NETL Water and Power Plants Review

A review meeting was held on June 20, 2006 of the NETL Water and Power Plants research program at the Pittsburgh NETL site.

Thomas Feeley, Technology Manager for the Innovations for Existing Plants Program, gave background information and an overview of the Innovations for Existing Plants Water Program.

Ongoing/Ending Projects

Alternative Water Sources

Michael DiFilippo, a consultant for EPRI, presented results from the project "Use of Produced Water in Recirculated Cooling Systems at Power Generating Facilities".

John Rodgers, from Clemson University, presented results from the project "An Innovative System for the Efficient and Effective Treatment of Non-traditional Waters for Reuse in Thermoelectric Power Generation".

Use of Waste Heat

Edward Levy, from Lehigh University, presented results from the project "Use of Coal Drying to Reduce Water Consumed in Pulverized Coal Power Plants".

Donald Erickson, from Energy Concepts Company, presented results from the project "Water-Conserving Steam Ammonia Power Cycle".

James Klausner, from the University of Florida, presented results from the project "An Innovative Fresh Water Production Process for Fossil Fired Power Plants Using Energy Stored in Main Condenser Cooling Water".

Recovery of Water from Flue Gas

Bruce Folkedahl, from the University of North Dakota, Energy and Environmental Research Center, presented results from the project "Water Extraction from Coal-Fired Power Plant Flue Gas".

Cooling Technology Improvements

Steven Seghi, from Ceramic Composites, prepared and planned to present results from the project **"**Enhanced Performance Carbon Foam Heat Exchanger for Power Plant Cooling".

Kick-offs for Starting Projects

Alternative Water Sources

Radisav Vidic, from the University of Pittsburgh, and David Dzombak, from Carnegie Mellon University, presented “Re-use of Internal or External Wastewaters in the Cooling Systems of Coal-Based Thermoelectric Power Plants”.

Paul Ziemkiewicz, from West Virginia University, presented “Development and Demonstration of a Modeling Framework for Assessing the Efficacy of Using Mine Water for Thermoelectric Power Generation”.

Enhancing Cycles of Concentration in Cooling Towers

Young I Cho, from Drexel University, presented “Application of Pulsed Electric Fields for Advanced Cooling in Coal-Fired Power Plants”.

Shih-Perng Tsai, from Nalco Company, presented “A Synergistic Combination of Advanced Separation and Chemical Scale Inhibitor Technologies for Efficient Use of Impaired Water as Cooling Water in Coal-Based Power Plants”.

Cooling Technology Improvements

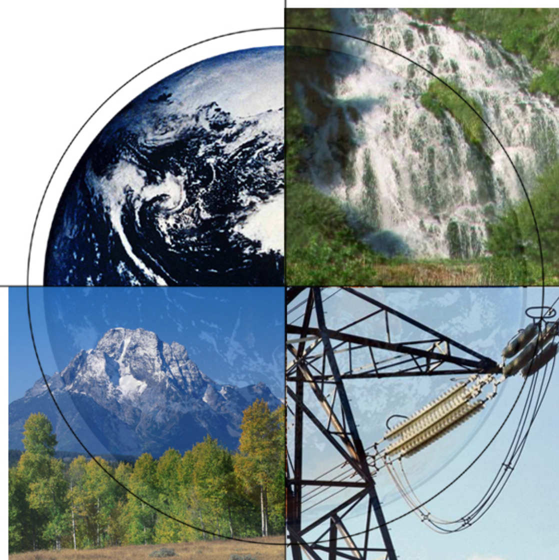
Ken Mortensen, from SPX Cooling Technologies, presented **“**Use of Air2Air™ Technology to Recover Fresh-Water from the Normal Evaporative Cooling Loss at Coal-Based Thermoelectric Power Plants”.

Recovery of Water from Flue Gas

Milton Owen, from URS Group, presented “Reduction of Water Use in Wet FGD Systems”.

Edward Levy, from Lehigh University, presented “Recovery of Water from Boiler Flue Gas”.

DOE/NETL Power Plant-Water Management R&D Program



Power Plant-Water R&D Kick-off Meeting

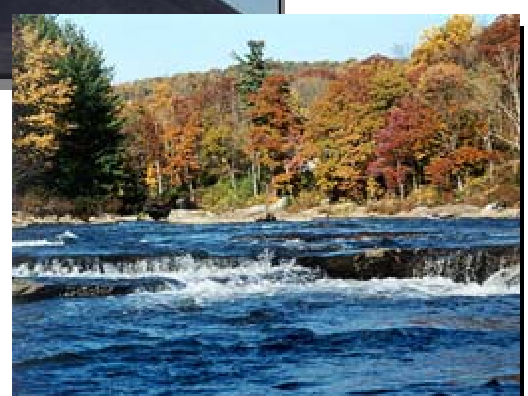
Pittsburgh
June 20, 2006

Thomas J. Feeley, IIII
National Energy Technology Laboratory

Three Things Power Plants Require

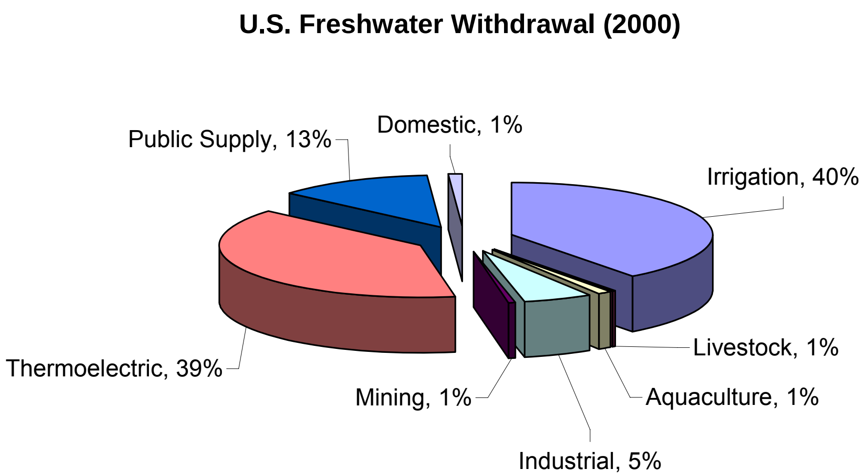
1) Access to transmission lines

2) Available fuel, e.g., coal or natural gas



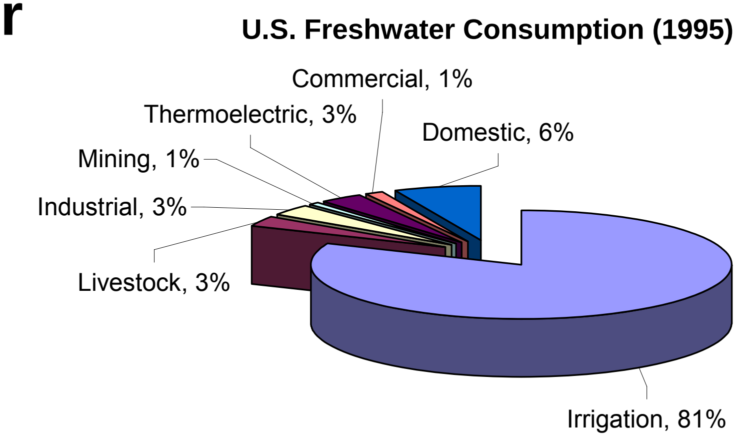
3) Water

The Issues: Competing Water Uses



- **2000 thermoelectric water requirements:**
  - **Withdrawal: ~ 136 BGD**
  - **Consumption: ~ 3 BGD**

- **Thermoelectric competes with other users, including in-stream use.**
- **Which is more important: drinking and personal use, growing food, or energy production?**



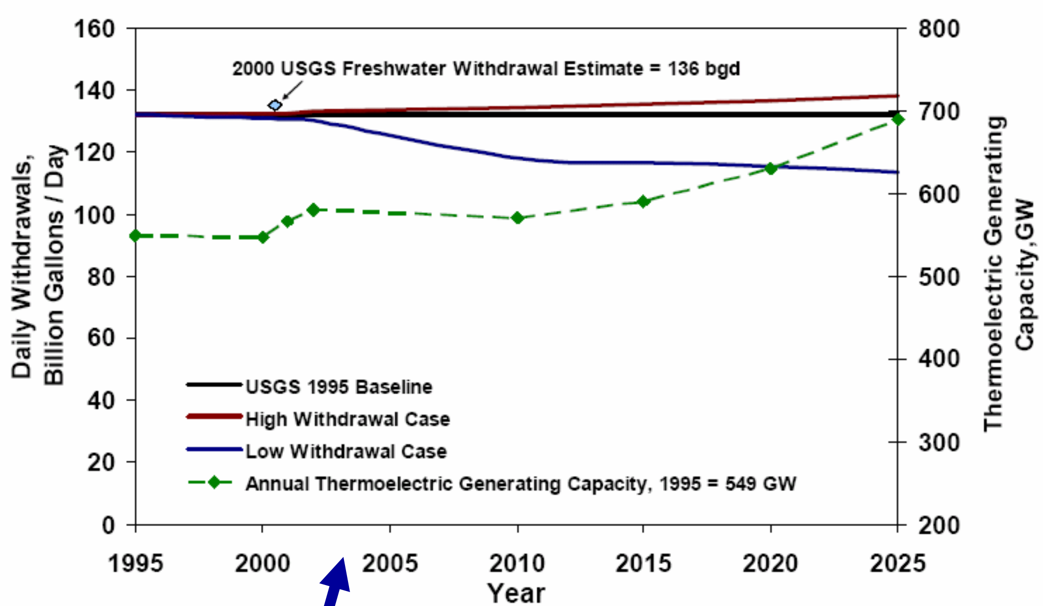
USGS, *Estimated Use of Water in the United States in 2000*, USGS Circular 1268, March 2004
USGS, *Estimated Use of Water in the United States in 1995*, USGS Circular 1200, 1998

Recent Articles on Water-Related Impacts on Power Plant Siting and Operation

- **Idaho May Adopt Moratorium on Coal Power Due to Water Issues**
  - *Reuters, March 2006*
- **Sempra Energy Halts Gerlach Project Study**
  - *Associated Press, March 2006*
- **Desert Rock Water Agreement Passes Navajo National Committee**
  - *The Daily Times, February 2006*
- **California's Efforts to End Use of Sea Water to Cool Plants Could Jeopardize 24 GW**
  - *POWERnews*, March 2006
- **New Power Plants to Dry Up Water Supplies?**
  - *Transcript from Great Lakes Radio Consortium, August 2005*
- **Feds Order Susquehanna Power Plants and Others to Stop Killing Off Fish**
  - *Lancaster New Era*, *February 2005*

Water Conservation – A Critical Issue

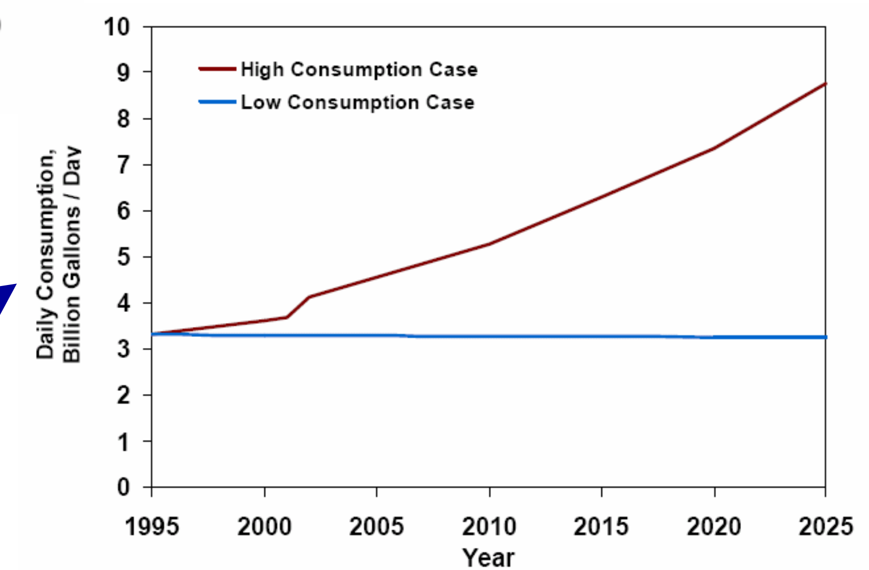
Thermoelectric Power Plant Water W&C: 2004 Study



- **National estimate of future freshwater withdrawal and consumption**

Withdrawal

Consumption

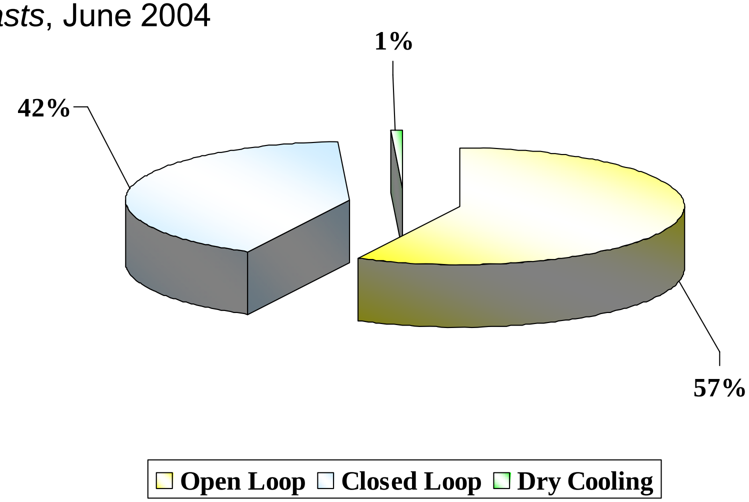


NETL

Thermoelectric Power Plant Water Withdrawal & Consumption (W&C): Key Assumptions

Plant Type	Cooling Technology	Withdrawal (gal/kWh)	Consumption (gal/kWh)
Fossil	Once-through	37.7	0.1
	Recirculating	1.2	1.1
Nuclear	Once-through	46.2	0.1
	Recirculating	1.5	1.5

Hoffman, J., Forbes, S. and Feeley, T., *Estimating Freshwater Needs to Meet 2025 Electricity Generating Capacity Forecasts*, June 2004



Platts, The McGraw-Hill Companies, Inc., *North American Energy Business Directory, World Electric Power Plants Database*, December 2005.

NETL Energy-Water RD&D Programs

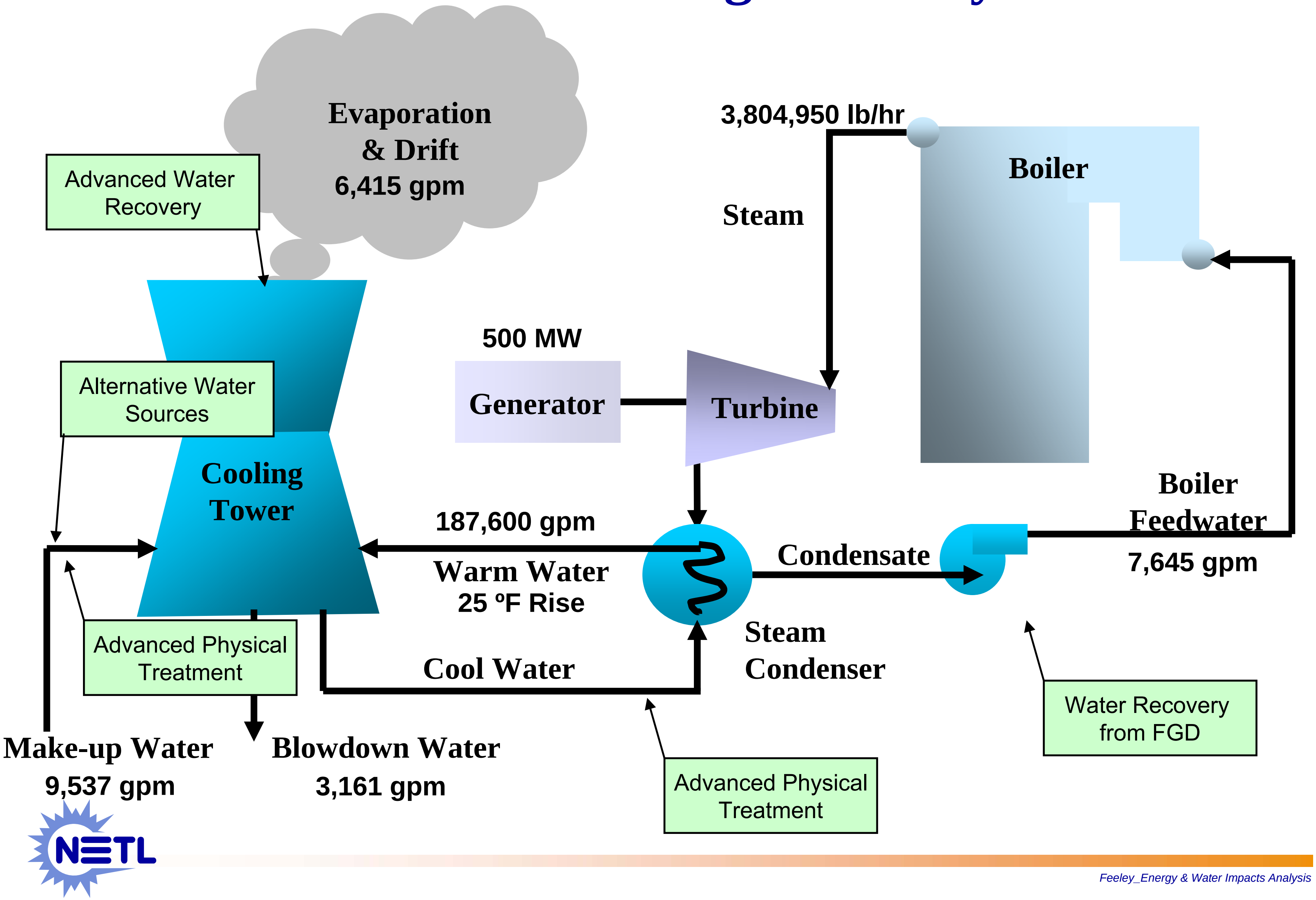
- Power Plant-Water Management
- Oil & Gas Produced Water Management
- Carbon Sequestration Produced Water Management
- Systems & Engineering Analysis Support
- Sensors and Materials Related Research

IEP Program: Energy-Water R&D

- **Program goal - to have technologies ready for commercial demonstration by 2015 that would lead to a 5% to 10% reduction in water withdrawal and consumption (once deployed).**
- **Competitive solicitations**
  - **Five projects awarded in August 2003**
  - **Seven projects awarded in November 2005**
- **Four program areas:**
  - **Non-Traditional Sources of Process and Cooling Water**
  - **Innovative Water Reuse and Recovery**
  - **Advanced Cooling Technology**
  - **Advanced Water Treatment and Detection Technology**

NETL

Power Plant Cooling Water System



August 2003 Solicitation Projects

- **Environmentally-Save Control of Zebra Mussel Fouling –** ***New York State Education Department***
- **Strategies for Cooling Electric Generating Facilities Utilizing Mine Water: Technical & Economic Feasibility –** ***West Virginia University***
- **Water Extraction from Coal-Fired Power Plant Flue Gas –** ***UNDEERC***
- **Fate of As, Se, Hg in a Passive Integrated System for Treatment of Fossil Plant Wastewater –** ***Tennessee Valley Authority***
- **Use of Produced Water in Recirculated Cooling Systems at Power Generating Facilities –** ***EPRI***

November 2005 Solicitation Projects

- Development of Model Framework for Assessing Use of Mine Water for Thermoelectric Power Generation – *West Virginia University*
- Recovery of Water from Boiler Flue Gas – *Lehigh University*
- Use of Air2Air™ Technology to Recover Fresh-Water at Thermoelectric Power Plants – *SPX Cooling Systems*
- Advanced Separation and Chemical Scale Inhibitor Technologies for Use of Impaired Water in Power Plants – *Nalco Company*
- Reuse of Treated Wastewaters in the Cooling Systems of Coal-Based Power Plants – *University of Pittsburgh*
- Reduction of Water Use in Wet FGD Systems – *URS Group, Inc.*
- Application of Pulsed Electrical Fields for Advanced Cooling in Coal-Fired Power Plants – *Drexel University*

Summary

- EIA projects significant energy demand growth through 2030, particularly in arid West and Southwest, and Southeast
- Thermoelectric generation will increasingly compete with other use sectors for limited supplies of freshwater
- New power projects and existing plant operations are already being impacted by water availability issues
- NETL is developing advanced technologies and concepts ready for commercial demonstration/deployment by 2015 to reduce power plant freshwater W&C by 5%-10%

DOE/NETL Innovations for Existing Plants Program

To find out more about DOE-NETL's IEP R&D activities visit us at:

http://www.netl.doe.gov/technologies/coalpower/ewr/water/index.html

Produced Water Project

San Juan Generating Station

PNM Water Issues in the San Juan Basin…..

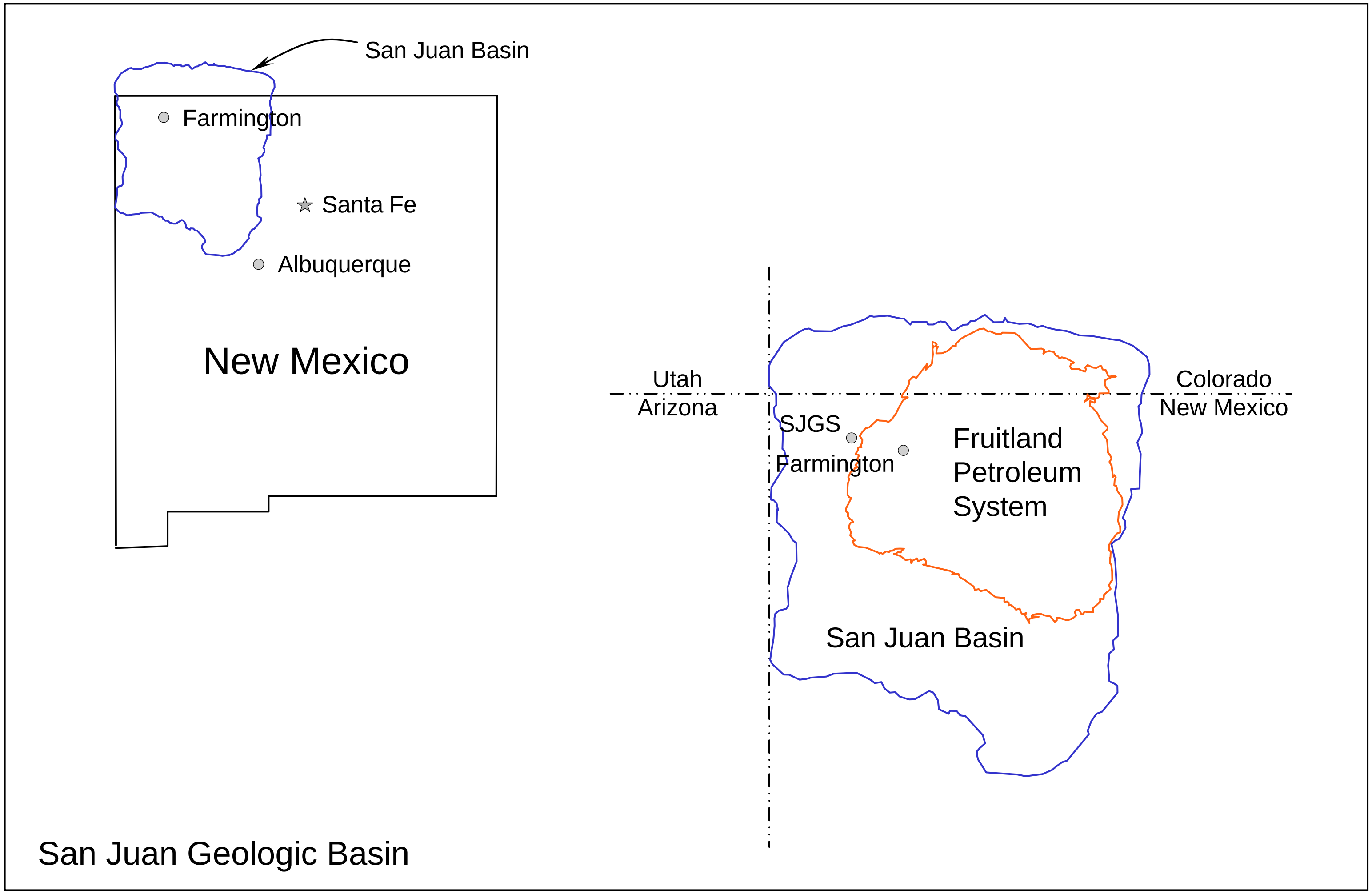
- San Juan Generating Station (SJGS) consumes 22,000 acre-feet of water per year (467,600 BPD or 13,640 gpm).
- SJGS is a base-loaded plant and needs a reliable source(s) of water to operate.
- Climate researchers at the University of Arizona predict an extended drought for the region – possibly lasting 40 to 50 years.
- SJGS is a long-term energy production site and will be there 25 years or more.
- PNM has negotiated short-term and long-term water contracts to ensure supply, however if a severe a drought develops water contracts are irrelevant.
- If SJGS uses less water through conservation and obtains alternative supplies (e.g. produced water), more water will be available for other beneficial uses.

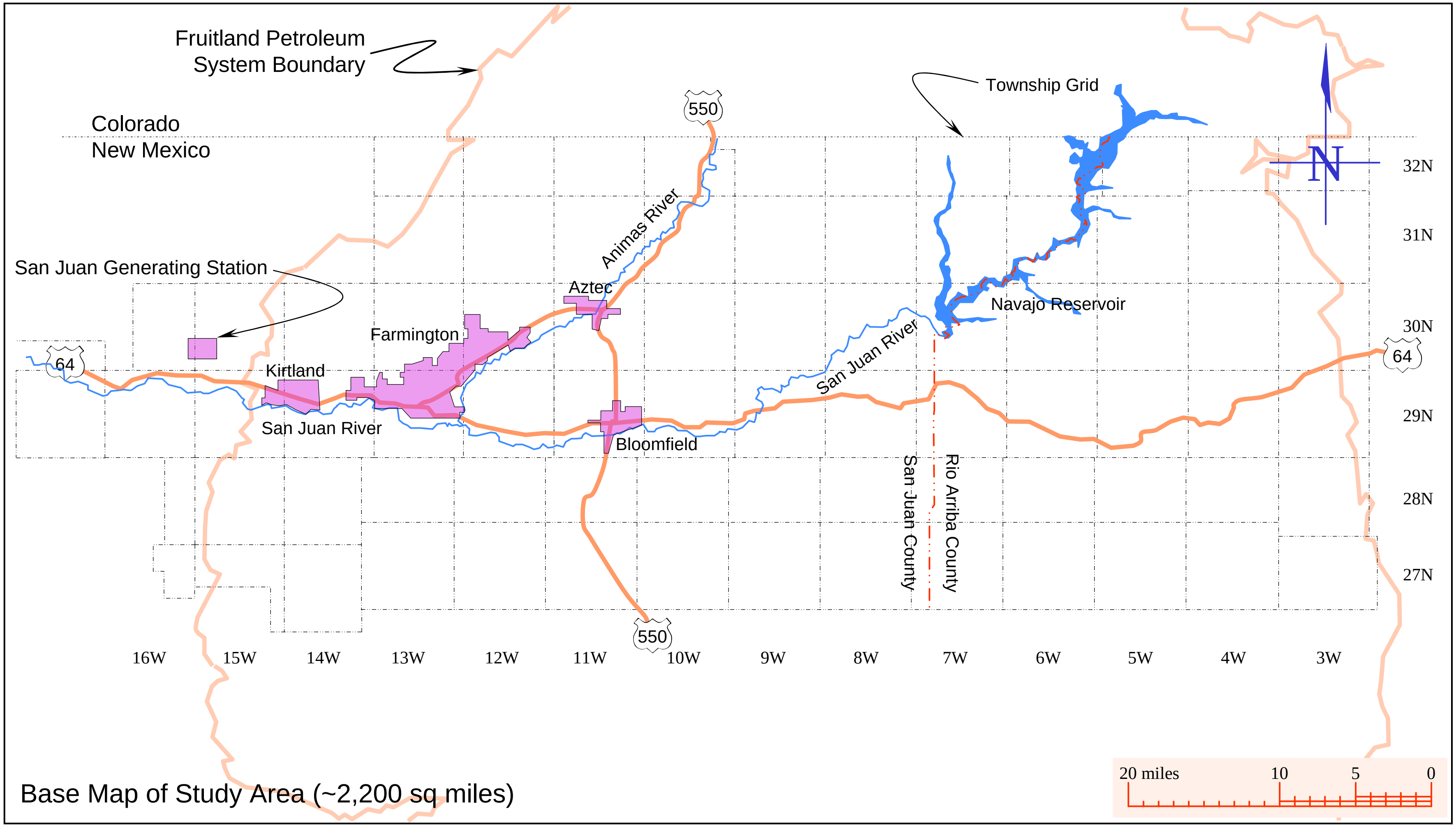
One drought scenario…..

