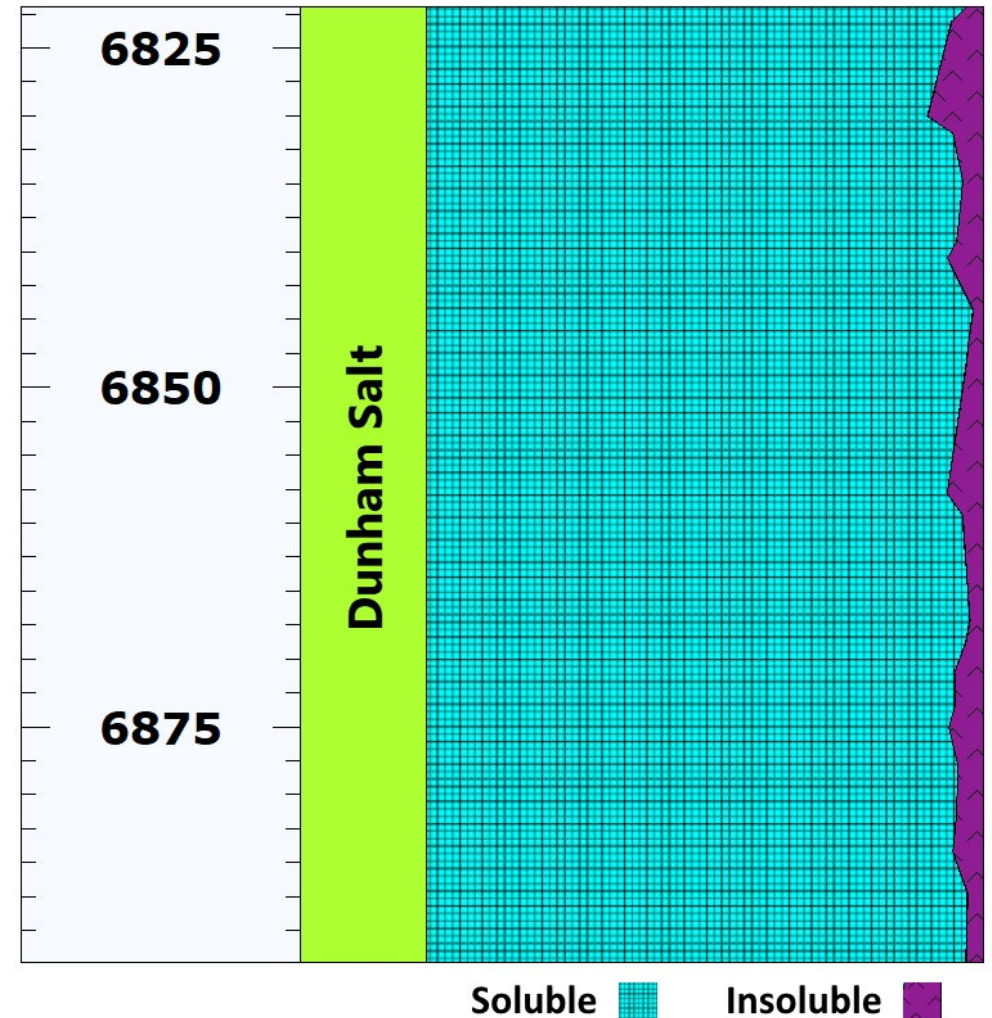
6902'



Spearfish FM, Saude Member (siltstone). This directly underlies the Dunham Member Salt

DUNHAM SALT COMPOSITION

- Dunham salt comprises nearly 100% halite:
 - Halite is soluble in water: a necessary factor for creating engineered salt caverns.
- Minor insoluble impurities exist:
 - This is common to bedded salt formations where caverns have successfully been developed and operated.
- This is encouraging for ND salt cavern development.

Soluble vs insoluble components based on XRD results



Soluble  Insoluble 
Critical Challenges. Practical Solutions.

CORE TESTING RESULTS

Pine Salt Member

- Overlying formations are tight and have thickness that will promote cavern roof stability.
- The Pine Member becomes much thicker (hundreds of feet in central and southern ND).



Spearfish FM, Saude Member (siltstone). This directly overlies the Pine Member Salt



Pine Member Salt (Halite with impurities)

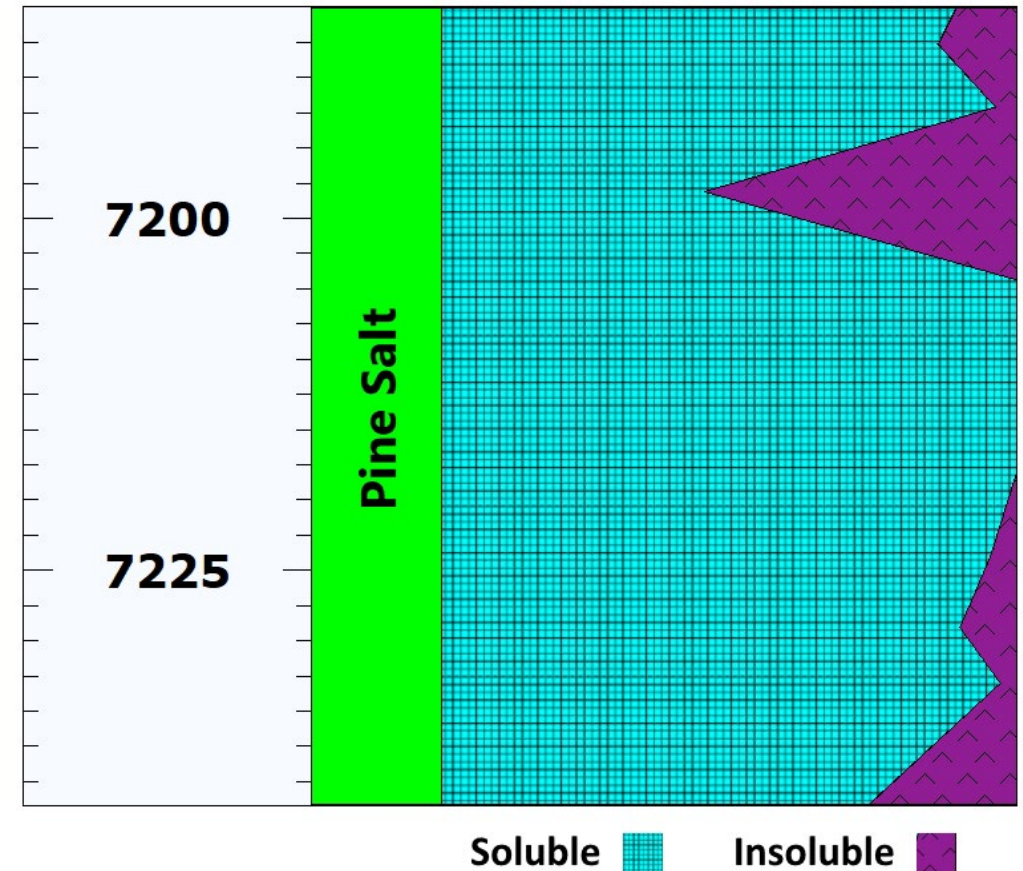


Spearfish FM, Belfield Member (siltstone). This directly underlies the Pine Member Salt

PINE SALT COMPOSITION

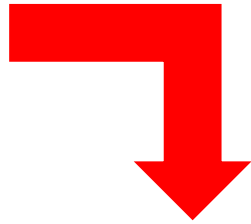
- Two soluble salts are prevalent in the Pine Member: halite and thenardite (sodium sulfate):
 - Thenardite is soluble in water but needs evaluation to determine mechanical stability during cavern operation.
 - The EERC will investigate other areas in North Dakota to determine if thenardite persists or if halite becomes predominant in the Pine Member.

