



***Optimized Solvent for Energy-Efficient, Environmentally-Friendly Capture of CO<sub>2</sub> at Coal-Fired Power Plants***

**Project Kick-Off Meeting  
DE-FE0007716  
November 30, 2011**



***George Farthing  
Principal Investigator***

# The Babcock & Wilcox Company



## ***B&W Technical Services Group, Inc.***

- Nuclear material handling, storage and security
- Nuclear laboratories
- Weapons complex
- Decontamination and decommissioning
- Strategic Petroleum Reserve



## ***B&W Nuclear Operations Group, Inc.***

- Virginia-Class submarine program
- Ford-Class carrier program
- Refueling
- Fuel processing and fabrication



## ***B&W Power Generation Group, Inc.***

- Coal-fired power generation
- Service, operation and maintenance
- Construction and EPC
- Environmental systems (FGD, SCR, Hg, Particulate, Carbon)
- Renewables (Biomass, solar, waste-to-energy)



## ***B&W Nuclear Energy, Inc.***

- Field services
- Plant modifications
- Component manufacturing and installation
- Fuel design, enrichment and fabrication
- B&W mPower™

# B&W Power Generation Group, Inc.

## *Business Footprint*

- **\$1.4 B Revenue in 2010**
- **\$1.6 B Backlog as of 12/31/10**
- **Headquartered in Barberton, OH**
- **Approximately 8,270 employees (including JVs)**

<b>Locations</b>	<b>Employees</b>
Ohio	3,113
Rest of U.S.	1,351
Canada	573
Mexico	199
Europe	434
Asia	2,600



## *Product Line Portfolio*



**Utility and industrial boilers**  
*Firing fossil fuels*



**Environmental products**  
*Control regulated emissions*



**Boiler cleaning and auxiliaries**



**Field services**  
*Upgrade, replace equipment*



**Construction**  
*Install all B&W supplied scope*



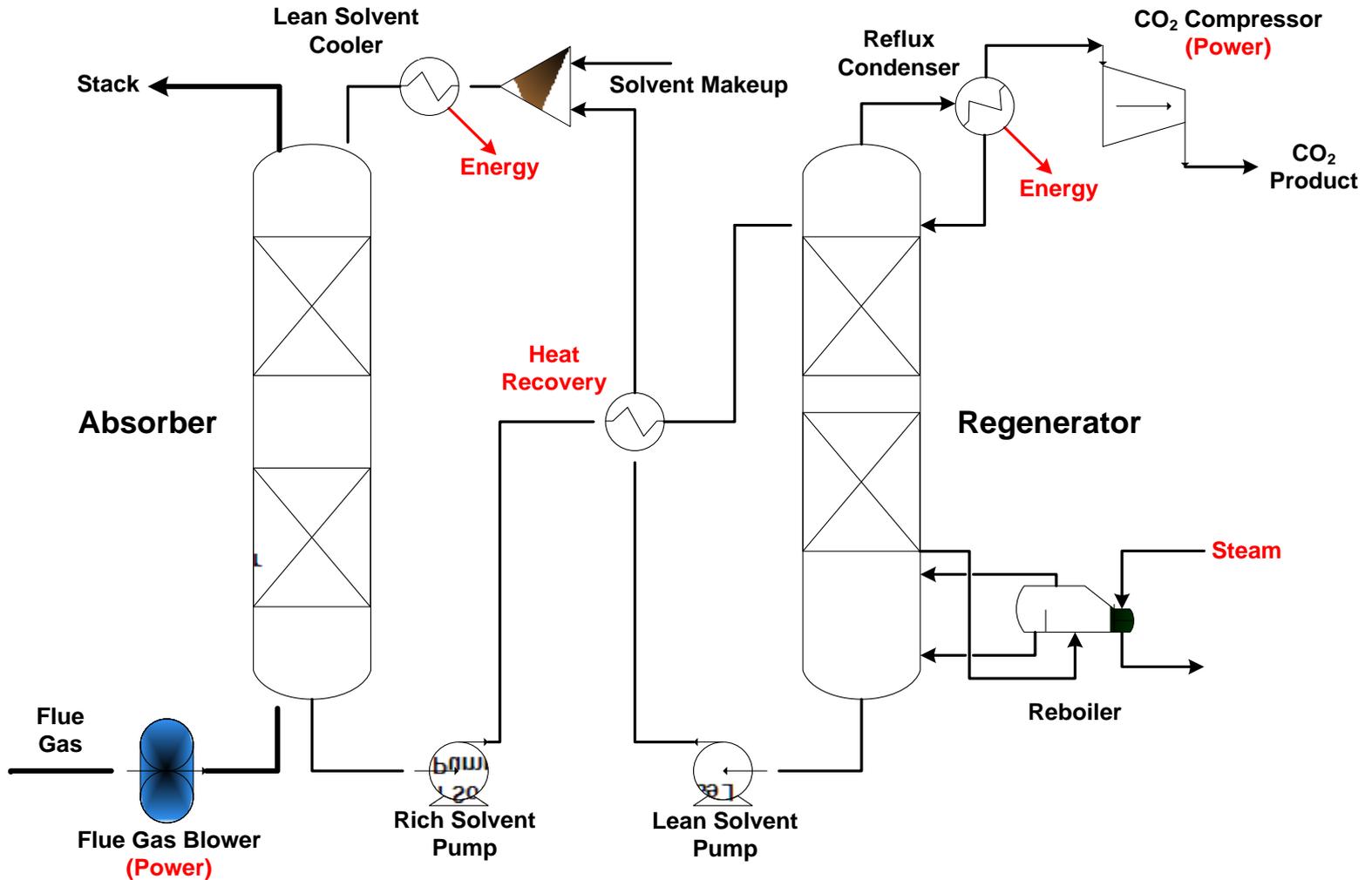
**O&M services**  
*Operate, maintain power plants*

# B&W is Positioned to Meet Utility and Environmental Needs

<b>Spray Dry FGD</b>	<b>Wet FGD</b>	<b>Circulating Dry Scrubber</b>	<b>Industrial and WTE Scrubbers</b>	<b>Fabric Filter</b>	<b>Dry ESP</b>	<b>Wet ESP / SO<sub>3</sub> Control</b>	<b>Multiclone</b>
							
							
<b>Mercury Control</b>	<b>Acid Gas Dry Sorbent Injection</b>	<b>CO<sub>2</sub> Control</b>	<b>SCR / Low NO<sub>x</sub> Burner</b>	<b>Emissions Monitoring</b>	<b>Aftermarket Services</b>	<b>Construction</b>	<b>Ash Management</b>

## Total Solutions Provider

# CO<sub>2</sub> Scrubbing Process



# Development Challenges

## Parasitic Power

- 20-30% reduction in plant output

## Cost of Electricity

- 50-100% increase

## Flue Gas

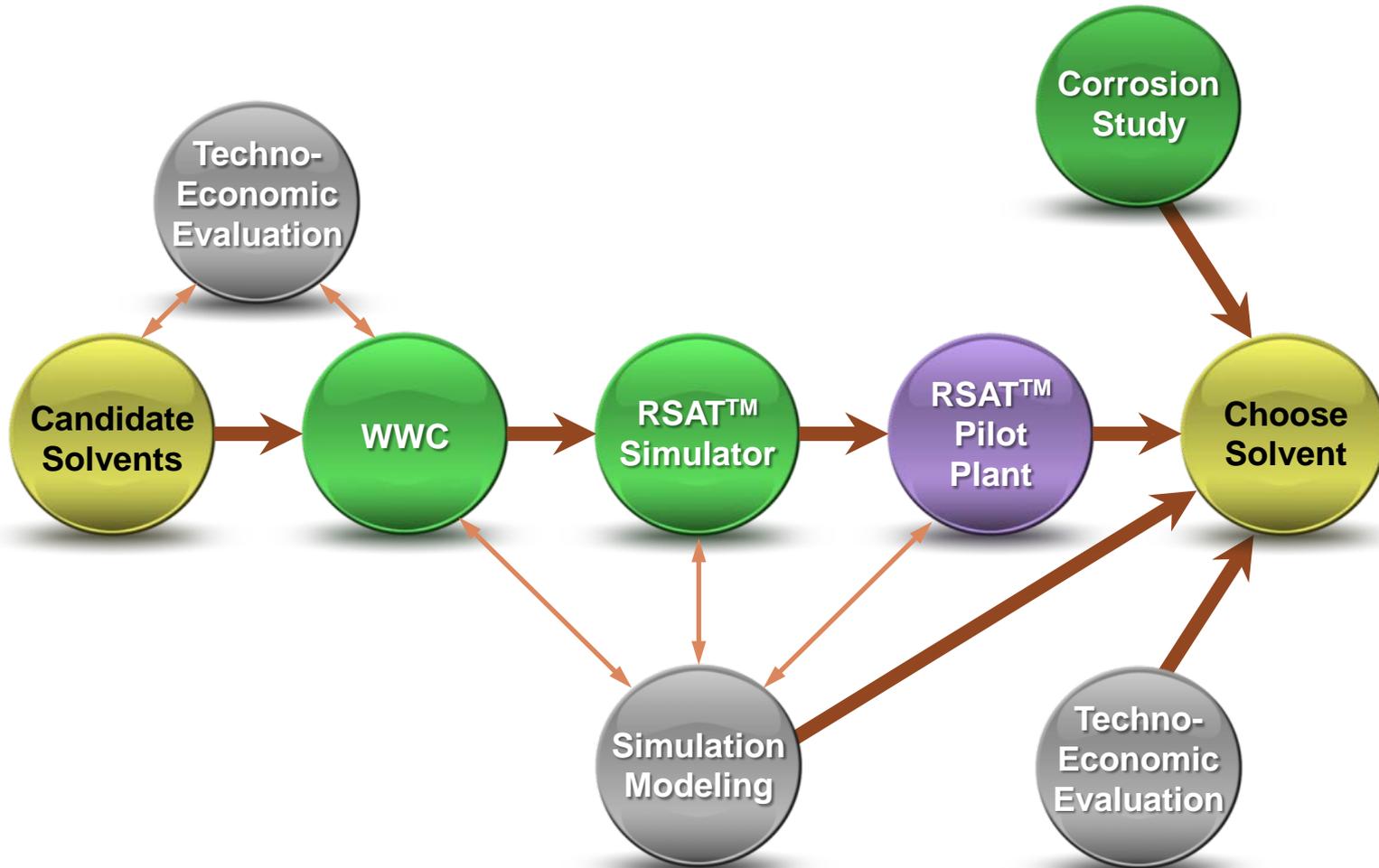
- Low CO<sub>2</sub> partial pressure
- Contaminants (O<sub>2</sub>, SO<sub>x</sub>, NO<sub>x</sub>, HCl, metals, ...)

## Scale

- 500 MWe plant produces 3.6 million tons CO<sub>2</sub> / yr



# Solvent Selection Methodology



RSAT™: Regenerable Solvent Absorption Technology

# Final Selection

Chemistry/Proposed	Substrate/ Substrate	Materials	Name of Supplier	Construction				Manufacturability
				Construction	Installation	Operation	Maintenance	
1. 100% Ethanol (100%)								
2. 95% Ethanol (95%)								
3. 90% Ethanol (90%)								
4. 85% Ethanol (85%)								
5. 80% Ethanol (80%)								
6. 75% Ethanol (75%)								
7. 70% Ethanol (70%)								
8. 65% Ethanol (65%)								
9. 60% Ethanol (60%)								
10. 55% Ethanol (55%)								
11. 50% Ethanol (50%)								
12. 45% Ethanol (45%)								
13. 40% Ethanol (40%)								
14. 35% Ethanol (35%)								
15. 30% Ethanol (30%)								
16. 25% Ethanol (25%)								
17. 20% Ethanol (20%)								
18. 15% Ethanol (15%)								
19. 10% Ethanol (10%)								
20. 5% Ethanol (5%)								

