Advanced Storage Concepts Workshop:

Advanced Design Criteria for Salt Caverns

RESPEC

Lined Rock Cavern Storage

Sofregaz U.S., Inc.

February 17, 2000

Sponsored by:

National Energy Technology Laboratory

U.S. Department of Energy
Office of Fossil Energy

Overview of Department of Energy's Gas Storage Program

National Energy Technology Laboratory
Gas Storage and Deliverability Team

- **Fossil Energy has supported a modest $1 million per year program in Gas Storage since 1993.**
  - HQ Program Manager - Christopher Freitas
  - NETL Product Manager - Brad Tomer
  - Implementing Team Members
    - Gary Sames
    - James Ammer
    - Thomas Mroz

Gas Storage

- **The Federal Role:**
  - Gas storage is a vital component of the nation's critical infrastructure, and as such reliability and system performance is important to the health and safety of the American people.
  - Gas storage plays a critical role in the ability of the U.S. to increase use of natural gas as both an environmentally friendly fuel and as a key to greater energy independence.
  - Improved gas storage technologies are necessary to enable the advanced and distributed power systems of the future envisioned in other program areas.

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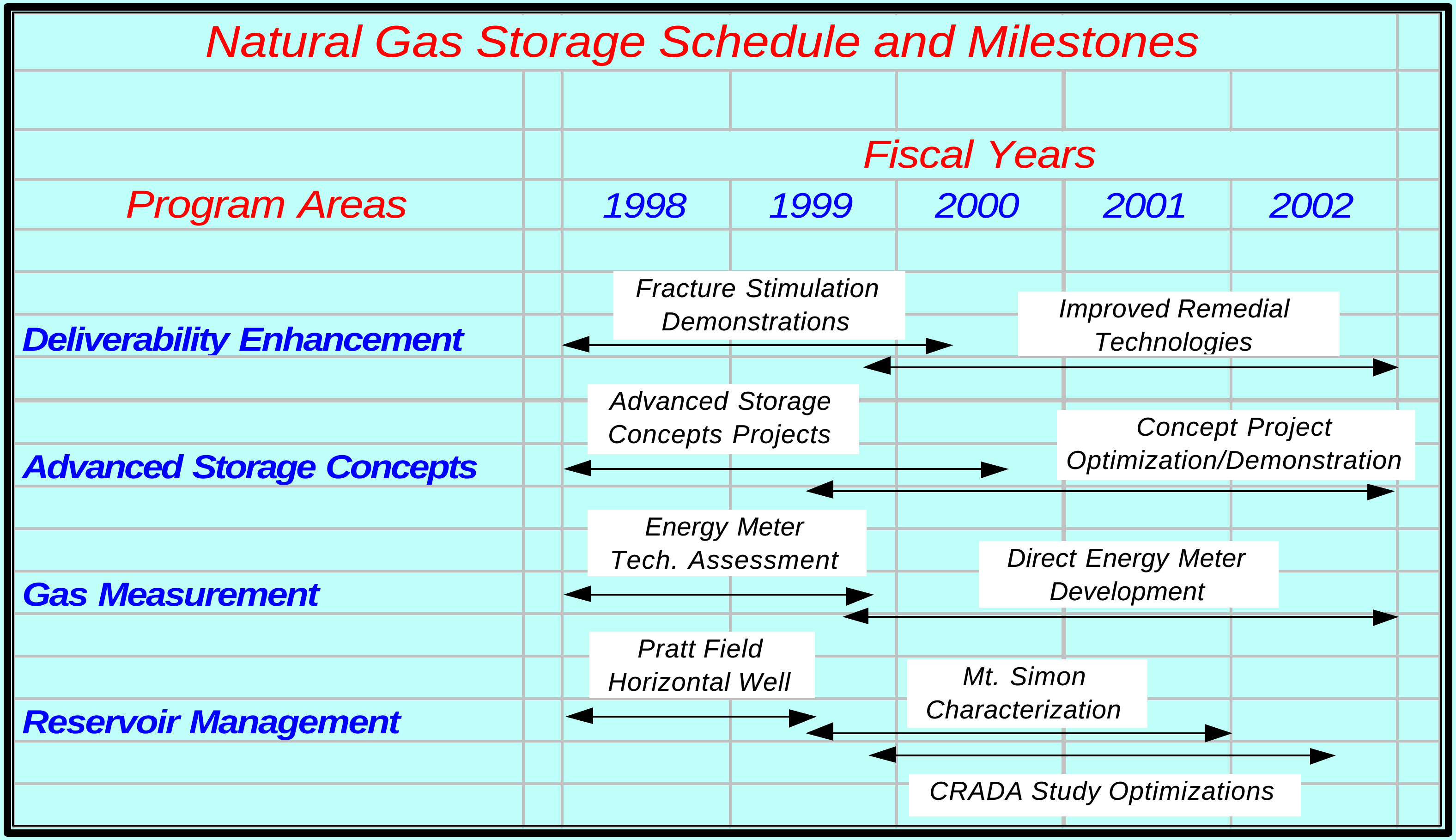
Gas Storage Program Purpose

- Promote the development of the advanced natural gas storage technologies necessary to improve storage and delivery of natural gas.
- Increase confidence in the long term availability, reliability, and safety of the natural gas system.

