Team 2: CO2-Circulated EGS Combined with IGCC in New Mexico

Integrated EGS and IGCC
with CO2 as the working fluid

Geology

Economics

Reservoir Simulation

Policy

Conclusions

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CO2-Circulated EGS Combined with IGCC in New Mexico

The Pennsylvania State University
In Partial Fulfillment of EME 580

Divya Chandra
Caleb Conrad
Vaibhav Rajput
Anukalp Narasimharaju

Problem Statement:

Resource assessment and utilization of geothermal energy potential of the Rio Grande Rift Basin: A technical overview and economic analysis of a combined EGS-IGCC system with CO_2 as the working fluid.

Why EGS and IGCC?

Semi Arid Region

Good Geothermal Energy Resource

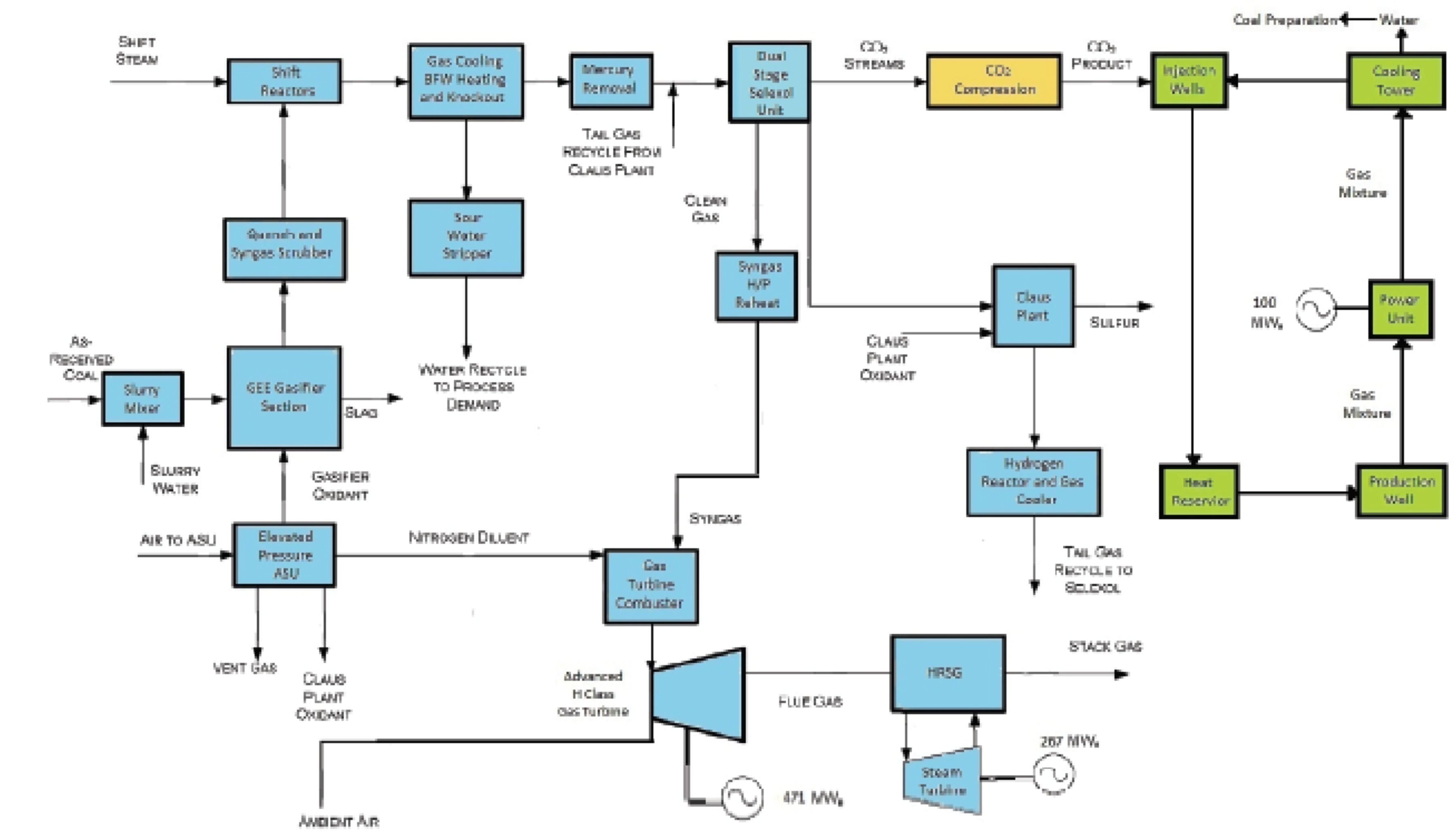
CO_2-by product of IGCC, will be used as working fluid

Question:

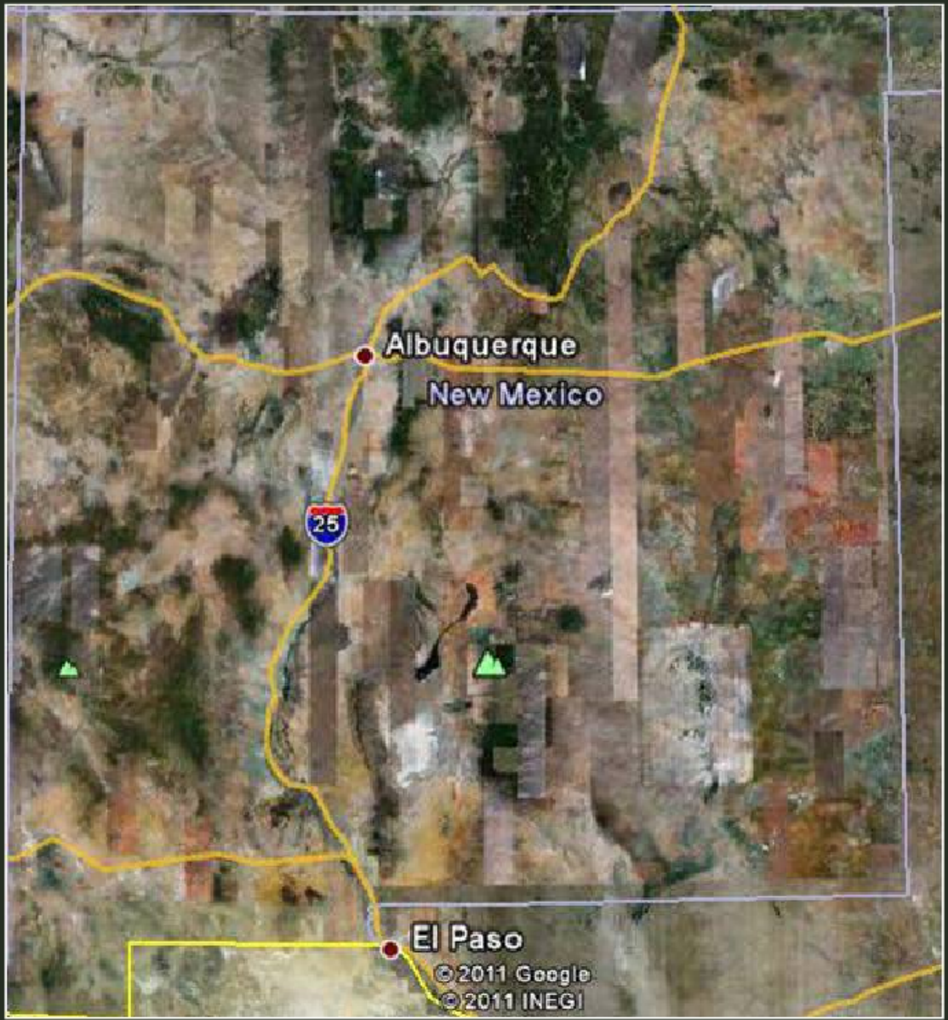
Is the available water resource being wisely used for power?

EGS only:
180kg/sec water =~150MW Ideal Power Output

EGS and IGCC:
180 kg/sec water =~ 650MW Real Power to the grid


Coal Preparation
Water
Shift Steam
Shift Reactors
Gas Cooling BFW Heating and Knockout
Mercury Removal
Tail Gas Recycle From Claus Plant
Dual Stage Selexol Unit
CO_2 Streams
CO_2 Compression
CO_2 Product
Injection Wells
Cooling Tower
Gas Mixture
Clean Gas
Sour Water Stripper
Quench and Syngas Scrubber
Syngas H/P Reheat
Claus Plant
Sulfur
100 MW_e
Power Unit
Claus Plant Oxidant
As-Received Coal
Slurry Mixer
GEE Gasifier Section
Slag
Water Recycle to Process Demand
Gas Mixture
Hydrogen Reactor and Gas Cooler
Heat Reservoir
Production Well
Slurry Water
Gasifier Oxidant
Syngas
Air to ASU
Elevated Pressure ASU
Nitrogen Diluent
Gas Turbine Combuster
Tail Gas Recycle to Selexol
Vent Gas
Claus Plant Oxidant
Advanced H Class Gas Turbine
HRSG
Stack Gas
Flue Gas
267 MW_e
Steam Turbine
471 MW_e
Ambient Air