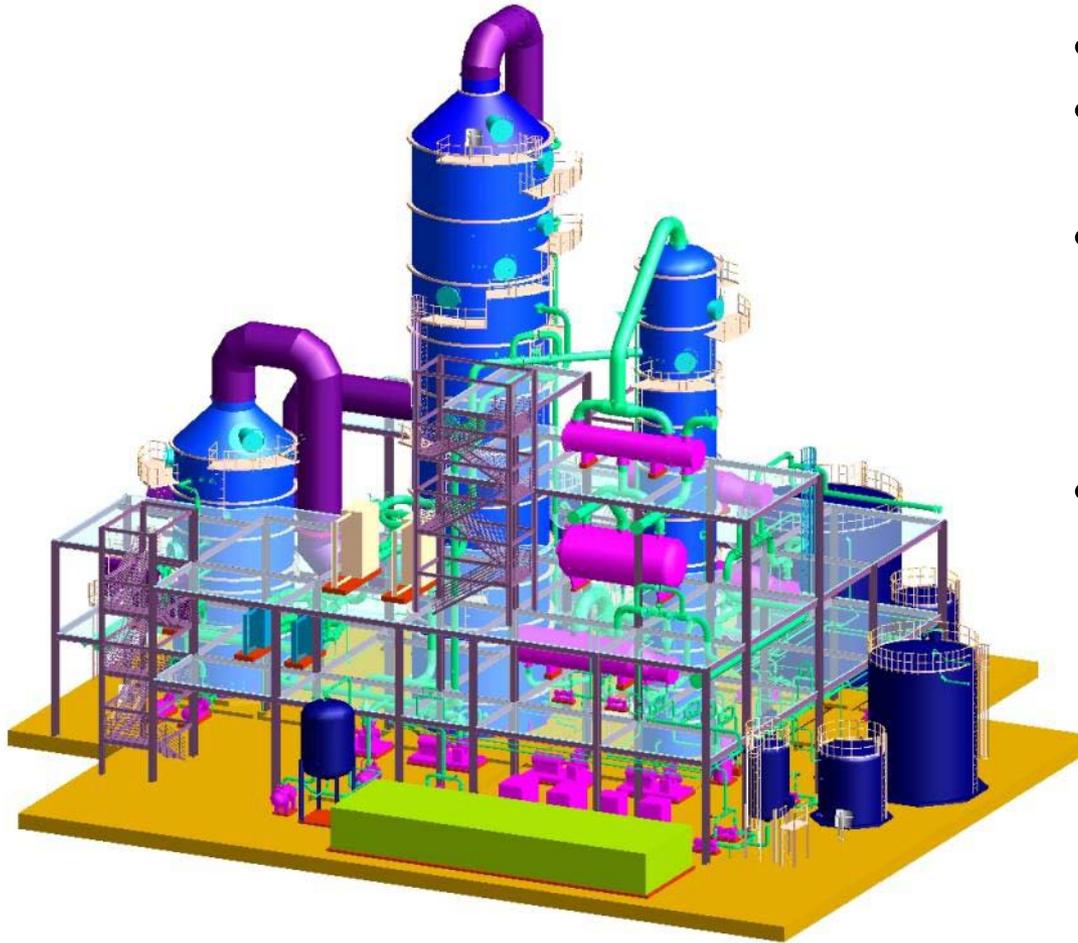


## Solvent Screening

## Solvent Selection

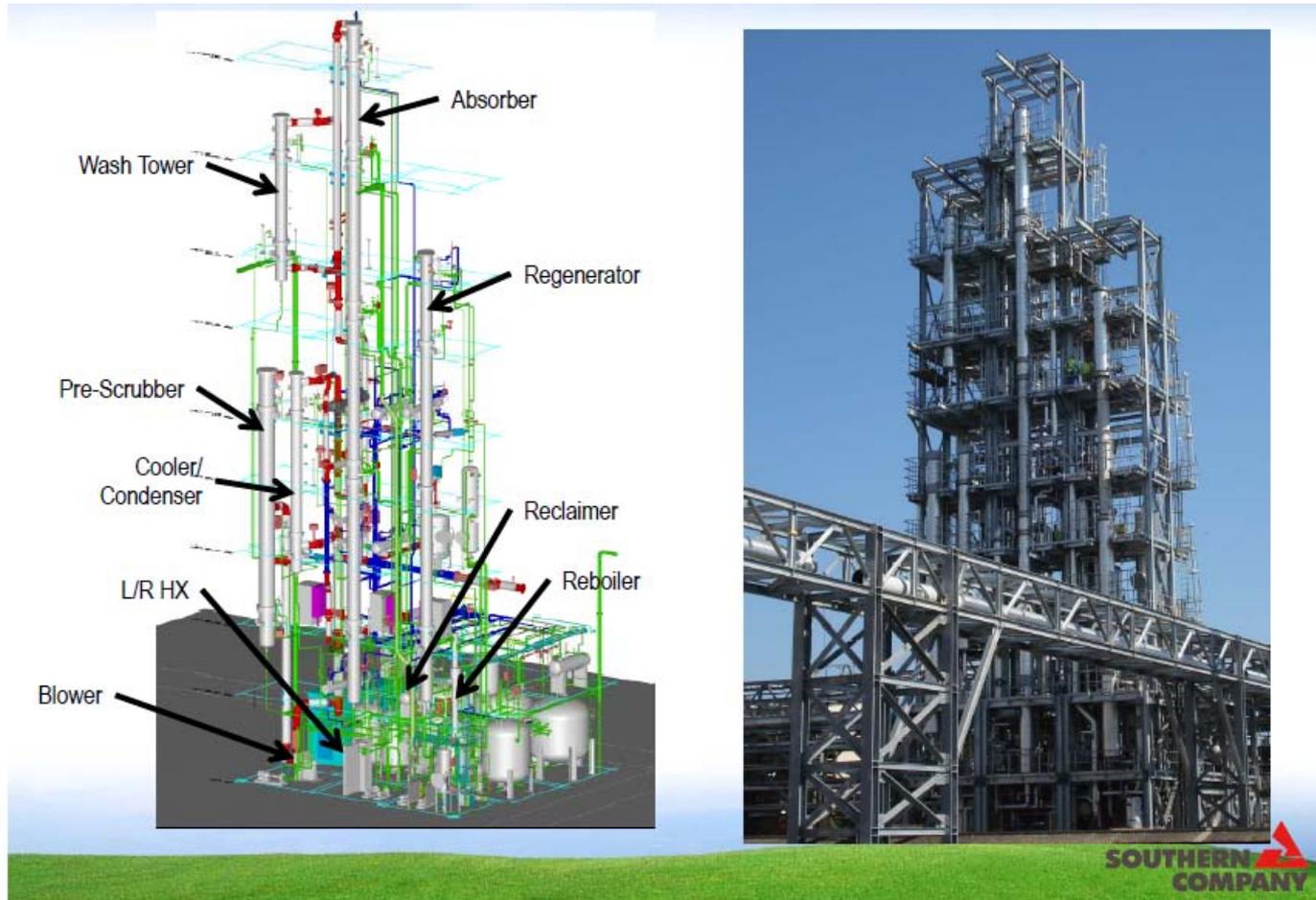
Requirement	CRQ Rank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50									
CO <sub>2</sub> Dissolved at High Pressure	1																																																											
Obtainable	2	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L			
Low Capital Cost	3																																																											
Low Steam Demand	4																																																											
Highly Flammable	5																																																											
Ready for NCCO	6																																																											
Noncorrosive	7																																																											
Stable	8																																																											
Stable to Oxidation	9																																																											
Easy to Operate	10																																																											
High Capacity/Volume Demand	11																																																											
Highly Flammable	12																																																											
Stable to Oxidation	13																																																											
Easy to Handle	14																																																											
Environmentally Friendly	15																																																											
Good Flow Properties	16																																																											
Low-Cost Solvent	17																																																											
Highly Flammable	18																																																											

# 1500 tpd RSAT™ Reference Plant Design



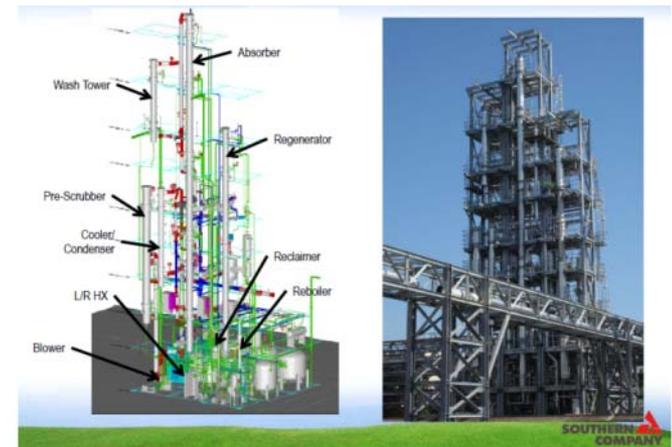
- 75 MWe equivalent
- Basis for capital cost estimates, demo
- Plant model, P&IDs, equipment lists, heat & material balances, construction estimates
- Supply chain of vendors/fabricators

# National Carbon Capture Center (NCCC) Wilsonville, AL



# Objectives of NCCC Testing

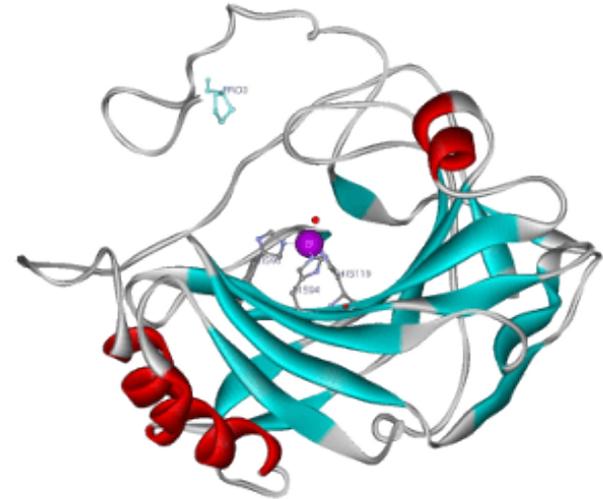
- Process simulation model validation
- Effluent streams characterization
  - Stack emissions
  - Wastewater characteristics
  - Reclaimer sludge amount & composition
- Solvent degradation & reclamation
  - Oxidative
  - Thermal
  - Chemical
- Corrosion studies



# Advanced Solvents

## Carbonic anhydrase (CA)

- ▶ One of fastest enzymes known
- ▶ Industrial partners



## Ionic Liquids

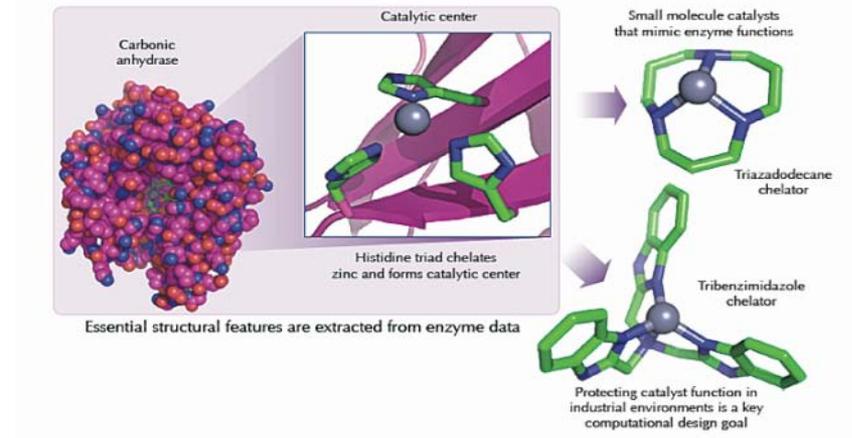
- ▶ University of Notre Dame
- ▶ Others
- ▶ US DOE-NETL



# Advanced Solvents (cont.)

## Small molecule CA mimics

- ▶ Lawrence Livermore National Lab
- ▶ University of Illinois
- ▶ ARPA-E



## Liquid phosphazene

- ▶ Idaho National Lab
- ▶ B&W PGG

# Other Concepts

## Solid Sorbents

- ▶ Metal Organic Frameworks
- ▶ Amine Fortified Zeolites
- ▶ Chemical Looping
- ▶ Calcium Looping

