CO_2 Transport and Storage Models in the IECM Framework

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Presentation to

EPRI Workshop on Costs of CO_2 Transport and Storage
Palo Alto, California

March 17, 2009

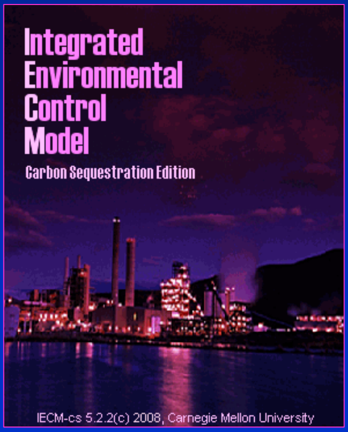
Outline of Talk

- The IECM modeling framework
- CO_2 pipeline model
- Saline aquifer storage model
- EOR storage model
- Work in progress; future plans

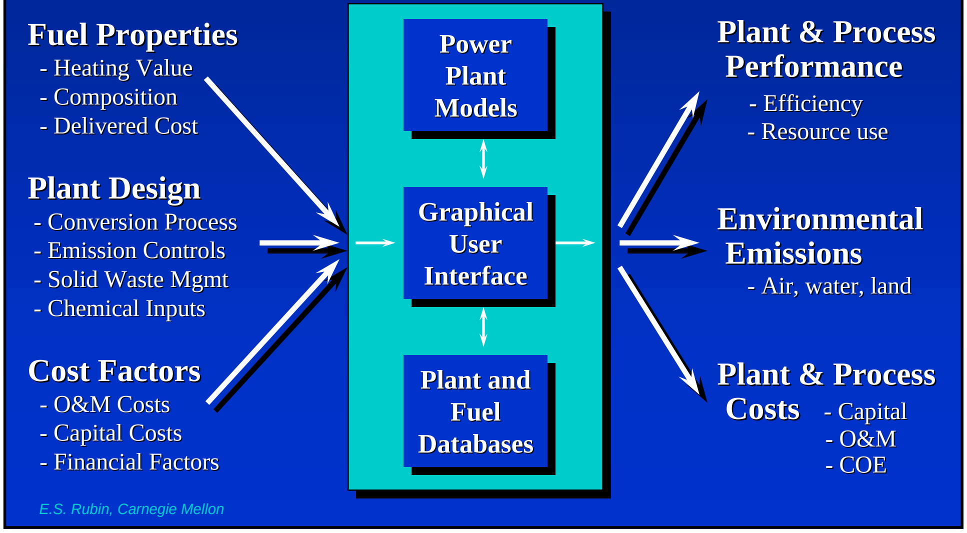
The IECM Framework:

Power Plant Performance, Emissions & Costs

- A desktop/laptop computer model developed for DOE/NETL; free and publicly available at: www.iecm-online.com
- Provides systematic estimates of performance, emissions, costs and uncertainties for preliminary design of:
  - PC, IGCC and NGCC plants
  - All flue/fuel gas treatment systems
  - CO_2 capture and storage options (pre- and post-combustion, oxy-combustion; transport, storage)



IECM Software Package



Fuel Properties
- Heating Value
- Composition
- Delivered Cost

Plant Design
- Conversion Process
- Emission Controls
- Solid Waste Mgmt
- Chemical Inputs

Cost Factors
- O&M Costs
- Capital Costs
- Financial Factors

Power Plant Models

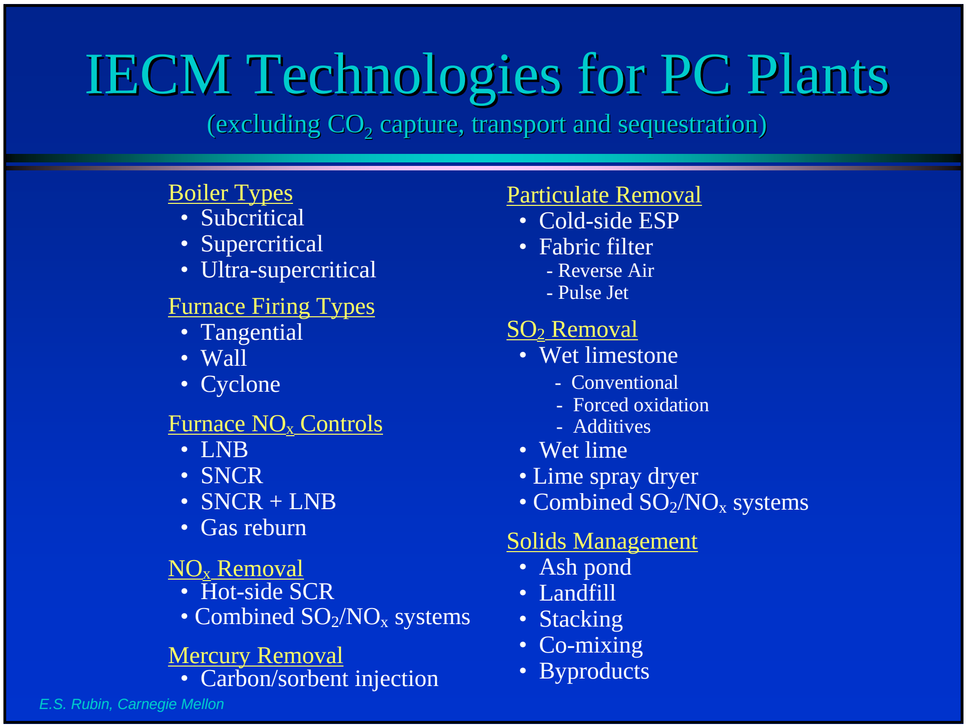
Graphical User Interface

Plant and Fuel Databases

Plant & Process Performance
- Efficiency
- Resource use

Environmental Emissions
- Air, water, land

Plant & Process Costs
- Capital
- O&M
- COE



IECM Technologies for PC Plants

(excluding CO_2 capture, transport and sequestration)

Boiler Types
- Subcritical
- Supercritical
- Ultra-supercritical

Furnace Firing Types
- Tangential
- Wall
- Cyclone

Furnace NO_x Controls
- LNB
- SNCR
- SNCR + LNB
- Gas reburn

NO_x Removal
- Hot-side SCR
- Combined SO_2/NO_x systems

Mercury Removal
- Carbon/sorbent injection

Particulate Removal
- Cold-side ESP
- Fabric filter
  - Reverse Air
  - Pulse Jet

SO_2 Removal
- Wet limestone
  - Conventional
  - Forced oxidation
  - Additives
- Wet lime
- Lime spray dryer
- Combined SO_2/NO_x systems

Solids Management
- Ash pond
- Landfill
- Stacking
- Co-mixing
- Byproducts

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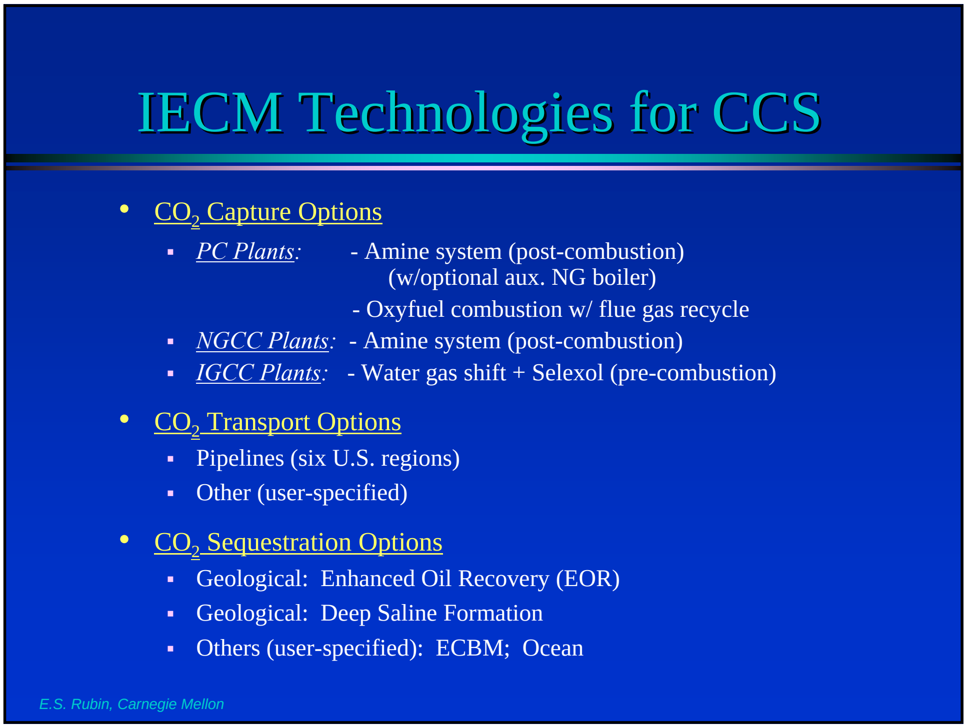

IECM Technologies for CCS

- CO_2 Capture Options
  - *PC Plants*: - Amine system (post-combustion) (w/optional aux. NG boiler)
    - Oxyfuel combustion w/ flue gas recycle
  - *NGCC Plants*: - Amine system (post-combustion)
  - *IGCC Plants*: - Water gas shift + Selexol (pre-combustion)
- CO_2 Transport Options
  - Pipelines (six U.S. regions)
  - Other (user-specified)
- CO_2 Sequestration Options
  - Geological: Enhanced Oil Recovery (EOR)
  - Geological: Deep Saline Formation
  - Others (user-specified): ECBM; Ocean

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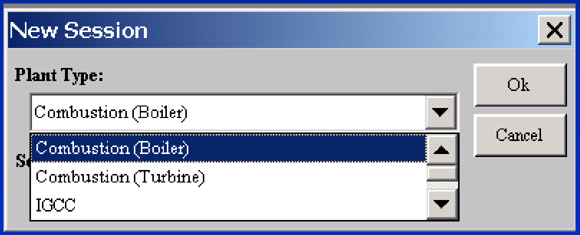
A Quick Tour of the IECM

