Comprehensive, Quantitative Risk Assessment of CO_2 Geologic Sequestration

Project Number DE-FE0001112

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Headwaters Clean Carbon Services LLC

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage

August 20-22, 2013

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Presentation Outline

- Benefits to the Program
- Project Overview: Objectives and Goals
- Project Team
- QFMEA Model
- Quantitative Risk Assessment Methodology
- Quantitative Risk Assessments Completed
  - SACROC Northern Platform CO_2-EOR Site
  - Farnsworth Unit CO_2-EOR Site
  - Pump Canyon CO_2-ECBM Site
- Accomplishments to Date
- Summary

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Benefit to the Program

- Program goals being addressed
  - Develop and validate technologies to ensure 99 percent storage performance.
  - Develop Best Practice Manuals for MVA; site screening, selection and initial characterization; public outreach, well management activities, and risk analysis and simulation
- Project benefits statement
  - This project developed a comprehensive, quantitative CO_2 risk assessment tool, based on a Quantitative Failure Modes and Effects Analysis (QFMEA) model, that can be customized to assess site-specific projects, integrated with other CO_2 storage assessment tools, and easily modified, improved or expanded. This tool helps identify and characterize risks and risk prevention/mitigation steps, and estimate associated costs to safely store CO_2 in deep saline aquifers (DSA), enhanced oil recovery (EOR) and enhanced coal bed methane (ECBM).

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Project Overview: Objectives & Goals

- Project Objectives
  - The primary objective of this project is to develop and apply an innovative, advanced, process-based risk assessment model and protocol to determine quantitative risks and predict quantitative impacts for CO_2 geologic sequestration project sites. The model shall be capable of integration with advanced simulation models and MVA technologies.
- Project goals
  - Identify and characterize technical and programmatic risks for CO_2 capture, transportation and sequestration in DSA, EOR and ECBM.
  - Employ probabilistic calculations, process- and system-level simulation models, and shortcut calculations to quantify risks
  - Develop a Quantitative Failure Modes and Effects Analysis (QFMEA) model.
  - Estimate capital, operating and closure costs, potential damage recovery costs, risk mitigation costs and potential cost savings with risk mitigation.
  - Conduct quantitative risk assessments on three different sites.

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Project Team

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FAULKNER & FLYNN
ENVIRONMENTAL MANAGEMENT CONSULTANTS

THE UNIVERSITY OF UTAH

Los Alamos NATIONAL LABORATORY

- **Headwaters Clean Carbon Services LLC** – Risk identification and characterization, QFMEA development, financial modeling, estimating potential damage recovery costs and mitigation costs. Project management. Review of overall work product.
- **MMA/Faulkner & Flynn** – Refining QFMEA, financial model, estimates of potential damage recovery costs and mitigation costs. Development of insurance schedule for CO_2 sequestration. Review of overall work product.
- **The University of Utah** – Process-level modeling and probability calculations. Review of overall work product.
- **Los Alamos National Laboratory** – System-level modeling. Review of overall work product.

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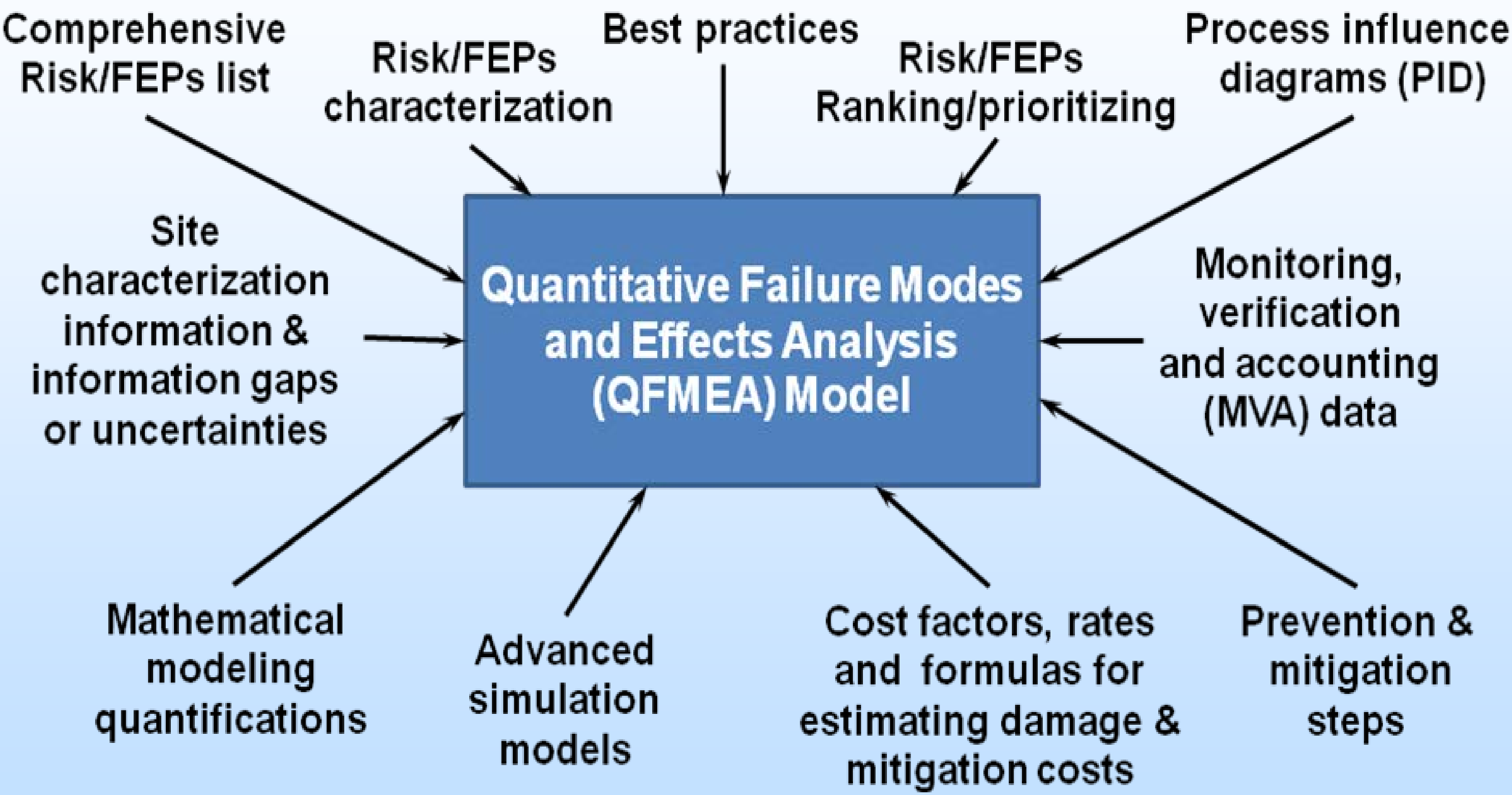
QFMEA Model



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Quantitative Risk Assessment Methodology

1. Gather site-specific information
2. Input site-specific information into the QFMEA model
3. Identify information gaps or uncertainties
4. Adjust failure modes, causes, severity, and methods of detection for site-specific conditions.
5. Eliminate risk areas that are not applicable
6. Input site-specific risk prevention and mitigation steps
7. Run simulation and financial models to quantify probability, severity and cost factors.
8. Input damage recovery costs (w/o and w/ risk mitigation), risk mitigation costs and potential cost savings.
9. Rank and prioritize risk areas based on probability, severity and detectability.
10. Submit results to a cross-functional team of experts for review.
11. Use results to manage risks during design, construction, operation and closure.
12. Update and revise as more information becomes available or conditions change.