- SJGS has to reduce power by 10% for an entire year.
- SJGS has a long-term take-or-pay fuel contract, i.e. PNM must pay for fuel whether it uses it or not.
- SJGS will have to purchase power from other generators (most likely gas-fired combined cycle plants).
- The financial impact for this scenario could be in excess of $45 million.
- PNM has looked at scenarios where water reductions approach 30%.

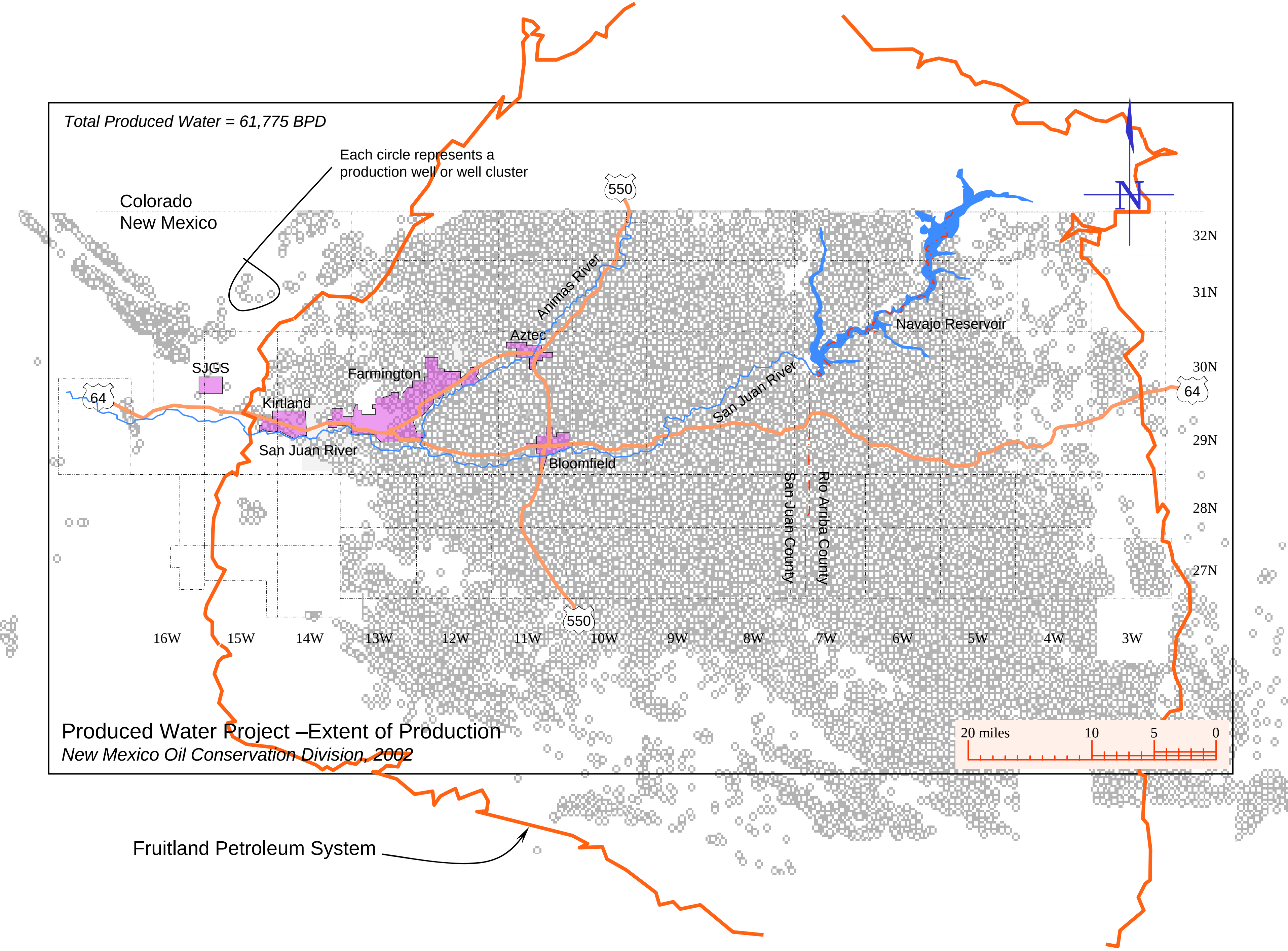
The basis for this project was to provide supplemental water to avoid or minimize the financial impact of such a scenario…..

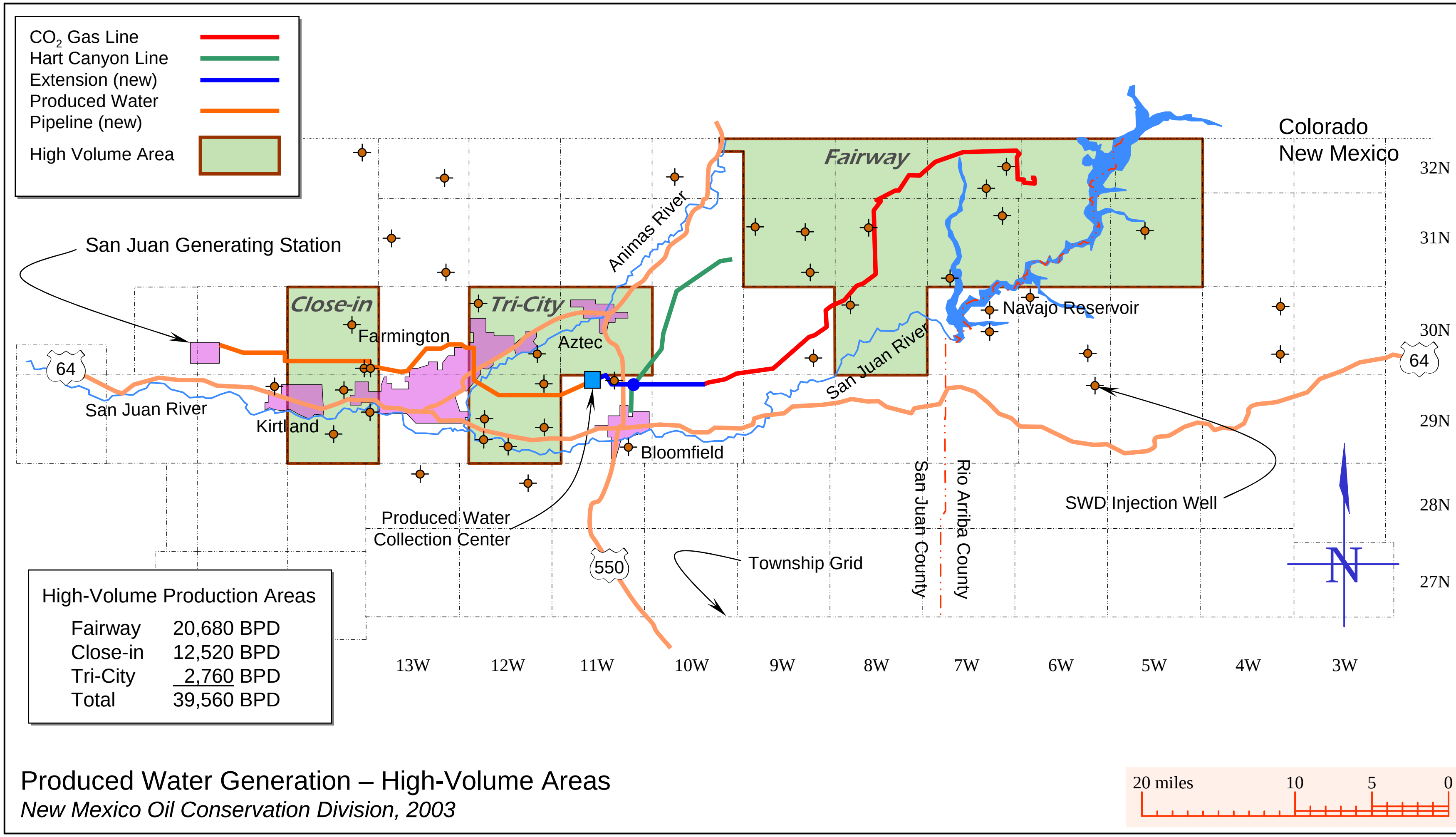
Project Setting


San Juan Basin
Farmington
Santa Fe
Albuquerque
New Mexico
Utah
Arizona
Colorado
New Mexico
SJGS
Farmington
Fruitland
Petroleum
System
San Juan Basin
San Juan Geologic Basin



Base Map of Study Area (~2,200 sq miles)


Total Produced Water = 61,775 BPD
Each circle represents a production well or well cluster
Colorado
New Mexico
550
Animas River
Aztec
SJGS
Farmington
64
Kirtland
San Juan River
Bloomfield
San Juan River
Navajo Reservoir
San Juan County
Rio Arriba County
64
32N
31N
30N
29N
28N
27N
16W
15W
14W
13W
12W
11W
10W
9W
8W
7W
6W
5W
4W
3W
550
N
20 miles
10
5
0
Produced Water Project –Extent of Production
New Mexico Oil Conservation Division, 2002
Fruitland Petroleum System



High-Volume Production Areas

Fairway	20,680 BPD
Close-in	12,520 BPD
Tri-City	2,760 BPD
Total	39,560 BPD

Produced Water Generation – High-Volume Areas

New Mexico Oil Conservation Division, 2003

Salt Water Disposal Facilities (SWDs)

McGrath SWD (Salt Water Disposal) Facility

McGrath is a large SWD near Farmington, New Mexico. Produced water generated at the wellhead is transported by tanker trucks to SWDs. At the SWD, oil is separated from the produced water. The water is then filtered and injected into a non-producing formation at depths that sometimes reach 5,000 feet. In some locations, injection pressures exceed 1,500 psi. There are 53 SWDs in the San Juan Basin.

Project Implementation

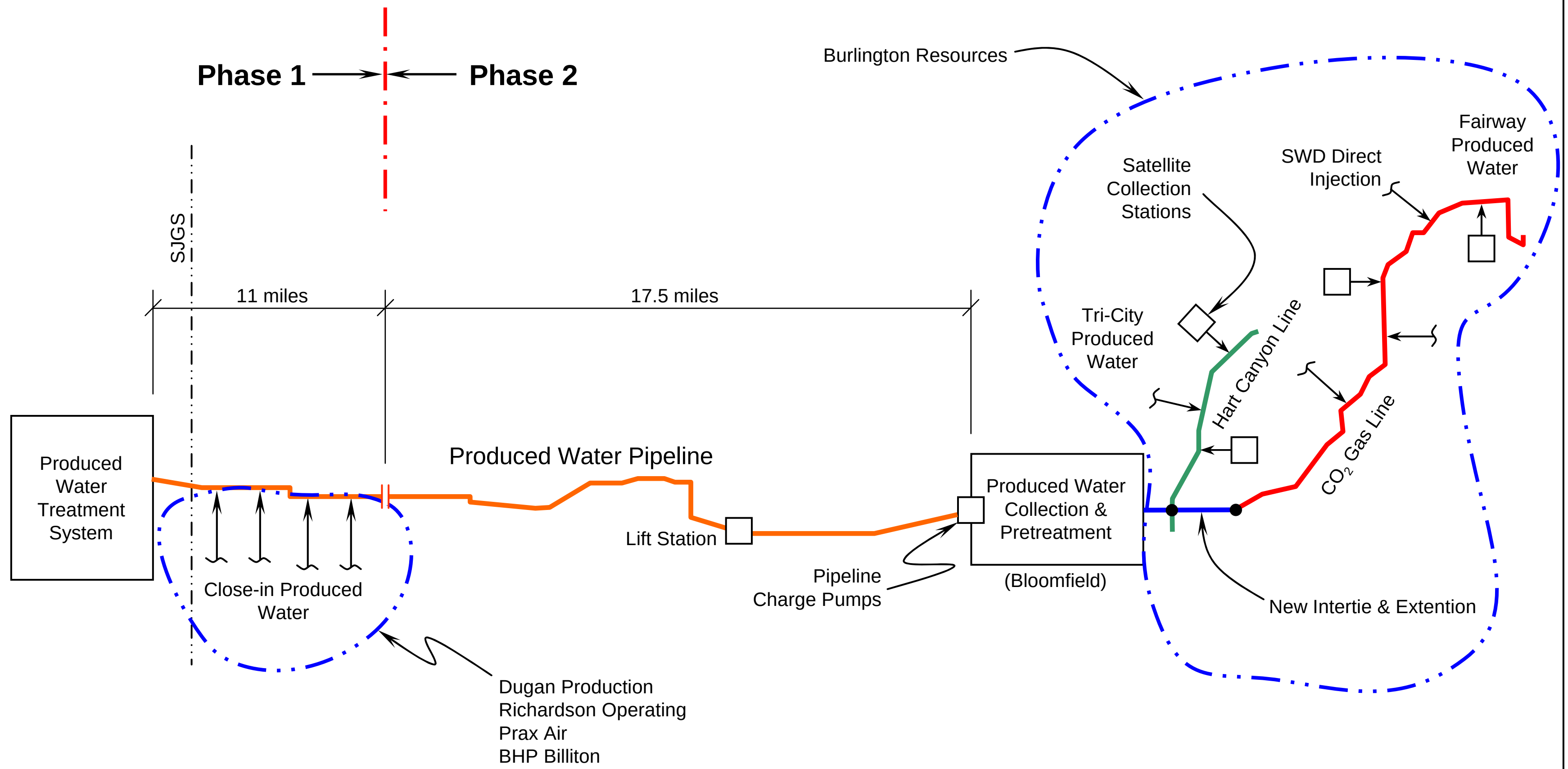
The project would be implemented in two phases.....

Phase 1

- An 11-mile pipeline would be build to collect water from Close-in producers (exclusively CBM production).
- Producers would inject filtered water into the line.
- Producer disposal costs would be reduced by $0.25/bbl.

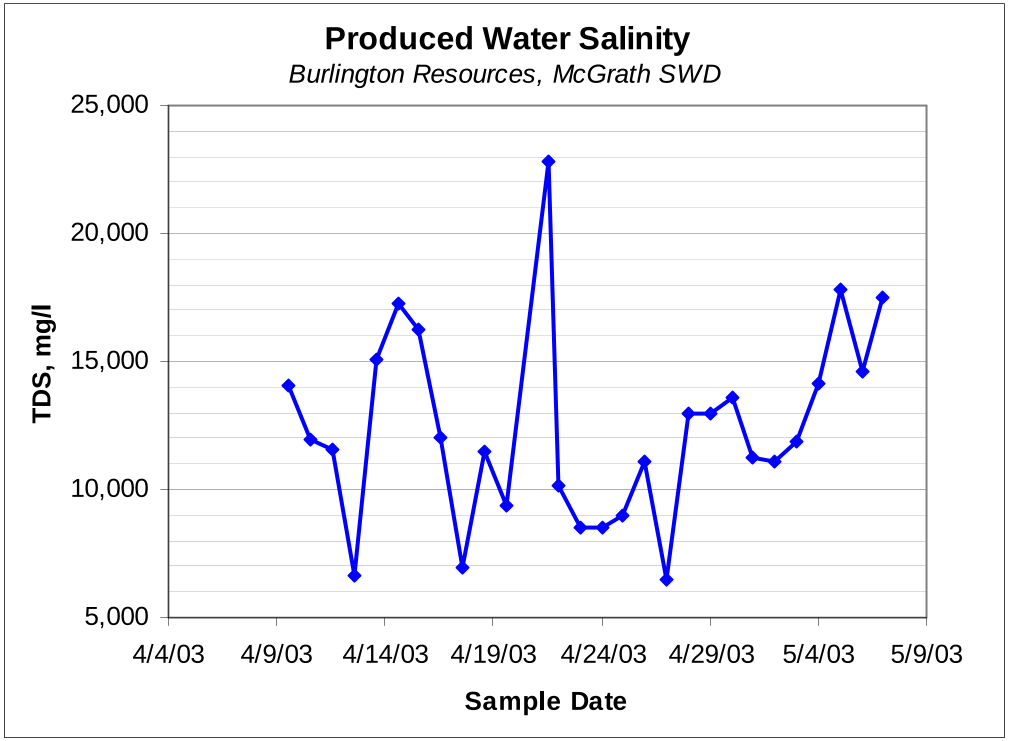
Phase 2

- PNM would extend the pipeline an additional 17.5 miles to Bloomfield.
- Burlington resources would refurbish two existing pipelines and install satellite collection stations to gather *theirs and other producer's water* in areas of heavy tanker-truck traffic.
- PNM would build a collection Center in Bloomfield to accept and pretreat water gathered by Burlington Resources.
- Producer disposal costs would be reduced by up to $1.00/bbl.
- Some SWDs could be put on stand-by and the life of costly injection wells ($1.5 to $2.5 million per well) would be extended.



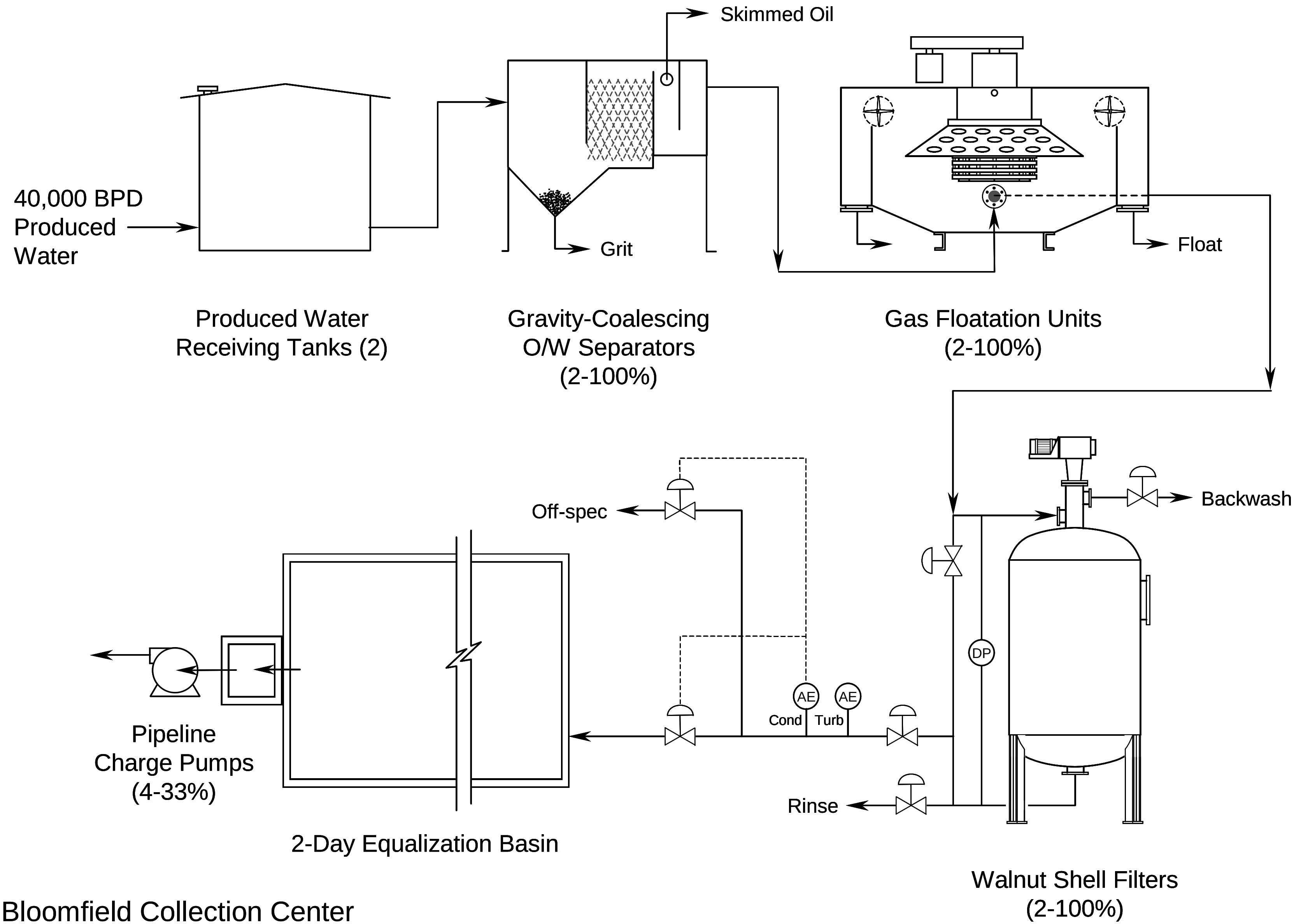
Produced Water Collection & Conveyance Schematic

PNM – Produced Water Project - SJGS



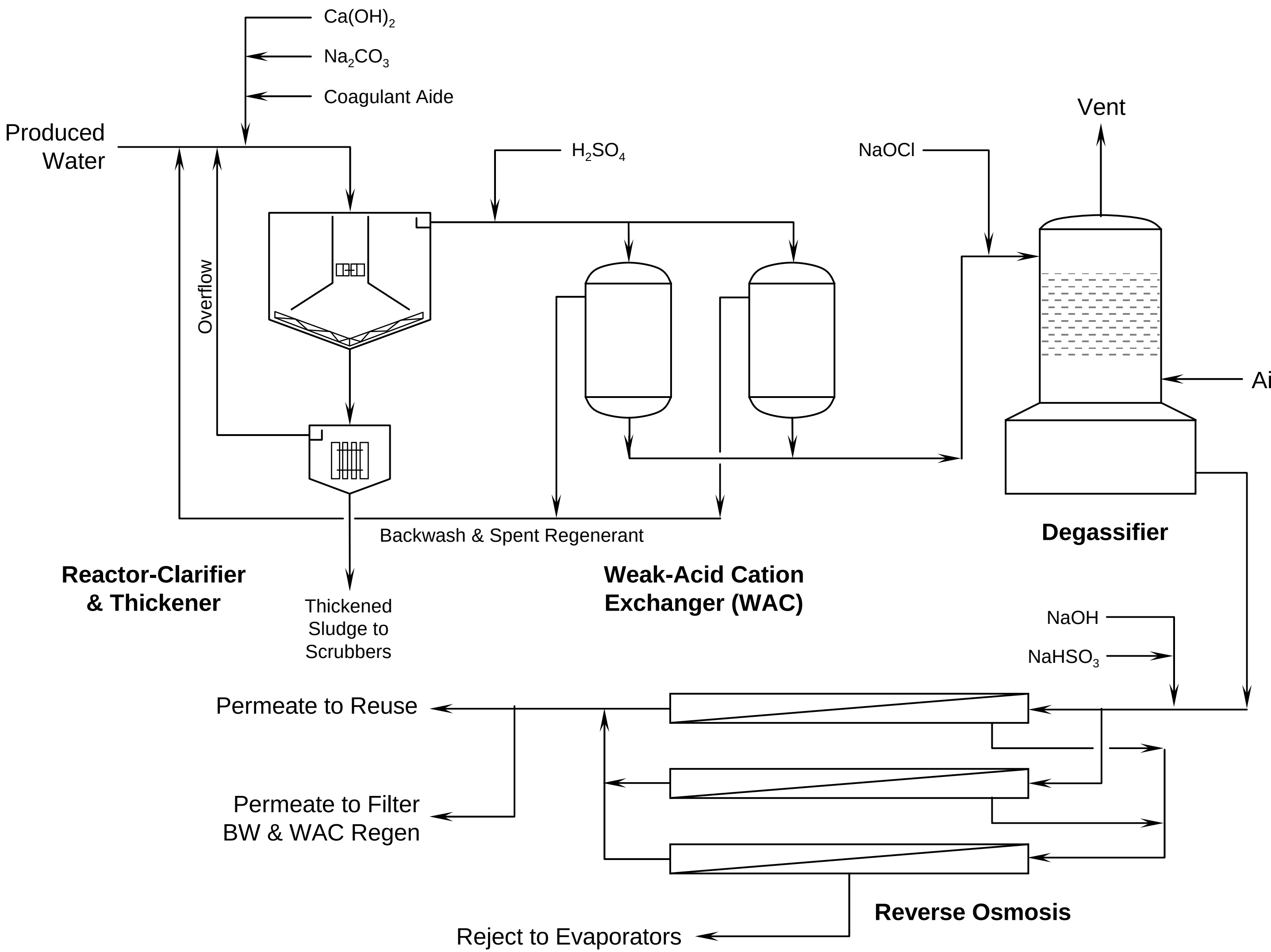
Produced Water Salinity
Burlington Resources, McGrath SWD
25,000
20,000
15,000
10,000
5,000
TDS, mg/l
4/4/03
4/9/03
4/14/03
4/19/03
4/24/03
4/29/03
5/4/03
5/9/03
Sample Date