Soluble vs insoluble components based on XRD results

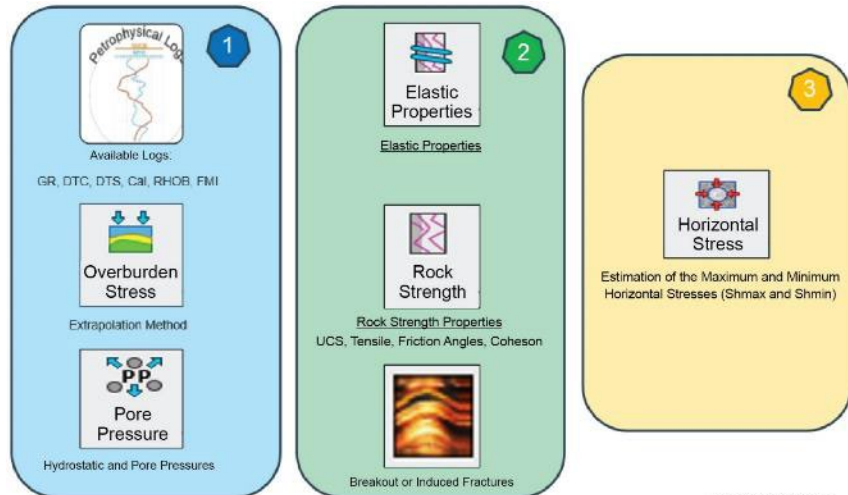


GEOMECHANICAL STUDY WORKFLOW FOR ENGINEERED SALT CAVERNS

Logging Data,
Core Testing,
Drilling Events



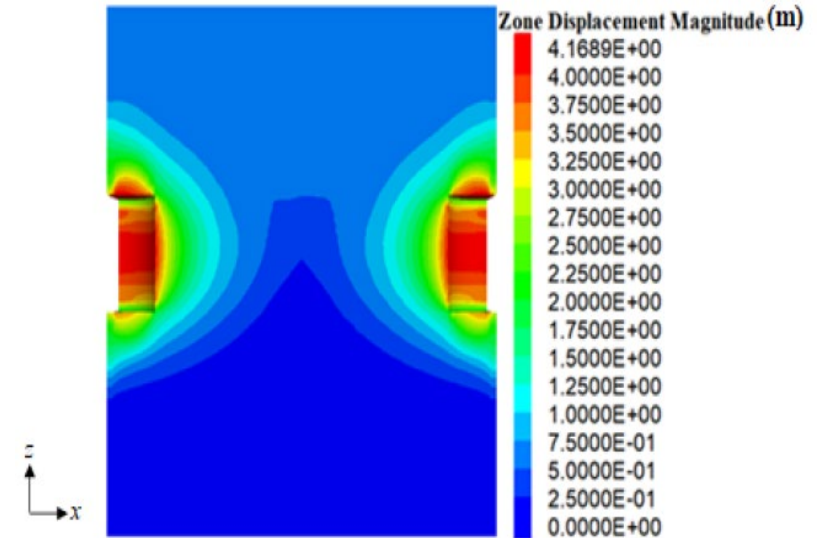
1D MEM @ Halite-1



Stress Conditions
Geologic Structures & Features
Mechanical Properties
Operational Conditions

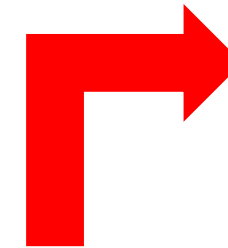


3D mechanical earth model (MEM)

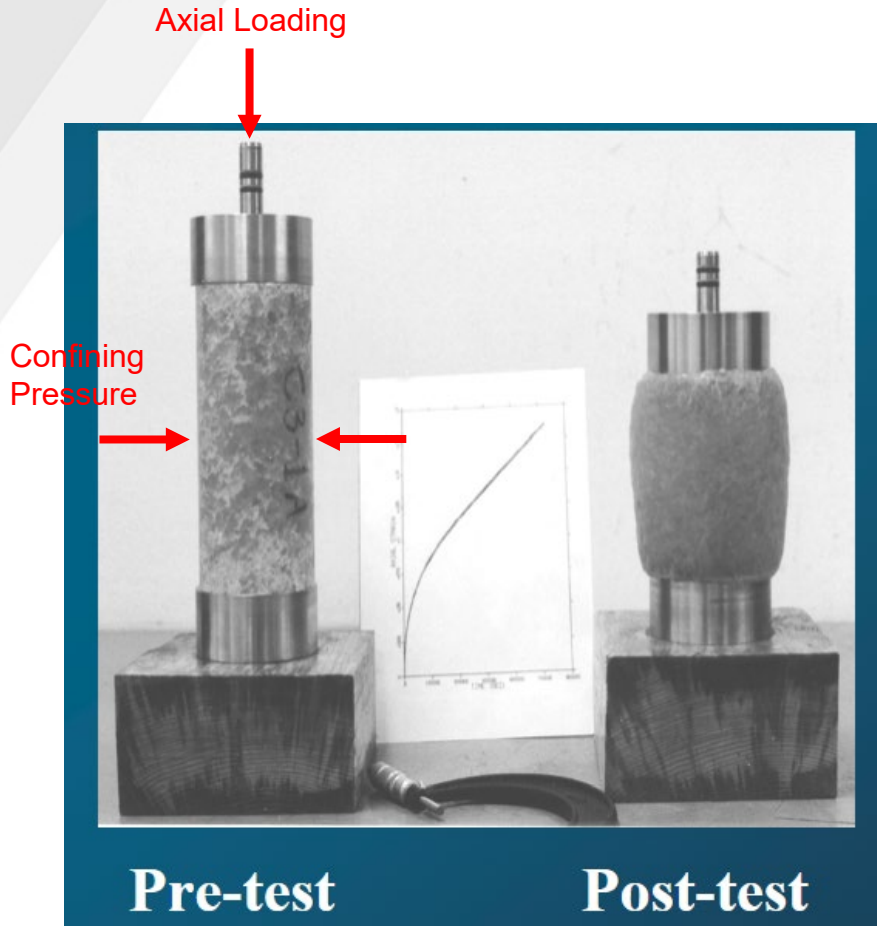


Predict the Stability (cavern closure, roof collapse, interbed slip, tensile fracture)

