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**Cost-Effective Remediation  
Strategies for Storing CO<sub>2</sub>  
in Geologic Formations**

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# Abstract

Because storage of CO<sub>2</sub> is still an emerging industry, little has been written on the topic of cost-effective remediation strategies for geological storage of CO<sub>2</sub>. The purpose of this presentation and paper is to begin to fill this gap in publically available technical information.

The paper compiles experience from the gas storage and the CO<sub>2</sub> enhanced oil recovery industries and adds an overlay of the unique facets of geological storage for establishing a remediation strategy for CO<sub>2</sub> storage, particularly in saline formations.

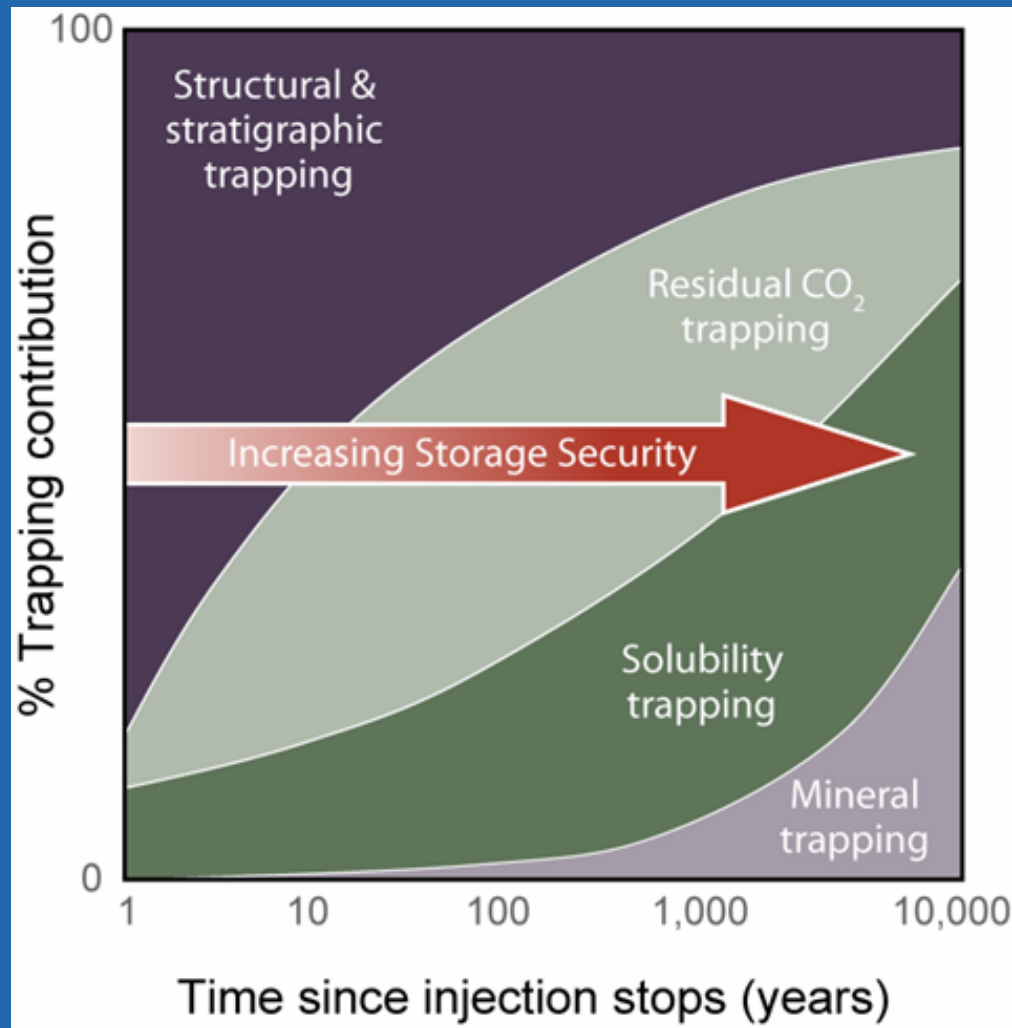
The paper also highlights the importance of thorough site selection, rigorous well design and completion practices and the need for a monitoring systems that provide an “early warning” of impending problems.

# Introduction

Risk assessments of storing CO<sub>2</sub> in rigorously selected geological formations indicate that the inherent risks and potential quantities of CO<sub>2</sub> leakage may be minimal and that storage of CO<sub>2</sub> becomes more secure with the passage of time.