Produced Water Treatment



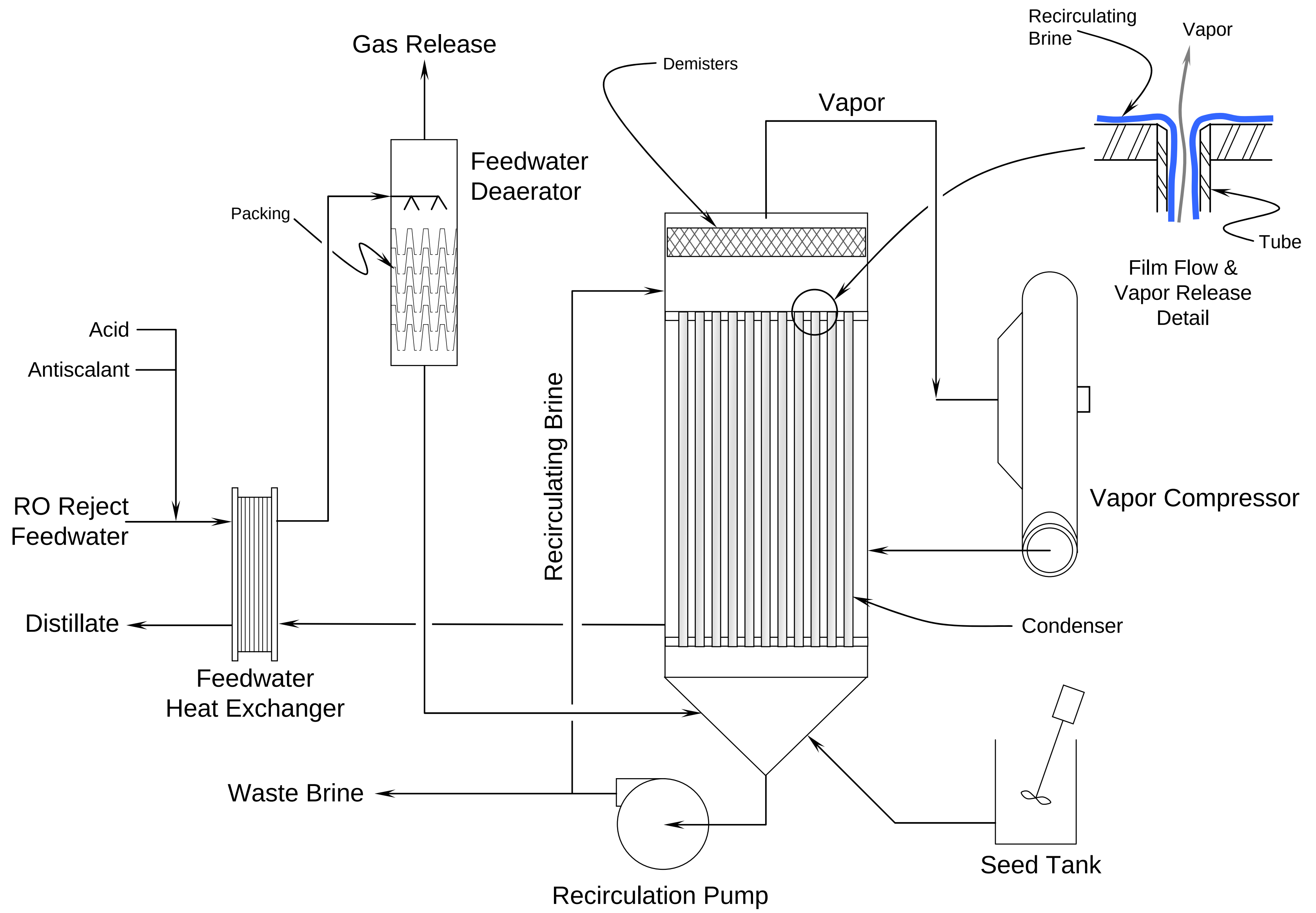
Bloomfield Collection Center

PNM – Produced Water Project - SJGS

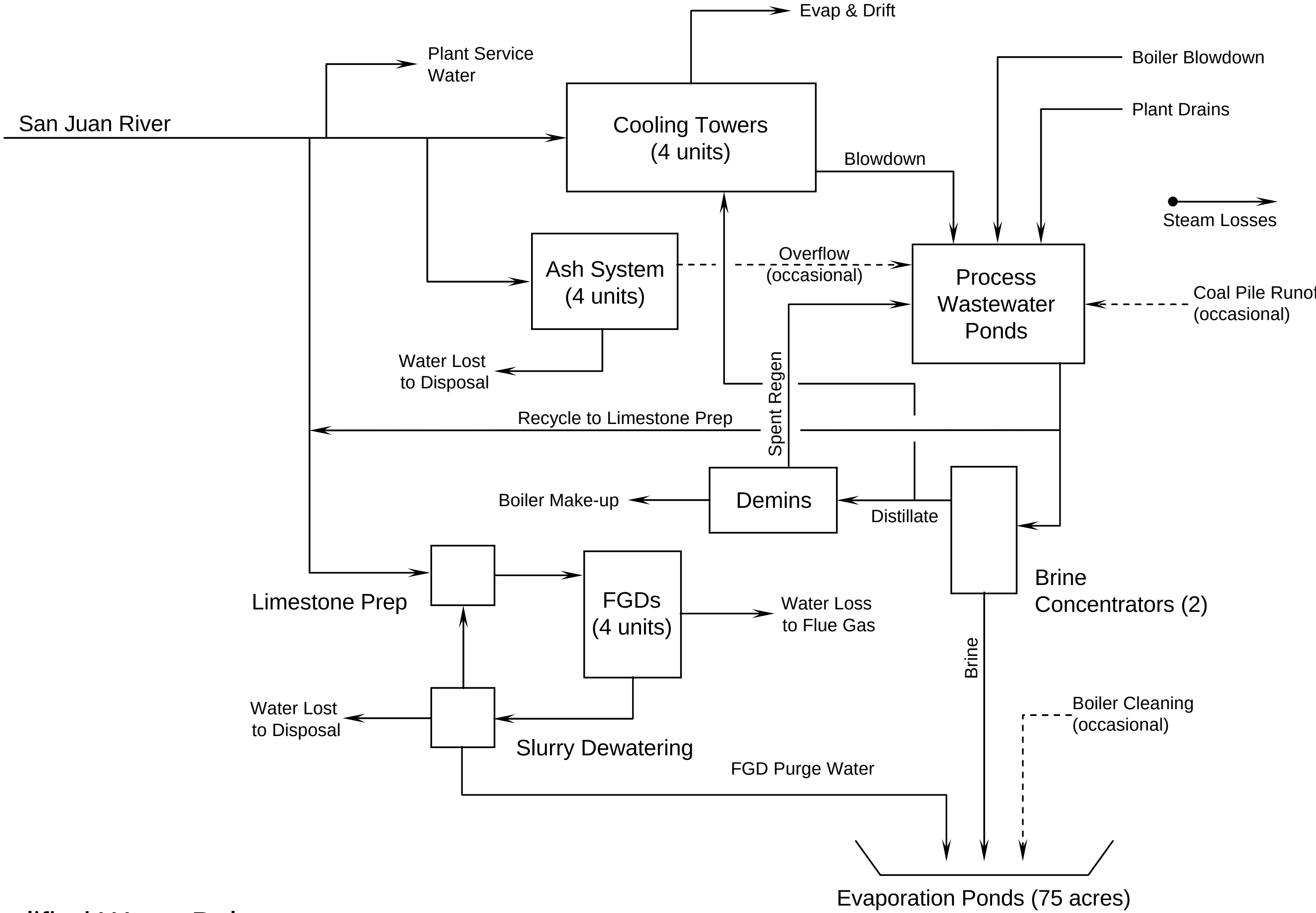


HERO System – Process Schematic

San Juan Generating Station

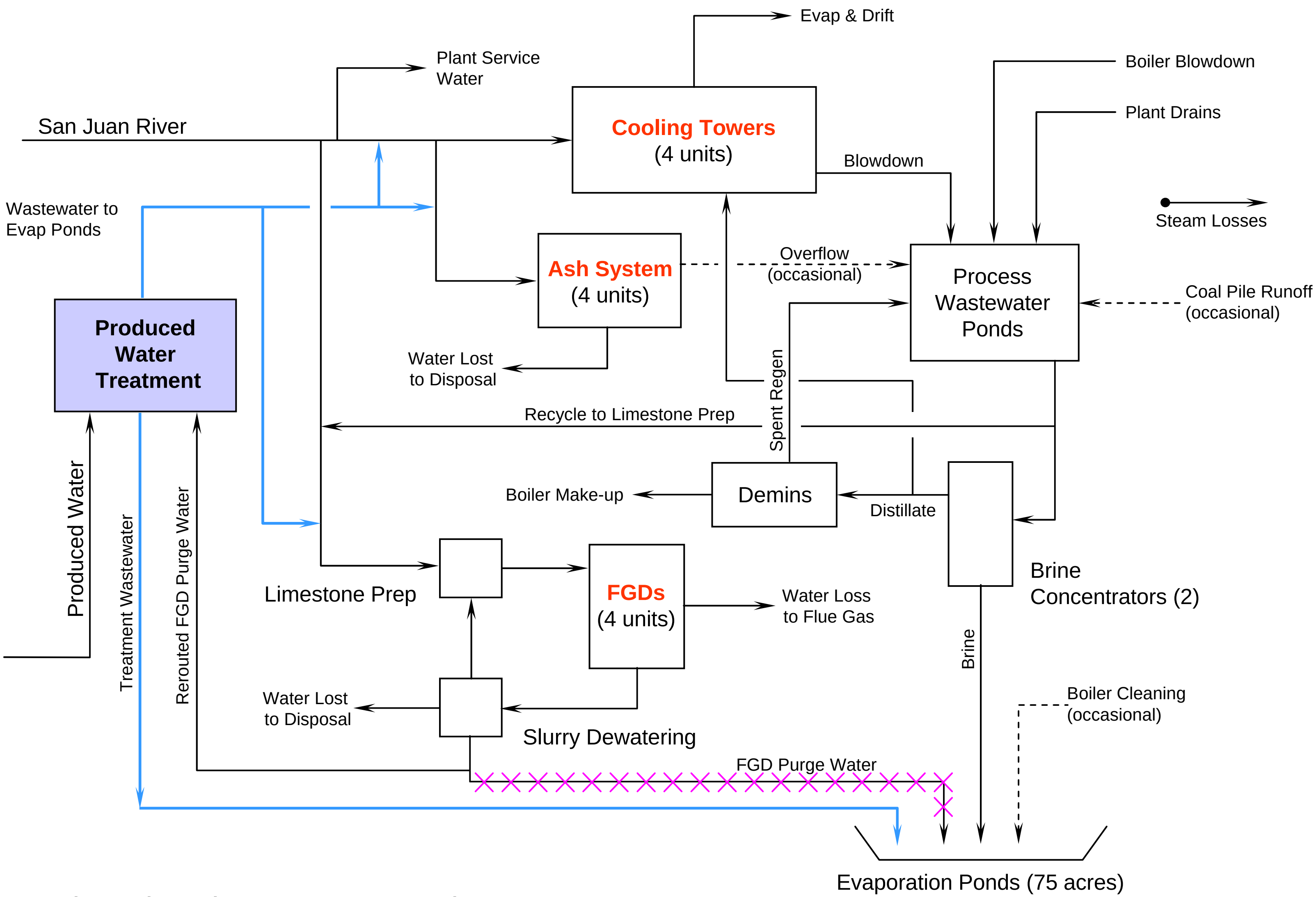


Brine Concentrator – Process Schematic



Simplified Water Balance

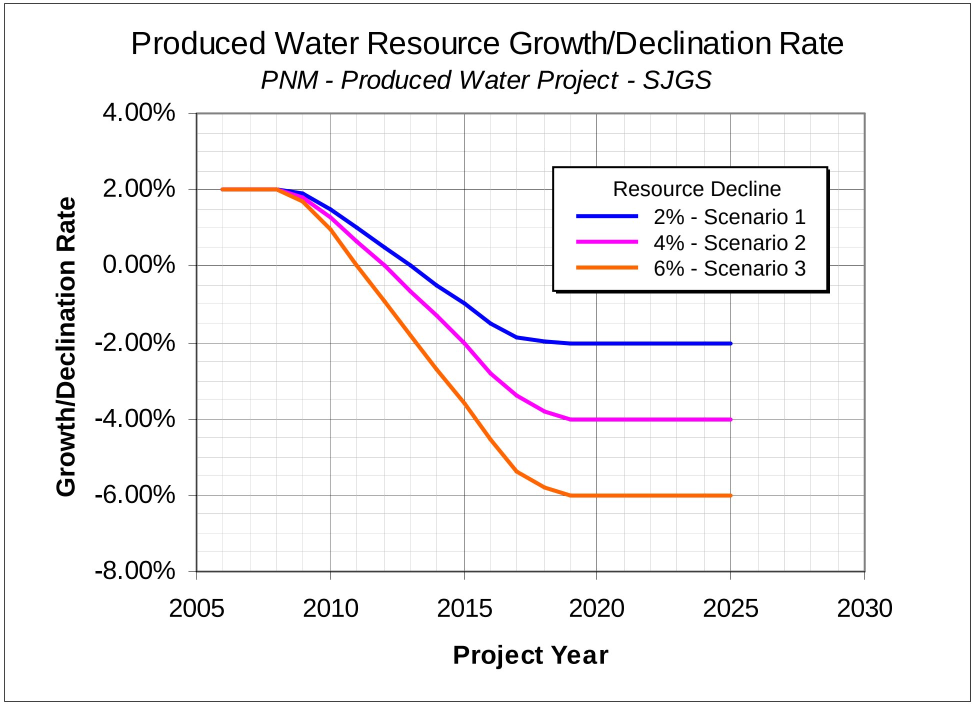
San Juan Generating Station

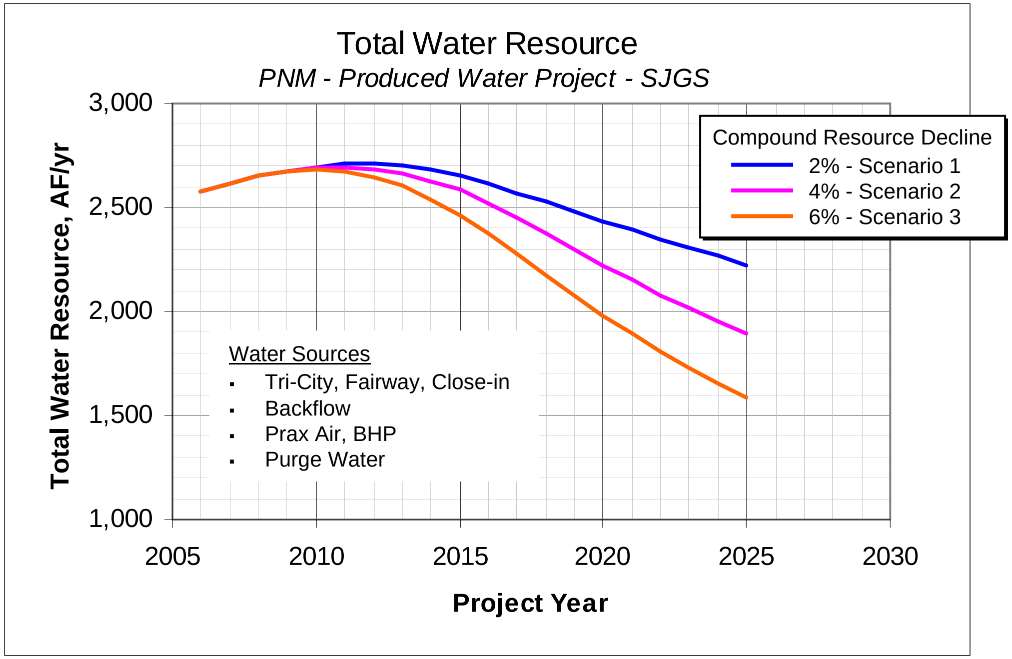


Treated Produced Water Reuse Points

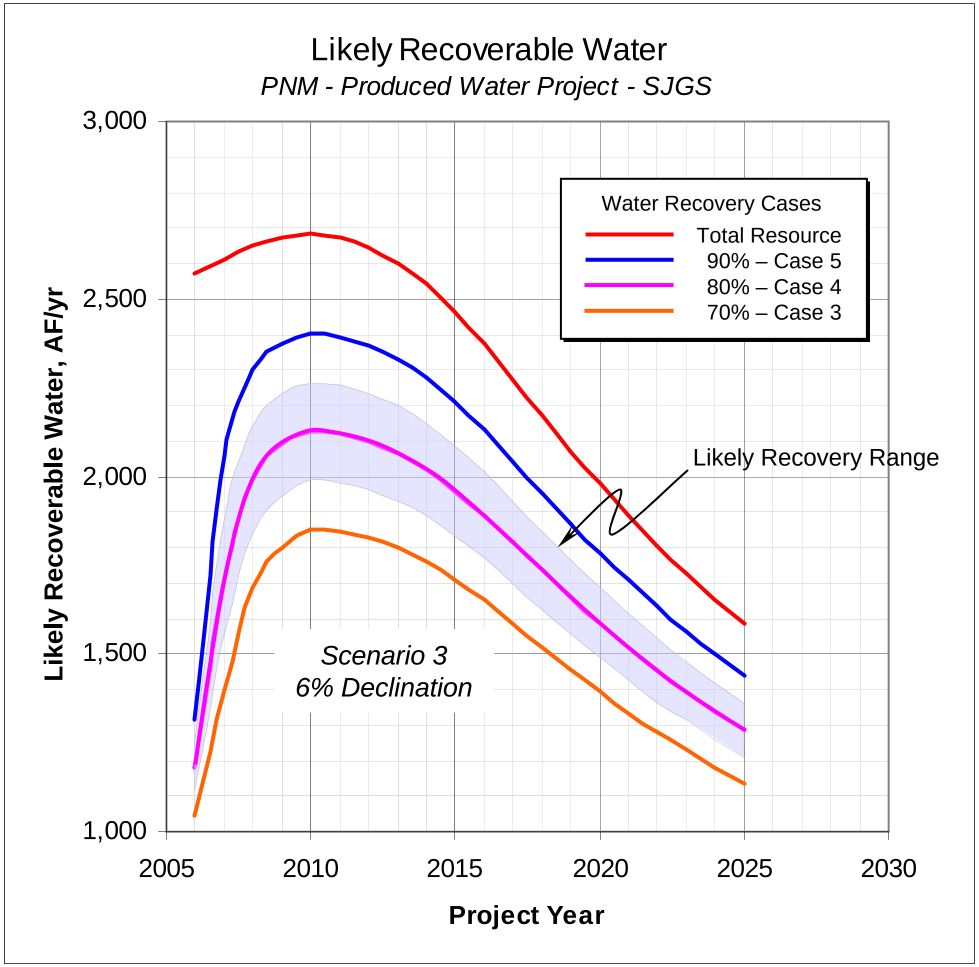
San Juan Generating Station

Economic Analysis


Produced Water Resource Growth/Declination Rate
PNM - Produced Water Project - SJGS
4.00%
2.00%
0.00%
-2.00%
-4.00%
-6.00%
-8.00%
Growth/Declination Rate
2005
2010
2015
2020
2025
2030
Project Year
Resource Decline
2% - Scenario 1
4% - Scenario 2
6% - Scenario 3


Total Water Resource
PNM - Produced Water Project - SJGS
Total Water Resource, AF/yr
3,000
2,500
2,000
1,500
1,000
2005
2010
2015
2020
2025
2030
Project Year
Compound Resource Decline
2% - Scenario 1
4% - Scenario 2
6% - Scenario 3
Water Sources
Tri-City, Fairway, Close-in
Backflow
Prax Air, BHP
Purge Water

Life-of-project recoverable water.....



Capital Costs Incurred by PNM

		Collection Center	14-inch Pipeline	HERO + BC 3	Total Project
Capacity, BPD		34,000	60,000	53,000	
Peak Conditions, BPD		30,670	44,710	48,130	
Equipment & Installation		$5,200,000	$12,900,000	$11,800,000	$29,900,000
Contingency	15%	$780,000	$1,940,000	$1,770,000	$4,490,000
NMGRT (1)	6.125%	$320,000	$790,000	$720,000	$1,830,000
PNM G&A (2)	5.5%	$290,000	$710,000	$650,000	$1,650,000
Total Project		$6,590,000	$16,340,000	$14,940,000	$37,870,000

Notes…..

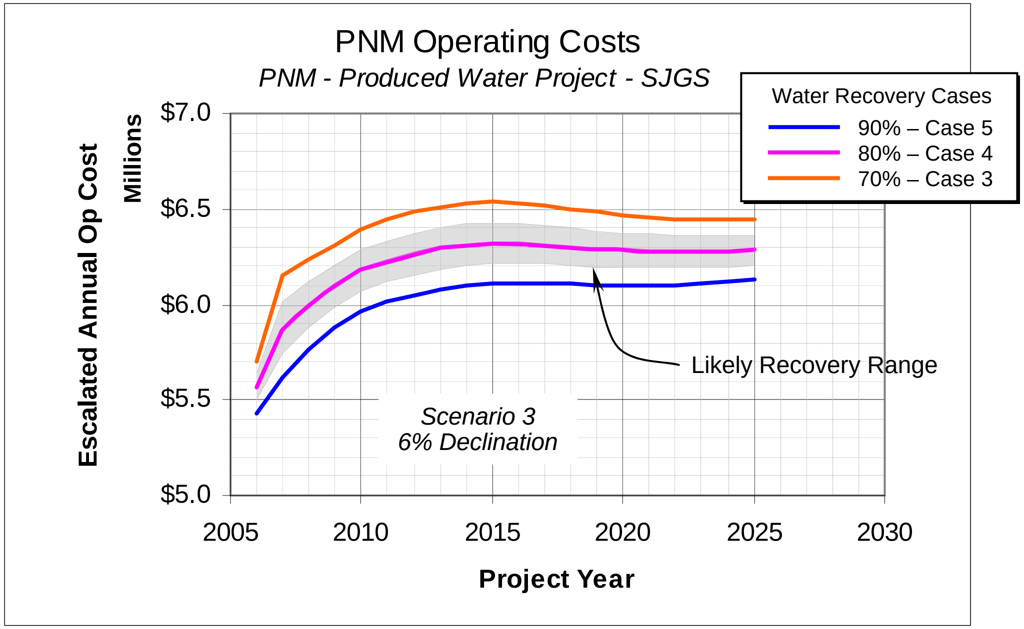
1. NMGRT is the New Mexico Gross Receipts Tax.
2. G&A is a "general and admistrative" charge applied to all PNM projects.

Total Project Capital Costs

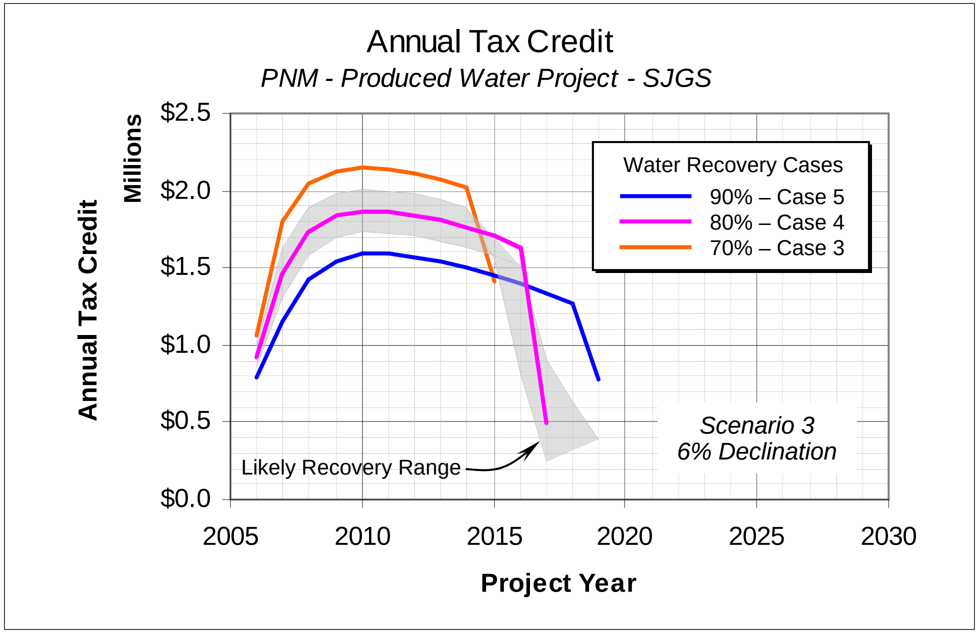
BR	Gathering system to Collection Center	$5,000,000
Dugan	Inject into pipeline	$100,000
Richardson	Inject into pipeline	$100,000
PNM	Collection Center, pipeline & treatment	$37,900,000
Total Project		$43,100,000

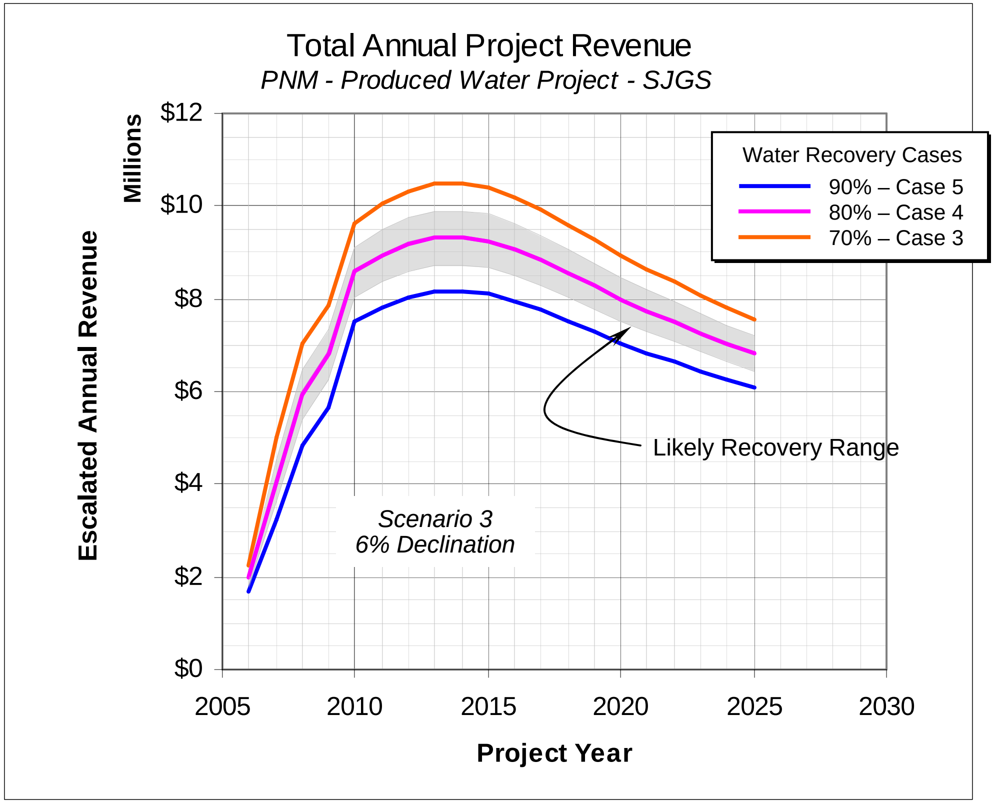
Notes.....

1. Installation costs for Dugan and Richardson are most likely high.

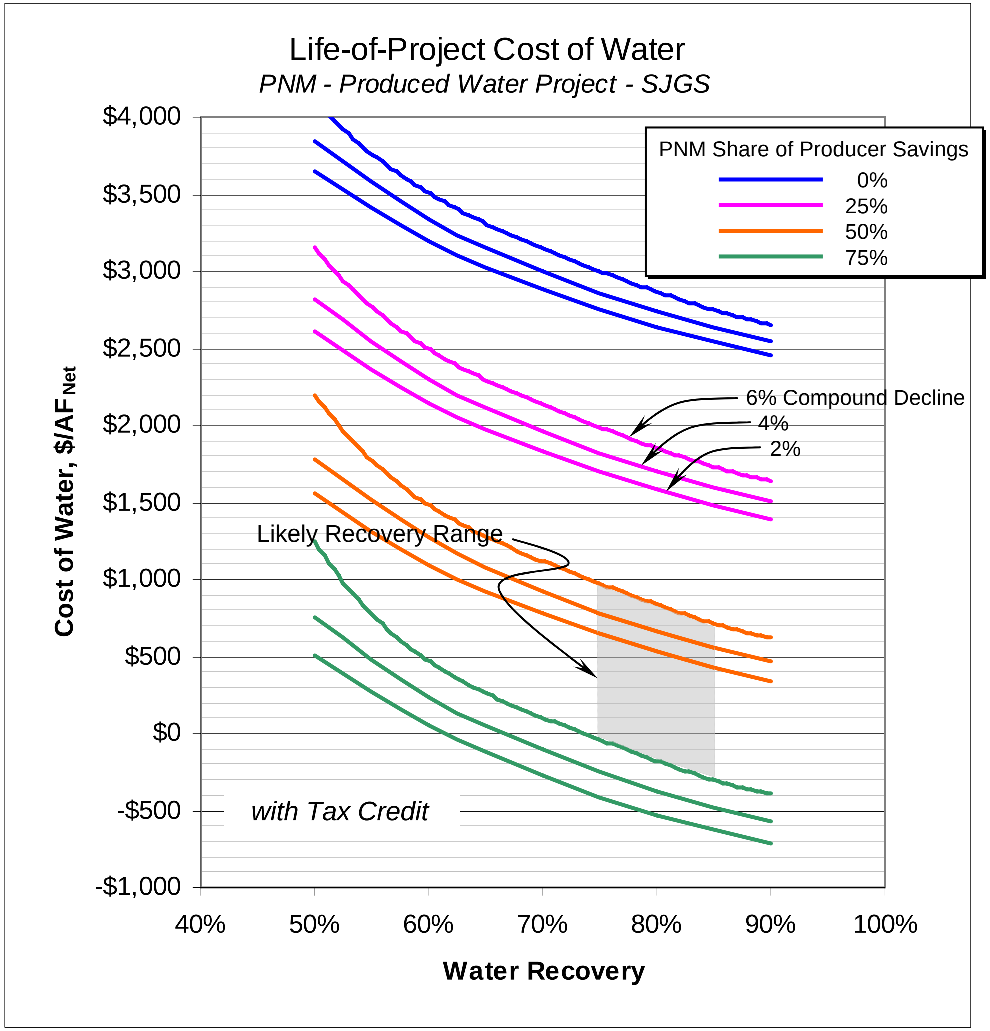

PNM Operating Costs
PNM - Produced Water Project - SJGS
Water Recovery Cases
90% – Case 5
80% – Case 4
70% – Case 3
Escalated Annual Op Cost
Millions
$7.0
$6.5
$6.0
$5.5
$5.0
2005
2010
2015
2020
2025
2030
Project Year
Likely Recovery Range
Scenario 3
6% Declination

PNM is negotiating with the State of New Mexico for a tax credit of $1,000/AF. The tax credit would have an annual limit and life-time cap.