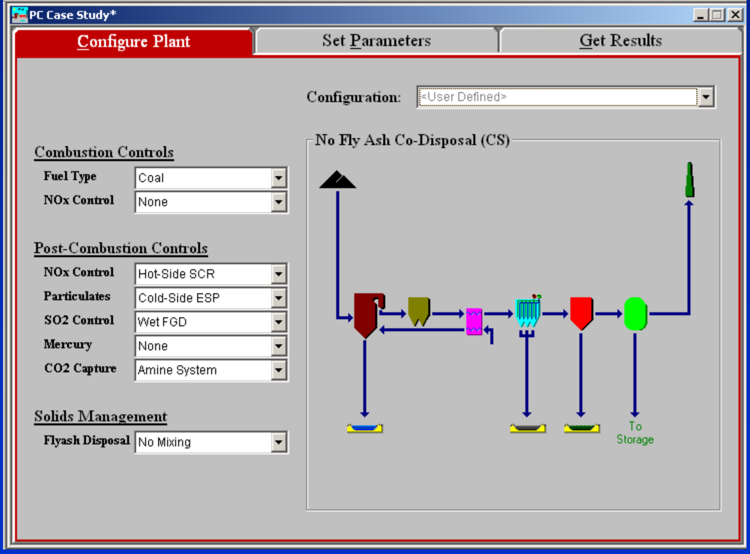
Select Plant Type



New Session

Plant Type: Combustion (Boiler)

PC Plant with Post- Comb. CCS



PC Case Study*

Configuration: <User Defined>

Combustion Controls

Fuel Type: Coal

NOx Control: None

Post-Combustion Controls

NOx Control: Hot-Side SCR

Particulates: Cold-Side ESP

SO2 Control: Wet FGD

Mercury: None

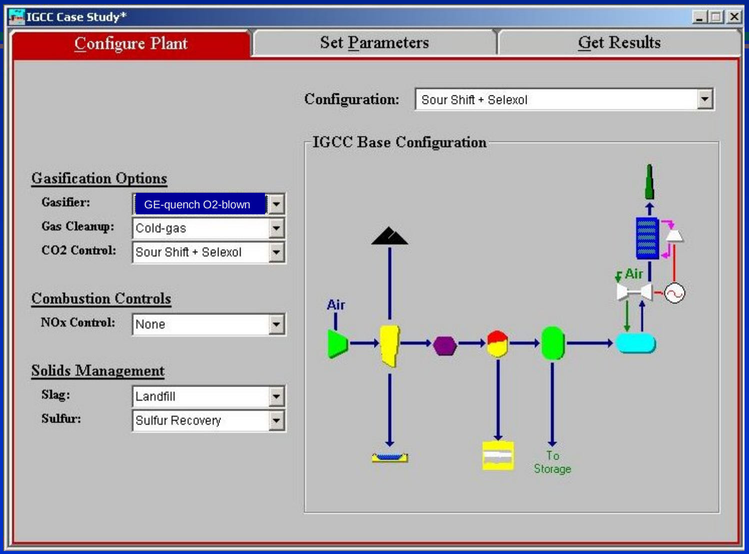
CO2 Capture: Amine System

Solids Management

Flyash Disposal: No Mixing

No Fly Ash Co-Disposal (CS)

IGCC Plant with CCS



Configuration: Sour Shift + Selexol

Gasification Options

- **Gasifier:** GE-quench O2-blown
- **Gas Cleanup:** Cold-gas
- **CO2 Control:** Sour Shift + Selexol

Combustion Controls

- **NOx Control:** None

Solids Management

- **Slag:** Landfill
- **Sulfur:** Sulfur Recovery

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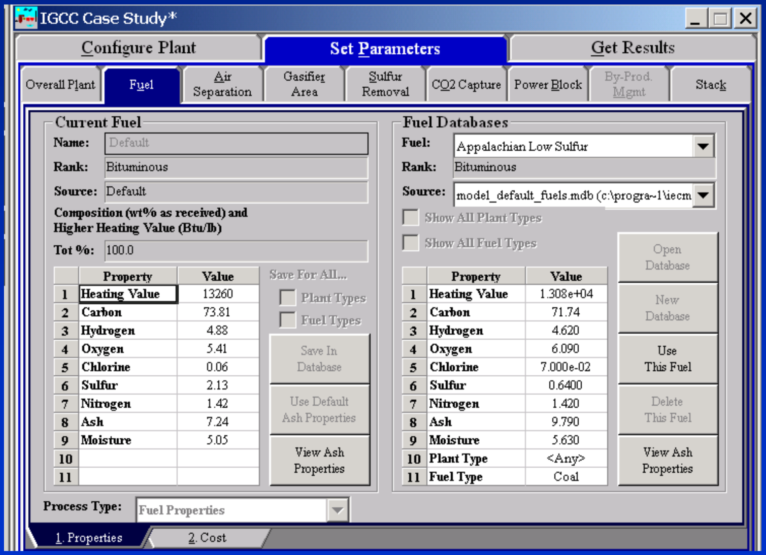
Specify Fuel Properties



Current Fuel

Name: Default
Rank: Bituminous
Source: Default

Composition (wt% as received) and Higher Heating Value (Btu/lb)

Tot %: 100.0

	Property	Value
1	Heating Value	13260
2	Carbon	73.81
3	Hydrogen	4.88
4	Oxygen	5.41
5	Chlorine	0.06
6	Sulfur	2.13
7	Nitrogen	1.42
8	Ash	7.24
9	Moisture	5.05
10		
11		

Fuel Databases

Fuel: Appalachian Low Sulfur
Rank: Bituminous
Source: model_default_fuels.mdb (c:\progra~1\iecm

☐ Show All Plant Types
☐ Show All Fuel Types

	Property	Value
1	Heating Value	1.308e+04
2	Carbon	71.74
3	Hydrogen	4.620
4	Oxygen	6.090
5	Chlorine	7.000e-02
6	Sulfur	0.6400
7	Nitrogen	1.420
8	Ash	9.790
9	Moisture	5.630
10	Plant Type	<Any>
11	Fuel Type	Coal

Process Type: Fuel Properties

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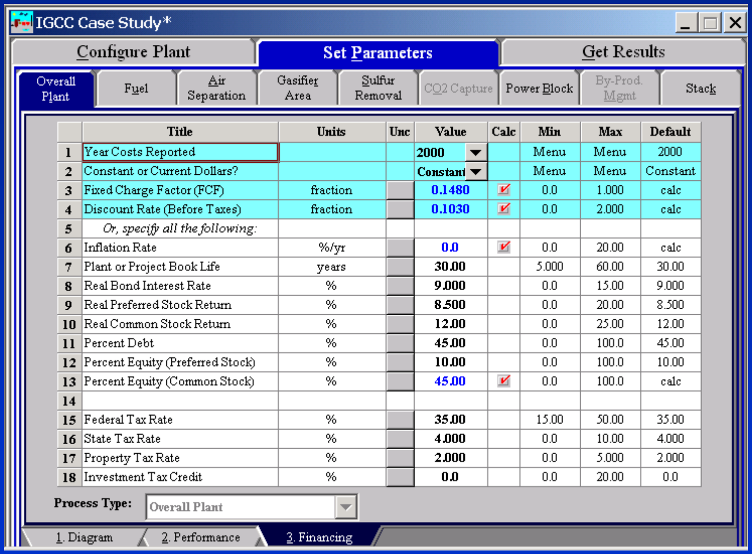
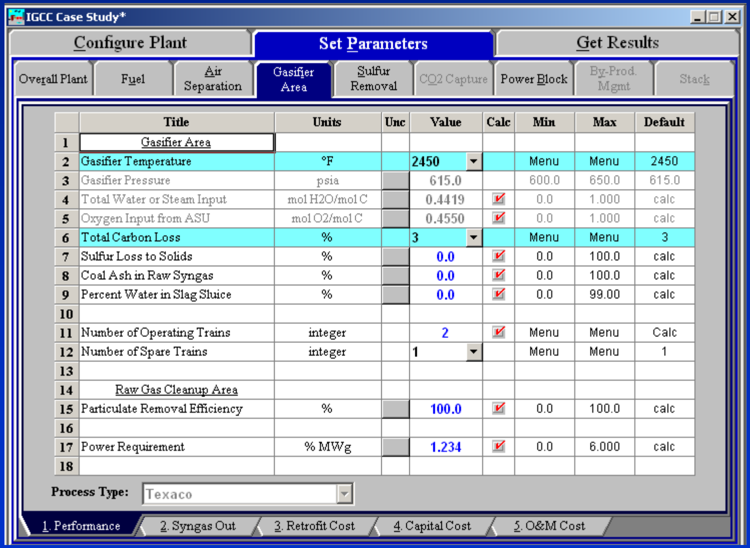
Specify Financial Parameters



	Title	Units	Unc	Value	Calc	Min	Max	Default
1	Year Costs Reported			2000 ▼		Menu	Menu	2000
2	Constant or Current Dollars?			Constant ▼		Menu	Menu	Constant
3	Fixed Charge Factor (FCF)	fraction		0.1480	☑	0.0	1.000	calc
4	Discount Rate (Before Taxes)	fraction		0.1030	☑	0.0	2.000	calc
5	*Or, specify all the following:*							
6	Inflation Rate	%/yr		0.0	☑	0.0	20.00	calc
7	Plant or Project Book Life	years		30.00		5.000	60.00	30.00
8	Real Bond Interest Rate	%		9.000		0.0	15.00	9.000
9	Real Preferred Stock Return	%		8.500		0.0	20.00	8.500
10	Real Common Stock Return	%		12.00		0.0	25.00	12.00
11	Percent Debt	%		45.00		0.0	100.0	45.00
12	Percent Equity (Preferred Stock)	%		10.00		0.0	100.0	10.00
13	Percent Equity (Common Stock)	%		45.00	☑	0.0	100.0	calc
14								
15	Federal Tax Rate	%		35.00		15.00	50.00	35.00
16	State Tax Rate	%		4.000		0.0	10.00	4.000
17	Property Tax Rate	%		2.000		0.0	5.000	2.000
18	Investment Tax Credit	%		0.0		0.0	20.00	0.0

Process Type: Overall Plant

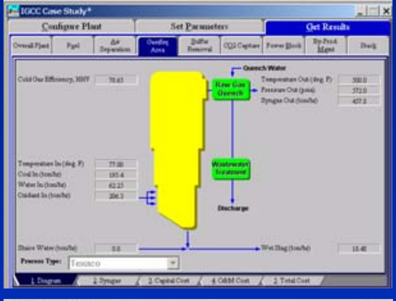
Specify Performance Parameters



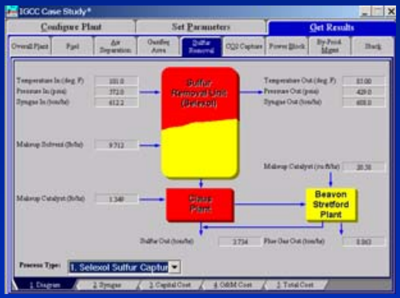
	Title	Units	Unc	Value	Calc	Min	Max	Default
1	Gasifier Area							
2	Gasifier Temperature	°F		2450 ▼		Menu	Menu	2450
3	Gasifier Pressure	psia		615.0		600.0	650.0	615.0
4	Total Water or Steam Input	mol H2O/mol C		0.4419	☑	0.0	1.000	calc
5	Oxygen Input from ASU	mol O2/mol C		0.4550	☑	0.0	1.000	calc
6	Total Carbon Loss	%		3 ▼		Menu	Menu	3
7	Sulfur Loss to Solids	%		0.0	☑	0.0	100.0	calc
8	Coal Ash in Raw Syngas	%		0.0	☑	0.0	100.0	calc
9	Percent Water in Slag Sluice	%		0.0	☑	0.0	99.00	calc
10								
11	Number of Operating Trains	integer		2	☑	Menu	Menu	Calc
12	Number of Spare Trains	integer		1 ▼		Menu	Menu	1
13								
14	Raw Gas Cleanup Area							
15	Particulate Removal Efficiency	%		100.0	☑	0.0	100.0	calc
16								
17	Power Requirement	% MWg		1.234	☑	0.0	6.000	calc
18								

