NATO CCMS Pilot Study on Clean Products and Processes
2003 Annual Meeting, May 11 - 15, 2003
Hotel San Michele, Cetraro, Italy

Development and Integration of New Processes for Greenhouse Gases Management in Multi-Plant, Chemical Production Complexes

T. A. Hertwig[a], A. Xu[b], D. B.Ozyurt[b], S. Indala[b] R.W. Pike[b], F. C. Knopf[b], J. R Hopper[c], and C. L. Yaws[c]

a IMC Phospates, Uncle Sam, LA 70792, tahertwig@imcglobal.com
b Louisiana State University, Louisiana State University, pike@che.lsu.edu, axu1@lsu.edu, knopf@che.lsu.edu
c Lamar University, Beaumont, TX 77710, hopperjr@hal.lamar.edu, yawscl@hal.lamar.edu

Abstract

The Chemical Complex and Cogeneration Analysis System is an advanced technology for energy conservation and pollution prevention. This System combines the Chemical Complex Analysis System with the Cogeneration Design System. The Chemical Complex (Multi-Plant) Analysis System is a new methodology that has been developed with EPA support to determine the best configuration of plants in a chemical complex based the AIChE Total Cost Assessment(TCA) for economic, energy, environmental and sustainable costs and incorporates EPA Pollution Assessment Methodology (WAR algorithm). The Cogeneration Design System examines corporate energy use in multiple plants and determines the best energy use based on economics, energy efficiency, regulatory emissions and environmental impacts from greenhouse gas emissions. It uses sequential layer analysis to evaluates each plant's current energy use as at an acceptable level or cost-effective improvements are possible. It includes cogeneration as a viable energy option and evaluates cogeneration system operating optimally.

The System uses a Windows graphical user interface. The process flow diagram for the complex is constructed, and equations for material and energy balances, rate equations and equilibrium relations for the plants entered and stored in the Access database using interactive data forms. Also, process unit capacities, availability of raw materials and demand for product are entered in the database. These equations give a complete description to predict the operations of the plants. The format for the equations is the GAMS programming language that is similar to Excel. The input includes incorporating new plants that use greenhouse gases as raw materials.

The System has been applied to an agricultural chemical production complex in the Baton Rouge-New Orleans Mississippi river corridor. Ammonia plants in this complex produce an excess of surplus of 0.65 million tons per year of high quality carbon dioxide that is being exhausted to the atmosphere. A new catalytic process that converts carbon dioxide and methane to acetic acid can use some of this excess, and preliminary results showed that replacing the conventional acetic acid process in the existing complex with the new process gave a potential savings of $750,000 per year for steam, 275 trillion BTUs per year in energy, 3.5 tons per year in NO_x and 49,100 tons per year in carbon dioxide emissions.

This System was developed in collaboration with process engineers and is to be used by corporate engineering groups for regional economic, energy, environmental and sustainable development planning to accomplish the following: energy efficient and environmentally acceptable plants and new products from greenhouse gases. With this System, engineers will have a new capability to consider projects in depths significantly beyond current capabilities. They will be able to convert the company's goals and capital into viable projects that are profitable and meet energy and environmental requirements by developing and applying a regional methodology for cogeneration, and conversion of greenhouse gases to saleable products.

The Advanced Process Analysis System is used to perform economic and environmental evaluations of a plant. The main components of this system are a flowsheeting program, an on-line optimization program, a chemical reactor analysis program, a heat exchanger network design program, and a pollution assessment module. A Windows interface has been used to integrate these programs into one user-friendly application. An accurate description of the process is obtained from process flowsheeting and on-line optimization. Then an evaluation of the best types of chemical reactors is performed to modify and improve the process, and pinch analysis is used to determine the best configuration for the heat exchanger network and determine the minimum utilities needed for the process. The pollution index evaluation is used to identify and minimize emissions. A tutorial has two plant simulations and two actual plants.

The Advanced Process Analysis System has been applied to actual plants including the alkylation plant at the Motiva refinery in Convent, Louisiana and sulfuric acid contact plant at IMC Agrico's agricultural chemicals complex in Uncle Sam, Louisiana. Detailed plant descriptions of the refinery alkylation process and the contact sulfuric acid process were used with the System in collaboration with the process engineers from these companies. This ensured that the programs work on actual plants and meet the needs and requirements of the process and design engineers.

These programs and users manuals with tutorials can be obtained from the LSU Minerals Processing Research Institute's web site, www.mpri.lsu.edu at no charge. The staff of the Minerals Processing Research Institute can provide assistance in using these programs.

Development and Integration of New Processes for Greenhouse Gases Management in Multi-Plant, Chemical Production Complexes

T. A. Hertwig, A. Xu, D. B.Ozyurt, S. Indala R.W. Pike,

F. C. Knopf, J. R Hopper,and C. L. Yaws

A joint industry-university research effort

IMC Phosphates, Motiva Enterprises,

Louisiana State University, Lamar University

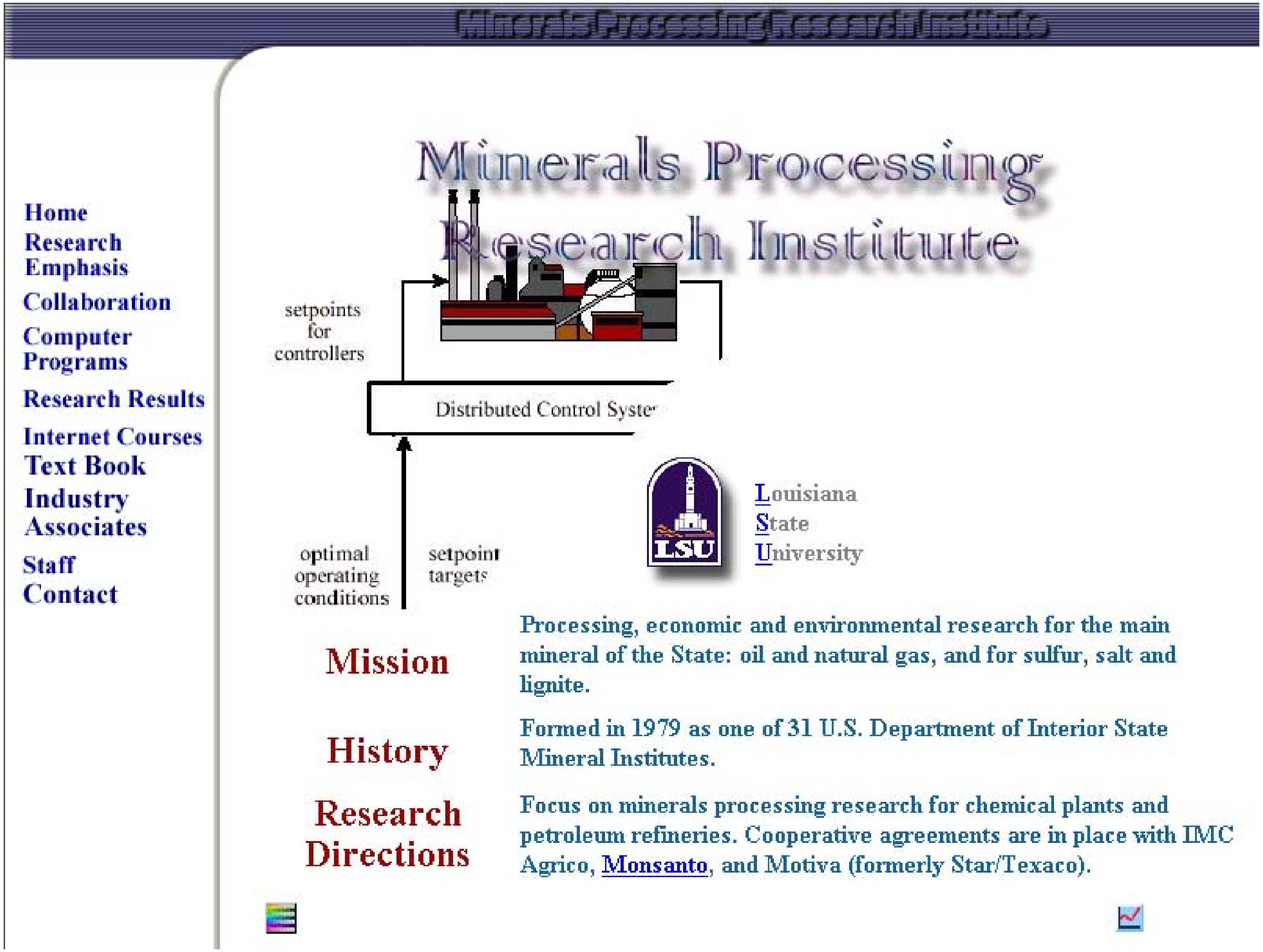
Sponsored by U. S. Environmental Protection Agency

NATO CCMS Pilot Study on Clean Products and Processes

2003 Annual Meeting, May 11 - 15, 2003

Hotel San Michele, Cetraro, Italy

LSU Mineral Processing Research Institute



Minerals Processing Research Institute

Louisiana
State
University

Mission Processing, economic and environmental research for the main mineral of the State: oil and natural gas, and for sulfur, salt and lignite.

History Formed in 1979 as one of 31 U.S. Department of Interior State Mineral Institutes.

Research Directions Focus on minerals processing research for chemical plants and petroleum refineries. Cooperative agreements are in place with IMC Agrico, Monsanto, and Motiva (formerly Star/Texaco).

All of the information given in this presentation is available at www.mpri.lsu.edu

Background

Pollution prevention
- was an environmental issue
- now a critical business opportunity

Long term cost of ownership must be evaluated with short term cash flows

Companies undergoing difficult institutional transformations
Emphasis on pollution prevention has broadened to include:

- Total (full) cost accounting
- Life cycle assessment
- Sustainable development
- Eco-efficiency (*eco*nomic and *eco*logical)

Broader Assessment of Current and Future Manufacturing in the Chemical Industry

Driving forces

  ISO 14000,
  "the polluter pays principle"
  Anticipated next round of Federal regulations associated with global warming
  Sustainable development

Sustainable development

  Concept that development should meet the needs of the present without sacrificing the ability of the future to meet its needs

Sustainable development costs - external costs

  Costs that are not paid directly
  Those borne by society
  Includes deterioration of the environment by pollution within compliance regulations.

Koyoto Protocol - annual limits on greenhouse gases proposed beginning in 2008 - 7% below 1990 levels for U.S.