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Ranking Factors for Risks

Ranking Factor	Probability of Failure Occurring	Severity of Failure Effect	Difficulty of Detecting Failure Early
5	**Likely** – frequency $\geq 1x10^{-1}$ per year (one event every 1 to 10 years)	**Catastrophic** – Multiple fatalities. Damages exceeding $100M. Project shut down.	**Almost Impossible** – No known control(s) available to detect failure early.
4	**Possible** – frequency from $1x10^{-2}$ to $1x10^{-1}$ per year (one event every 10 to 100 years)	**Serious** – Isolated fatality. Damages $10M-$100M. Project lost time greater than 1 year.	**Low** – Low likelihood current control(s) will detect failure early.
3	**Unlikely** – frequency from $1x10^{-4}$ to $1x10^{-2}$ per year (one event every 100 to 10,000 years)	**Significant** – Injury causing permanent disability, Damages exceeding $1M to $10M. Project lost time greater than 1 month. Permit suspension. Area evacuation.	**Moderate** - Moderate likelihood current control(s) will detect failure early
2	**Extremely Unlikely** – frequency from $1x10^{-6}$ to $1x10^{-4}$ per year (one event every 10,000 to 1,000,000 years)	**Moderate** – Injury causing temporary disability. Damages $100k to $1M. Project lost time greater than 1 week. Regulatory notice.	**High** – High likelihood current control(s) will detect failure early
1	**Incredible** – frequency $<1x10^{-6}$ per year (less than one event every 1,000,000 years)	**Light** – Minor injury or illness. Damages less than $100k. Project lost time less than 1 week.	**Almost Certain** – Current control(s) almost certain to detect the failure early. Reliable detection controls are known with similar processes.

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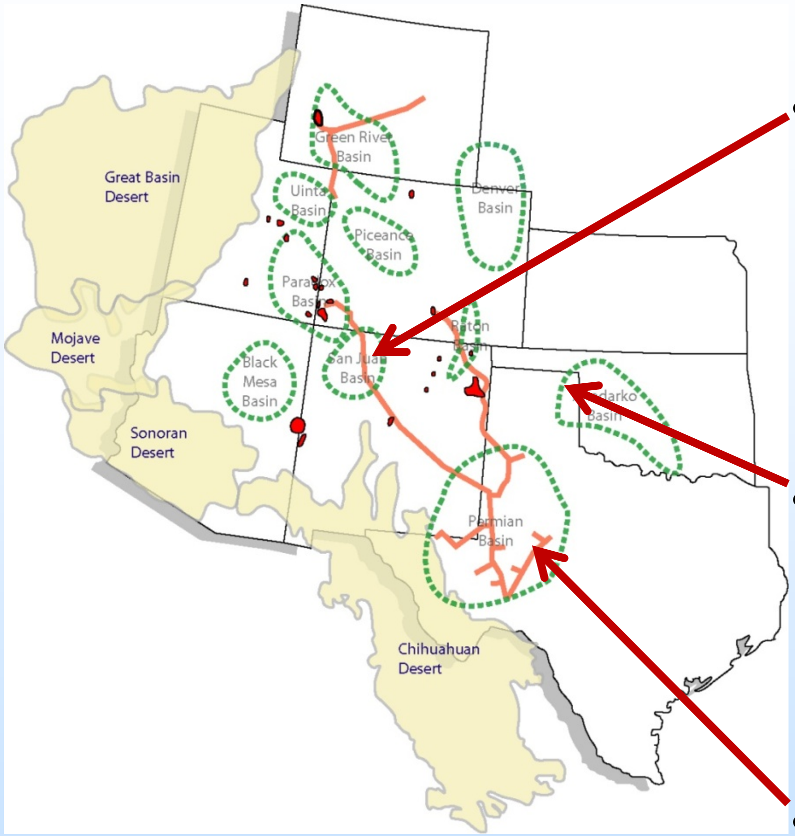
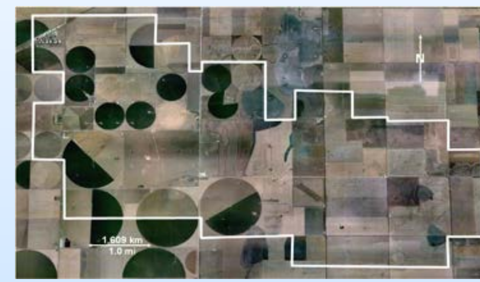
Quantitative Risk Assessments Completed



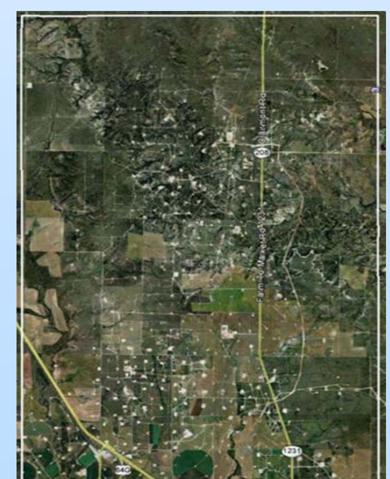
Source: McPherson 2009

- Pump Canyon CO_2-ECBM Site in the San Juan Basin (San Juan County, NM)

- Farnsworth Unit CO_2-EOR Site in the Anadarko Basin (Ochiltree County, TX)



- Mature, SACROC Northern Platform CO_2-EOR Site in the Permian Basin (Scurry County, TX)



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Comparison of SACROC Unit and Farnsworth Unit CO_2-EOR Operations