Introduction



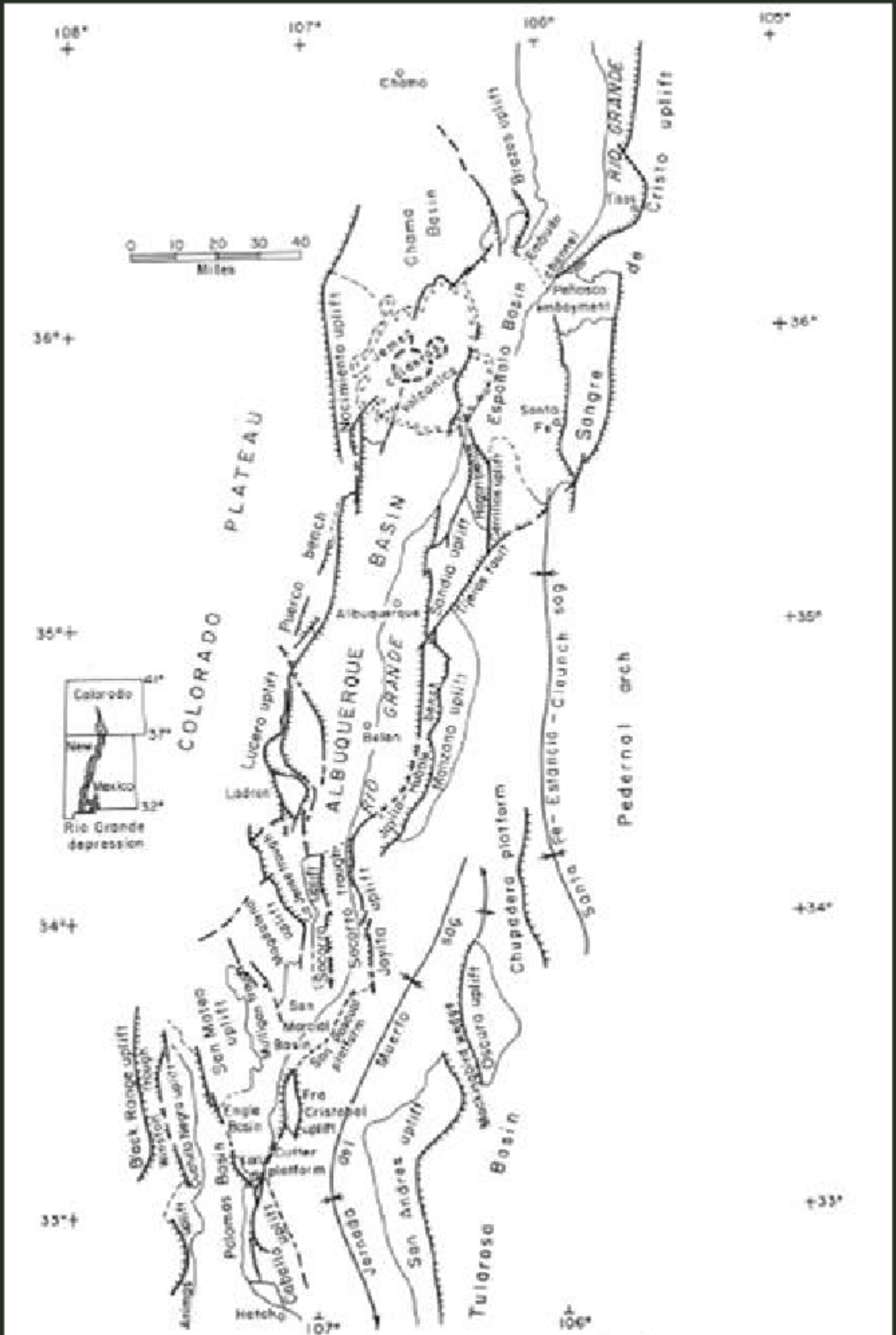
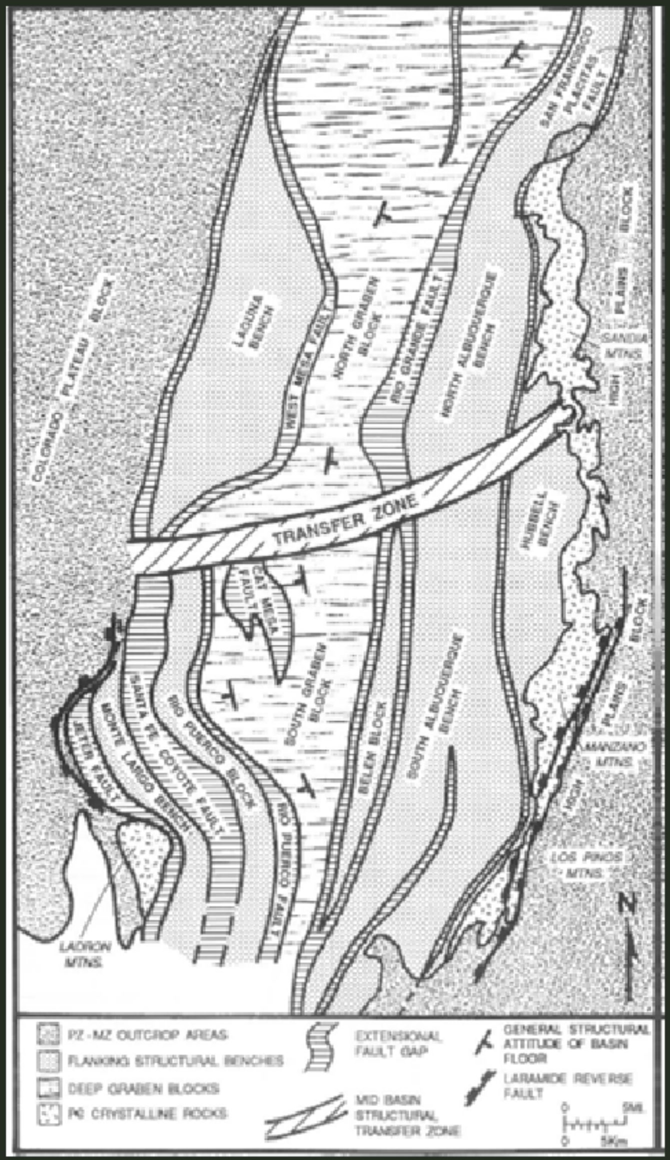


FIGURE 11—Tectonic map of Rio Grande rift system in New Mexico.

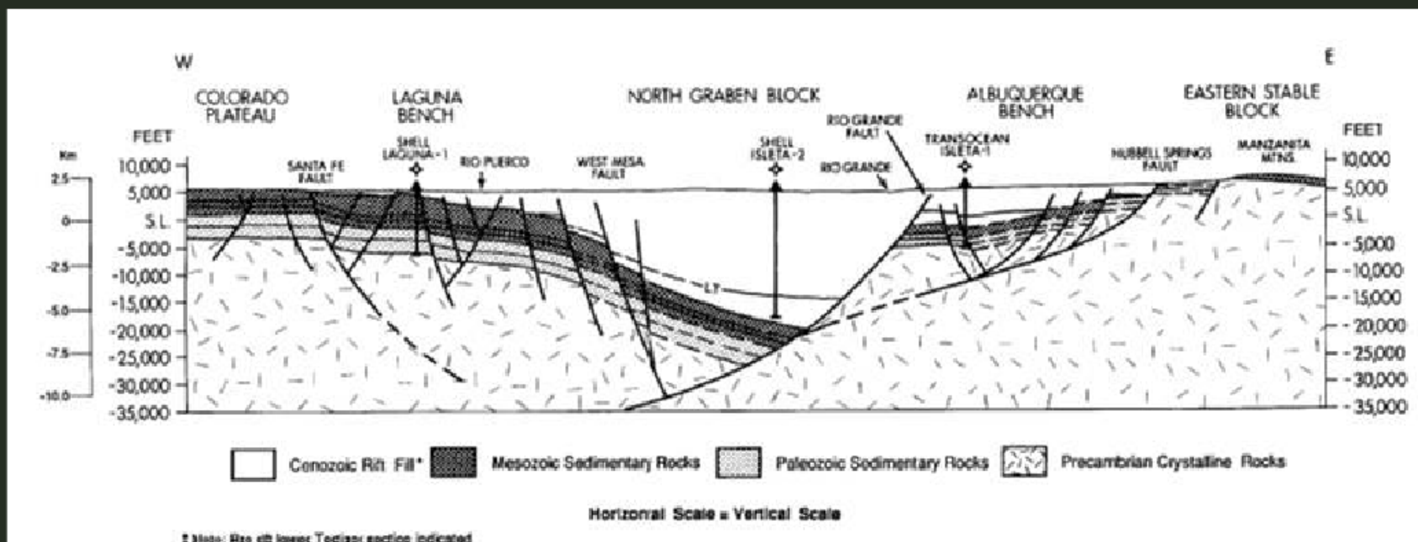
Tectonic Map of the Rio Grande Rift Basin in New Mexico (Kelley 1977)

Generalized Structure of Albuquerque Basin



(Russel and Snelson 1994)

Geologic Cross-section Across the Site



(Russel and Snelson 1994)

<u>Source Characteristics:</u>

- Depth: 3.2 km to 5 km
- Temperature: 200 °C
- Temperature Gradient:
  - 39 °C/km
- Reservoir Rocks:
  - Crystalline Basement
- Reservoir Type:
  - Geo-pressured System

<u>Available Data:</u>

- Seismic Reflection
- Existing borehole data
  - Rock Types
  - Mud weights
  - Geophysical logs
- Geologic Mapping
- Aerial Magnetic Data

Reservoir Simulation

Important Questions to be answered in Geothermal Reservoir Simulation:

1. What is the most suitable development plan of the reservoir? ✓
2. How many wellbores should be drilled to reach the most suitable development plan? What would be the well pattern? ✓
3. What will be the production rates of the wellbores? ✓
4. How much heat will be recovered? ✓
5. How will the change in reservoir temperature be? ✓

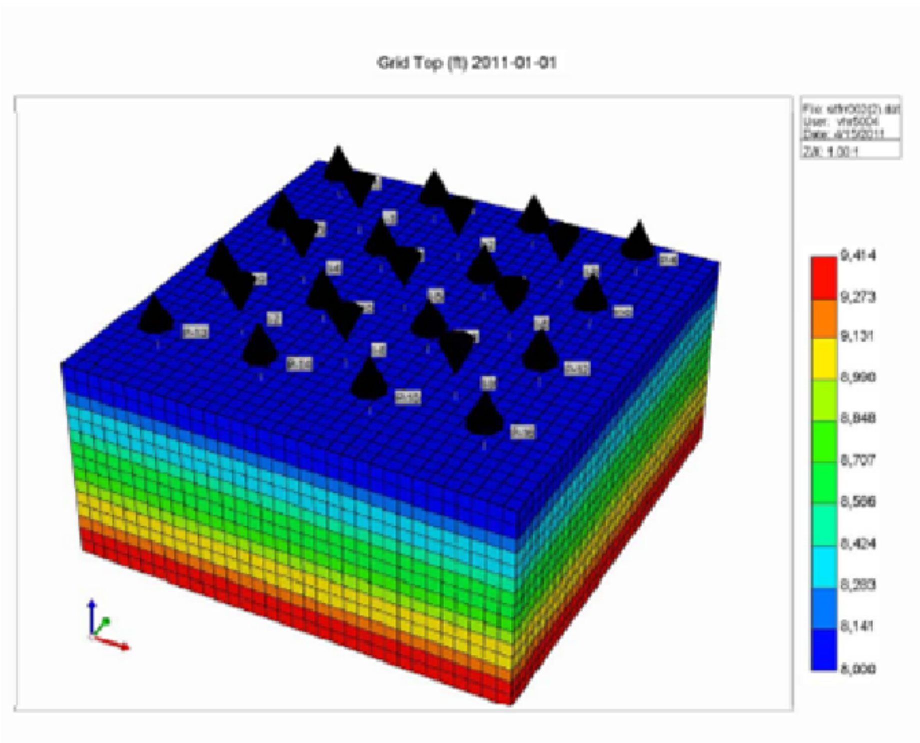
Assumptions made while preparation of the model:

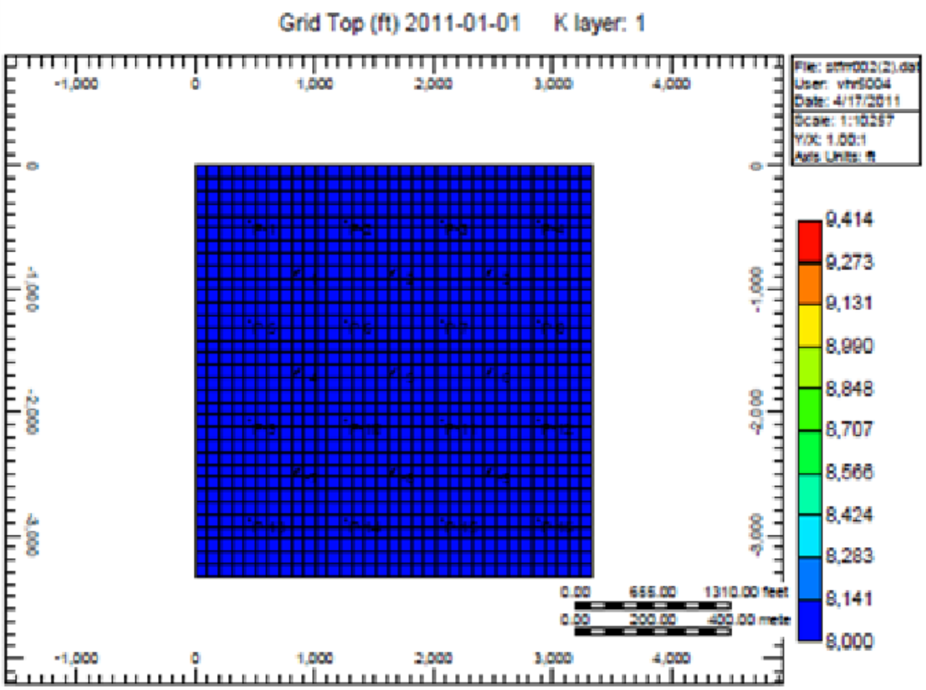
1. Thermal equilibrium exists everywhere at all times
2. Only CO_2 (50%) and water (50%) exist at initial reservoir condition
3. Injection is pure CO_2
4. Dual porosity model

Parameters for the model

Parameter	Value
Initial formation temperature	392 °F (200 °C)
Initial reservoir pressure	5000 psia
Total formation thickness	1500 ft
Reservoir depth	8000 ft
Matrix porosity	0.1
Fracture porosity	0.1
Matrix permeability	0.01 md
Fracture permeability	0.6 md
Fracture Spacing	30 ft
Injector-Producer distance	500 ft
Injection temperature	60 °F
Initial water saturation	0.5
Residual water saturation	0.3
Rock thermal conductivity	2.1 W/m/°C
Rock specific heat	1000 J/kg/°C

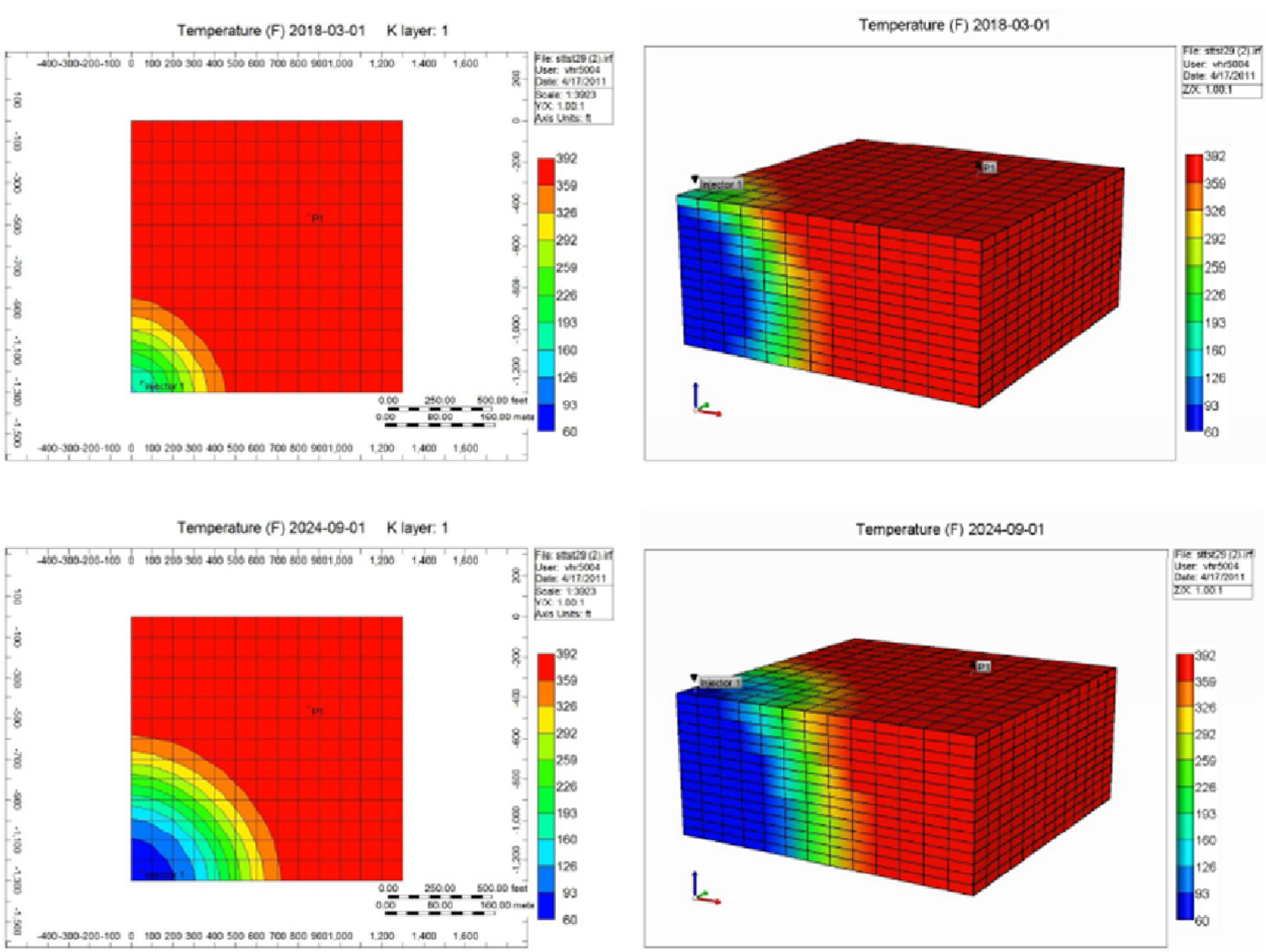
CMG STARS™ Results





Reservoir Geometry:

- 9 Injectors, 16 Producers
- 5-spot pattern
- Injector–Producer distance: 500 ft
- Additional 400 ft space for CO_2 migration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File: sttst29 (2).irf
User: vhr5004
Date: 4/17/2011
Scale: 1:3923
Y/X: 1.00:1
Axis Units: ft
392
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226
193
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P1
Injector 1
0.00 250.00 500.00 feet
0.00 80.00 160.00 meters
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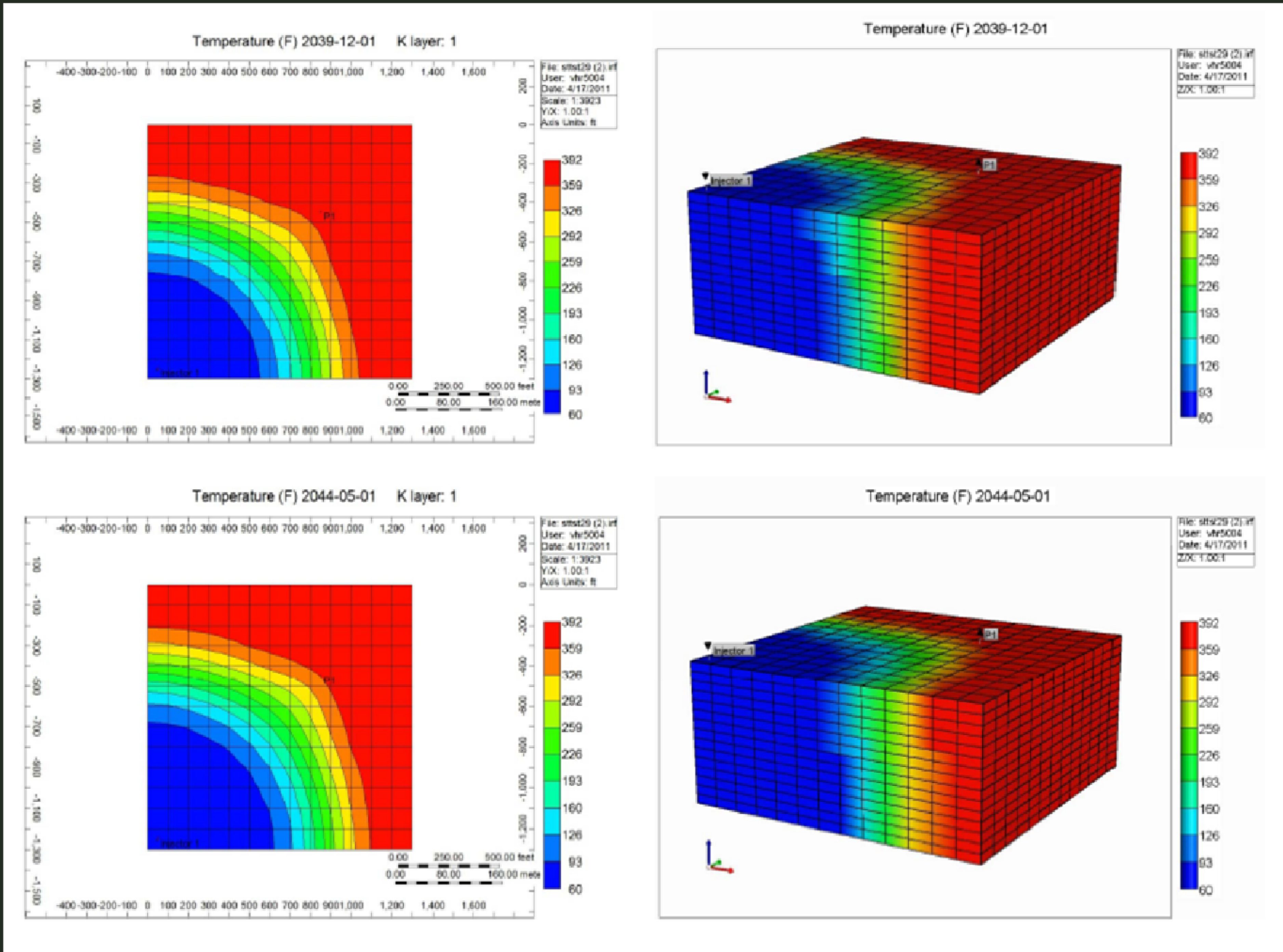
Temperature (F) 2039-12-01 K layer: 1
File: sttst29 (2).irf
Date: 4/17/2011
Scale: 1:3923
Y/X: 1.00:1
Axis Units: ft
Injector 1
P1
0.00 250.00 500.00 feet
0.00 80.00 160.00 meters
392
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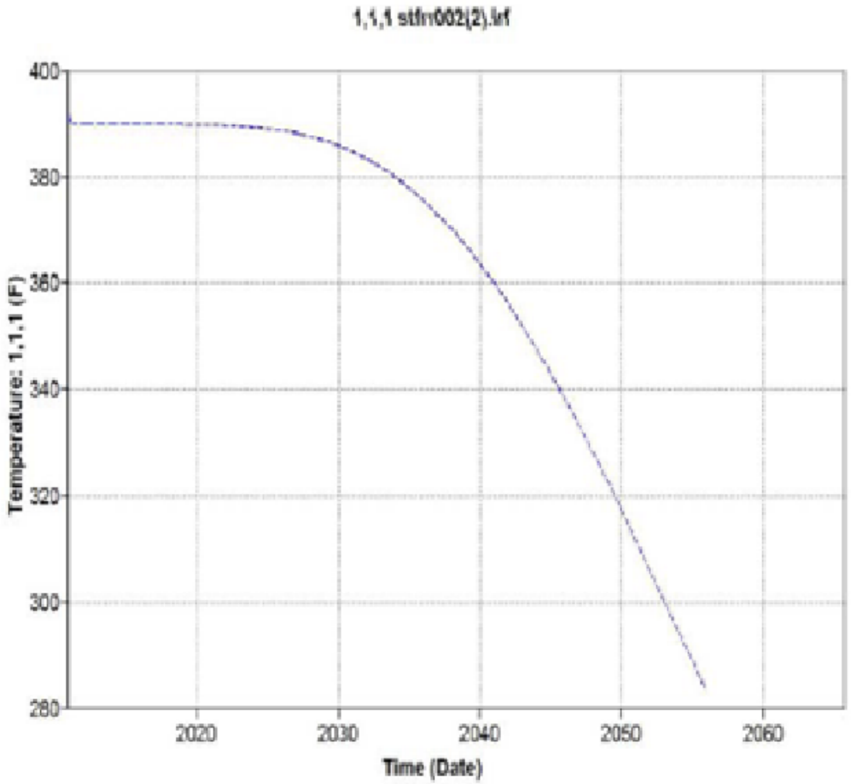
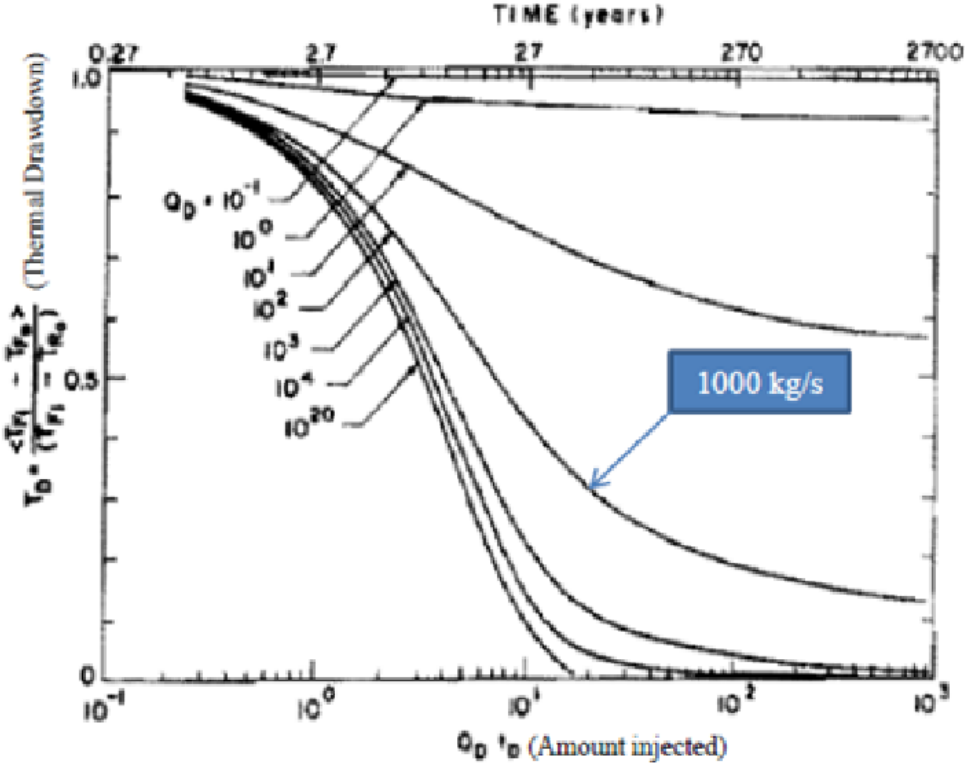
Temperature (F) 2039-12-01
Z/X: 1.00:1
Temperature (F) 2044-05-01 K layer: 1
Temperature (F) 2044-05-01

Thermal Drawdown

- CMG STARS™ results were compared with those of Spherical Reservoir Model (SRM)





CO_2 corrosion

- Carbon dioxide in presence of water forms acid, which corrodes the piping equipment
- Prevention methods include formation of a protective iron carbonate layer.

  Conditions favoring formation of this layer include:

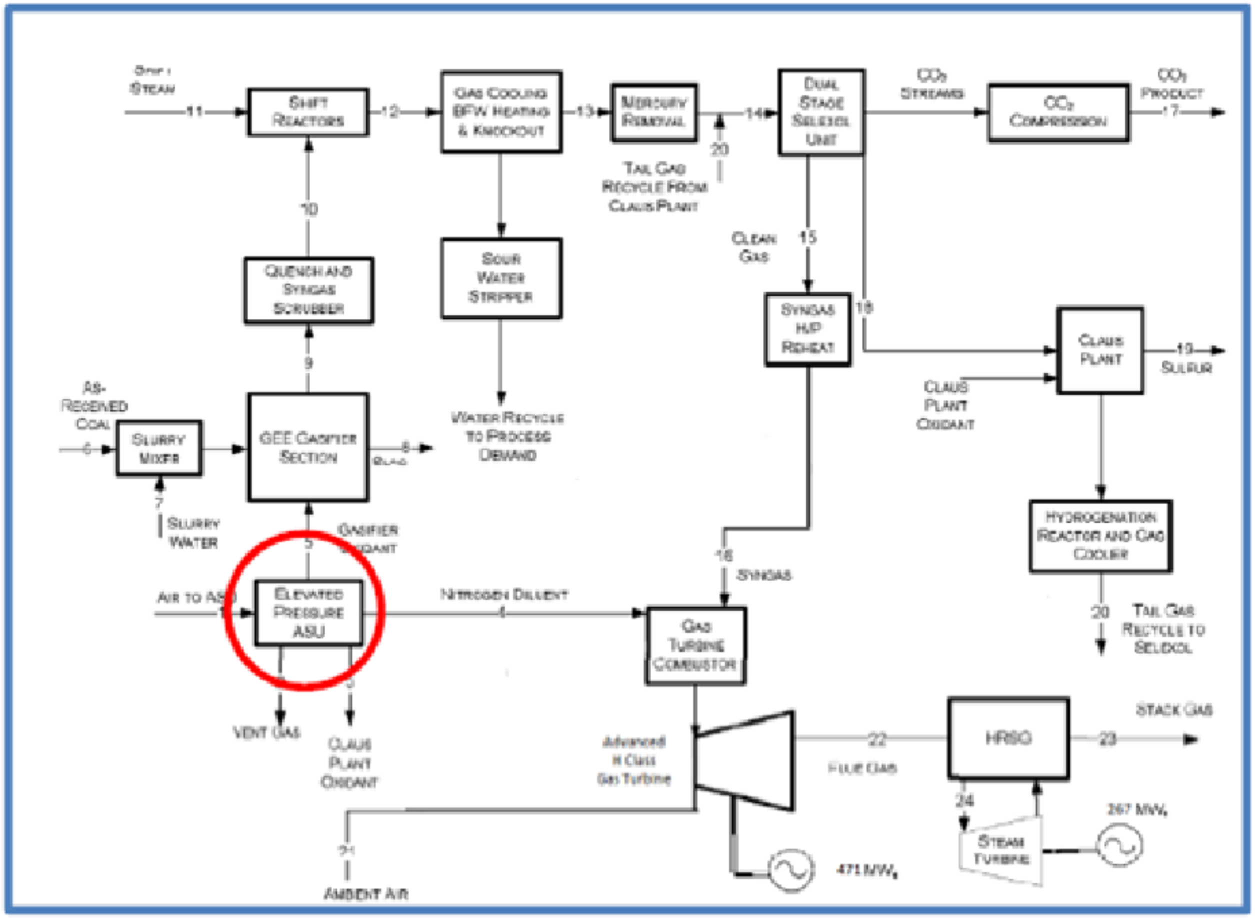
  1. Elevated temperature ✓
  2. Increased pH ✗
  3. Lack of turbulent flow regime ✗
- Another option: Use of high Ni austenitic stainless steel:

  Corrosion is prevented mainly due to Cr(18%) and Ni(8%) content

Important Results from Simulation and Literature study

- Water+CO_2 production occurred till 3 years and 8 months
- After irreducible water saturation (30%) was reached, only CO_2 was produced
- Abandonment or limiting temperature: 190 °F
- Period of operation: 33 – 40 years
- High Ni austenitic stainless steel has to be used to prevent corrosion

IGCC Plant Design-ASU



Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. DOE/NETL Revision 2, November 2010

Air Separation Unit

Air Separation Unit's primary purpose:

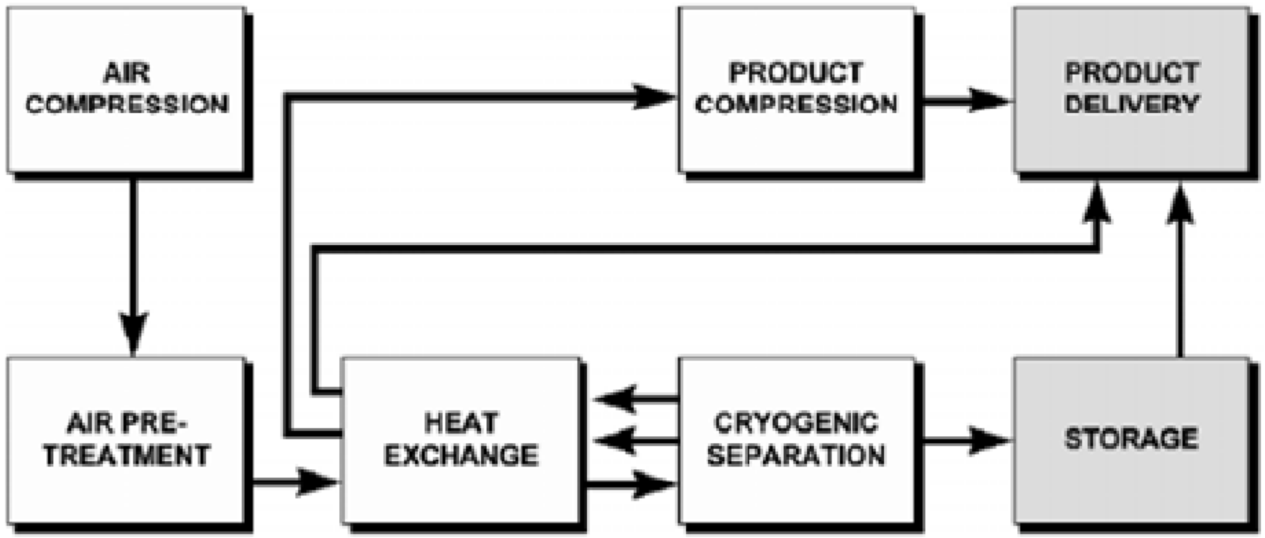
- To supply oxygen for gasification process.
- Nitrogen to Turbines as diluents.