4 Focus Areas in
Gas Storage and Deliverability

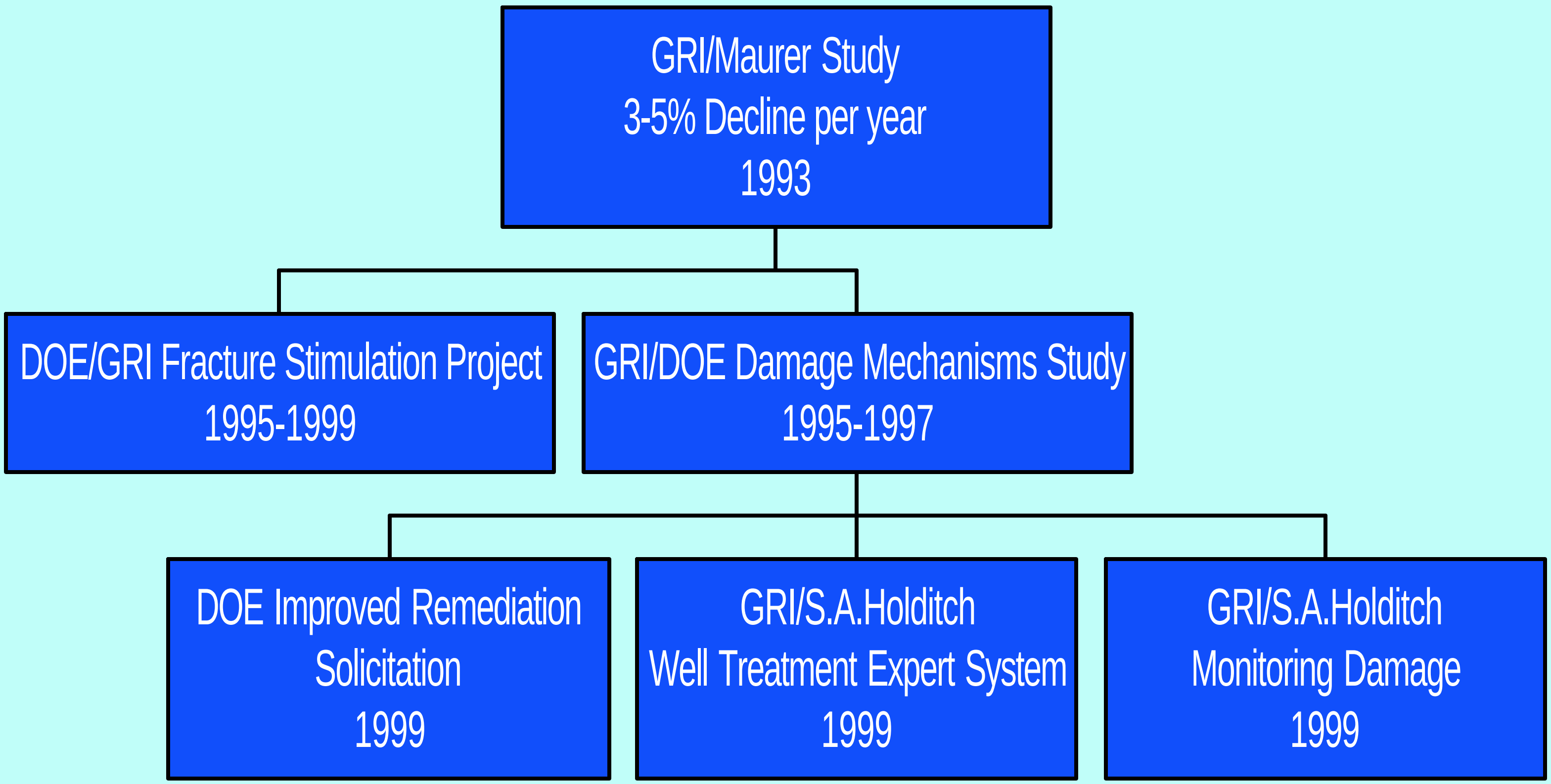
- **Deliverability Enhancement**
- **Gas Measurement**
- **Reservoir Management**
- **Advanced Storage Concepts**


Natural Gas Storage Schedule and Milestones
Fiscal Years
Program Areas
1998
1999
2000
2001
2002
Deliverability Enhancement
Fracture Stimulation Demonstrations
Improved Remedial Technologies
Advanced Storage Concepts
Advanced Storage Concepts Projects
Concept Project Optimization/Demonstration
Gas Measurement
Energy Meter Tech. Assessment
Direct Energy Meter Development
Reservoir Management
Pratt Field Horizontal Well
Mt. Simon Characterization
CRADA Study Optimizations

Deliverability Enhancement

- Conduct RD&D efforts to provide cost-effective means to both maintain and increase the deliverability of the natural gas storage system.

Deliverability Enhancement Timeline



New and Novel Fracture Stimulation Project

Advanced Resources International

- **GOAL: Demonstrate New and Novel Fracture Stimulation Technologies for Restoring Lost Deliverability in Gas Storage Wells**

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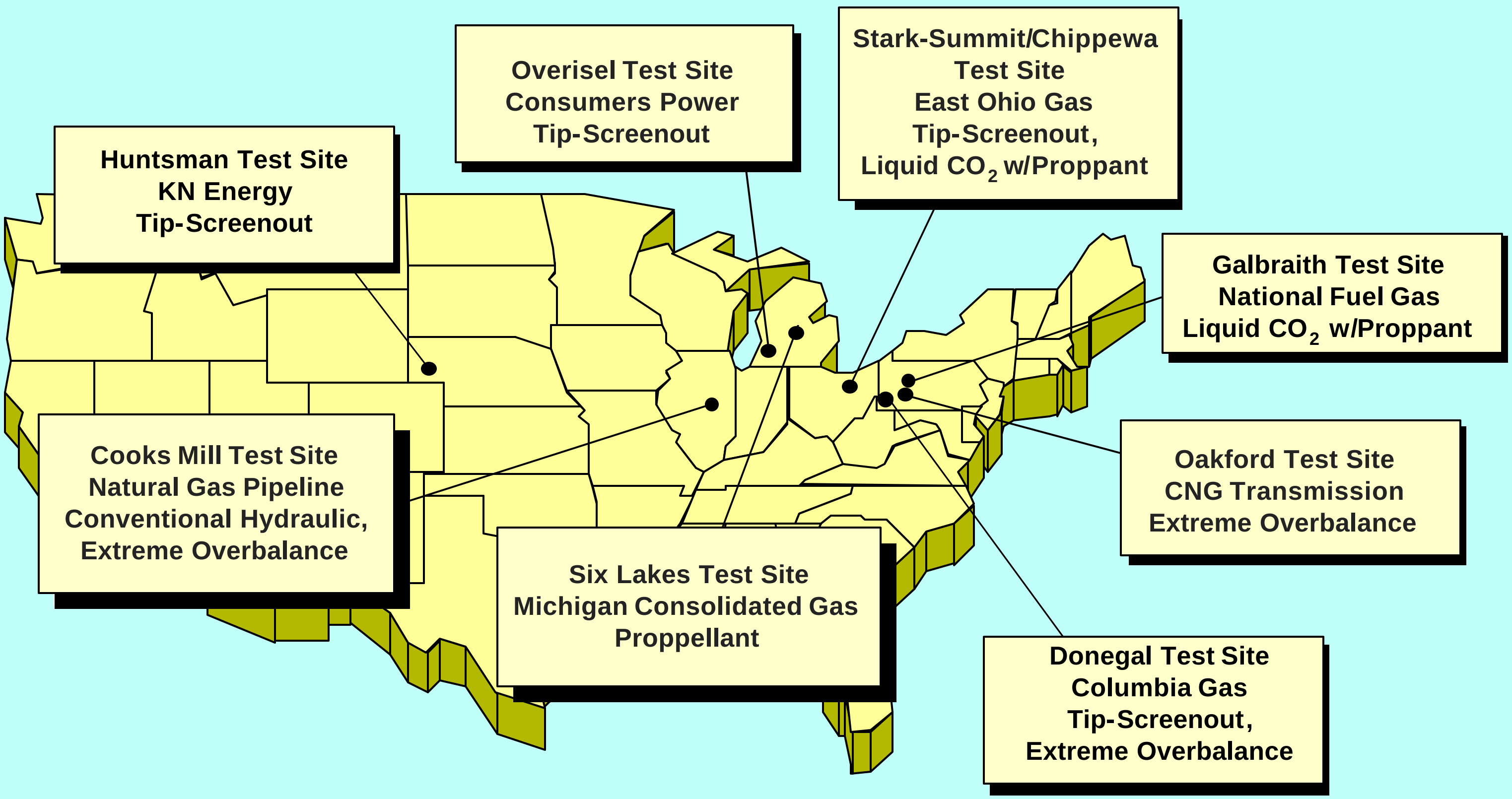
Accomplishments