Site:	**SACROC Unit**	**Farnsworth Unit**
Location	Scurry County, TX	Ochiltree County, TX
Basin	Permian Basin	Anadarko Basin
Owner/operator	Kinder Morgan	Chaparral Energy
Type of operation	Mature CO_2-EOR	Early CO_2-EOR.
Start of CO_2-EOR	January 1972	December 2010
Reservoir lithology	Carbonate	Sandstone
Reservoir depth	2,042 m (6,700 ft)	2,408 m (7,900 ft)
Reservoir thickness	15 to 244 m (50 to 800 ft)	3 to 16.5 m (10 to 54 ft)
Average net pay thickness	48.8 m (160 ft)	6.9 m (22.5 ft)
Reservoir area	202 km^2 (50,000 acres)	51.4 km^2 (12,698 acres)
Formation fluid salinity	159,000 mg/L TDS	4,000 mg/L TDS
CO_2 type	Natural	Anthropogenic
CO_2 injection rate	Purchased: 6,312 t/d Recycled: 46,291 t/d	Purchased: 526 t/d Recycled: 105 t/d
Oil production	28,000 STB/d	1,000 STB/d

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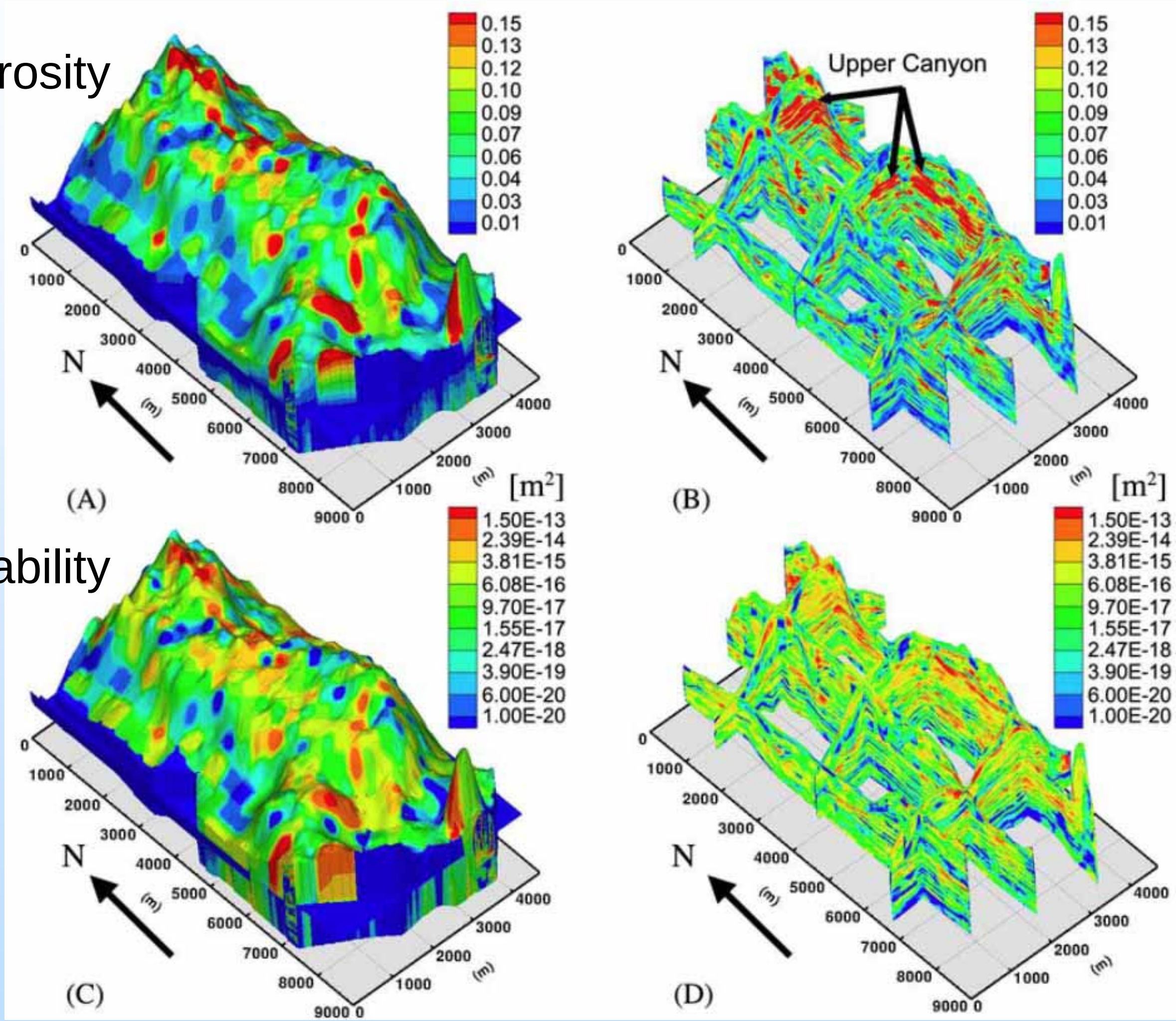
SACROC Northern Platform Geologic Model

Porosity

Permeability



Source: Han 2010

CO_2-EOR Financial Modeling

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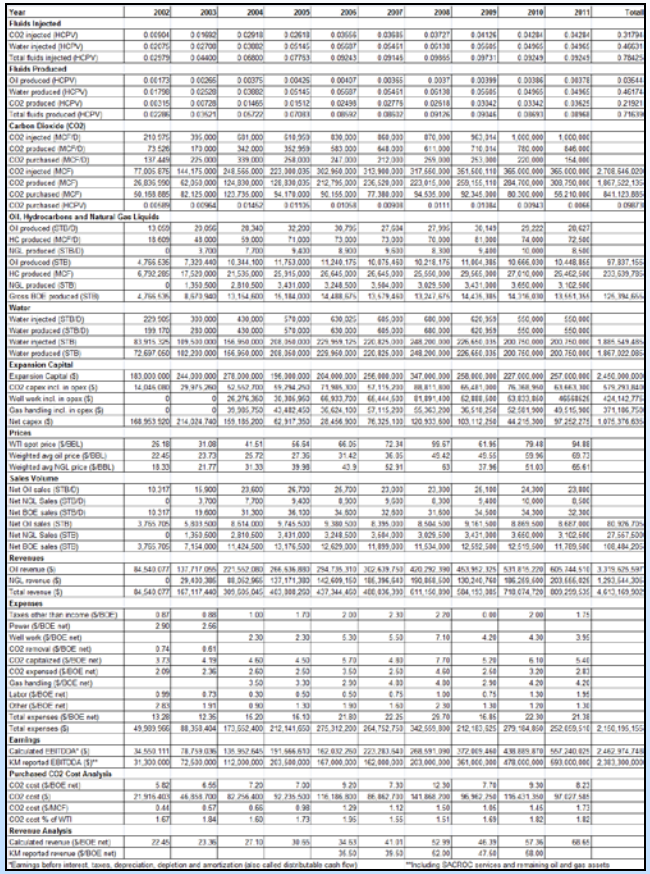
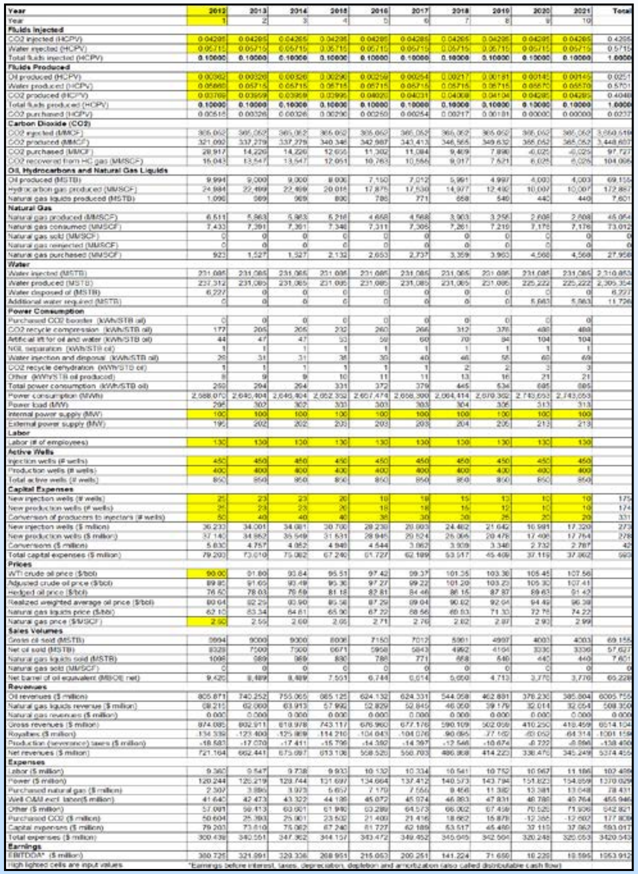
- Fluid volumes injected and produced (hydrocarbon pore volumes)
- CO_2 purchased, injected and recovered
- Oil, HC, NG and NGL produced and recovered
- Water injected, recovered and disposed
- Power consumption and generation
- Labor
- Active wells
- Capital expenses
- Prices
- Sales volumes
- Revenues
- Operating expenses
- Earnings