Overview of Presentation

Chemical Complex and Cogeneration Analysis System

for multi-plant chemical production complexes

Advanced Process Analysis System

for operating plants

Chemical Complex and Cogeneration Analysis System

Objective: To give corporate engineering groups new capability to design:

- New processes for products from greenhouse gases
- Energy efficient and environmentally acceptable plants

Introduction

- Opportunities
  - Processes for conversion of greenhouse gases to valuable products
  - Cogeneration

- Methodology
  - Chemical Complex and Cogeneration Analysis System
  - Application to chemical complex in the lower Mississippi River corridor

Related Work and Programs

- Aspen Technology
- Department of Energy (DOE)
  www.oit.doe.gov/bestpractice
- Environmental Protection Agency (EPA)
  www.epa.gov/opptintr/greenengineering

Chemical Complex and Cogeneration Analysis System

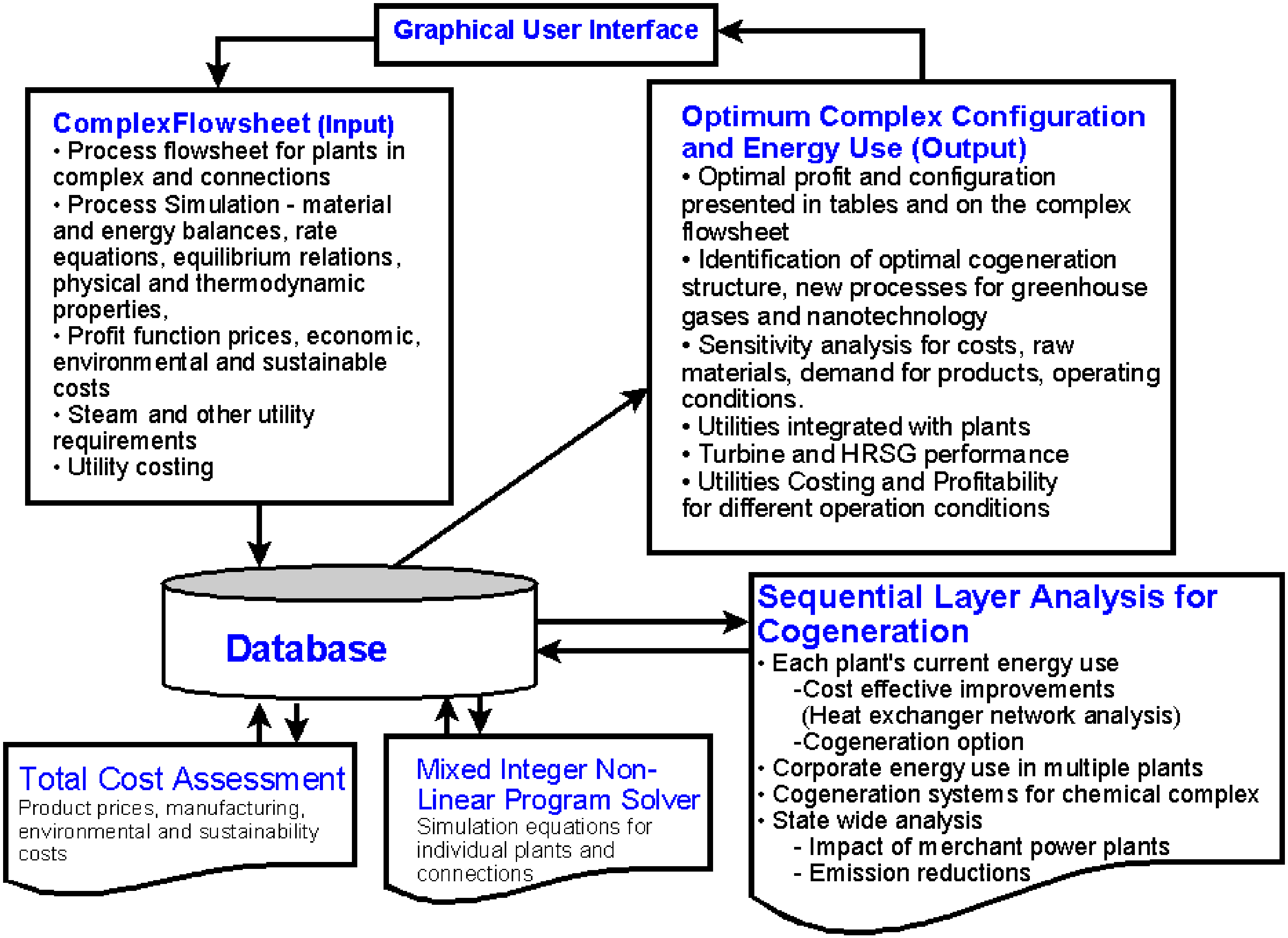
Chemical Complex Analysis System

Determines the best configuration of plants in a chemical complex based on the AIChE Total Cost Assessment (TCA) and incorporates EPA Pollution Index methodology (WAR) algorithm

Cogeneration Analysis System

Determines the best energy use based on economics, energy efficiency, regulatory emissions and environmental impacts from greenhouse gas emissions.

Structure of the System



Graphical User Interface

ComplexFlowsheet (Input)
- Process flowsheet for plants in complex and connections
- Process Simulation - material and energy balances, rate equations, equilibrium relations, physical and thermodynamic properties,
- Profit function prices, economic, environmental and sustainable costs
- Steam and other utility requirements
- Utility costing

Optimum Complex Configuration and Energy Use (Output)
- Optimal profit and configuration presented in tables and on the complex flowsheet
- Identification of optimal cogeneration structure, new processes for greenhouse gases and nanotechnology
- Sensitivity analysis for costs, raw materials, demand for products, operating conditions.
- Utilities integrated with plants
- Turbine and HRSG performance
- Utilities Costing and Profitability for different operation conditions

Database

Sequential Layer Analysis for Cogeneration
- Each plant's current energy use
  - -Cost effective improvements (Heat exchanger network analysis)
  - -Cogeneration option
- Corporate energy use in multiple plants
- Cogeneration systems for chemical complex
- State wide analysis
  - - Impact of merchant power plants
  - - Emission reductions

Total Cost Assessment
Product prices, manufacturing, environmental and sustainability costs

Mixed Integer Non-Linear Program Solver
Simulation equations for individual plants and connections

AIChE Total Cost Assessment

- -Includes five types of costs: I direct, II overhead, III liability, IV internal intangible, V external (borne by society - sustainable)

- Sustainable costs are costs to society from damage to the environment caused by emissions within regulations, e.g., sulfur dioxide 4.0 lb per ton of sulfuric acid produced

- Environmental costs – compliance, fines, 20% of manufacturing costs

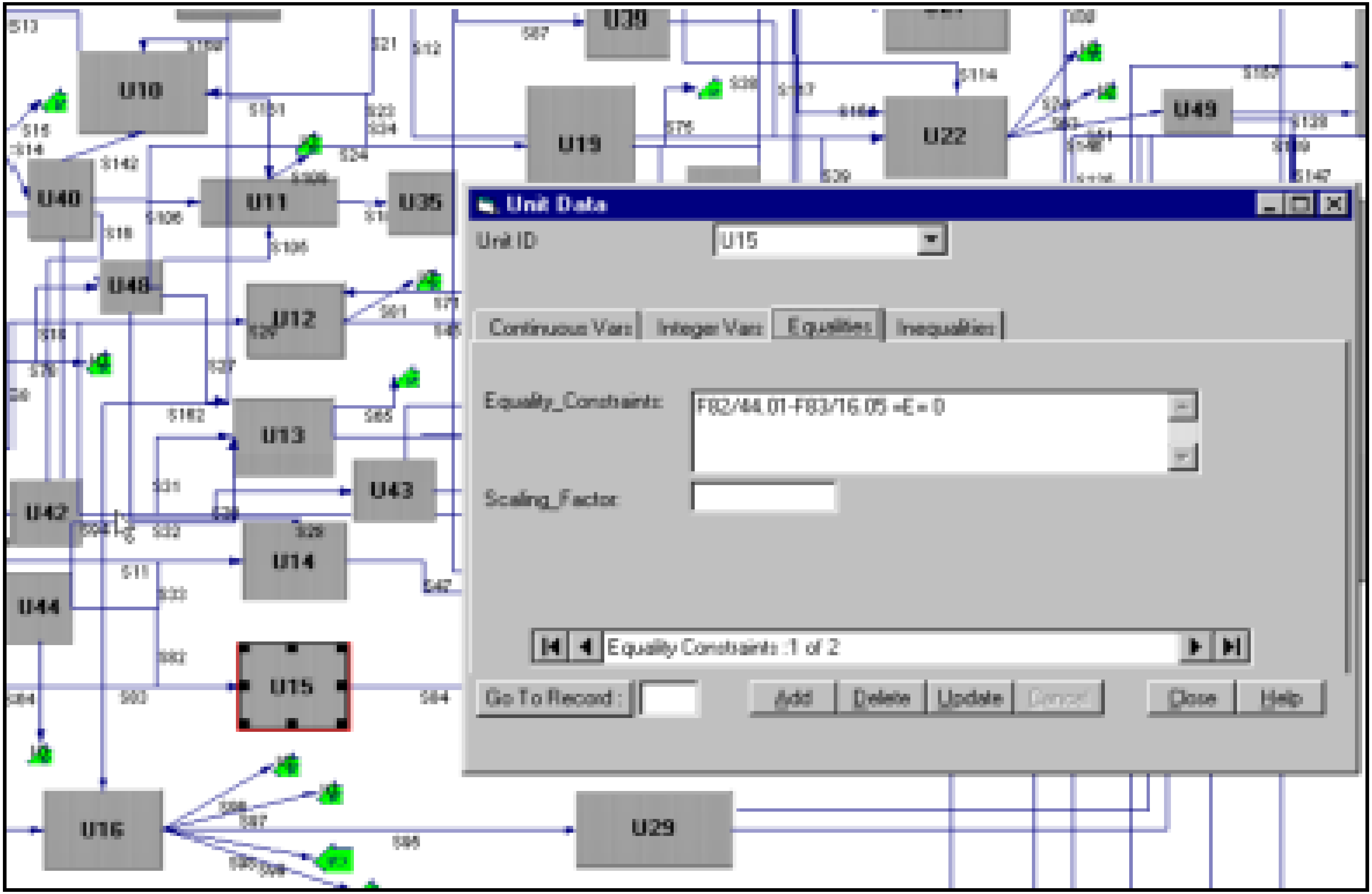
- Combined five TCA costs into economic, environmental and sustainable costs