Optimal Operation Conditions for Stable Salt Cavern Storage



CREEP: MOST CRITICAL MECHANICAL PROPERTY FOR ENGINEERED SALT CAVERNS

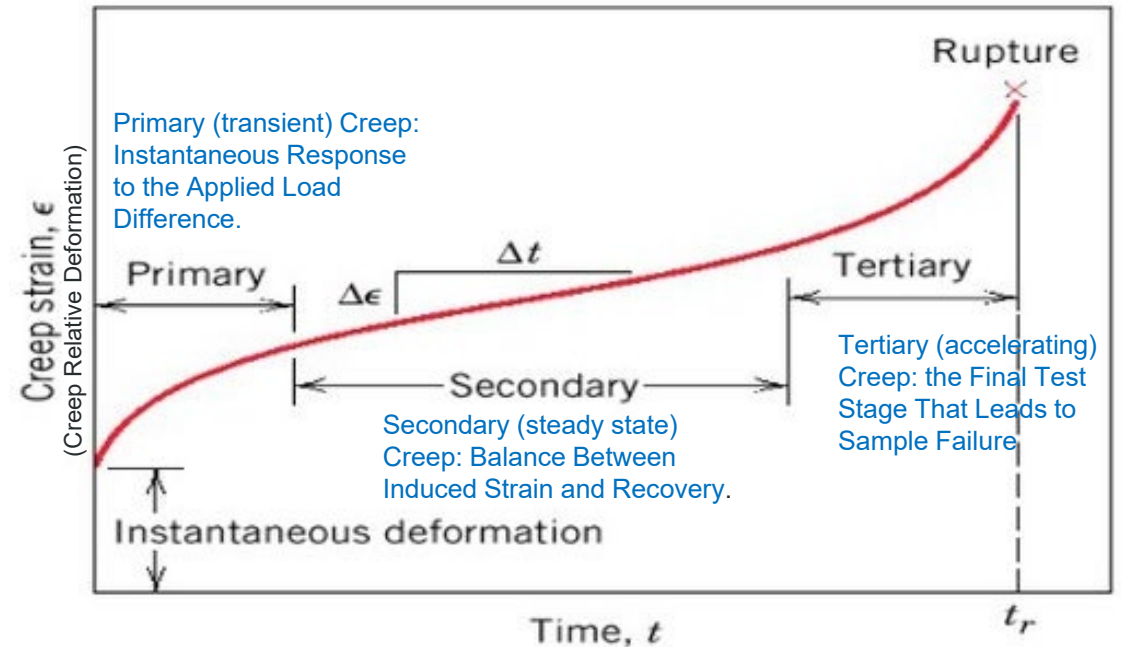


Core Test

Under Load Difference:
 Axial Loading –
 Confining Pressure > 0
 In Real Cases,
 Overburden –
 Operational Pressure
 Inside a Cavern > 0



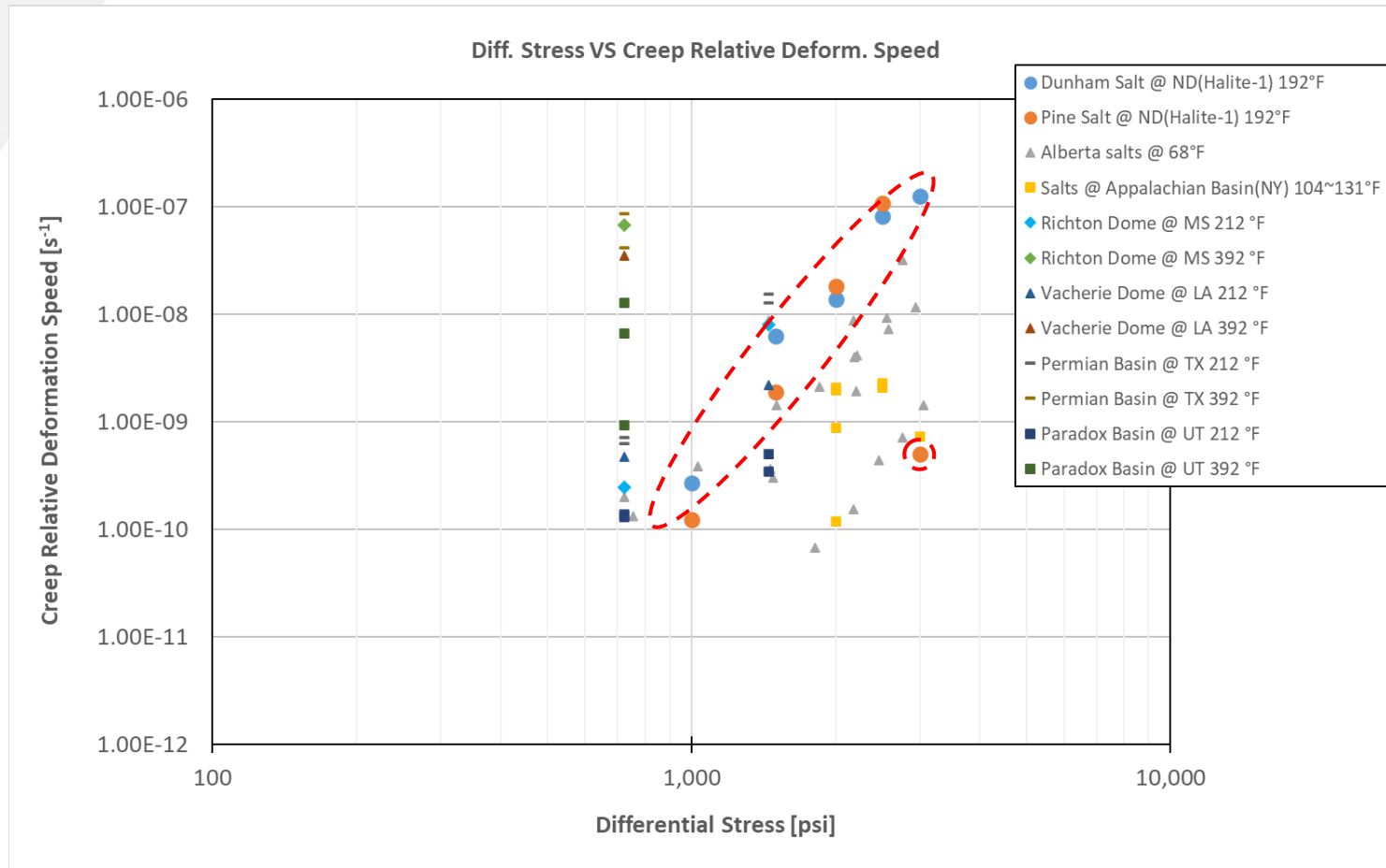
- Salt formations are known to flow (i.e., deform) under **subsurface temperature** and **load difference** conditions.
- This phenomenon is called **Creep**. Successful cavern development and operation are dependent on it.
- Creep tests are performed to provide input data for the development and operational stability of engineered salt caverns.



B. Tech In in Metallurgy and Materials Engineering, Veer Surendra Sai
 University of Technology

Creep

CREEP PROPERTIES COMPARISON



- Salt creep properties mainly depend on **subsurface temperature** and **load difference** conditions.
- The loading difference is simply overburden stress minus operational pressure inside a salt cavern.
- Generally, salt creep *deforms faster* under *higher temperature* or *higher load difference*.
- ✓ Other salt creep properties are compared with Halite-1 in graph.
- ✓ Dunham salt and Pine salt of Halite-1 show similar creep properties even if testing temperature is higher than others.
- ✓ Also, maintaining small load difference during operation is critical in engineered salt caverns.

GEOMECHANICAL CORE TESTING

Geomechanical core testing is performed to provide input data for the development and operational stability of engineered salt caverns.