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- If sustained CO<sub>2</sub> leakage were to occur to any significant degree, by any pathway, the advantage of geological storage would be reduced.
- As important, the positive image of this technology would be impaired in the views held by policy makers, environmental groups and the public.

# CO<sub>2</sub> Storage Trapping Mechanisms and Increasing Storage Security with Time



# Introduction

Importantly, in the rare cases where leakage does occur, we believe that remediation options are available to respond, though some may be costly.

Inevitably, attempts to save money during the site selection, project design and field implementation stages could result in costs substantially greater than proper storage site selection, design and implementation.

# Methodology

We studied the information available on industry's leakage remediation experience with natural gas storage, involving nearly 100 years of operation in currently over 600 gas storage sites in the United States, as well and throughout the world.

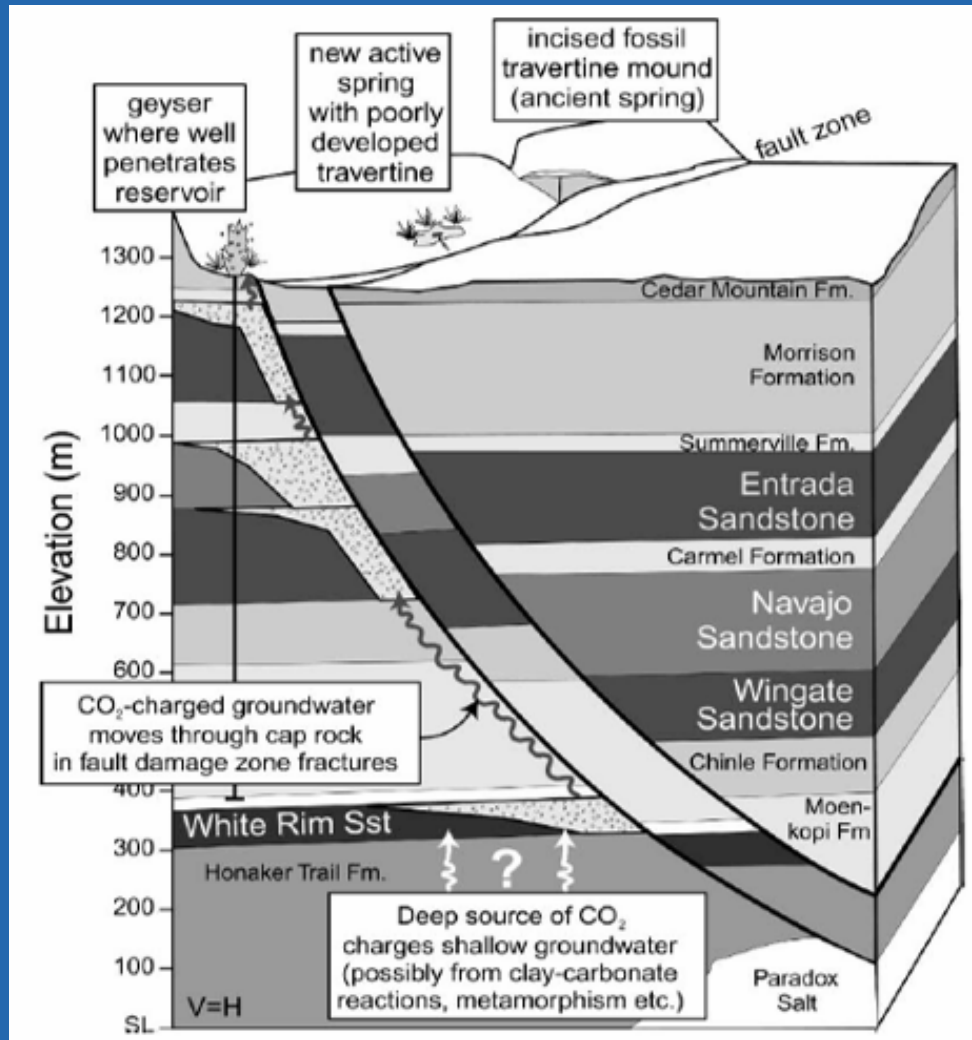
The “lessons learned” from this pool of experience, particularly testing procedures for safe site selection, field monitoring procedures for leak detection, and mitigation actions for responding to leaks, have been incorporated into our analysis.