SACROC Unit History 2002-2011



SACROC Unit Projection 2012-2021



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SACROC Northern Platform CO_2-EOR Site Top 10 Risk Areas

Rank	Risk Area/FEP	Failure Probability (P = 1 to 5)	Failure Severity (S = 1 to 5)	Difficulty of Failure Detection (D = 1 to 5)	Risk Priority Number (PxSxD = 1 to 125)
1	Hedging	5	4	3	60
2	Price of oil (or other related commodities)	4	4	3	48
3	EOR oil reservoir heterogeneity	5	4	2	40
4	Precipitation of carbonate minerals (scale buildup)	5	4	2	40
5	Loss of containment	4	3	3	36
6	EOR viscosity relations	4	4	2	32
7	EOR hydrocarbon precipitation	4	4	2	32
8	Reservoir water chemistry	4	4	2	32
9	Formation damage	3	3	3	27
10	EOR injection and production well pattern and spacing	3	4	2	24

HSE risk (orange rows) | Economic risk (green rows)

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SACROC Northern Platform CO_2-EOR Site Top 10 Potential Fatal Risk Areas

Rank	Risk Area/FEP	Failure Probability (P = 1 to 5)	Failure Severity (S = 1 to 5)	Difficulty of Failure Detection (D = 1 to 5)	Risk Priority Number (PxSxD = 1 to 125)
1	Accidents and unplanned events	3	4	2	24
2	Excavation/drilling	3	4	2	24
3	Pipeline rupture	3	4	2	24
4	Explosions and crashes	2	5	2	20
5	CO_2 release processes	2	4	2	16
6	CO_2 release to the atmosphere	2	4	2	16
7	Health effects of CO_2	2	4	2	16
8	Elevated CO_2 in air	2	4	2	16
9	Toxicity of contaminants (H_2S)	2	4	2	16
10	Moving equipment	2	4	2	16

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SACROC Northern Platform CO_2-EOR Site Risk Assessment Conclusions

- Over 40 years of successful (safe) CO_2-EOR operation
- “Not significant” environmental risk due to nearly ideal subsurface* and surface** conditions, long-term operating experience and extent of technical knowledge.
- Top four risks (hedging, oil price, reservoir heterogeneity, and scale buildup) impact profitability rather than health, safety or environment.
- 639 deep wells penetrate the caprock, but operator has a preventative maintenance program for evaluating and reworking “at risk” wells.
- The presence of H_2S in the reservoir increases the toxicity of recycled gas, but also helps earlier detection of small to moderate leaks.

*Deep reservoir, balanced injection/production, intact caprock, multiple stacked seals and sinks, and no significant faults.

**Sparse population, no sensitive receptors, and no significant environmental targets.

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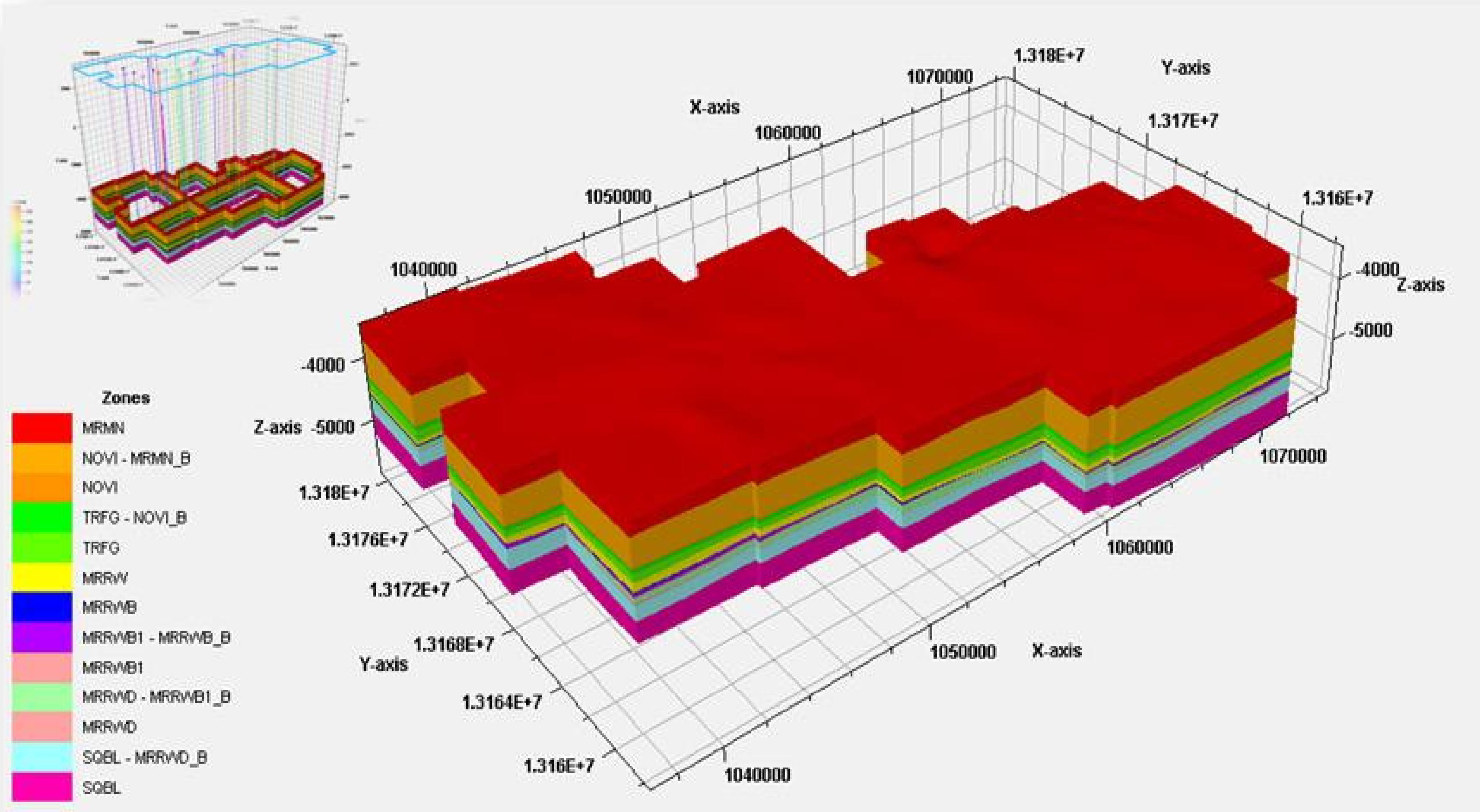
Farnsworth Unit CO_2-EOR Site Geologic Model