Process Type: Texaco

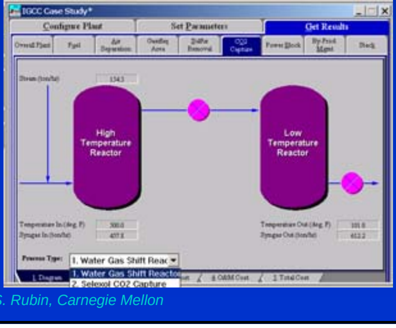
Get Results for Specific Components



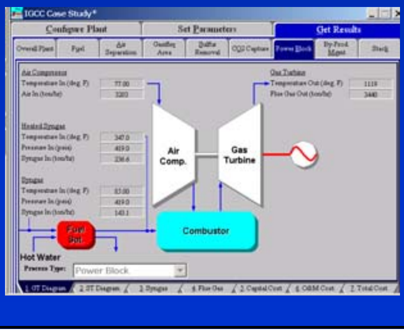
Cold Gas Efficiency, HHV: 78.63
Temperature Out (deg. F): 300.0
Pressure Out (psia): 372.0
Syngas Out (tons/hr): 437.8
Temperature In (deg. F): 77.00
Coal In (tons/hr): 195.4
Water In (tons/hr): 62.25
Oxidant In (tons/hr): 206.3
Slurry Water (tons/hr): 0.0
Wet Slag (tons/hr): 18.48
Process Type: Texaco



Temperature In (deg. F): 101.0
Pressure In (psia): 372.0
Syngas In (tons/hr): 612.2
Temperature Out (deg. F): 83.00
Pressure Out (psia): 429.0
Syngas Out (tons/hr): 608.0
Makeup Solvent (lb/hr): 9.712
Makeup Catalyst (cu ft/hr): 20.38
Makeup Catalyst (lb/hr): 1.348
Sulfur Out (tons/hr): 3.734
Flue Gas Out (tons/hr): 0.063
Process Type: 1. Selexol Sulfur Captur



Steam (tons/hr): 134.3
Temperature In (deg. F): 300.0
Syngas In (tons/hr): 437.8
Temperature Out (deg. F): 101.0
Syngas Out (tons/hr): 612.2
Process Type: 1. Water Gas Shift Reac
1. Water Gas Shift Reactor
2. Selexol CO2 Capture



Air Compressor
Temperature In (deg. F): 77.00
Air In (tons/hr): 3283

Gas Turbine
Temperature Out (deg. F): 1119
Flue Gas Out (tons/hr): 3440

Heated Syngas
Temperature In (deg. F): 347.0
Pressure In (psia): 419.0
Syngas In (tons/hr): 236.6

Syngas
Temperature In (deg. F): 83.00
Pressure In (psia): 419.0
Syngas In (tons/hr): 143.1

Process Type: Power Block

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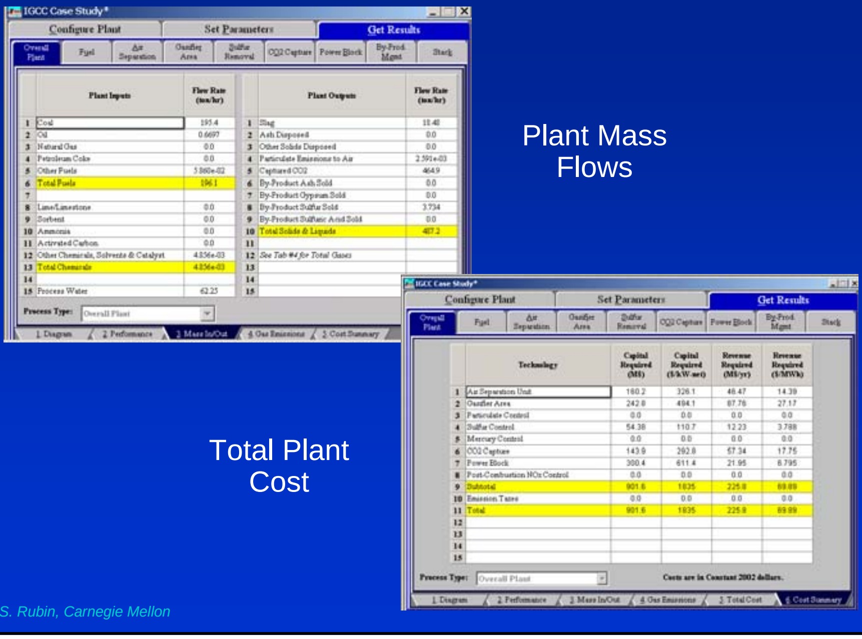
Get Results for Overall Plant



Plant Mass Flows

	Plant Inputs	Flow Rate (ton/hr)		Plant Outputs	Flow Rate (ton/hr)
1	Coal	195.4	1	Slag	18.48
2	Oil	0.6697	2	Ash Disposed	0.0
3	Natural Gas	0.0	3	Other Solids Disposed	0.0
4	Petroleum Coke	0.0	4	Particulate Emissions to Air	2.591e-03
5	Other Fuels	5.860e-02	5	Captured CO2	464.9
6	Total Fuels	196.1	6	By-Product Ash Sold	0.0
7			7	By-Product Gypsum Sold	0.0
8	Lime/Limestone	0.0	8	By-Product Sulfur Sold	3.734
9	Sorbent	0.0	9	By-Product Sulfuric Acid Sold	0.0
10	Ammonia	0.0	10	Total Solids & Liquids	487.2
11	Activated Carbon	0.0	11		
12	Other Chemicals, Solvents & Catalyst	4.856e-03	12	*See Tab #4 for Total Gases*	
13	Total Chemicals	4.856e-03	13		
14			14		
15	Process Water	62.25	15		

Process Type: Overall Plant

Total Plant Cost

	Technology	Capital Required (M$)	Capital Required ($/kW-net)	Revenue Required (M$/yr)	Revenue Required ($/MWh)
1	Air Separation Unit	160.2	326.1	46.47	14.39
2	Gasifier Area	242.8	494.1	87.76	27.17
3	Particulate Control	0.0	0.0	0.0	0.0
4	Sulfur Control	54.38	110.7	12.23	3.788
5	Mercury Control	0.0	0.0	0.0	0.0
6	CO2 Capture	143.9	292.8	57.34	17.75
7	Power Block	300.4	611.4	21.95	6.795
8	Post-Combustion NOx Control	0.0	0.0	0.0	0.0
9	Subtotal	901.6	1835	225.8	69.89
10	Emission Taxes	0.0	0.0	0.0	0.0
11	Total	901.6	1835	225.8	69.89
12					
13					
14					
15					

Process Type: Overall Plant

Costs are in Constant 2002 dollars.

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Model Applications

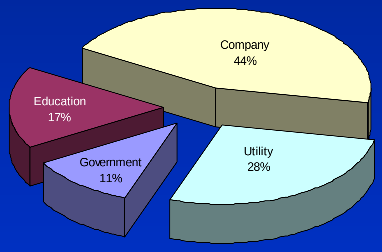
- Process design
- Technology evaluation
- Cost estimation
- R&D management
- Risk analysis
- Environmental compliance
- Marketing studies
- Strategic planning