# 1. Selecting Favorable Storage Sites With Low Risks of CO<sub>2</sub> Leakage.

The dominant strategy for leak prevention and remediation is avoiding the need for remediation in the first place, by selecting storage sites with extremely low risk of leakage over geologic time.

- Caprock (Seal) Integrity
- Natural Confinement
- Wellbore Integrity
- Reservoir Storage Capacity

# Schematic Cross-Section of a Typical Oil and Gas Field Showing How Faults Can Act as Seals or Barriers to Movement



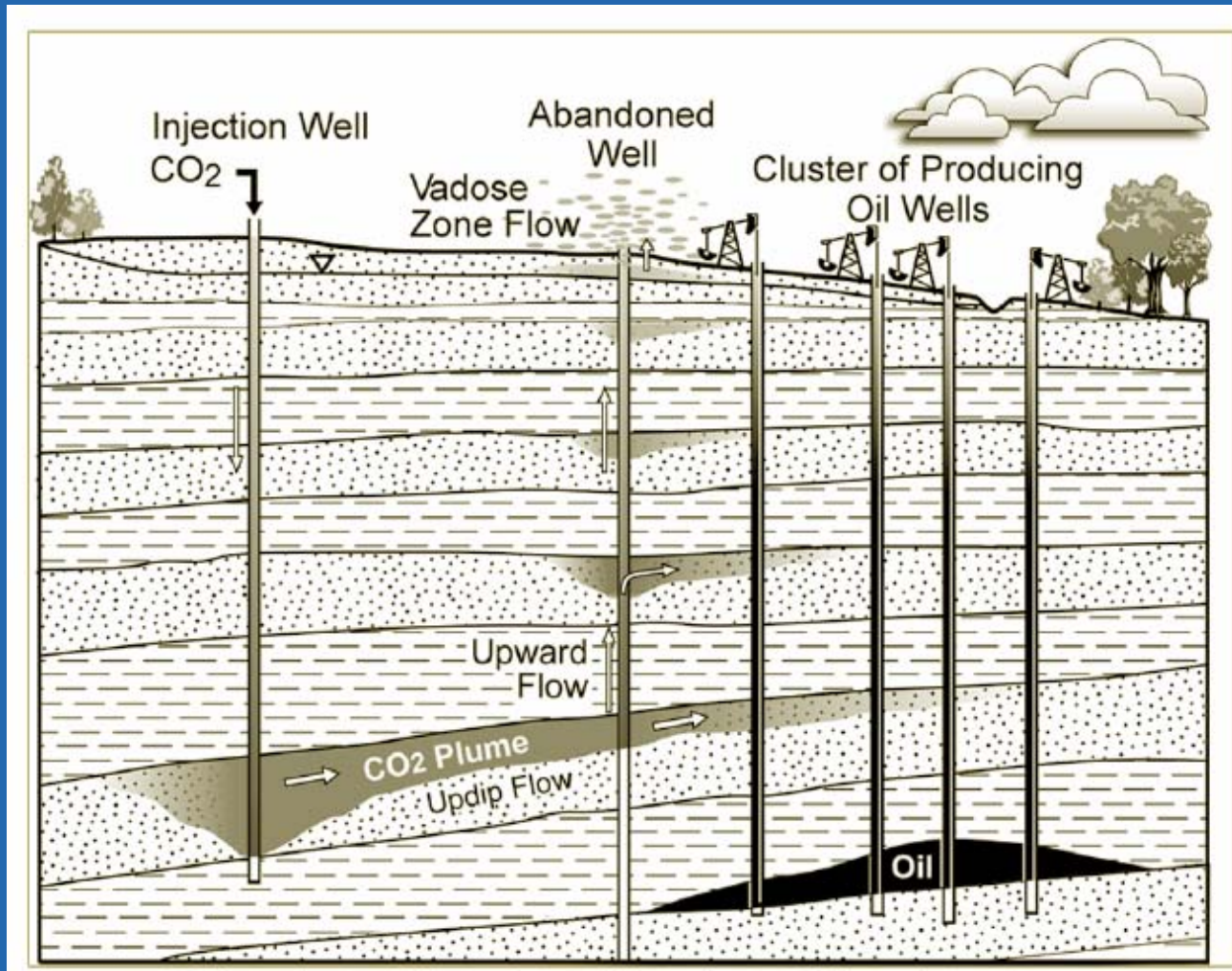
## 2. Placing Emphasis on Well Integrity

The first step is identifying the older, abandoned wells in the vicinity of the proposed CO<sub>2</sub> storage site and replugging these wells.