  economic – raw materials, utilities, etc

  environmental – 67% of raw materials

  sustainable – estimated from sources

Illustration of Input to the System for Unit Data



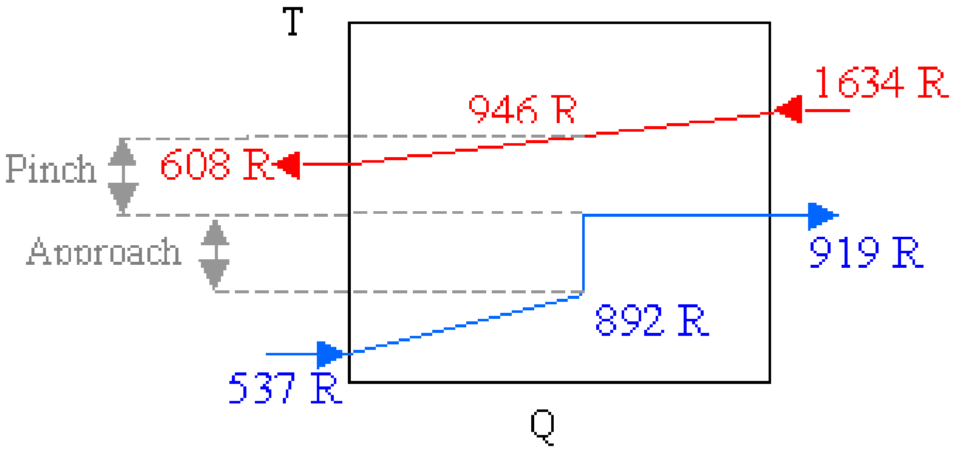
Unit ID: U15

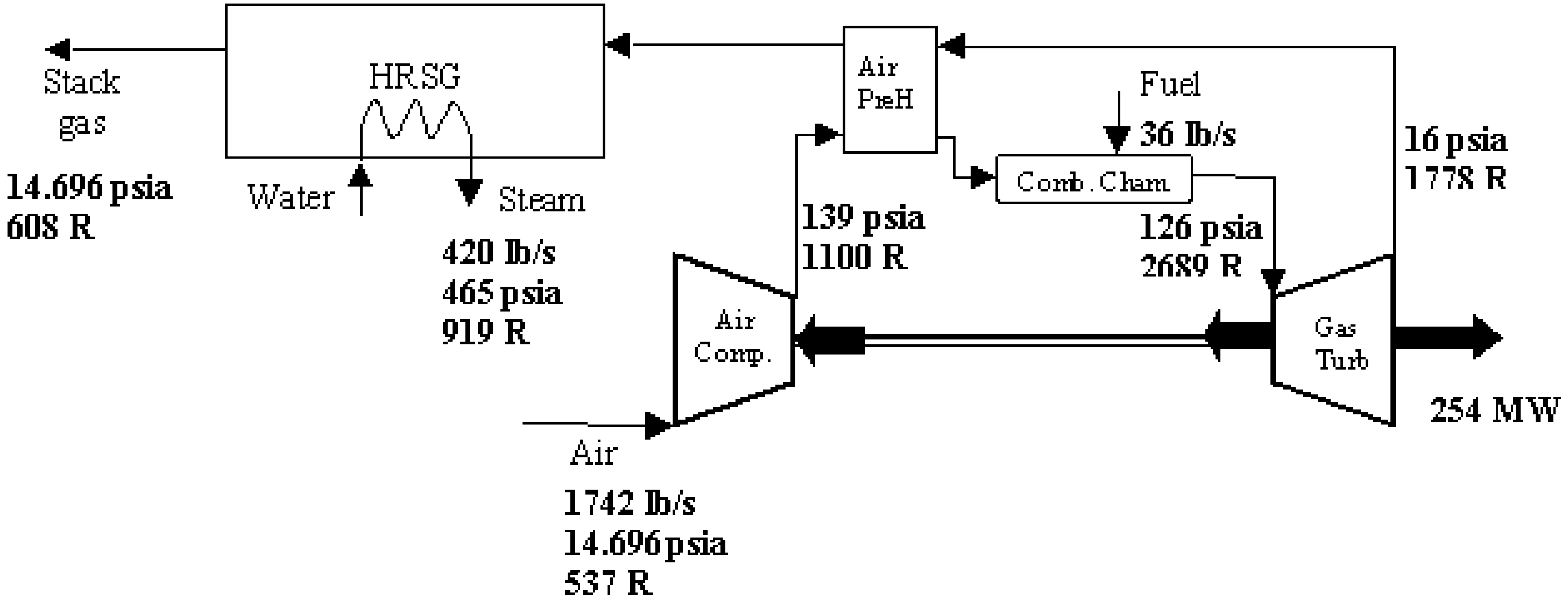
Equality_Constraints: F82/44.01-F83/16.05 =E= 0

Scaling_Factor:

Equality Constraints :1 of 2

Typical Cogeneration Results on the CHP Diagram

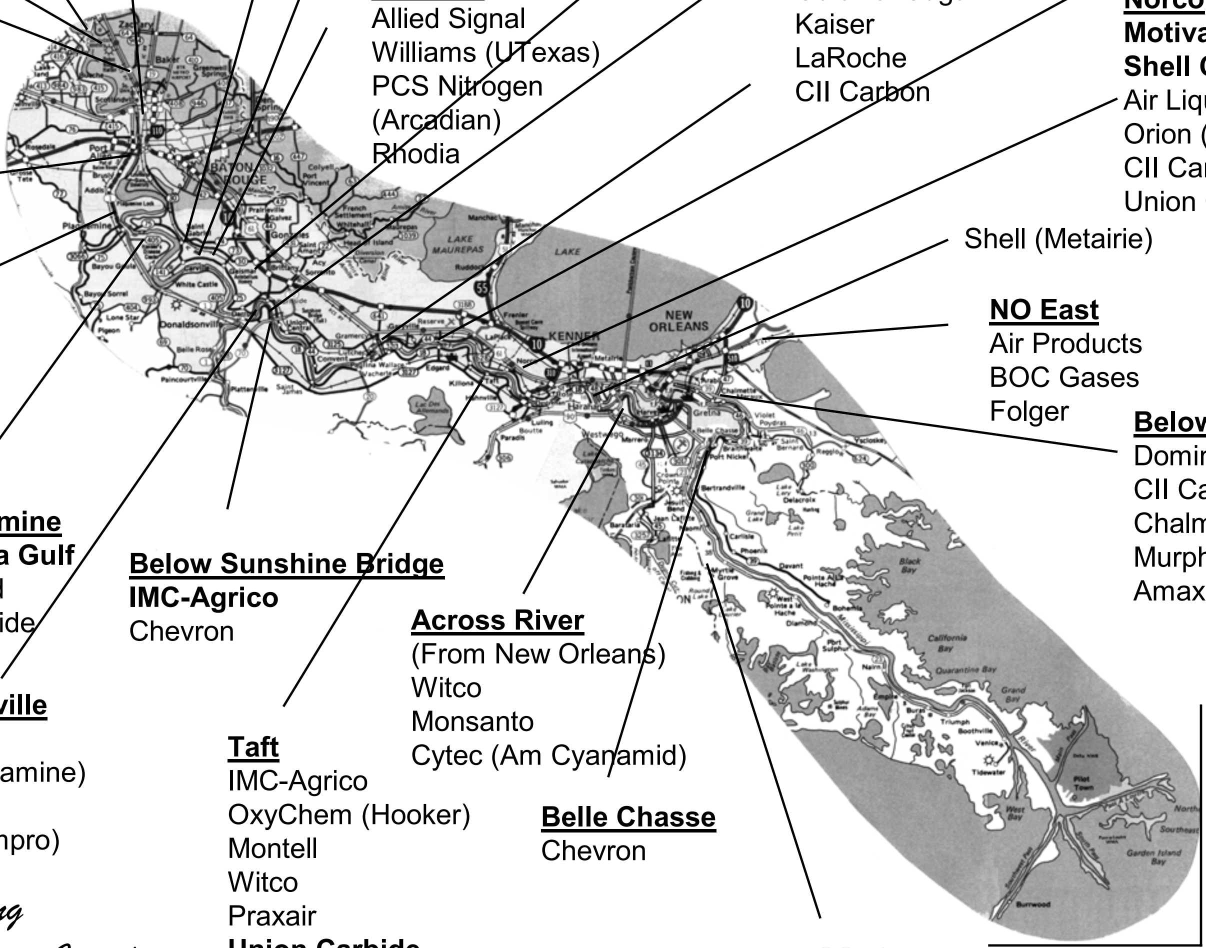




Comparison of Power Generation

	Conventional	Cogeneration
Operating efficiency	33%	77%
Heat rate (BTU/kWh)	>10,000	5,000-6,000
NO_x emission (lbs of NO_x / MWh)	4.9	0.167
CO_2 emission (tons of CO_2 / MWh)	1.06	0.30

Plants in the lower Mississippi River Corridor



Port Hudson
Georgia-Pacific

Saint Francisville
Crown Vantage

North of Baton Rouge
Ferro (Grant)
Safety - Kleen (Laidlaw)
Exxon (Allied / Paxon)
Exxon Resins
Deltech (Foster Grant)
Exxon Plastics

Baton Rouge
Rhodia (Stauffer)
LaRoche (Kaiser)
DSM (Copolymer
Albemarle (Ethyl)
Formosa (Allied)
Exxon - Refinery
Exxon Chemical
Allied Signal

St Gabriel
Air Products
Novartis (Ciba Geigy)
Ciba
Pioneer (Stauffer)
ICI
Zeneca

Carville
Cosmar
Fina

Geismar
Borden
Air Liquide
Uniroyal
Rubicon
Praxair
BASF
Shell Chem
Air Prod
Vulcan

Geismar
Allied Signal
Williams (UTexas)
PCS Nitrogen
(Arcadian)
Rhodia

Sunshine Bridge & Below
Air Products
Motiva (Star/Texaco)
DuPont
OxyChem (Convent)
IMC - Agrico

Gramercy
Colonial Sugar
Kaiser
LaRoche
CII Carbon

Garyville
Nalco
Marathon
Epsilon
Betz (Reserve)
DuPont (LaPlace)

Norco
Motiva (Shell NMC)
Shell Chemical
Air Liquide
Orion (TransAmerican)
CII Carbon
Union Carbide

Shell (Metairie)

Port Allen
Placid
Exxon - Lubes

Addis / Plaquemine
Borden (OxyChem)
Sid Richardson
DSM Copolymer
Dow
Geon
Air Liquide
Air Products

Plaquemine
Georgia Gulf
Ashland
Air Liquide
Praxair

Donaldsonville
CF
Borden (Melamine)
Triad #1
Triad #2 (Ampro)

Below Sunshine Bridge
IMC-Agrico
Chevron

Taft
IMC-Agrico
OxyChem (Hooker)
Montell
Witco
Praxair
Union Carbide

Across River
(From New Orleans)
Witco
Monsanto
Cytec (Am Cyanamid)