Source: Grigg 2012

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Farnsworth Unit CO_2-EOR Site Top 10 Risk Areas

Rank	Risk Area/FEP	Failure Probability (P = 1 to 5)	Failure Severity (S = 1 to 5)	Difficulty of Failure Detection (D = 1 to 5)	Risk Priority Number (PxSxD = 1 to 125)
1	Price of oil (or other related commodities)	4	4	3	48
2	Hedging or derivative positions	4	3	3	36
3	Formation damage	3	3	3	27
4	Loss of containment	3	3	3	27
5	Extreme weather event causing human injury/death	3	4	2	24
6	Accidents and unplanned events	3	4	2	24
7	Excavation/drilling	3	4	2	24
8	Pipeline rupture	3	4	2	24
9	Caprock fracture pressure	2	4	3	24
10	Leaks and spills (oil spills)	2	4	3	24

HSE risk

Economic risk

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Farnsworth Unit CO_2-EOR Site Top 10 Potential Fatal Risk Areas

Rank	Risk Area/FEP	Failure Probability (P = 1 to 5)	Failure Severity (S = 1 to 5)	Difficulty of Failure Detection (D = 1 to 5)	Risk Priority Number (PxSxD = 1 to 125)
1	Extreme weather event causing human injury/death	3	4	2	24
2	Accidents and unplanned events	3	4	2	24
3	Excavation/drilling	3	4	2	24
4	Pipeline rupture	3	4	2	24
5	Explosions and crashes	2	5	2	20
6	CO_2 release processes	2	4	2	16
7	CO_2 release to the atmosphere	2	4	2	16
8	Health effects of CO_2	2	4	2	16
9	Elevated CO_2 in air	2	4	2	16
10	Buildings	2	4	2	16

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Farnsworth Unit CO_2-EOR Site Risk Assessment Conclusions

- The CO_2-EOR operation represents a “not significant” environmental risk.
  - The caprock is intact.
  - Multiple stacked sinks and seals separate the reservoir from the Ogallala aquifer.
  - The surface is flat cropland and sparsely populated.
  - There are no sensitive receptors or significant environmental targets nearby.
- 169 deep wells penetrate the caprock. This will require a preventative maintenance program for evaluating and reworking “at risk” wells.
- Extreme weather (tornadoes) is a more significant risk at this Site than the other sites.
- The presence of H_2S in the reservoir increases the toxicity of recycled gas, but also helps earlier detection of small to moderate leaks.
- The planned injection of 2.9 million tonnes of purchased CO_2, from 2011 through 2024, in the West side of the Farnsworth Unit, represents 0.3 Hydrocarbon Pore Volume (HCPV). This is consistent with current best practices for CO_2-EOR operation.

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Pump Canyon CO_2-ECBM Geologic Model

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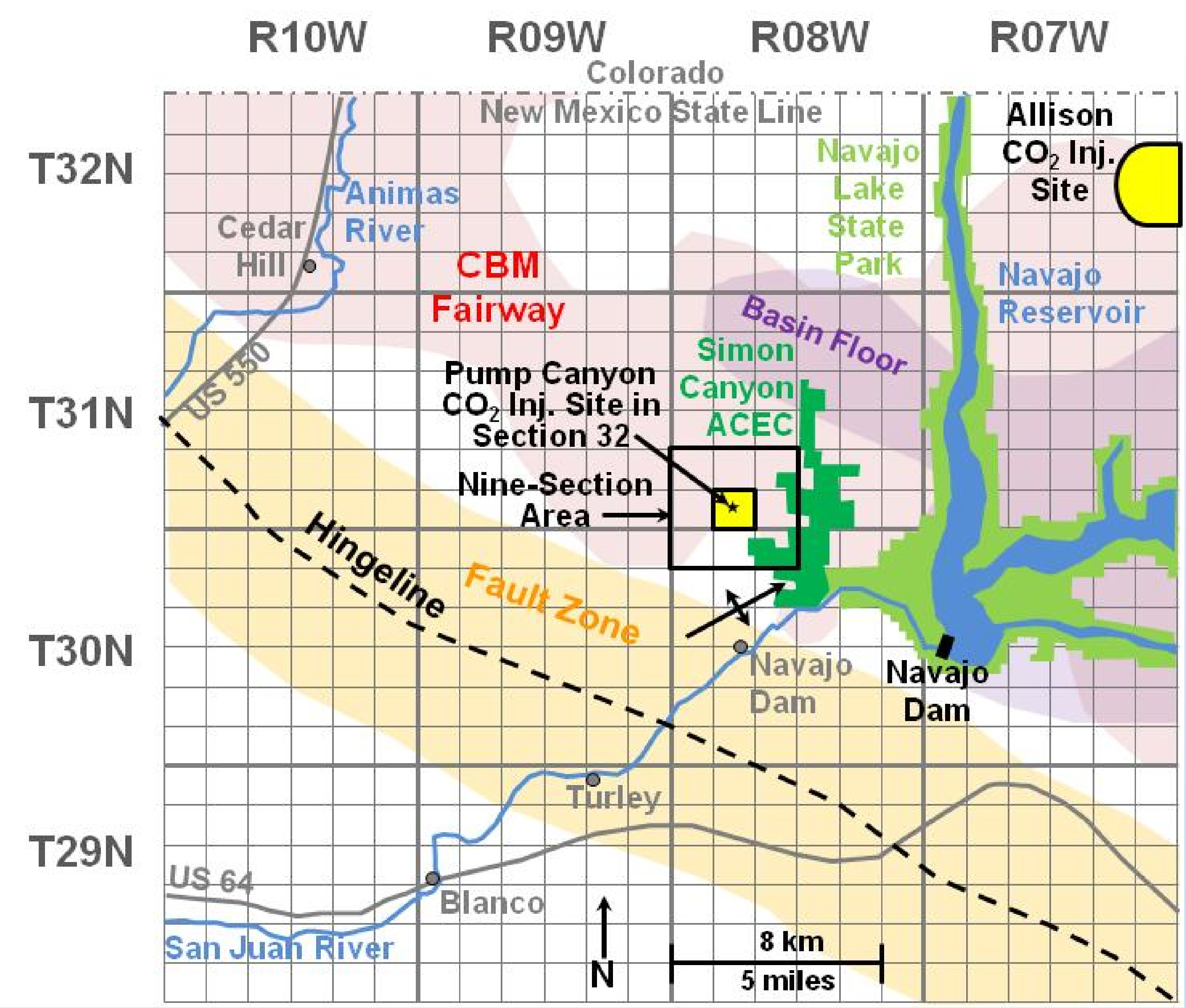
Pump Canyon CO_2-ECBM Three Site Reference Areas



