Eighth Annual Conference on Carbon Capture & Sequestration

SAND2009-2507C

Geologic Storage - Saline

Combining Power Plant Water Needs and Carbon Storage using Saline Formations: An Assessment Tool

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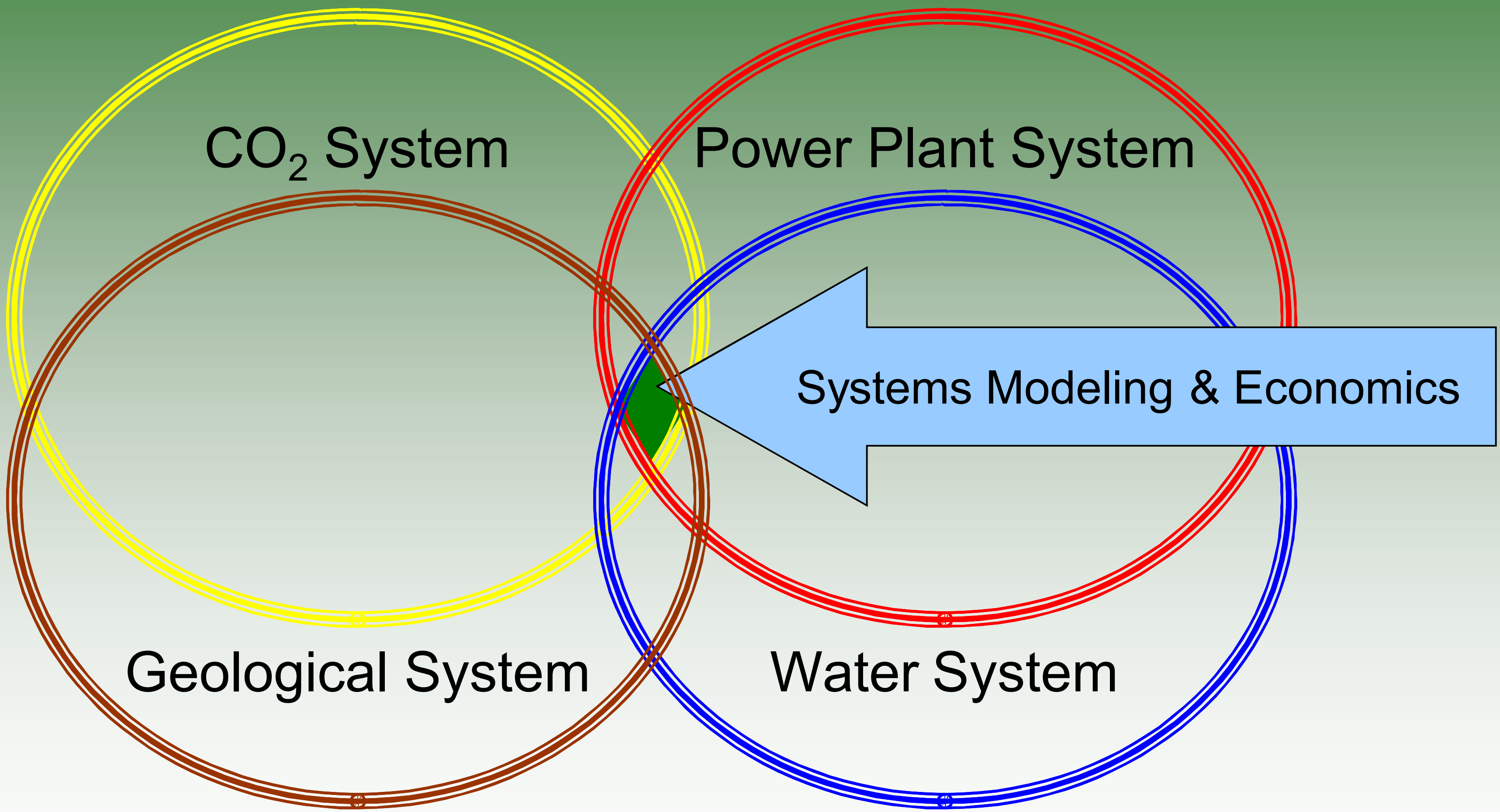
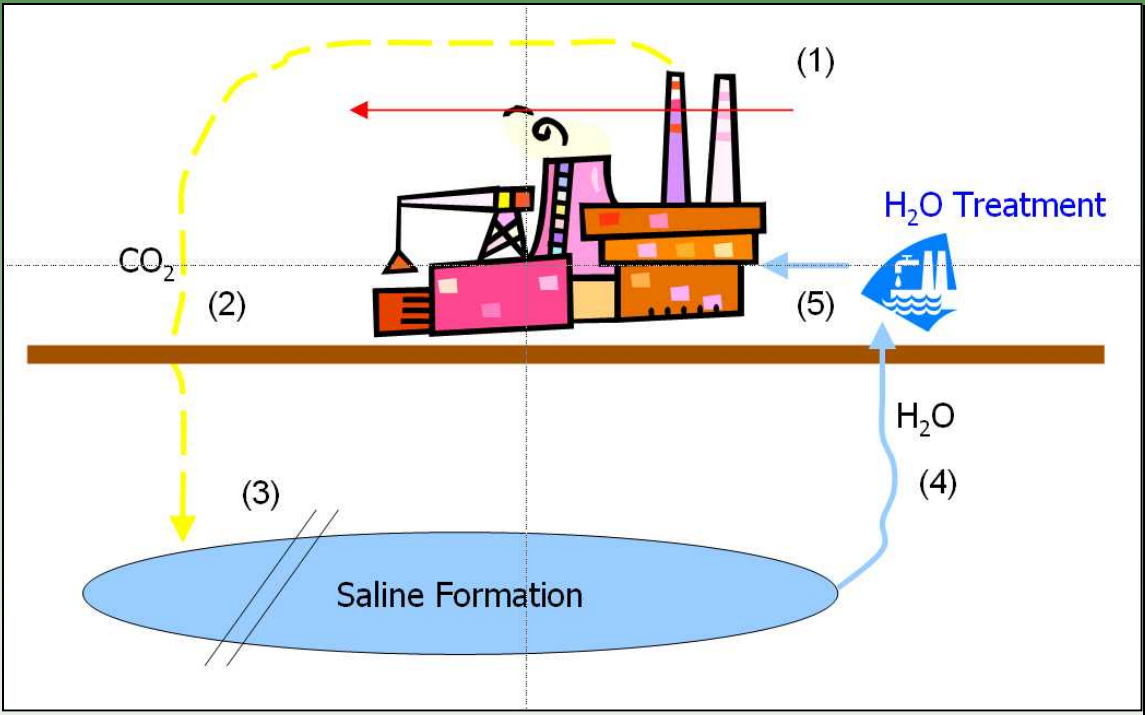
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

Energy-Economic Modeling Conceptual Layout of the Project



Can a power plant sequester Carbon Dioxide in a geological saline formation, while also utilizing treated water for cooling or other uses?

Developing the Interactive Model & Methodology



A) Geochemical & Hydrologic Assessment of Geology

B) Geomodeling Assessment of Selected Formation

C) Water Treatment Module

D) Interactive Model:

1: CO_2 power plant emissions

2: CCS Potential

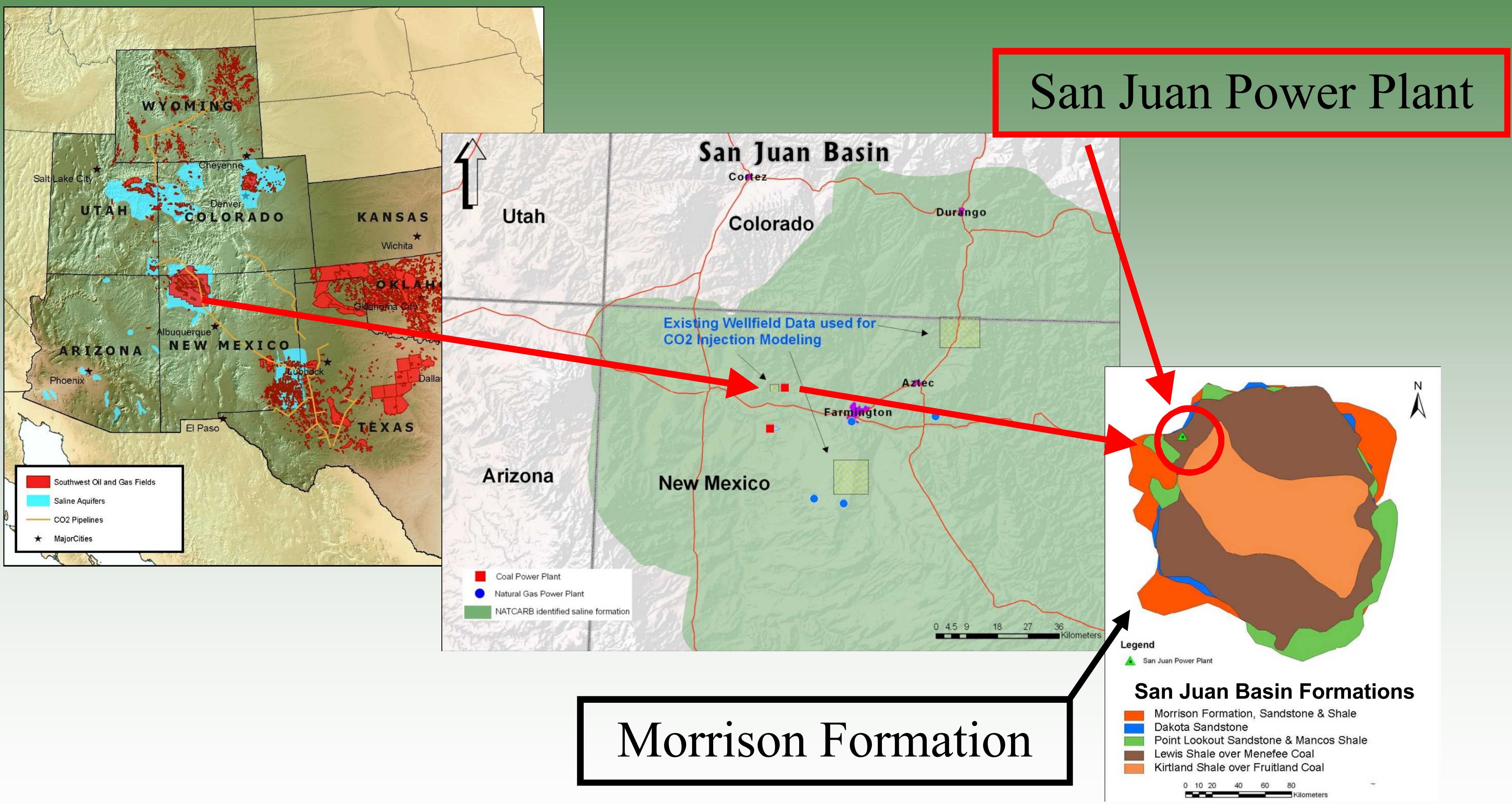
3: Saline Formation CO_2 sequestration potential

4: Pump Saline Formation for use at the power plant

5: Desalinate water for use at the power plant

Note: Carbon Capture and Sequestration (CCS)

San Juan Basin Assessment



Sources: Biediger, 2006; Klise 2008, 2009; NATCARB

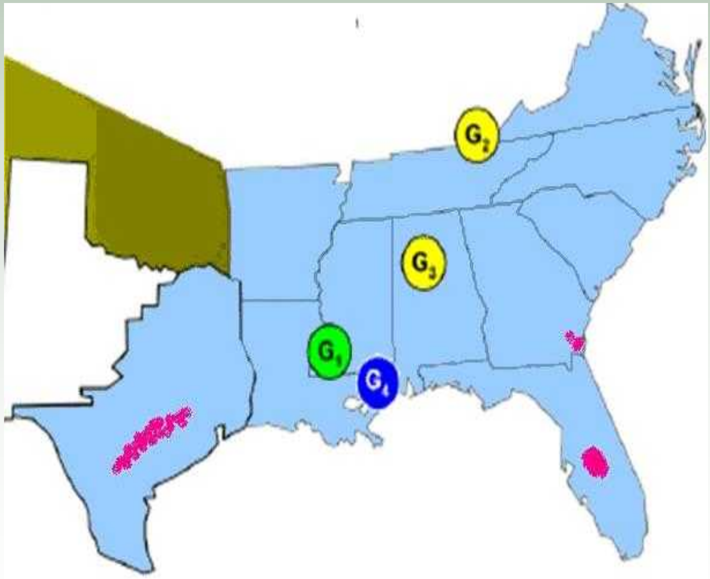
Site Selection Results:

Expanding the Scope

- Finding suitable formations in the SECARB area was more difficult than in the San Juan Basin.
  - Through much of the Gulf Coast region high salinities at shallow depths are common due to the regional occurrence of rock-salt beds in the geologic section.

- Four areas were identified as having potential:
  - South-Central Texas (Wilcox-Carrizo Fm.)
  - Central Florida
  - Southeast Georgia Basin
  - Black Warrior Basin ("G3")

- Other areas lacking permeable formations at the required depths or the saline Formations are very/too salty



SECARB Regional designation with four NETL pilot test sites locations (Map adapted from NETL, 2008)

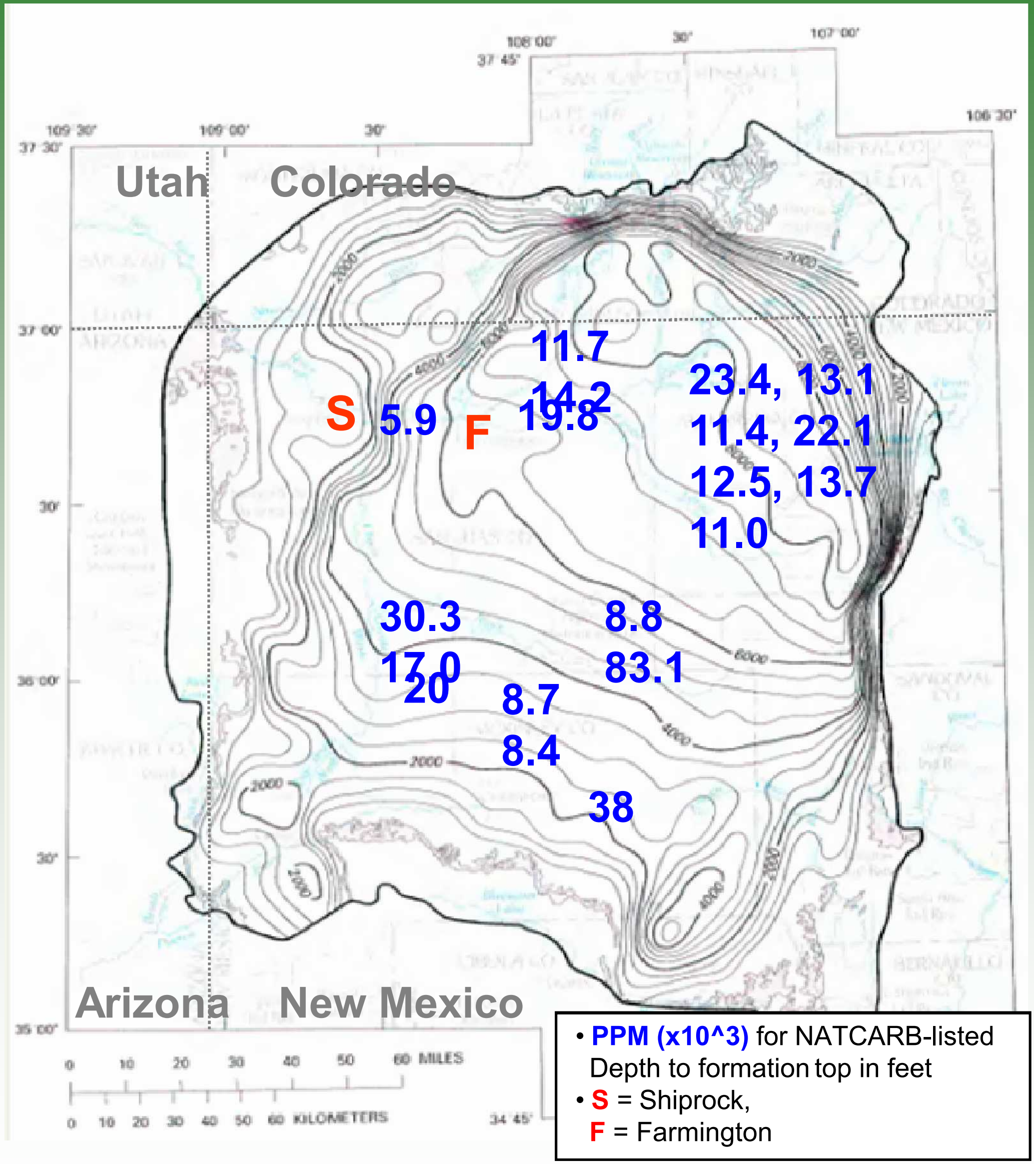
Geostudies (Geochemistry):

Formation CO_2 REACT 'box model' studies

- Several Formations were studied in these formations:
  - Mesa Verde / Point Lookout
  - Dakota
  - Hermosa / Paradox
  - Morrison
- Site Search Criteria
  - Depth greater than 2,500 feet
  - Salinity between 10,000 and 20,000 ppm
  - Lower salinity water is protected as a potential drinking water source
  - Above 20,000 — 30, 000 ppm, brackish water treatment economics become unfavorable
- Insights:
  - Morrison may have the more favorable geochemical/geospatial conditions for CCS & water treatment and use
  - Reactive transport ("REACT") modeling showed that only limited groundwater-CO_2-rock interactions would occur in the first few centuries; with little CO_2 mineralization likely.
  - Morrison has a broad regional occurrence and relatively low salinity