Some Recent IECM Users

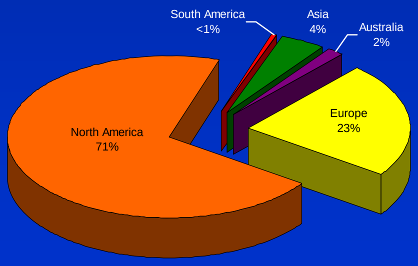
ABB Lummus Global, Inc.
AEP-SCR Eng'r
Air Liquide
Air Products plc
Airborne Clean Energy
Akzo Nobel FunctionalChem
Alberta Economic Dev.
Alberta Env.
Alberta Res. Council
ALCOA Power Gen., Inc.
Allegheny Energy Supply
Alliant Energy
Alstom (Switzerland)
Alstom Power Boiler GmbH
ALSTOM PowerCentrales
Alstom Power Inc.
Alstom Power Plant Lab.
American Electric Power
American Transmission Co.
Ankara University
APAT
Apogee Scientific, Inc.
ARCADIS
Argonne National Lab.
ATCO Power
Balcke-Durr GmbH
Basin Electric Power Coop.
Battelle
Battelle Northwest
Bechtel Power Corp.
Black & Veatch Corp.
BOC Gases
Boiler SystemsEng'r, E.S.O.
BP
BP Int'l Limited
BP Power Ltd.
BP Sunbury
Canada Env.
Canada Natural Resources
Canadian Clean Power Coalition
Carnegie Mellon University
Chalmers University
Chinese Academy ofSci.
Cinergy Power Gen. Services, LLC
Clean Energy Systems Inc.
Coal in Sustainable Dev., Tech Transfer
Coaltek LLC / Jupiter Oxygen Corp.
Cogentrix Energy, Inc.
Columbia University
CONSOL Energy, Inc.
Consumers Energy
Coop. Res. Centre for Greenhouse Gas
COORETEC
CQ, Inc.
Croll-Reynolds
CSEnergy
Dept. of Energy (DOE)
Dept. of Energy, Instituto de Carboquimica
Dept. of Env. and Natural Res.- NC
Dept. of Env. Protection- NJ (DEP)
Dept. of Env. Protection- PA (DEP)
Dept. of Env. Quality - VA (DEQ)
Dept. of Env. Services - NH (DES)
Detroit Edison Co.
DMCR/Dutch Ministry ofEnv. (VROM)
DONG Energy Gen.
Dont Inc.
Doosan Babcock Energy Ltd.
Dynegy Midwest Gen.
E. On UK
E.ON Energie AG
Edison Mission Energy
Electric Energy, Inc. (EEI)
Electric Power Gen. Assoc.
Electric Power Res. Inst. (EPRI)
Electricite de France (EDF)
Emera Inc.
Enel
AmerenUE
Energetics, Inc.
Energi E2
Energy & Env. Res. Center (EERC)
Energy & Env. Res. Corp.
Energy & Env. Strategies
Energy Res. Centre of the Netherlands
ENSR, Inc.
Env. & Renewable Energy Systems
Env. Defense
Env. Protection Agency- IL (EPA)
Env. Protection Agency (EPA)
First Energy Corp.
FirstEnergy Corp.
Florida Power & Light Co.
FLS Miljo A/S
Fluent, Inc.
Fluor Daniel Canada, Inc.
Ford
Fortum Power and HeatOy
Fossil Energy Res. Corp.
Foster Wheeler Energia Oy
Friedman, Billings, Ramsey & Co.
Fuel Tech, Inc.
Gas Tech. Inst. (GTI)
Gassnova
GE Global Res.
GE Infra, Energy
General Electric Co.
Generators for Clean Air (GCA)
GM R&D Center
Great River Energy
Gyeongsang National University
H&W Mgmt. Sci. Consultants
Hamon Res. Cottrell, Inc.
Harvard University
Hatch Acres
Holland Board of Public Works
IEA Clean Coal Centre
IEA Env. Projects, Ltd.
IEA Greenhouse Gas R&D
IFP
Illinois Clean Coal Inst.
Illinois Dept. of Natural Resources
Illinois Inst. of Tech.
Imperial College
Indian Inst. of Tech.
Industries Limited
INERCO
Institut Teknologi Bandung (ITB)
Inst. of Applied Energy (IAE)
Inst. of Energy- EC/JRC
Intermountain Power Service Corp.
Ishikawajima-Harima Heavy Industry
Jack R. McDonald, Inc.
Japan Petroleum Exploration Co.
Kanazawa University
Kansas City Power & Light Co.
KEMA Nederland B.V.
Kennecott Energy
Kinectrics
Korea Electric Power Corp.
Korea Inst. of Energy Res.
Korea Western Power Co.
LAB SA
Lehigh University
Lincoln Electric System
Lower Colorado River Authority
MacQuarie University
Massachusetts Inst. of Tech. (MIT)
Michigan State University
MidAmerican Energy Co.
Midwest Gen. EME, LLC
Minnkota Power Coop., Inc.
Nanyang Technological University
National Energy Tech. Lab. (NETL)
National Power Plc.
Neill and Gunter
NESCAUM
New Energy & Ind. Tech. Org. (NEDO)
Nicholson & Hall Corp.
Niksa Energy Associates
NIPSCO
Niro A/S
Norman Plaks Consulting
Norsk Hydro ASA
Norsk Hydro ASA, Oil & Energy Res.
North Carolina State University
Norwegian University ofSci. and Tech.
Nova Scotia Power, Inc.
NRDC Natural Res. Defence Council
NTNU/Statoil
NTPC Limited
Ontario Power Gen.
OREC/Buckeye Power, Inc.
Pace Global Energy Services
Pacific Corp.
Pacific Northwest National Lab. (PNNL)
Pembina Inst.
Pinnacle West Energy
PIRA Energy Group
PowerGen
Powergen Power Tech.
PPL Gen., LLC
Prairie Adaptation Res. Coll.
Praxair Inc.
Princeton University
Reaction Eng'r Inst.
Reaction Eng'r Int'l
Res. Inst. of Innovative Tech. Earth
Res. Triangle Inst.
RMB Consulting & Res., Inc.
RWE Power AG
SAIC
Salt River Project
Salt River Project (SRP)
Sargent & Lundy
SaskPower
Savvy Eng'r, LLC
Sci. Applications Int'l. Corp. (SAIC)
Scientech
SFA Pacific, Inc.
Shell Chemical Co.
Shell Global Solutions Int'l
Siemens
Sierra Pacific Power Co.
Sintef Energy Res.
SNC Lavalin
Southern Co. Gen.
Southern Co. Services, Inc.
Statoil
Steven Coons Consulting
Superior Adsorbents, Inc.
Syncrude
Tampa Electric Co.
Tennessee Valley Authority (TVA)
Terra Humana Clean Tech.Eng'r Ltd.
Tetra Tech EM Inc.
Texas A&M University
Texas Municipal Power Agency
TMommer Consultants
TNO Env., Energy and ProcessInnov
Toshiba Corp.
TransAlta
TU Dresden
Twenty-First Strategies, LLC
TXU Electric
University of Aberdeen
University of Bath
University of Calgary
University of California
University of Edinburgh
University of Lecce
University of Maine
University of Manchester Inst.Sci. Tech.
University of New Orleans
University of Newcastle
University of North Carolina
University of Pittsburgh
University of Queensland
University of Regina
University of Salvador UNIFACS
University of South Wales
University of Stuttgart
University of Texas
University of Toronto
University of Twente
University of Waterloo
URS Corp
Vattenfall AB
Vattenfall Utveckling AB
W.L. Gore & Associates, Inc.
Washington Power
Wheelabrator Air Poll. Control Inc.
Wisconsin Dept. of Natural Res.
Wisconsin Public Service Corp.
Wolk Integrated Technical Services
World Bank

Profile of Recent IECM Users

Type of Organization



Geographic Region



~ 500 organizations

The transport and storage models

Full details in technical reports & papers:
http://www.iecm-online.com/Rubin_pubs_1.html

Technical Documentation:
The Economics of CO_2 Transport by Pipeline and Storage in Saline Aquifers and Oil Reservoirs

Final Report of

Work Performed Under Contract No.: DE-AC26-04NT41817
Reporting Period Start, June 2007
Reporting Period End, May 2008

Report Submitted, April 2008

to

U.S. Department of Energy
National Energy Technology Laboratory

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An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage

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ARTICLE INFO
Article history:
Received 6 July 2007
Received in revised form
7 October 2007
Accepted 8 October 2007

ABSTRACT
Carbon dioxide capture and storage (CCS) involves the capture of CO_2 at a large industrial facility, such as a power plant, and its transport to a geological (or other) storage site where CO_2 is sequestered. Previous work has identified pipeline transport of liquid CO_2 as the most economical method of transport for large volumes of CO_2. However,

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GHGT-9

Variability and Uncertainty in the Cost of Saline Formation Storage

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Abstract

Cost estimates for CO_2 capture and storage (CCS) systems typically focus on details of the CO_2 capture process and make simplistic assumptions about the cost per ton of CO_2 for the transport and storage components of the system. These ad hoc assumptions ignore the large variability in the storage cost from site-to-site caused by variation in storage reservoir

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GHGT-9

The effect of high oil prices on EOR project economics

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Abstract

This paper examines two questions: (1) in a high oil price (and operating cost) environment what are typical breakeven prices for CO_2? and, (2) are these prices sufficient to incentivize development of large-scale CCS projects? To address these questions we have developed an engineering-economic model for geological storage of CO_2 through EOR. In this paper we briefly describe the performance and cost models for CO_2-flood EOR, and use them to estimate the breakeven price for CO_2 as a function of

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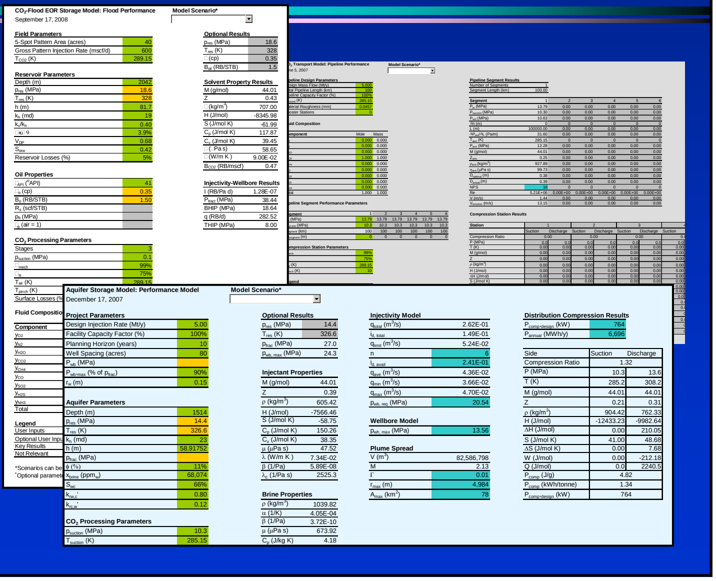
Model Implementation & Availability

- Pipeline model is fully integrated into the IECM; also available as a stand-alone spreadsheet
- Aquifer and EOR storage models are spreadsheets w/ manual links to IECM inputs
- All spreadsheet models available on request



CO_2-Flood EOR Storage Model: Flood Performance
September 17, 2008

Model Scenario*

Field Parameters	
5-Spot Pattern Area (acres)	40
Gross Pattern Injection Rate (mscf/d)	600
T_{CO2} (K)	289.15

Reservoir Parameters	
Depth (m)	2042
p_{res} (MPa)	18.6
T_{res} (K)	328
h (m)	81.7
k_h (md)	19
k_v/k_h	0.40
□ho□ 9	3.9%
V_{DP}	0.68
S_{orw}	0.42
Reservoir Losses (%)	5%

Oil Properties	
$□_{API}$ (°API)	41
$□_o$ (cp)	0.35
B_o (RB/STB)	1.50
R_s (scf/STB)	
p_b (MPa)	
$□_g$ (air = 1)	

CO_2 Processing Parameters	
Stages	3
$p_{suction}$ (MPa)	0.1
$□_{mech}$	99%
$□_{is}$	75%
T_{air} (K)	289.15
T_{pinch} (K)	
Surface Losses (%	

Fluid Compositio

Component
y_{O2}
y_{N2}
y_{H2O}
y_{CO2}
y_{CH4}
y_{CO}
y_{SO2}
y_{H2S}
y_{NH3}
Total

Legend
User Inputs
Optional User Inpu
Key Results
Not Relevant

*Scenarios can be
⁺Optional paramete

Optional Results	
p_{res} (MPa)	18.6
T_{res} (K)	328
□ (cp)	0.35
B_{oil} (RB/STB)	1.5

Solvent Property Results	
M (g/mol)	44.01
Z	0.43
□ (kg/m³)	707.00
H (J/mol)	-8345.98
S (J/mol K)	-61.99
C_p (J/mol K)	117.87
C_v (J/mol K)	39.45
□ (□Pa s)	58.65
□ (W/m K)	9.00E-02
B_{CO2} (RB/mscf)	0.47

Injectivity-Wellbore Results	
I (RB/Pa d)	1.28E-07
P_{fract} (MPa)	38.44
BHIP (MPa)	18.64
q (RB/d)	282.52
THIP (MPa)	8.00

Aquifer Storage Model: Performance Model
December 17, 2007

Model Scenario*

Project Parameters	
Design Injection Rate (Mt/y)	5.00
Facility Capacity Factor (%)	100%
Planning Horizon (years)	10
Well Spacing (acres)	80
P_{wb} (MPa)	
$P_{wb,max}$ (% of p_{frac})	90%
r_w (m)	0.15