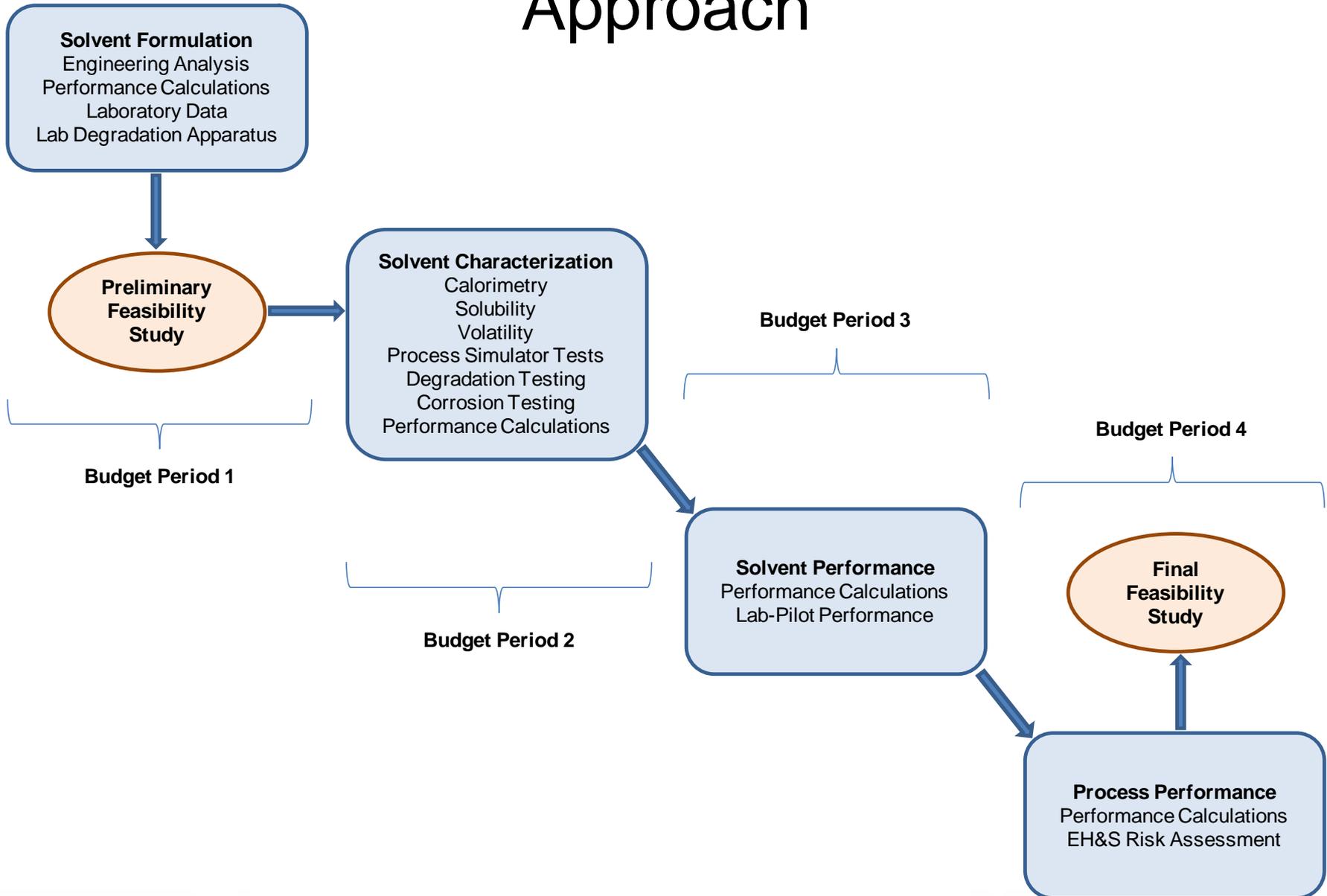
## Membranes

- ▶ CO<sub>2</sub> Separation Membrane

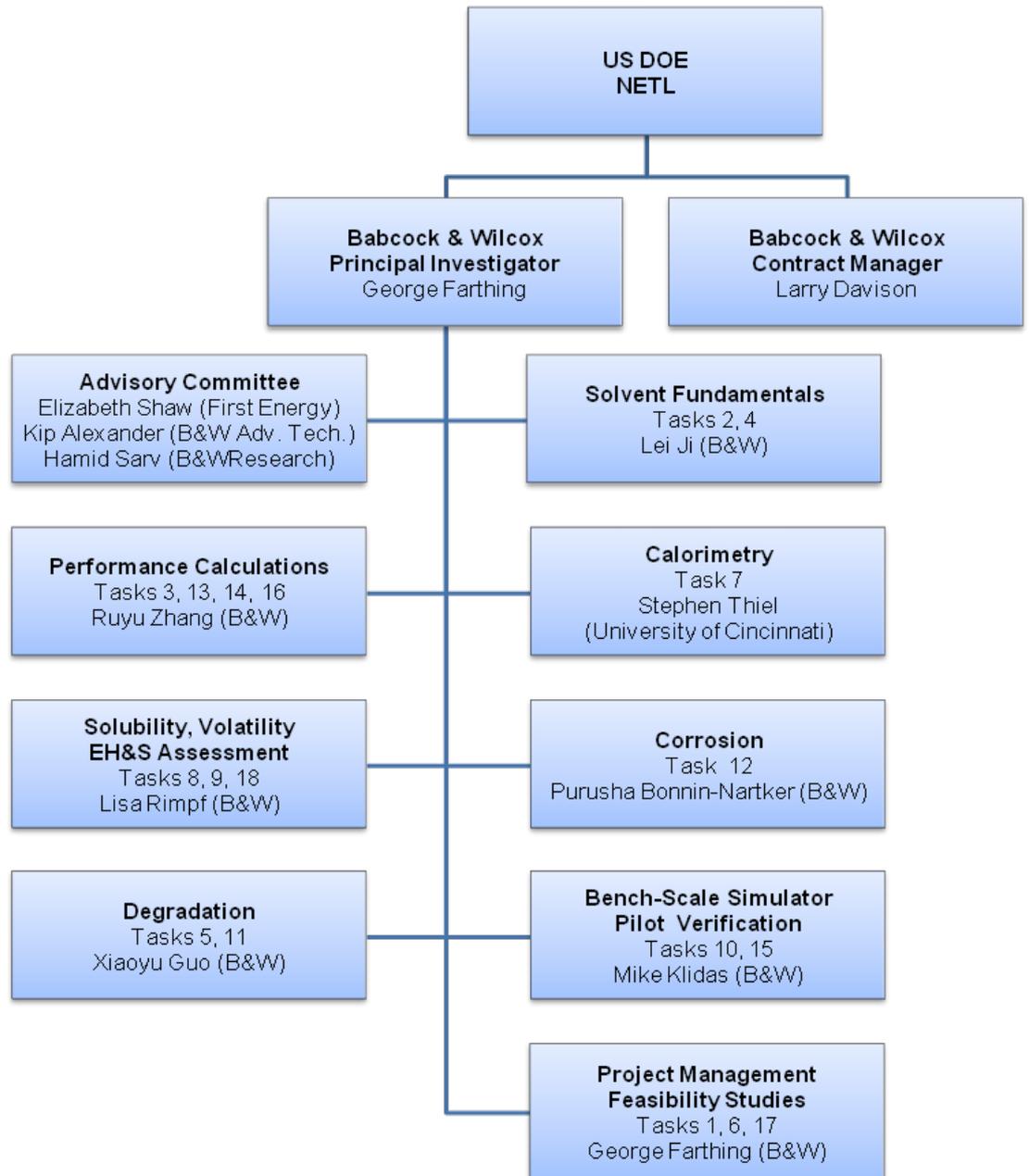
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***DE-FE0007716***

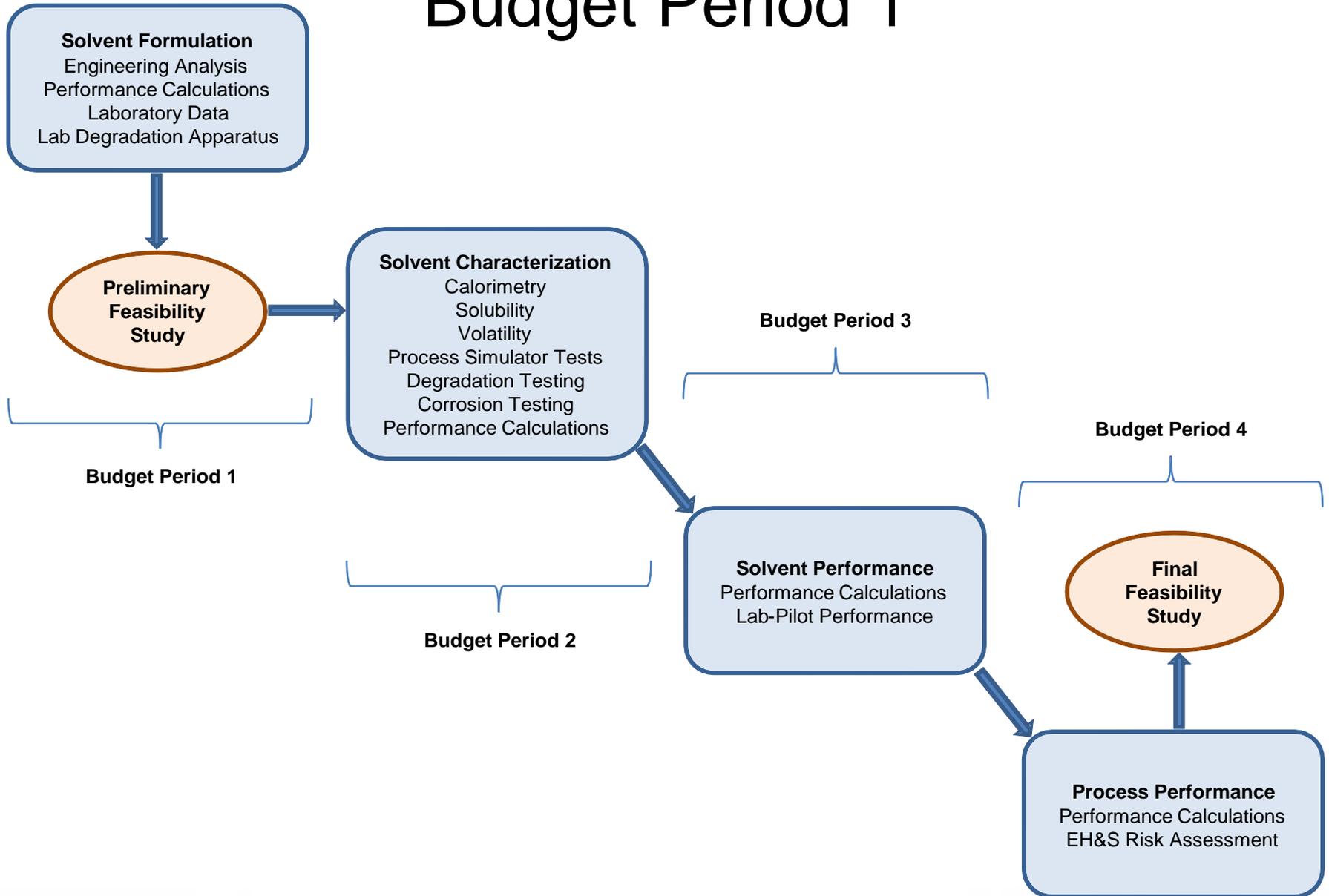
# Approach



# Project Organization



# Budget Period 1



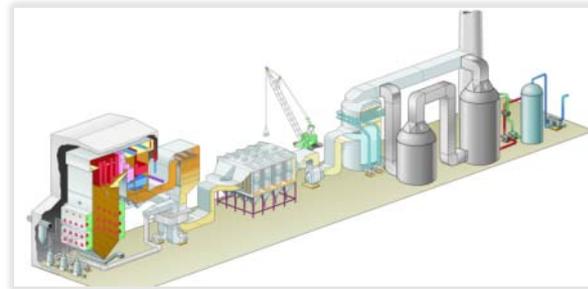
# Budget Period 1 Solvent Formulation



**Task 2  
Engineering Analysis**



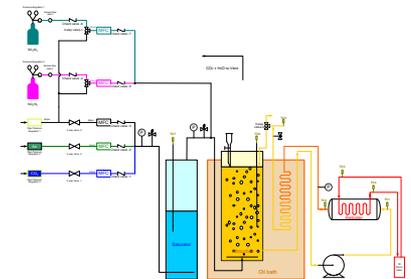
**Task 3  
Performance**



**Task 6  
Preliminary Feasibility**



**Task 4  
Laboratory Data**



**Task 5  
Degradation Apparatus**

# Budget Period 1 Solvent Formulation



**Task 2  
Engineering Analysis**

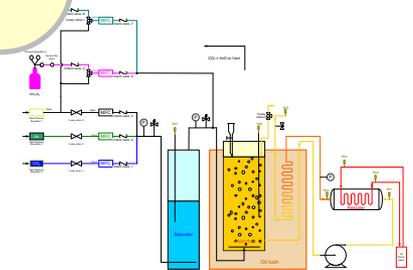


**Task 3  
Performance**

- Objectives
  - Define solvent formulations
  - Plan/evaluate lab results
- Approach
  - Literature data
  - Previous B&W testing/analyses
  - Engineering analysis