Salinity Profile for the Morrison Formation

- Has been recognized for its CO_2 sequestration potential
- Meets much of the assessment's criteria by having a relatively low salinity throughout
- Morrison wells in the San Juan Basin



(Sources: Map and data adapted from the following; NATCARB Database approximation; Craigg, 2000; Other Information available through Hovorka et al., 2000, Sequestration of Greenhouse Gases in Brine Formations; Texas Bureau of Economic Geology)

Geochemistry

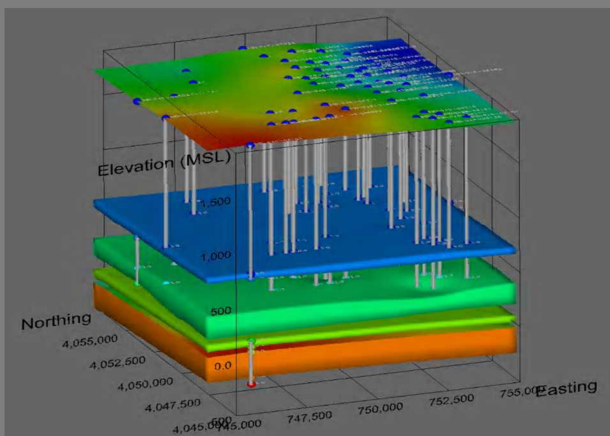
- Geochemical "Box Models" using REACT
  - Purpose: Determine when CO_2 injection occurs, what are the resultant down hole geochemistry conditions (e.g., change pH, mineral interaction, etc.)
  - REACT determines the most chemically stable arrangement given formation parameters listed below

Formation	pH	Na	Ca	Mg	Cl	SO_4	HCO_3	TDS
		ppm	ppm	ppm	ppm	ppm	ppm	ppm
Fruitland - initial, 2402'	8.4	4050	44	27	1460	5.6	8015	13,620
Fruitland - second, 2795'	8.6	5,798	48	12	922	6.8	11,800	18,587
Point Lookout - Mesa Verde	7.9	1572	87	28	2,500	4.2	256	4,447
Gallop Sandstone in Mancos	8.4	3,378	8	7	4,060	7.7	1,684	9,145
Dakota	8.6	741	16	10	356	1.4	959	2,083
Morrison - initial, 4115'	7.9	1,491	313	49	58	3,764	272	5,947
Morrison - second, 6359'	7.2	5,372	286	34	2,529	7,915	882	17,018
Hermosa/Paradox	8	2,654	368	49	425	5,500	708	9,704

Geostudies (Geomodeling):

Modeling Supercritical CO_2 injection into San Juan Basin Saline Formations (Morrison & Fruitland Formations)

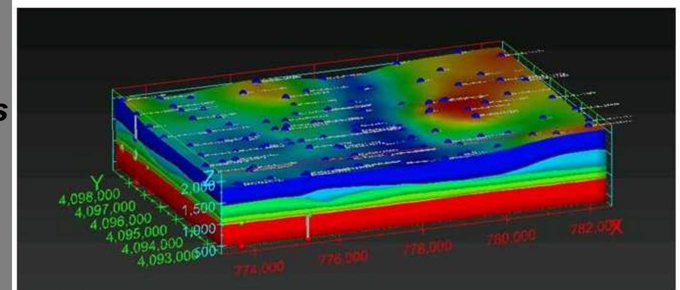
Geologic Framework Models



- Point Lookout Ss
- Gallup Ss
- Dakota Ss
- Morrison Formation

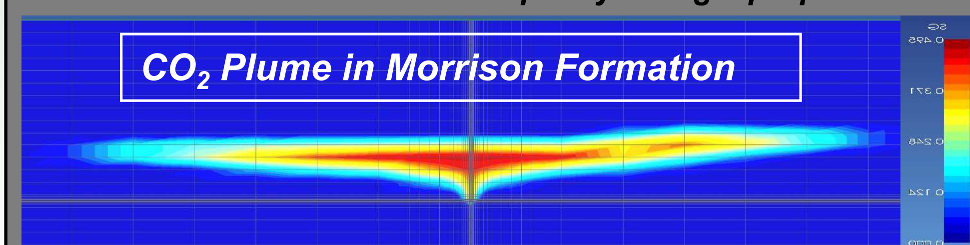
Sandstone reservoirs above and including Morrison Fm; also showing well control

Fruitland Formation as injection target and Kirtland Shale as proposed caprock, plus strata above and below



- Nacimiento Formation and Basin Fill
- Ojo Alamo Sandstone
- Kirtland Formation (caprock seal)
- Fruitland Formation (injection target)
- Pictured Cliffs Sandstone
- Lewis Formation (confining layer)

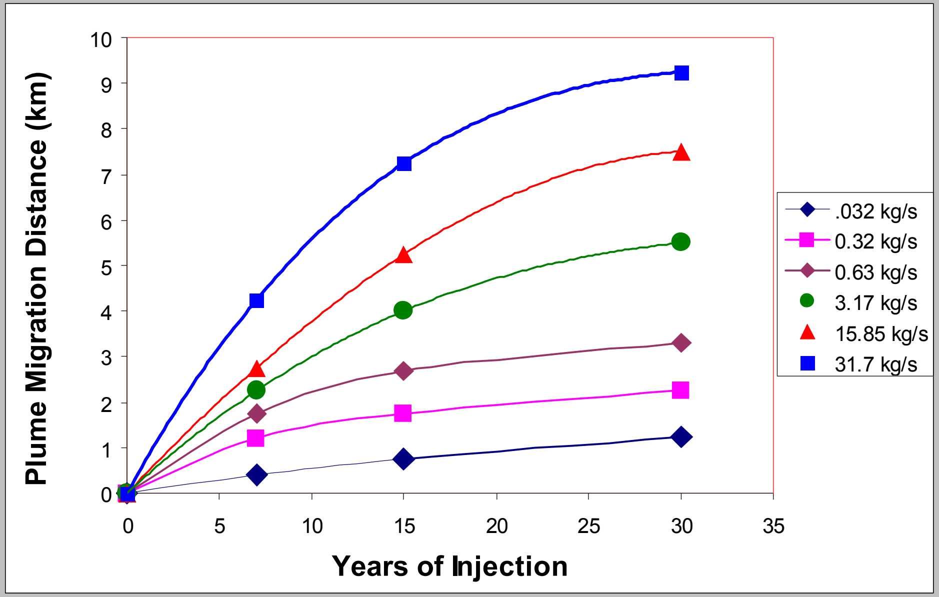
Updip and upsection migration of CO_2 in Morrison Fm. This TOUGH2 model assumes isotropic hydrologic properties



Modeling CO_2 Injection in San Juan Basin:
Calculating Storage Capacity & Manageable CO_2 Injection Rates

- Morrison Formation
  - TOUGH2 simulations constrain the amount of storage capacity and the CO_2 plume migration distance
  - Calculated Storage Capacity for the Morrison 1 Site, ~3,300 million metric tons