Aquifer Parameters	
Depth (m)	1514
p_{res} (MPa)	14.4
T_{res} (K)	326.6
k_h (md)	23
h (m)	58.91752
p_{frac} (MPa)	
ϕ (%)	11%
x_{brine} (ppm_w)	68,074
S_{wc}	66%
$k_{rw,c}'$	0.80
$k_{rc,w}'$	0.12

CO_2 Processing Parameters	
$p_{suction}$ (MPa)	10.3
$T_{suction}$ (K)	285.15

Optional Results	
p_{res} (MPa)	14.4
T_{res} (K)	326.6
p_{frac} (MPa)	27.0
$p_{wb,\,max}$ (MPa)	24.3

Injectant Properties	
M (g/mol)	44.01
Z	0.39
ρ (kg/m³)	605.42
H (J/mol)	-7566.46
S (J/mol K)	-58.75
C_p (J/mol K)	150.26
C_v (J/mol K)	38.35
μ (μPa s)	47.52
λ (W/m K)	7.34E-02
β (1/Pa)	5.89E-08
λ_c (1/Pa s)	2525.3

Brine Properties	
ρ (kg/m³)	1039.82
α (1/K)	4.05E-04
β (1/Pa)	3.72E-10
μ (μPa s)	673.92
C_p (J/kg K)	4.18

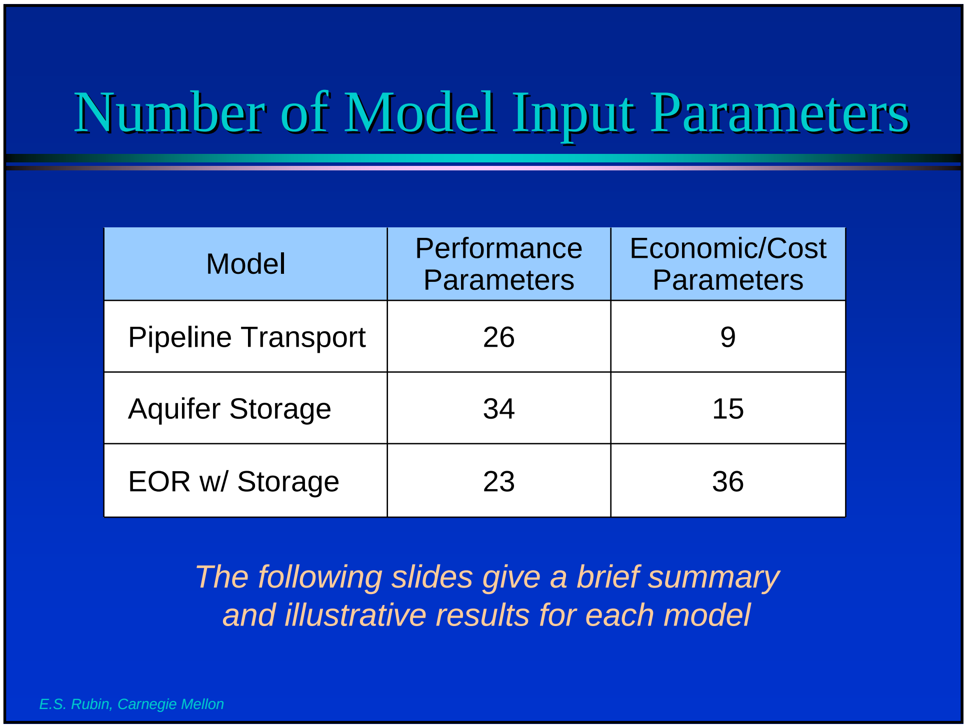
Injectivity Model	
q_{total} (m³/s)	2.62E-01
$i_{d,\,total}$	1.49E-01
q_{limit} (m³/s)	5.24E-02
n	6
$i_{d,\,avail}$	2.41E-01
q_{ave} (m³/s)	4.36E-02
q_{min} (m³/s)	3.66E-02
q_{max} (m³/s)	4.70E-02
$p_{wb,\,req}$ (MPa)	20.54

Wellbore Model	
$p_{wh,\,max}$ (MPa)	13.56

Plume Spread	
V (m³)	82,586,798
M	2.13
Γ	0.01
r_{max} (m)	4,984
A_{max} (km²)	78

Distribution Compression Results	
$P_{comp,design}$ (kW)	764
P_{annual} (MWh/y)	6,696

Side	Suction	Discharge
Compression Ratio	1.32	
P (MPa)	10.3	13.6
T (K)	285.2	308.2
M (g/mol)	44.01	44.01
Z	0.21	0.31
ρ (kg/m³)	904.42	762.33
H (J/mol)	-12433.23	-9982.64
ΔH (J/mol)	0.00	210.05
S (J/mol K)	41.00	48.68
ΔS (J/mol K)	0.00	7.68
W (J/mol)	0.00	-212.18
Q (J/mol)	0.0	2240.5
P_{comp} (J/g)	4.82	
P_{comp} (kWh/tonne)	1.34	
$P_{comp,design}$ (kW)	764	



Number of Model Input Parameters

Model	Performance Parameters	Economic/Cost Parameters
Pipeline Transport	26	9
Aquifer Storage	34	15
EOR w/ Storage	23	36

The following slides give a brief summary and illustrative results for each model

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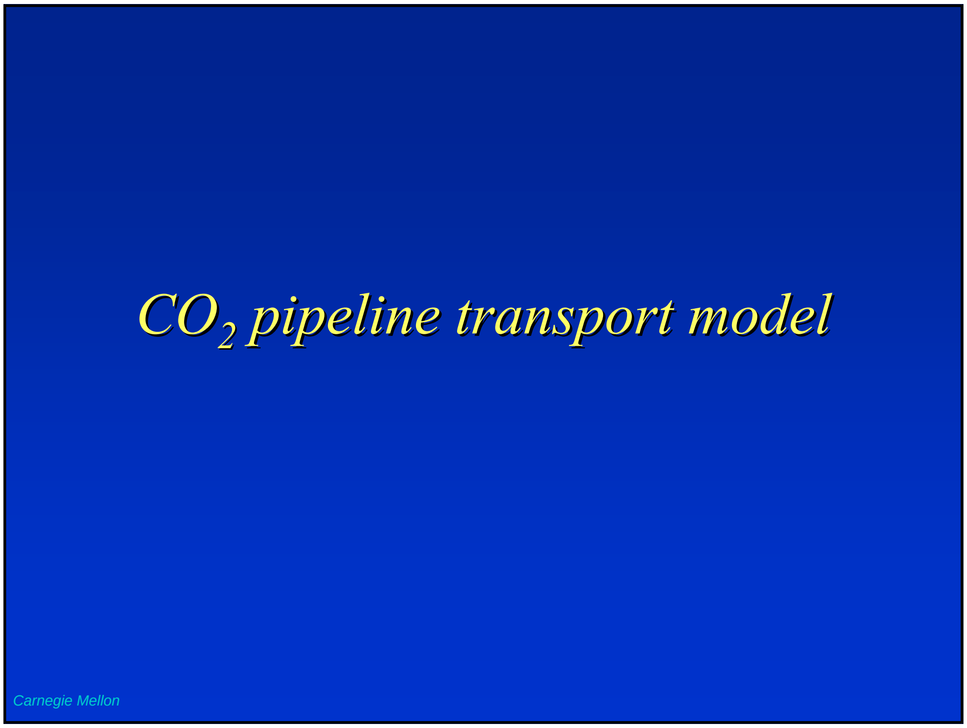
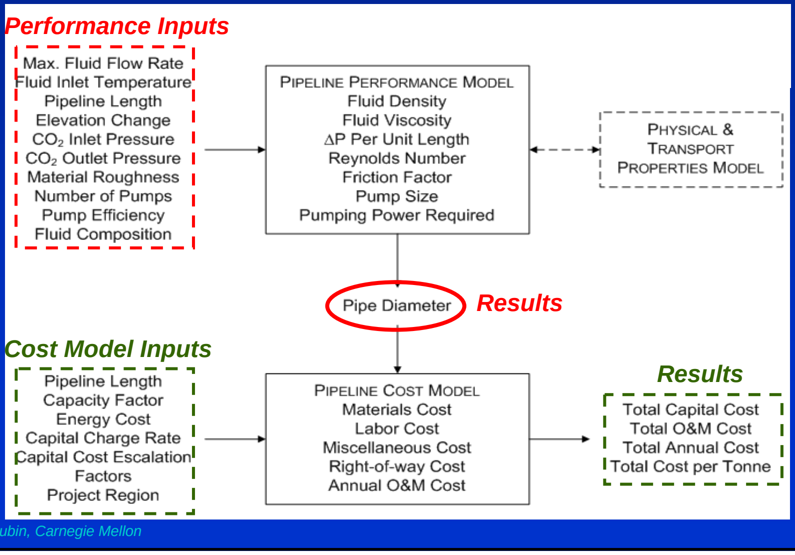


CO_2 pipeline transport model

Carnegie Mellon

IECM Pipeline Transport Model



Performance Inputs

Max. Fluid Flow Rate
Fluid Inlet Temperature
Pipeline Length
Elevation Change
CO_2 Inlet Pressure
CO_2 Outlet Pressure
Material Roughness
Number of Pumps
Pump Efficiency
Fluid Composition

PIPELINE PERFORMANCE MODEL
Fluid Density
Fluid Viscosity
ΔP Per Unit Length
Reynolds Number
Friction Factor
Pump Size
Pumping Power Required

PHYSICAL & TRANSPORT PROPERTIES MODEL

Pipe Diameter

Results

Cost Model Inputs

Pipeline Length
Capacity Factor
Energy Cost
Capital Charge Rate
Capital Cost Escalation Factors
Project Region

PIPELINE COST MODEL
Materials Cost
Labor Cost
Miscellaneous Cost
Right-of-way Cost
Annual O&M Cost

Results

Total Capital Cost
Total O&M Cost
Total Annual Cost
Total Cost per Tonne

Pipeline Diameter Calculation

$$D = \left\{ \frac{-64 Z_{ave}^2 R^2 T_{ave}^2 f_F \dot{m}^2 L}{\pi^2 \left[g_c M Z_{ave} R T_{ave} \left(p_2^2 - p_1^2 \right) + 2 g P_{ave}^2 M^2 \left(h_2 - h_1 \right) \right]} \right\}^{1/5}$$