Total Annual Project Revenue
PNM - Produced Water Project - SJGS
Escalated Annual Revenue
Millions
$12
$10
$8
$6
$4
$2
$0
2005
2010
2015
2020
2025
2030
Project Year
Water Recovery Cases
90% – Case 5
80% – Case 4
70% – Case 3
Likely Recovery Range
Scenario 3
6% Declination


Life-of-Project Cost of Water
PNM - Produced Water Project - SJGS
PNM Share of Producer Savings
0%
25%
50%
75%
6% Compound Decline
4%
2%
Likely Recovery Range
with Tax Credit
$4,000
$3,500
$3,000
$2,500
$2,000
$1,500
$1,000
$500
$0
-$500
-$1,000
40%
50%
60%
70%
80%
90%
100%
Cost of Water, $/AF Net
Water Recovery

Project Economics.....

- Produced water project economics are based on capital and operating costs as well as a revenue stream.
- PNM's operating costs include treatment chemicals, power, labor, materials, maintenance and *capital recovery costs*.
- Revenue streams offset PNM operating costs.
- The first revenue stream would be a tax credit of $1,000/AF provided by the State of New Mexico (the tax credit would have an annual limit and life-time cap).
- The second revenue stream would be a share of the oil-producer savings derived from reduced disposal of produced water and deferred costs of injection wells.
- Depending on the revenue scenario, the 20-year, life-of-project costs would vary as follows:

50-50 Share of producers savings with the New Mexico tax credit	$720 to $970/AF ($125 to $150/AF)*	$1.3 to $1.7 million/year
50-50 Share of producers savings without the tax credit	$1,200 to $1,500/AF ($160 to $200/AF)*	$2.0 to $2.6 million/year
No revenue streams	$2,500 to $3,000/AF ($260 to $330/AF)*	$4.3 to $5.1 million/year

**Blended water costs – San Juan River @ $75/AF plus treated produced water.*

PNM Project Benefits…..

- Conserve river water for other beneficial uses in New Mexico.
- Enable the San Juan Generating Station to be more drought resistant.
- Avoid costly fuel-delivery penalties and power purchase costs.

Oil & Gas Producer Benefits.....

- Reduce the volume of produced water that must be handled and injected.
- Establish an infrastructure to minimize produced water injection in the San Juan Basin.
- Establish area-wide opportunities to reduce produced water handling and injection costs.

An Innovative System for the Efficient and Effective Treatment of Non-traditional Waters for Reuse in Thermoelectric Power Production

DE-FG26-05NT42535

John H. Rodgers, Jr.
Department of Forestry and Natural Resources

James W. Castle
Departments of Geological Sciences
and Environmental Engineering & Science
Clemson University
Clemson, SC 29634

Overall Objective

Evaluate specifically designed constructed wetland treatment systems for treatment of targeted constituents in non-traditional waters for reuse in thermoelectric power generation or other purposes.

Non-traditional waters:

- Ash basin waters
- Cooling waters
- Produced waters
- Flue gas desulfurization waters

Specific Objectives / Tasks

- Identify targeted constituents for treatment in four non-traditional waters;
- Determine reuse or discharge criteria (performance criteria for treatment);
- Configure appropriate pilot-scale constructed wetland treatment systems for each of the four non-traditional waters;
- Measure performance of the pilot-scale constructed wetland treatment systems and removal rates and extents using both analytical and toxicological techniques;
- Determine the suitability of the treated non-traditional waters for reuse or discharge to receiving aquatic systems;
- Develop a decision support system for using this approach to renovate non-traditional waters for reuse or other purposes.

Project Schedule

	Year 1 (2005-2006)				Year 2 (2006-2007)				Year 3 (2007-2008)			
	Q 1	Q2	Q3	Q4	Q 1	Q2	Q3	Q4	Q 1	Q2	Q3	Q4
Task 1: **Water Characterization**												
Task 2: **Reuse & Discharge Criteria**												
Task 3: **Design & Construct CWTS**												
Task 4: **System Performance**												
Task 5: **Suitability Reuse**												
Task 6: **Decision Support System**												

Task 1. Water Characterization

Ash basin waters

low ionic strength, Se, Hg, As, Cr, Zn, TSS

Cooling waters

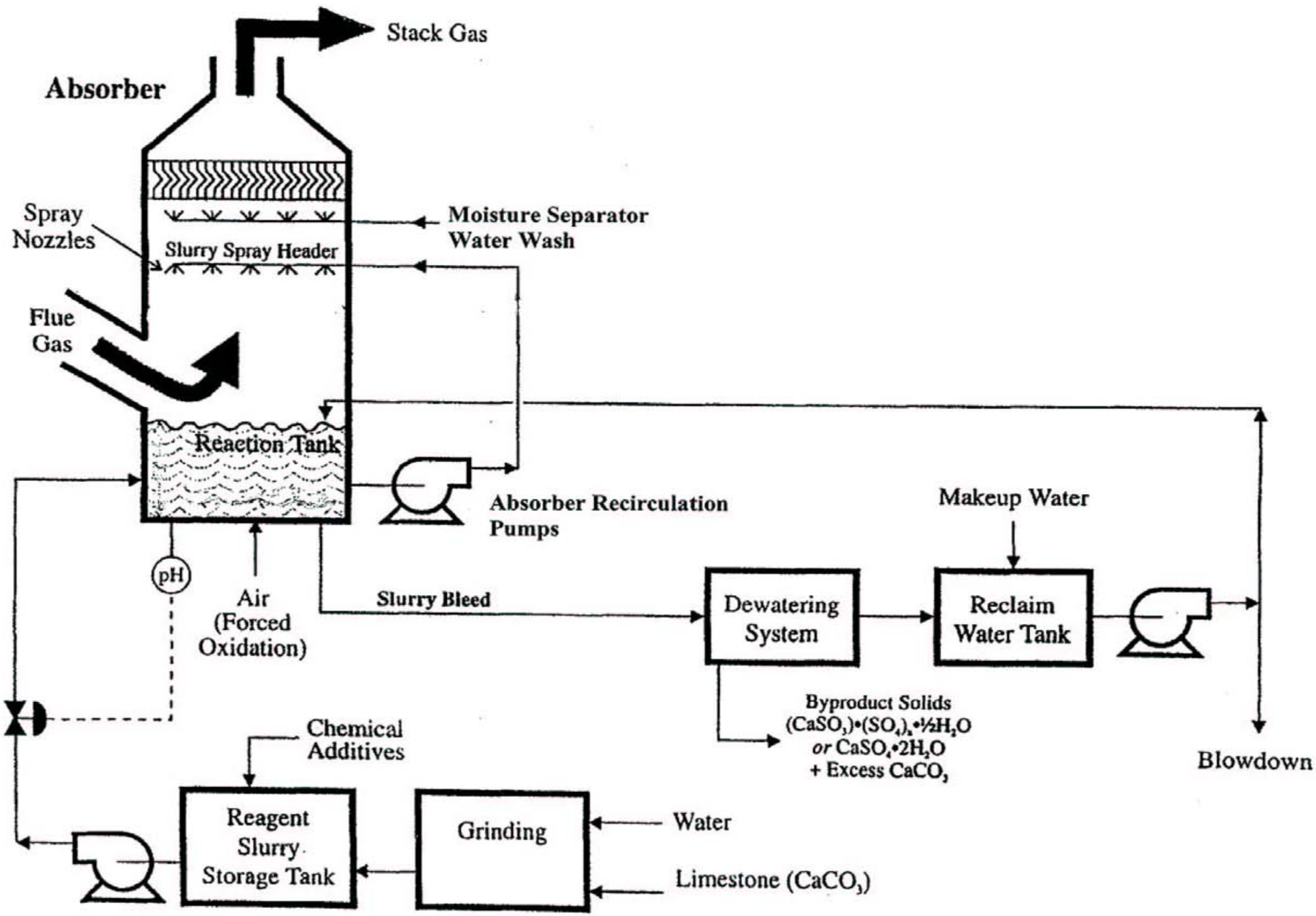
site specific ionic strength, biocides, oxidants, Cu, Zn, Pb

Produced waters

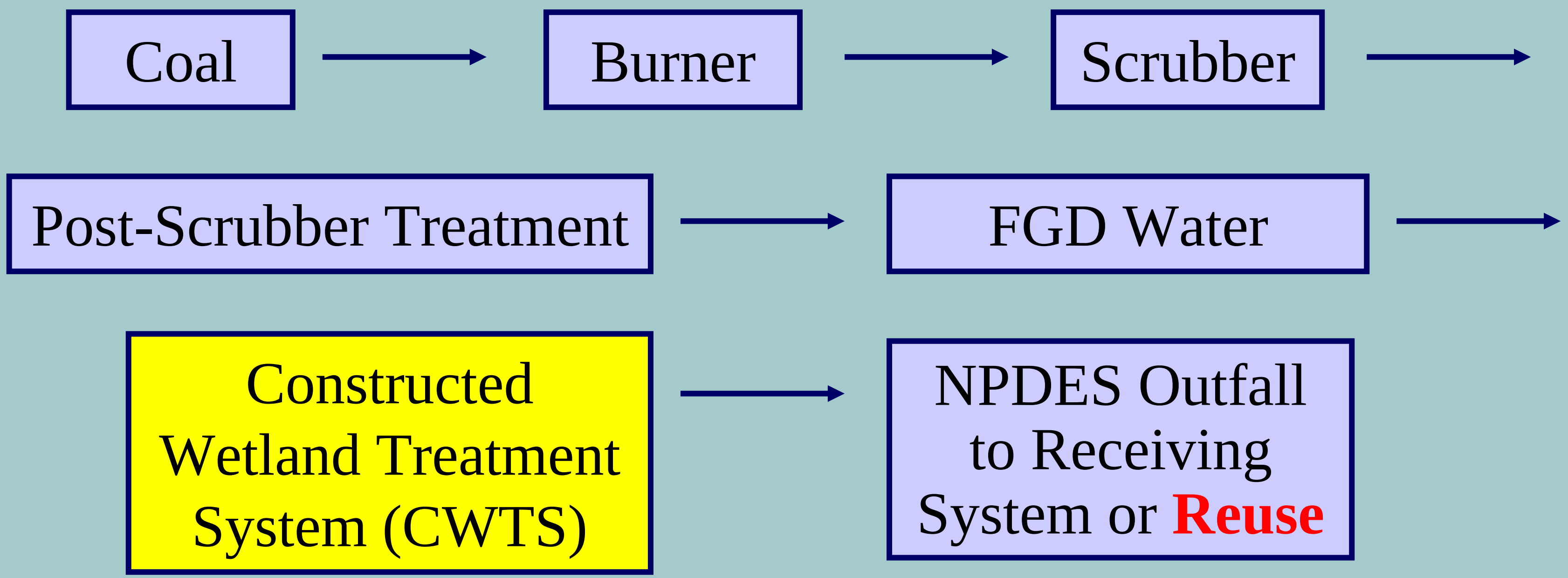
chlorides (high ionic strength), Zn, As, Cd, Pb, Cu, Se, organics (oil and grease)

Flue gas desulfurization waters

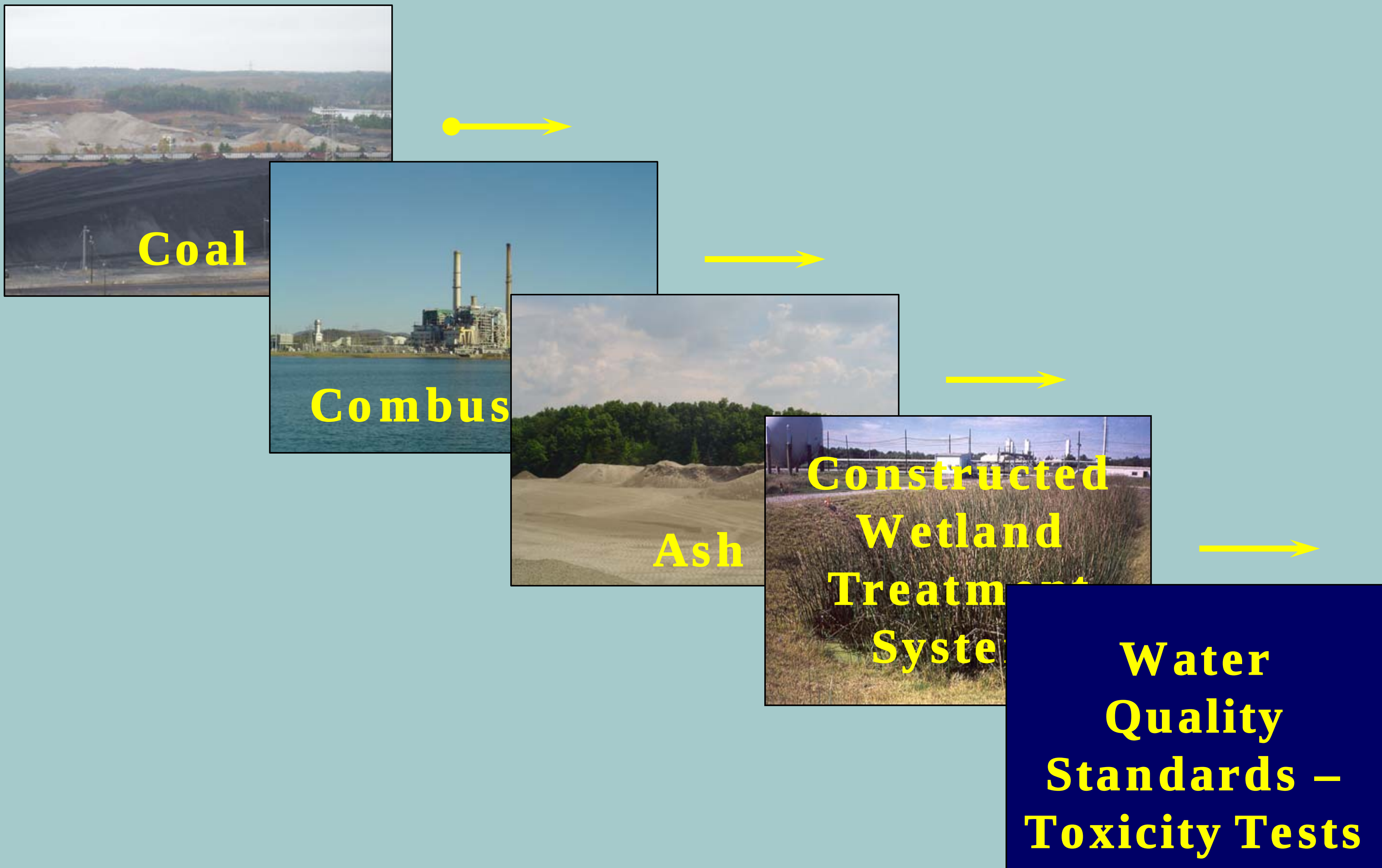
Wet Limestone FGD System (Scrubber)



Flue Gas Desulfurization (Scrubber) Waters



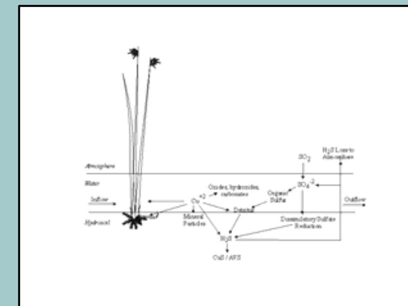
Task 2. Reuse and Discharge Criteria



Task 3. Design and Construct CWTS

Literature

Theoretical Modeling



Pilot-Scale Physical Model of CWTS

Full-scale System

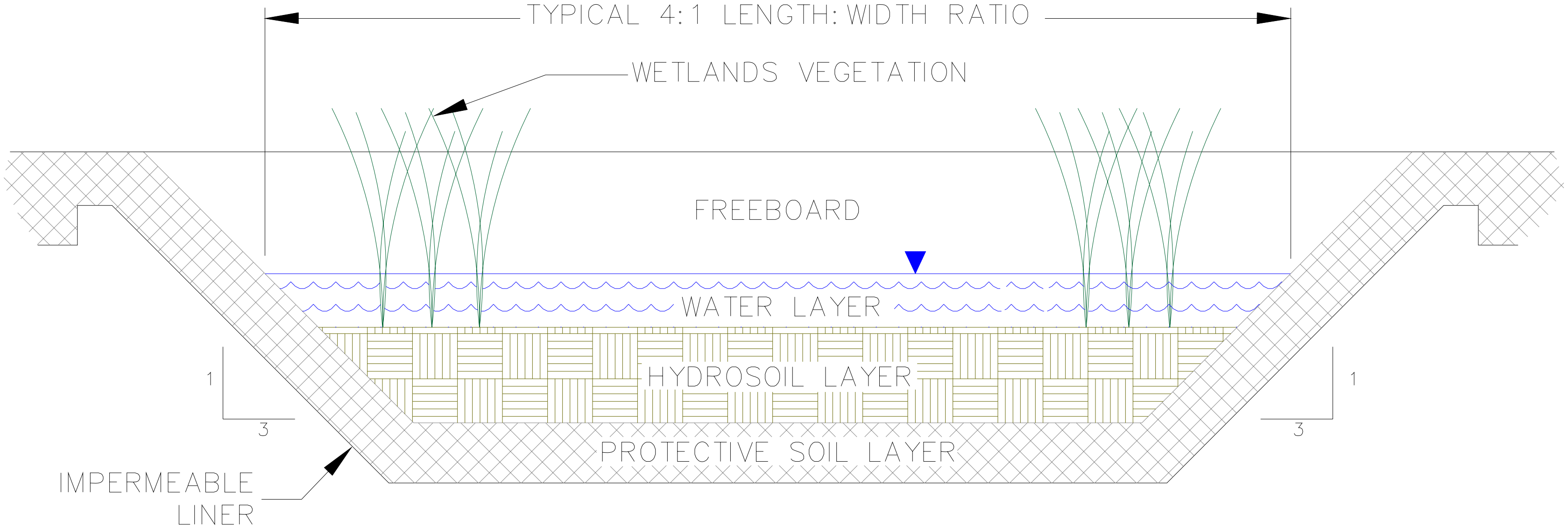
Approach

- Characterize FGD waters
- Measure performance of a pilot-scale constructed wetland treatment system (CWTS) in terms of decreases in targeted constituents in FGD water.
- Determine how observed performance is achieved in CWTS.
- Assess performance of CWTS in terms of decreased bioavailability of targeted elements (outflow toxicity and sediment toxicity).

What Are Constructed Wetland Treatment Systems (CWTS)?

Systems carefully designed to "treat" (transfer or transform) constituents in water in order to decrease the environmental risk these constituents may pose in receiving systems (downstream lakes, reservoirs, rivers, streams, etc.) or in order to make the water suitable for reuse.

CWTS Design


TYPICAL 4:1 LENGTH: WIDTH RATIO
WETLANDS VEGETATION
FREEBOARD
WATER LAYER
HYDROSOIL LAYER
PROTECTIVE SOIL LAYER
IMPERMEABLE LINER
1
3
1
3

Constructed Wetland Treatment System

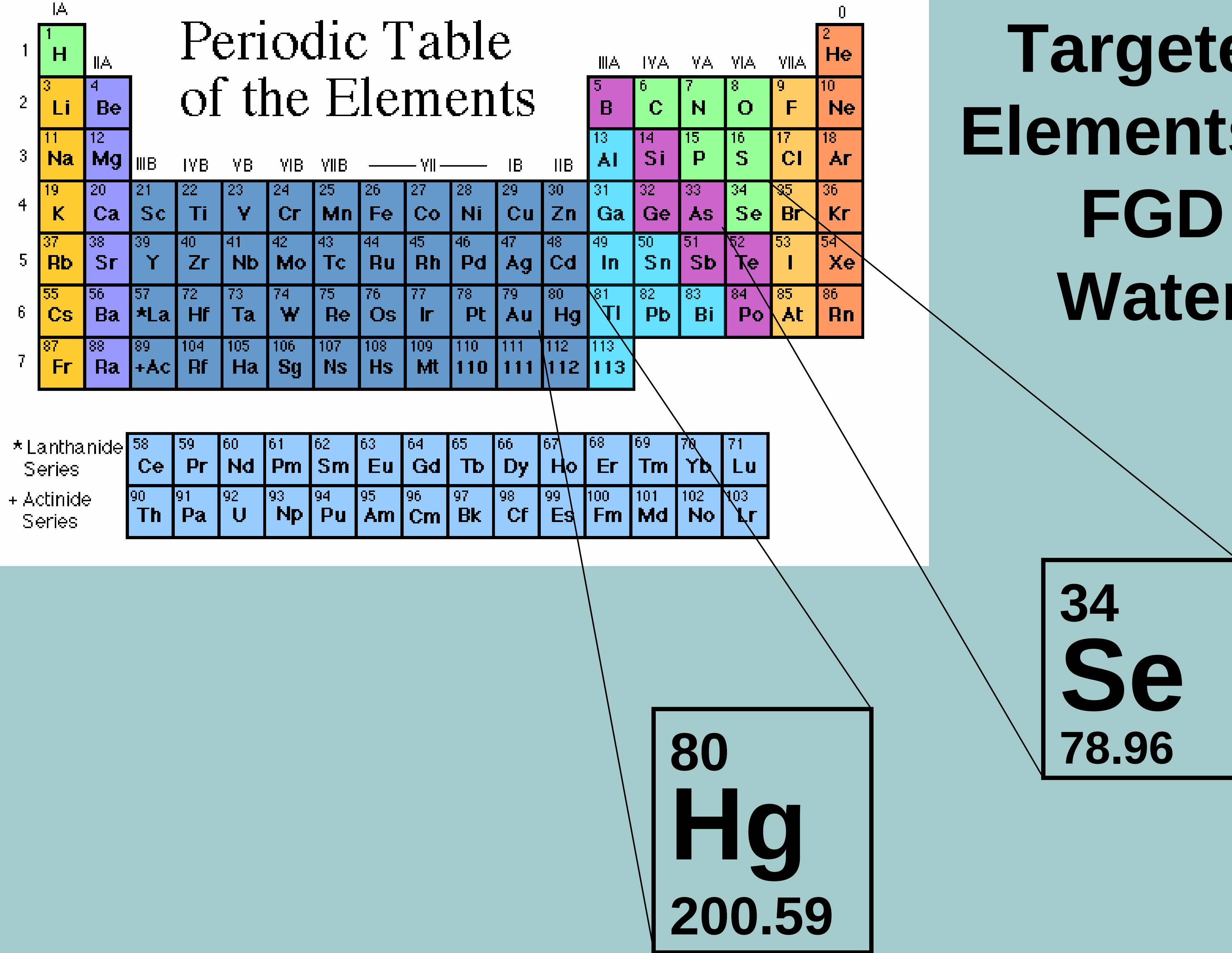
Features of Constructed Wetland Treatment Systems

- Largely self-maintaining
- Treat multiple constituents; wide range of concentrations
- Design for seasonal variations
  - e.g., annual plant dieback renews sediment binding surfaces
- Permitted as water treatment systems

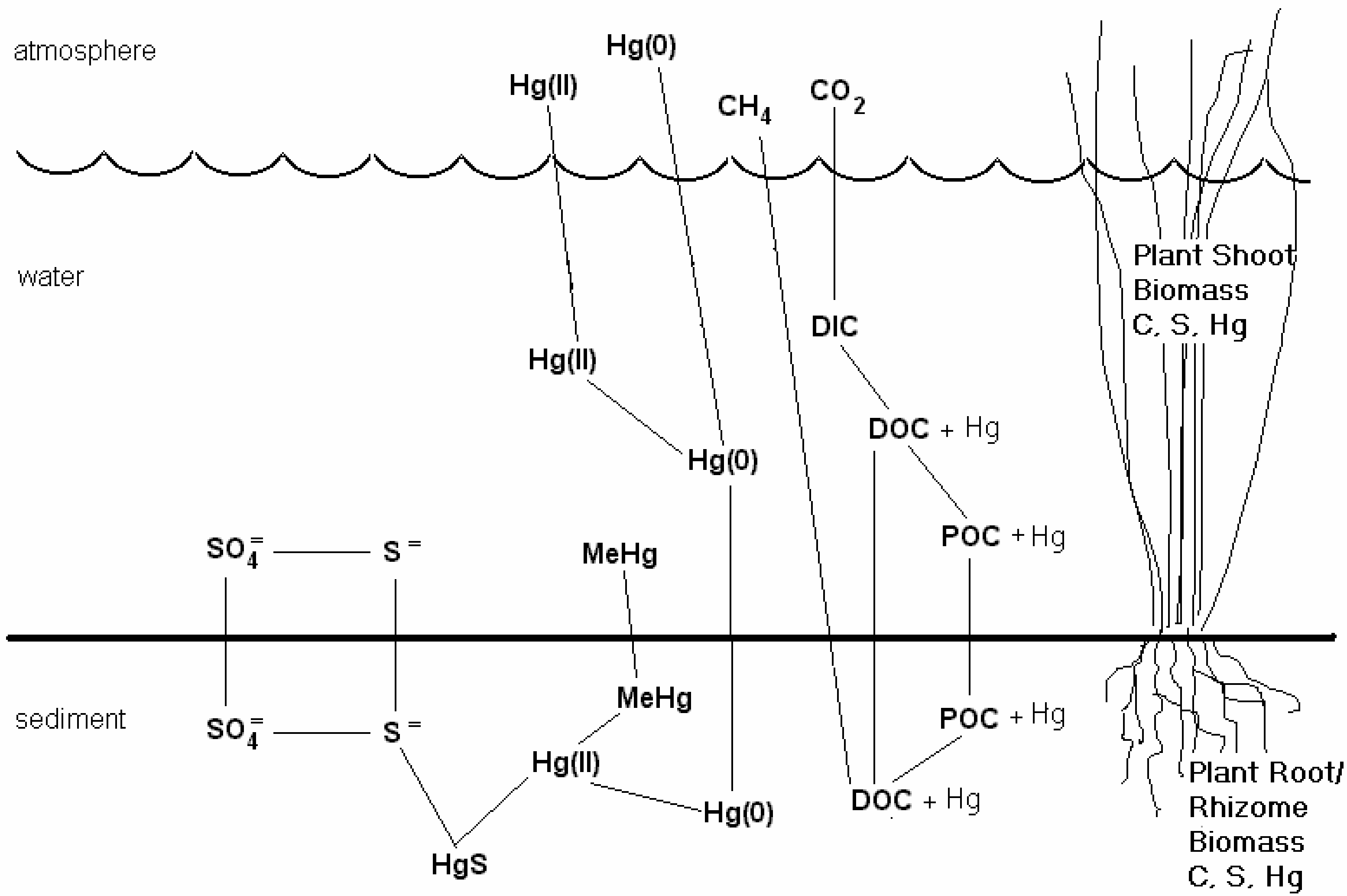
Major Benefits

- Typically cost 50% to 90% less than conventional treatment systems
  - Low construction cost
  - Low operating expense
- Provide effective water treatment (achieve NPDES requirements)
- Support of regulatory community
- Water conservation and reuse