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Pump Canyon CO_2-ECBM Three Site Reference Areas

	One-Section Area (Section 32)	**Nine-Section Area**	**Sixteen-Township Area**
Area	2.59 km^2 1 mi^2	23.3 km^2 9 mi^2	1,424 km^2 550 mi^2
Estimated coal in place	56.7 Mt	510 Mt	28 Gt
Estimated original methane gas in place	22.5 BCF	200 BCF	9 TCF
Initial # of CBM wells	Production: 4	Production: 36	Production: 684
Final # of CO_2-ECBM wells	Production: 2 Injection: 2	Production: 18 Injection: 18	Production: 324 Injection: 324
CO2-ECBM capital expense	$740,000	$9,386,000	$151,148,000
CO_2 purchase over 10 yrs	260,000 t 4.9 BCF	2,360,000 t 44.9 BCF	31,500,000 t 599 BCF
Methane prod. over 10 yrs (CO_2-ECBM mode)	1.9 BCF	17.5 BCF	247 BCF
Methane prod. over 10 yrs (CBM mode)	0.7 BCF	6.5 BCF	118 BCF

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Pump Canyon CO_2 Sequestration Three Site Reference Areas

	One-Section Area (Section 32)	Nine-Section Area	Sixteen-Township Area
Area	2.59 km^2 1 mi^2	23.3 km^2 9 mi^2	1,424 km^2 550 mi^2
Estimated coal in place	56.7 Mt	510 Mt	28 Gt
Estimated original methane gas in place	637 Mm^3 22.5 BCF	5.66 Gm^3 200 BCF	256 Gm^3 9 TCF
Number of existing deep wells	Active: 10 Shut in: 1 Plugged: 2 Total: 13	Active: 76 Shut in: 1 Plugged: 8 Total: 85	Active: 5,308 Shut in: 25 Plugged: 797 Total: 6,201
Estimated CO_2 adsorption capacity at 2.83 MPa (411 psia)	562,239 t 10.7 BCF	5 million t 95 BCF	82 million t 1.6 TCF
Estimated number of CO_2 wells needed	4 injection wells	36 injection wells	648 injection wells

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CO_2-ECBM and CBM Financial Modeling

- CO_2 purchased, injected and recovered
- Methane produced and recovered
- Water produced and disposed
- Number of injection and production wells
- Capital expenses
- Prices
- Sales volumes
- Revenues
- Operating expenses
- Gross margin