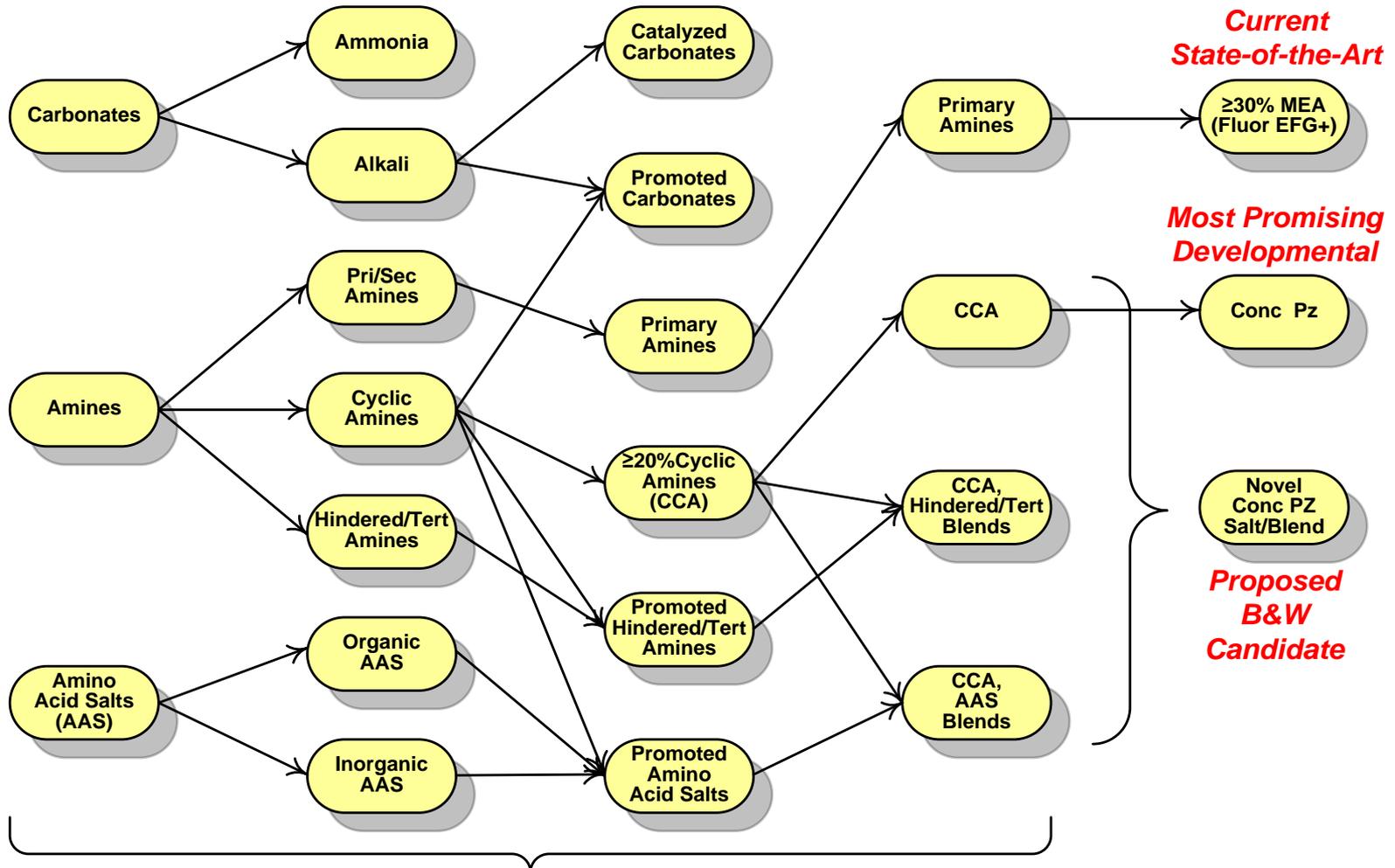
**Task 4  
Laboratory Data**



**Task 5  
Degradation Apparatus**

# Candidate Formulations

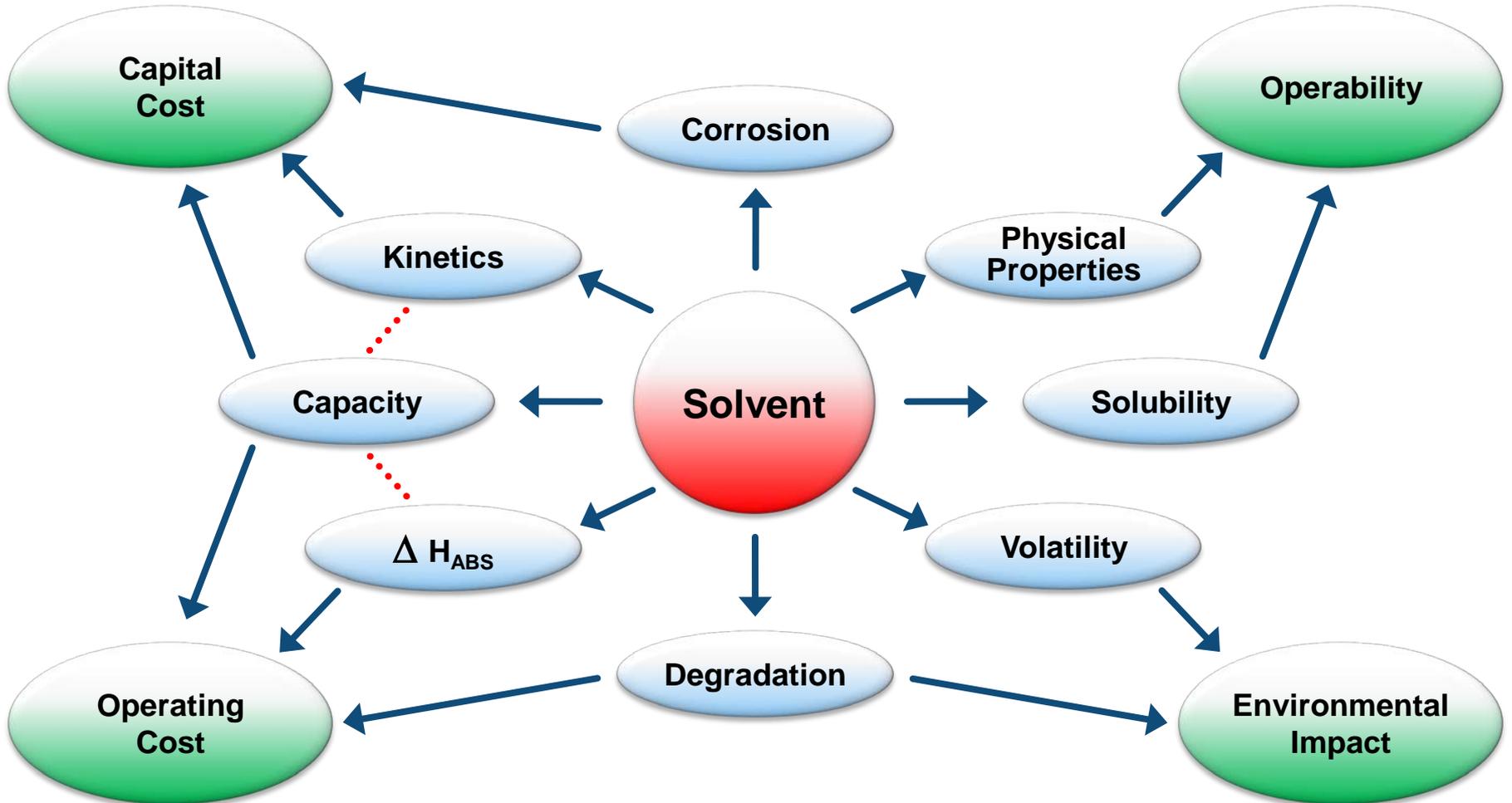
## Better Solvents (B&W's Downselect Process)



## B&W's 5-Year Solvent Development Effort

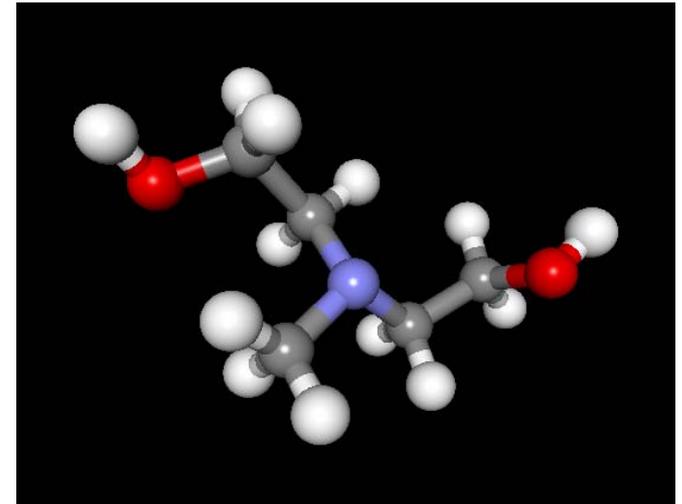
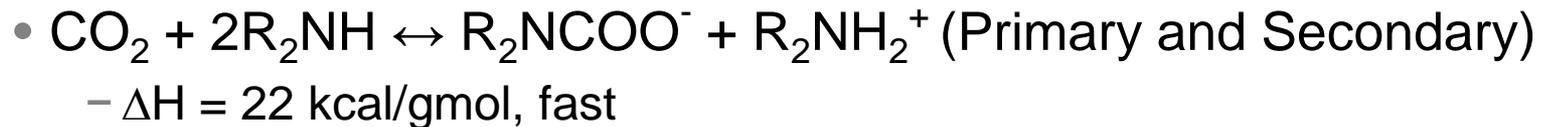
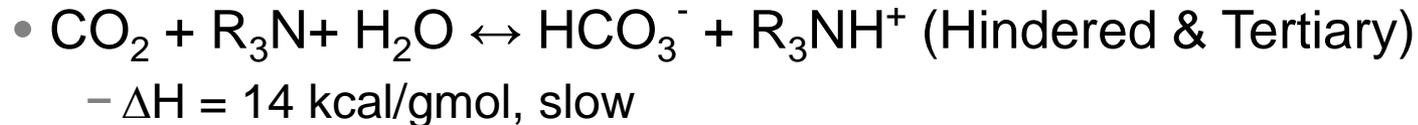
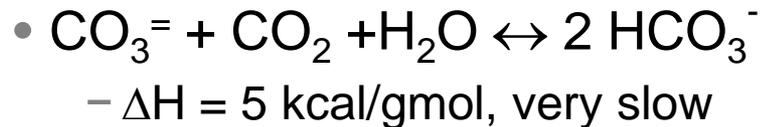
GAF 3/18/11

# Impacts of Solvent



# Solvent Characteristics

## ▶ Three basic types of chemistry



Source: Professor Gary Rochelle, University of Texas at Austin

# Budget Period 1 Solvent Formulation



**Task 2  
Engineering A**

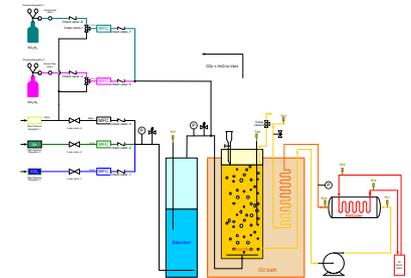
- Objectives
  - Solvent performance predictions
  - Support selection of formulations
- Approach
  - In-house semi-empirical models
  - Rate-based Aspen Plus
  - Calculations



**Task 3  
Performance**



**Task 4  
Laboratory Data**



**Task 5  
Degradation Apparatus**

# Budget Period 1 Solvent Formulation



**Task 2  
Engineering Analysis**

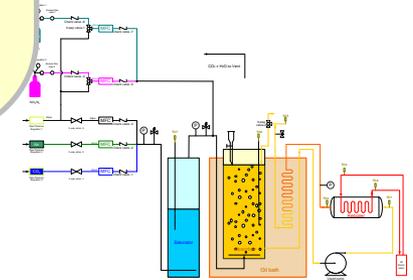


**Task 3  
Performance**



**Task 4  
Laboratory Data**

- Objectives
  - Solvent property data
  - Support formulation selection
- Approach
  - Wetted-Wall Column
    - Mass transfer
    - Chemical kinetics
    - Vapor-liquid equilibrium
  - Laboratory Screening
    - Solubility
    - Volatility
    - Degradation

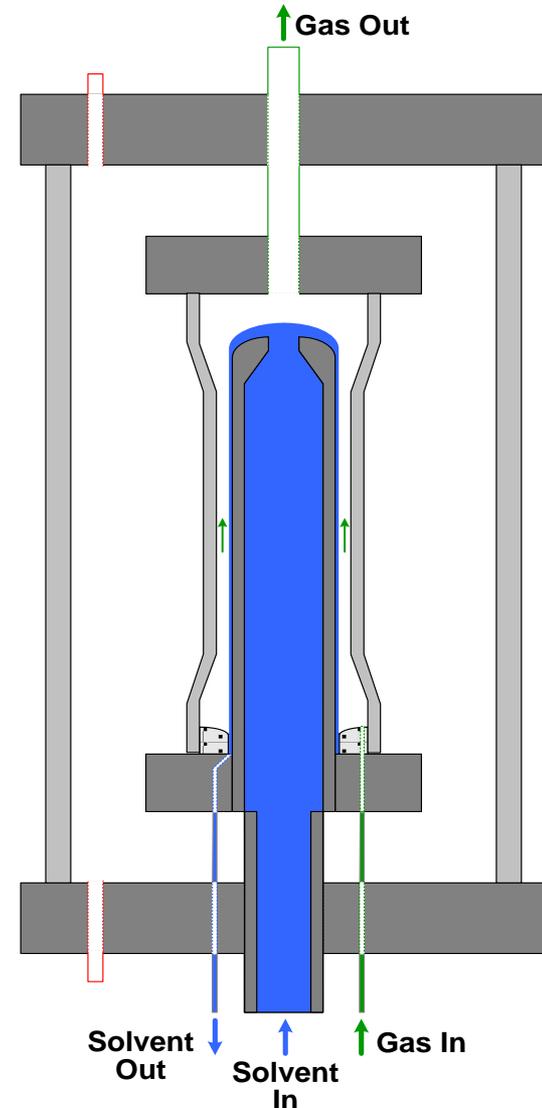


**Task 5  
Degradation Apparatus**

# Wetted-Wall Column

## Key Features:

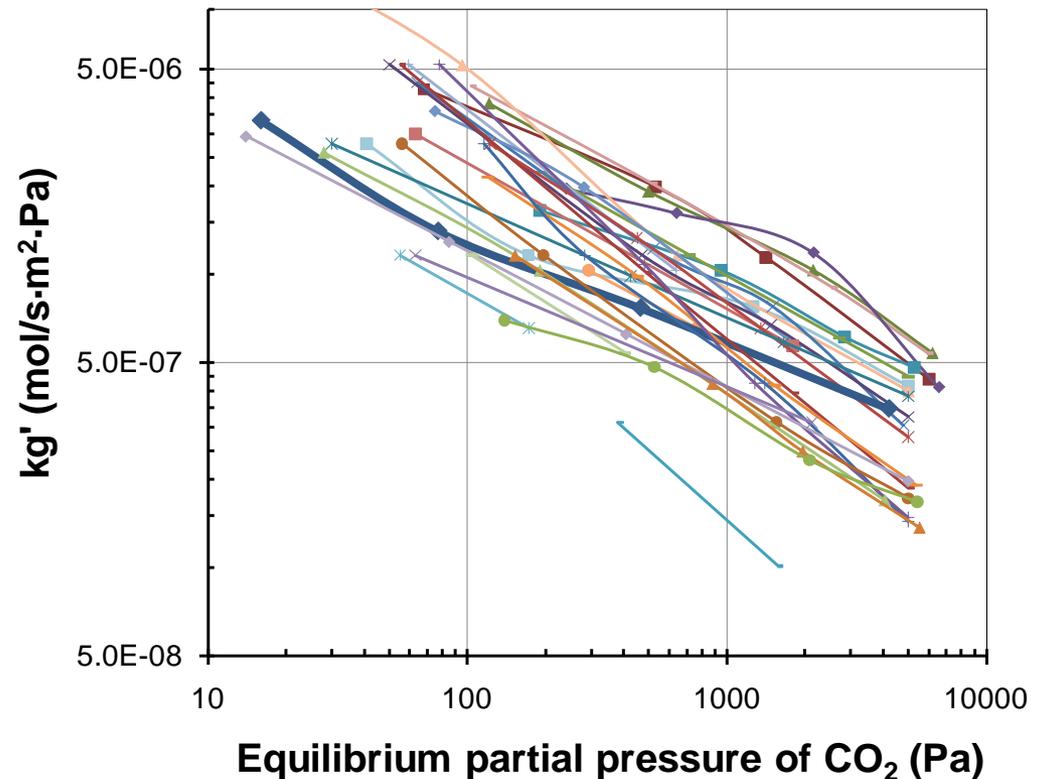
- Gas/liquid contactor
- Differential reactor
  - “Slice” of absorber or regenerator
- Known process conditions
  - Contact area
  - T, p, compositions, flow rates



# WWC – Applications

- ▶ Fundamental solvent data
  - Thermodynamic equilibrium (VLE)
  - Mass transfer coefficients
  - Chemical reaction rate constants
- ▶ Input for simulation models

## Solvent Comparison – Mass Transfer



# Budget Period 1 Solvent Formulation



**Task 2  
Engineering Analysis**

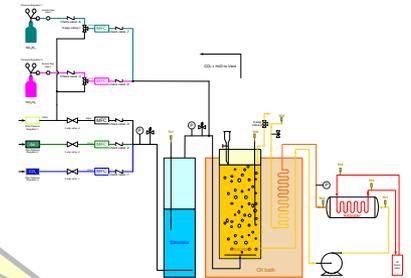
- Objective
  - Design and installation (new)
- Approach
  - Long-term, unattended operation
  - Representative
    - Absorption/regeneration
    - Temperature, pressure
    - CO<sub>2</sub> loading
    - Flue gas contaminants



**Task 3  
Performance**



**Task 4  
Laboratory Data**

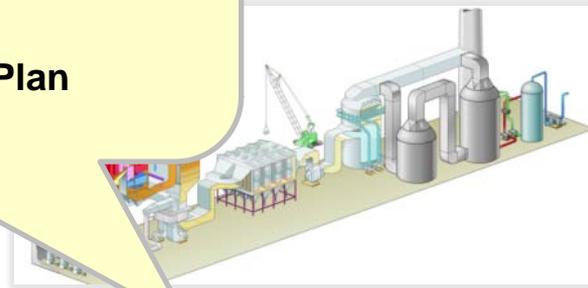


**Task 5  
Degradation Apparatus**

# Budget Period 1 Solvent Formulation



- Objectives
  - Initial techno-economic assessment
  - Identify information gaps
  - Go/No-Go decision
- Approach
  - Per Project Management Plan