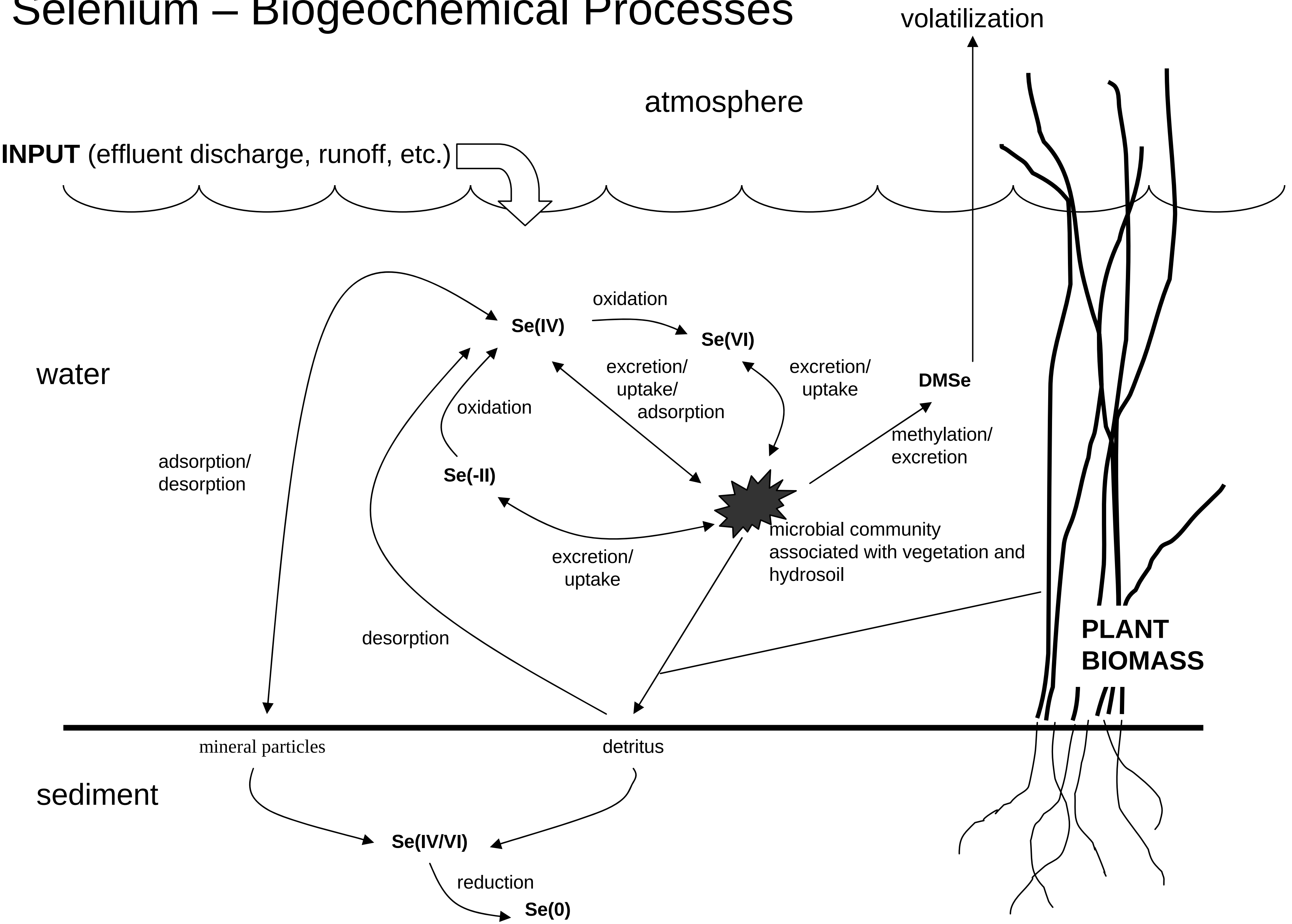
Targeted Elements in FGD Water



Mercury – Biogeochemical Processes



Selenium – Biogeochemical Processes



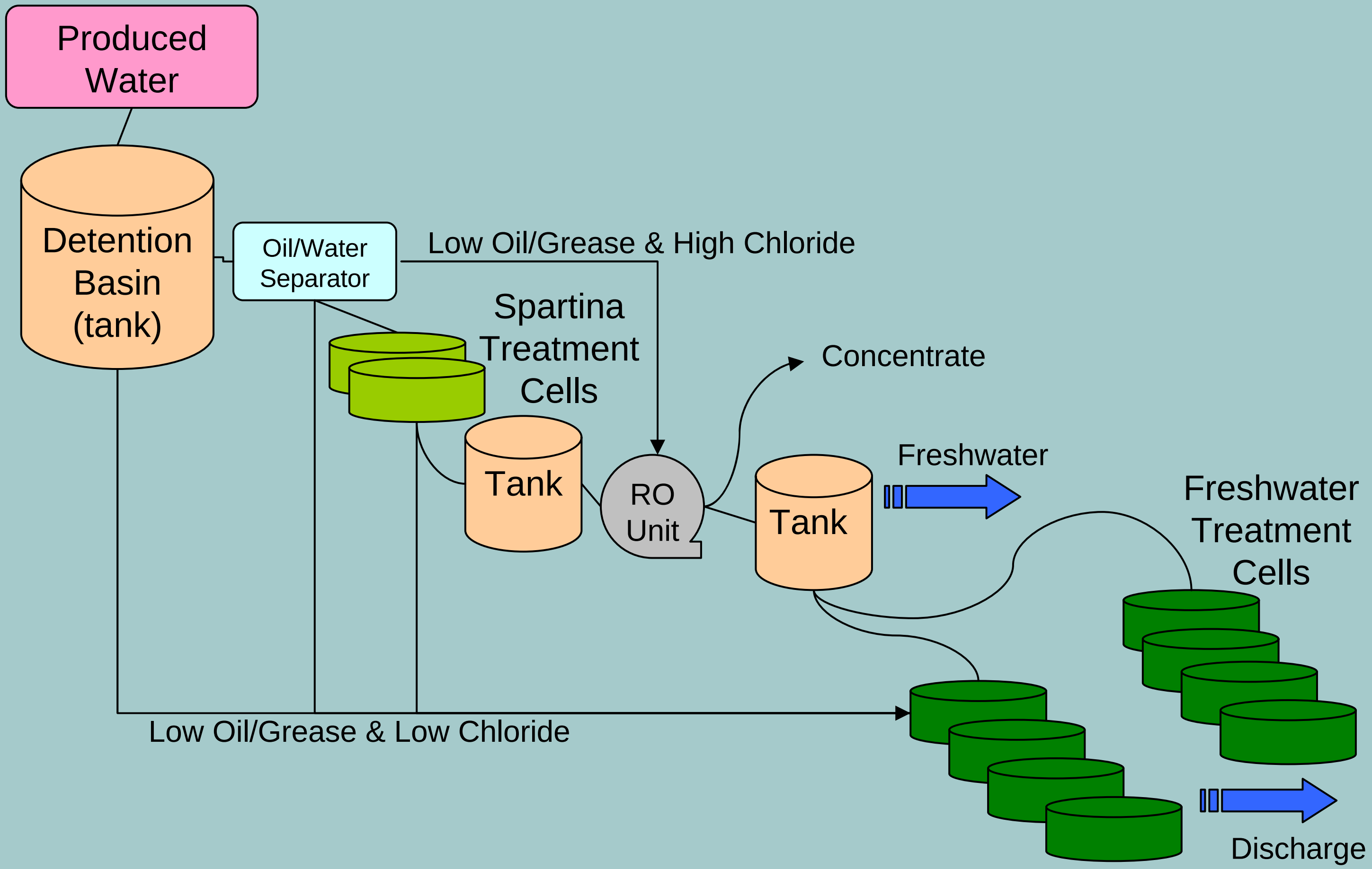
Constructed Wetland Treatment System Treatment Strategy for Targeted Constituents

Targeted Constituents	Treatment Strategy
Hg	Mercury stabilization in sediment (sorption and reduction) Sorption to OC and CEC Hg + S $\rightarrow$ HgS (mercuric sulfide, cinnabar) > S:Hg and ~ -200 mV
Se	Selenium stabilization in sediment. Reduce Se to Se^0 (ferroselenite, seleniferous pyrites)

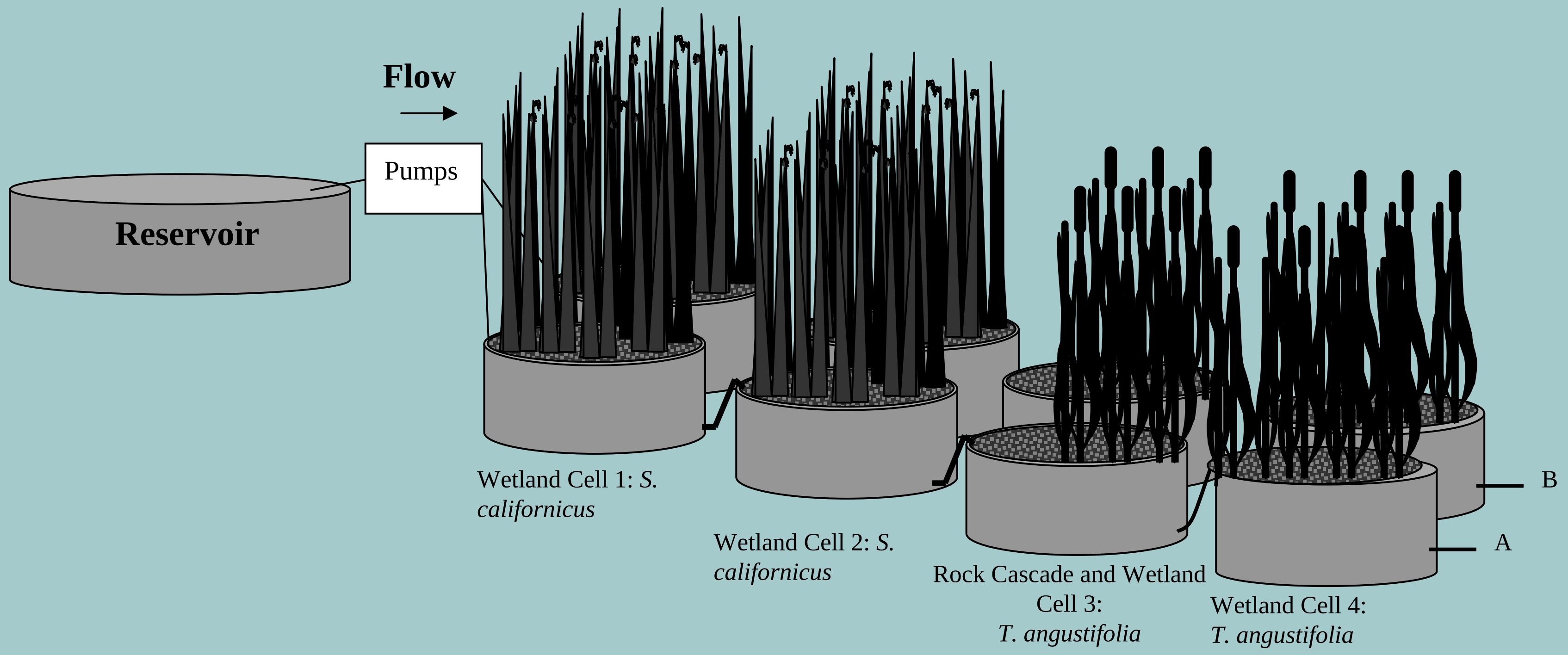
Key Concepts

- Goal is to remove targeted constituents from aqueous phase and partition these to sediments in non-bioavailable forms.
- Plants provide organic matter that supplies carbon and energy source for sulfate-reducing bacteria.
- Performance is evaluated by decrease in aqueous concentrations and in toxicity measured in upstream and downstream samples and in inflow and outflow of pilot-scale wetland cells.

Task 3: Design and Construct Pilot-Scale CWTS



Pilot-Scale Constructed Wetland System to Treat FGD Water




Task 3: Design and Construct Pilot-Scale CWTS


FGD Water Treatment Experimental Design

- Simulated FGD water
- Actual FGD water
- Actual amended FGD wastewater
- Pilot-scale scrubber water


Carolina
Trailer Leasing


527

FGD Pilot Scrubber

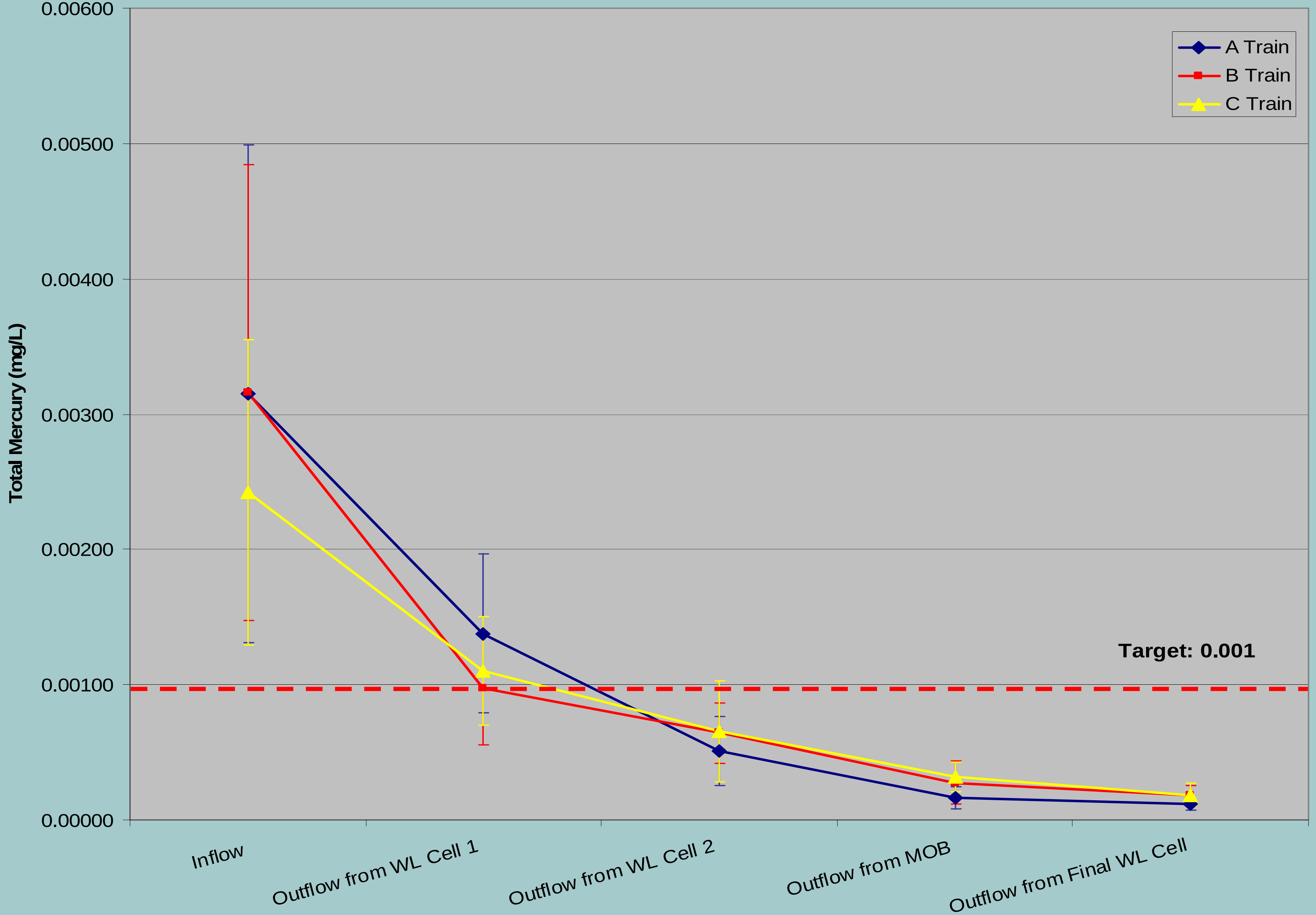
FGD Water Characteristics

	Simulated FGD Wastewater		Actual FGD Wastewater	Actual FGD Wastewater Amended	Pilot Scrubber Wastewater	Target Outflow
	Conc. (mg/L)	Source	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Mercury	0.02	$Hg(NO_3)_2$-H_2O	<0.0002	0.2*	0.0004 - 0.0432	0.001
Selenium	7.4	$NaSeO_4$	0.15	2*	0.61 - 2.98	0.4
Arsenic	0.28	$NaAsO_2$	0.0064	0.0064	0.0047 - 0.1012	
Chloride	12,500	$CaCl_2$, $MgCl_2$-$6H_20$	9,300	9,300	3150 - 4225	
Sulfate	3,000	$CaSO_4$	1645	1645	1245 - 1611	
COD	100	Dibasic Acid	938	938	268 - 693	
TSS	1,000	Flyash	25	25	6 - 356	

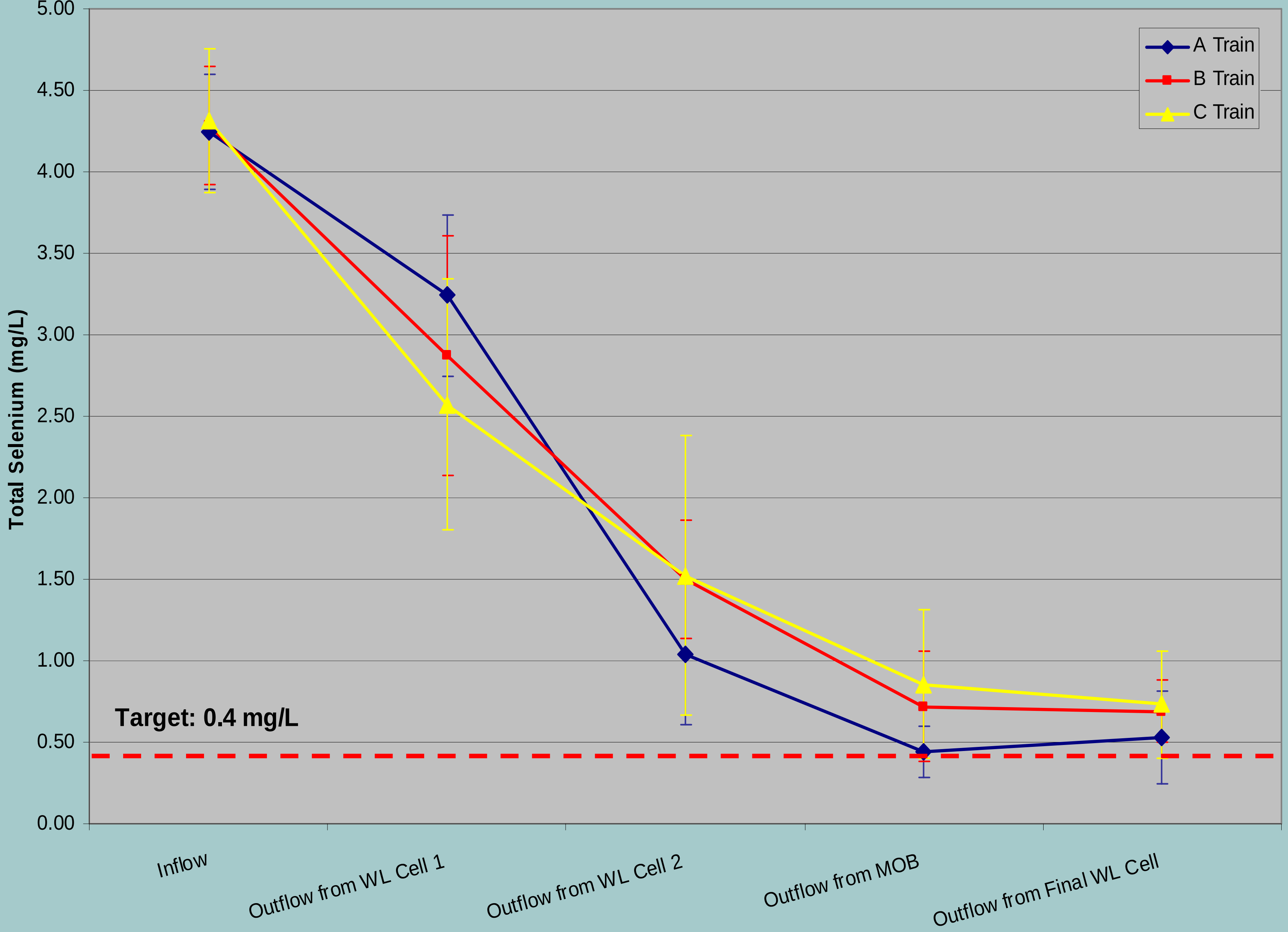
* Amended concentrations.

Task 4: Evaluate Treatment Performance (in progress)

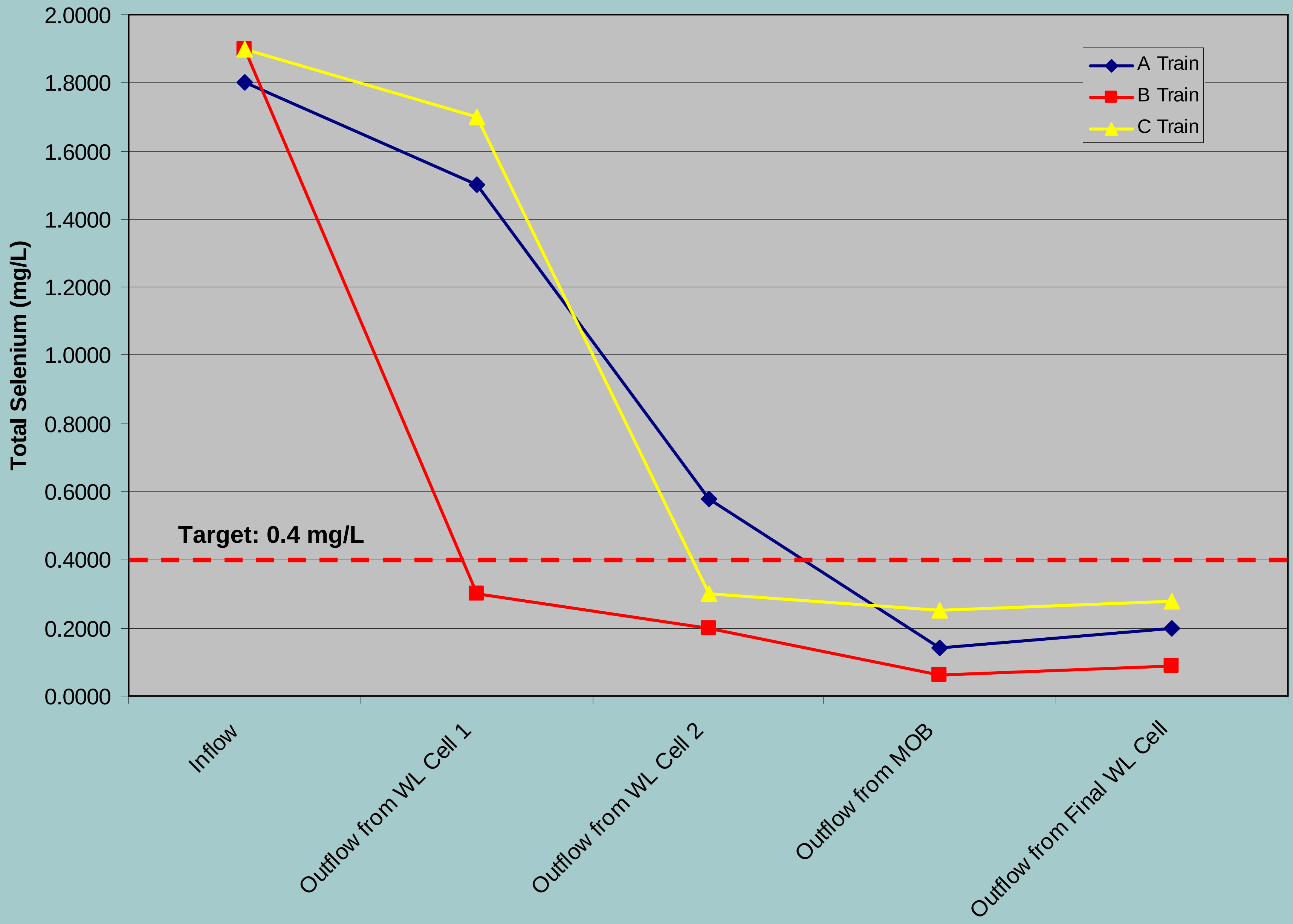
Mercury (Simulated FGD Wastewater)

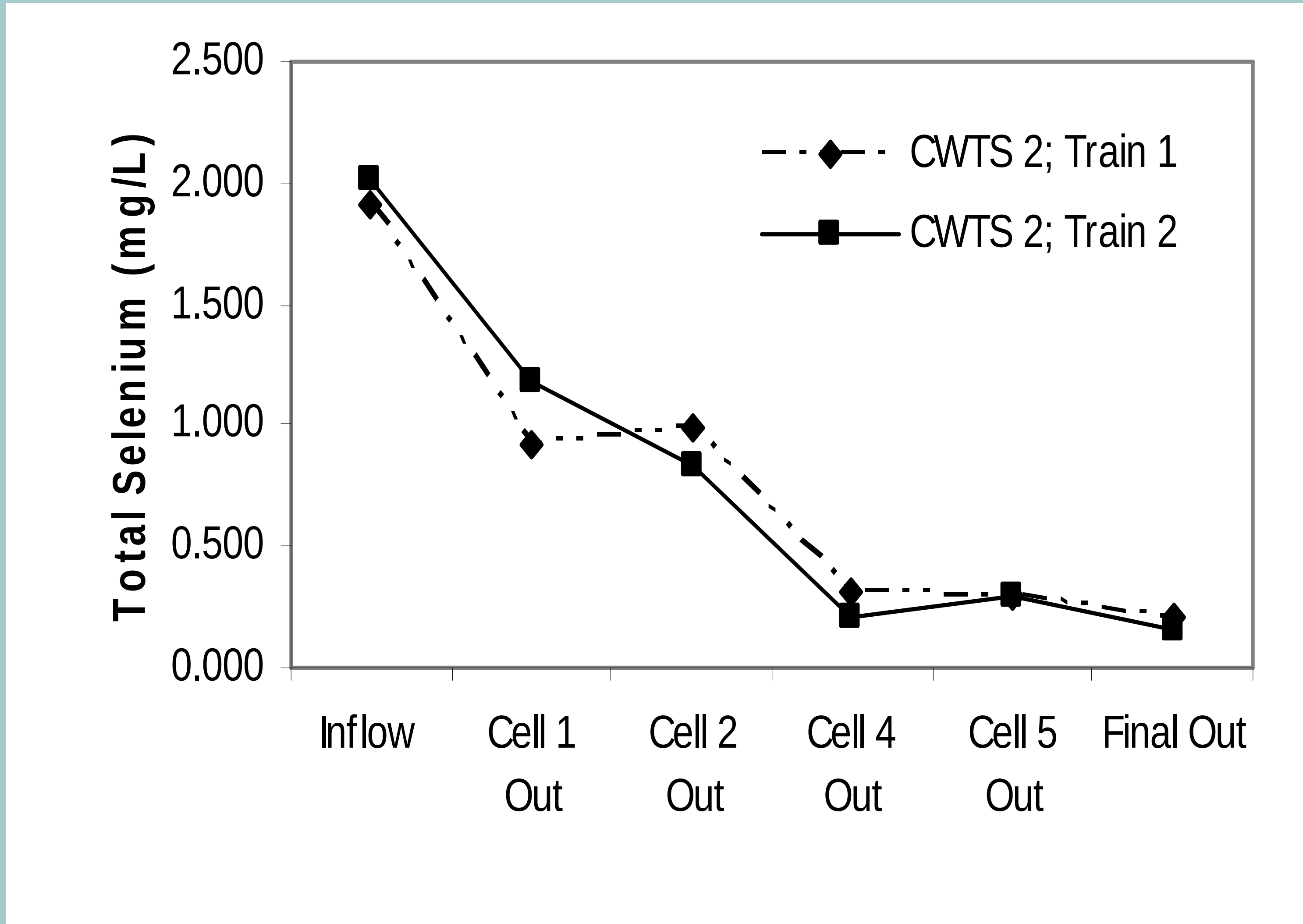


Total Selenium (Simulated FGD Wastewater)