Belle Chasse
Chevron

NO East
Air Products
BOC Gases
Folger

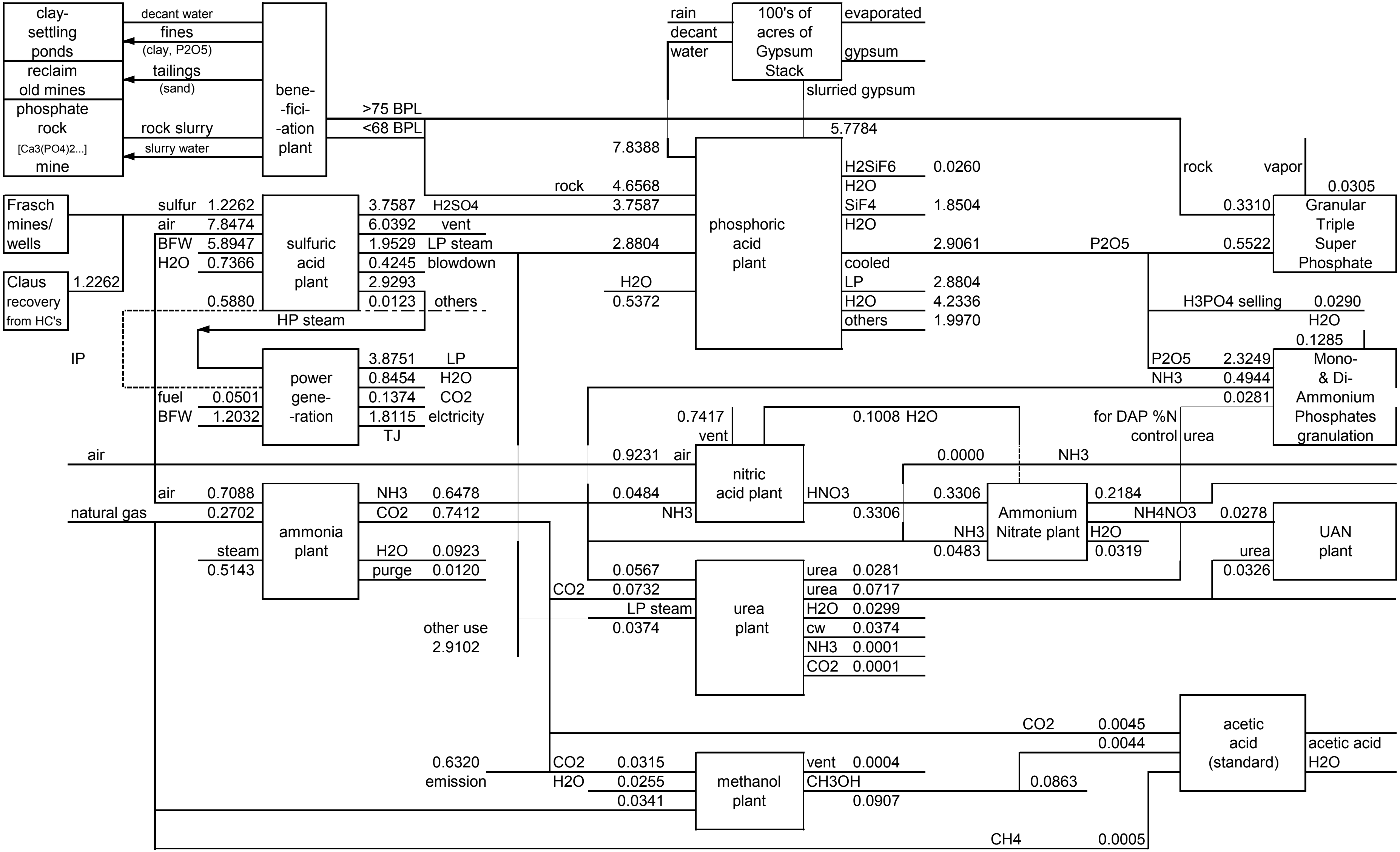
Below NO
Domino Sugar
CII Carbon
Chalmette Ref (Mobil)
Murphy
Amax

BP Amoco

son, R.W., 2000

Petrochemical Plants Along
The lower Mississippi River Corridor

Expanded Agricultural Chemical Complex

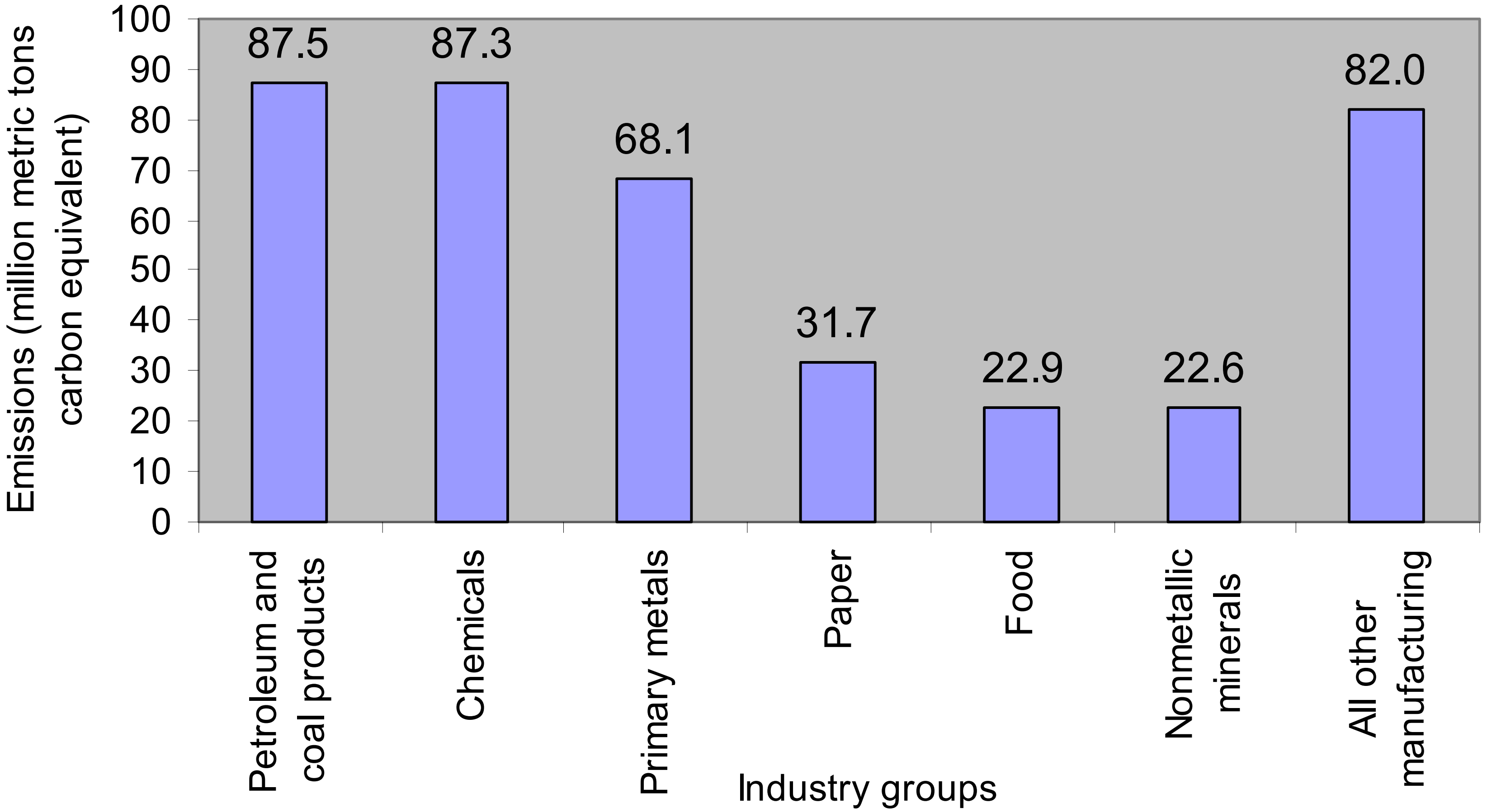


Plants in the lower Mississippi River Corridor, Base Case. Flow Rates in Million Tons Per Year

Some Chemical Complexes in the World

Continent	Name and Site	Notes
North America	•Gulf coast petrochemical complex in Houston area (U.S.A.) and •Chemical complex in the Baton Rouge-New Orleans Mississippi River Corridor (U.S.A.)	•Largest petrochemical complex in the world, supplying nearly two-thirds of the nation’s petrochemical needs
South America	•Petrochemical district of Camacari-Bahia (Brazil) •Petrochemical complex in Bahia Blanca (Argentina)	•Largest petrochemical complex in the southern hemisphere
Europe	•Antwerp port area (Belgium)	•Largest petrochemical complex in Europe and world wide second only to Houston, Texas
	•BASF in Ludwigshafen (Germany)	•Europe’s largest chemical factory complex
Asia	•The Singapore petrochemical complex in Jurong Island (Singapore)	•World’s third largest oil refinery center
	•Petrochemical complex of Daqing Oilfield Company Limited (China)	
	•SINOPEC Shanghai Petrochemical Co. Ltd. (China)	
	•Joint-venture of SINOPEC and BP in Shanghai under construction (2005) (China)	•Largest petrochemical complex in Asia
	•Jamnagar refinery and petrochemical complex (India)	
	•Sabic company based in Jubail Industrial City (Saudi Arabia)	
	•Petrochemical complex in Yanbu (Saudi Arabia)	•World’s largest polyethylene manufacturing site
	•Equate (Kuwait)	•World’s largest & most modern for producing ethylene glycol and polyethylene
Oceania	•Petrochemical complex at Altona (Australia) •Petrochemical complex at Botany (Australia)	
Africa	petrochemical industries complex at Ras El Anouf (Libya)	one of the largest oil complexes in Africa

CO_2 Emissions from Industries



Total Energy-Related Carbon Dioxide Emissions for Selected Manufacturing Industries, 1998, from EIA, 2001

Carbon Dioxide Emissions and Utilization

(Million Metric Tons Carbon Equivalent Per Year)

CO_2 emissions and utilization	Reference
Total CO_2 added to atmosphere Burning fossil fuels 5,500 Deforestation	IPCC (1995)
Total worldwide CO_2 from consumption and flaring of fossil fuels United States 1,600 China Russia Japan All others	EIA (2002)
1,526 U.S. CO_2 emissions Industry 792 Buildings 440 307 Transportation 3,258 Total	Stringer (2001)
U.S. industry (manufacturing) 630 Petroleum, coal products and chemicals	EIA (2001)
524 473 175 Chemical and refinery (BP) 1,627 Combustion and flaring Noncombustion direct CO_2 emission 3%	McMahon (1999)
Agricultural chemical complex in the lower Mississippi River corridor excess high purity CO_2 97%	Hertwig et al. (2002)
CO_2 used in chemical synthesis	Arakawa et al. (2001)

Commercial Uses of CO_2

- 110 million tons of CO_2 for chemical synthesis
  - Urea (chiefly, 90 million ton of CO_2)
  - Methanol (1.7 million tons of CO_2)
  - Polycarbonates
  - Cyclic carbonates
  - Salicylic acid
  - Metal carbonates