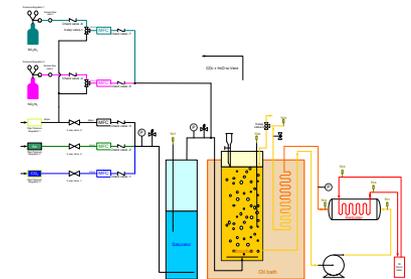
**Task 6  
Preliminary Feasibility**



**Task 3  
Performance**

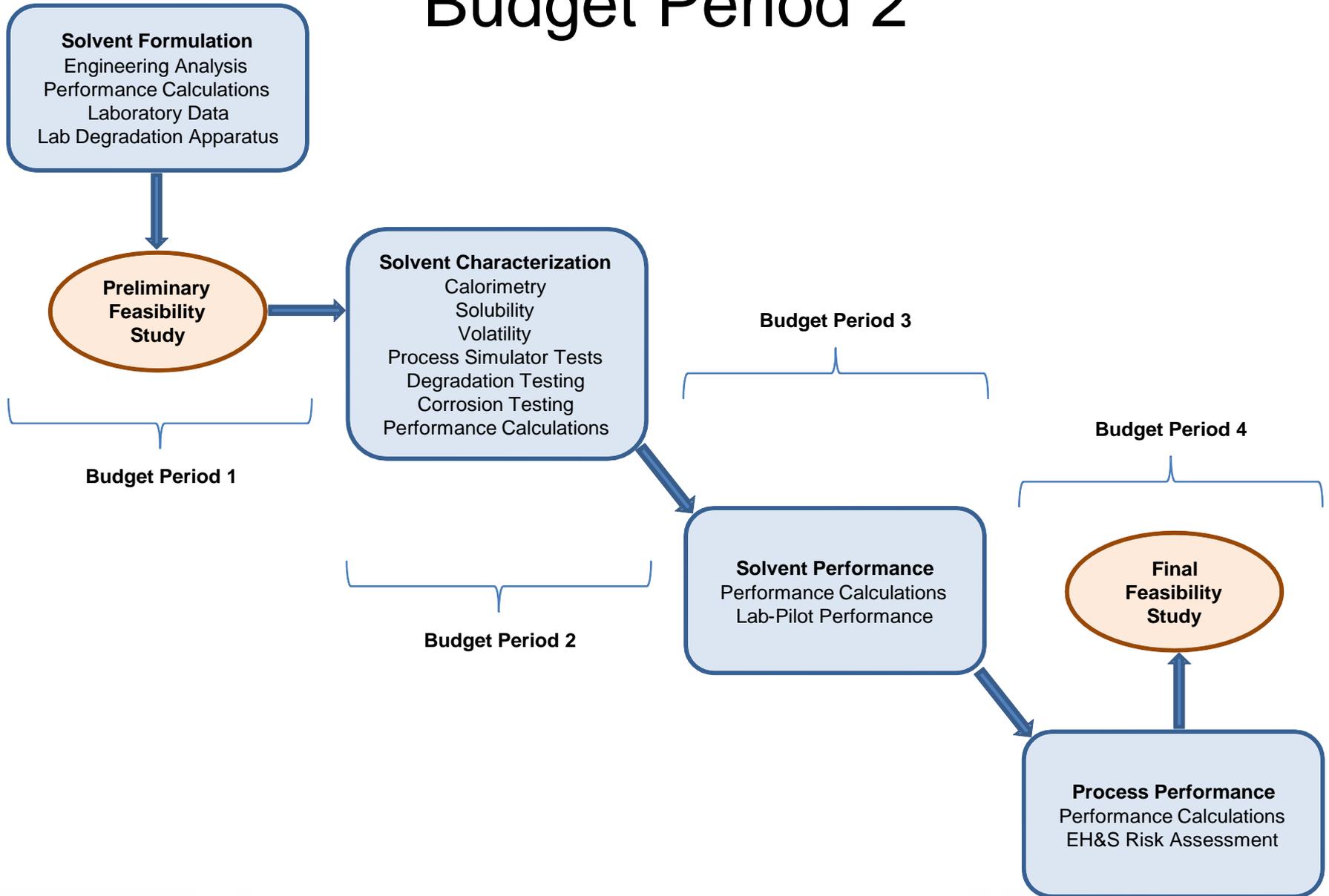


**Task 4  
Laboratory Data**



**Task 5  
Degradation Apparatus**

# Budget Period 2

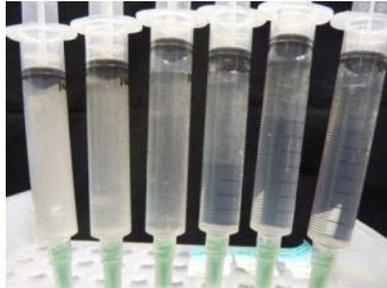


# Budget Period 2

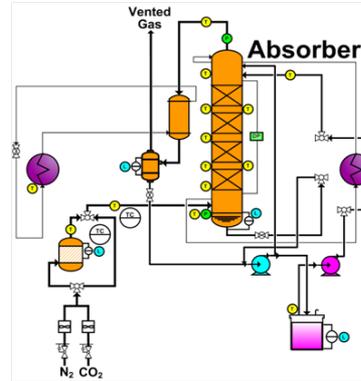
## Solvent Characterization



**Task 7**  
**Calorimetry**



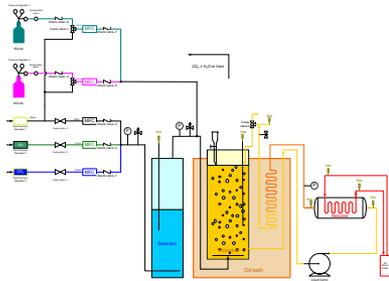
**Task 8**  
**Solubility**



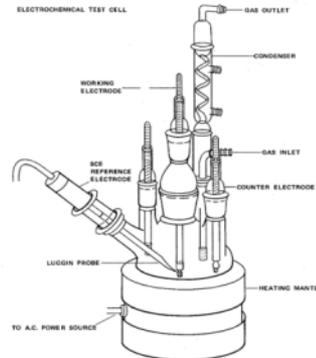
**Task 9**  
**Volatility**



**Task 10**  
**Parametric Tests**



**Task 11**  
**Degradation**



**Task 12**  
**Corrosion**



**Task 13**  
**Performance**

# Budget Period 2

## Solvent Characterization



**Task 7**  
**Calorimetry**



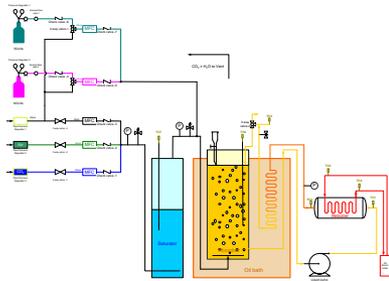
**Task 8**  
**Solubility**

- Objective
  - Solvent characterization
- Approach
  - Calorimeter
    - Heat capacity
  - Calorimeter with mixing cell
    - VLE & heat of absorption (simultaneous)

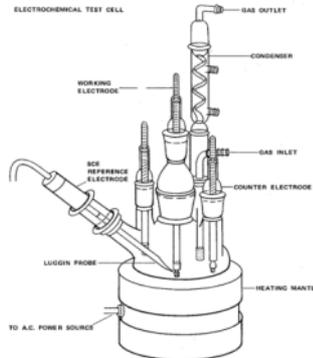


**Task 9**  
**Volatility**

**Task 10**  
**Parametric Tests**



**Task 11**  
**Degradation**



**Task 12**  
**Corrosion**



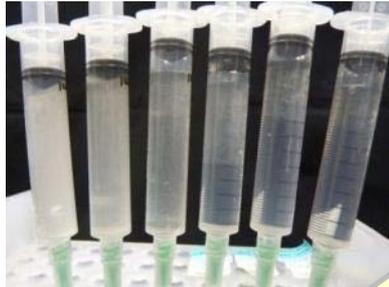
**Task 13**  
**Performance**

# Budget Period 2

## Solvent Characterization



**Task 7**  
**Calorimetry**

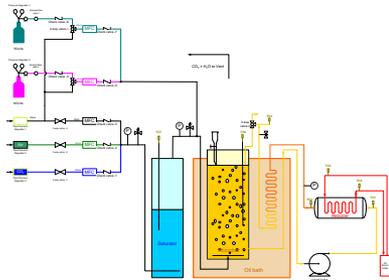


**Task 8**  
**Solubility**

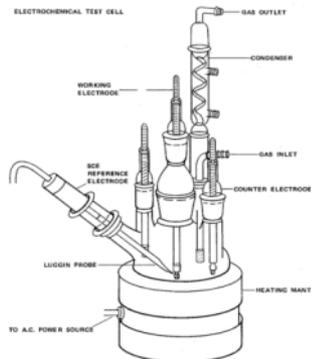
- Objective
  - Solvent characterization
- Approach
  - Laboratory testing
    - Phase equilibria
    - Solubility “window”
    - Kinetics of crystallization
    - Contaminants

**Volatility**

**Parametric Tests**



**Task 11**  
**Degradation**

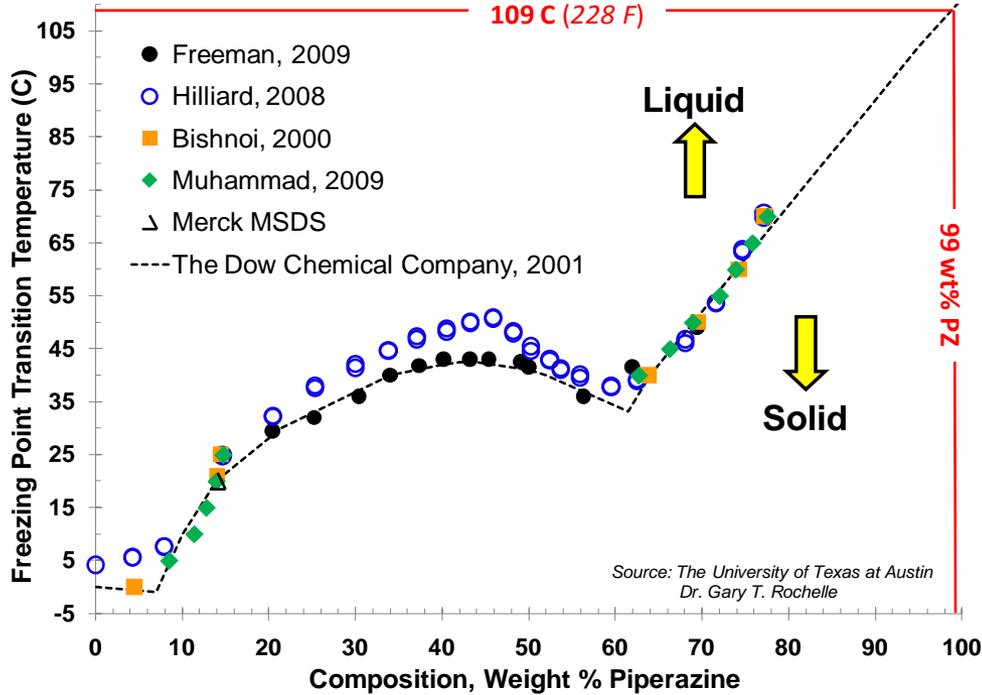


**Task 12**  
**Corrosion**



**Task 13**  
**Performance**

# Solubility Studies – PZ



L  
E  
A  
N

Reaction between CO<sub>2</sub> and PZ alters solubility



R  
I  
C  
H

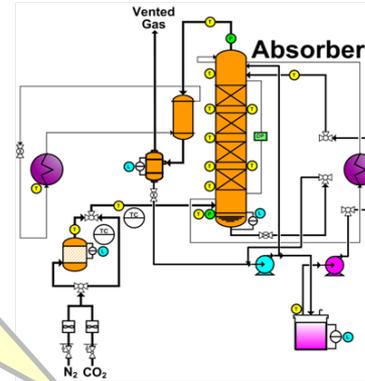
## Factors Affecting Solubility

- ✓ PZ Concentration
- ✓ CO<sub>2</sub> Loading
- ✓ Temperature
- ✓ Contaminants – water quality, flue gas, process

# Budget Period 2

## Solvent Characterization

- Objective
  - Solvent characterization
- Approach
  - Modified Process Simulator
  - Solvent volatility
  - Absorber outlet conditions

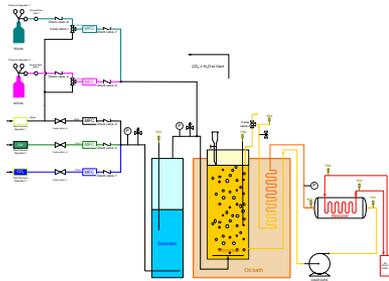


**Task 7**  
Calorimetry

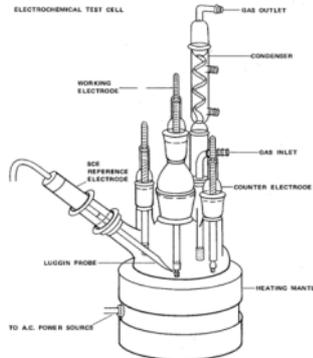
**Task 8**  
Solubility

**Task 9**  
Volatility

**Task 10**  
Parametric Tests



**Task 11**  
Degradation



**Task 12**  
Corrosion

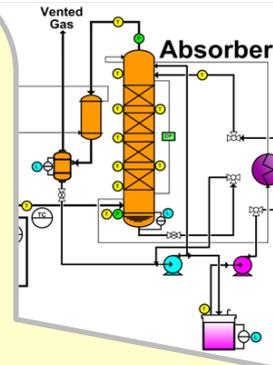


**Task 13**  
Performance

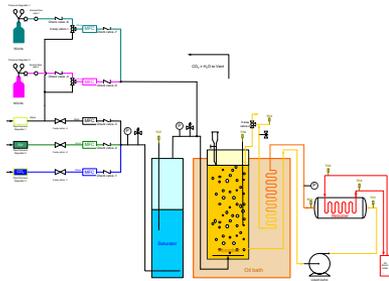
# Budget Period 2

## Solvent Characterization

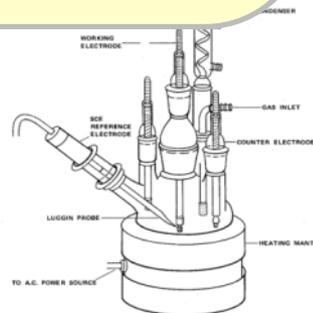
- Objective
  - Solvent characterization
- Approach
  - Bench-Scale Process Simulator
    - Performance
      - Removal, L/G
      - Rich/lean loadings
    - Operability
      - Viscosity, foaming, wettability
      - Solubility, phase separation