Plume Migration, function of injection rate

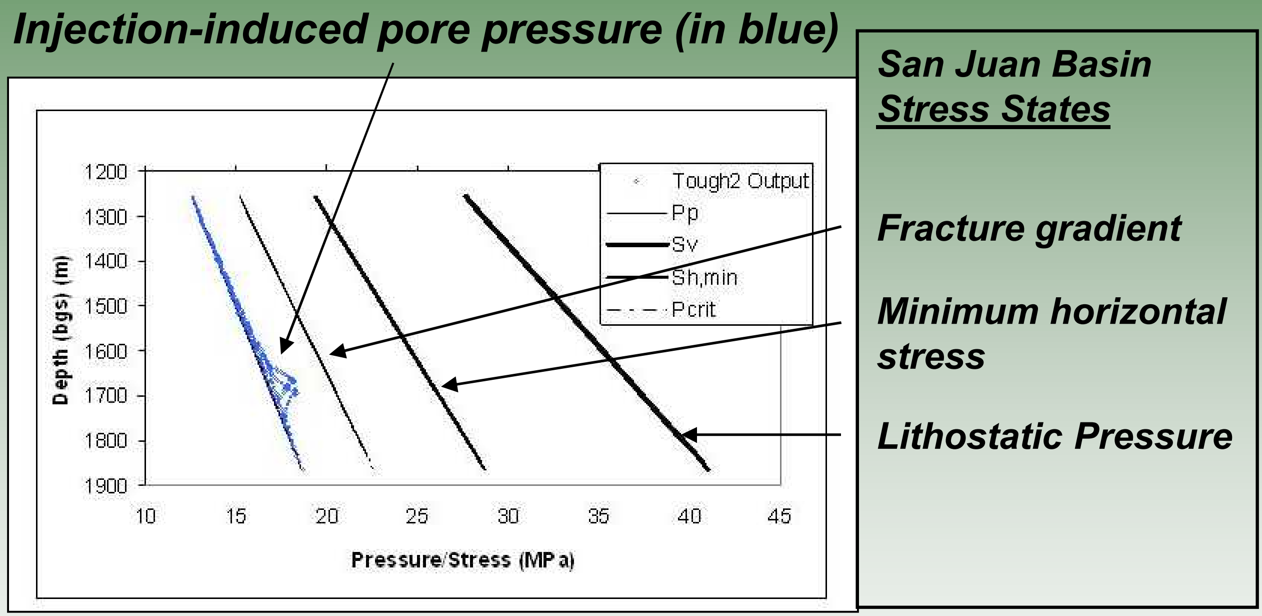


References: Pruess et al., 1999, LBNL-43134; Pruess, 2005, LBNL-57952

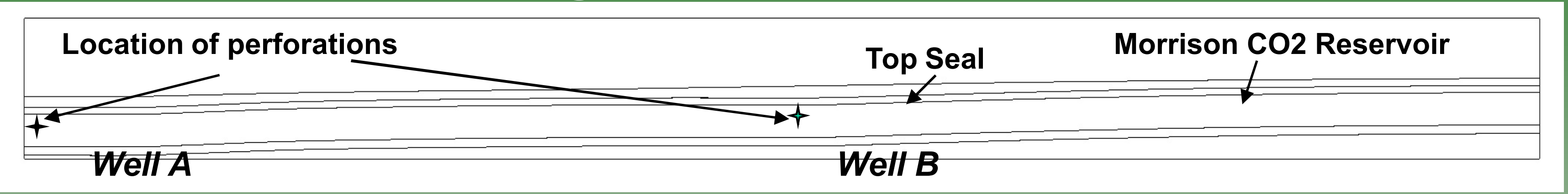
Modeling CO_2 Injection in San Juan Basin:

Calculating Storage Capacity & Manageable CO_2 Injection Rates

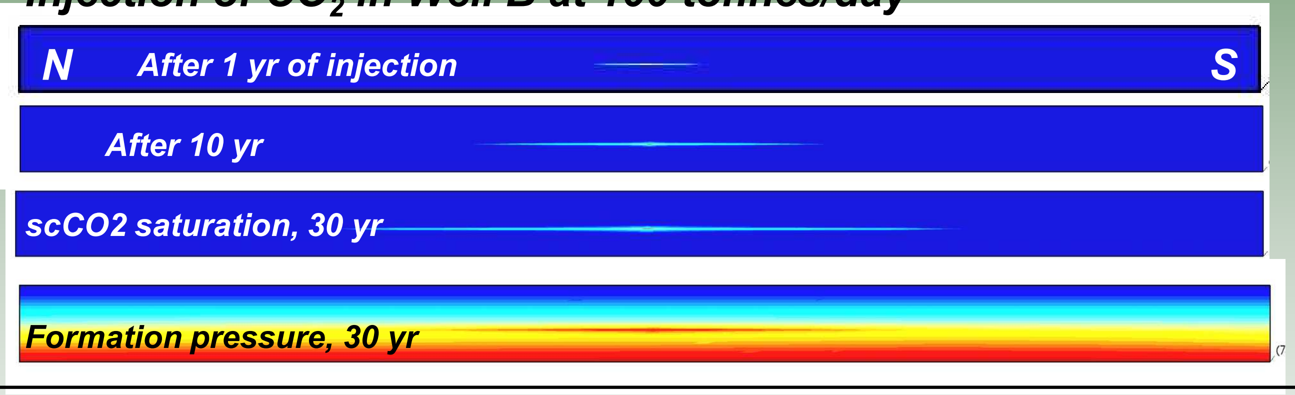
- Injection rate of *2,500 metric tons/day* can be achieved without near-wellbore damage
- Representative injection rates / pressures far below fracture gradient

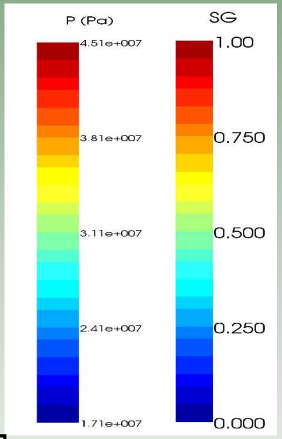


CO_2 Plume Migration Rates and Reservoir Pressure Mitigation: Morrison Reservoir



Injection of CO_2 in Well B at 100 tonnes/day





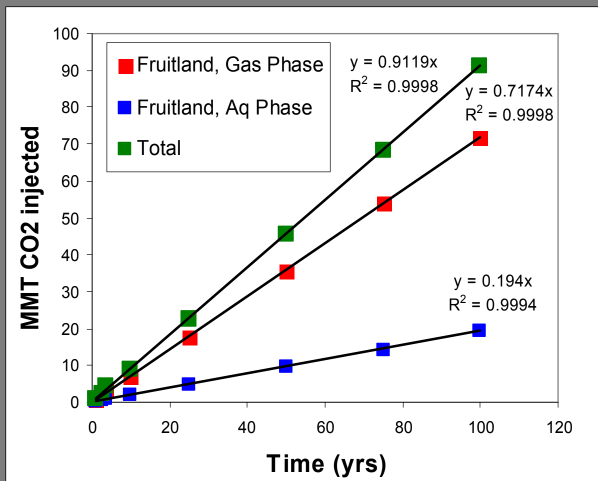
Injection of CO_2 in Well A at 1000 tonnes/day

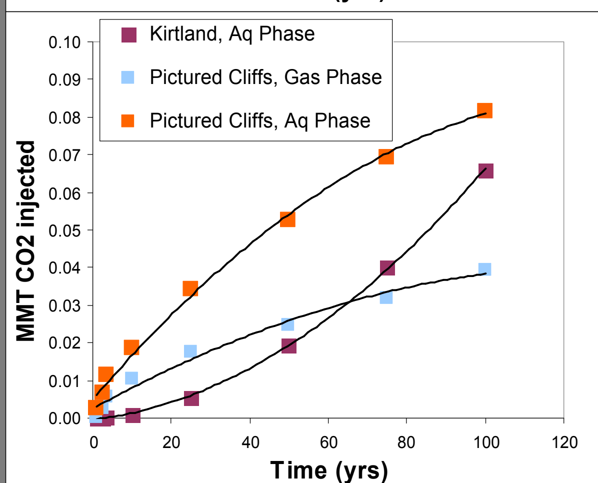
Large pressure increase sufficient to frac wellbore?

Pressure after equi-volume withdrawal of formation water at well B, 30 yr

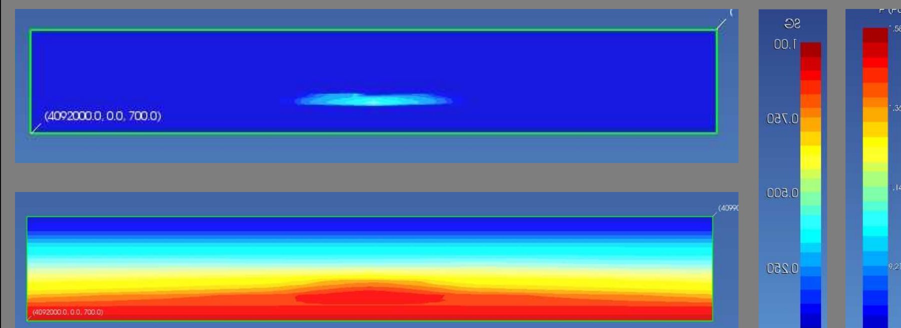
Geostudies (Geomodeling):

Modeling Supercritical CO_2 injection into San Juan Basin Saline Formations (Fruitland Formation)





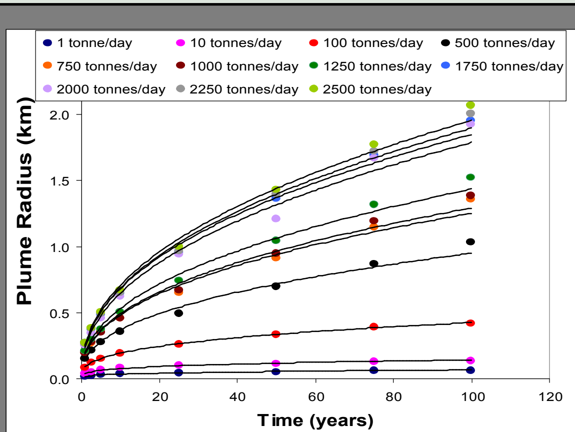
Mass conservation during injection at 2,500 tonnes /day into Fruitland Fm (shows partitioning into dissolved and $scCO_2$)