CO2-ECBM FINANCIAL MODEL											
Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Year (#)	0	1	2	3	4	5	6	7	8	9	10
PERFORMANCE PARAMETERS											
CO2 purchased (t/y)	0	236,000	236,000	236,000	236,000	236,000	236,000	236,000	236,000	236,000	236,000
Estimated CO2 produced and recycled (t/y)	0	32,765	62,011	66,911	67,050	66,334	65,533	64,790	64,126	63,537	63,015
CO2 injected (t/y)	0	268,765	298,011	302,911	303,050	302,334	301,533	300,790	300,126	299,537	299,015
Calculated CO2 produced and recycled (t/y)	0	32,765	62,011	66,911	67,050	66,334	65,533	64,790	64,126	63,537	63,015
Number of production wells (#)	36	20	18	18	18	18	18	18	18	18	18
Number of injection wells (#)	0	16	18	18	18	18	18	18	18	18	18
Total number of active wells (#)	36	36	36	36	36	36	36	36	36	36	36
Number of new wells (#)	0	0	0	0	0	0	0	0	0	0	0
Number of well conversions (#)	0	16	18	18	18	18	18	18	18	18	18
CH4 production from CBM (MCF)	1,202,652	591,304	470,974	416,812	368,878	326,457	288,915	255,689	226,285	200,262	177,232
CH4 production from ECBM (MCF)	0	1,277,306	1,416,297	1,439,585	1,440,245	1,436,842	1,433,036	1,429,504	1,426,349	1,423,550	1,421,069
Total CH4 production (MCF)	1,202,652	1,868,610	1,887,271	1,856,396	1,809,123	1,763,300	1,721,950	1,685,194	1,652,634	1,623,812	1,598,301
Water production (Barrels)	962	1495	1840	1877	1850	1815	1781	1750	1723	1699	1678
In situ CO2 production (MCF)	400,884	622,870	156,991	138,937	122,959	108,819	96,305	85,230	75,428	66,754	59,077
Injected CO2 production (MCF)	0	0	1,021,845	1,133,038	1,151,668	1,152,196	1,149,474	1,146,428	1,143,604	1,141,079	1,138,840
Total CO2 production (MCF)	400,884	622,870	1,178,836	1,271,975	1,274,627	1,261,015	1,245,779	1,231,658	1,219,032	1,207,833	1,197,917
Total gas production (MCF)	1,603,536	2,491,479	3,066,107	3,128,371	3,083,750	3,024,315	2,967,729	2,916,852	2,871,666	2,831,645	2,796,218
CH4 in produced gas (vol. %)	75	75	62	59	59	58	58	58	58	57	57
CO2 in produced gas (vol. %)	25	25	38	41	41	42	42	42	42	43	43
CAPITAL EXPENDITURES											
Permitting ($)	272,000	34,000	0	0	0	0	0	0	0	0	0
Hot tap into CO2 pipeline ($)	100,000	0	0	0	0	0	0	0	0	0	0
CO2 trunk pipeline ($)	1,200,000	0	0	0	0	0	0	0	0	0	0
CO2 lateral pipeline ($)	1,800,000	0	0	0	0	0	0	0	0	0	0
CO2 distribution lines ($)	800,000	100,000	0	0	0	0	0	0	0	0	0
New well drilling & completion ($)	0	0	0	0	0	0	0	0	0	0	0
Converted wells ($)	2,560,000	320,000	0	0	0	0	0	0	0	0	0
Recycled gas compression and dehydration ($)	2,200,000	0	0	0	0	0	0	0	0	0	0
Total capital expenditures ($)	8,932,000	454,000	0	0	0	0	0	0	0	0	0
REVENUE											
CH4 sales (MCF)	1,142,519	1,775,179	1,792,907	1,763,576	1,718,667	1,675,135	1,635,853	1,600,934	1,570,002	1,542,621	1,518,386
CH4 sales ($)	4,570,078	7,100,716	7,171,629	7,054,305	6,874,669	6,700,538	6,543,411	6,403,737	6,280,009	6,170,486	6,073,544
Total revenues ($)	4,570,078	7,100,716	7,171,629	7,054,305	6,874,669	6,700,538	6,543,411	6,403,737	6,280,009	6,170,486	6,073,544
OPERATING EXPENSES											
Purchased CO2 cost ($)	0	7,627,520	7,627,520	7,627,520	7,627,520	7,627,520	7,627,520	7,627,520	7,627,520	7,627,520	7,627,520
Well O&M ($)	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000
Injection well CO2 maintenance ($)	0	67,191	74,503	75,728	75,763	75,584	75,383	75,198	75,032	74,884	74,754
Produced gas processing ($)	801,768	1,245,740	1,533,053	1,564,186	1,541,875	1,512,157	1,483,865	1,458,426	1,435,833	1,415,823	1,398,109
Recycled gas compression & dehydration	0	229,355	434,077	468,377	469,350	464,338	458,731	453,530	448,882	444,759	441,105
Water treatment and disposal ($)	481	747	920	939	925	907	890	875	861	849	839
General & administrative costs ($)	500,000	500,000	500,000	500,000	500,000	500,000	500,000	500,000	500,000	500,000	500,000
Royalties ($)	388,457	603,561	609,588	599,616	584,347	569,546	556,190	544,318	533,801	524,491	516,251
Severance & property taxes ($)	388,457	603,561	609,588	599,616	584,347	569,546	556,190	544,318	533,801	524,491	516,251
Total operating expenses ($)	2,511,162	11,309,675	11,821,250	11,867,981	11,816,127	11,751,598	11,690,769	11,636,184	11,587,730	11,544,818	11,506,829
GROSS MARGIN ($)	2,058,915	-4,208,959	-4,649,621	-4,813,675	-4,941,458	-5,051,059	-5,147,358	-5,232,447	-5,307,720	-5,374,332	-5,433,285

CBM FINANCIAL MODEL (NO CO2 INJECTION)											
Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Year (#)	0	1	2	3	4	5	6	7	8	9	10
PERFORMANCE PARAMETERS											
Number of production wells (#)	36	36	36	36	36	36	36	36	36	36	36
CH4 production from CBM (MCF)	1,202,652	1,064,347	941,947	833,623	737,757	652,915	577,829	511,379	452,570	400,525	354,464
In situ CO2 production (MCF)	400,884	354,782	313,982	277,874	245,919	217,638	192,610	170,460	150,857	133,508	118,155
Total gas production (MCF)	1,603,536	1,419,129	1,255,929	1,111,498	983,675	870,553	770,439	681,839	603,427	534,033	472,619
Water production (Barrels)	962	851	754	667	590	522	462	409	362	320	284
CH4 in produced gas (vol. %)	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00
CO2 in produced gas (vol. %)	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
CAPITAL EXPENDITURES											
Total capital expenditures ($)	0	0	0	0	0	0	0	0	0	0	0
REVENUE											
CH4 sales (MCF)	1,142,519	1,011,130	894,850	791,942	700,869	620,269	548,938	485,810	429,942	380,499	336,741
CH4 sales ($)	4,570,078	4,044,519	3,579,399	3,167,768	2,803,475	2,481,075	2,195,752	1,943,240	1,719,768	1,521,994	1,346,965
Total revenues ($)	4,570,078	4,044,519	3,579,399	3,167,768	2,803,475	2,481,075	2,195,752	1,943,240	1,719,768	1,521,994	1,346,965
OPERATING EXPENSES											
Well O&M ($)	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000	432,000
Produced gas processing ($)	801,768	709,565	627,965	555,749	491,838	435,276	385,220	340,919	301,714	267,017	236,310
Water treatment and disposal ($)	481	426	377	333	295	261	231	205	181	160	142
General & administrative costs ($)	500,000	500,000	500,000	500,000	500,000	500,000	500,000	500,000	500,000	500,000	500,000
Royalties ($)	388,457	343,784	304,249	269,260	238,295	210,891	186,639	165,175	146,180	129,370	114,492
Severance & property taxes ($)	388,457	343,784	304,249	269,260	238,295	210,891	186,639	165,175	146,180	129,370	114,492
Total operating expenses ($)	2,511,162	2,329,559	2,168,839	2,026,603	1,900,723	1,789,320	1,690,728	1,603,475	1,526,255	1,457,916	1,397,435
GROSS MARGIN ($)	2,058,915	1,714,960	1,410,560	1,141,165	902,751	691,755	505,023	339,765	193,512	64,078	-50,471

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Pump Canyon CO_2-ECBM Site
Top 10 Risk Areas

Rank	Risk Area/FEP	Failure Probability (P = 1 to 5)	Failure Severity (S = 1 to 5)	Difficulty of Failure Detection (D = 1 to 5)	Risk Priority Number (PxSxD = 1 to 125)
1	Coal swelling (decreased injectivity)	5	5	2	50
2	Coal seam permeability (decreased injectivity)	5	5	2	50
3	Reservoir permeability and injectivity	5	5	2	50
4	CO_2 quantities, injection rate	5	5	2	50
5	Buildings	3	4	3	36
6	CO_2 release processes	3	4	3	36
7	Topography and morphology	3	4	3	36
8	CO_2 release to the atmosphere	3	4	3	36
9	Geographical location	3	4	3	36
10	Complex structural geology of coal seams	4	3	3	36

HSE risk

Economic risk

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Pump Canyon CO_2-ECBM Site Top 10 Potential Fatal Risk Areas