Types of Air Separation Technologies

Non Cryogenic Technologies
1 Adsorption
2 Polymeric Membranes
3 Ion Transport Membranes

Cryogenic Technology

Cryogenic Technology



Cryogenic Processing

- Uses cryogenic distillation to separate oxygen and nitrogen
- Removes water, CO_2 and hydro-carbons
- Most Efficient and cost effective
- Liquid products

Smith A.R (2001)

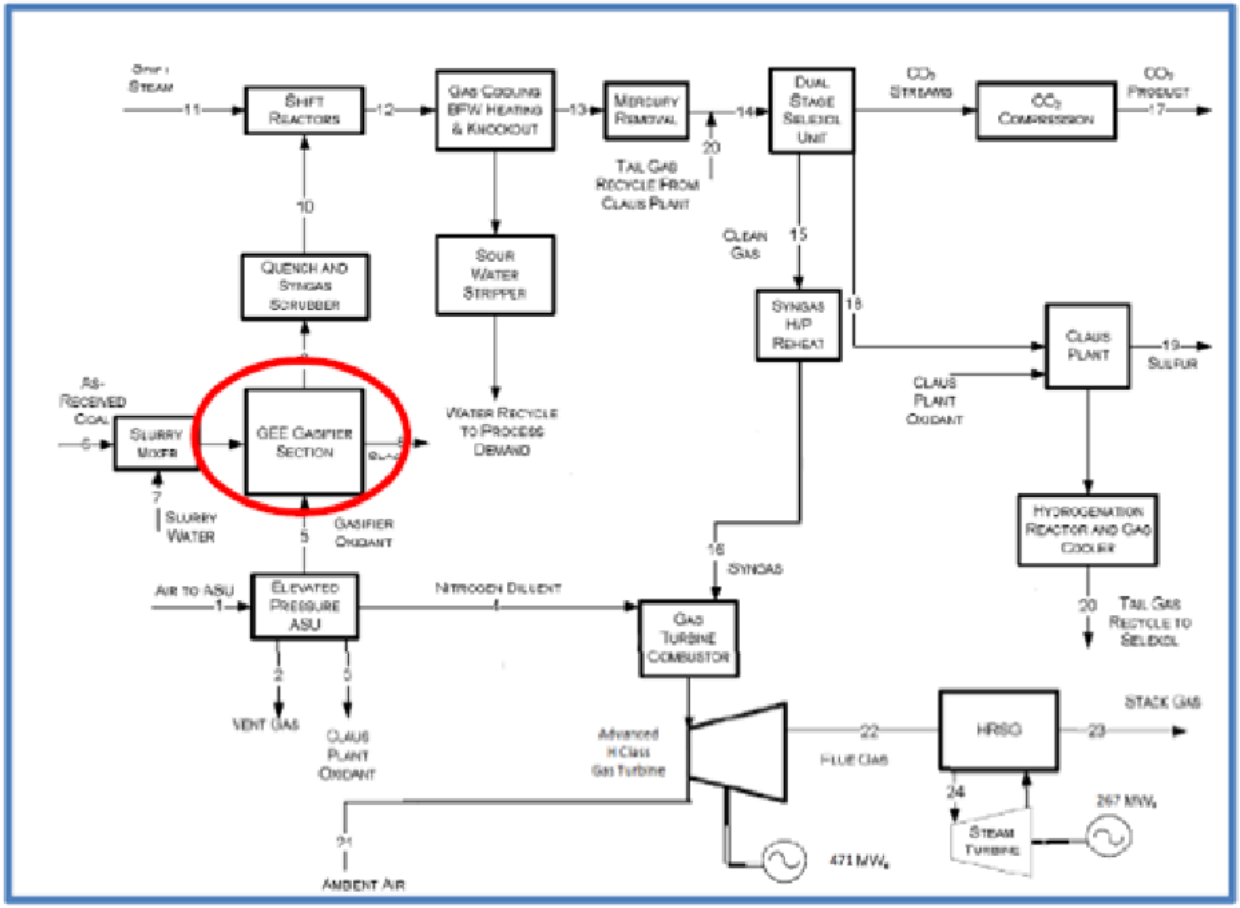
Air Separation Unit

- Air Separation units are selected basis on
- Purity
- Pressure
- Use pattern
- Specific rate
- Integration opportunities with other process

Technology Comparison Table (Smith A.R (2001))

Process	Status	Economic range(sTPD)	Byproduct capability	Purity limit(vol%)	Start-up time
Adsorption	Semi-mature	<150	Poor	95	Minutes
Membrane	Semi-mature	<20	Poor	40	Minutes
ITM	Developing	undetermined	Poor	99+	Hours
Cryogenic	mature	>20	excellent	99+	Hours

IGCC Plant Design-Gasifier



Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. DOE/NETL Revision 2, November 2010

Gasification
How it works

Steam Reformation

0.59kg water per 1 kg coal

$$H_2O + C(s) \rightarrow H_2 + CO$$
$$2H_2O + C(s) \rightarrow 2H_2 + CO$$

Partial Oxidation

0.95 kg O_2 per 1kg coal

$$C(s) + O_2 \rightarrow CO_2$$
$$2C(s) + O_2 \rightarrow 2CO$$

Liu et al, *Hydrogen and Syngas Production and Purification Technologies*

Reactor Type
GE energy(Texaco) model

Common Reactors
- Long Residence Times
- Solid Feed into Pressurized Reactor
- Coal Type Limitations
- Moderate Temperatures

GE Advantages
- Short Residence Time
- High Temperature
- Few Coal Constraints
- Coal Water Slurry Feed.

Phillips, *Different Types of Gasifiers and Their Integration with Gas Turbine*

Operational Parameters
standard operation

Coal composition: Bituminous coal

Coal water slurry ratio: 63%

Temperature: 1300°C

Pressure: 5.6 MPa

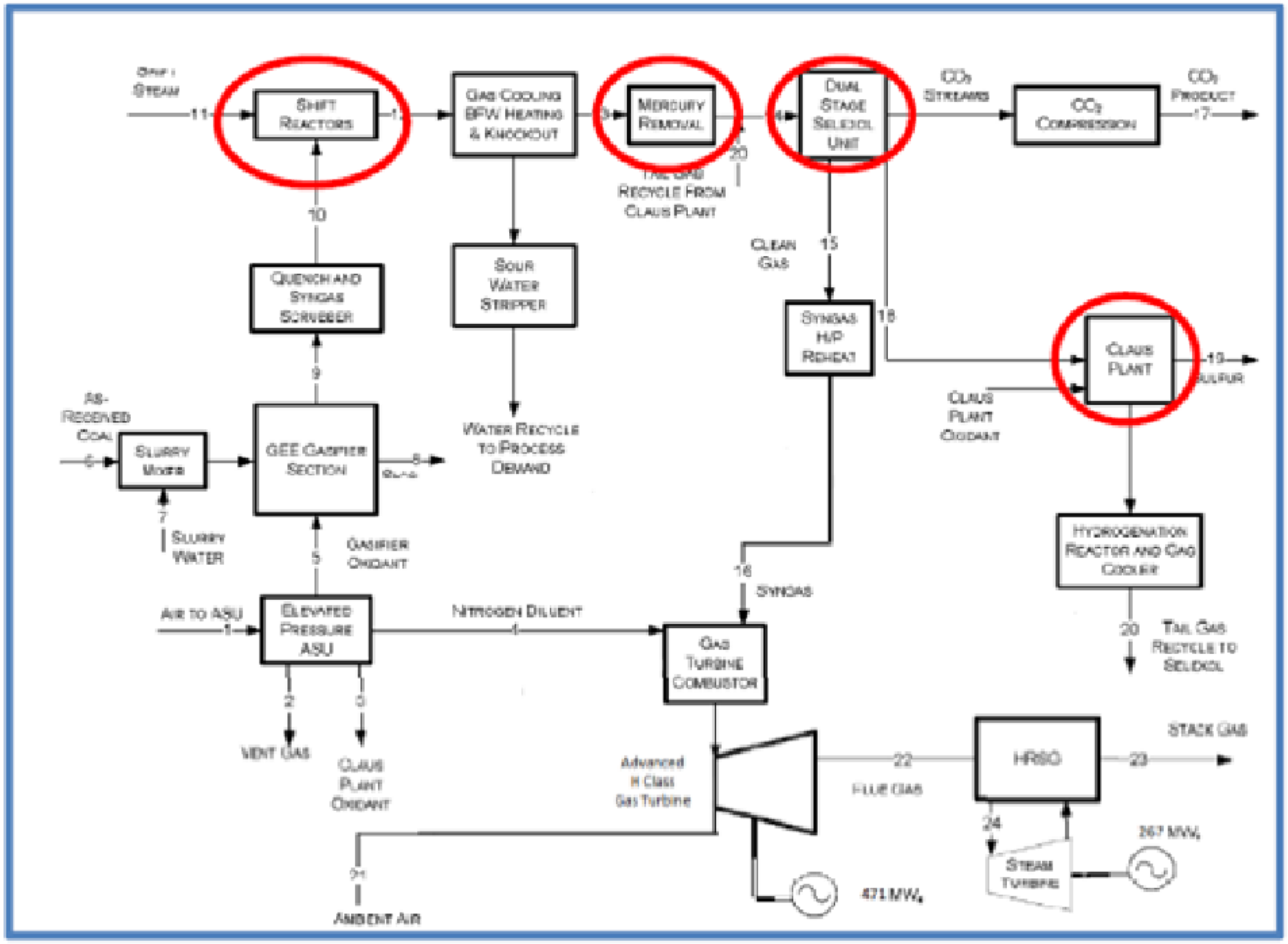
Residence time: 5-15 seconds

Oxygen/carbon ratio: 0.95

Efficiency : 73%

Liu et al, *Hydrogen and Syngas Production and Purification Technologies*

IGCC Plant Design-Gas Cleaning Units



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Water Gas Shift (WGS) Reactor