- **31 Fracture Stimulation Treatments**
- **4 Stimulation Types**
  - Liquid CO_2 Sand
  - Tip-Screenout
  - Extreme Overbalanced (EOB)
  - Propellant
- **8 Storage Fields**
- **5 States**

LOCATION OF TEST SITES



Accomplishments

- **First Liquid CO_2 Sand Fracs in Storage Wells**
- **First Downhole Treatment Records in Storage**
  - Liquid CO_2 Sand
  - EOB
  - Propellant
- **Side-by-Side Comparison of Aqueous and Non-Aqueous Fracturing Fluids**
- **Enhancements to Simulator for Design and Execution of EOB Fracturing**

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Accomplishments

- **Major Diagnositics Collected**
  - Over 110 Modified Isochronal Multi-Point Pressure Transient Tests (Pre, Post, and 1-year Anniversary)
  - Over 50 Other Diagnostics
    - Downhole Camera
    - Tracer Surveys
    - Mini-fracs
    - Bottomhole Treating Records
    - Temperature and Acoustic Logs
    - Step Rate Tests

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Major Findings

- **Fracturing Technologies can Provide Attractive Deliverability Enhancement but are not a Cure-All**
- **Gas Storage Formations are Highly Sensitive to Any Amount of Aqueous Liquids**
  - Results of Liquid CO2 Sand Fracs indicate that this technology provides immediate benefits

Major Findings

- **Several Technology/Methodology Advances are Needed:**
  - Additional downhole data, modeling improvements for design and analysis, and overall understanding of:
    - Liquid CO2 Sand
    - EOB
    - Propellant
  - Candidate selection
  - Economic evaluation of treatment success vs. other alternatives, especially long term

Improved Natural Gas Storage Well Remediation

- **Support research to develop effective, economic remediation technologies for damage mechanisms identified in previous DOE/GRI study as prevalent causes of shallow wellbore damage:**
  - 1) Inorganic precipitates (gypsum, carbonates, etc)
  - 2) Hydrocarbons, organic residues, production chemicals
  - 3) Bacterial fouling and plugging
  - 4) Particulate fouling and plugging
- **Demonstrate the improved remedial technologies tailored for these specific damage mechanisms in the field**

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Improved Remedial Design Projects

- **Objective:** Demonstrate improved remedial technologies tailored for specific damage mechanisms
- **Key Features:**
  - Phase 1: Characterization of geochemical environment(s) and damage mechanism(s); laboratory validation of mitigation strategies
  - Phase 2: Field verification of proposed techniques

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Treatment of Storage Well HOPS Damage through Application of CO_2

Advanced Resources International

- **Summary:**
  - Addresses damage caused by Hydrocarbons, Organic Residues, and Production Chemicals (HOPs)
  - Will treat HOPs using CO_2 as the primary treatment fluid
- **Key Technical Partners:**
  - Stim-Lab

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Damage Characterization and Removal in Gas Storage Reservoirs

Holditch-Reservoir Technologies

- **Summary:**
  - Addresses damage caused by Hydrocarbons, Organic Residues, and Inorganic Precipitates
  - Innovative laboratory characterization effort and strong field testing plan
  - Presents synergy opportunity with GRI work
- **Key Technical Partner:**
  - Penn State

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Sonication Tool Development for Treating Storage Well Damage

Furness-Newburge, Inc

- **Summary:**
  - Develop integrated sonication remediation tool to both identify and treat storage well damage (including inorganic precipitates, particulate fouling, organic residues)
- **Key Technical Partners:**
  - Argonne National Lab, Nicor Technologies, Inc.

Gas Measurement

Goals:

- Conduct RD&D efforts to provide improved accuracy and real-time measurement of both gas volume and energy content at gas storage facilities.

Ultrasonic Meter Testing and Evaluation for Gas Storage Application

Southwest Research Institute - Phase I

- **Ultrasonic Meters Can Provide the Required Accuracy for Gas Storage Facilities**
  - Extremely accurate at high flow rates
  - Accurate in both flow directions
    - Effect of thermowell upstream is very small
  - Basically insensitive to changes in temperatures
  - Higher measurement error at low flow rate is offset by the small overall volume at these rates

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Ultrasonic Meter Testing and Evaluation for Improved Accuracy

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M98001157C

A Technology Assessment and Feasibility Evaluation of Natural Gas Energy Flow Measurement Alternatives

Southwest Research Institute - Phase II

Phase II Results

- **A Gross Inferential Approach to Energy Measurement was Identified**
- **Feasibility was Demonstrated**
- **Potential to Upgrade Any Flow Meter to Energy Measurement**
  - Order-of-magnitude lower cost than traditional composition assay

Development of a Low Cost Inferential Natural Gas Energy Flow Rate Prototype Retrofit Module

Phase III - Initiated June 1999

Southwest Research Institute

Co-funded by Gas Research Institute

Reservoir Management

Goals:

- **Conduct RD&D efforts to increase the efficiency of storage operations through industry and FETC partnerships (CRADAs).**

Modeling Studies

- **Objective: Demonstrate the importance of geologic modeling and reservoir simulation for optimizing the development and operation of gas storage fields**
- **Main Focus: Horizontal Wells**
- **Cooperative Research and Development Agreements (CRADAs) Have Been the Mechanism**
  - National Fuel Gas Supply Corporation
  - Equitrans, Inc.
  - Northern Indiana Public Service Company

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Results

- **National Fuel**
  - Horizontal wells would provide better efficiency and cost savings (SPE 31002)
- **Equitrans**
  - Remediation of well damage and horizontal wells would help provide a 10-day or 30-day peaking service (DOE Natural Gas Conference Proceedings)
  - Horizontal well drilled July 1999
- **NIPSCO**
  - Still under investigation

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Advanced Storage Concepts

- The Advanced Storage Concepts Program is DOE's first attempt to address storage issues that can limit the future growth of natural gas use in residential service, as an industrial fuel, and in electric power generation in many important regions of the U.S.