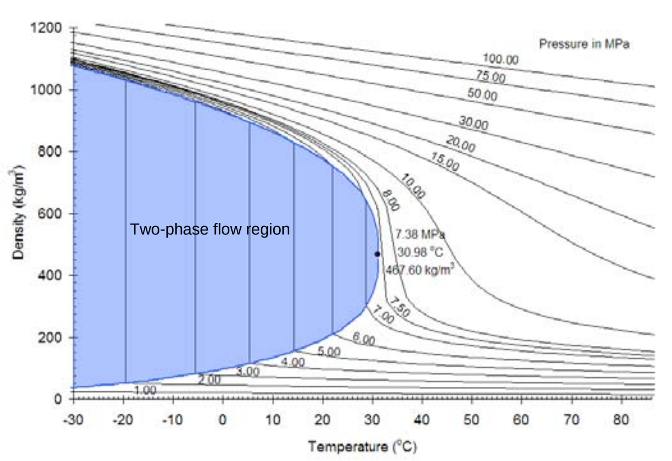
Iterative solution

$$\mathrm{Re} = \frac{4\dot{m}}{\mu \pi D}$$

$$\frac{1}{2\sqrt{f_F}} = -2.0 \log \left\{ \frac{\varepsilon/D}{3.7} - \frac{5.02}{\mathrm{Re}} \log \left[\frac{\varepsilon/D}{3.7} - \frac{5.02}{\mathrm{Re}} \log \left(\frac{\varepsilon/D}{3.7} + \frac{13}{\mathrm{Re}} \right) \right] \right\}$$

p	Absolute pressure
R	Gas constant
T	Absolute temperature
Z	Compressibility factor
M	Molecular mass
g	Acceleration due to gravity
g_c	Gravitational constant
h_i	Height at location *i*
f_F	Fanning friction factor
L	Pipe segment length
$\dot{m}$	Mass flow rate
D	Pipe inner diameter
ε	Pipe roughness
Re	Reynolds number
μ	Viscosity

The IECM Includes a Full CO_2 Physical Properties Model



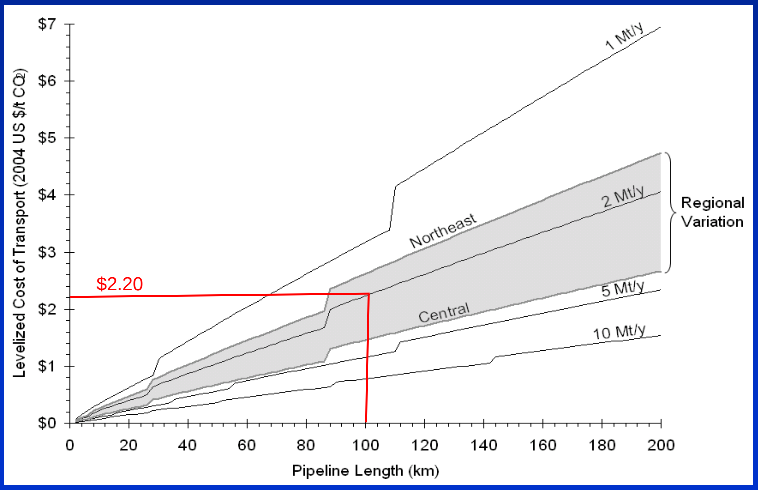
Pipeline Cost Model

- Multi-variate regression models based on data from 236 on-shore natural gas pipelines constructed in the U.S. from 1994 to 2003
  - Capital cost model is linear in pipe diameter, logarithmic in pipe length; reported in $2004.
- Separate models for 6 regions
- Cost breakdowns for:
  - Materials
  - Labor
  - Eng’g, Overheads, AFUDC
  - Right-of-way

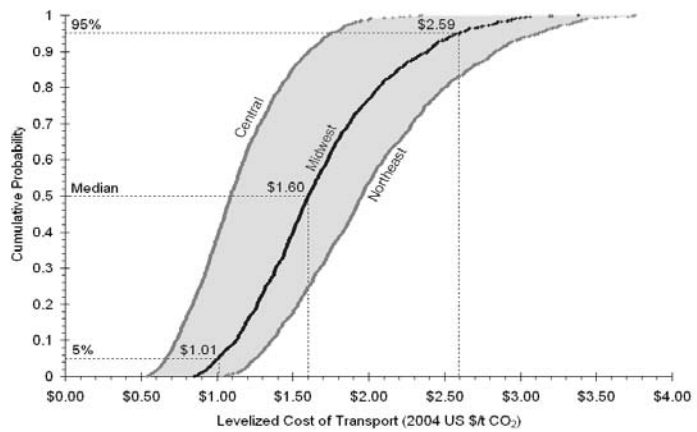
Pipeline Cost Model:
Illustrative Case Study

Model Parameter	Deterministic Value	Uncertainty Distribution
Pipeline Performance Model Parameters		
Elevation Change	0 m	
Booster Pumps	0	
Pipeline Capacity Factor	100%	Uniform (50%, 100%)
Ground Temperature	12 °C	
Inlet Pressure	13.79 MPa	Uniform (12, 15 MPa)
Minimum Outlet Pressure	10.3 MPa	
Pipeline Cost Model Parameters		
Project Region	Midwest	
Capital Recovery Factor	15%	Uniform (10%, 20%)
Annual O&M Cost	\$3,250/km/y	Uniform (\$2150, \$4350)
Cost Multiplier for Materials	1.0	Uniform (0.75, 1.25)
Cost Multiplier for Labor	1.0	Uniform (0.75, 1.25)
Cost Multiplier for ROW	1.0	Uniform (0.75, 1.25)
Cost Multiplier for Miscellaneous	1.0	Uniform (0.75, 1.25)
Cost Multiplier for Compression	1.0	Uniform (0.75, 1.25)

Levelized Cost of Transport:
Deterministic Results



Levelized Cost of Transport:
Probabilistic Results



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Storage in saline formations

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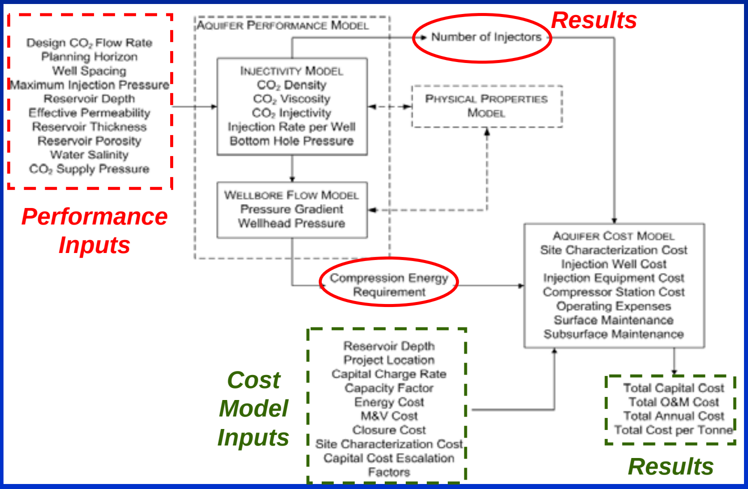
Saline Formation Storage Model



Design CO_2 Flow Rate
Planning Horizon
Well Spacing
Maximum Injection Pressure
Reservoir Depth
Effective Permeability
Reservoir Thickness
Reservoir Porosity
Water Salinity
CO_2 Supply Pressure

Performance Inputs

AQUIFER PERFORMANCE MODEL

INJECTIVITY MODEL
CO_2 Density
CO_2 Viscosity
CO_2 Injectivity
Injection Rate per Well
Bottom Hole Pressure

WELLBORE FLOW MODEL
Pressure Gradient
Wellhead Pressure

PHYSICAL PROPERTIES MODEL

Number of Injectors

Results

Compression Energy Requirement

AQUIFER COST MODEL
Site Characterization Cost
Injection Well Cost
Injection Equipment Cost
Compressor Station Cost
Operating Expenses
Surface Maintenance
Subsurface Maintenance

Cost Model Inputs

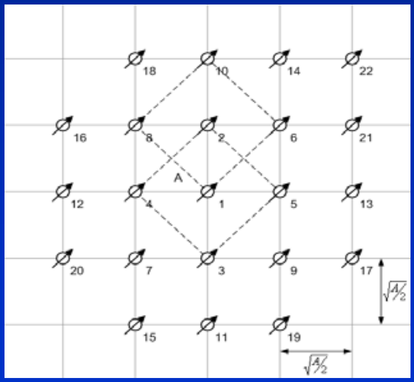
Reservoir Depth
Project Location
Capital Charge Rate
Capacity Factor
Energy Cost
M&V Cost
Closure Cost
Site Characterization Cost
Capital Cost Escalation Factors

Total Capital Cost
Total O&M Cost
Total Annual Cost
Total Cost per Tonne

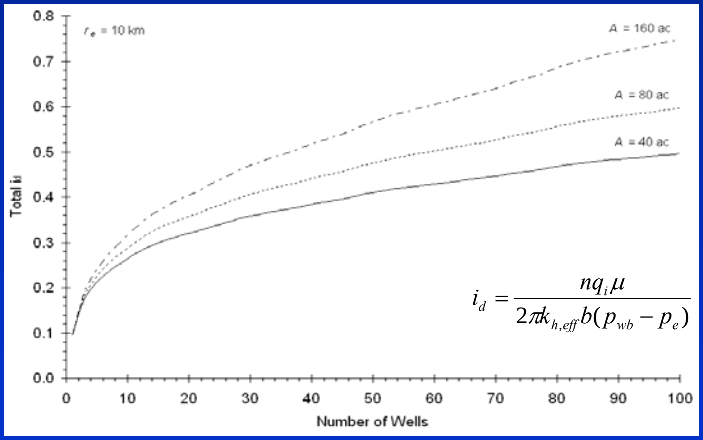
Results

Assumed System Geometry

- Multiple injection wells spaced on a regular grid
- Spacing between wells is determined by specifying an area (dashed lines)
- Model allows for up to 100 injection wells