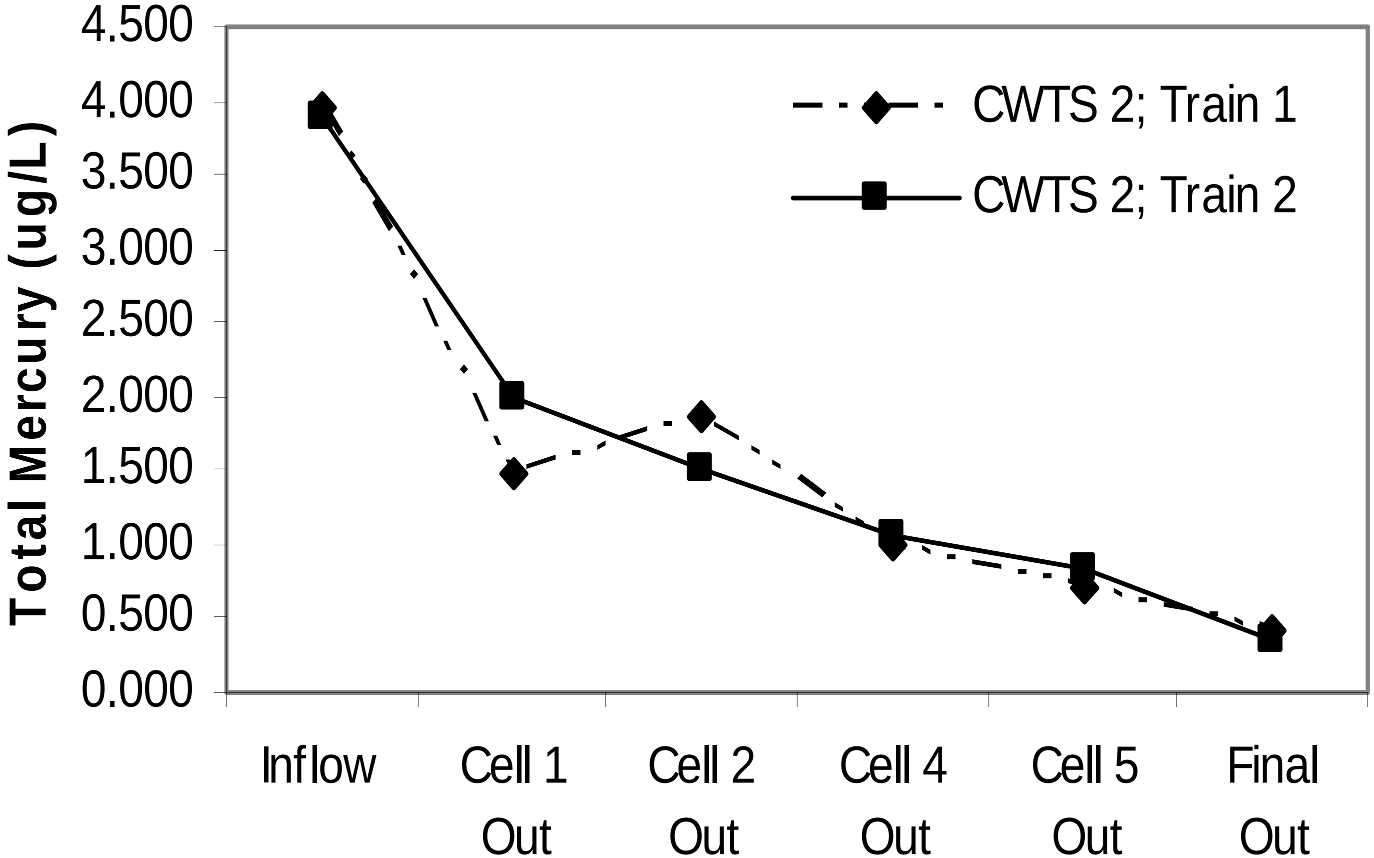


Total Selenium (Actual FGD Wastewater)

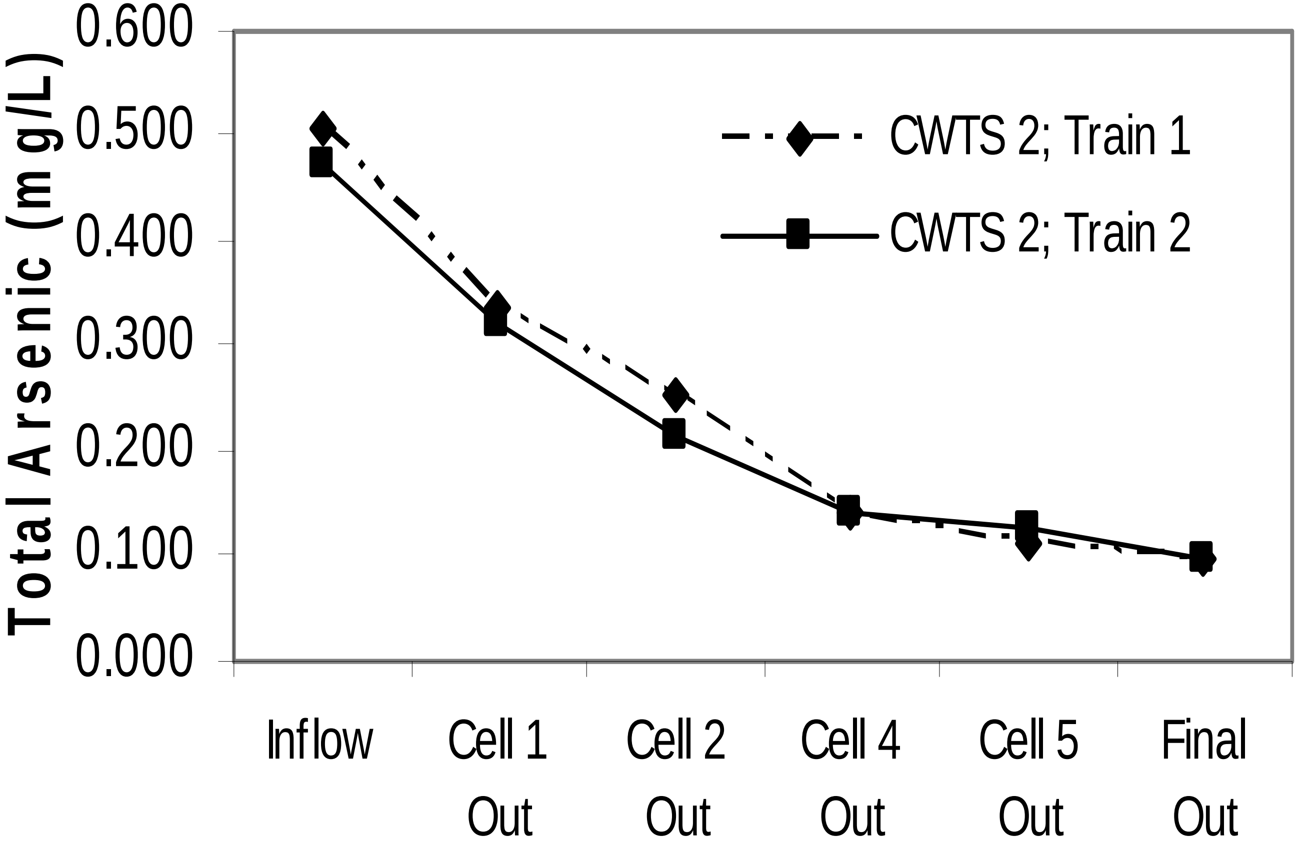


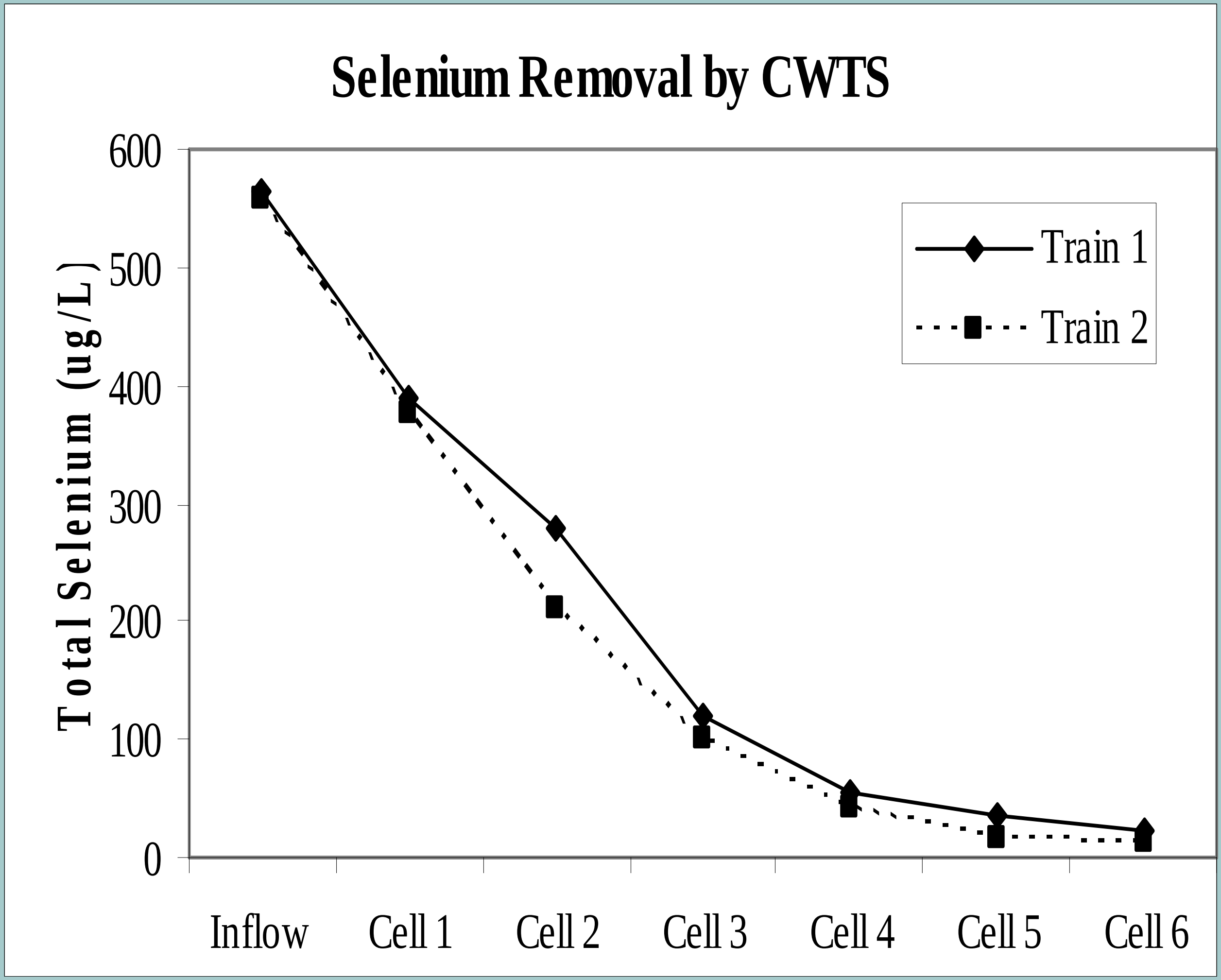


Total Selenium (mg/L)
2.500
2.000
1.500
1.000
0.500
0.000
CWTS 2; Train 1
CWTS 2; Train 2
Inflow
Cell 1 Out
Cell 2 Out
Cell 4 Out
Cell 5 Out
Final Out

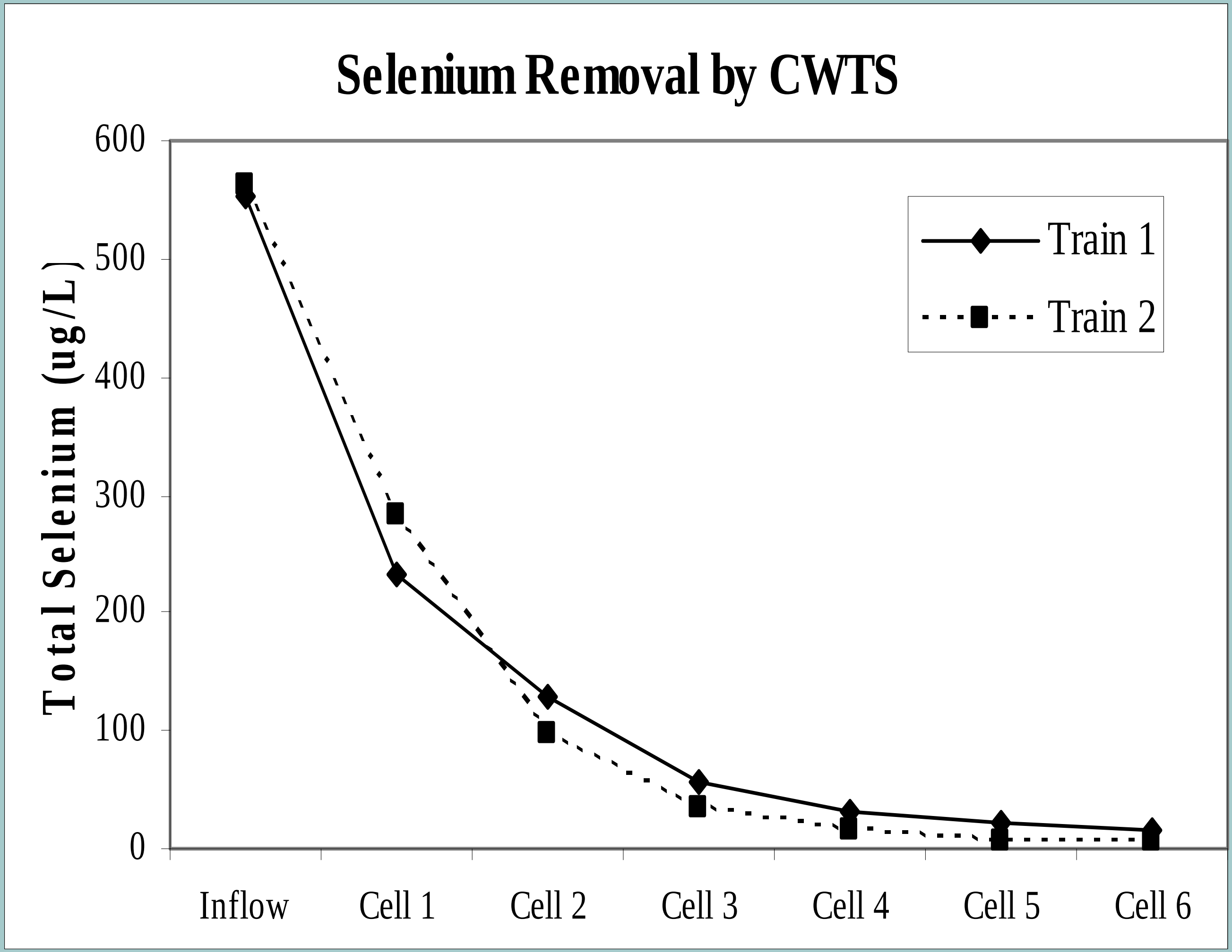


Total Mercury (ug/L)
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
CWTS 2; Train 1
CWTS 2; Train 2
Inflow
Cell 1 Out
Cell 2 Out
Cell 4 Out
Cell 5 Out
Final Out

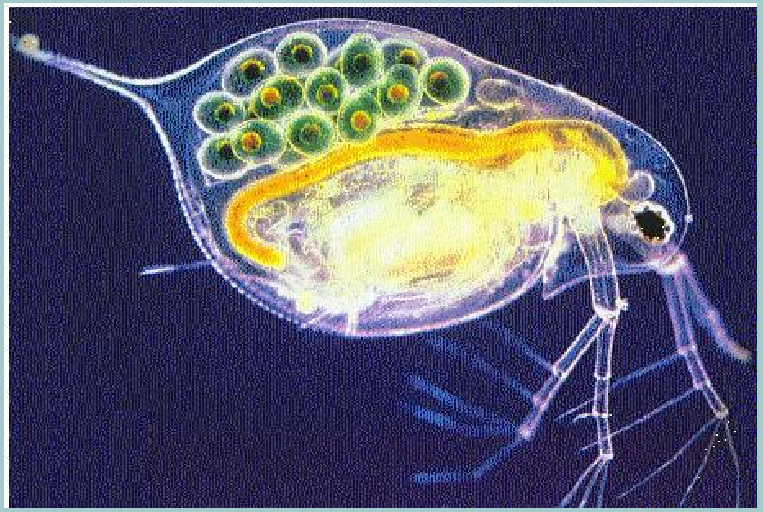

Total Arsenic (mg/L)
0.600
0.500
0.400
0.300
0.200
0.100
0.000
CWTS 2; Train 1
CWTS 2; Train 2
Inflow
Cell 1 Out
Cell 2 Out
Cell 4 Out
Cell 5 Out
Final Out



Selenium Removal by CWTS
Total Selenium (ug/L)
600
500
400
300
200
100
0
Inflow
Cell 1
Cell 2
Cell 3
Cell 4
Cell 5
Cell 6
Train 1
Train 2


Selenium Removal by CWTS
Total Selenium (ug/L)
600
500
400
300
200
100
0
Train 1
Train 2
Inflow
Cell 1
Cell 2
Cell 3
Cell 4
Cell 5
Cell 6

Toxicity Tests: *Ceriodaphnia dubia*



Toxicity

- **With transformation of Hg and Se and co-management of chlorides, no aqueous toxicity observed for:**
  - ***Ceriodaphnia dubia* (survival, reproduction)**
  - ***Hyalella azteca* (survival, growth)**
- **Both sediments and detritus are toxic initially to *H. azteca* (survival, growth). However, toxicity diminishes over time.**

Conclusions

- Ecological risk mitigated
  - Pilot-scale CWTS achieved target Hg (0.001 mg/L) and Se (0.4 mg/L) levels for compliance with NPDES requirements.
  - No aqueous toxicity observed in final effluent.
- Targeted constituents in FGD water are being treated successfully for discharge or reuse.
- The pilot CWTS is providing removal rate coefficients for Hg and Se and full-scale design parameters.

Overall Objective

Evaluate specifically designed constructed wetland treatment systems for treatment of targeted constituents in non-traditional waters for reuse in thermoelectric power generation or other purposes.

Non-traditional waters:

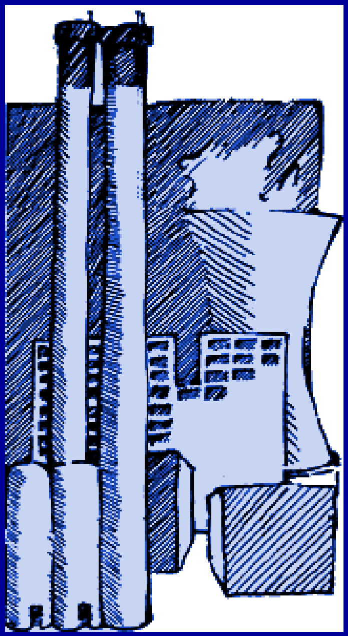
- Ash basin waters
- Cooling waters
- Flue gas desulfurization waters
- Produced waters

Project Schedule

	Year 1 (2005-2006)				Year 2 (2006-2007)				Year 3 (2007-2008)			
	Q 1	Q2	Q3	Q4	Q 1	Q2	Q3	Q4	Q 1	Q2	Q3	Q4
Task 1: **Water Characterization**												
Task 2: **Reuse & Discharge Criteria**												
Task 3: **Design & Construct**												
Task 4: **System Performance**												
Task 5: **Suitability**												
Task 6: **Support System**												

USE OF COAL DRYING TO REDUCE WATER CONSUMED IN PULVERIZED COAL POWER PLANTS

DOE Project DE-FC26-03NT41729



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LEHIGH

NETL Water Program Review Meeting, June 20, 2006, NETL Pittsburgh Site

LOW RANK U.S. COALS

- LIGNITE (North Dakota and Texas)

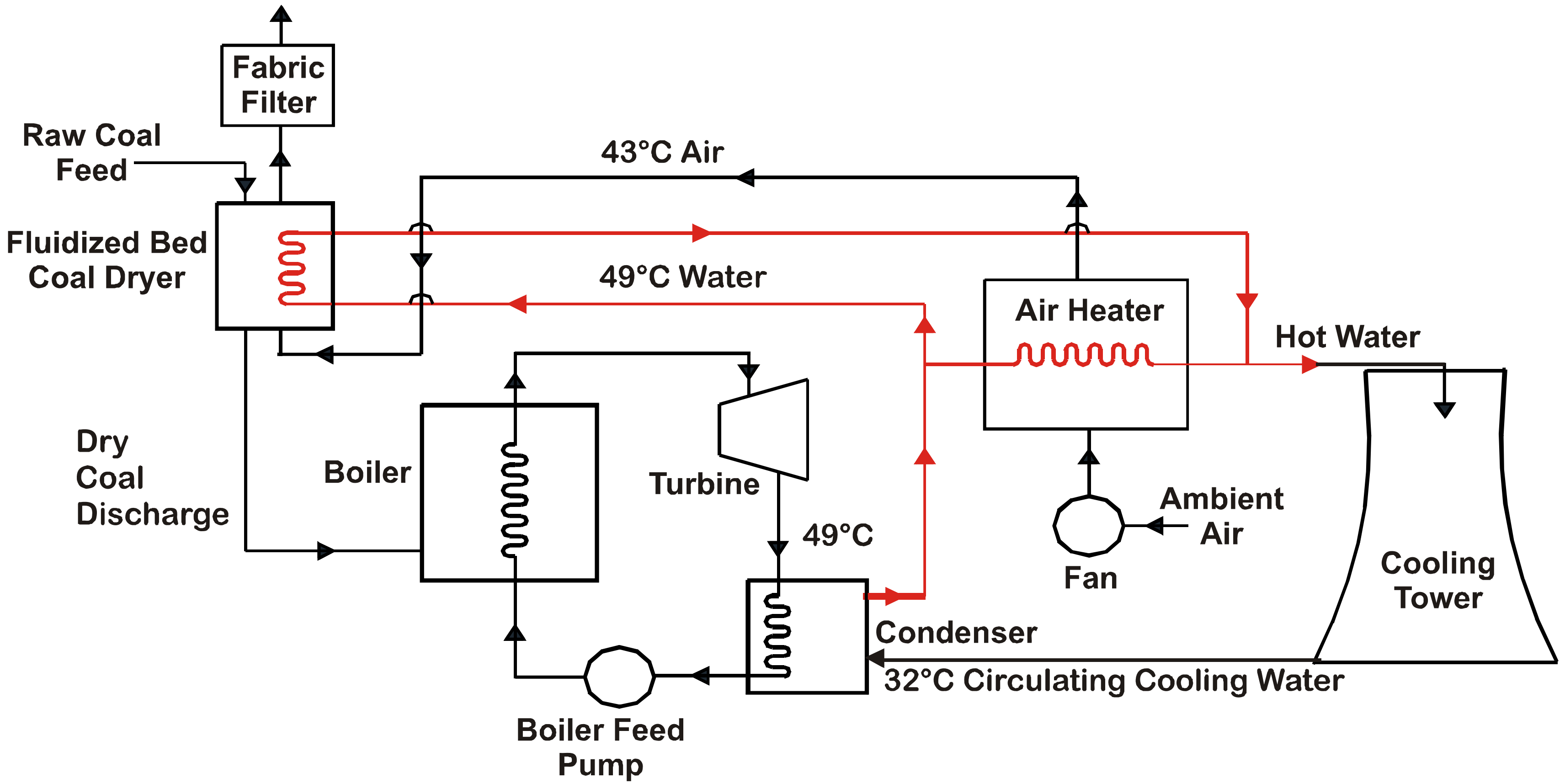
  25 to 40% Moisture

- SUB-BITUMINOUS (Colorado and Wyoming)

  15 to 30% Moisture

POTENTIAL BENEFITS OF USING POWER PLANT HEAT SOURCES TO PREDRY COAL

- Reduce Cooling Tower Makeup Water
- Improve Boiler Efficiency and Heat Rate
- Reduce Station Service Power – Fans and Mills
- Reduce Stack Emissions
- Reduce Maintenance Costs: Coal Handling/Pulverizing/Transport



Schematic of Plant Layout, Showing Air Heater and Coal Dryer

ESTIMATED WATER SAVINGS FOR 550 MW UNIT

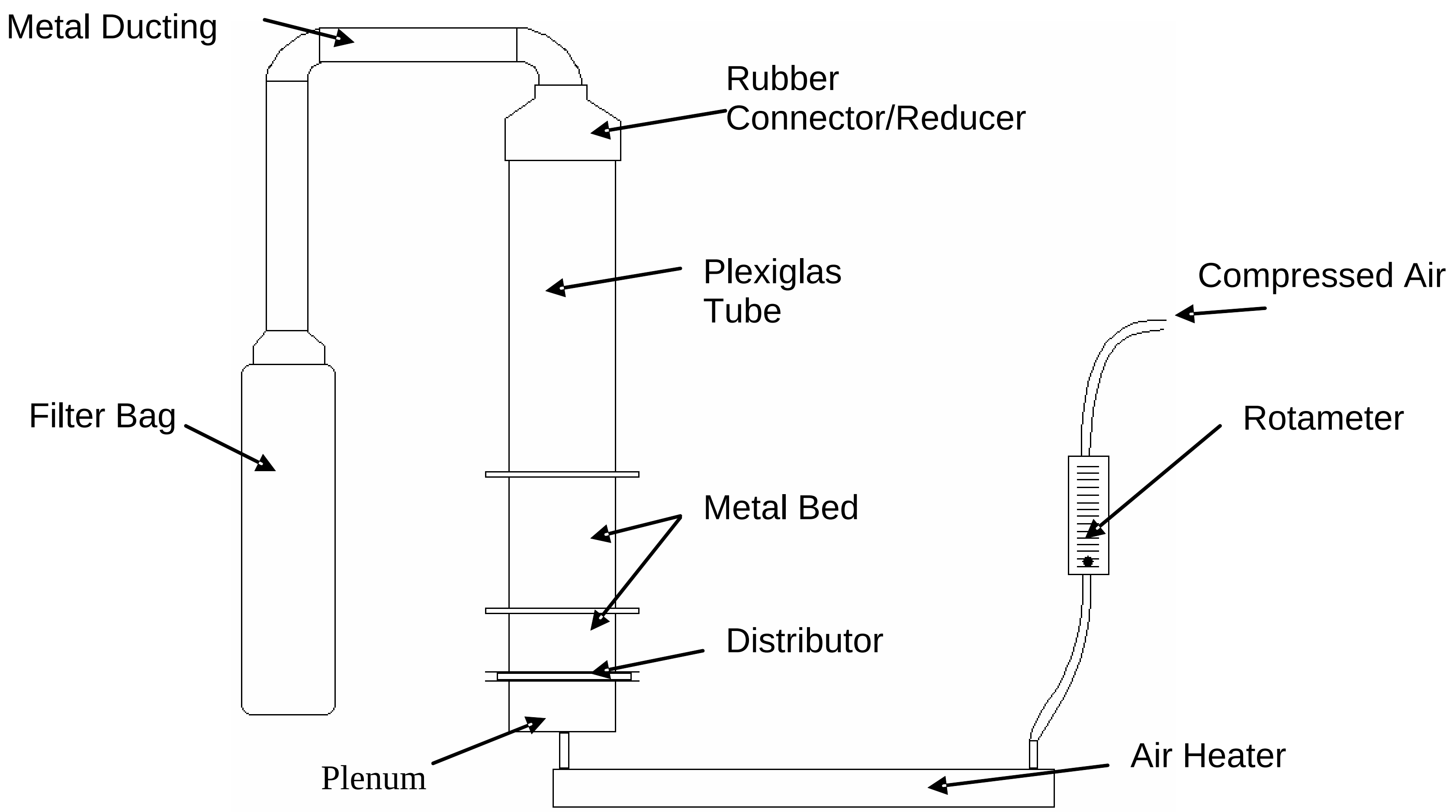
- **Normal makeup for evaporative losses – 6×10^6 to 10×10^6 gallons/day, depending on ambient conditions.**
- **If dry coal from 40 to 25% moisture, reductions in makeup water are 0.29×10^6 to 1.1×10^6 gallons/day.**