Advanced Storage Concepts

Goals:

- Build the peaking and base load balancing capacity that is necessary to enable natural gas to provide reliable service in a future where gas use is predicted to increase by 5 Tcf by 2010.
- Provide storage alternatives for the many important regions of the U.S. where natural gas has the greatest growth potential, but that lack conventional storage geology.

Summary of 2010 Peaking and Market Area Gas Storage Requirements of Selected Regions of the US (1994)

Region	Peaking/Market Area Storage Needs (MMCF/day)
New England	269
Mid Atlantic (NY/NJ)	1,352
South Atlantic (DL/MD/VA)	450
South Atlantic (NC/SC/GA)	1,190
Pacific Northwest (WA/OR)	401

Source: GRI Topical Report ♦ Future Seasonal Natural Gas Loads and Gas Delivery Capacity Requirements in the Lower 48 United States (1/94)

Advanced Storage Concepts

Projects:

Refrigerated-Mined Cavern Storage

Lined Rock Cavern Storage

Gas Storage as Hydrates

Advanced Design Criteria for Salt

Chilled Gas Storage in Bedded Salt Caverns

Gas Storage in Basalt

Refrigerated-Mined Cavern Storage

Project Partners

- PB-KBB -- Prime Contractor, Facility Design
- Merimack Energy -- Market Analysis
- Frontier-Kemper -- Mining Contractor, Construct-Ability and Cost Estimating
- RESPEC -- Rock Mechanics and Mine Thermodynamics
- Department of Energy -- Program Management

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Project Overview

- DOE solicitation identified five areas that do not have favorable geological conditions of storage such as salt, depleted gas fields, and aquifers
- The areas were New England, Mid-Atlantic (NY/NJ), South Atlantic (DL/MD/VA) South East Atlantic (NC/SC/GA), and the Pacific Northwest (WA/OR)
- Of the five, one was selected for the conceptual design based on pipelines interconnects and future market growth
- The area selected was Howard and Montgomery Counties, Maryland, near both Baltimore and Washington, D.C.

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Project Overview - cont.

- Provide storage that is competitive with alternative available high deliverable storage methods
- Available alternatives considered are salt cavern storage and LNG
- Provide natural gas storage with multiple cycles per year
- Provide high deliverability

1994 EIA Baseline Projection

	New Peaking/Market Area Storage Needs, 2010 (1) (MMCFD)	New Annual Delivery Capacity Needs, 2010 (MMCFD)	Planned or Completed Pipeline & Expansion Projects, 1994-1997 (2) (MMCFD)	Net Requirement (MMCFD)
New England (ME/VT/NH/MA/CT/RI)	269	1,130	978	421
Mid Atlantic (NY/NJ)	1,412	1,158	2,650	(80)
South Atlantic (DL/MD/VA)	450	803	272	981
South Atlantic (NC/SC/GA)	1,190	688	11,197	681
Pacific Northwest (WA/OR/ID)	401	366	695	73

Note: (1) Assumed "high bound" on peak shaving
(2) DOE/EIA Natural Gas 1996 Issues and Trends (December, 1995) and in-house data.

Refrigerated-Mined Cavern Storage

- **Hard Rock**
- **Cavern Volume: 50 Million Cu Ft**
  - 80 ft by 80 ft rooms
  - 7 tunnels of 1,000 ft length
- **Pressure: 1,250 psi**
- **Temperature: -20 ºF**
- **Depth: 3,000 ft**
- **Working Gas: 5 Bcf**
- **20 Day Injection, 20 Day Withdrawal**

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Representative Unit Capital Costs for New Gas Storage and LNG Projects

Type of Project	Location	Project Name	Working Gas Capacity (BCF)	Total Cost ($MM)	Unit Cost ($/MCF)	Notes
Depleted Field	California	Putah Sink	15.000	40.000	2.67	(1)
Depleted Field	Colorado	Douglas Creek	10.000	30.000	3.00	(1)
Depleted Field	Utah	Clay Basin Expansion	15.200	49.600	3.26	(1)
Depleted Field	Oklahoma	Manchester	15.000	30.000	2.00	(1)
				Average>>	2.73	
Aquifer	Indiana	Carbon-Calcutta	3.900	12.275	3.15	(1)
Aquifer	Illinois	Hillsborough Expansion	4.500	36.600	8.13	(1)
				Average>>	5.64	
Salt Cavern	Alabama	S. Alabama-McIntosh	2.700	30.000	11.11	(1)
Salt Cavern	Mississippi	Hattiesburg phase 1 & 1A	3.500	47.000	13.43	(2)
Salt Cavern	Louisiana	Napoleonville Phase 1	4.600	45.000	9.78	(1)
				Average>>	11.44	
LNG	North Carolina	Pine Needle	4.000	107.000	26.75	(2)
LNG	Maine	Granite Slate	2.000	44.222	22.11	(2)
				Average>>	24.43	
Refrigerated mined Cavern		Mid-Atlantic	5.000	178.000	35.60	

Notes: (1) EIA/The Value of Underground Storage in Today's Natural Gas Industry.
(2) Brant Energy Data.

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SUMMARY OF UNIT COST FOR VARIOUS STORAGE METHODS

Depleted Field	California	$2.67/mcf
Depleted Field	California	3.00
Depleted Field	Utah	3.26
Depleted Field	Oklahoma	2.00
Aquifer	Indiana	3.15
Aquifer	Illinois	8.13
Salt Cavern	Alabama	11.11
Salt Cavern	Miss.	13.43
Salt Cavern	Napoleonville, La	9.78
LNG	North Carolina	22.11
LNG	Maine	24.43
Chilled Gas	Many Places	35.90

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Refrigerated-Mined Cavern Storage Status

- **Workshops**
  - November 3, 1998: Houston
  - November 5, 1998: Pittsburgh
- **Final Report Available on CD-ROM**
- **Cost Comparison Showed that RMC can Provide Similar Cost of Service to LNG for Single Cycle and Better Cost of Service for Multiple Cycles**