Surplus Carbon Dioxide

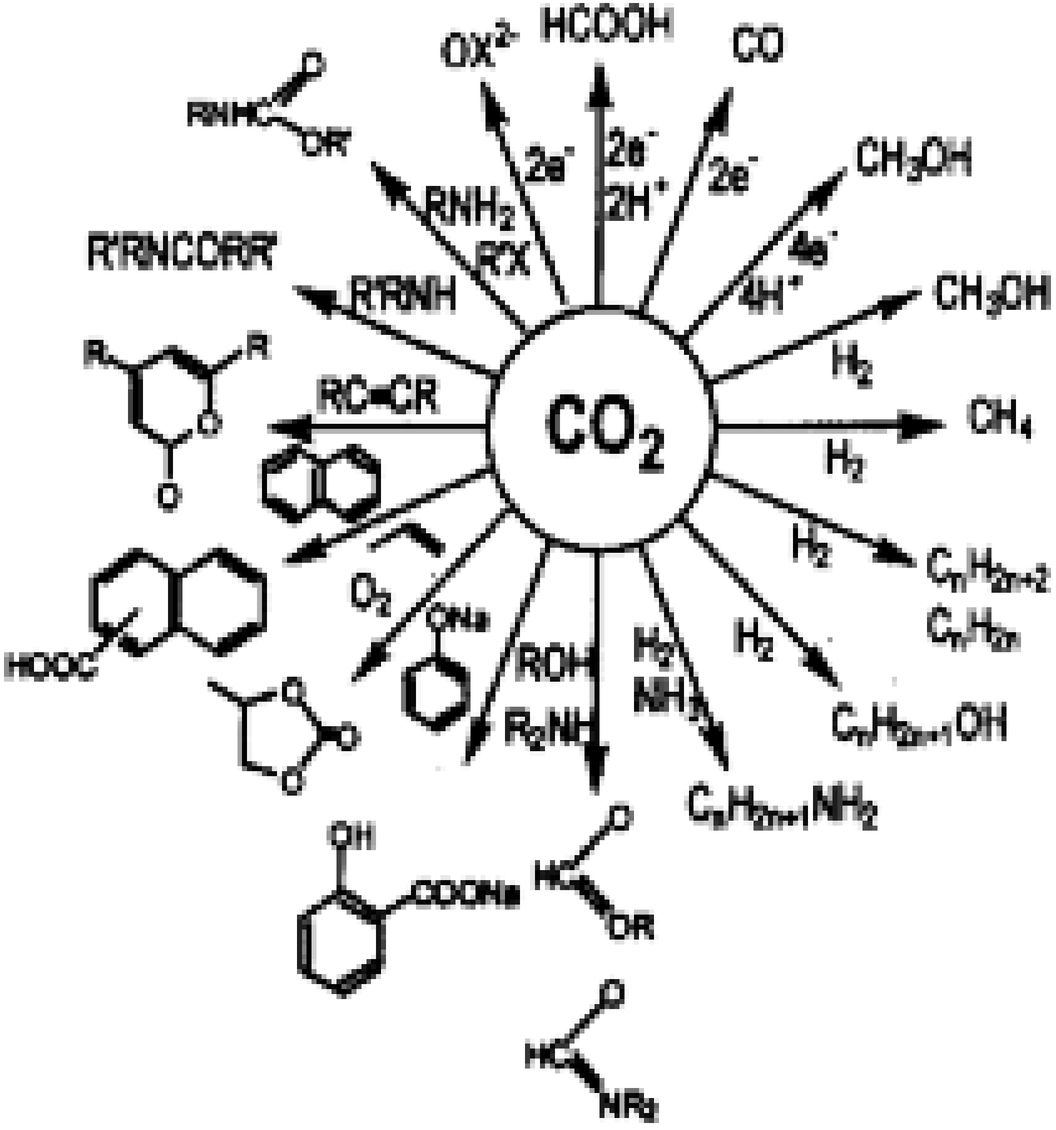
Ammonia plants produce 1.2 million tons per year in lower Mississippi River corridor

Methanol and urea plants consume 0.15 million tons per year

Surplus high-purity carbon dioxide 1.0 million tons per year vented to atmosphere

Greenhouse Gases as Raw Material

- Intermediate of fine chemicals for the chemical industry
  -C(O)O-: Acids, esters, lactones
  -O-C(O)O-:Carbonates
  -NC(O)OR-: Carbamic esters
  -NCO: Isocyanates
  -N-C(O)-N: Ureas
- Use as a solvent
- Energy rich products
  CO, CH_3OH



From Creutz and Fujita, 2000

Catalytic Reactions of CO_2 from Various Sources

Hydrogenation

$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$ methanol

$2CO_2 + 6H_2 \rightarrow C_2H_5OH + 3H_2O$ ethanol

$CO_2 + H_2 \rightarrow CH_3\text{-}O\text{-}CH_3$ dimethyl ether

Hydrolysis and Photocatalytic Reduction

$CO_2 + 2H_2O \rightarrow CH_3OH + O_2$

$CO_2 + H_2O \rightarrow HC{=}O\text{-}OH + 1/2O_2$

$CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$

Hydrocarbon Synthesis

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ methane and higher HC

$2CO_2 + 6H_2 \rightarrow C_2H_4 + 4H_2O$ ethylene and higher olefins

Carboxylic Acid Synthesis

$CO_2 + H_2 \rightarrow HC{=}O\text{-}OH$ formic acid

$CO_2 + CH_4 \rightarrow CH_3\text{-}C{=}O\text{-}OH$ acetic acid

Other Reactions

CO_2 + ethylbenzene → styrene

$CO_2 + C_3H_8 \rightarrow C_3H_6 + H_2 + CO$
dehydrogenation of propane

$CO_2 + CH_4 \rightarrow 2CO + H_2$ reforming

Graphite Synthesis

$CO_2 + H_2 \rightarrow C + H_2O$

$CH_4 \rightarrow C + H_2$
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

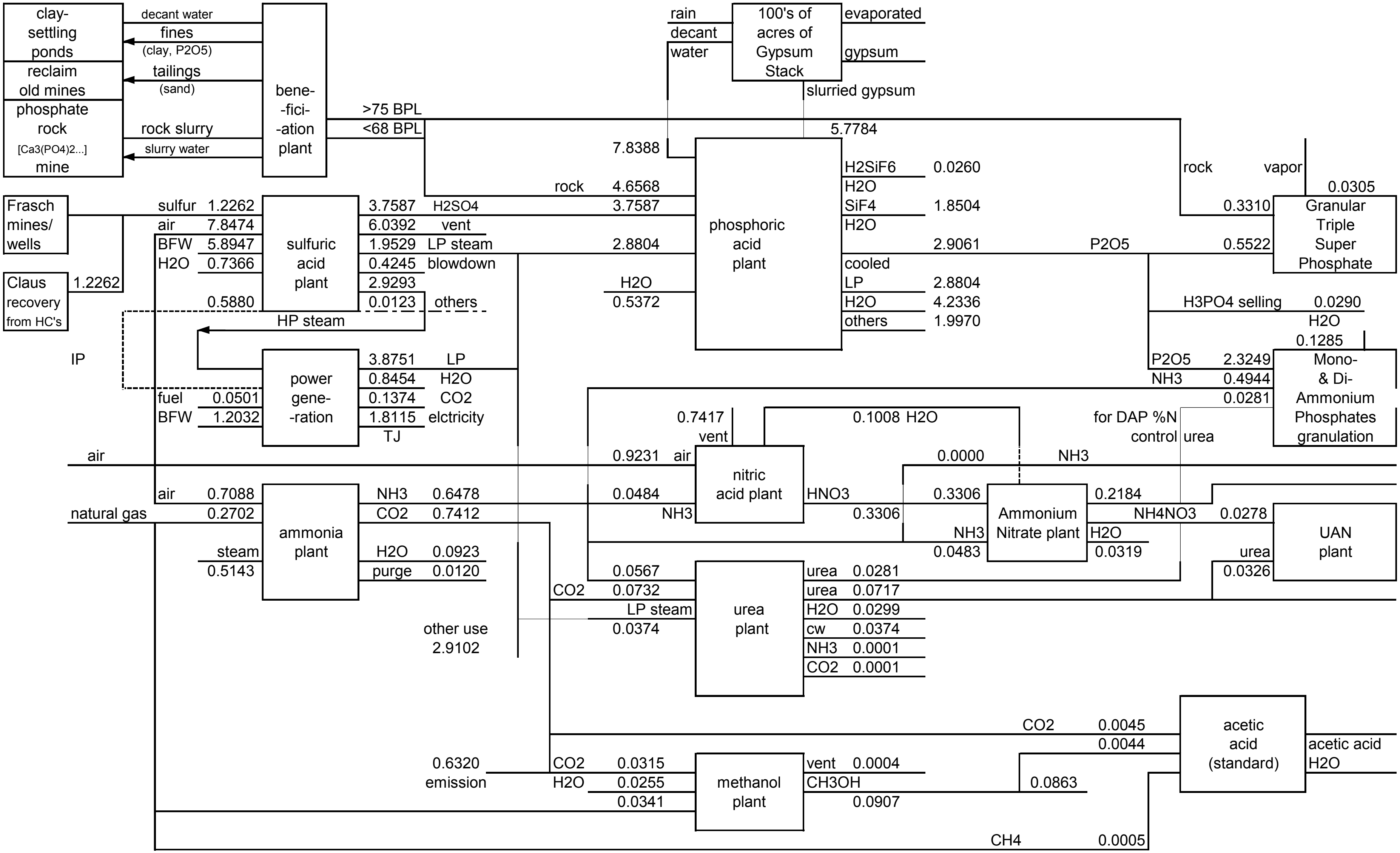
Amine Synthesis

$CO_2 + 3H_2 + NH_3 \rightarrow CH_3\text{-}NH_2 + 2H_2O$ methyl amine and higher amines

Application of the System to Chemical Complex in the Lower Mississippi River Corridor