Discovered over two centuries ago

Used for various chemical processes

Positioned up or downstream of AGR → Upstream

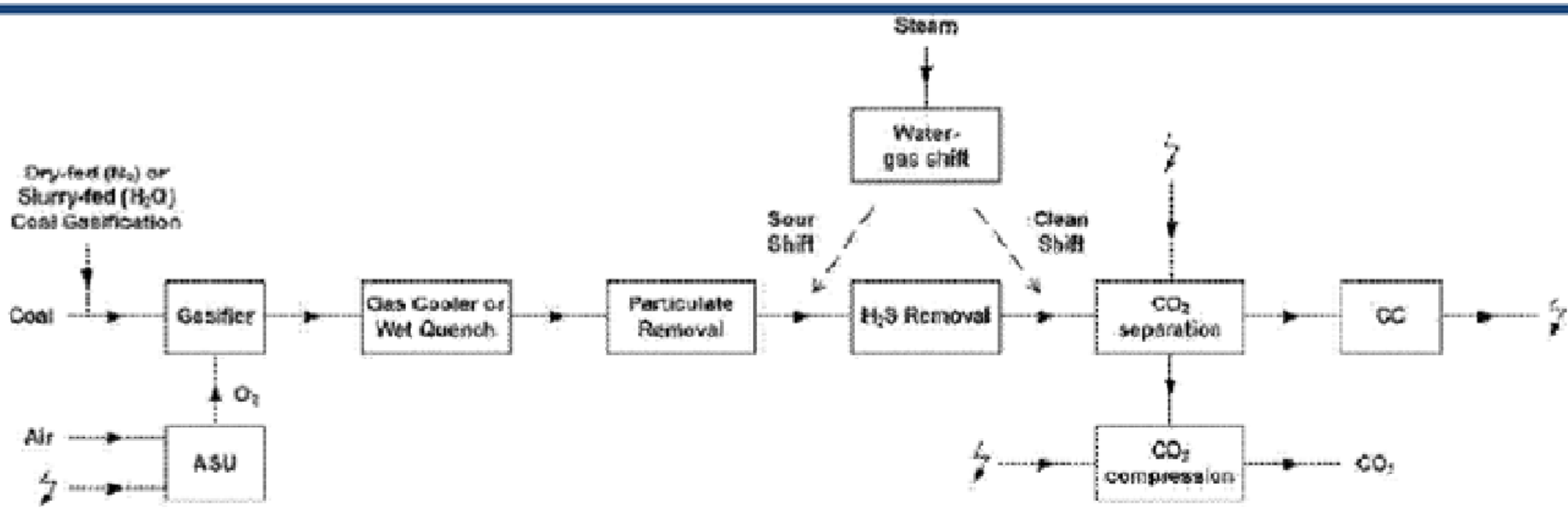


Fig. 1. Integrated Gasification Combined Cycle (IGCC) with pre-combustion CO_2 capture.

Steam demand reduction of water-gas shift reaction in IGCC power plants with pre-combustion CO2 capture, Carbo, Boon, Jansen

Water Gas Shift (WGS) Reactor

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

Thermodynamically favored at lower temperatures

But

Kinetically driven at higher temperatures

$=$ Two stage reaction

Two-stage Sour Gas Shift Reaction

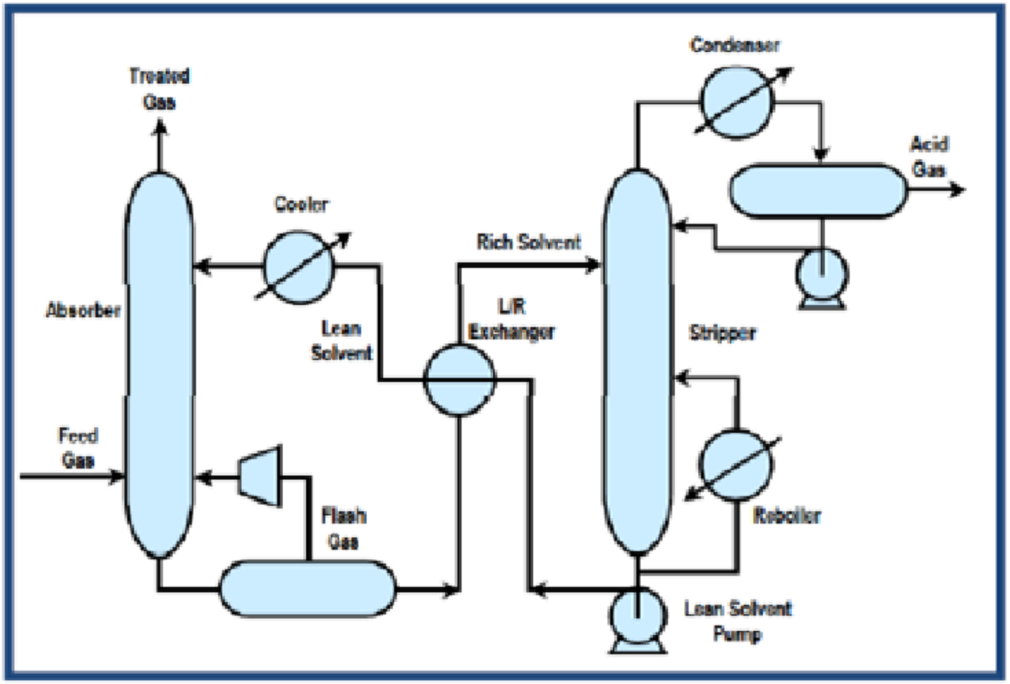
- **Same catalyst for both stages**
  - Catalyst: $CoMo/Al_2O_3$
    - Sulfur Resistant
    - Hydrolizes COS to H_2S
- **High Temperature (HT) Shift (340-530°C)**
  - Rapid CO conversion
- **Low Temperature (LT) Shift (180-230°C)**
  - Promotes Lower CO levels

97% Conversion of CO

Mercury Removal

Catalyst (Absorbent):	Activated, sulfur impregnated, Carbon
Operation Parameters:	Low Temp (30 - 38°C) High Pressure (6.2 MPa)
Removal Efficiency:	90 - 95%
Carbon Bed Life:	18 – 24 Months Hg buildup 0.6 - 1.1 wt.% (20 wt.% max)

Flow Diagram of Selexol Process

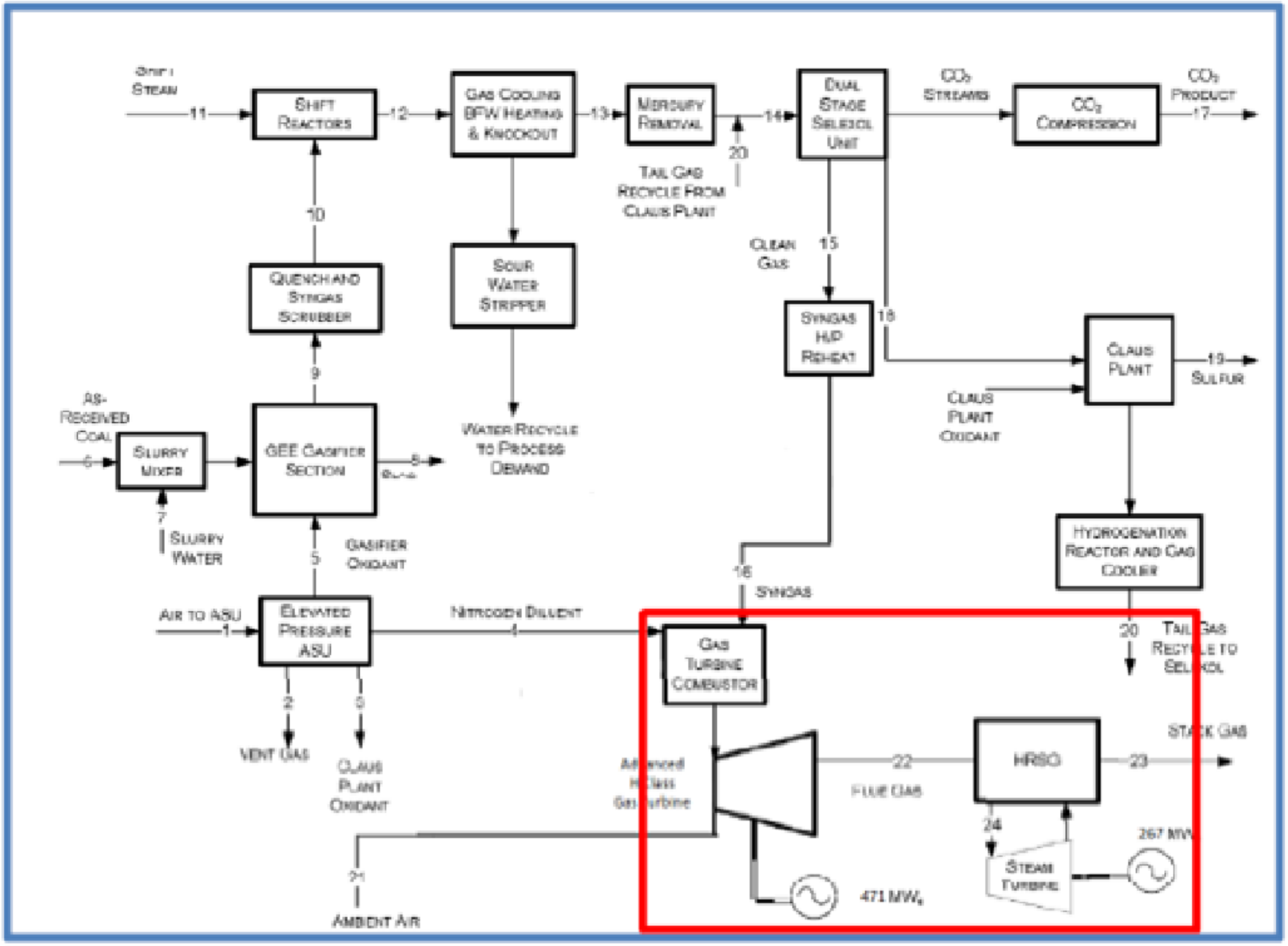


<u>Physical Absorption of Acid Gases</u>

- Low temperature and high pressure favor absorption
- Gases stripped in separation unit
  - Solvent regenerated and sent back to absorber
- H_2S removed and sent to Claus Plant
  - S-capture 99.7%
  - Generates sulfur for economic value
- CO_2 recovered and sent to EGS
  - 90.3% captured from syngas stream
  - Used as heat transfer fluid instead of water

Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. DOE/NETL Revision 2, November 2010

IGCC Plant Design- Power Unit



IGCC - Turbines

Gas Turbines

- Compressor
  - Aerodynamic Design enables higher firing temperature
- Combustion Chamber
  - Combustion of hydrogen fuels with less Nox production and minimal combustion instability

Steam Turbines – Heat Recovery Steam Generation

- Heat Recovery Steam Generation
  - Thermal Energy is extracted from flue gases of CT
  - Generates superheated steam
  - Provides feed water heating
- Turbine
  - Consist of LP, IP and HP sections.
  - Used steam is sent to HRSG
  - The reheated steam is used for IP and LP section

IGCC - Turbines

Justification for H-Class
•Higher maximum net energy production •Higher thermal efficiency •Higher operating temperatures (less nitrogen dilution required) •More expensive

Dimensions
Length – 12m (39.4 ft) Diameter – 5m (16.4 ft) Weight – 370 tons 14 total combustion chambers

Safe Drinking Water Act

Federal law that monitors, sets standards and ensures the quality of drinking water all over the country

With respect to wells, the SDWA has an Underground Injection Control (UIC) program that "…is responsible for regulating the construction, operation, permitting, and closure of injection wells that place fluids underground for storage or disposal."