Categories of Geomechanical Laboratory Core Tests Performed			
	Elastic Properties (the <i>time-independent</i> mechanical properties)	Rock Strength (the <i>time-independent</i> mechanical properties)	Creep (the <i>time-dependent</i> mechanical properties)
Main Properties	Young's modulus (E) Poisson's ratio (ν)	Tensile strength (Ts) Cohesion (Co) Unconfined compressive strength (UCS) Frictional angle (FA)	Creep multiplier (A) Creep time exponent (m) Creep stress exponent (n)
Meaning	How much does a salt deform under given loading conditions? These properties are used to calculate salt's <i>time-independent</i> deformation under operational conditions.	How strong is a salt under given loading conditions? These properties will be used to calculate salt's strengths under given loading conditions. This is related to salt's stability (Safety).	How much does a salt deform under given loading conditions over time? These properties will be used to calculate salt's <i>time-dependent</i> deformation under given loading conditions.
Tests Performed in This Study (test numbers)	<ul style="list-style-type: none"> Constant strain rate standard triaxial compression and unconfined compression tests (44) 	<ul style="list-style-type: none"> Brazilian indirect tensile strength (22) Constant strain rate standard triaxial compression and unconfined compression tests (44) Constant mean stress tests (8) Direct shear testing (pending) 	<ul style="list-style-type: none"> Creep (10)

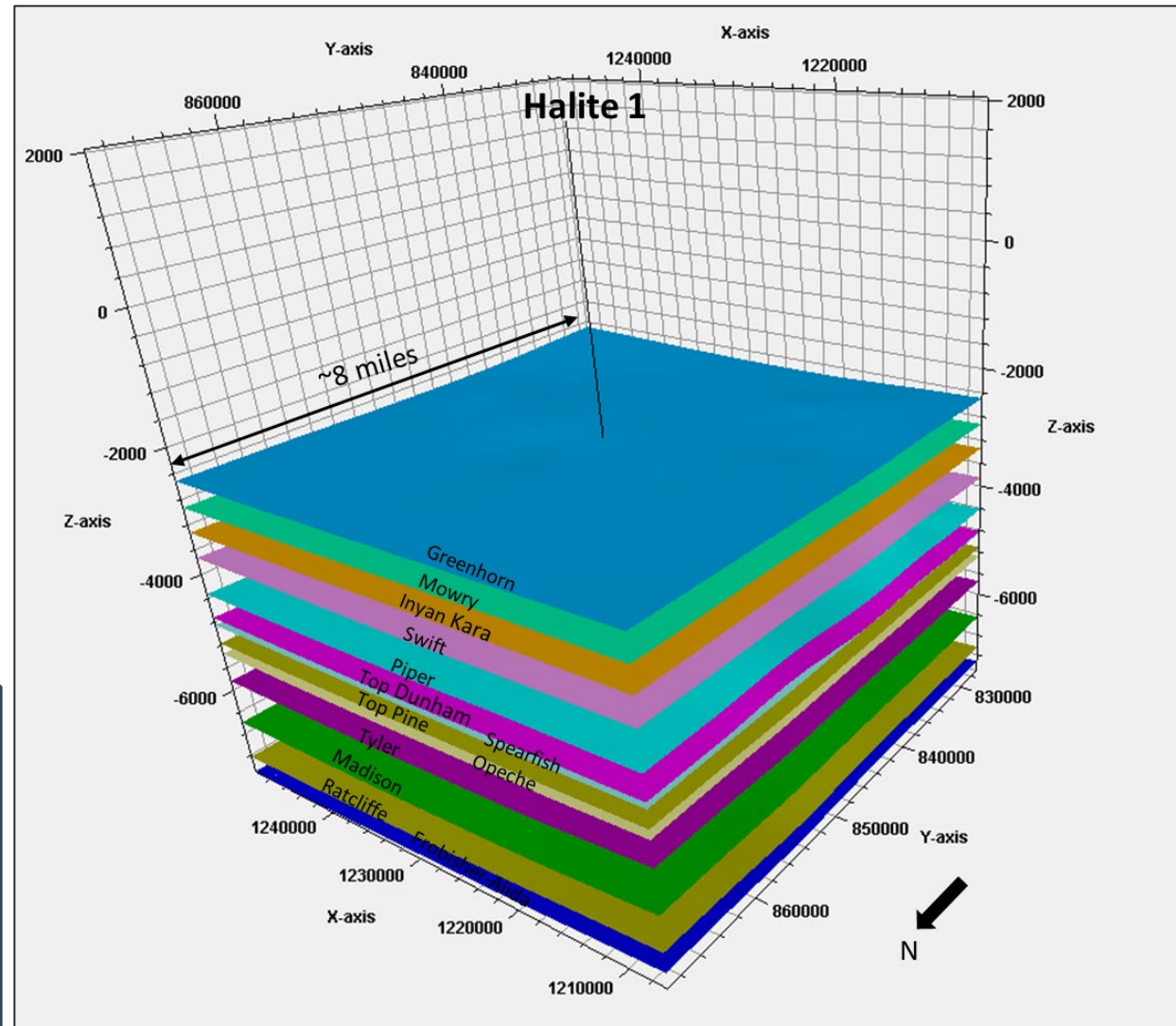
GEOLOGIC AND GEOMECHANICAL (1D & 3D MEM) MODELING

Modeling Is in Progress

- Local-scale geologic modeling of the Halite-1 site based on site-specific coring, logging, and laboratory test results.
- Geomechanical simulation will determine cavern dimensions and operational stability.

Additional modeling for alternate locations in the Williston Basin where cavern development has potential based on:

- *Salt depth.*
- *Thickness.*
- *Commercial opportunity.*



ENGINEERING ANALYSIS AND DESIGN WORKFLOW

- Investigation of fluids stored and requirements for different fluids
- Notional flow diagram development

2022: Preliminary Engineering Design and Analysis



Present: Iteration with Data unique to North Dakota

- Cavern size, depth, location information from drilling of test well
- Choose appropriate fluids from preliminary
- Choose appropriate facility mechanisms from preliminary