- Base case
- Superstructure
- Optimal structure

Base Case of Actual Plants

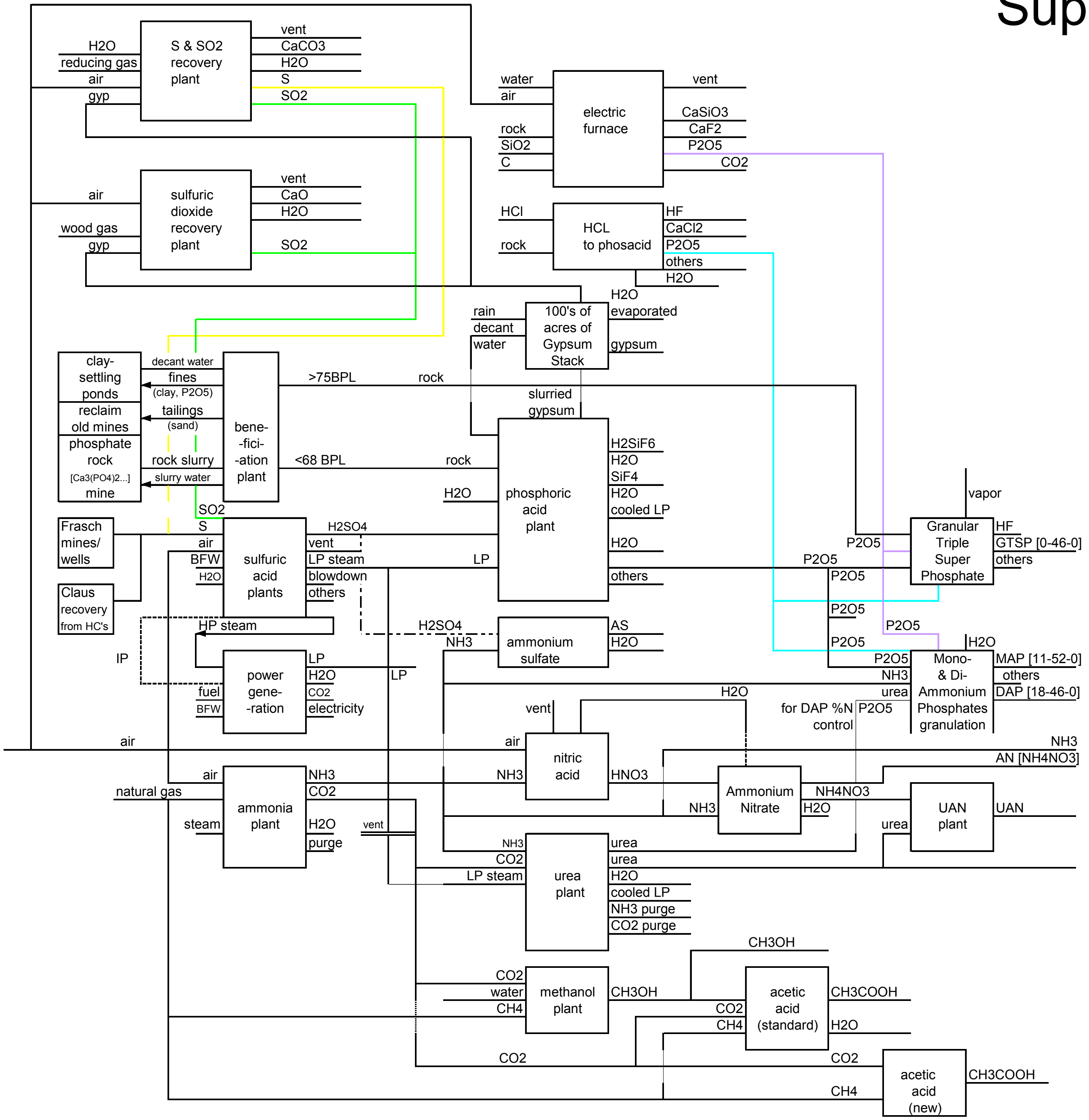


Plants in the lower Mississippi River Corridor, Base Case. Flow Rates in Million Tons Per Year

Processes in the Superstructure

<table>
<tr><th colspan="2">Processes in Superstructure</th></tr>
<tr><th>Processes in Base Case</th><td rowspan="2">Electric furnace process for phosphoric acid
HCl process for phosphoric acid
Ammonium sulfate
SO_2 recovery from gypsum process
S & SO_2 recovery from gypsum process
Acetic acid – new CO2-CH4 catalytic process</td></tr>
<tr><td>Ammonia
Nitric acid
Ammonium nitrate
Urea
UAN
Methanol
Granular triple super phosphate
MAP & DAP
Power generation
Contact process for Sulfuric acid
Wet process for phosphoric acid
Acetic acid-conventional process</td></tr>
</table>

Superstructure



Superstructure Characteristics

Options

- Three options for producing phosphoric acid
- Two options for producing acetic acid
- One option for sulfuric acid
- Two options for recover sulfur and sulfur dioxide
- New plants for
  - ammonium sulfate
  - recover sulfur and sulfur dioxide

Mixed Integer Nonlinear Program

594 continuous variables

7 integer variables

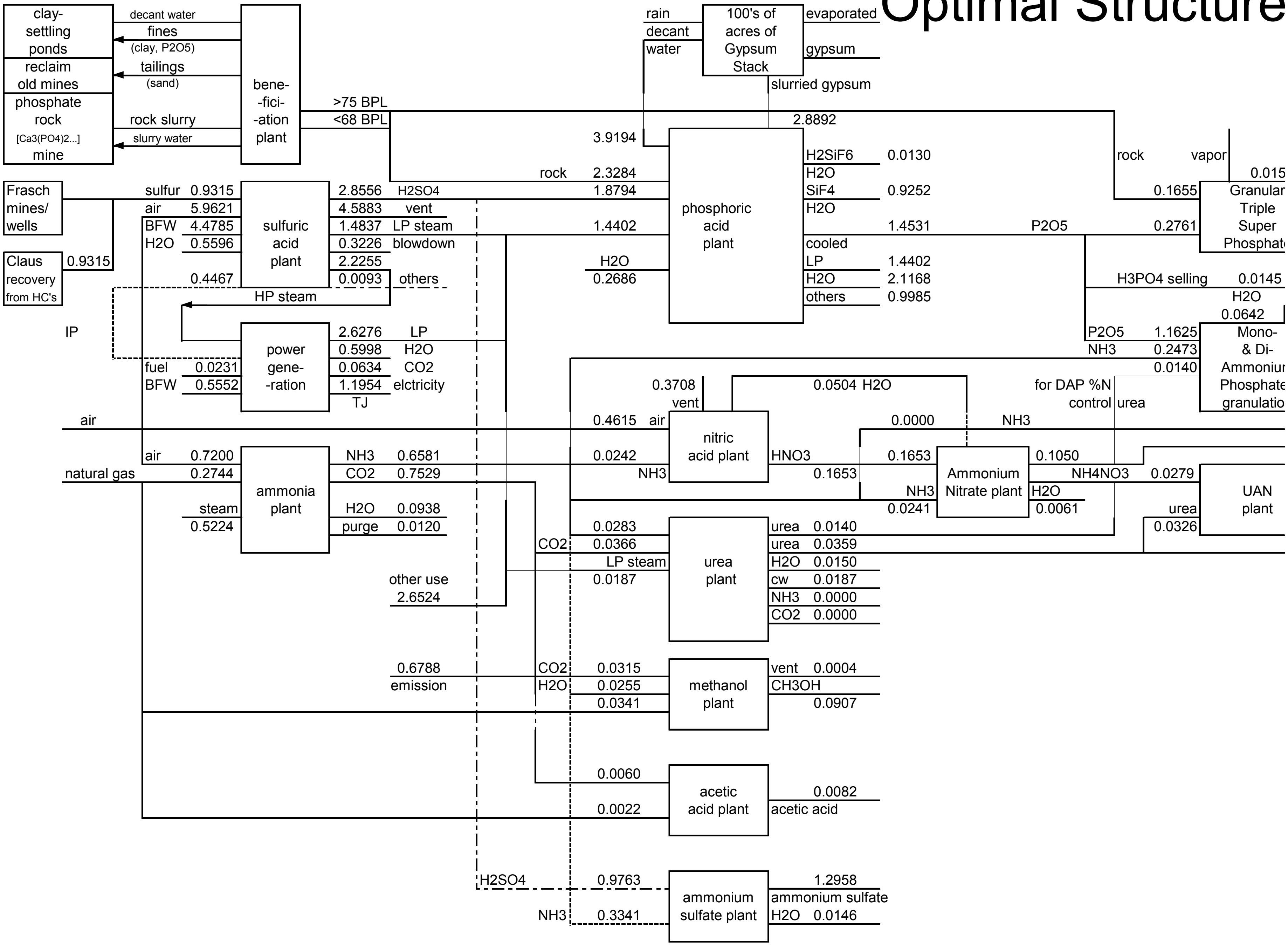
505 equality constraint equations
for material and energy balances

27 inequality constraints for availability of raw materials
demand for product, capacities of the plants in the complex

Raw Material and Product Prices

Raw Materials	Cost ($/mt)	Raw Materials	Cost ($/mt)	Products	Price ($/mt)
Natural Gas	245	Market cost for short term		Ammonia	190
Phosphate Rock		purchase		Methanol	96
wet process		Reducing gas		Acetic Acid	623
electrofurnace	24	Wood gas		GTSP	
HCl process	25	Sustainable Costs and Credits		MAP	180
	27		1394		
GTSP process	30	Credit for CO_2	6.50	DAP	
				142	
HCl		Consumption		$_4NO_3$	
Sulfur		Debit for CO_2	3.25	UAN	
				165	
Frasch		Production 634		Urea 153	154
Claus	38	Credit for HP Steam		H_3PO_4	
				112	
C electrofurnace	760	Credit for IP Steam	6.4	$(NH_4)_2SO_4$	187
	42				
50					
			10	320	
		Credit for gypsum			
		Consumption			
		NH Debit for gypsum	2.5		
			5		
		Production			
		Debit for NO_x			
		Production			
			1025		

Optimal Structure



Comparison of Base Case and Optimal Structure

		Base case		Optimal structure	
Profit (U.S.$/year)		148,087,243		246,927,825	
Environmental cost (U.S.$/year)		179,481,000		123,352,900	
Sustainability cost (U.S.$/year)		-17,780,800	energy	-16,148,900	energy
Plant name	Capacity (mt/year)	Capacity	requirement	Capacity	requirement
	(upper-lower bounds)	(mt/year)	(TJ/year)	(mt/year)	(TJ/year)
Ammonia	329,030-658,061	647,834	3,774	658,061	3,834
Nitric acid	0-178,547	178,525	-649	89,262	-324
Ammonium nitrate	113,398-226,796	226,796	116	113,398	26
Urea	49,895-99,790	99,790	127	49,895	63
Methanol	90,718-181,437	90,719	1,083	90,719	1,083
UAN	30,240-60,480	60,480	0	60,480	0
MAP	0-321,920	321,912		160,959	
DAP	0-2,062,100	2,062,100	2,127	1,031,071	1,063
GTSP	0-822,300	822,284	1,036	411,150	518
Contact process sulfuric acid	1,851,186-3,702,372	3,702,297	-14,963	2,812,817	-11,368
Wet process phosphoric acid	697,489-1,394,978	1,394,950	7,404	697,489	3,702
Electric furnace phosphoric acid	697,489-1,394,978	na	na	0	0
HCl to phosphoric acid	697,489-1,394,978	na	na	0	0
Ammonium sulfate	0-2,839,000	na	na	1,295,770	726
Acetic acid (standard)	0-8,165	8,165	268	0	0
Acetic acid (new)	0-8,165	na	na	8,165	92
SO2 recovery from gypsum	0-1,804,417	na	na	0	0
S & SO2 recovery from gypsum	0-903,053	na	na	0	0
Ammonia sale		0		0	
Ammnium Nitrate sale		218,441		105,043	
Urea sale		39,076		3,223	
Wet process phosphoric acid sale		13,950		6,975	
Methanol sale		86,361		90,719	
Total energy requirement from fuel gas			2,912		1,344