Rank	Risk Area/FEP	Failure Probability (P = 1 to 5)	Failure Severity (S = 1 to 5)	Difficulty of Failure Detection (D = 1 to 5)	Risk Priority Number (PxSxD = 1 to 125)
1	CO_2 release processes (methane seeps)	3	4	3	36
2	Topography and morphology	3	4	3	36
3	Buildings	3	4	3	36
4	CO_2 release to the atmosphere	3	4	3	36
5	Geographical location	3	4	3	36
6	Accidents and unplanned events	3	4	2	24
7	Excavation/drilling	3	4	2	24
8	Explosions and crashes	2	5	2	20
9	Health effects of CO_2	2	4	2	16
10	Elevated CO_2 in air	2	4	2	16

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Pump Canyon CO_2-ECBM Site Risk Assessment Conclusions

- CO_2-ECBM is technically feasible at this site but not economically feasible at current market prices for CO_2 and natural gas.
- Coal swelling, during CO_2 injection, significantly decreases injectivity.
- The presence of natural CO_2 in the Fruitland Formation and the presence of methane in the Fruitland Formation and in all of the overlying formations will complicate MVA activities for CO_2 sequestration.
- Methane gas seeps are a more probable risk than CO_2 leakage. Methane seeps have been observed in the area since the 1880s.
- Conversion of CBM wells to CO_2 injection wells may be hindered by open-hole cavity completions.
- As long as current CBM operations remain viable, it is unlikely that CO_2 sequestration would be considered in the Fruitland Formation. CBM favors low reservoir pressure and CO_2 sequestration favors high reservoir pressure. Repressurization of the Fruitland Formation via CO_2 injection may be difficult due to limited injectivity.

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Accomplishments to Date

- Identified and characterized a comprehensive list of technical and programmable risks for CO_2 capture, transport and sequestration in DSA, EOR and ECBM operations.
- Developed a comprehensive Quantitative Failure Modes and Effects Analysis (QFMEA) model for CO_2 capture, transport, and sequestration in DSA, EOR and ECBM.
- Developed and employed probability calculations, process- and system-level simulation models, and shortcut calculations to quantify risks.
- Developed cost factors and financial models for CO_2 DSA, EOR and ECBM operations to quantify damage recovery costs, mitigation costs and potential cost savings.
- Completed comprehensive, quantitative risk assessments on three sites:
  - SACROC Northern Platform CO2-EOR Site in the Permian Basin
  - Pump Canyon CO2-ECBM Site in the San Juan Basin
  - Farnsworth Unit CO2-EOR Site in the Anadarko Basin

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Summary

- **Key Findings**
  - QFMEA is an effective tool for quantitative risk assessment and generates the necessary thought process for risk management during design, construction, operation and closure.
  - The CO_2-EOR operations are technically and commercially feasible at current market prices. The breakeven oil price is approximately $40/bbl.
  - The CO_2-ECBM operation is technically feasible, but not commercially feasible at current market prices. The CO_2 cost would need to be close to free or the natural gas price would need to double to be commercially sustainable.
- **Lessons Learned**
  - Most CO_2 sequestration risks can be avoided by proper site selection.
  - Compliance with regulations, codes, permits and best practices is critical.
- **Future plans**
  - Complete final project report.

APPENDIX

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Project Schedule

Description	Work Days	Budget Period 1	Budget Period 2	Budget Period 3	BP 4
		FY2010	FY2011	FY2012 / FY2013	
		O N D J F M A M J J A S	O N D J F M A M J J A S	O N D J F M A M J J A S / O N D J F M A M J	J A S
Project Management, Planning and Reporting					
Update the Project Management Plan	65				
Planning and Reporting	865				
Final report submitted to DOE					
Identify and Characterize Risks					
List of Risks	65				
Comprehensive risk list submitted to DOE					
Features, Events and Processes	63				
FEPS registry submitted to DOE					
Risk Characterization	65				
Risk characterization database submitted to DOE					
Process Influence Diagrams	66				
Process influence diagrams submitted to DOE					
Risk Quantification by Mathematical Modeling					
Develop Process-Level Models	260				
Develop System-Level Models	260				
Probabilistic Calculations	260				
Functioning mathematical models. Summary reports on mathematical modeling submitted to DOE					
Failure Modes and Effects Analysis (FMEA) Model					
Set up FMEA and Prioritize Risks	130				
Functioning FMEA model. FMEA report submitted to DOE					
Evaluate the Impact of Risk Mitigation	130				
Risk Mitigation Cost Savings					
Develop Method for Damage Recovery and Cost Savings	130				
Report on risk mitigation cost savings submitted to DOE					
Application of Risk Assessment Model					
Risk Assessment of CO_2 Sequestration Sites	455				
CQRA report for Site A submitted to DOE					
CQRA report for Site B submitted to DOE					
CQRA report for Site C submitted to DOE					

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Bibliography

- Lepinski, J.A., 2010, Risk assessment and management tools for CO_2 geologic sequestration. Energy and Environmental Conference (EUEC), Phoenix, AZ, February 1, 2010.
- Lepinski, J.A., 2010, Comprehensive and quantitative risk assessment of CO_2 geologic sequestration. DOE/EPA Collaborative Review Meeting, Pittsburgh, PA, March 23, 2010.
- Wriedt, J.; Deo, M.; Lee, S-Y; Han, W.S.; McPherson, B.; and Lepinski, J.A., 2011, A methodology for quantifying risk and likelihood of failure for carbon dioxide injection into saline aquifers. Tenth Annual Conference on Carbon Capture & Sequestration, Pittsburgh, PA, May 2-5, 2011.
- Keating, G. N., Viswanathan, H. S., Letellier, B. C., Han, W. S., Wriedt, J., Lee, S-Y, Deo, M., and Lepinski, J. A., 2011, CO_2 leakage risk: assigning metrics. Tenth Annual Conference on Carbon Capture & Sequestration. Pittsburgh, PA, May 2-5, 2011.
- Lepinski, J.A., 2012, Comprehensive and quantitative risk assessment of CO_2 geologic sequestration DE-FE0001112 annual review. NETL WebEx, February 15, 2012.
- Viswanathan, H., Keating, G., Letellier, B., Keating, E., Dai, Z., Pawar, R., Lopano, C., Hakala, J., 2012, Uncertainty quantification of shallow groundwater impacts due to CO_2 sequestration. SIAM Conference on Uncertainty Quantification, Raleigh, NC, April 2-5, 2012.
- Lepinski, J.A., 2012, Comprehensive and quantitative risk assessment of CO_2 geologic sequestration DE-FE0001112, NETL Carbon Storage R&D Project Review Meeting, Pittsburgh, PA, August 21-23, 2012.
- Wriedt, J., Deo, M., Han, W.S., Lepinski, J.A., 2013, Application of best practices carbon dioxide injection for the northern platform of the SACROC unit in the Permian Basin, technical poster presented at the Permian Basin CCUS Center Interactive Two-Day Forum, Odessa, TX, March 25-26, 2013.