OVERVIEW OF PRESENTATION

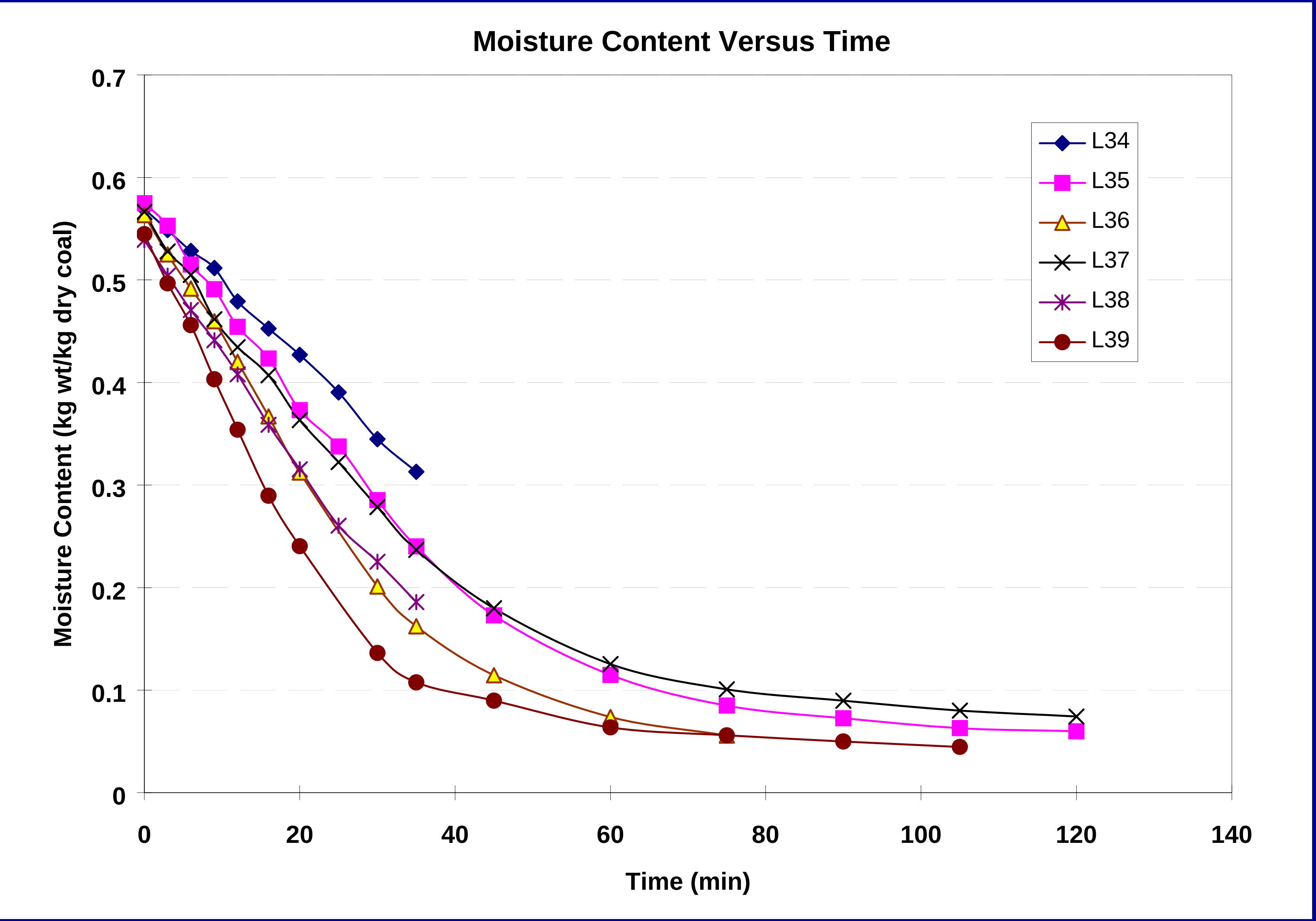
- Laboratory Drying Studies
- Analysis of Power Plant and Cooling Tower Impacts
- Economic Analysis of Drying Options

BENCH SCALE FLUIDIZED BED DRYING EXPERIMENTS

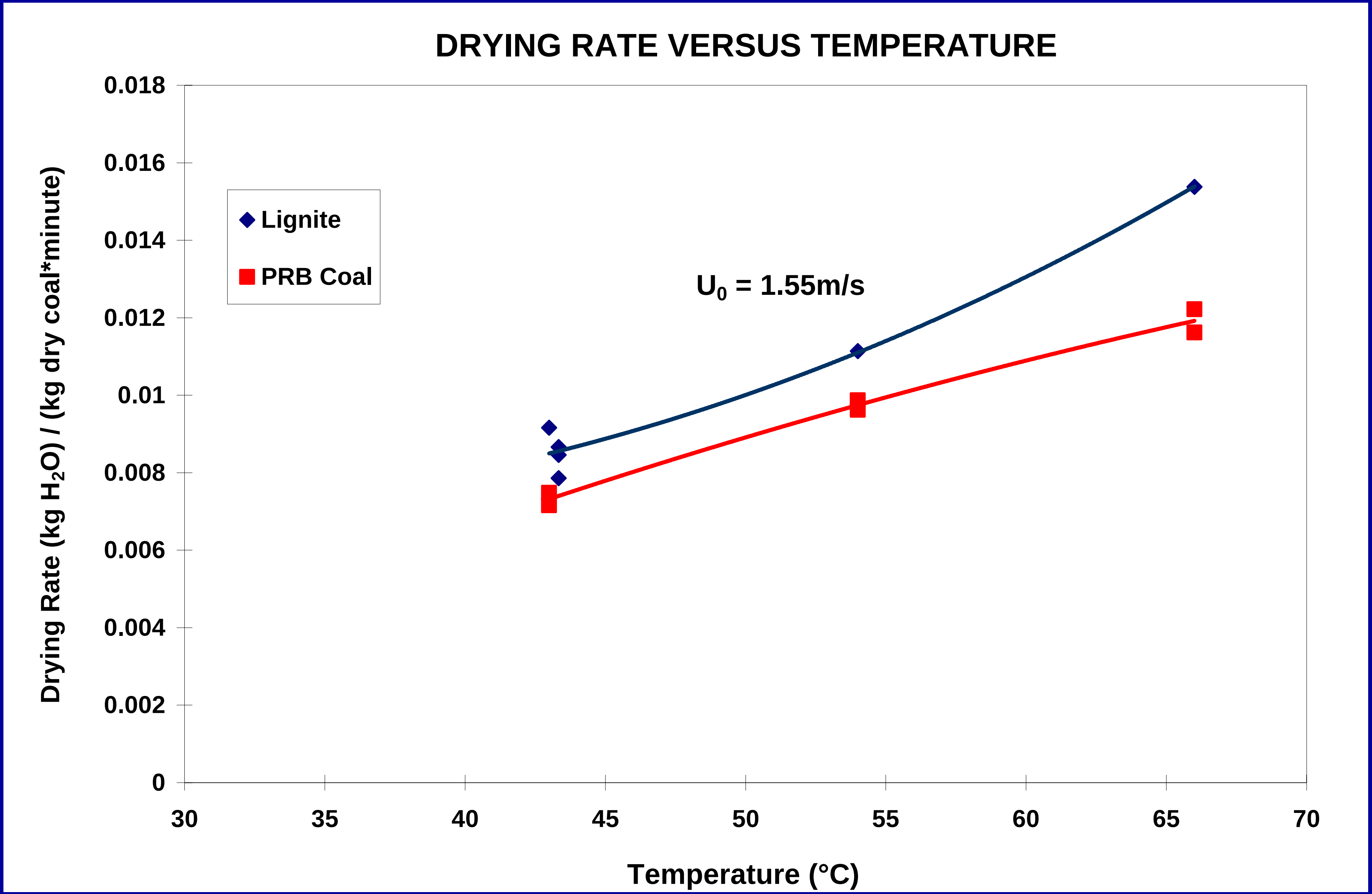
- Lignite and PRB Coals
- Batch Bed
- Crushed Coal ~1/4” Top Size



Sketch of Experimental Bed Setup



Moisture Content Versus Time



Comparison of Drying Rates for Lignite and PRB. Effect of Bed and Inlet Air Temperature.

FIRST PRINCIPLE DRYING MODEL

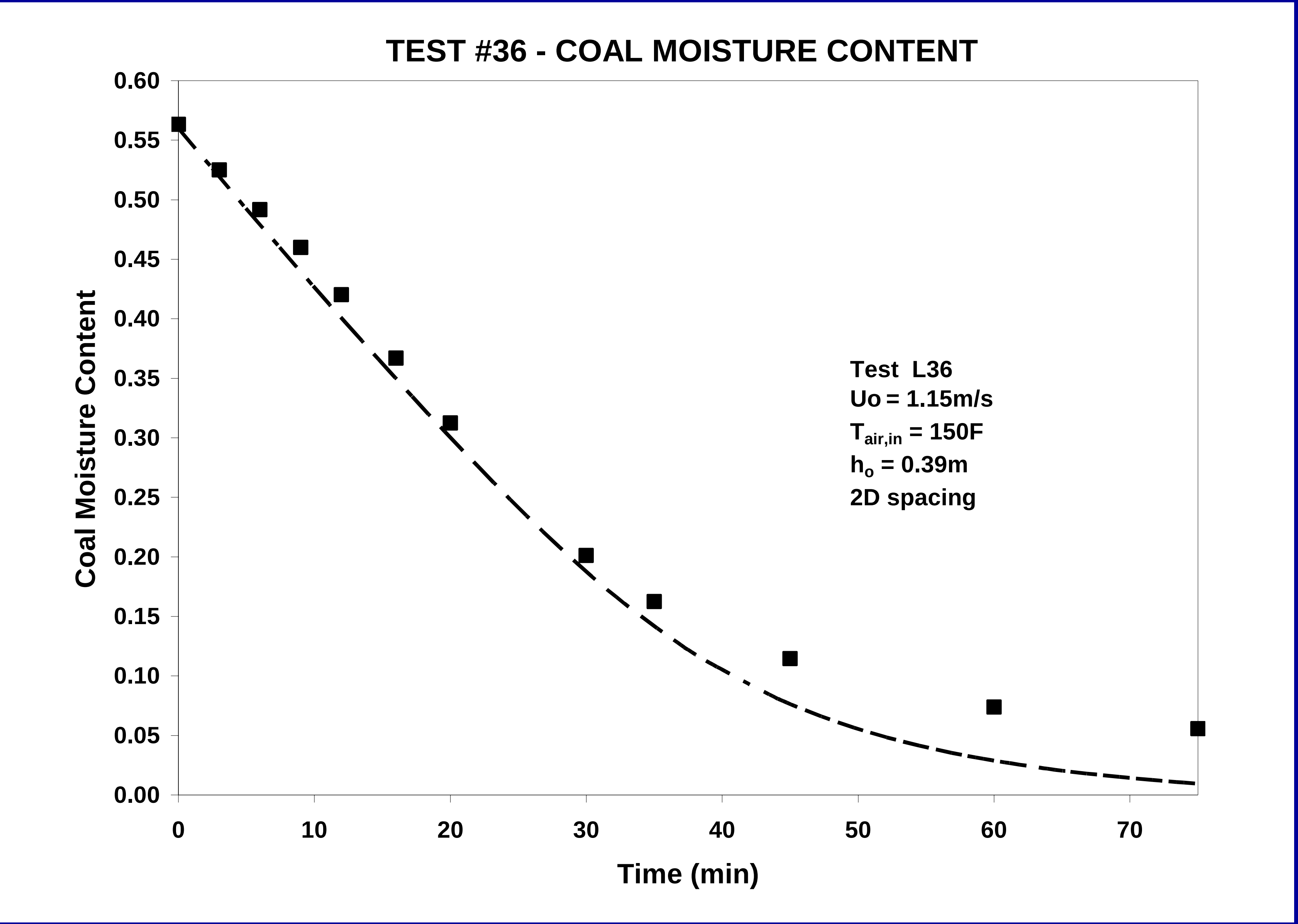
Conservation of Mass

$$\frac{d\Gamma}{dt} = -\frac{\dot{m}_a}{m_{DC}}\left(\omega_2 - \omega_i\right)$$

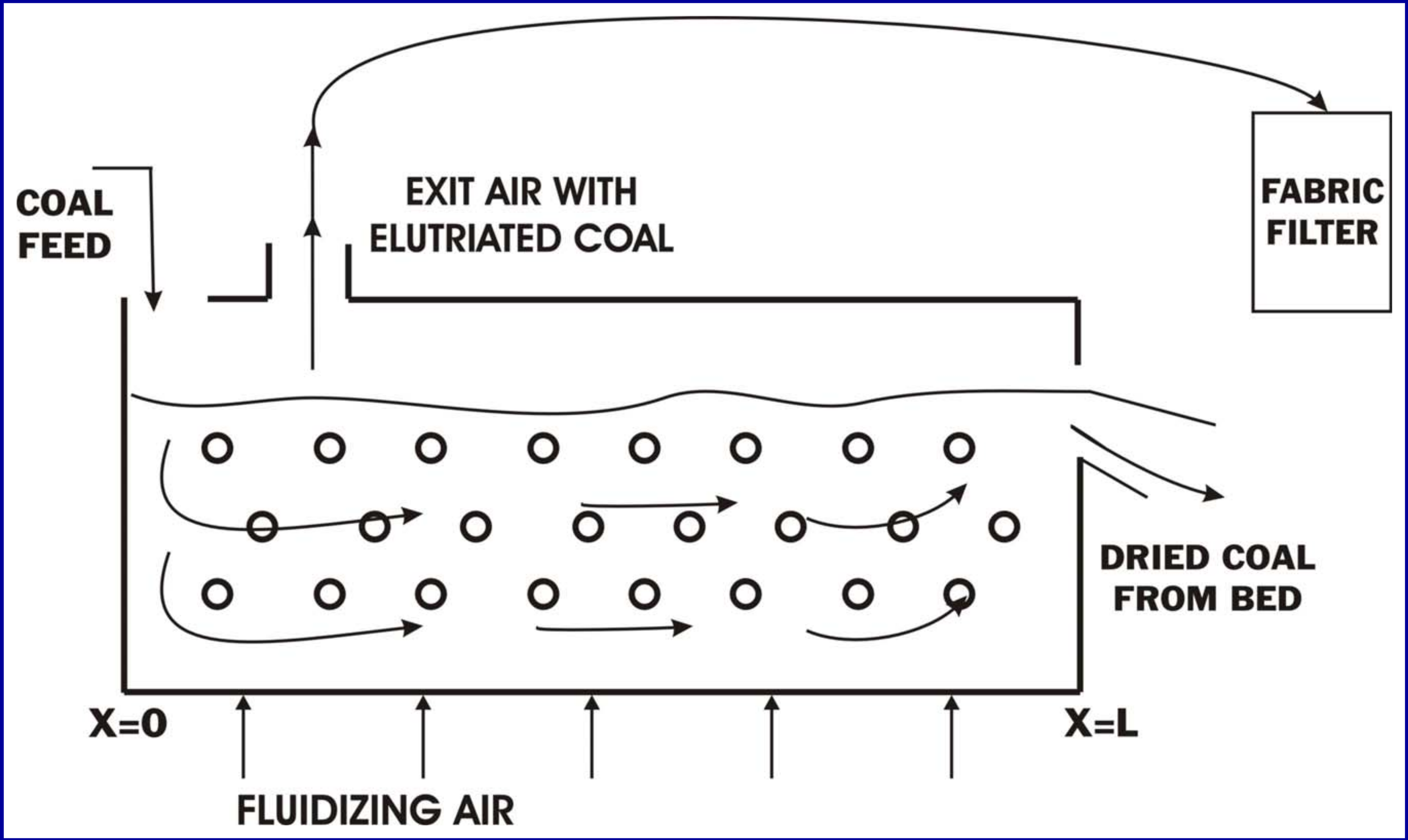
Conservation of Energy

$$\dot{Q}_{TUBES} - \dot{Q}_{LOSS} = m_{DC}\left[\left(C_C + \Gamma C_L\right)\frac{dT_2}{dt} + u_L\left(-\frac{\dot{m}_a}{m_{DC}}\right)\left(\omega_2 - \omega_1\right)\right]$$

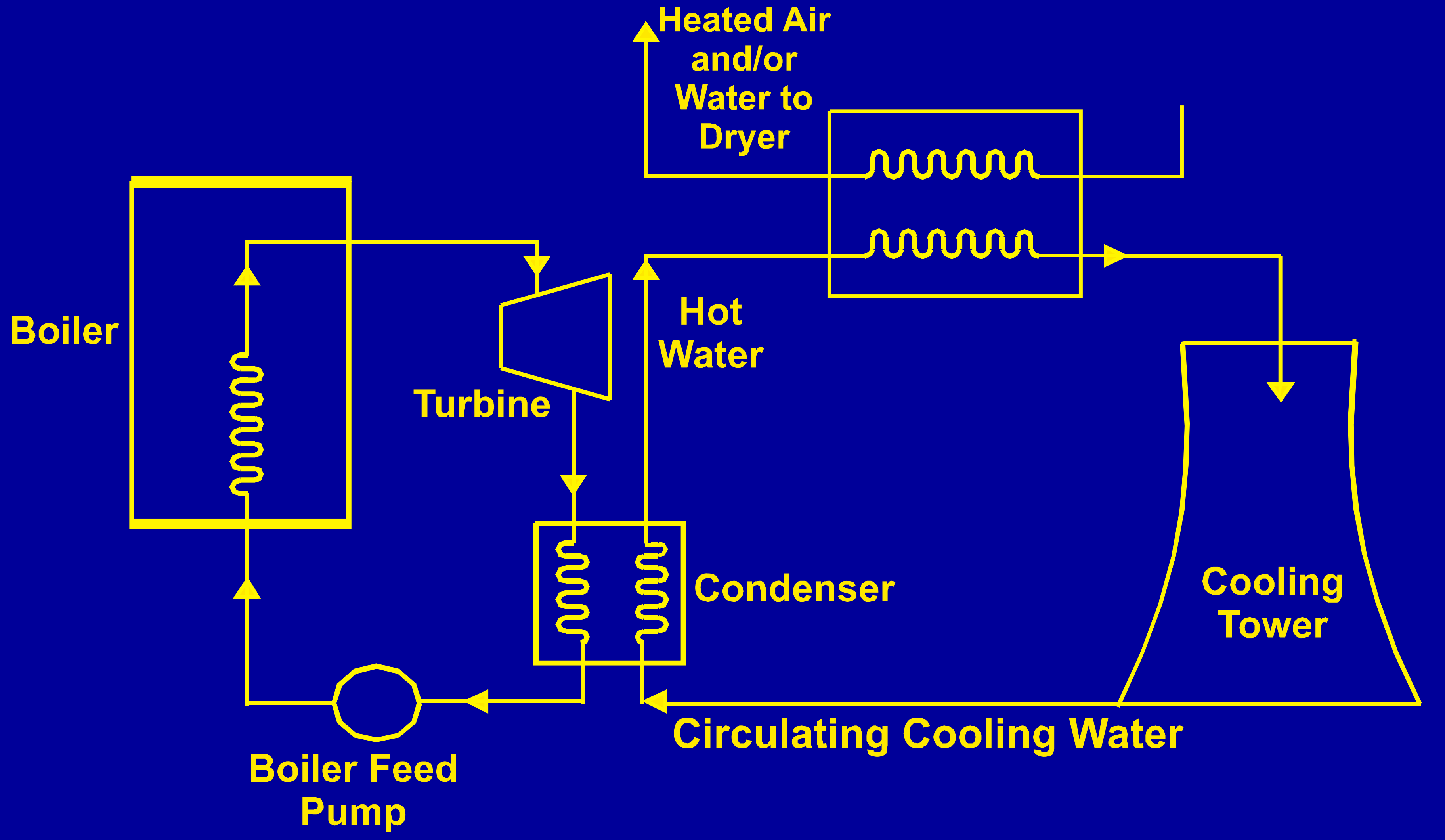
$$+\dot{m}_a\left[C_{pa}\left(T_2 - T_1\right) + \omega_2 hg_2 - \omega_1 hg_1\right]$$



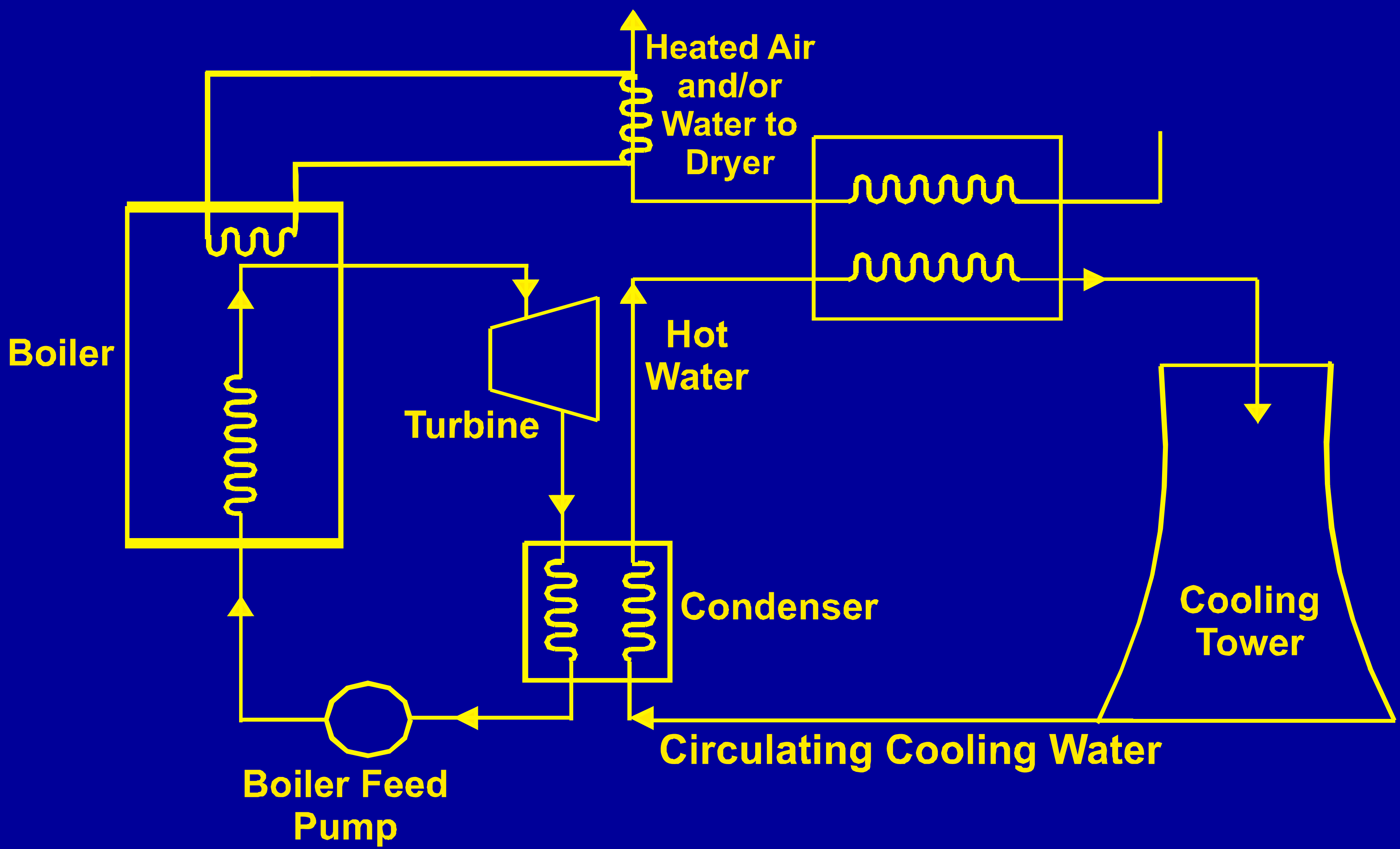
Lignite Drying Curve for Test 36 – Comparison Between Theory and Experiment