**Task 10**  
**Parametric Tests**



**Task 11**  
**Degradation**



**Task 12**  
**Corrosion**

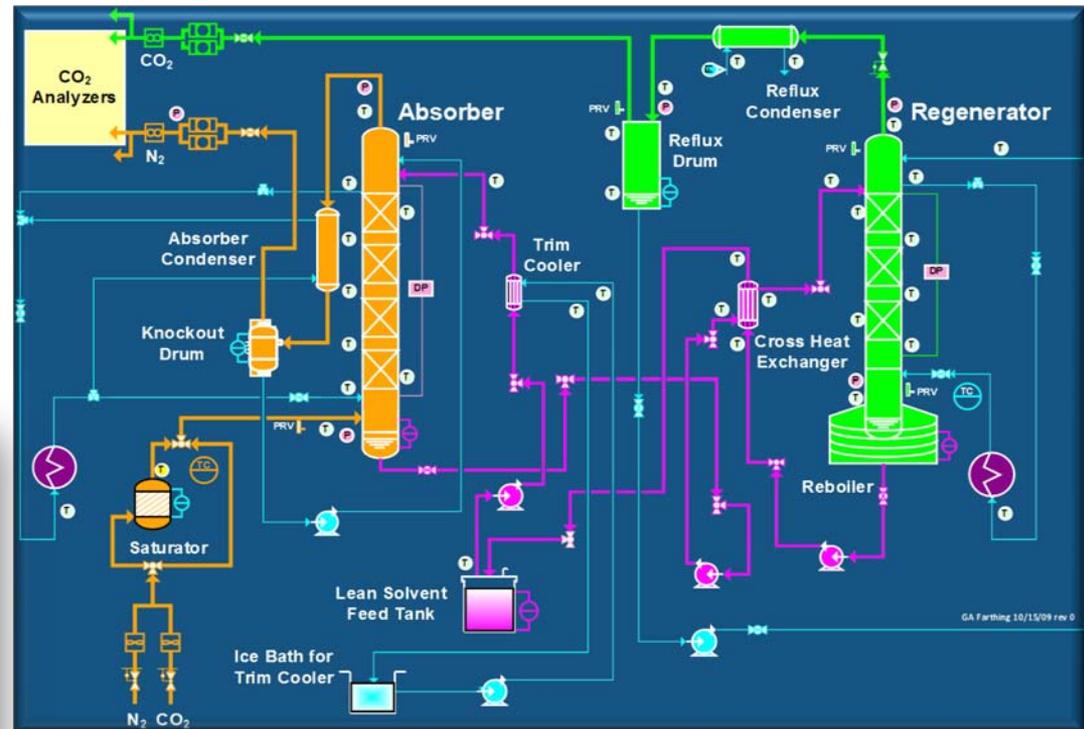


**Task 13**  
**Performance**

# Bench-Scale Simulator

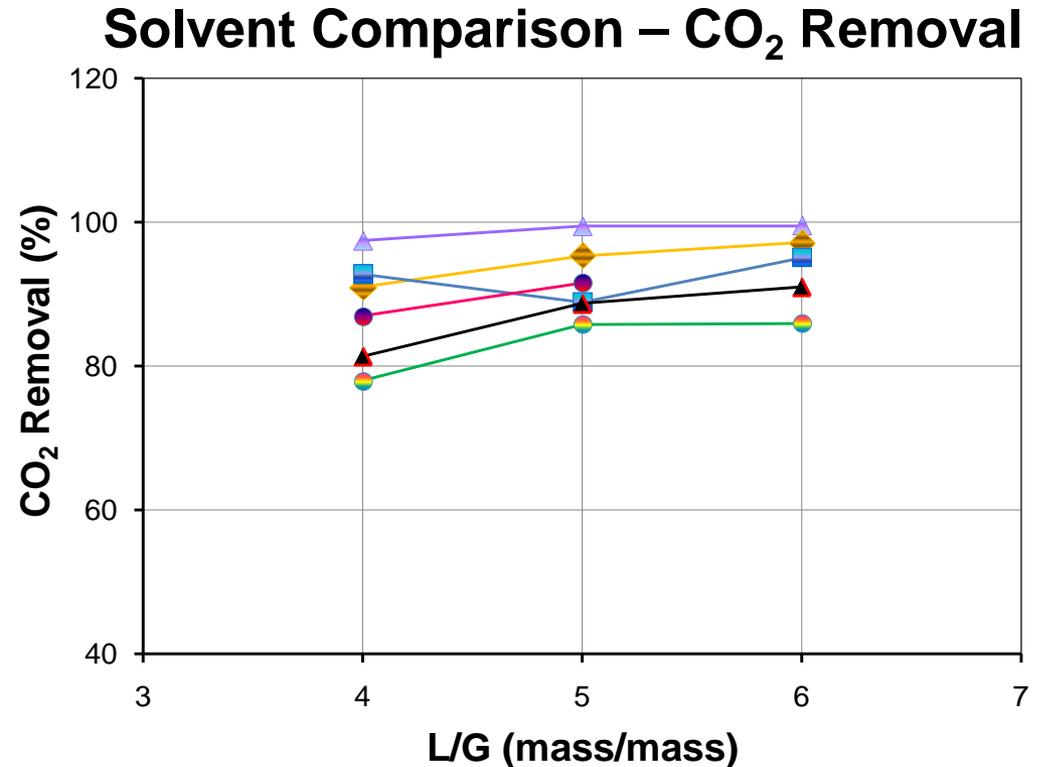
## Key Features:

- ▶ 1 kg/hr CO<sub>2</sub> capture
- ▶ Fully-integrated process
- ▶ Flexible, modular design
- ▶ Multiple modes of operation



# Simulator – Applications

- ▶ First look at new solvents
- ▶ Select operating conditions
  - L/G, T, p, CO<sub>2</sub> loading
- ▶ Operability studies
- ▶ Mass and energy balances
- ▶ Solvent management studies

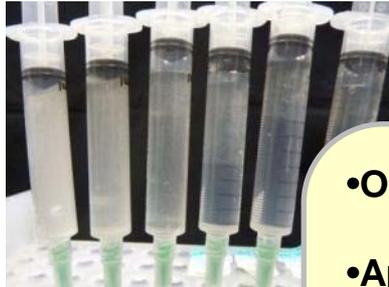


# Budget Period 2

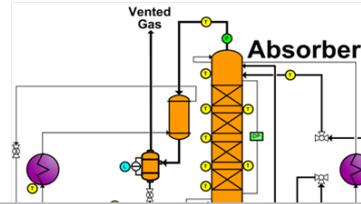
## Solvent Characterization



**Task 7**  
**Calorimetry**

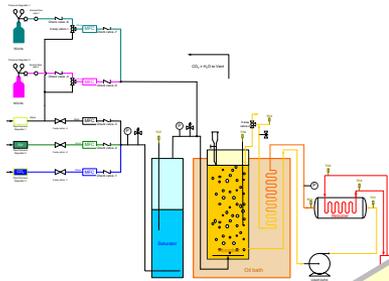


**Task 8**  
**Solubility**

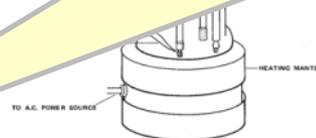


**Task 10**  
**Electric Tests**

- Objective
  - Solvent characterization
- Approach
  - Lab-scale degradation facility (New)
  - Degradation rates
    - Representative
    - Long-term, many cycles
    - Operating conditions
    - Contaminants



**Task 11**  
**Degradation**



**Task 12**  
**Corrosion**



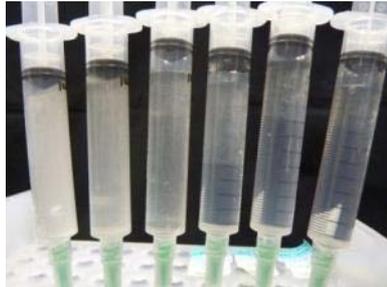
**Task 13**  
**Performance**

# Budget Period 2

## Solvent Characterization

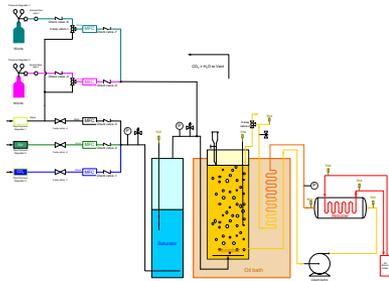


**Task 7**  
**Calorimetry**

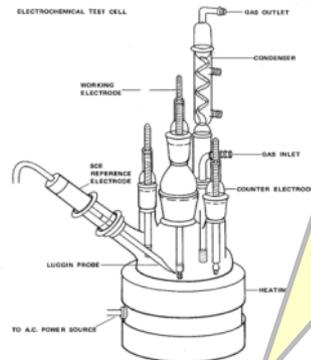


**Task 8**  
**Solubility**

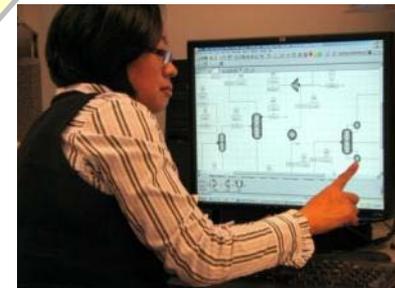
- Objective
  - Solvent characterization
- Approach
  - Electrochemical cell
    - Corrosion rates
    - Representative solvent
    - Different metallurgies
  - Weight loss
    - Validate electrochemical data



**Task 11**  
**Degradation**



**Task 12**  
**Corrosion**



**Task 13**  
**Performance**

# Budget Period 2

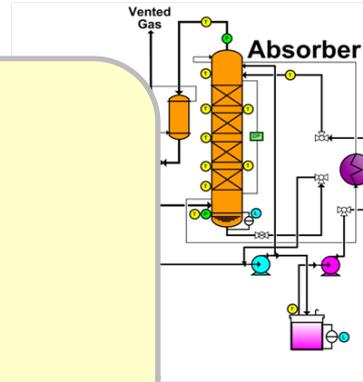
## Solvent Characterization

- Objectives
  - Solvent performance predictions
  - Support selection of formulations
- Approach
  - In-house semi-empirical models
  - Rate-based Aspen Plus
  - Calculations