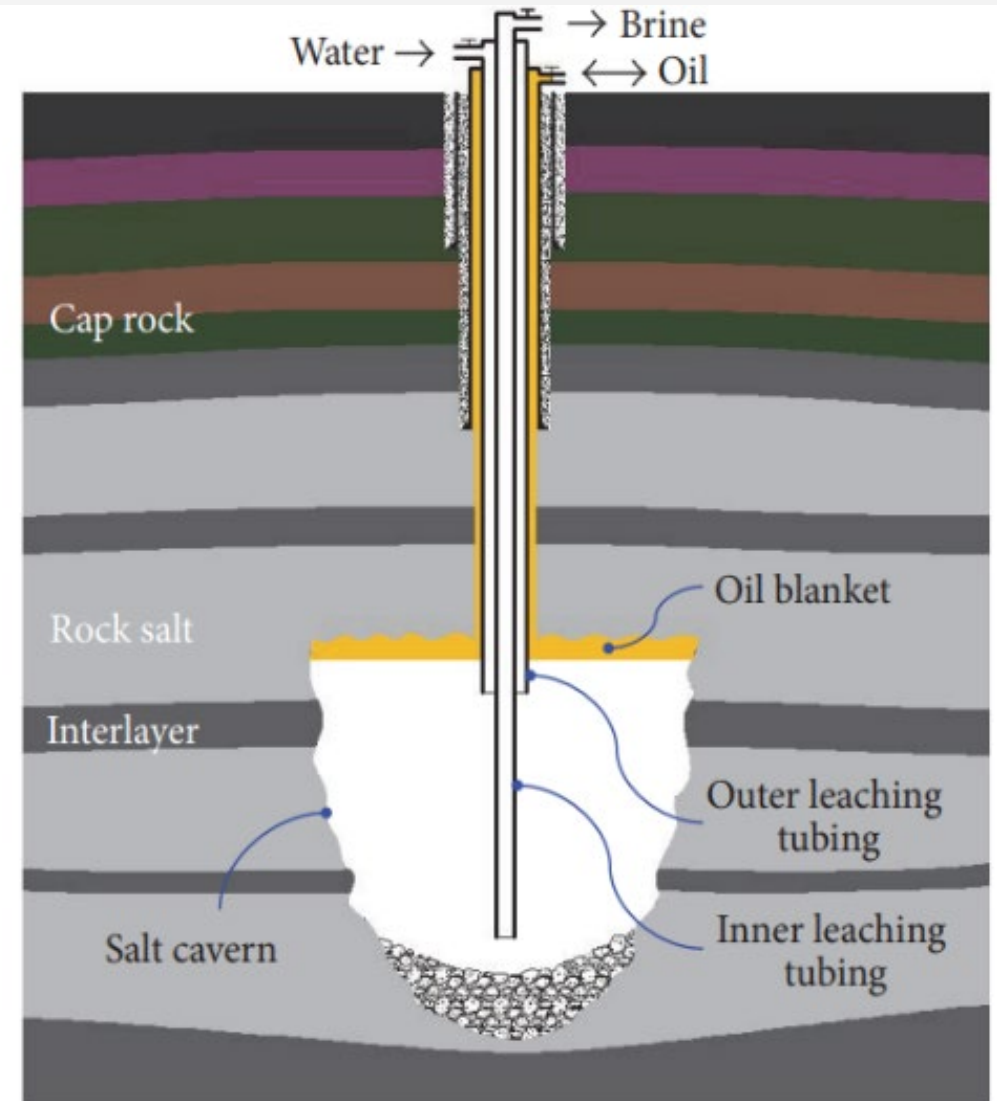
- Design unique for North Dakota storage scenarios
- Costing and economic case for storage facilities
- Recommended further steps

Deliverable: Final Model and Economics

SITE-SPECIFIC IMPLEMENTATION

- Scenarios to develop in final design
 - Hydrogen: salt caverns are key to hydrogen hubs:
 - As of 2020, only four caverns exist for hydrogen in the world: North Dakota can join in.
 - Natural gas liquids: added value proposition for existing fractionation facilities, securing higher price for the same liquids already produced.
 - Natural gas: seasonal storage and supply interruption reserves.
 - Petrochemical feedstocks: new industry for North Dakota.

Task Milestone: Site-specific implementation plans for future cavern development.

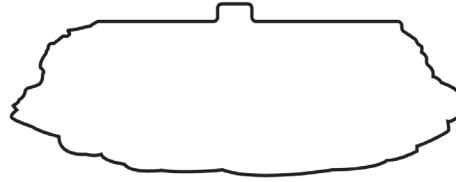


**NORTH DAKOTA – STATEWIDE INVESTIGATION
FOR POTENTIAL CAVERN DEVELOPMENT AND
OPERATION**

ALTERNATE LOCATION SCREENING

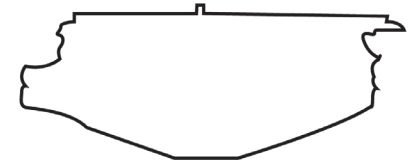
- As of 2006, over 200 caverns have been developed in bedded salts throughout the United States and Canada:
 - This is the majority (nearly 80%) of caverns developed in bedded salts globally.
- Many of these are developed in salts that have thicknesses similar to the Dunham and Pine Salts.
- A key consideration for commercial operation is depth:
 - Alberta and Saskatchewan caverns are developed deeper than many U.S. caverns.
 - This current investigation will provide additional insight into the impact of depth on mechanical, operational cavern stability.

Arizona



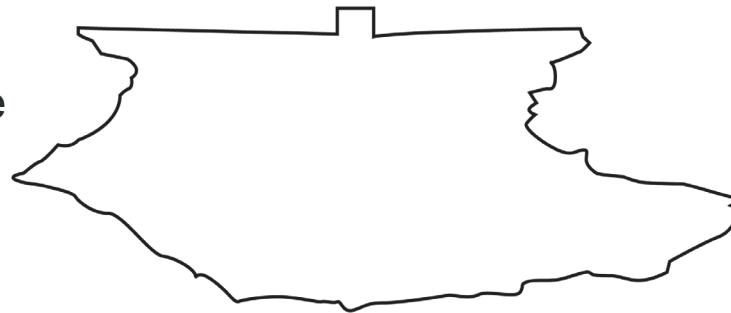
Average Depth 900 ft
Average Height 60 ft
Average Width 160 ft

Kansas



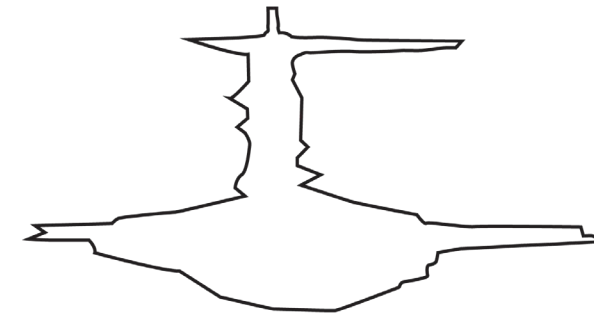
Average Depth 700 ft
Average Height 60 ft
Average Width 150 ft