Gas Storage as Hydrates

Mississippi State University

- **Determine the Technical and Economical Feasibility of Storing Natural Gas as Hydrates**
- **Improve Rate of Formation**
- **Improve Rate of Decomposition**
- **Investigate Storage stability**
- **Conceptual Design and Costs**

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Gas Storage as Hydrates Status

- **Phase I Feasibility Completed May 1999**
- **Phase II Conceptual Design Completed December 1999**

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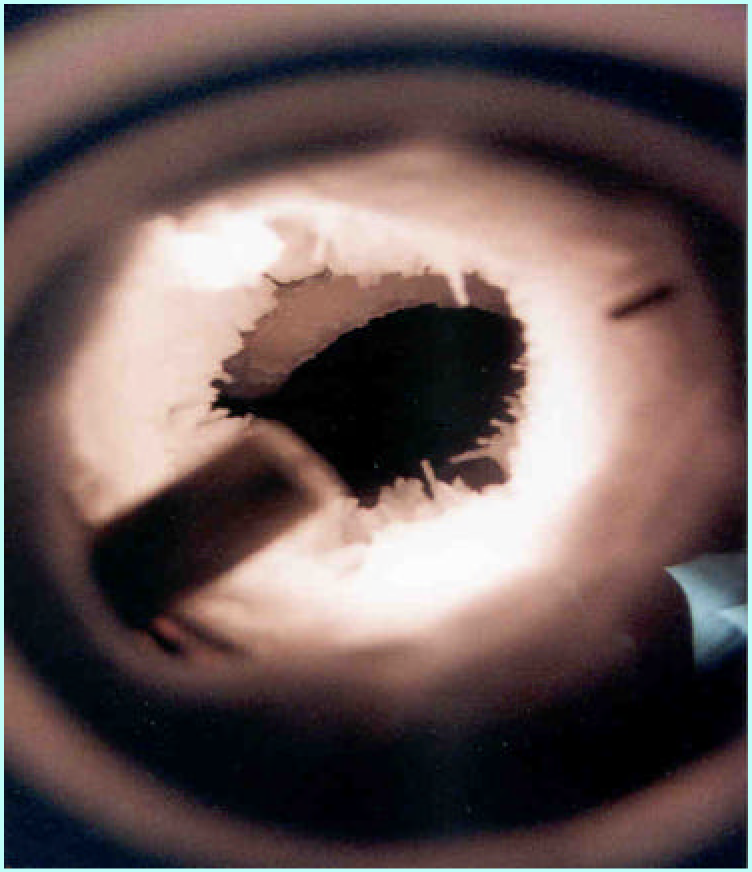
Hydrate Storage Process

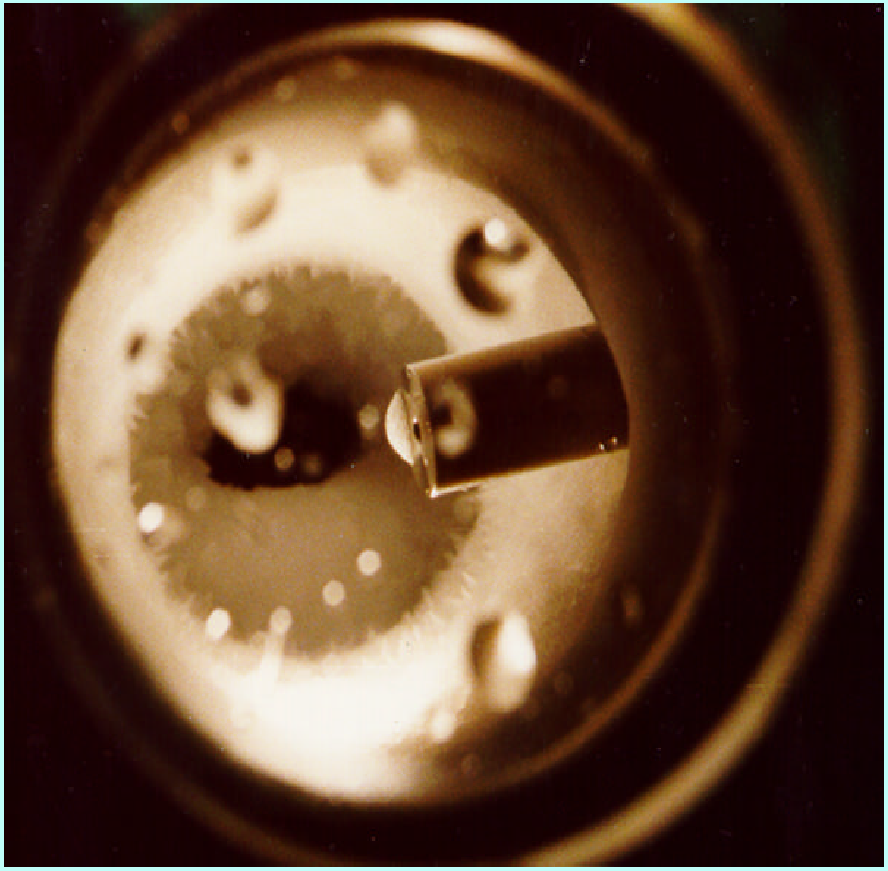


Hydrates adsorb on walls of test cell:

- Quiescent water and natural gas system
- 286 ppm surfactant increases hydrate formation rate 700x

550 psi, 37°F

Hydrate Storage Process



High rate of hydrate formation continues as interstitial water converts to hydrates.

Hydrate particles pack symmetrically on walls with high gas density.