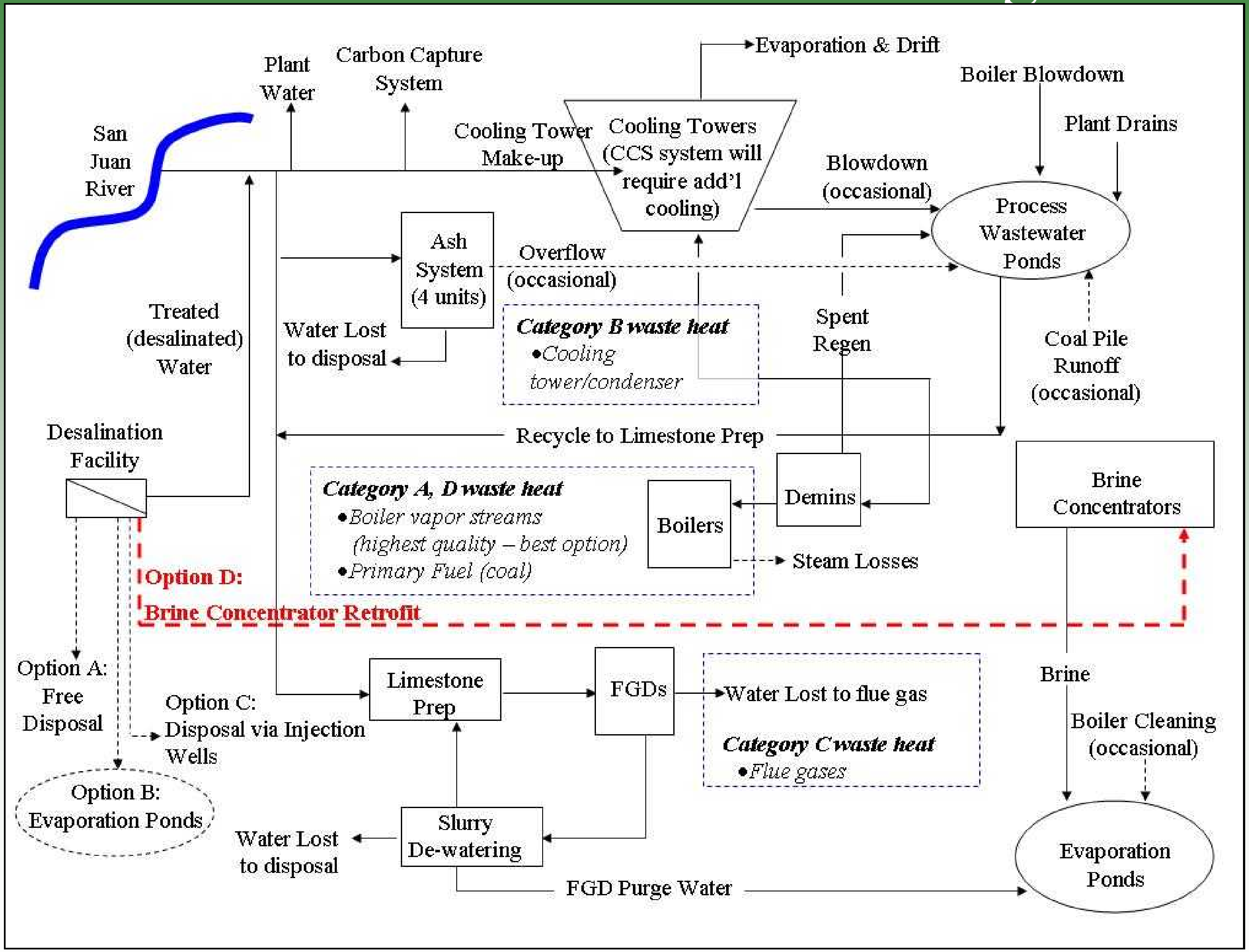
Example cross section of TOUGH2 model of injection within the ***Fruitland Formation****, with anisotropic hydrologic properties.*

Plume spreads laterally and up against the Kirtland Shale caprock (top) and induces a "mound" of overpressure (bottom).

$scCO_2$ plume migration distance as a function of injection rate for Fruitland site



Simplified San Juan Generating Station Water Flow & Waste Heat Diagram



Adapted from DeFilippo, M. "Semi-Annual Technical Progress Report, October 1, 2005 to March 31, 2006: Use of Produced Water in Recirculating Cooling Systems at Power Generating Facilities." EPRI. 2006. October 23, 2007 http://www.netl.doe.gov/technologies/coalpower/ewr/water/pp-mgmt/epri.html

Water Treatment Cost Estimations
(all using Initial Morrison Formation)

Total Cost - includes equipment & O&M for desalination and concentrate disposal (e.g. ponds)	Option A BWRO-**no conc disposal** $/1000 gal		Option B BWRO-**evap ponds** $/1000 gal		Option C BWRO-**injection well** $/1000 gal		Option D HERO + **BC retrofit** $/1000 gal	
Annualized Total Capital	$	2.90	$	5.04	$	3.24	$	2.59
Annual O&M	$	2.31	$	2.35	$	2.32	$	2.73
Electrical	$	0.42	$	0.42	$	0.42		
Membrane Replacement	$	0.00	$	0.00	$	0.00		
Other	$	0.54	$	0.54	$	0.54		
Total Cost (O&M+cap)	**$**	**5.21**	**$**	**7.39**	**$**	**5.56**	**$**	**5.31**

Cost of Desalination only - includes only equipment & O&M for desalination (i.e. no ponds, no GW pumping)	Option A BWRO-no conc disposal $/1000 gal		Option B BWRO-evap ponds $/1000 gal		Option C BWRO-injection well $/1000 gal		Option D HERO+BC retrofit $/1000 gal	
Annualized Total Capital	$	1.59	$	1.59	$	1.59	$	1.28
Annual O&M	$	1.34	$	1.34	$	1.34	$	1.43
Electrical	$	0.42	$	0.42	$	0.42	$	0.86
Membrane Replacement	$	0.08	$	0.08	$	0.08	$	-
Other	$	0.59	$	0.62	$	0.59	$	0.64
Total Cost (O&M+cap)	**$**	**2.93**	**$**	**2.93**	**$**	**2.93**	**$**	**2.72**

Water Treatment Cost Estimations

(all using Initial Morrison Formation)

	Base Case	Value
Water TDS (mg/L)	Used Morrison formation	6,000*
Design Flow rate (gpm)	based on 24/7 pumping of brackish aquifer, and % CO_2 capture	1,807
Design Flow rate (MGD)	Used 2.0 MGD desalination output (treated water)	
Design Annual flow (Mgal/yr)	based on 0.85 plant capacity factor (USBR recommendation)	400
Electrical Cost ($/kwh)		0.1
Pipeline distance from brackish well to desal plant (mi)	based on radial distance, Morrison formation	3
Well Depth (ft)	based on Morrison formation	4,725
Capital Costs:		
Pump & Pipe - Produced Water Gathering Capital	Used USBR Desalting Handbook, Fig. 9-18	$2,000/ft
Piping from gathering station to desal plant	Used USBR Desalting Handbook, Fig. 9-11	$126,810/mi
Concentrate Disposal pipeline & well	Used USBR Desalting Handbook, Fig. 9-11&9-13	
Evaporation ponds	Used USBR Desalting Handbook, Fig. 9-12	
Desalination Total Construction Cost	Used USBR Desalting Handbook, Fig. 9-7	$2000/mg/L TDS for options A-C NETL/EPRI (2006) value for option D
O&M		
Labor (for 2 MGD)	Used USBR Desalting Handbook, Fig. 9-37	
Electrical-BWRO (for 6,000 mg/L TDS, 2 MGD)	Used USBR Desalting Handbook, Fig. 7-8&9-45	
Electrical-GW pumping (for 1807 gpm/2 MGD)	Used equations to estimate pump power	
Membrane Replacement	Used USBR Desalting Handbook, BWRO	$0.08/1000 gal plant capacity
Chemicals (used surface water)	Used USBR Desalting Handbook, Fig. 9-41	
Other Maintenance	Used USBR Desalting Handbook	1.5% of capital

* Initial value for working framework

Exploring Waste Heat Sources:

Objective, use waste heat to produce clean water

<u>Category A – steam to condenser units (highest energy)</u>

- Diffusion Driven Desalination (DDD), Univ. of Florida
- Membrane Distillation (MD), Arrakis/New Jersey Institute of Tech.
- Wet Surface Air Cooler (WSAC), EPRI
- Carrier Gas Enhanced Atmospheric Pressure Desalination, ASU
- Low Temperature Evaporation (LTE), Bhabha Atomic Research Centre, India

<u>Category B – cooling tower hot water side (low energy)</u>

- No substantial development in this area at present

<u>Category C – flue gas stream/ water recovery</u>

- WETEX (Liquid Desiccant Process), University of North Dakota's Energy & Environmental Research Center, Siemens Power Generation