Saskatchewan



Average Depth 5000 ft
Average Height 120 ft
Average Width 240 ft

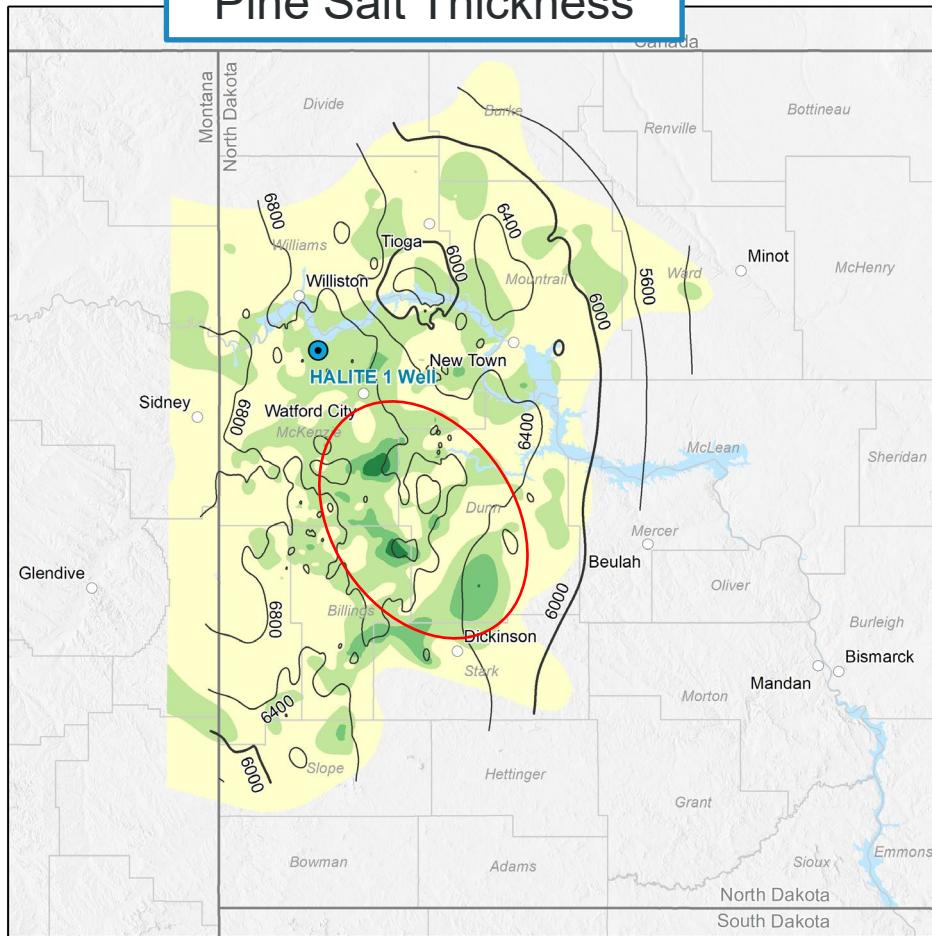
Alberta



Average Depth 5700 ft
Average Height 120 ft
Average Width 210 ft

ALTERNATE LOCATION SCREENING: DUNHAM

Pine Salt Thickness



Dunham Salt Isopach, feet

- 0-50
- 50-100
- 100-150
- 150-200

● HALITE 1 Well

— Depth Contour (C.I. = 400 feet)

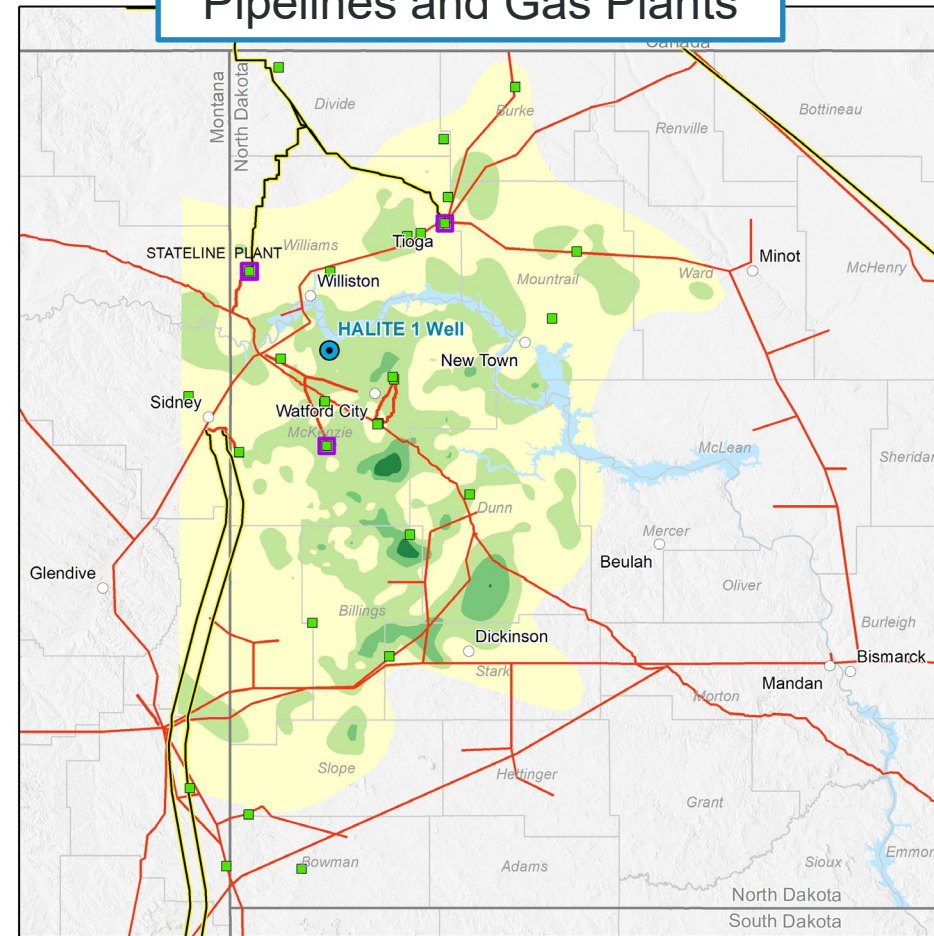


0 25 50 miles
0 25 50 kilometers



M0704

Pipelines and Gas Plants



Dunham Salt Isopach, feet

- 0-50
- 50-100
- 100-150
- 150-200

- Natural Gas-Processing Plant
- Ethane Fractionation
- Natural Gas Pipeline
- HGL Pipeline
- HALITE 1 Well