The second step is designing and installing the CO<sub>2</sub> injection wells so that they will resist loss of cement integrity and corrosion of casing from the acidic CO<sub>2</sub> and water mixture.

The third priority is properly closing the CO<sub>2</sub> storage site after CO<sub>2</sub> injection has been completed to promote long-term storage integrity.

# Abandoned and Producing Well Leakage Pathway



### 3. Conducting a Phased Series of Reservoir Simulation-Based Modeling to Track and Project the Movement of the CO<sub>2</sub> Plume.

Based on experiences, multiple phases of reservoir simulation are essential:

- The first phase of reservoir simulation and modeling would be undertaken during the initial site selection process.
- The second phase would be undertaken after the CO<sub>2</sub> injection and observation wells have been drilled, providing more site specific geological and reservoir data have been collected.
- The third phase of reservoir simulation, which would involve repeated runs of the model, would be initiated once the CO<sub>2</sub> monitoring systems provide new information on the flow direction and location of the CO<sub>2</sub> plume.

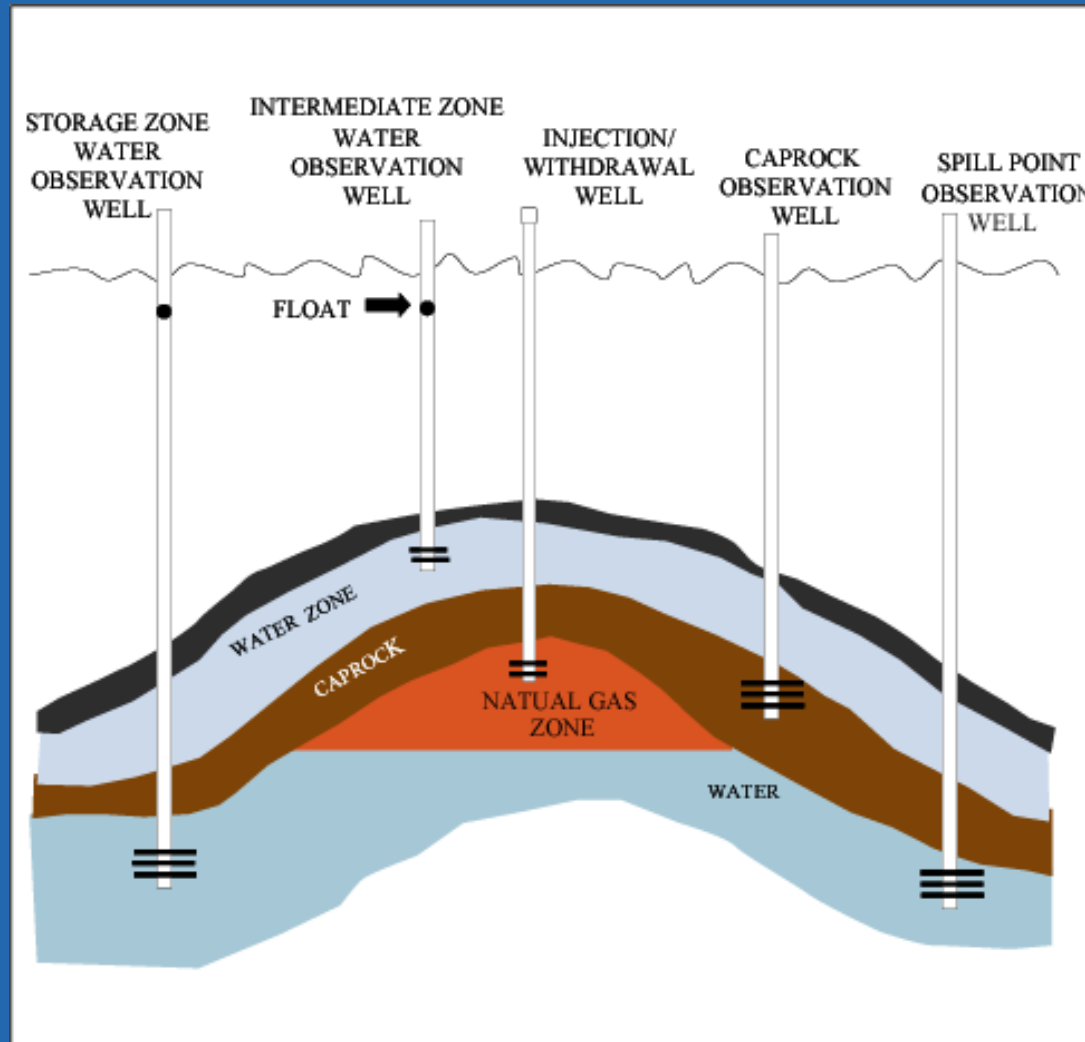
## 4. Installing and Maintaining a Comprehensive Monitoring System for the CO<sub>2</sub> Storage Site.