<u>Category D – coal drying</u>

- Coal Drying, Energy Research Center/Lehigh University

Exploring Waste Heat Sources:

Cost Data relatively limited at present, water chemistry dependent, information from laboratory & pilot scale studies

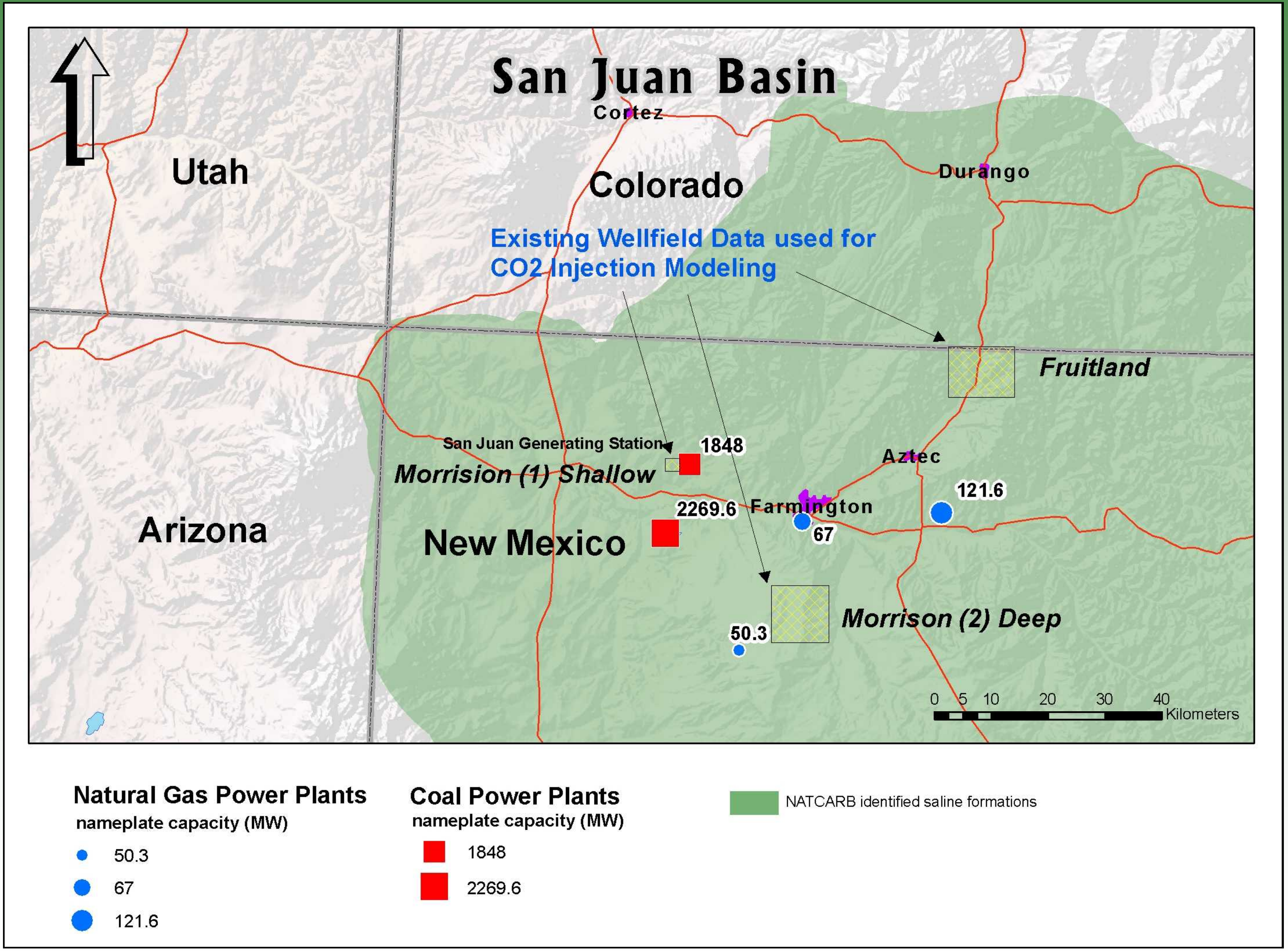
Technology	Description	Development State	Cost ($/1000 gal)
Reverse Osmosis	Baseline Technology in Water Treatment High pressure forces water across membrane.	Fully developed	2.5 – 5
DDD (Diffusion Driven Desalination)	Low temp & pressure, utilizes natural thermal energy storage in large water bodies (ocean)	Lab scale, Univ. of Florida	0.2 – 1 (a) Theoretically derived
MD (Membrane Distillation)	Heated water vapor crosses hydrophobic membrane at low pressure	Pilot scale, New Jersey Institute of Tech/Arrakis	2.97 (b)
CGP (Carrier Gas Enhanced Process)	Dewvaporation (Humidification dehumidification process)	Lab-scale, Arizona State Univ.	1.7 – 3.7 (c)

(a) Annual Report, “Innovative Fresh Water Production Process for Fossil Fuel Plants, September 2005, University of Florida, Klausner, James F. and Mei, Renwei

(b) “Novel Membrane and Device For Direct Contact Membrane Distillation-Based Desalination Process: Phase II, New Jersey Institute Of Technology, Newark, NJ, July 2003, U.S. Department of the Interior Bureau of Reclamation Denver Office

(c) Final Report, “Carrier-Gas Enhanced Atmospheric Pressure Desalination”, Arizona State University, Tempe, Arizona, U.S. Dept Of the Interior Bureau of Reclamation, October 2002, pg. 1.

Systems Integrated Assessment Model:
The Water, Energy and Carbon Sequestration Model (WECS)



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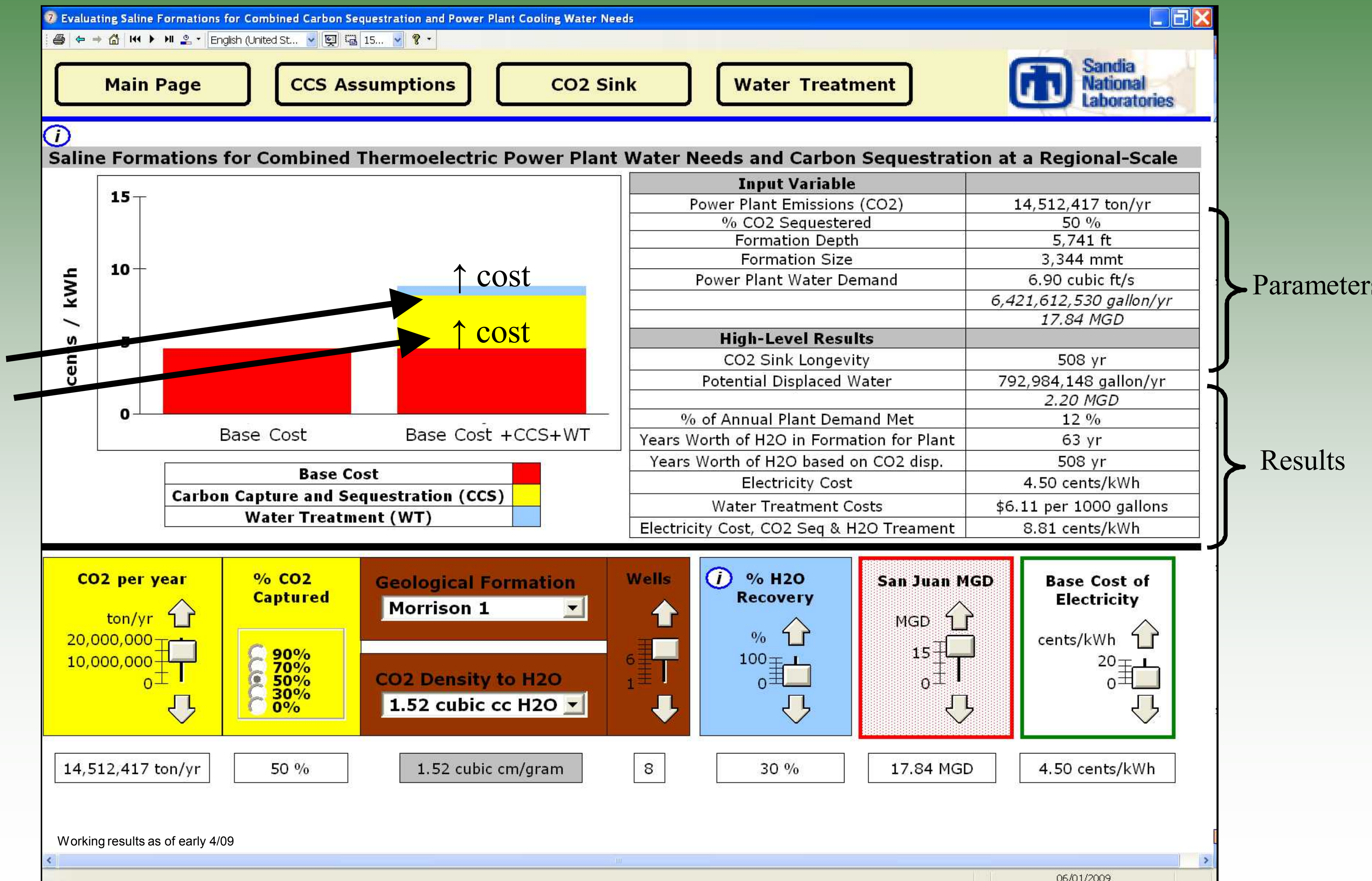