0 25 50 miles
0 25 50 kilometers



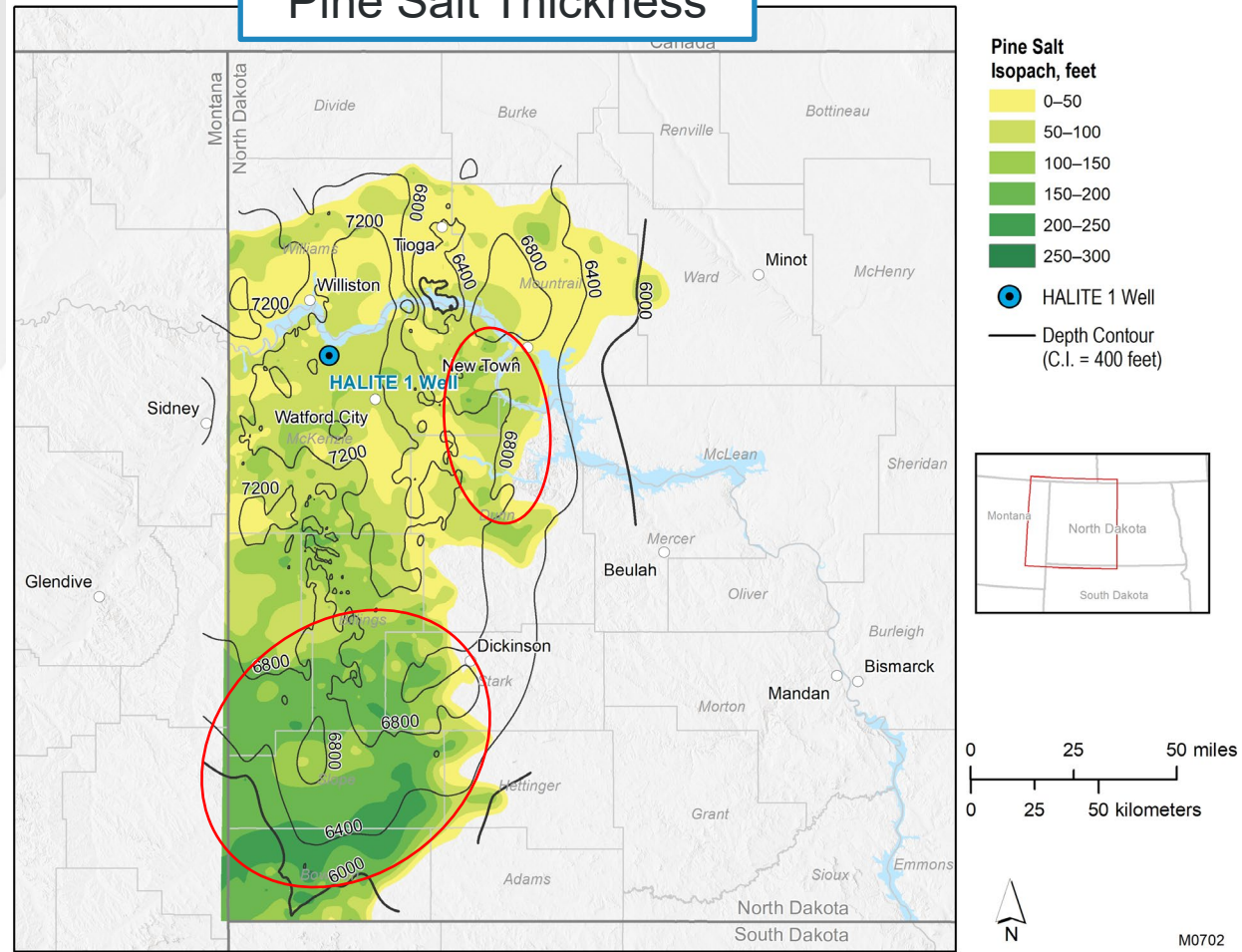
M0703



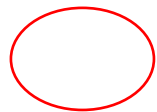
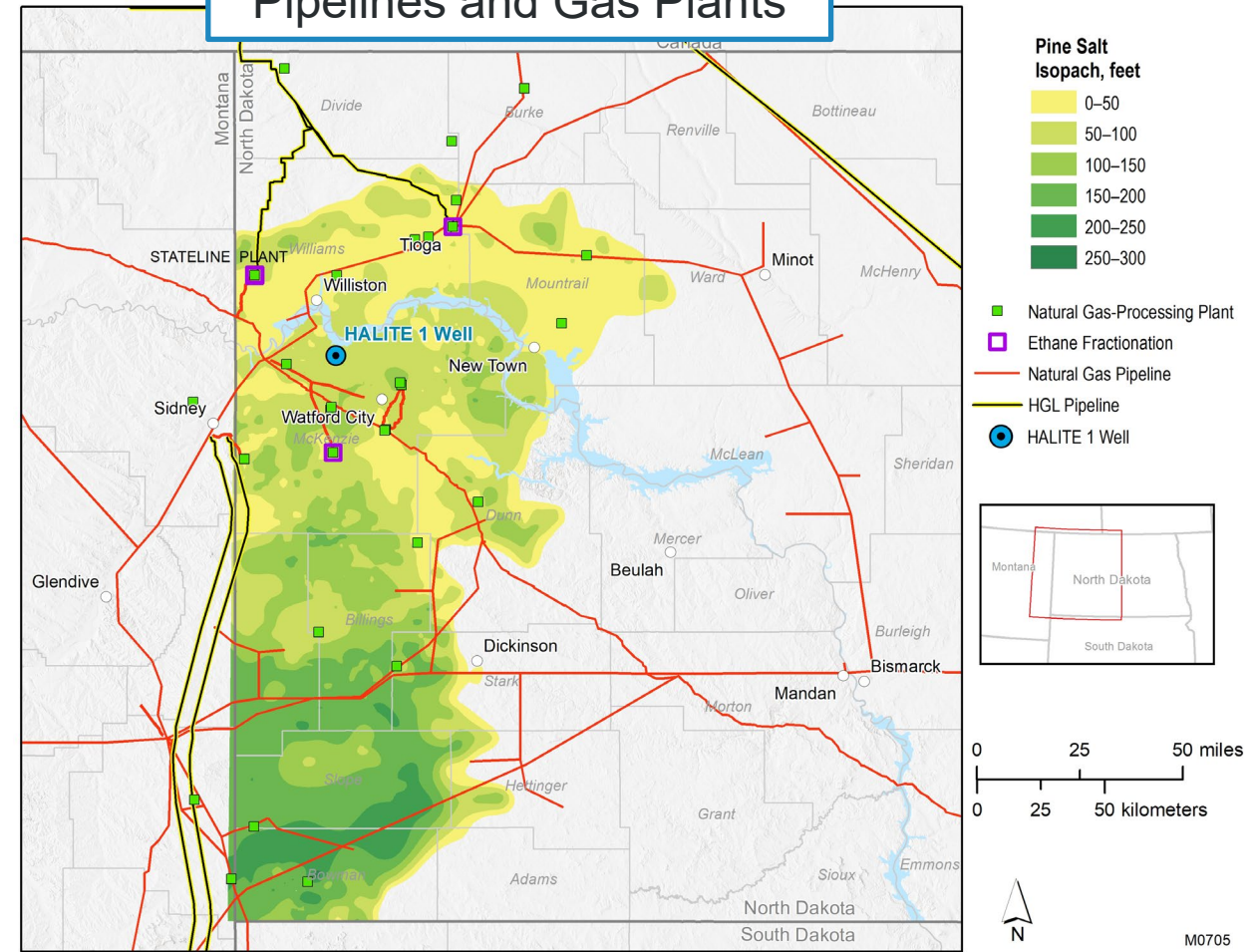
Additional screening will be focused within areas that have potential for thick salt members