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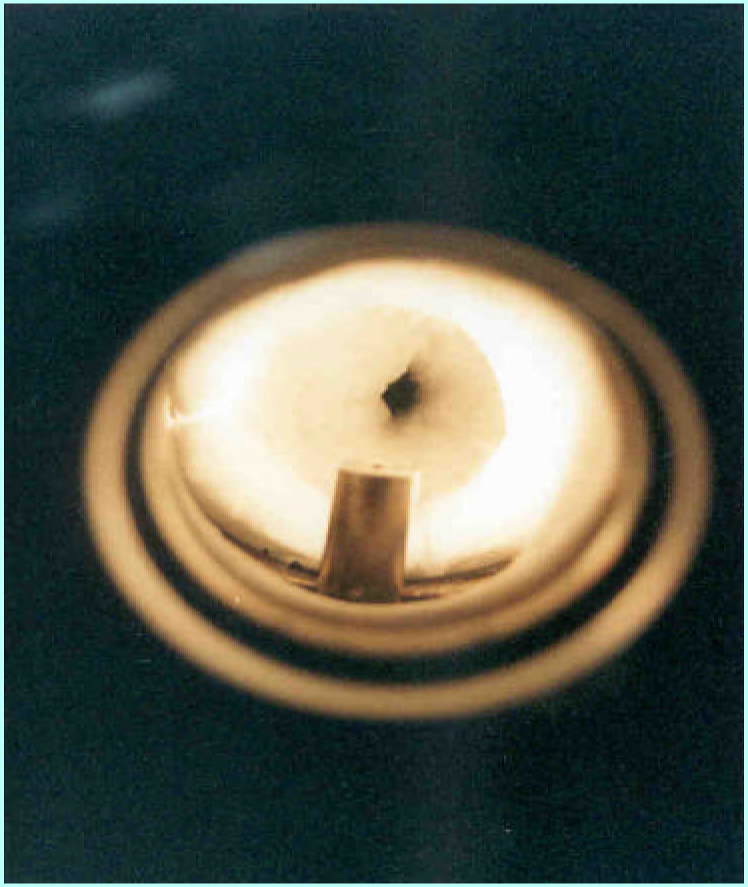
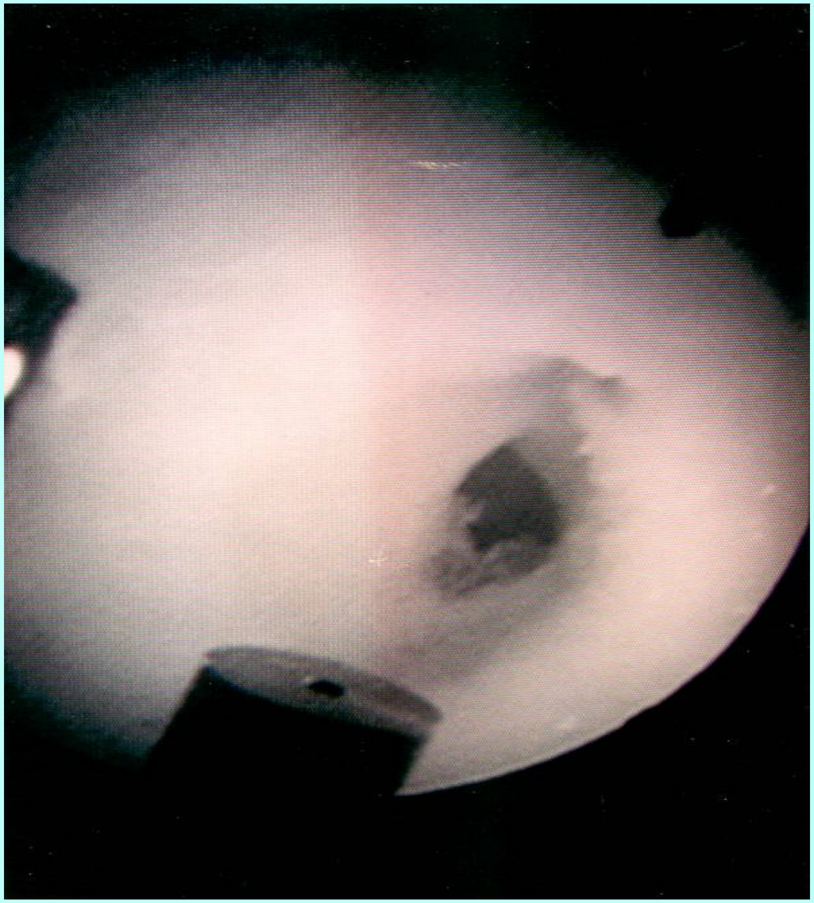
Hydrate Storage Process



Hydrates continue to build concentrically on test cell wall as water level drops and gas is added to solid structure of hydrates.

(Black area of center = bottom of test cell.)

Hydrate Storage Process

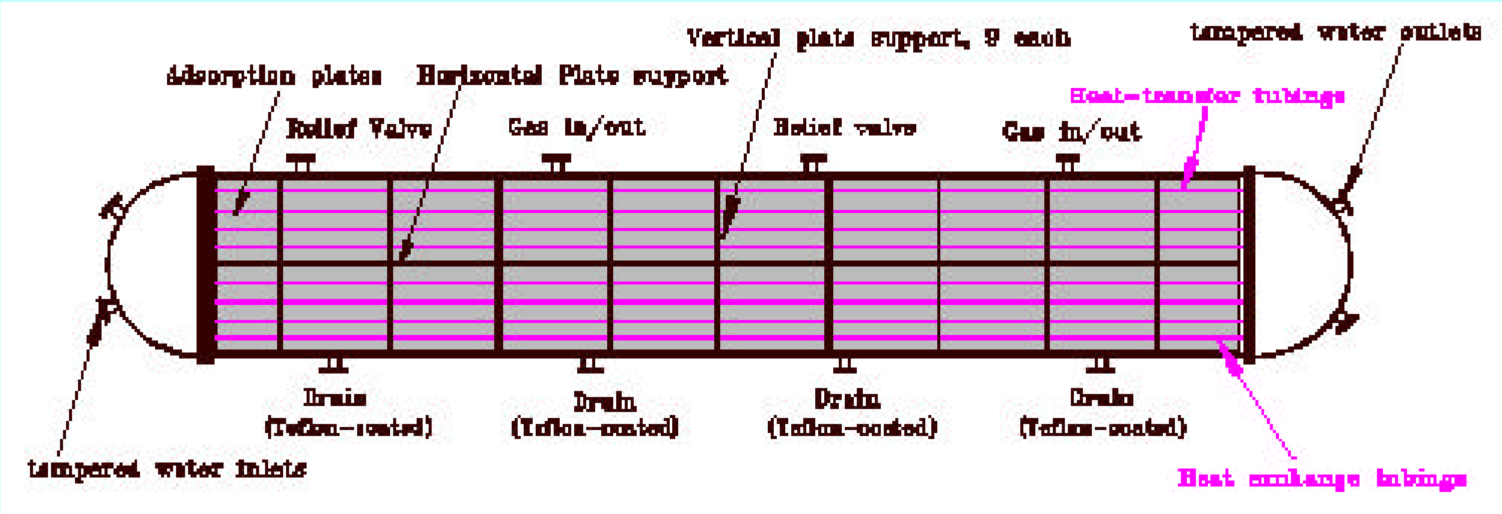


Test cell nears capacity.