Input Variable	
Power Plant Emissions (CO2)	14,512,417 ton/yr
% CO2 Sequestered	50 %
Formation Depth	5,741 ft
Formation Size	3,344 mmt
Power Plant Water Demand	6.90 cubic ft/s
	6,421,612,530 gallon/yr
	17.84 MGD
High-Level Results	
CO2 Sink Longevity	508 yr
Potential Displaced Water	792,984,148 gallon/yr
	2.20 MGD
% of Annual Plant Demand Met	12 %
Years Worth of H2O in Formation for Plant	63 yr
Years Worth of H2O based on CO2 disp.	508 yr
Electricity Cost	4.50 cents/kWh
Water Treatment Costs	$6.11 per 1000 gallons
Electricity Cost, CO2 Seq & H2O Treament	8.81 cents/kWh

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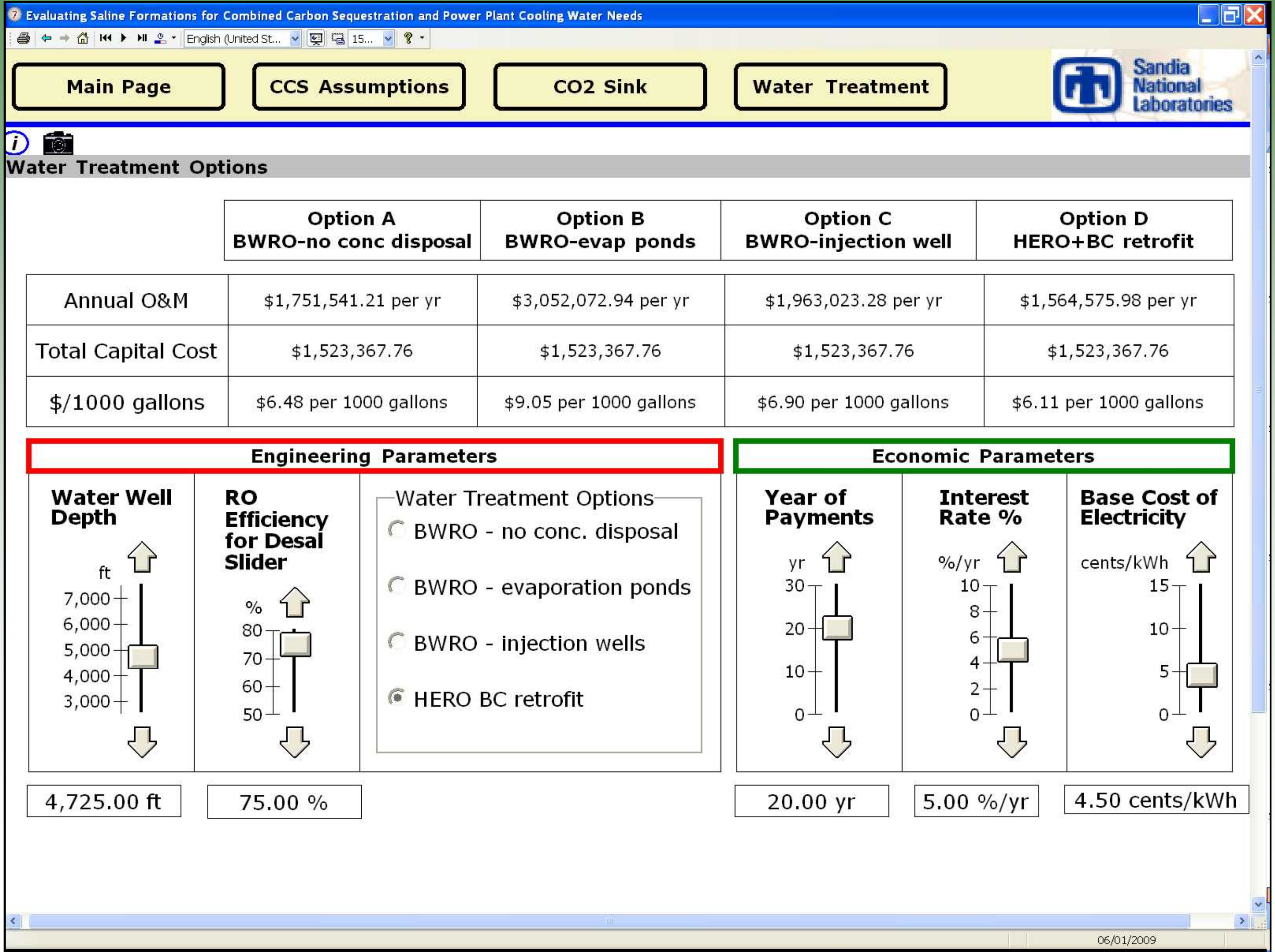
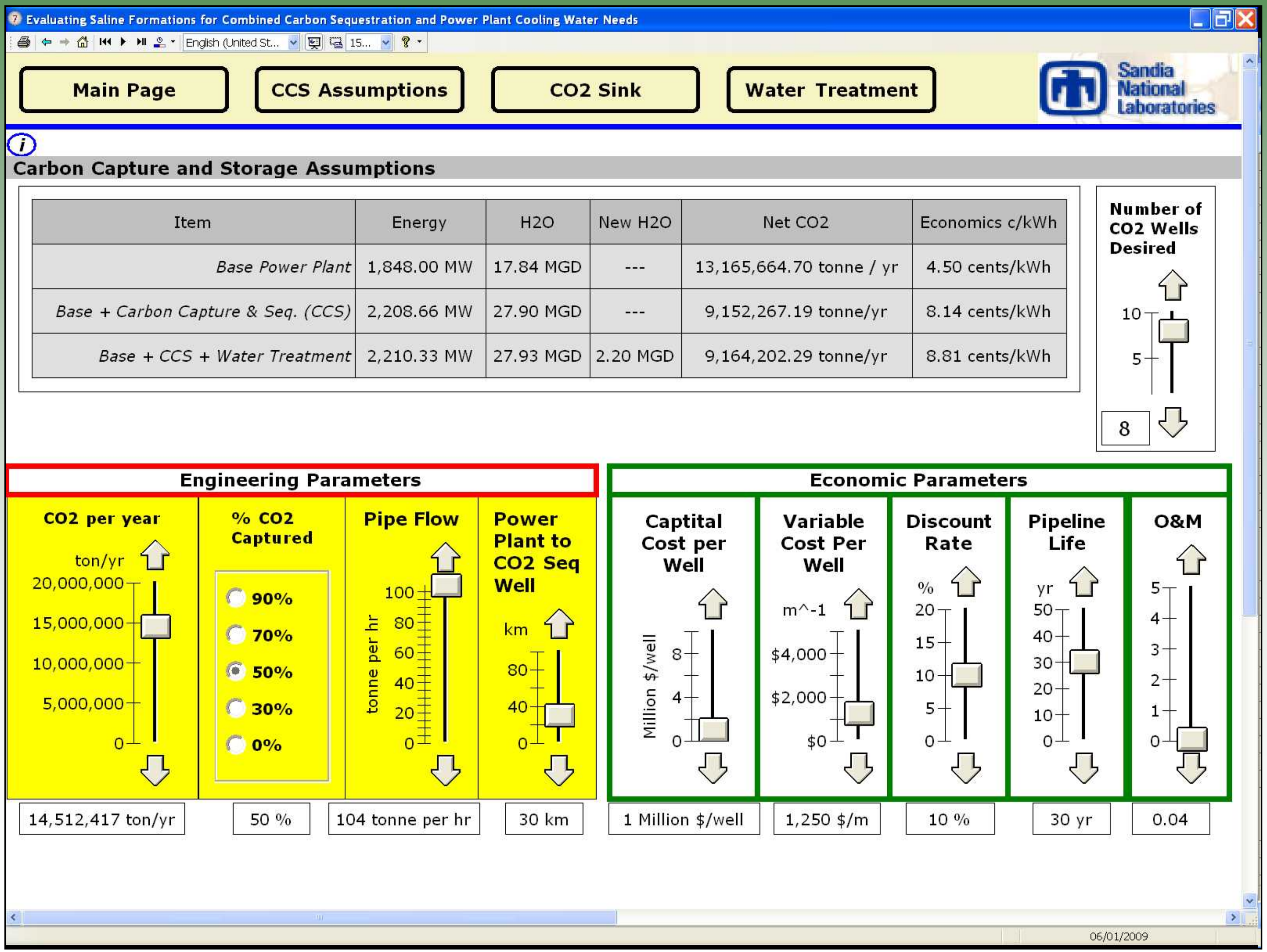