Source: http://water.epa.gov/type/groundwater

Section 1422

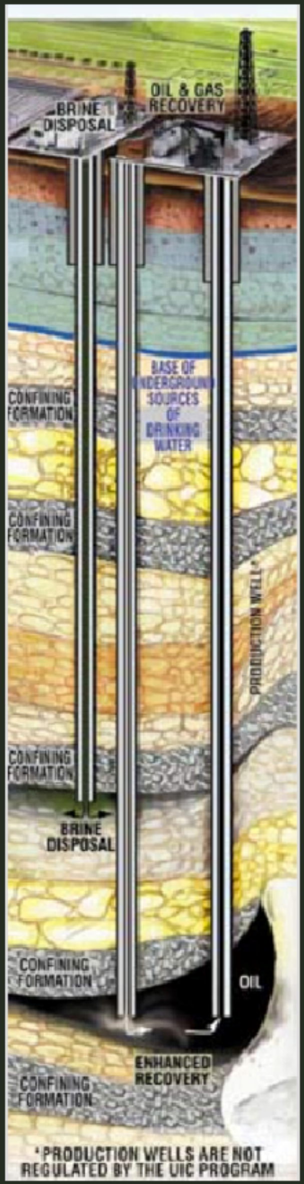
Requires states to meet EPA's minimum requirements for UIC programs.

Must include construction, operating, monitoring and testing, reporting, and closure requirements for well owners or operators.

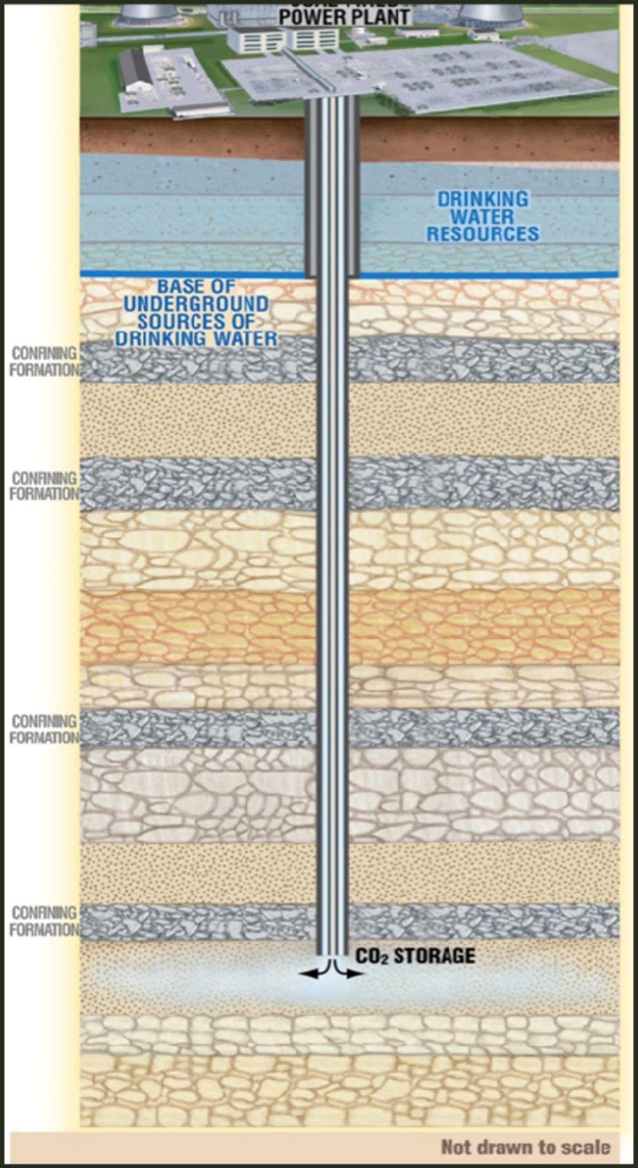
The owners or operators of the wells must meet all applicable requirements, including strict construction and conversion standards and regular testing and inspection

Source: http://water.epa.gov/type/groundwater

Class II



Class VI

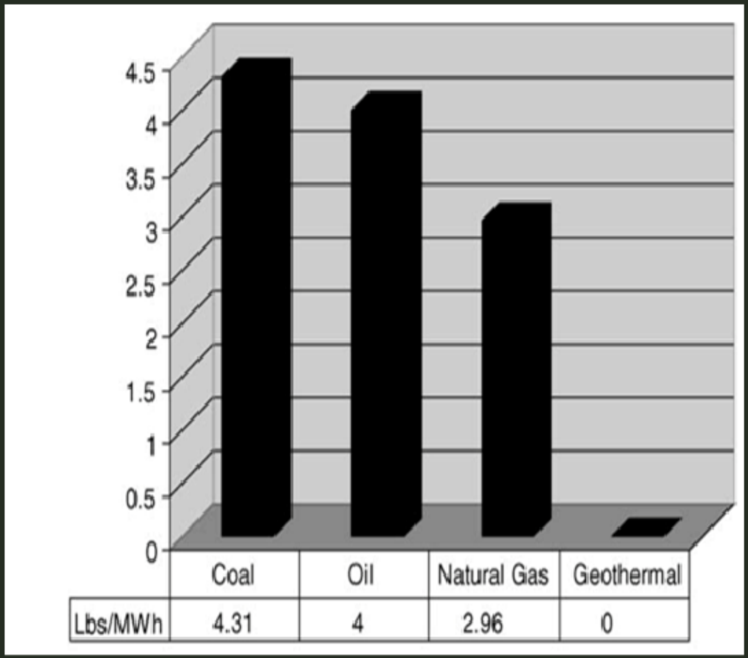


Source: http://water.epa.gov/type/groundwater

Nitrogen Oxides

Major Source is the Burning off of Hydrogen Sulfide through abatement systems.

On comparison with coal, current generation of 15 Billion kWh reduces NOx emissions by around 32,000 Tons compared with coal plants.



Coal, oil, and geothermal reported as average existing power plant emissions; natural gas reported as average existing steam cycle, simple gas turbine, and combined cycle power plant emissions.[6]

Nitrogen Oxide Comparison

Source: Promoting Geothermal Energy: Air Emissions Comparison and Externality Analysis, Alyssa Kagel and Karl Gawell

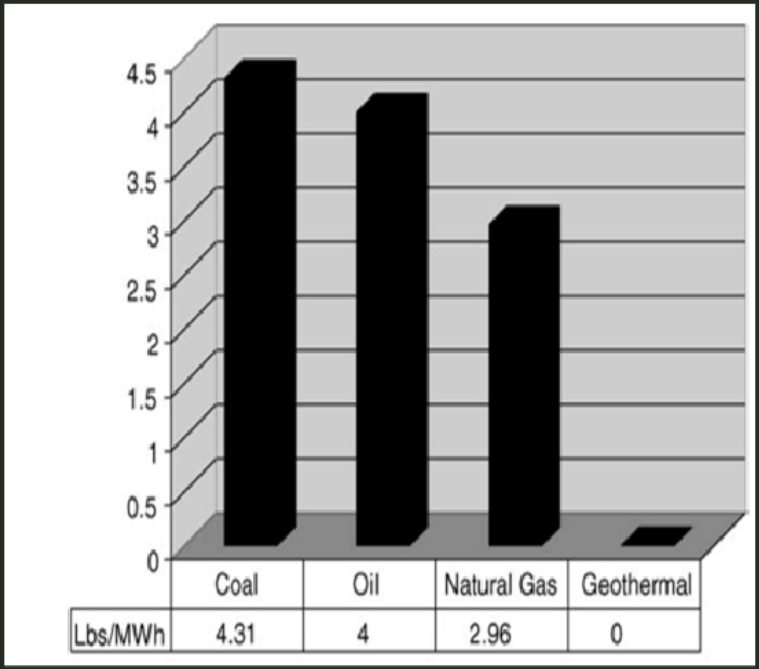
Sulfur Dioxide and Hydrogen Sulfide

Sulfur Dioxide (SO_2):

The hydrogen sulfide released into the atmosphere oxidizes naturally in the air and oxidizes to sulfur dioxide and sulfuric acid.

The current geothermal generation of about 15 billion kWh avoids the potential release of 78,000 tons of sulfur oxides

H_2S:
Hydrogen Sulfide abatement systems are able to remove over 99.7% of the H_2S
Converted Sulfur can be used as fertilizer feedstock and as a soil amendment



*Calculation converts hydrogen sulfide to sulfur dioxide for comparison only
Coal, oil, and geothermal reported as average existing power plant emissions; natural gas reported as average existing steam cycle, simple gas turbine, and combined cycle power plant emissions.

Sulfur Dioxide Comparison

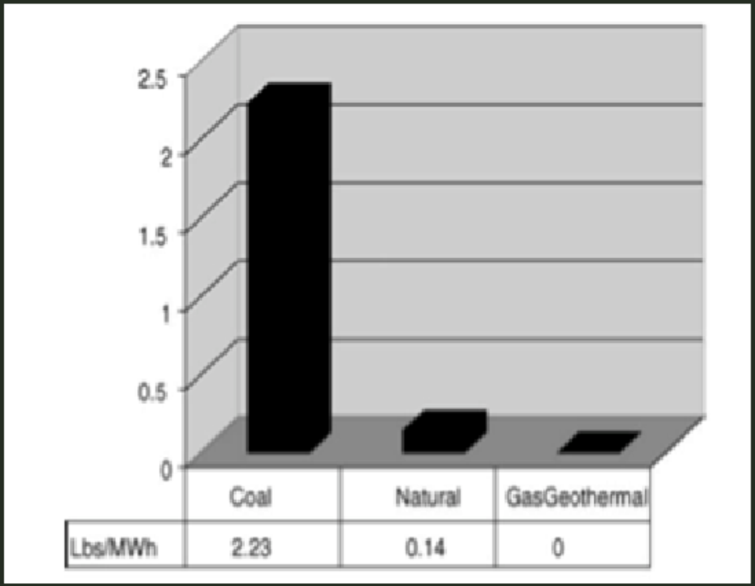
Source: Promoting Geothermal Energy: Air Emissions Comparison and Externality Analysis, Alyssa Kagel and Karl Gawell

Particulate Matter

Coal plants and Oil-fired plants give out 100s of tons of PM per year.