ALTERNATE LOCATION SCREENING: PINE

Pine Salt Thickness



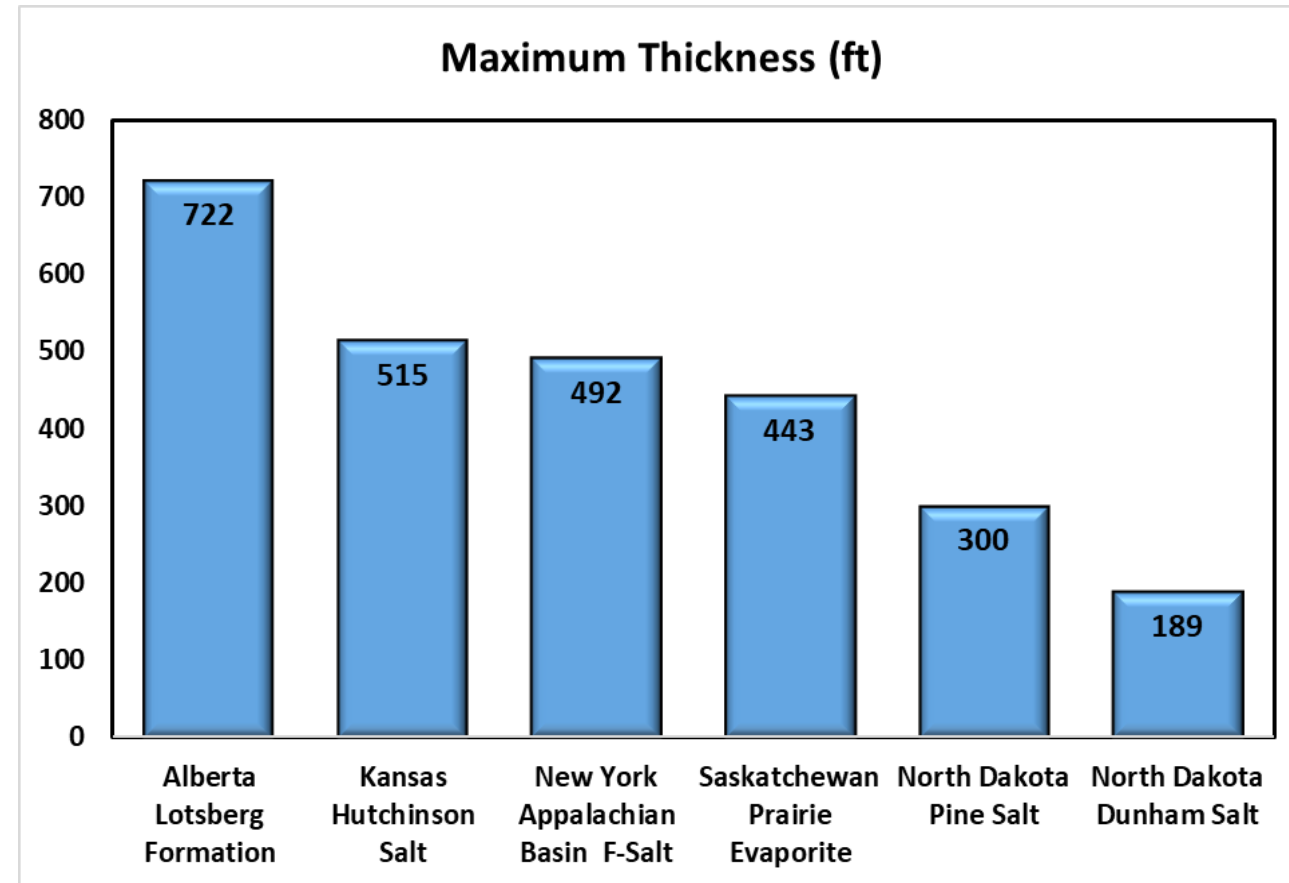
Pipelines and Gas Plants



Additional screening will be focused within areas that have potential for thick salt members

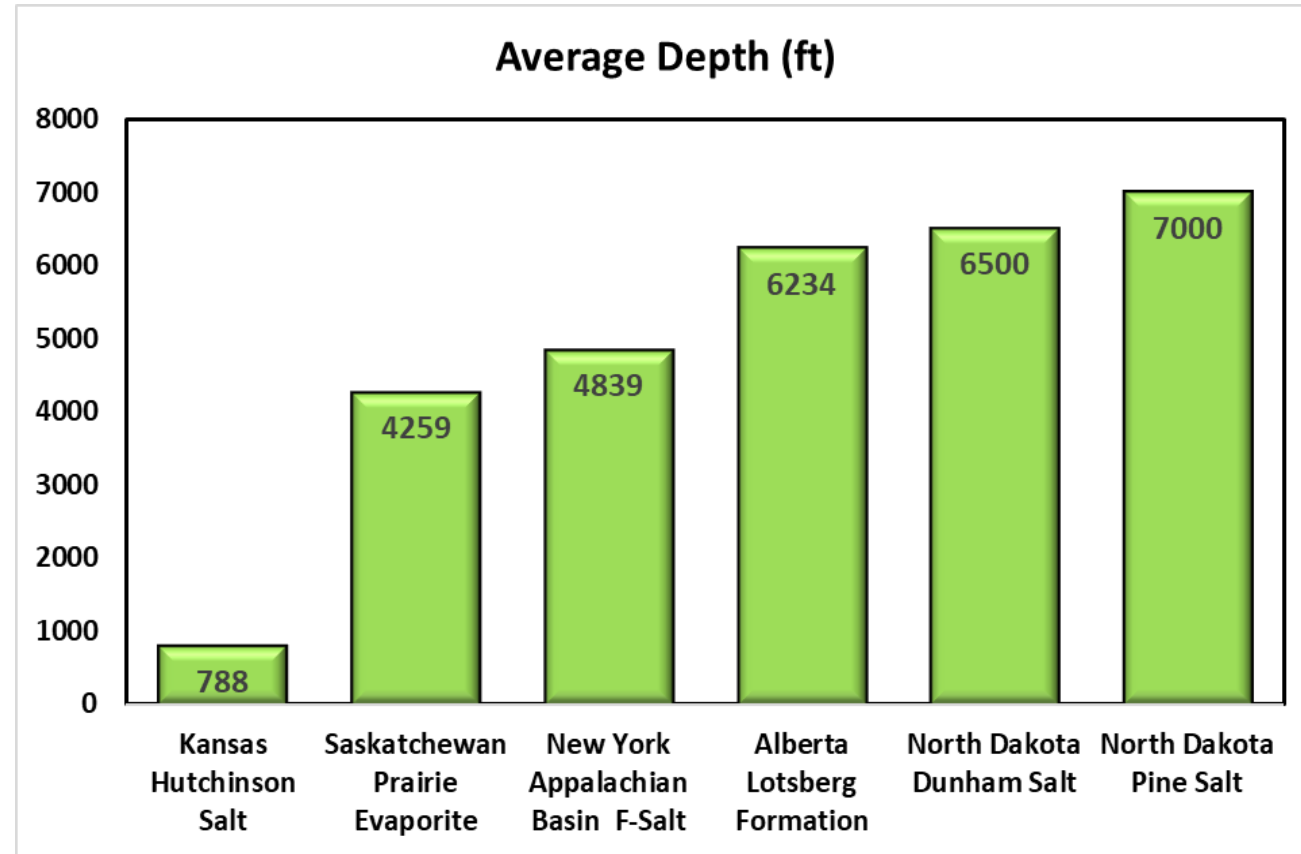
COMPARISON OF NORTH DAKOTA SALTS TO OTHER SALTS

- Compared to some of the major salts throughout North America, North Dakota salts show less thickness. However, Dunham and Pine Salts fulfill some of the critical factors for the development of engineered caverns:
 - Dunham salt is almost entirely halite.
 - Pine Salt consists mainly of halite and thenardite, both of which are soluble in water.
 - High-quality lithology is encouraging for ND salt cave development regardless of thickness.



COMPARISON OF NORTH DAKOTA SALTS TO OTHER SALTS

- The top depth of the Dunham and Pine salts in North Dakota is deeper than the other salts in this comparison:
 - The average depth of the Dunham and Pine Salt is comparable to the Alberta Lotsberg Formation.
 - Six natural gas storage caverns have been constructed within the Lotsberg Formation in Alberta (Research Report No. 2003-5-SMRI).
 - Rock salt in the Lotsberg Formation is mainly composed of coarse crystalline, clear halite, comparable to Dunham salt.





UND UNIVERSITY OF
NORTH DAKOTA

Steve Smith
Assistant Director, Integrated Analytical Solutions
ssmith@undeerc.org
701.777.5108 (phone)

**Energy & Environmental
Research Center**
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

www.undeerc.org
701.777.5000 (phone)
701.777.5181 (fax)

A wide-angle photograph of a university campus at sunset. The sun is low on the horizon, casting a warm glow over the scene. In the foreground, there are large trees with some yellowing leaves. In the background, several multi-story brick buildings and a parking lot filled with cars are visible under a clear sky.

THANK YOU

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