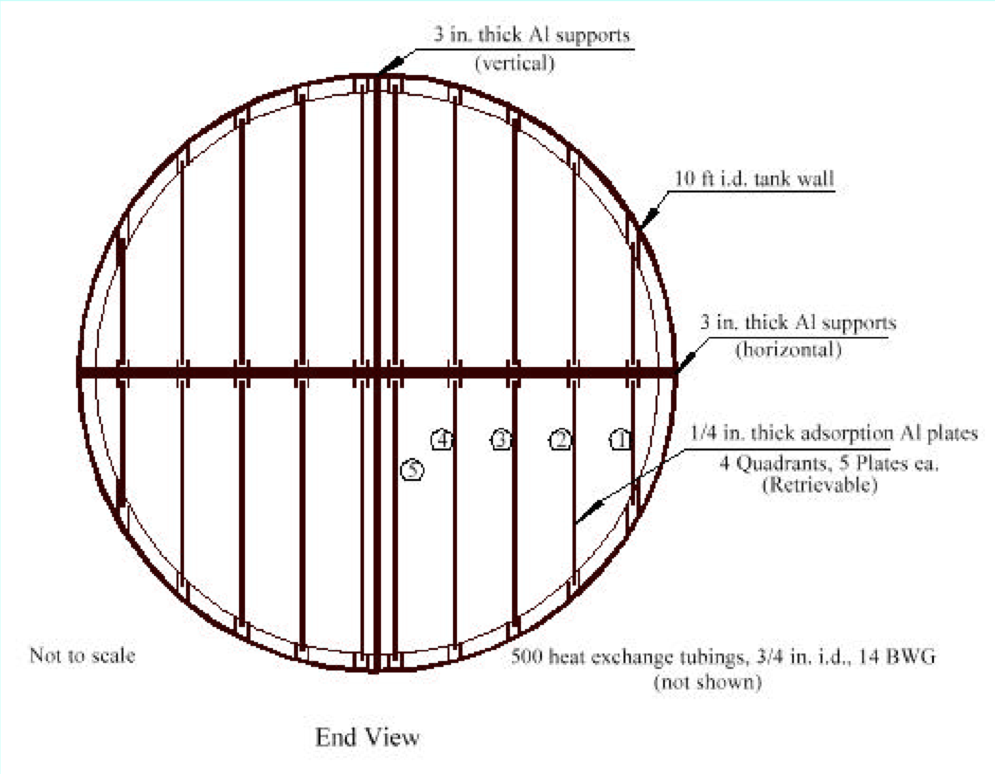
Note: Symmetry maintained such that cell bottom still visible.

156 vol gas (STP)/vol hydrate stored and packed at 550 psig and 37°F in <3 hours, no mechanical stirring; 86% of theoretical capacity.

System Design



System Design - cont.



Capital Investment for 2.25 Mmcf Storage Facility

Item	Factor	Cost
Direct Costs		
Purchased equipment, delivered	1	$2,202,189
Equipment installed	0.39	$858,854
Instrument., controls installed	0.13	$286,285
Piping installed	0.31	$682,679
Electrical installed	0.1	$220,219
Buildings	0.29	$638,635
Yard Improvements	0.1	$220,219
Total Direct Plant Cost		**$5,109,079**
Indirect Costs		
Engineering and supervision	0.1	$220,219
Construction expenses	0.17	$374,372
Total Direct and Indirect Costs		**$5,703,670**
Contractor's fee	0.18	$396,394
Contingency	0.36	$792,788
Fixed Capital Investments		$6,892,852

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Operating Costs for Hydrate Storage

ITEM	DETERMINED BY	COST	BASIS
Raw Matls	Calculate	$181	per cycle
Operating Labor	Calculate	$257,400	per year
Utilities	Calculate	$1,888	per cycle
Supervisory Labor	15% Operating Labor	$38,610	per year
Maintenance and Repair	6% Fixed Capital Investment	$20,679	per year
Operating Supplies	15% Maintenance and Repairs	$3,102	per year
Laboratory Charges	15% Operating Labor	$38,610	per year
Depreciation	Calculate	$110,109	per year
Property Taxes	4% Fixed Capital Investment	$27,571	per year
Insurance	1% Fixed Capital Investment	$3,446	per year
Plant Overhead	70% Operating Labor+Supervision+Maintenance	$221,682	per year
Administrative	25% Operating Labor	$64,350	per year
Contingency	1% Total Product Cost	$7,876	per year

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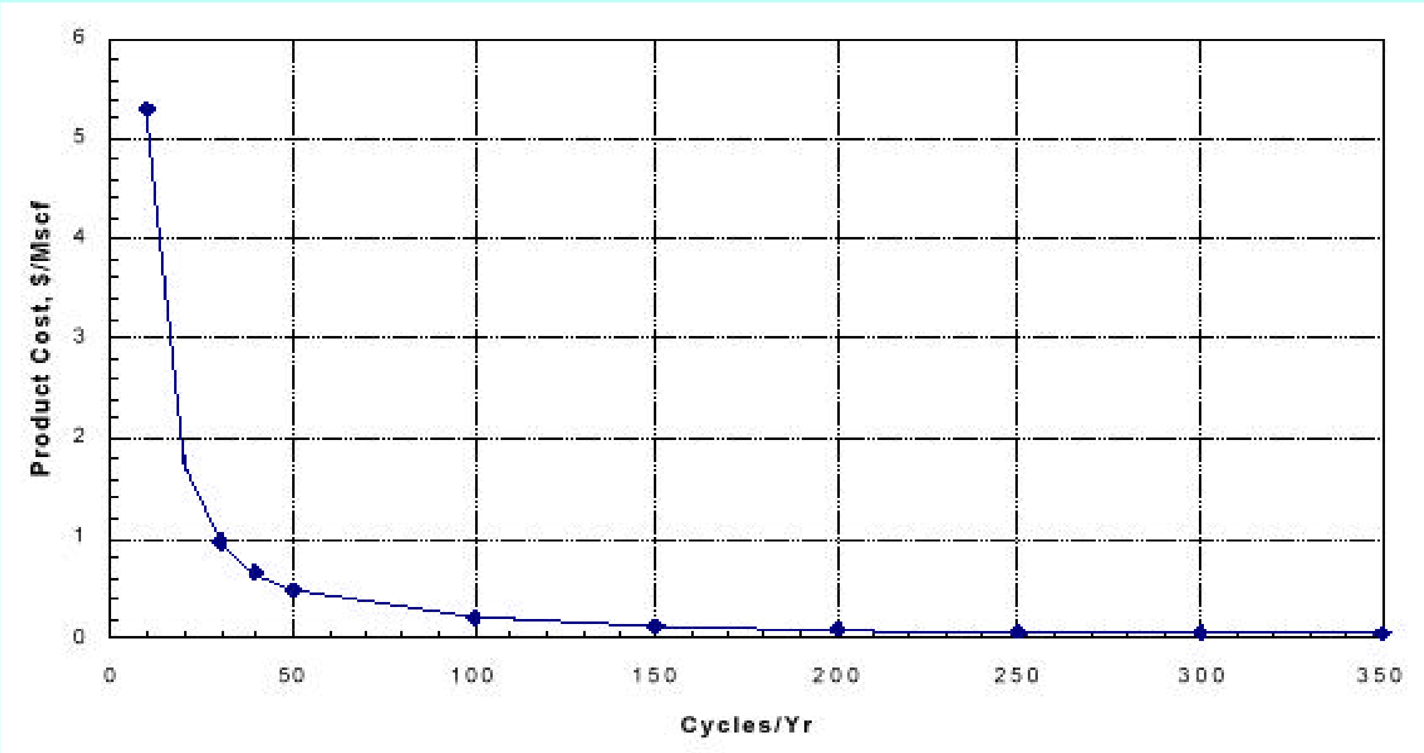
Operating Costs per Mcf per Number of Cycles