In Geothermal plants, during the Cooling Cycle, very small amounts of PM are given off from the cooling tower.

Annual Saved PM each year:17,000 tons



Comparing pulverized coal boiler, natural gas combined cycle, and geothermal.

Particulate Matter Comparison

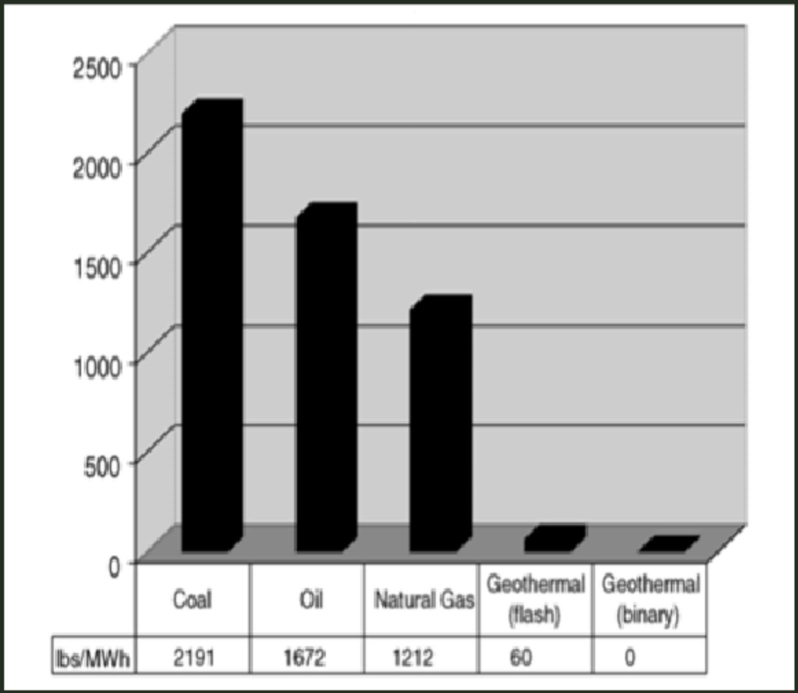
Source: Promoting Geothermal Energy: Air Emissions Comparison and Externality Analysis, Alyssa Kagel and Karl Gawell

Carbon Dioxide

Emissions of CO_2 from the plant.

Saved Emissions compared to Coal fired plants: 17 Million tons.

Binary plants are closed loop. The geothermal fluid is never exposed to the atmosphere.



Coal, oil, biomass, and geothermal reported as average existing system emissions; natural gas reported as average existing steam cycle, simple gas turbine, and combined cycle system emissions.

Carbon Dioxide Comparison

Source: Promoting Geothermal Energy: Air Emissions Comparison and Externality Analysis, Alyssa Kagel and Karl Gawell

The Acid Deposition Control Program

An allowance is an authorization to emit one ton of SO_2

New facilities that are set up will have to obtain allowances from holders of existing allowances.

Utilities may obtain allowances from other industries under certain regulations specified by the EPA or may be banked for future use.

The SO_2 emission cap for utilities was set at 8.9 million tons

If utilities don’t have enough allowances to cover its emissions, a penalty of $2000 per ton of SO_2 will be charged and will be required to reduce its emissions by another ton the following year.

SO2 Allowance Trading Prices

YEAR	MINIMUM PRICE ($)	MAXIMUM PRICE ($)	AVERAGE PRICE ($)
1993	0.26	450	131
1994	24	400	150
1995	1	350	130
1996	39	300	66.05
1997	0.02	121.02	106.75
1998	56.91	228.92	116.96
1999	41.16	230	207.03
2000	80.05	250	130.69
2001	105	225	173.57
2002	150	215	160.5
2003	2.06	250	171.81
2004	107	300	272.82
2005	300	750	702.51
2006	650	1700	860.07
2007	300	1120	444.39
2008	0.27	651	389.91
2009	0.06	500	69.74
2010	0.06	300	36.2
2011	0.06	66.67	2.81

Source: http://www.epa.gov/captrade/allowance-trading.html

Chicago Climate Futures Exchange

Cap and trade programs use emission allowances as the currency to comply with emission reduction requirements. These programs display the following key features:

An emissions "cap": A limit on the total amount of pollution that can be emitted (released) from all regulated sources (e.g., power plants); the cap is set lower than historical emissions in order to reduce emissions.

Allowances: An authorization to emit a fixed amount of a pollutant.

Measurement: Accurate tracking of all emissions.

Flexibility: Sources can choose how to reduce emissions, including whether to buy additional allowances from other sources that reduce emissions.

Allowance trading: Sources can buy or sell allowances on the open market. Because the total number of allowances is limited by the cap, emission reductions are assured.

Compliance: At the end of each compliance period, each source must own at least as many allowances as its emissions.

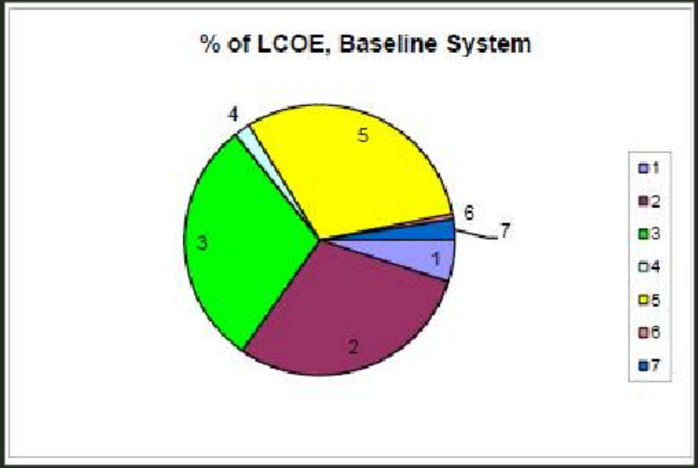
EGS Economics:

Assumptions:

- EGS is sized to the IGCC
- Sequestered CO_2 levels match IGCC output
- Supercritical CO_2 will be used as the working fluid
- Binary Energy Conversion System selected

EGS Financial Summary:

- Size: 100 MW
- Captial Cost: $177,400,00
- Total Cost: $487,600,000
- Cost cents per kWh: 15.35



A. Baseline Case	Capital	O&M	Total	% of all Costs
Expl & Conf	0.86	0.00	0.86	5%
Well Field	4.17	1.00	5.17	30%
Well Field Makeup	5.13	0.00	5.13	30%
Field, Other	0.34	0.00	0.34	2%
Power plant	3.32	2.00	5.32	31%
Royalty	0.00	0.11	0.11	1%
Contingency	0.44	0.00	0.44	3%
Total	**14.26**	**3.11**	**17.38**	**100%**
% of all Costs:	**82%**	**18%**	**100%**	

Legend for Pie Chart Sectors:
1. Exploration and Confirmation
2. Wells in Field, after Confirmation phase
3. Field, Make up costs
4. Field, Other (Pipes, Pumps, Well Stimulation, Make Up Costs)
5. Energy Conversion System
6. Royalty
7. Contingency

IGCC-Economics

- PSFM model
- Assumptions
  - Capital Expenditure Period: 5 years
  - Operational Period: 30 years
  - Inflation: 3%
  - Capacity Factor: 0.80

Total Equipment & Material	**1,490,000,000$**
Fixed Operating Cost(per year)	63,500,000$
Variable Operating Cost (per year)	106,000,000$
Total Cost	1,659,500,000$ ~ 1.6 billion dollars
LCOE	12.6 cents/KWH

Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. DOE/NETL Revision 2, November 2010

Water Supply:

Requirement by type	Amount
IGCC	4.2 Million Gallons per day

Range of Losses	Required Water Per Day
7 Percent	294,000 Gallons per day
10 Percent	420,000 Gallons per day

Make-up-Water Tanks	Total Capacity	Costs ($530,000 per Tank)
37,700 Gallons X 11 Tanks	414,700 Gallons	$5,830,000

Specifications	Value
Diameter	97 mm
Flow Rate	420,000 Gallons per day

Required Water 420,000 Gallons per day
Distance to Municipal Water supply & Sewer Plant 5 miles

Type	Unit Cost (per Mile)	Total Cost
Pipeline	$28,000	$530,200
Gathering System	$1610	$320,000

Total Project Cost Estimation	$850,200

Source: THE GEYSERS PIPELINE PROJECT, Mark Dellinger and Eliot Allen
http://www.ccpa.com/pipeline101.aspx?page_guid=05817B50-0D2D-4388-9600-A915F34D1CE7

Coal Supply:

REQUIREMENTS

5300 Tons per day of Bituminous coal with low ash content

AVERAGE COAL PRICE (2009) FROM SAN JUAN

$30.71 per Ton

TOTAL COST OF BUILDING A RAILWAY LINE OF 8 MILES: $16 M

Source: Annual Coal Report 2009, U.S. Energy Information Administration
http://www.railway-technical.com/finance.shtml

Burlington Northern Santa Fe (BNSF) Transportation Costs

Distance	150 Miles
Minimum Number of cars	104-115 cars
Per car capacity	143 Tons
Total Capacity	15,730 Tons of Coal per day

Cost per ton of coal in USD	$14.37
Cost per car	$2,050
Cost per train	$226,040
Transportation Costs per Month	$1,695,000
Cost of Coal per Month	$4,890,000
Annual Total Costs on Coal and Transportation	**$79 MILLION**

Source: The Burlington Northern and Santa Fe Railway Company ("BNSF") Common Carrier Pricing Authority BNSF 57966

Cost Summary:

EGS:

Captial Cost: $177,400,000

Annual O&M: $20,507,000

IGCC:

Captial Cost: $1,490,000,000

Annual O&M: $169,500,000

Total:

Capital Cost: $1,667,400,000

Annual O&M: $190,007,000

Conclusions

EGS:

- Drilling advances are significantly reducing well costs.
- Energy conversion advances are also occuring.

IGCC:

- Air separation membranes can reduce power consumption and cost of ASU

Policy:

- Government incentives and financing are necessary for this project.

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Team 2: CO2-Circulated EGS Combined with IGCC in New Mexico

Geology

Economics

Integrated EGS and IGCC
with CO2 as the working fluid

Reservoir Simulation

Policy

Conclusions

IGCC