Task 9  
Calorimetry

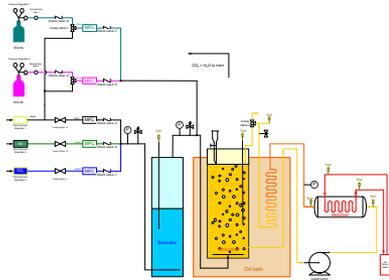
Solubility



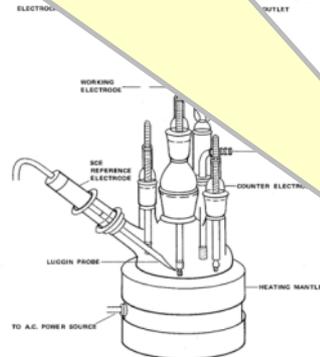
Task 9  
Volatility



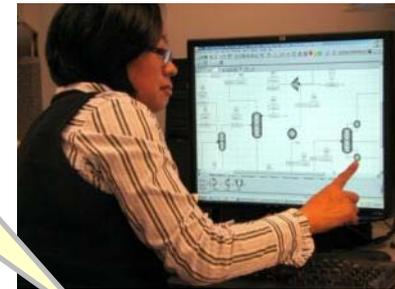
Task 10  
Parametric Tests



Task 11  
Degradation

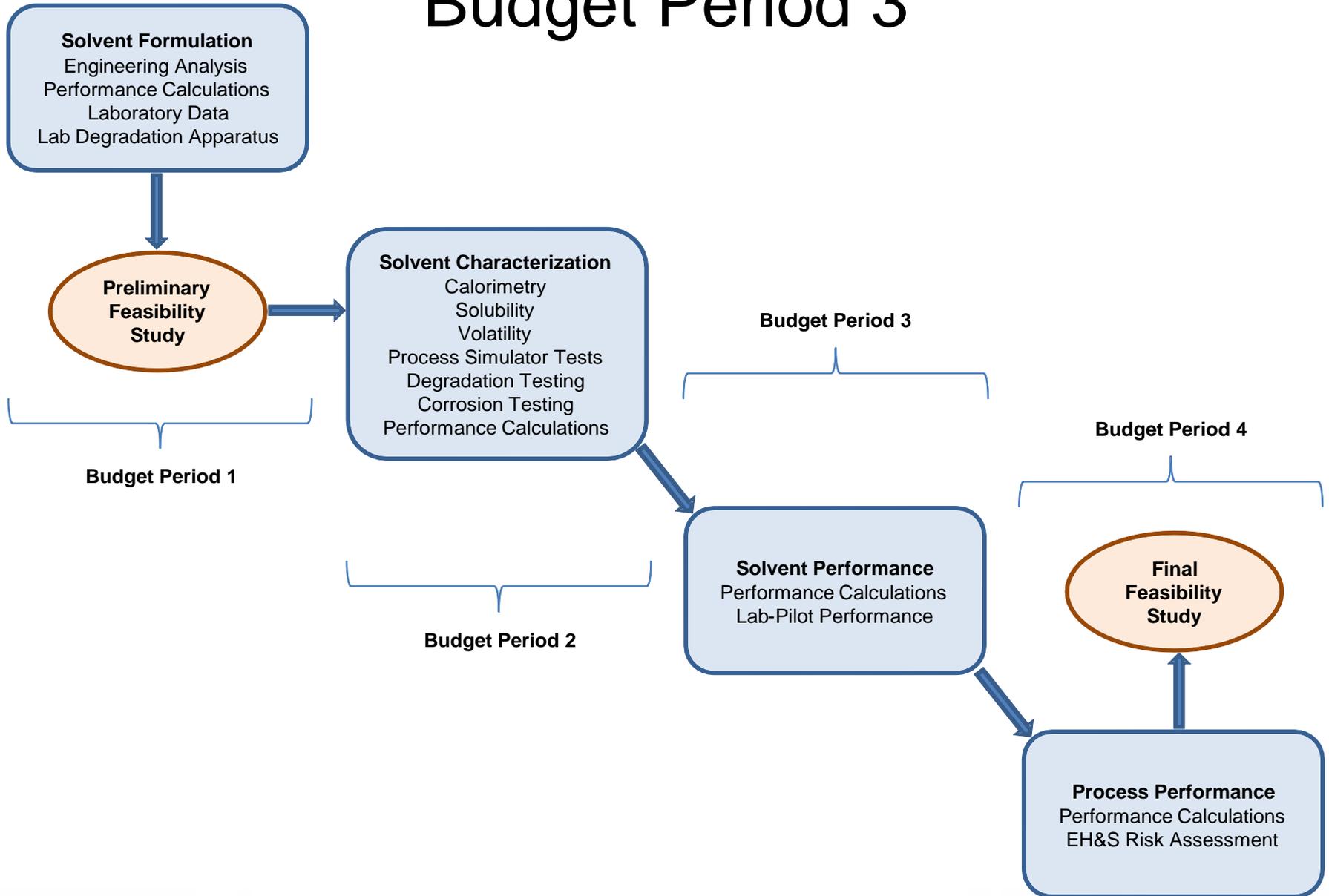


Task 12  
Corrosion



Task 13  
Performance

# Budget Period 3

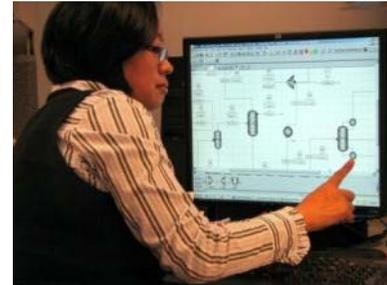


# Budget Period 3

## Solvent Performance



**Task 14**  
**Pilot Verification**



**Task 15**  
**Performance**

# Budget Period 3

## Solvent Performance



**Task 14  
Pilot Verification**

- **Objectives**

- Solvent / process performance
- Simulation model validation
- Corrosion

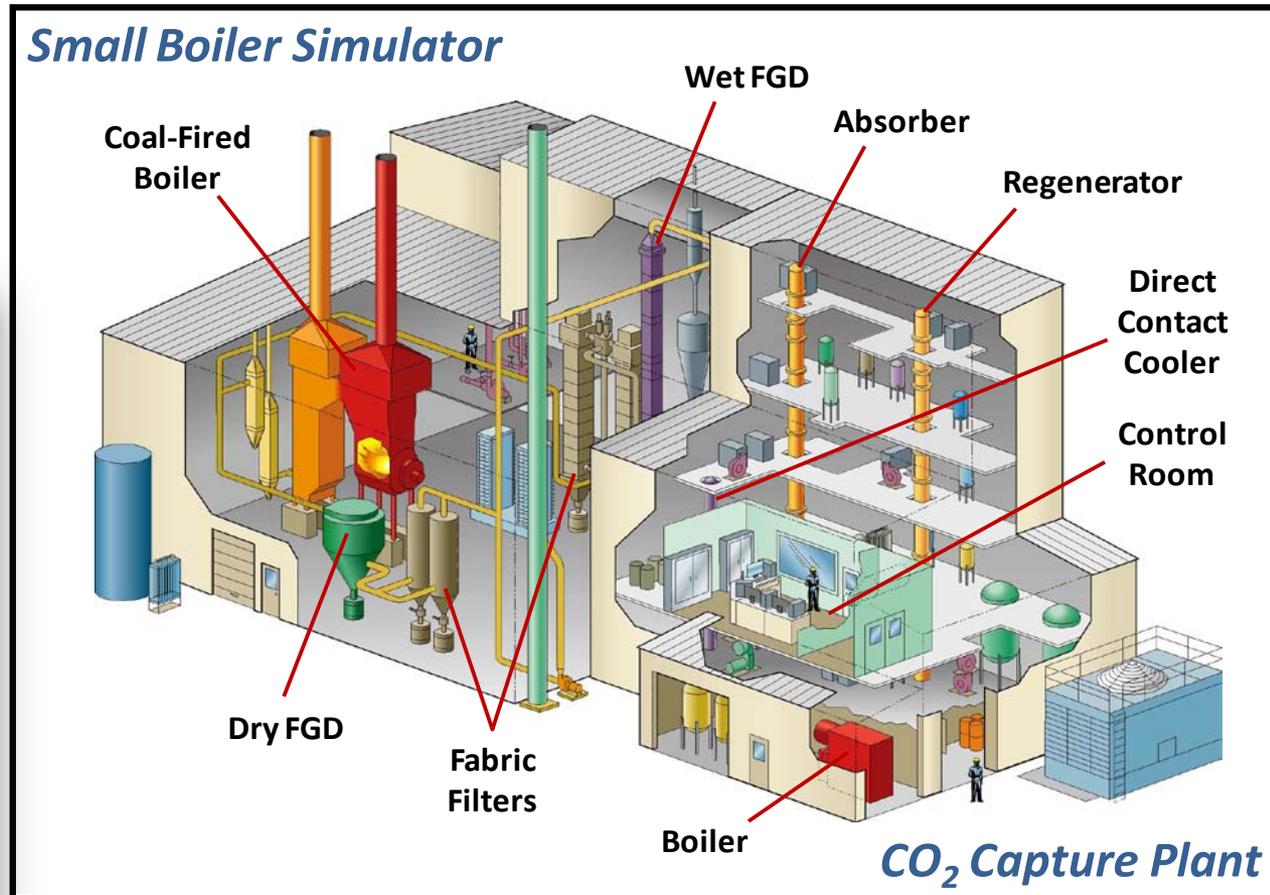
- **Approach**

- 7 ton/day Lab-Pilot
  - Representative performance
    - CO<sub>2</sub> removal
    - Reboiler heat duty
  - Operability
  - Emissions
- Electrical resistance probes
  - Corrosion rates

# 7 Ton/Day Pilot Plant

## Key Features:

- ▶ High quality, representative data
- ▶ Coal flue gas

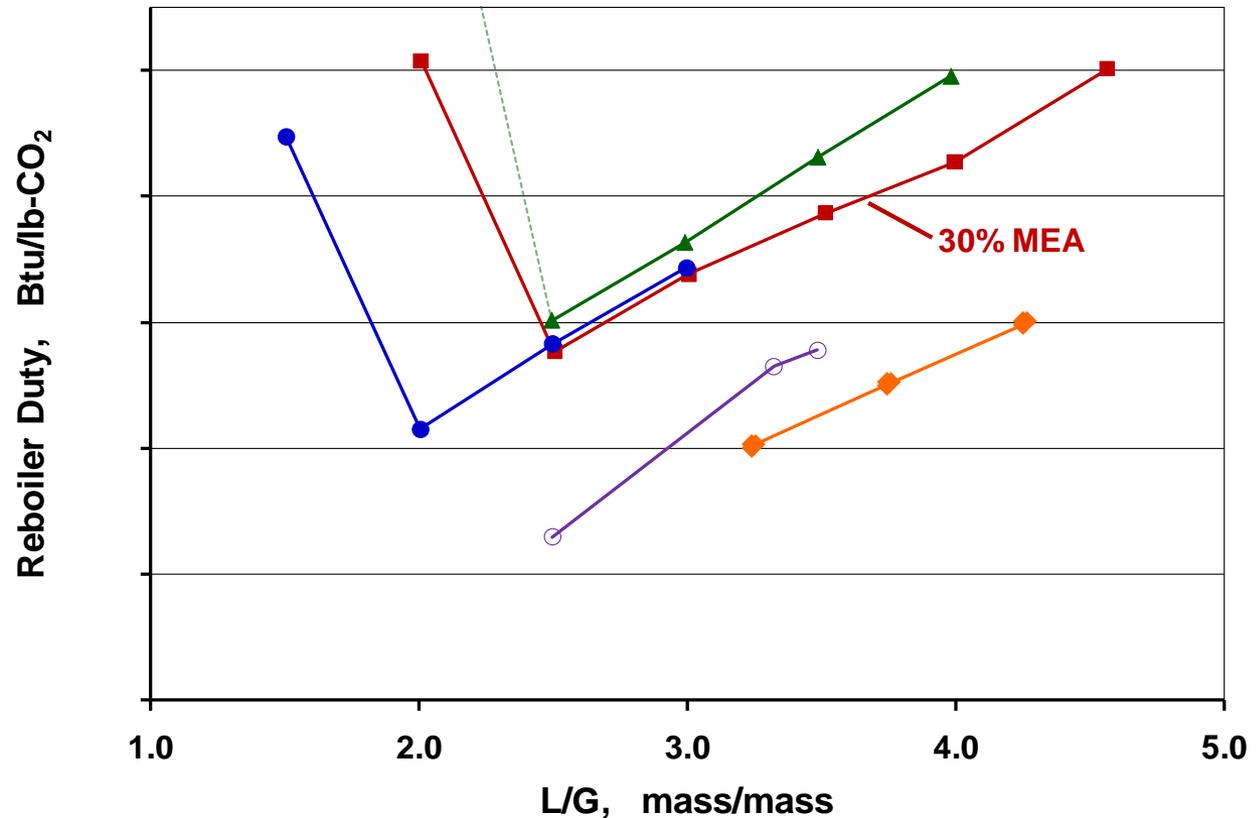


# Pilot Plant – Applications

- ▶ Performance data
- ▶ Process optimization
- ▶ Accurate mass and energy balances
- ▶ Simulation model validation

## Solvent Comparison – Reboiler Heat Duty

G=3100 lb/hr, 14% CO<sub>2</sub> concentration, 90% Removal

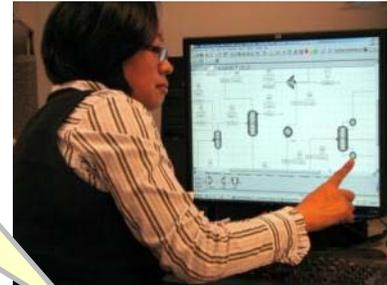


# Budget Period 3

## Solvent Performance

- Objectives
  - Solvent performance predictions
  - Guide lab-pilot testing
- Approach
  - Rate-based Aspen Plus model
  - Model validation using lab-pilot data

**Task 14**  
**Pilot Verification**



**Task 15**  
**Performance**

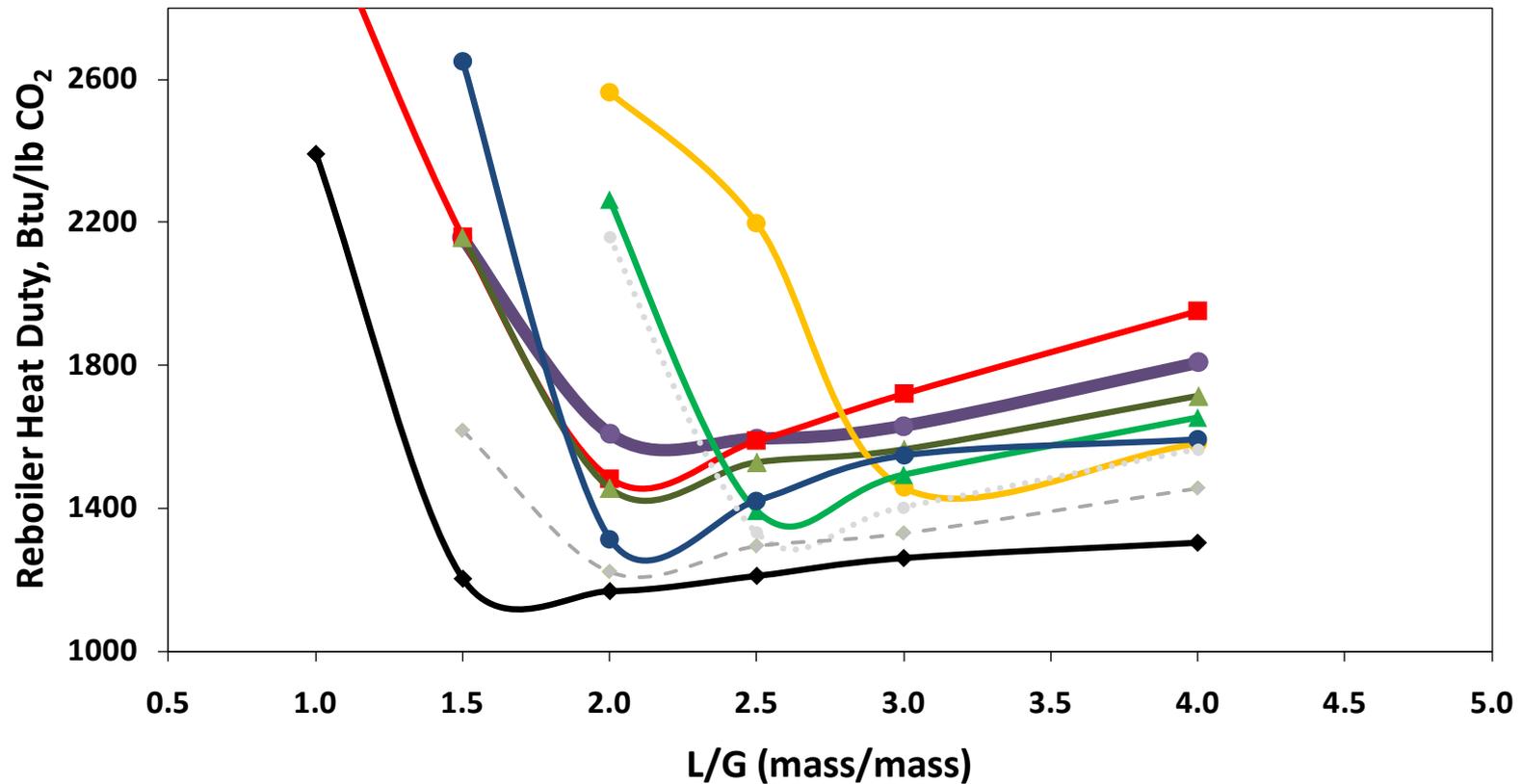
# Simulation Modeling

- ▶ Complicated process
  - Multiple components, multiple phases
  - Thermodynamics, chemical reactions, mass & heat transfer
  - Non-ideal solution (aqueous electrolytes)
- ▶ Evaluation of process concepts
- ▶ Performance prediction
- ▶ Support pilot/demo testing
- ▶ Facilitate full-scale plant design