Comparison of Acetic Acid Processes

Process	Conventional Process	New Catalytic Process
Raw Materials	Methanol, Carbon Monoxide	Methane, Carbon Dioxide
Reaction Condition	450K, 30bar	350K, 25bar
Conversion of methane	100%	97%
Equipment	reactor, flash drum, four distillation columns	reactor, distillation column

Production Costs for Acetic Acid

Moulijn, et al., 2001

Plant Production Cost, (cents per kg)	Methanol Carbon Monoxide	Methane Carbon Dioxide
Raw materials	21.6	21.6
Utilities	3.3	1.7
Labor	1.2	1.2
Other (capital, catalyst)	10.1	10.1
Total Production Cost	36.2	34.6

Current market price 79 cents per kg

Catalytic Process for Acetic Acid

Capacity: 100 million pound per year of acetic acid

36,700 tons per year of carbon dioxide raw material

Potential Savings

Reduction in utilities costs for process steam $750,000

Energy savings from not having to produce this steam

275 trillion BTUs per year

Reduction in NOx emissions base on steam and power generation by cogeneration

3.5 tons per year

Reduction in carbon dioxide emissions

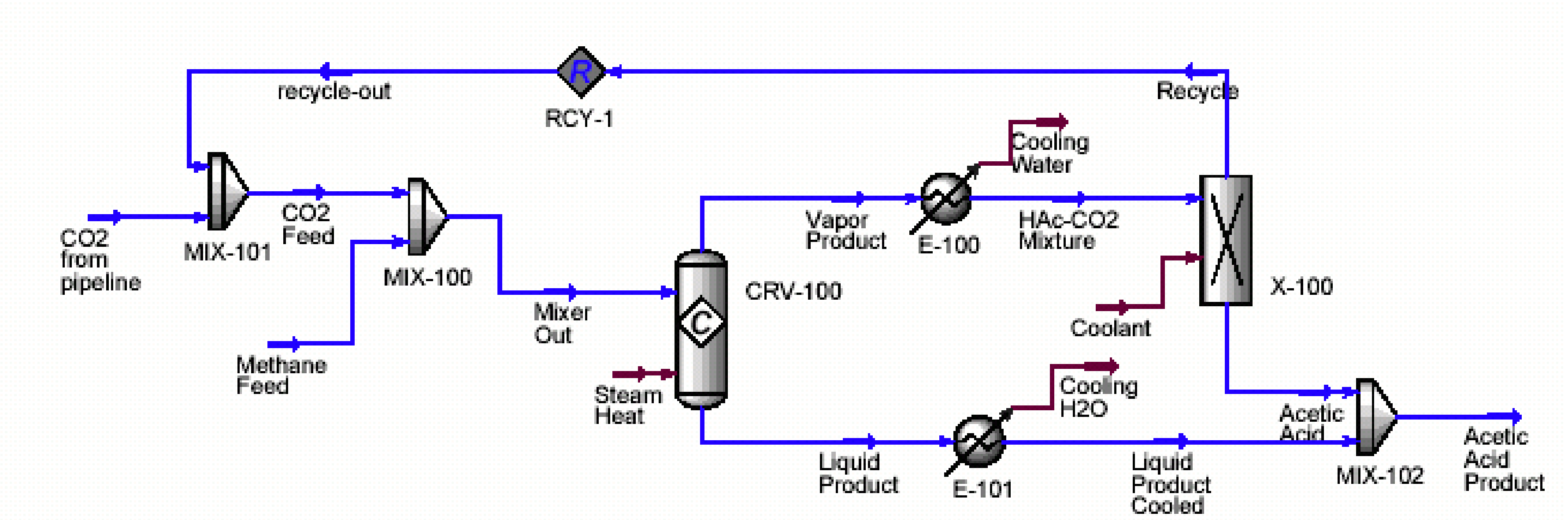
12,600 tons per year from the steam production

36,700 tons per year conversion to a useful product

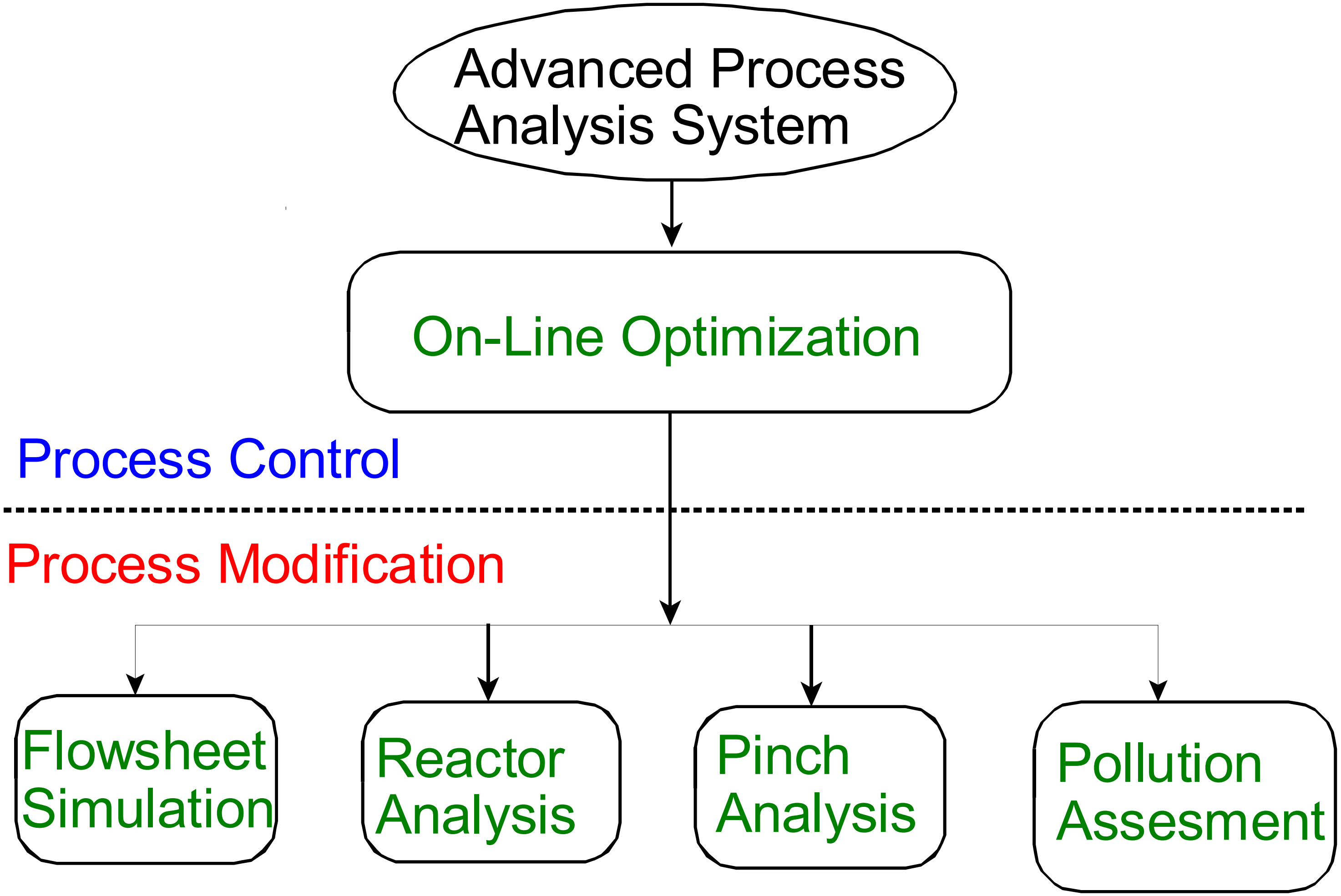
Develop Process Information for the System

- Simulate process using HYSYS and Advanced Process Analysis System.
- Estimate utilities required.
- Perform economic analysis.
- Obtain process constraint equations from HYSIS and Advanced Process Analysis System.
- Maximize the profit function to find the optimum process configuration with the System.
- Incorporate into superstructure.