	Option A BWRO-no conc disposal	Option B BWRO-evap ponds	Option C BWRO-injection well	Option D HERO+BC retrofit
Annual O&M	$1,751,541.21 per yr	$3,052,072.94 per yr	$1,963,023.28 per yr	$1,564,575.98 per yr
Total Capital Cost	$1,523,367.76	$1,523,367.76	$1,523,367.76	$1,523,367.76
$/1000 gallons	$6.48 per 1000 gallons	$9.05 per 1000 gallons	$6.90 per 1000 gallons	$6.11 per 1000 gallons

Systems Integrated Assessment Model:

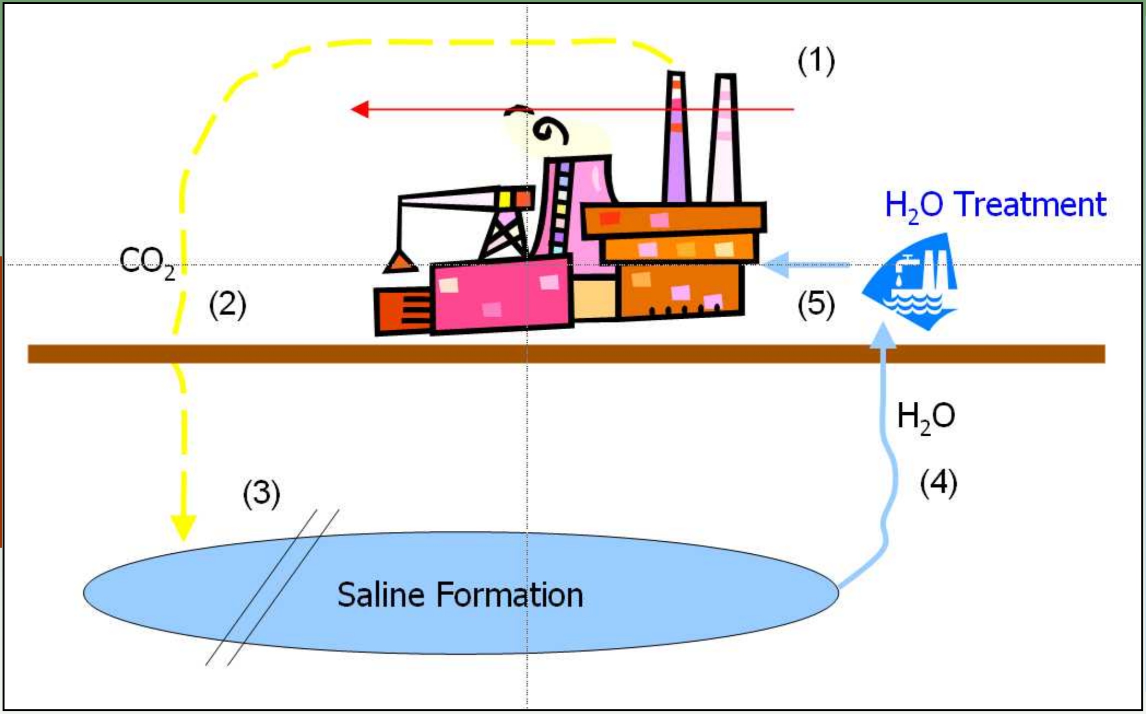
The Water, Energy and Carbon Sequestration Model (WECS)



Item	Energy	H2O	New H2O	Net CO2	Economics c/kWh
Base Power Plant	1,848.00 MW	17.84 MGD	---	13,165,664.70 tonne / yr	4.50 cents/kWh
Base + Carbon Capture & Seq. (CCS)	2,208.66 MW	27.90 MGD	---	9,152,267.19 tonne/yr	8.14 cents/kWh
Base + CCS + Water Treatment	2,210.33 MW	27.93 MGD	2.20 MGD	9,164,202.29 tonne/yr	8.81 cents/kWh

Integrated Assessment Highlights

(1) Carbon Capture and Sequestration (CCS),
20%+ Energy Penalty ↑ costs ~100%, ↑H_2O demands



(2) CCS, 50% capture and sequestration, ~4 mmt/yr

(5) Produced Water Treatment, ↑ costs ~10%, meet potentially a portion of Power Plant's annual H_2O demand

(3) Morrison Formation, 3,000+ mmt, 100s yrs. worth of CO_2 sequestration capacity

(4) <1 - 4 Million Gallons per Day for ~50-100s yrs., Assuming 30% recoverable water potential

Integrated Assessment:

Initial Test Case and Working Model Methodology

Section	Description	Assumption	Units
1	**Power Plant**	1848	MW
	Capacity Factor	72	%
	Carbon Dioxide Capture	50	%
	CO_2 Emissions	14,512,417.50	tons/year (EPA, eGRID)
	CO_2 Sequestered	6,582,722	tonnes/year (2,500 tonnes/day/well)
2	**Saline Formation**	3,343	mmt
	Representative Depth	5,700	feet
	Years' worth of CO2 storage resource	500+	Years
3	**Saline Water displaced**	170	bar
	CO_2 displacing H_2O	1.52	Cubic centimeters of H_2O per gram of CO_2
4	**H2O displaced and Demand**	402	Billion gallons total
	Annual H2O displaced	792	Million gallons / year
	Power Plant cooling towers' H2O demand	6.4	Billion gallons / year
	Years' worth of H2O supply	500+	Years (based on water displaced)
	Years' worth of H2O supply	60+	Years (based on plant demand)
5	**Desalination Costs – Base Case**	5.32	$ / thousand gallons

Integrated Assessment:
Initial Test Case and Working Model Methodology

Carbon Capture, Water Treatment and Electricity Cost Scenarios.

Percent of CO_2 Captured ▪	**0**	**30**	**50**	**70**	**90**
CO_2 Sink Longevity (years)	n/a	850	500	360	280
Displaced Water (million gallons /year)	n/a	480	790	1,110	1,430
Annual Plant Cooling Towers' Demand Met (%)	n/a	7	12	17	22
Years Worth of H_2O in Formation (years based on the Plant's demand)	n/a	63	63	63	63
Water Treatment Costs ($ per thousand gallons)	n/a	9.20	6.10	4.80	4.00
Electricity Cost, CO_2 Seq., Pipelines, injection wells & H_2O Treatment (cents/kWh)**	n/a	8	9	10	12

n/a: not applicable, *Rounded where appropriate for illustration,** Preliminary cost calculations, assuming a 100 km pipeline.

Anticipated Benefits

- Developing the analytical framework may provide a step-by-step methodology to assess additional power plants and saline formation CO_2 sequestration and water use cases in other regions
- The Earth Model developed will address CO_2 plume migration in a coupled-use system
- The Water Treatment technological assessment is more broadly applicable to other types of saline waters (looking for economical treatment in the face of unconventional water sources for multiple uses)
- The Assessment Model (WECS) provides an integrating framework to highlight the physical and economic opportunities and challenges for a coupled system

Technology Development Pathway

Timeline
2008
Summer
Fall
2009
Summer

- **Completed Phase I:**
  - Developed a Test Case Model
  - Initial results: may be 100s years worth of CO_2 storage capacity
  - Potential to displace and extract these waters
    - with treatment, could supplement the additional water requirements (parasitic loads due to CCS and producing and treating the water)
- **Ongoing Phase II:**
  - **Additional Geosystems Analysis**
    - Detailed TOUGH 2 modeling of coupled fluid/gas flow calculations of the 2 Morrison Formation Locations & 1 Fruitland Formation sites
    - Detailed Geochemistry insights (for saline formation waters), detailed CO_2-brine-rock interaction
- **Where we are going:**
  - Developing additional water treatment/waste heat components
  - Final Product
    - **User Analysis Model for Distribution** -- assessment for new candidate sites via WECS model and framework
    - Final Report, Carbonsq Conference Participation

Future Plans

Timeline

2009

Winter

2010

Summer+

- **Expanding the Scope**
  - Assess Nation-Wide Formation Data
    - Based on NatCarb and other sources
- **Analyzing the Formations**
  - Down-select other potential coupled CO_2 and extracted, treated water locations
  - Model representative/selected formations (e.g., TOUGH2, & caprock analysis)
- **Expand the User Model**
  - Include the Nation-wide data assessment for a first-order user model
  - Refine interface for user options

Eighth Annual Conference on Carbon Capture & Sequestration

Geologic Storage - Saline

Combining Power Plant Water Needs and Carbon Storage using Saline Formations: An Assessment Tool

Acknowledgements

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