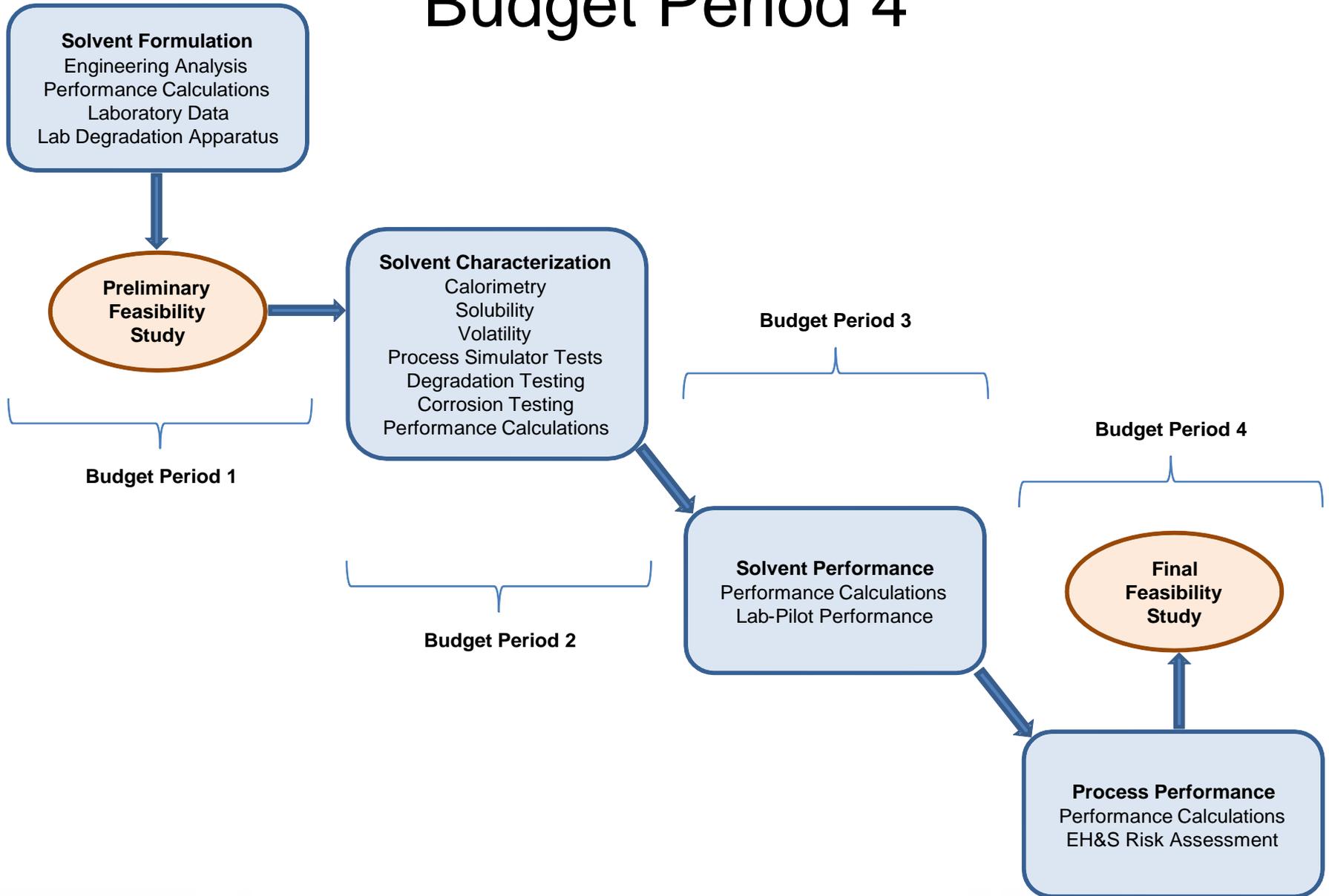


# Simulation Modeling – Applications

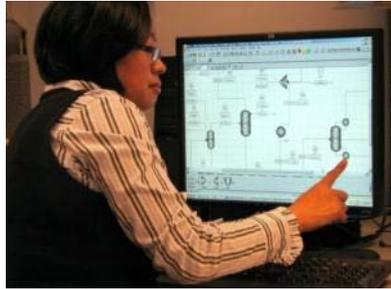
Reboiler Heat Duty @ 90% CO<sub>2</sub> Removal Efficiency



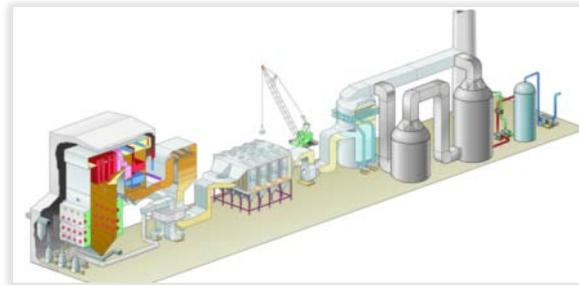
# Budget Period 4



# Budget Period 4 Process Performance



**Task 16  
Performance**



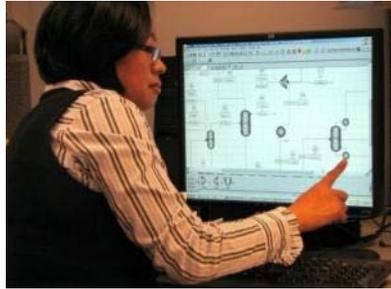
**Task 17  
Final Feasibility**



**Task 18  
EH&S Risks**

# Budget Period 4

## Process Performance



**Task 16  
Performance**

- **Objectives**
  - **Commercial system performance predictions**
  - **Support feasibility study**
- **Approach**
  - **Rate-based Aspen Plus model**
    - **Performance**
    - **Emissions**
    - **Water balance**

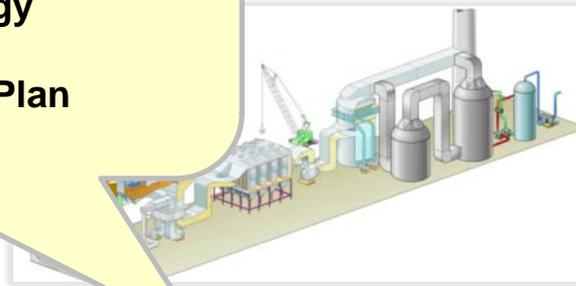
**Final Feasibility**



**Task 18  
EH&S Risks**

# Budget Period 4 Process Performance

- Objectives
  - Final techno-economic assessment
  - Demonstrate feasibility
  - Commercialization strategy
- Approach
  - Per Project Management Plan

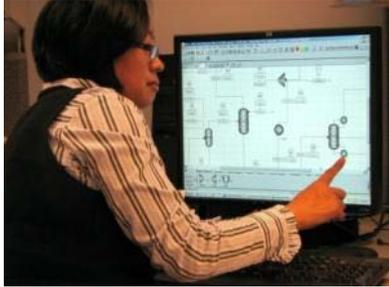


**Task 17  
Final Feasibility**



**Task 18  
EH&S Risks**

# Budget Period 4 Process Performance



**Task 16  
Performance**

- **Objectives**
  - **EH&S risk assessment**
  - **Demonstrate feasibility**
- **Approach**
  - **B&W EH&S professionals**
  - **Per Project Management Plan**
  - **Emissions, wastes, water**
  - **Solvent, waste handling**

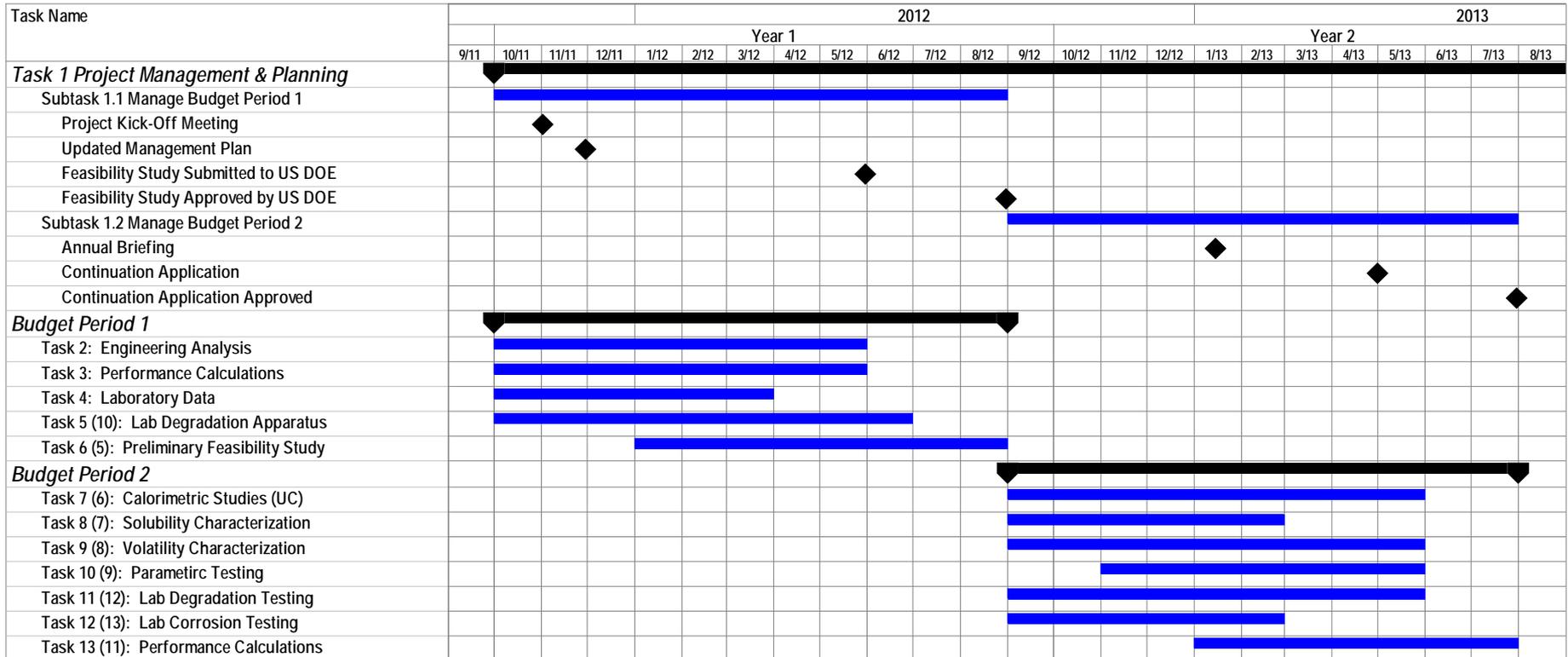
Final Feasibility



**Task 18  
EH&S Risks**

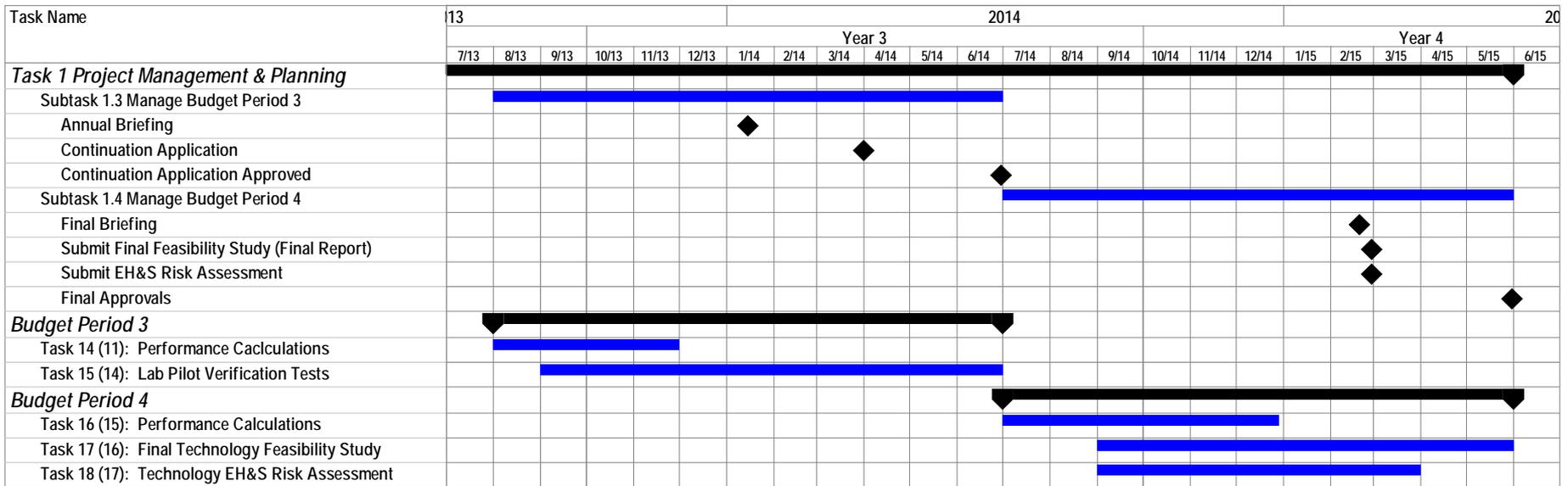
# Project Schedule

## Budget Periods 1 & 2



# Project Schedule

## Budget Periods 3 & 4



# Meeting US DOE Goals

- ▶ Meeting aggressive US DOE goals will require
  - Advanced solvent (this project)
  - Innovative design (equipment size, materials of construction, etc.)
  - Innovative process heat integration
  - Optimal integration with power plant
- ▶ Advanced solvent expected to provide
  - Low reboiler heat duty
  - Smaller absorber / high removal efficiency
  - Lower compression costs
  - Reduced material cost
  - Reduced emissions / waste