Illustrative Injectivity Results for an *n*-Well System

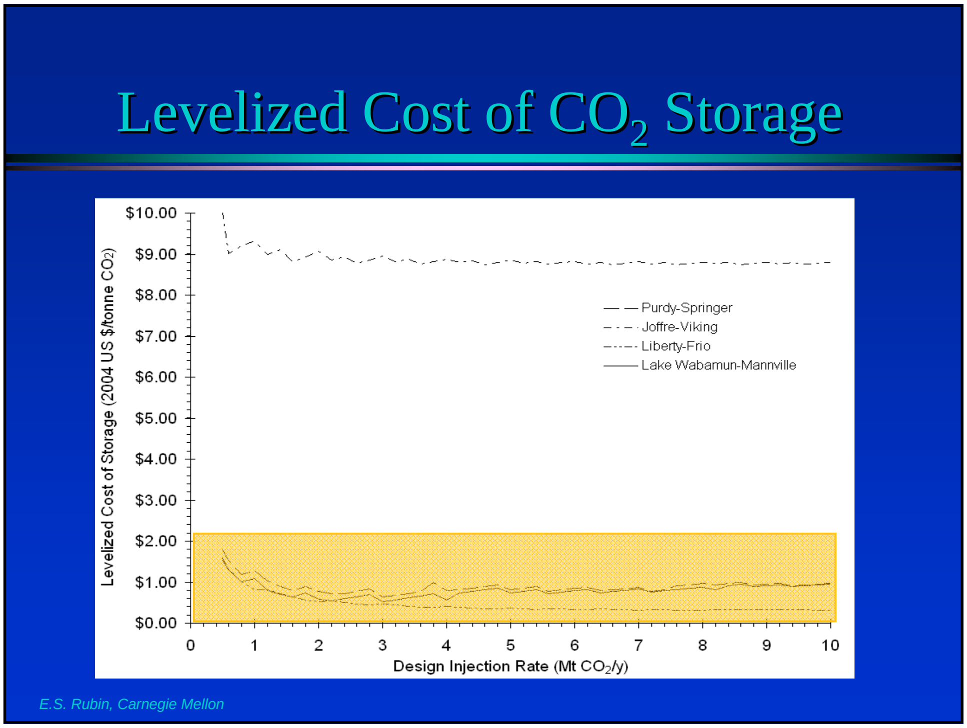


$$i_d = \frac{nq_i\mu}{2\pi k_{h,eff} b(p_{wb} - p_e)}$$

Illustrative Case Studies

- Data from 4 sites, with *kh* values from 4,500 to 940,000 md·ft
- Capital recovery factor =15% for all cases

Parameter	**Northeast Purdy Unit**	**Joffre-Viking Pool**	**South Liberty**	**Lake Wabamun Area**
Location	Oklahoma	Alberta	Texas	Alberta
Reservoir	Purdy Springer A	Viking Aquifer	Frio Formation	Mannville Aquifer
Lithology	Sandstone	Sandstone	Sandstone	Sandstone
Depth (m)	2,499	1,500	1,850	1,514
Permeability, *k* (md)	44	507	944	23
Net Sand, *h* (m)	91	30	300	59



Levelized Cost of CO_2 Storage

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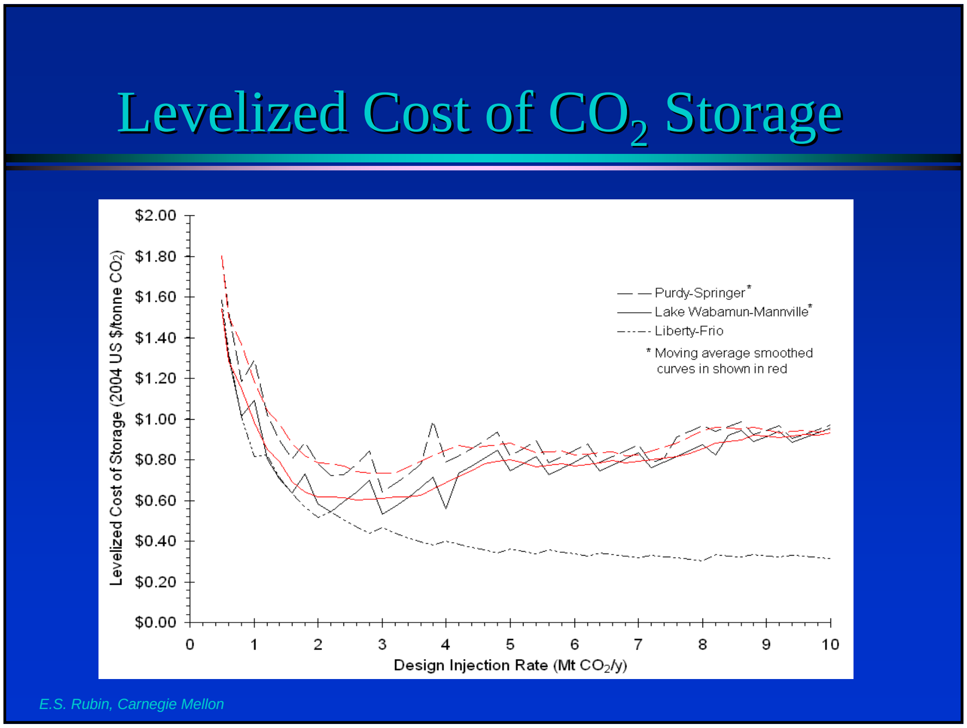

Levelized Cost of CO_2 Storage

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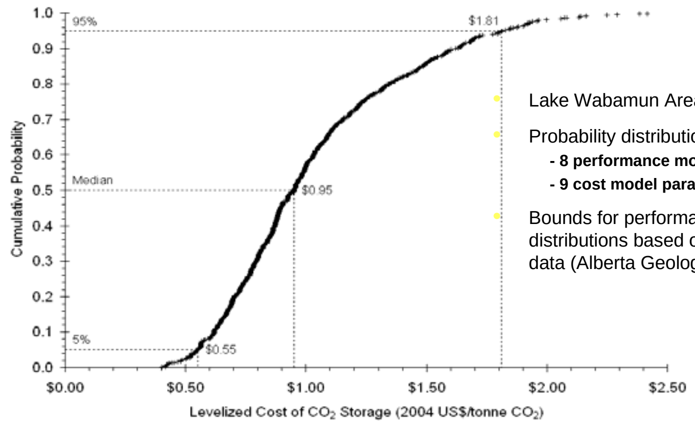
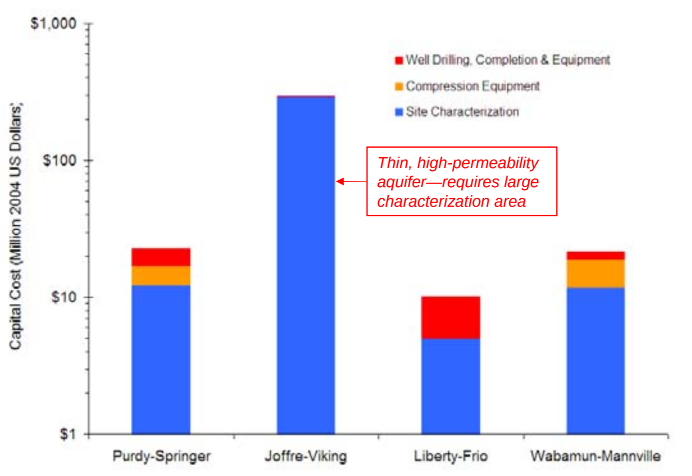
Levelized Cost of CO_2 Storage:

Probabilistic Results



- Lake Wabamun Area Case Study
- Probability distributions assigned to:
  - **- 8 performance model parameters**
  - **- 9 cost model parameters**
- Bounds for performance parameter distributions based on reported field data (Alberta Geological Survey, 2006)

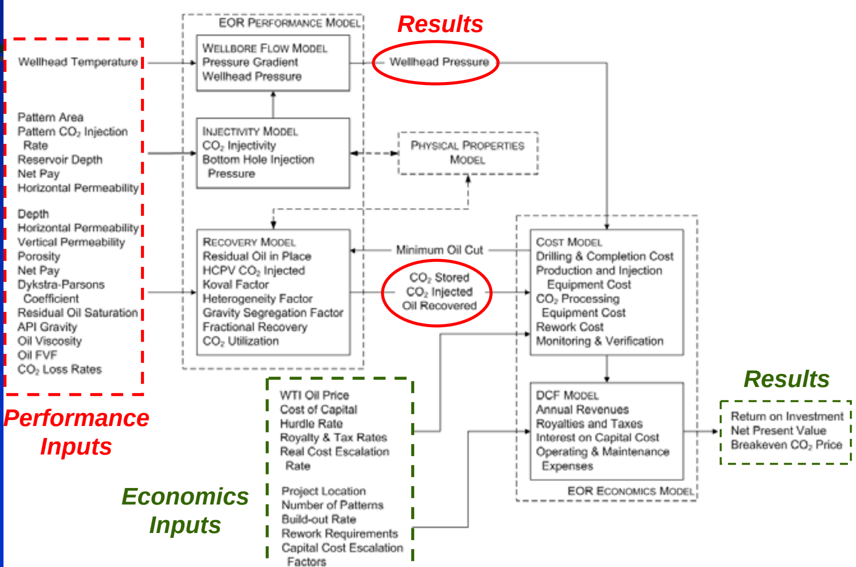
Capital Cost Breakdown



Thin, high-permeability aquifer—requires large characterization area

Storage in oil reservoirs with EOR

EOR Storage Model



Performance Inputs

Wellhead Temperature

Pattern Area
Pattern CO_2 Injection Rate
Reservoir Depth
Net Pay
Horizontal Permeability

Depth
Horizontal Permeability
Vertical Permeability
Porosity
Net Pay
Dykstra-Parsons Coefficient
Residual Oil Saturation
API Gravity
Oil Viscosity
Oil FVF
CO_2 Loss Rates

EOR PERFORMANCE MODEL

WELLBORE FLOW MODEL
Pressure Gradient
Wellhead Pressure

INJECTIVITY MODEL
CO_2 Injectivity
Bottom Hole Injection Pressure

PHYSICAL PROPERTIES MODEL

RECOVERY MODEL
Residual Oil in Place
HCPV CO_2 Injected
Koval Factor
Heterogeneity Factor
Gravity Segregation Factor
Fractional Recovery
CO_2 Utilization

Results

Wellhead Pressure

Minimum Oil Cut

CO_2 Stored
CO_2 Injected
Oil Recovered

Economics Inputs

WTI Oil Price
Cost of Capital
Hurdle Rate
Royalty & Tax Rates
Real Cost Escalation Rate

Project Location
Number of Patterns
Build-out Rate
Rework Requirements
Capital Cost Escalation Factors

COST MODEL
Drilling & Completion Cost
Production and Injection Equipment Cost
CO_2 Processing Equipment Cost
Rework Cost
Monitoring & Verification

DCF MODEL
Annual Revenues
Royalties and Taxes
Interest on Capital Cost
Operating & Maintenance Expenses