Gas Storage in Basalt

- **Industry Partner - Pacific Gas Transmission**
- **Performing Partner - Pacific Northwest National Laboratory**
- **Hydrogeologic characterization of Columbia River Basalt aquifers for natural gas storage**

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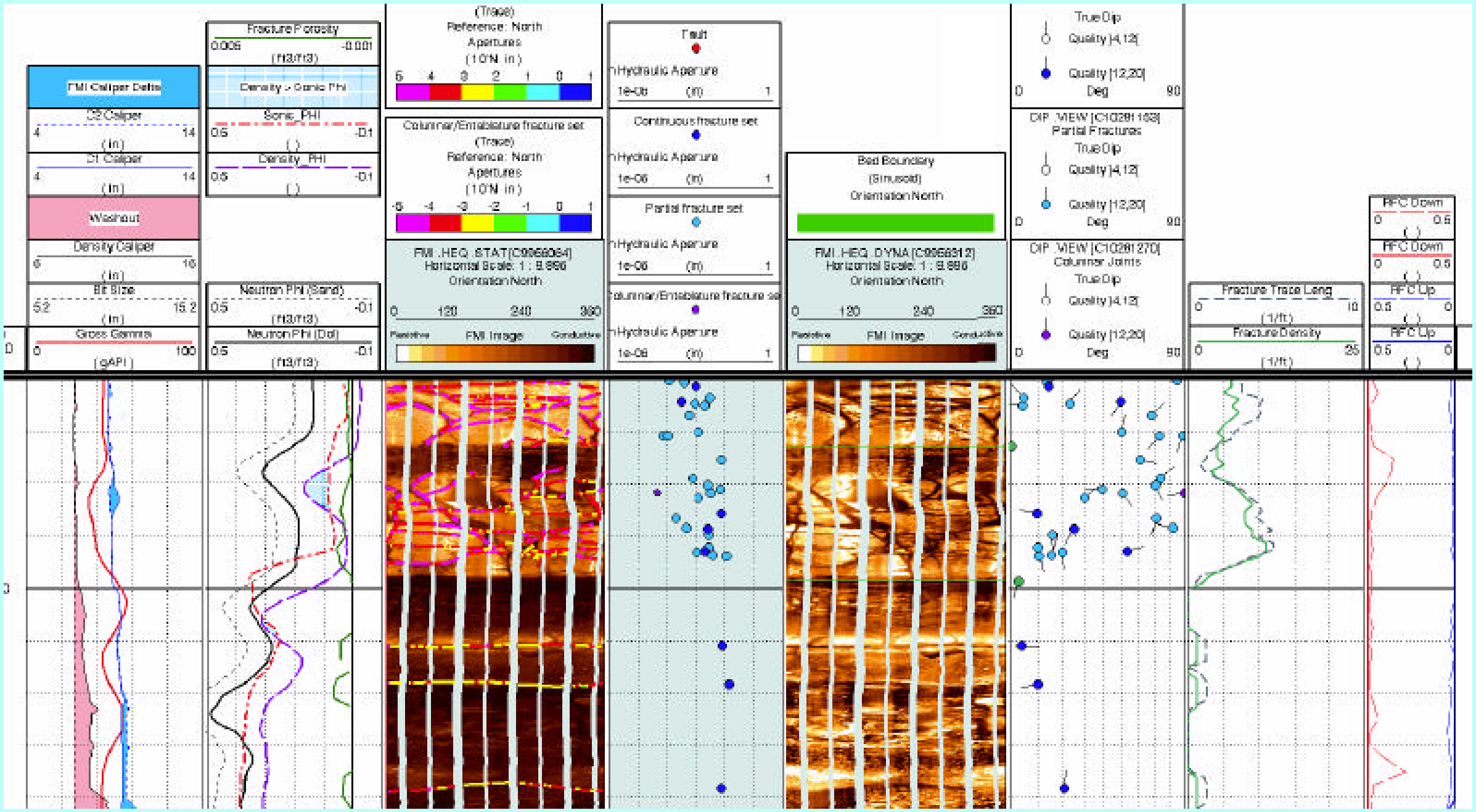
Basalt Plans

- Hydrogeologic characterization through cross hole pump tests
- "How To" report for evaluating the feasibility of storing natural gas in Columbia River basalts.
- Report will have universal application in other basaltic volcanic enviromnments

Basalt Study



Chilled Gas Storage in Bedded Salt Caverns

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- **Objective: Evaluate the feasibility of storing chilled gas in bedded salt deposits**
  - Bedded salt is of interest because of brine disposal limitations
  - It may be possible to dramatically increase working gas capacity of a given storage volume in planned or existing bedded salt caverns

Project Work Plan - Phase I

- **Laboratory evaluation of low-temperature thermal properties of salt**
  - Thermal conductivity to predict temperature distribution, thermally induced stress, and cooling load requirements in salt caverns.
- **Evaluate cooling load requirements to maintain a design temperature**
  - Finite element modeling of injection-withdrawal scenarios for cooling equipment requirements
- **Preliminary Design and Cost Analysis**
  - Capital and Operating costs in dollars per unit increase in working gas capacity

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Project Work Plan - Phase II

- **Laboratory determination of low-temperature mechanical properties of salt**
  - Effects of reducing ambient conditions on strength and creep properties
- **Thermomechanical analysis of salt stability in chilled bedded salt caverns**
  - Finite element simulations of temperature and stress distributions at -20^{o}F design temperature
  - Assess potential for tensile fracturing and strength reduction through intergranular microfracturing

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Questions?