HYSYS Process Flow Diagram for Acetic Acid Process



Advanced Process Analysis System



Advanced Process Analysis System

On-Line Optimization

Process Control

Process Modification

Flowsheet Simulation

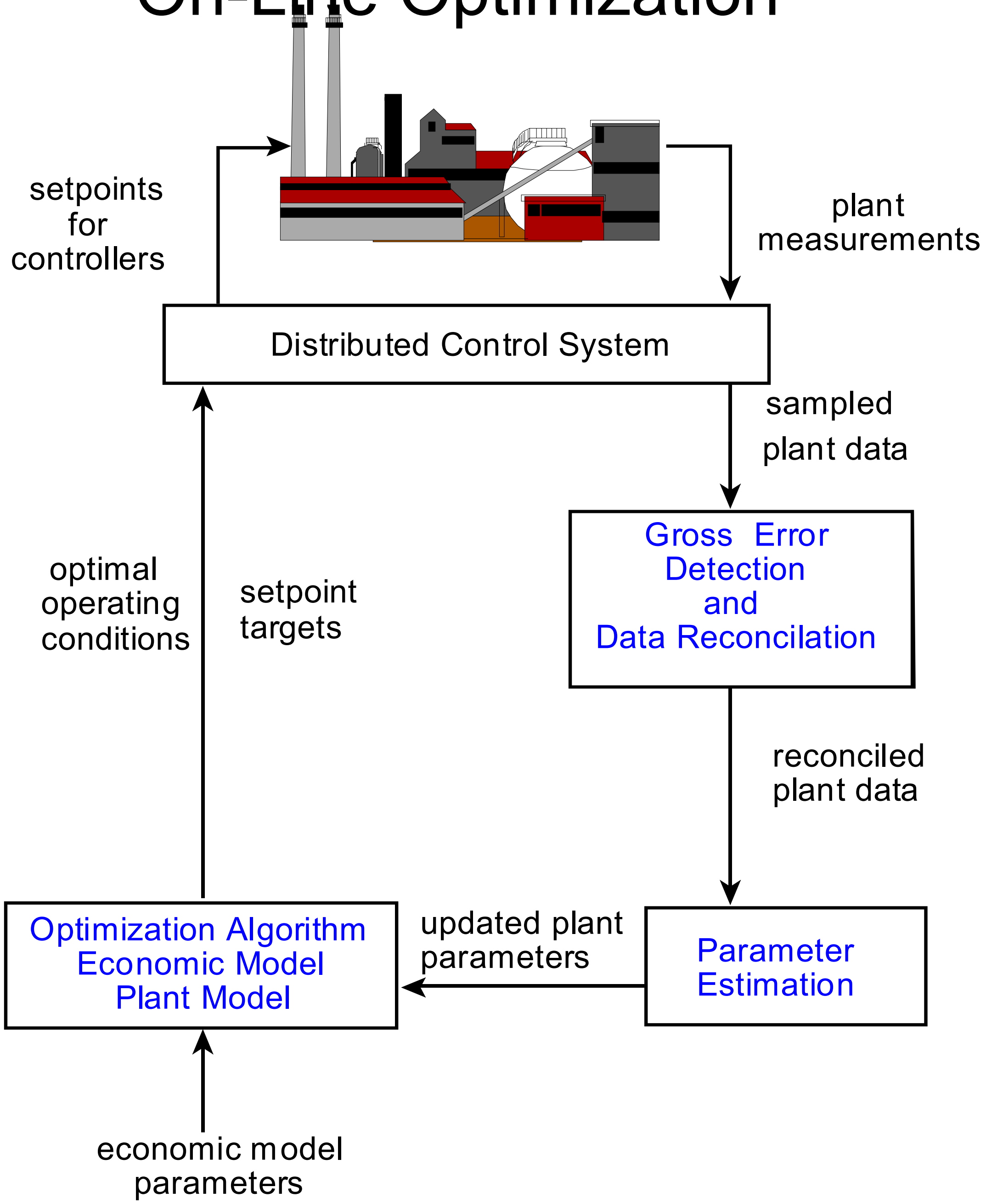
Reactor Analysis

Pinch Analysis

Pollution Assesment

Fig. 1 Overview of Advanced Process Analysis System

On-Line Optimization



setpoints
for
controllers

plant
measurements

Distributed Control System

sampled
plant data

Gross Error
Detection
and
Data Reconciliation

reconciled
plant data

Parameter
Estimation

updated plant
parameters

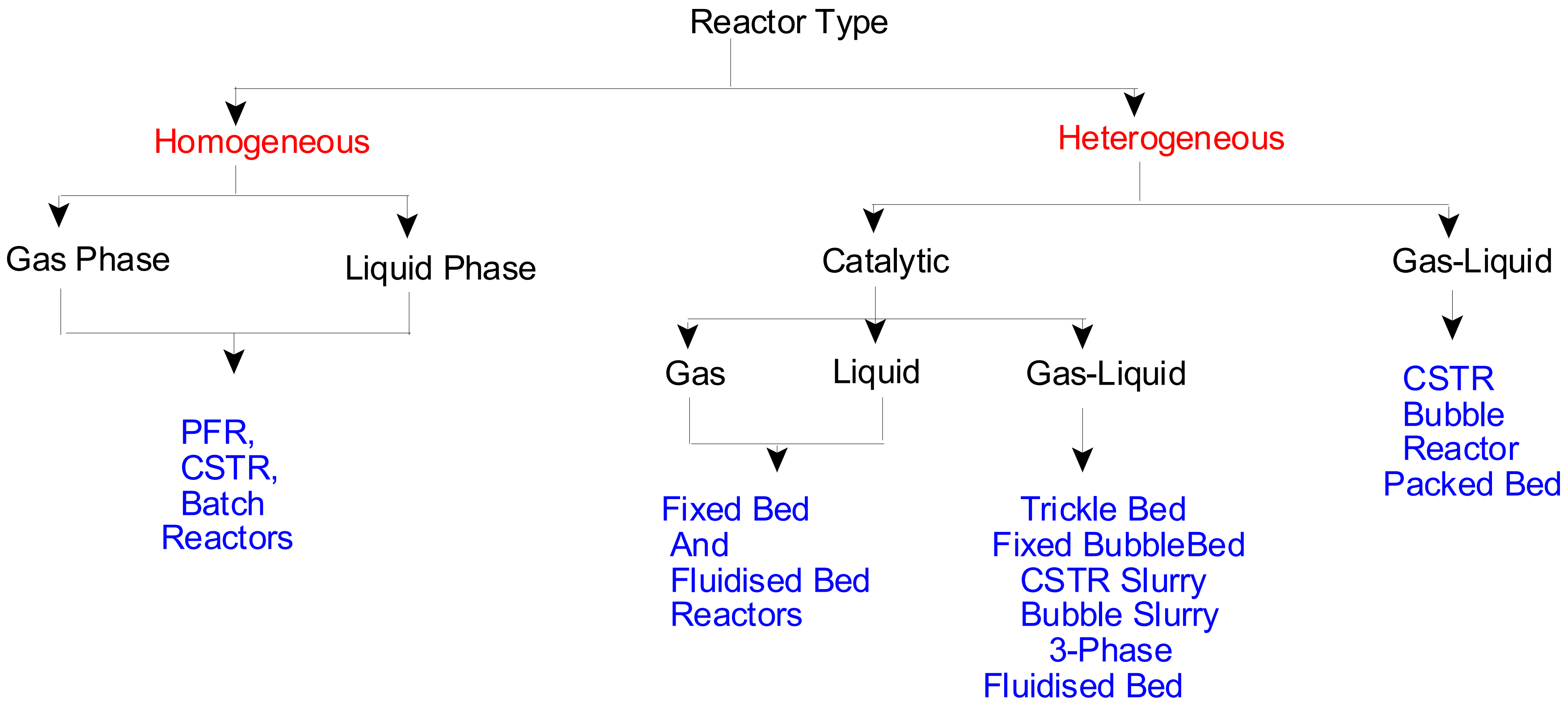
Optimization Algorithm
Economic Model
Plant Model

economic model
parameters

optimal
operating
conditions

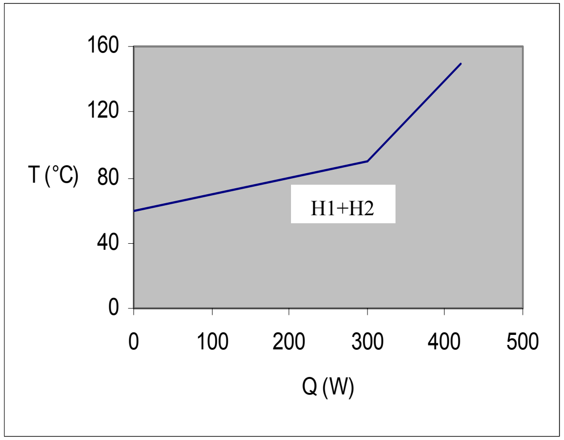
setpoint
targets

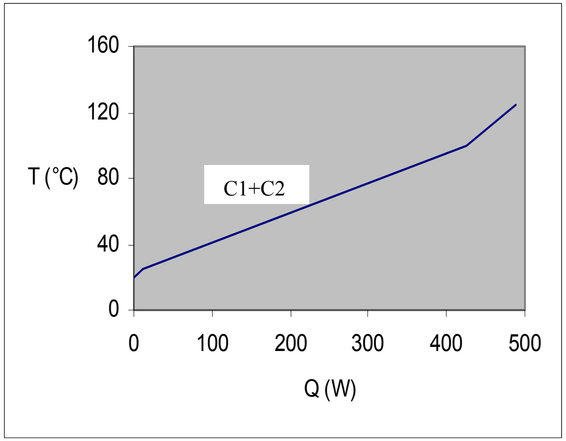
Reactor Analysis

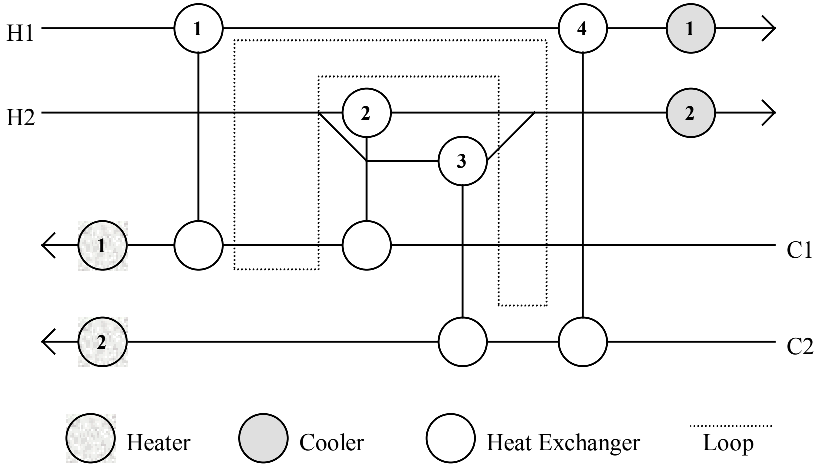


- Reactor Type
  - Homogeneous
    - Gas Phase
    - Liquid Phase
      - PFR, CSTR, Batch Reactors
  - Heterogeneous
    - Catalytic
      - Gas
      - Liquid
        - Fixed Bed And Fluidised Bed Reactors
      - Gas-Liquid
        - Trickle Bed
        - Fixed BubbleBed
        - CSTR Slurry
        - Bubble Slurry
        - 3-Phase Fluidised Bed
    - Gas-Liquid
      - CSTR
      - Bubble Reactor
      - Packed Bed

Energy Integration – Pinch Analysis







Pollution Assessment

Waste Reduction Algorithm (WAR) and
Environmental Impact Theory

Pollution Index

I = wastes/products = - (ΣOut + ΣFugitive) / ΣP_n

Potential Environmental Impact

$$\Psi_k = \sum_l \alpha_l \Psi^s_{k,l}$$

α_l relative weighting factor

$\Psi^s_{k,l}$ units of potential environmental impact/mass of chemical k

Conclusions

- The System has been applied to an extended agricultural chemical complex in the lower Mississippi River corridor

- Economic model incorporated economic, environmental and sustainable costs.

- An optimum configuration of plants was determined with increased profit and reduced energy and emissions

- For acetic acid production, new catalytic process is better than conventional process based on energy savings and the reduction of NO_x and CO_2 emissions.

Conclusions

- Based on these results, the methodology could be applied to other chemical complexes in the world for reduced emissions and energy savings.
- The System includes the program with users manuals and tutorials. These can be downloaded at no cost from the LSU Mineral Processing Research Institute’s web site www.mpri.lsu.edu

Future Work

- Add new processes for carbon dioxide
- Expand to a petrochemical complex in the lower Mississippi River corridor
- Add processes that produce fullerines and carbon nanotubes