EOR ECONOMICS MODEL

Results

Return on Investment
Net Present Value
Breakeven CO_2 Price

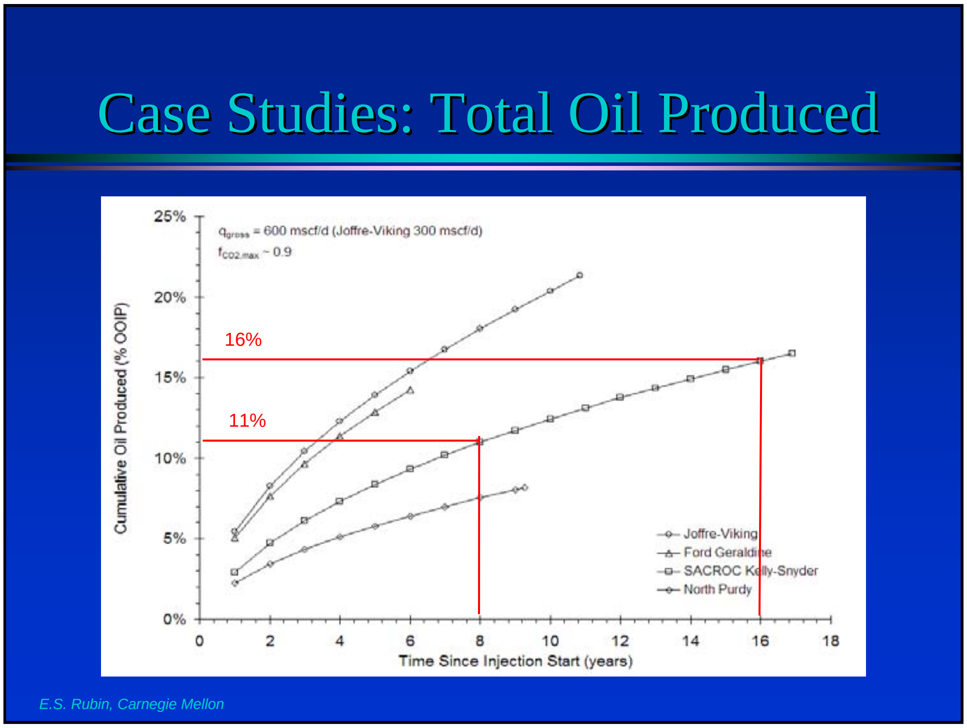
EOR Performance Model Assumptions

- Unstable miscible CO_2-flood
- 5-spot injection pattern, scaled to the larger field
- CO_2 injected at a specified constant rate
- No water injection (i.e., water alternating gas)
- No mobile water in reservoir
- Fractional flow is based only on mobility ratio

Illustrative Case Studies

- Four case studies covering a range of reservoir parameters:
  - *kh* values from 1,500 to 5,200 md·ft
  - Project sizes from 130,000 to 13,000,000 acre·ft

Parameter	**Northeast Purdy Unit**	**SACROC Unit, Kelly-Snyder Field**	**Ford Geraldine Unit**	**Joffre-Viking Pool**
Location	Oklahoma	Texas	Texas	Alberta
Reservoir Name	Purdy Springer A Sand	Canyon Reef	Ramsey	Viking
Lithology	Sandstone	Limestone	Sandstone	Sandstone
Previous Oil Recovery	Primary & Waterflood	Primary & Waterflood	Primary & Waterflood	Primary & Waterflood



Case Studies: Total Oil Produced

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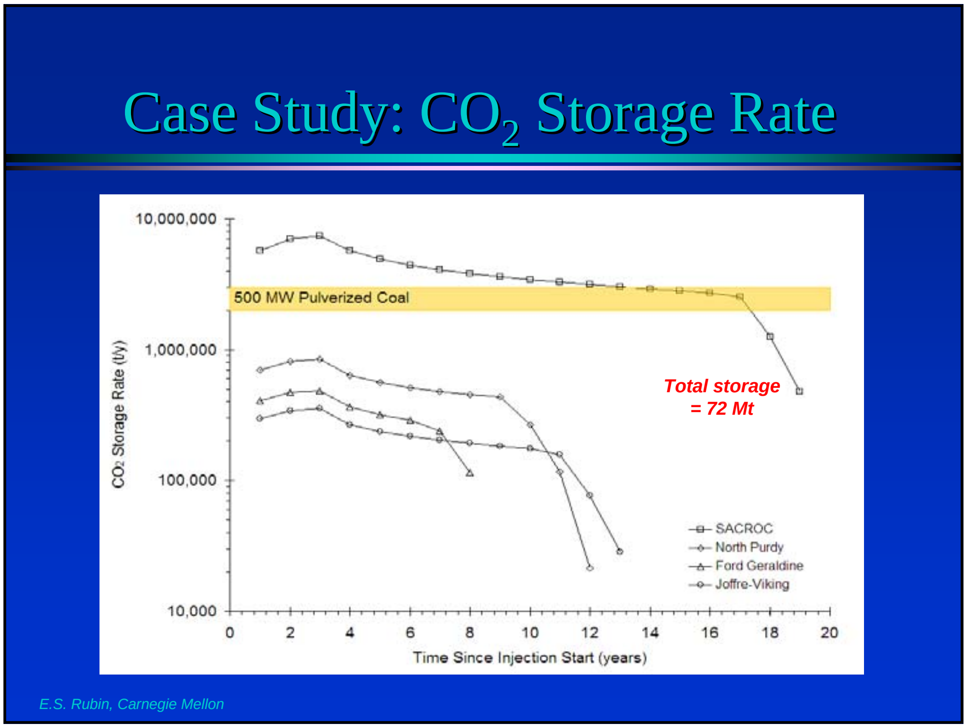

Case Study: CO_2 Storage Rate

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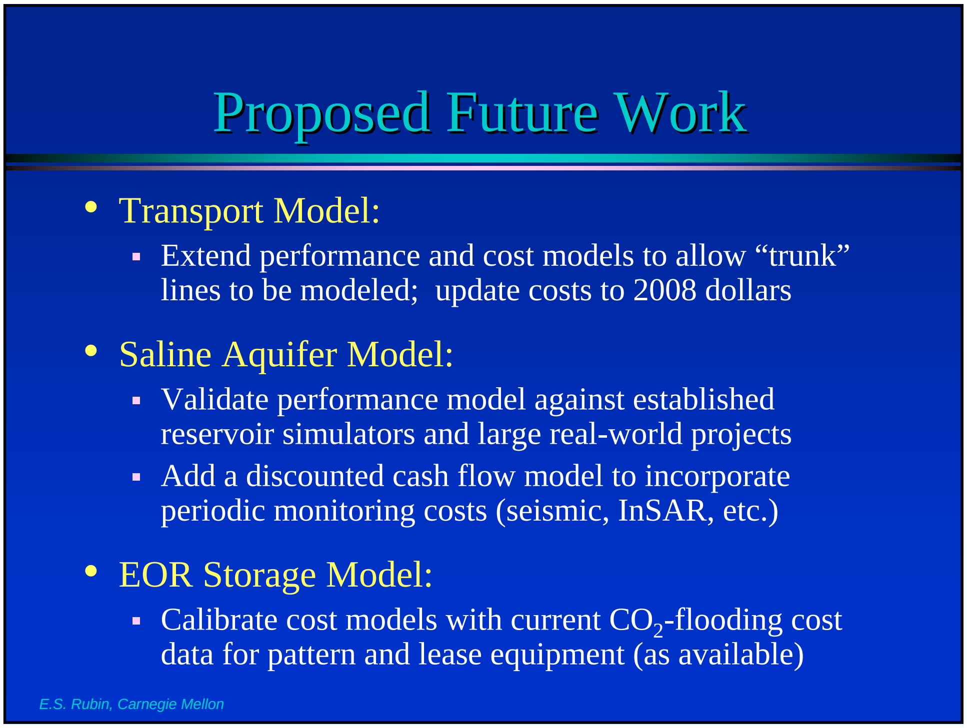
Current and future work

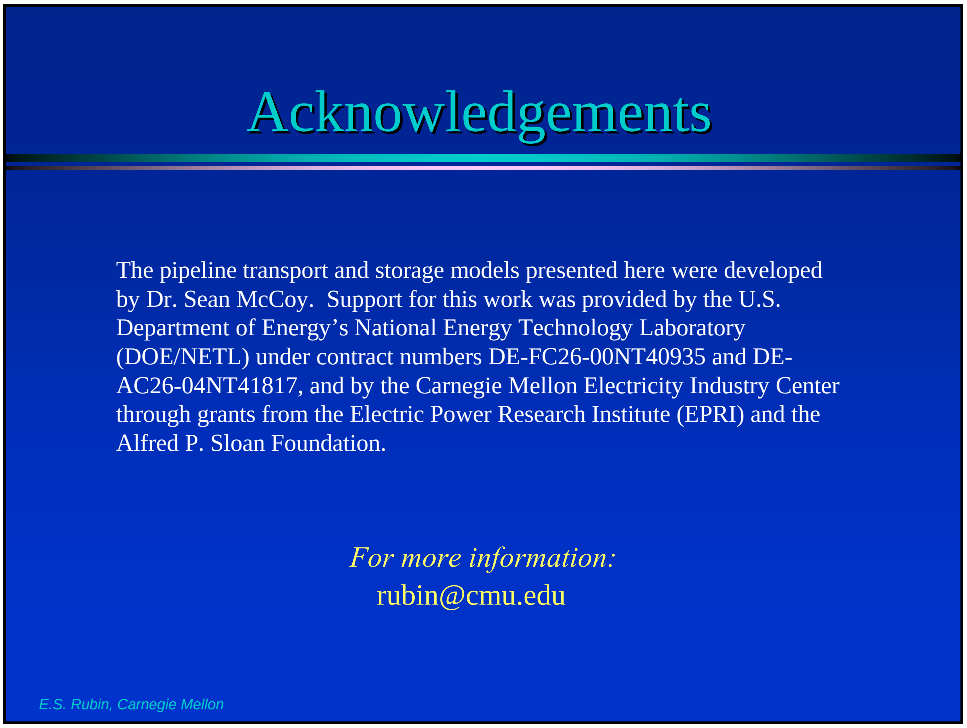
New IECM Options Under Development

- *Expand IECM to model plant water use and effluents:*
  - Prevailing PC plant designs
  - Performance and cost of major systems
- *New power plant options with and w/o CO_2 capture:*
  - Additional IGCC system options
  - PC plants with advanced amine systems
  - Both low rank and bituminous coals



Proposed Future Work

- Transport Model:
  - Extend performance and cost models to allow “trunk” lines to be modeled; update costs to 2008 dollars
- Saline Aquifer Model:
  - Validate performance model against established reservoir simulators and large real-world projects
  - Add a discounted cash flow model to incorporate periodic monitoring costs (seismic, InSAR, etc.)
- EOR Storage Model:
  - Calibrate cost models with current CO_2-flooding cost data for pattern and lease equipment (as available)



Acknowledgements

The pipeline transport and storage models presented here were developed by Dr. Sean McCoy. Support for this work was provided by the U.S. Department of Energy’s National Energy Technology Laboratory (DOE/NETL) under contract numbers DE-FC26-00NT40935 and DE-AC26-04NT41817, and by the Carnegie Mellon Electricity Industry Center through grants from the Electric Power Research Institute (EPRI) and the Alfred P. Sloan Foundation.

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