The CO<sub>2</sub> monitoring system needs to be designed to serve several purposes:

- An “early warning system” of any impending CO<sub>2</sub> leakage.
- Information on the movement and immobilization of the CO<sub>2</sub> plume.

Natural gas storage can provide valuable examples for designing a comprehensive monitoring system

# Locating Observation Wells for Monitoring Storage



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## 5. Establishing a “Ready-to-Use” Contingency Plan/Strategy for Remediation.

A pre-established response and mitigation strategy can ensure rapid, effective response should a leak in the CO<sub>2</sub> storage field be detected.

- Reduce the pressure in the storage formation to reduce the driving force in the leaking storage compartment,
- Increase the pressure in the overlying formation into which the leakage is occurring to form a “pressure boundary” and stop (or reduce) leakage, and
- Intercept the CO<sub>2</sub> plume and extract the CO<sub>2</sub> from the overlying reservoir before it leaks into the groundwater or the surface.

# Costs Of Leak Prevention And Remediation

To illustrate the costs of remediation, we have selected a sample saline aquifer CO<sub>2</sub> storage site

For consistency, we have constructed this illustrative CO<sub>2</sub> storage example to be relatively similar to the “enhanced” monitoring systems saline aquifer example set forth by Benson (2005).

# Costs Of Leak Prevention And Remediation

Our estimate of the overall costs a comprehensive CO<sub>2</sub> leak prevention and monitoring program, plus establishing and operating the above remediation strategy, is estimated to be on the order of \$80 to \$100 million per site.

Assuming the injection of 250 million tonnes of CO<sub>2</sub> in 30 years, the cost per tonne for these efforts would be in the range of \$0.20 to \$0.25 per tonne.

However, should the CO<sub>2</sub> leakage problems not be able to be remediated, the costs would become significantly larger.

# Representative Costs for Leak Prevention and Remediation

Activity	Mid-Range Costs	Comments
	(millions)	
<i>A. BASIC COSTS*</i>		
1. Site Selection and Design	\$40 to \$45	Site selection, two deep characterization wells plus seismic.
2. Monitoring and Leak Detection	\$30 to \$35	6 deep observations wells, 6 shallow wells.
3. Wellbore Integrity/Other	\$10 to \$20	Multiple diagnostic cement bond logs, well integrity tests, modeling and system management.
Sub-Total	\$80 to \$100	

\*Does not include cost of designing, installing or operating the CO2 storage site for 30 years.

# Representative Costs for Leak Prevention and Remediation

Activity	Mid-Range Costs	Comments
	(millions)	
<i>B. REMEDIATION COSTS (If Needed)</i>		
1. Locating Sources of CO <sub>2</sub> Leaks		
· Old, Abandoned Wells	\$1 to \$2	10 well surveys.
· New CO <sub>2</sub> Injection Wells	\$3 to \$5	10 sets of diagnostic logs.
· Caprock/Spill Point	\$8 to \$12	2 horizontal leak detection wells plus diagnostics and seismic.
2. Well Plugging	\$4 to \$10	Plugging of 20 old wells.
3. Well Remediation	\$6 to \$10	10 well remediations, one new CO <sub>2</sub> injection well.
4. Caprock Leakage		
· Pressure Boundary	\$10 to \$15	Two horizontal water injection wells plus water plant.
· Other Problems	Large	Abandon original storage site; build new storage site.

# Summary

This paper on CO<sub>2</sub> leak prevention and remediation serves as merely a first step forward. Fruitful next steps would include the following:

1. Develop a “Best Practices” Remediation Manual.
2. Study Remediation in the Natural Gas Storage Industry.
3. Invest in Research and Technology Development in Remediation for CO<sub>2</sub> Storage.
4. Develop New Procedures and Technology for Locating and Assessing the Integrity of Abandoned Wells.
5. Launch a Series of “Best Practice”, Large-Scale Field Tests of CO<sub>2</sub> Storage.