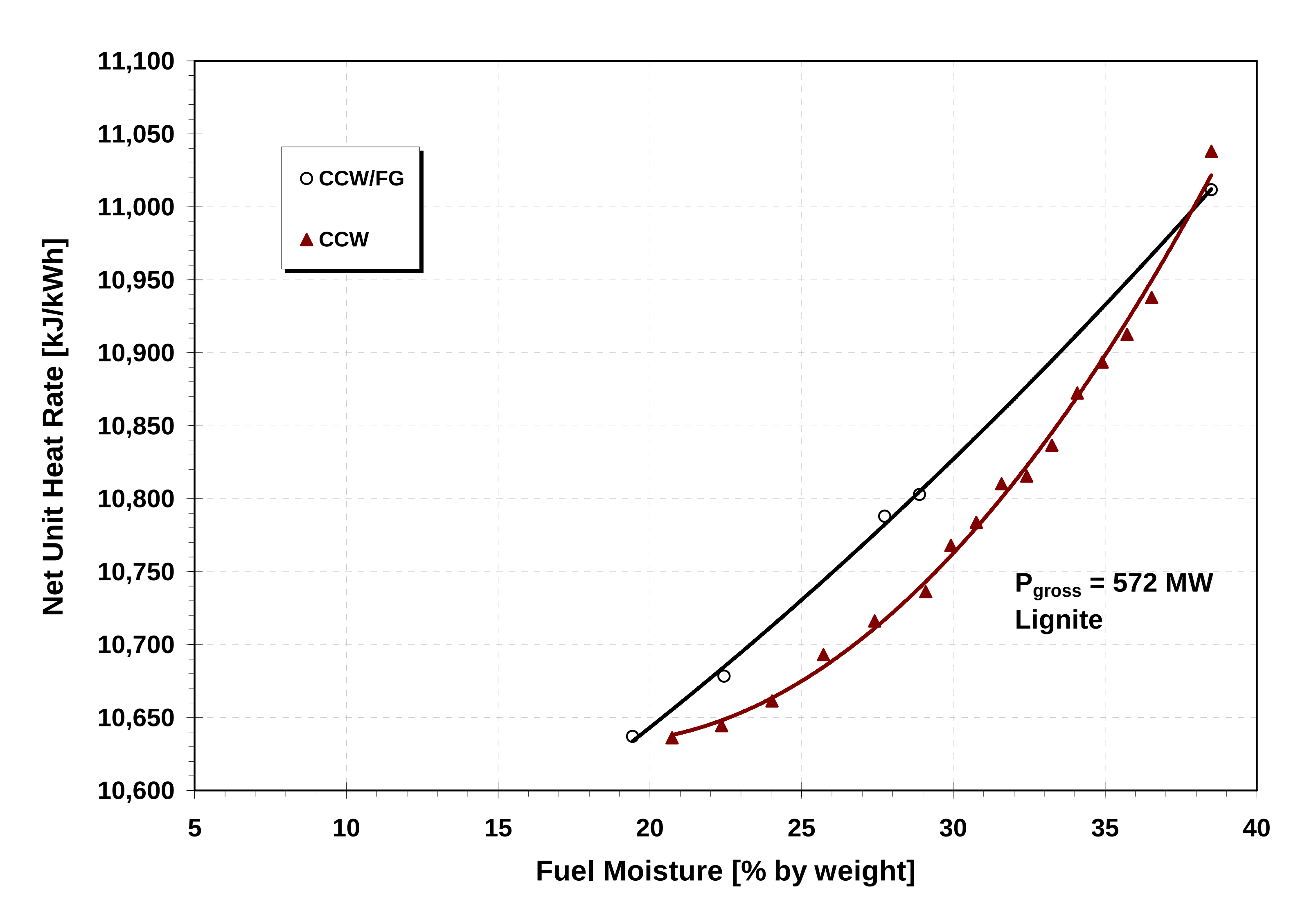
Sketch of Continuous Flow Dryer



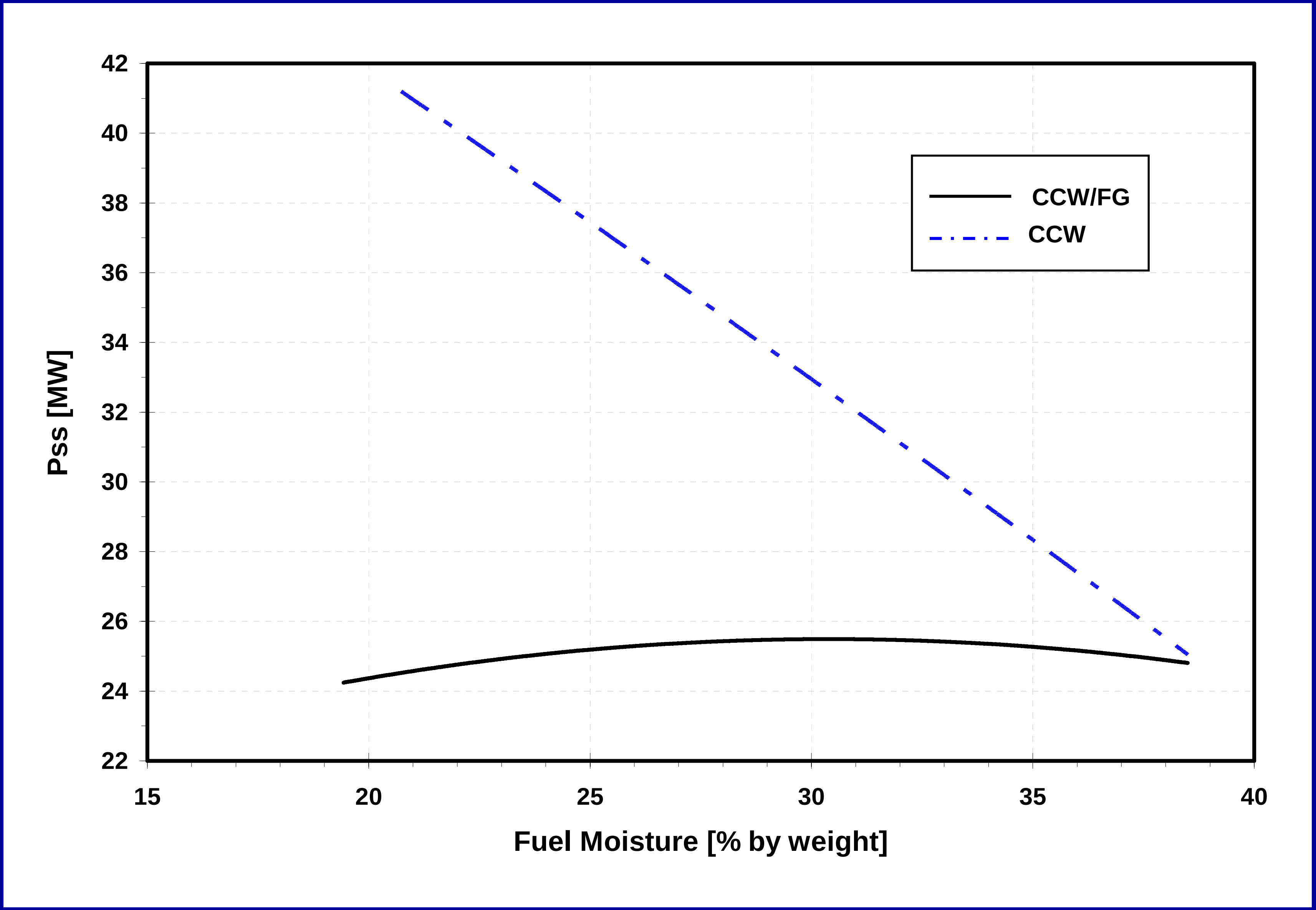
CCW Drying System: Uses Condenser Cooling Water as Heat Source



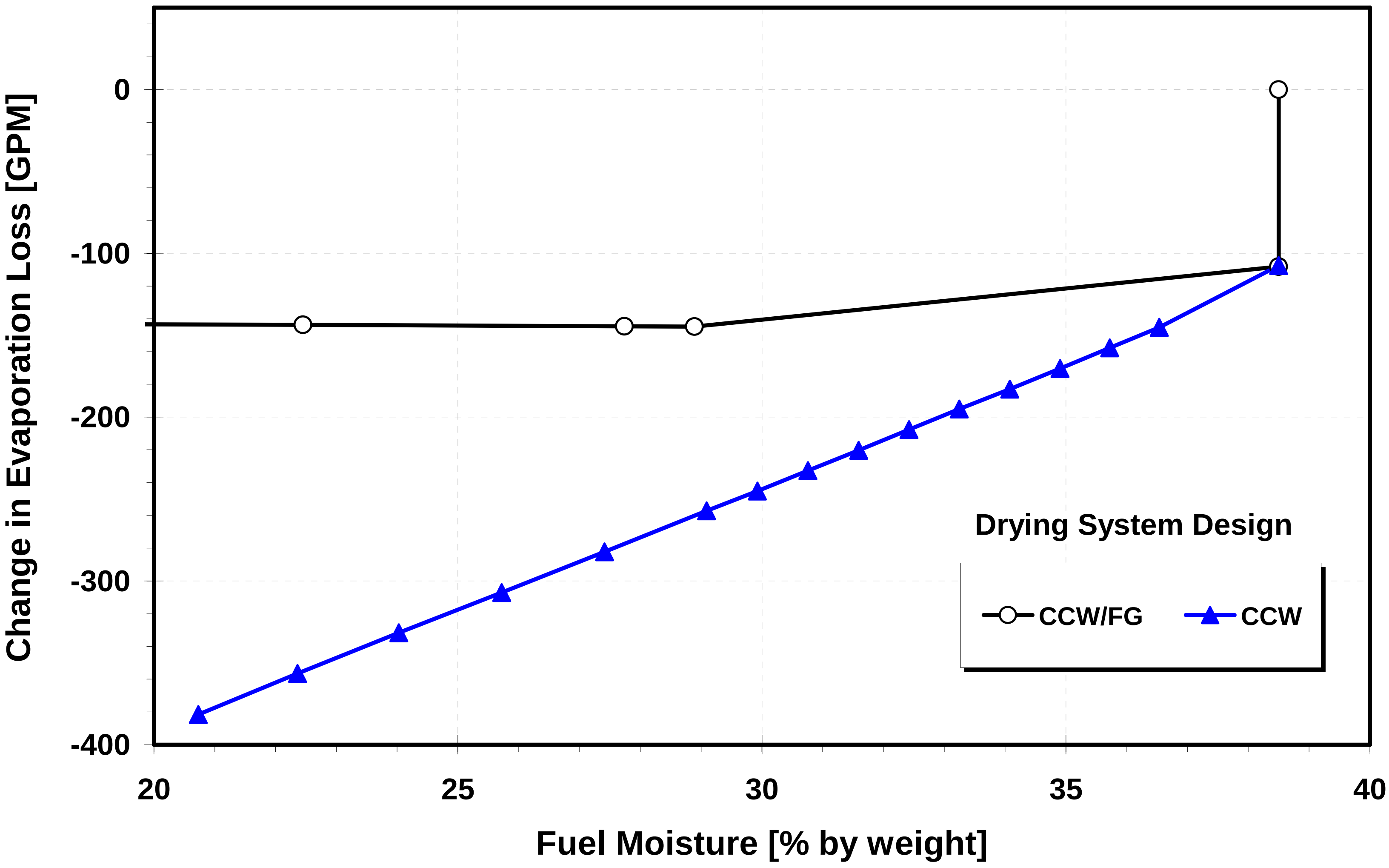
CCW/FG Drying System: Uses Combination of Condenser Cooling Water and Boiler Flue Gas as Heat Source



Net Unit Heat Rate



Station Service Power



Reduction in Cooling Tower Water Evaporation Loss

ECONOMIC EVALUATION

- Estimate Installed Capital Costs
  - Heat exchangers, fans, fluidized bed dryers, coal crushers, baghouses, duct work, conveyors
- Compute Annual Fixed Costs and O&M Costs
- Compute Change in Station Service Power
- Compute Total Annual Costs
- Estimate Benefits
- Compute ROI

INSTALLED EQUIPMENT COSTS

	CCW/FG $\$ \times 10^6$	CCW $\$ \times 10^6$
Dryers	4	30
FA Fan	2	11
Baghouse	2	13
Heat Exchangers	15	35

CCW/FG System – Capital and Operating and Maintenance Costs

% CHANGE IN MOISTURE	TOTAL INSTALLED COST	TOTAL ANNUAL FIXED[1] AND O&M COSTS
9.60	$23,446,409	$4,363,786
10.80	$23,550,919	$4,380,976
16.00	$24,034,968	$4,460,593
19.00	$24,387,259	$4,518,537

(1) Not including the effect of drying on station service power.

CCW System – Capital and Operating and Maintenance Costs

% CHANGE IN MOISTURE	TOTAL INSTALLED COST	TOTAL ANNUAL[1] FIXED AND O&M COSTS
2.00%	$21,887,000	$4,107,295
6.10%	$39,884,000	$7,067,441
12.80%	$68,582,000	$11,787,688
17.80%	$91,350,000	$15,532,569

(1) Not including the effect of drying on station service power.

7.5% Annual Interest

STATION SERVICE POWER

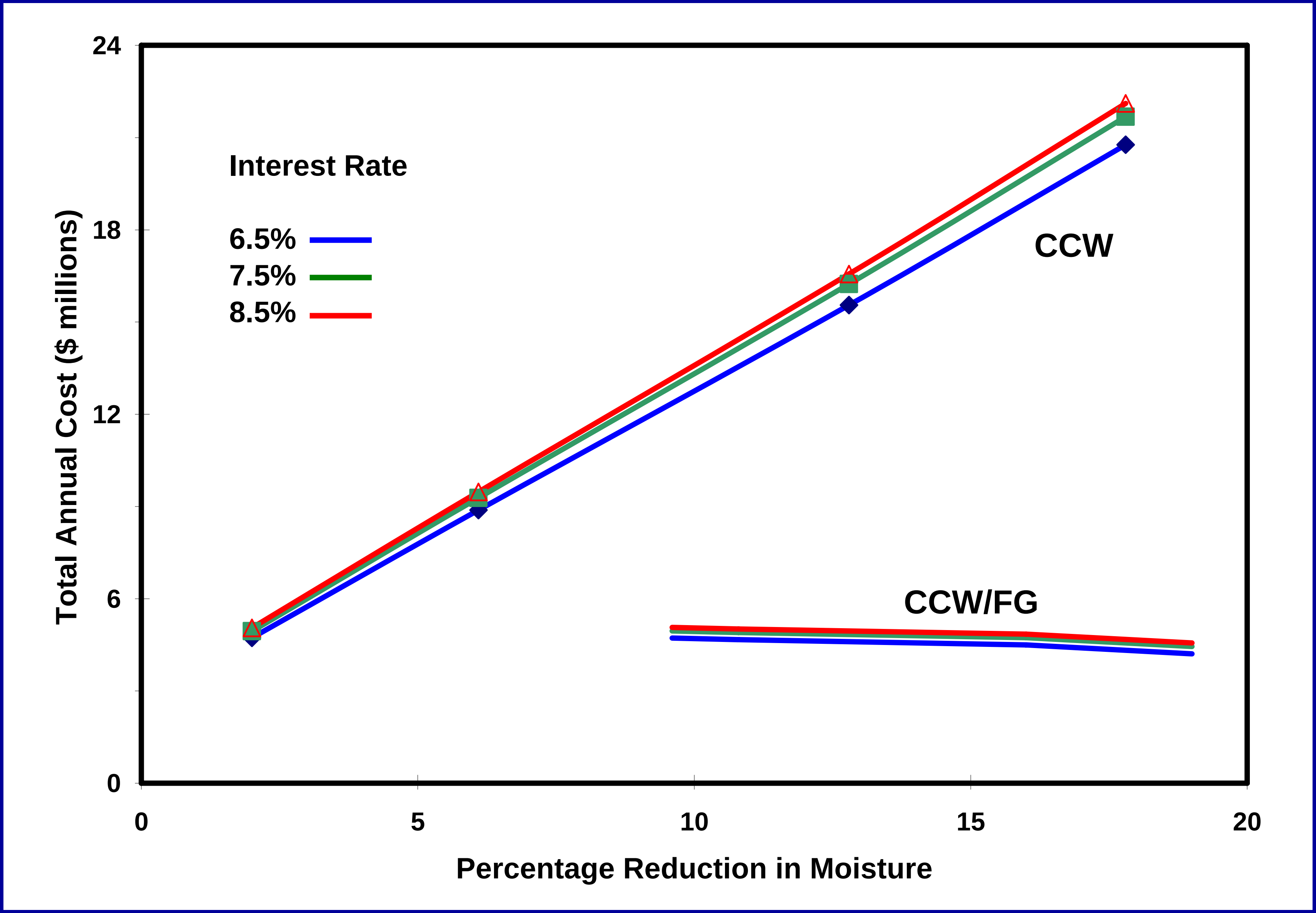
	Increase	Decrease
• Pulverizers		✓
• Forced Draft Fans		✓
• Induced Draft Fans		✓
• Fluidizing Air Fans	✓	

Incremental Cost of Station Service Power – CCW/FG System

% Moisture Reduction	Change in Station Service Power (MW)	$/year
0.00	0	0
9.61	+1.583	+589,350
10.76	+1.400	+521,220
16.05	+0.732	+272,524
19.07	-0.188	-69,992

Incremental Cost of Station Service Power – CCW System

% Moisture Reduction	Change in Station Service Power (MW)	$/year
2.0	+2.25	+837,675
6.1	+5.95	+2,215,185
12.8	+11.95	+4,448,985
17.8	+16.51	+6,146,673



Total Annual Costs – CCW and CCW/FG Systems

FINANCIAL BENEFITS

- Water Savings
- Reduced Fuel Costs
- Reduced Ash Disposal Costs
- Avoided Costs of Emissions Control
- Reduced Mill Maintenance Costs
- Reduced Lost Generation Due to Mill Outages

Annual Water Savings – CCW/FG System

% Moisture Reduction	Water Savings (Gallons/Year)	Water Savings ($/year)		
		Minimum[a]	Mean[b]	Maximum[c]
9.61	62.5×10^6	$31,273	$93,819	$187,638
10.76	62.5×10^6	$31,273	$93,819	$187,638
16.05	62.5×10^6	$31,273	$93,819	$187,638
19.07	62.5×10^6	$31,273	$93,819	$187,638

(a) \$0.50/10^3 gallon, (b) \$1.50/10^3 gallon, (c) \$3.00/10^3 gallon

Annual Water Savings – CCW System

% Moisture Reduction	Water Savings (Gallons/Year)	Water Savings ($/year)		
		Minimum[a]	Mean[b]	Maximum[c]
2.0	71.48×10^6	35,740	107,220	214,440
6.1	98.29×10^6	49,145	147,435	294,870
12.8	138.5×10^6	69,250	207,750	415,500
17.8	169.8×10^6	84,900	254,700	509,400

(a) \$0.50/10^3 gallon, (b) \$1.50/10^3 gallon, (c) \$3.00/10^3 gallon

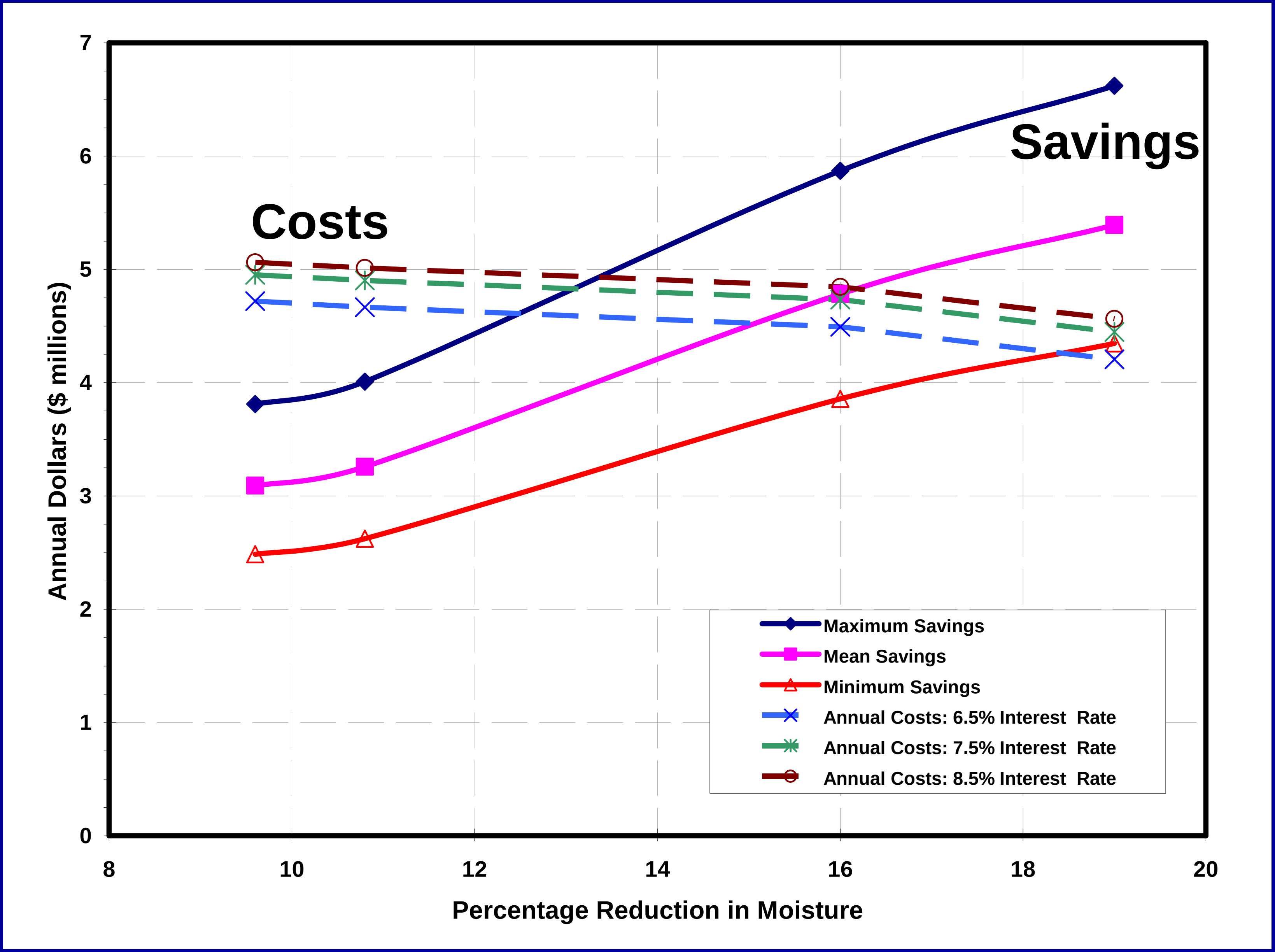
Unit Costs of Emissions

NO_x	$2,400/ton
SO_2	$750 to $1,500/ton
Hg	$20,000/lbm
CO_2	$9.10 to $18.20/ton

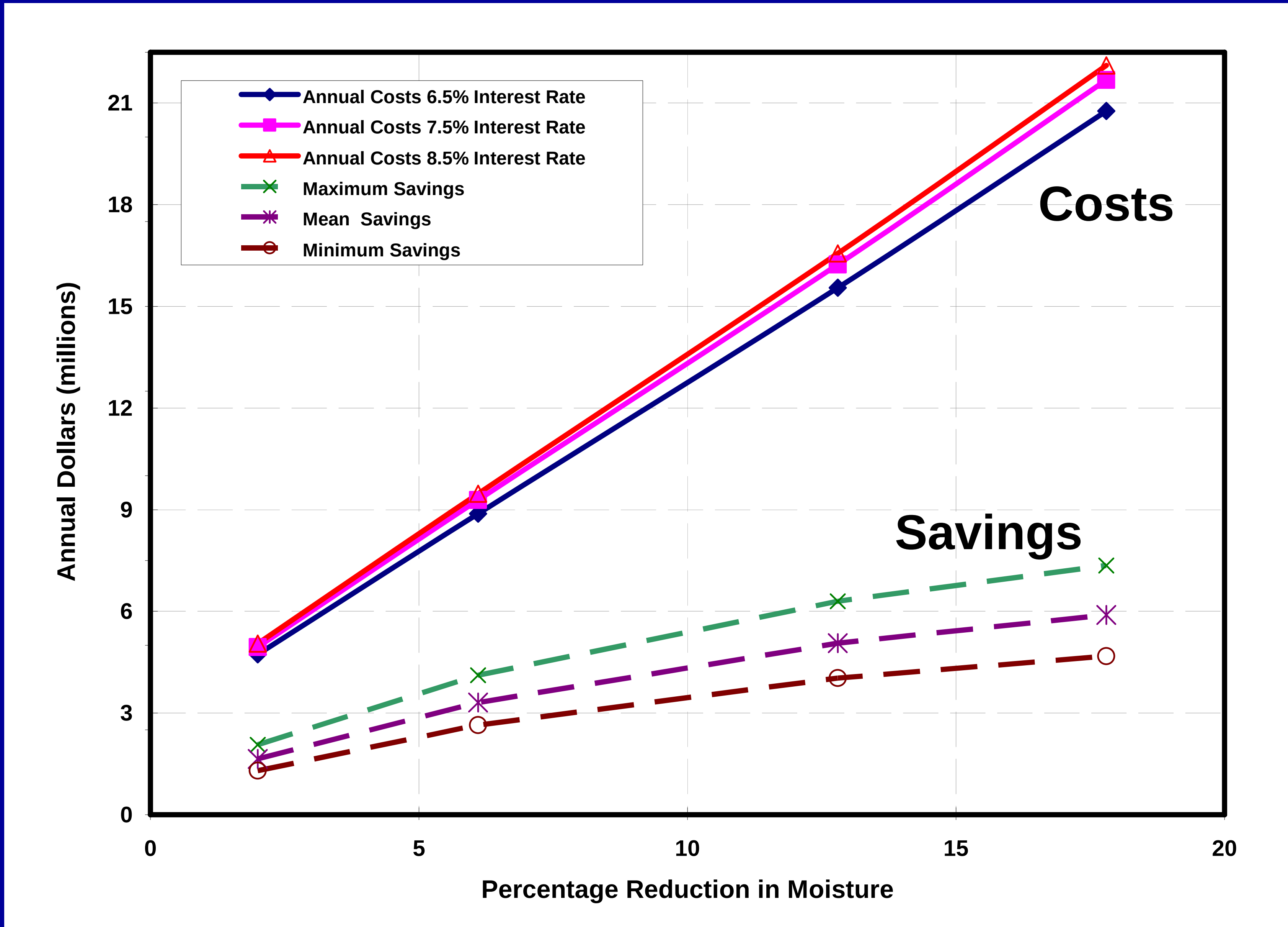
Avoided Costs of Emissions Control (CCW/FG System)

% Moisture Reduction	NO_x	Hg	SO_2		
			Minimum	Mean	Maximum
9.61	$85,240	$85,757	$251,159	$334,879	$502,318
10.76	$89,726	$90,270	$264,378	$352,504	$528,756
16.05	$134,590	$135,405	$396,567	$528,756	$793,134
19.07	$152,535	$153,459	$449,443	$599,257	$898,885

% Moisture Reduction	CO_2		
	Minimum	Mean	Maximum
9.61	$761,188	$1,141,782	$1,522,376
10.76	$801,251	$1,201,876	$1,602,501
16.05	$1,201,876	$1,802,814	$2,403,752
19.07	$1,362,126	$2,043,189	$2,724,252



Comparison of Annual Costs and Benefits – CCW/FG System



Comparison of Annual Costs and Benefits – CCW System

CONCLUSIONS

COAL DRYING RATE/DRYER DESIGN

- PRB and Lignite Are Both Easily Dried in a Fluidized Bed
- Coal Drying Rate Increases with Bed Temperature

IMPACTS OF COAL DRYING ON UNIT OPERATIONS

Effects of Lignite Drying on Changes in Key Plant Performance Parameters with a 20 Percent Product Moisture

	CCW	CCW/FG
Boiler Efficiency	+5.5%	+3%
Net Unit Heat Rate	-3.3%	-3.3%
Stack Emissions	-3.3%	-3.3%
Station Service Power	+17 MW	Negligible
Cooling Tower Makeup Water	380 gallons/minute	140/gallons/minute

- **Performance Impacts with PRB and Lignite Coals are Similar in Magnitude**

ECONOMIC EVALUATION

Assume: 38.5 → 19.5% Moisture
572 Gross MW
20 Year Life
7.5 Percent Interest

ANNUAL COSTS

- Depend Strongly on Drying System Design
- Annual Fixed Costs, O&M Costs and Costs Due to Increase in Station Service Power

CCW/FG	$4.6 Million
CCW	$22.1 Million

ANNUAL SAVINGS

- Reduced Fuel Costs
- Reduced Ash Disposal Costs
- Avoided Costs of Emissions Control
- Water Savings
- Reduced Mill Maintenance Costs
- Reduced Lost Generation Due to Mill Outages

ANNUAL SAVINGS *(continued)*

- Most Important are Fuel Savings and Avoided Costs Due to Reduction of SO_2 and CO_2 Emissions
- Annual Savings ≈ $7.0 Million

RETURN ON INVESTMENT

- ROI for CCW/FG Drying System is 21 Percent at 19 Percent Moisture Reduction
- CCW Drying System is Not Cost Effective

ADDITIONAL COMMENTS

- Costs and Benefits Depend Heavily on Site-Specific Factors
- Would Need Detailed Analyses to Determine Most Cost-Effective Design for a Particular Application
- This Study Was for Retrofit Applications; However, Comparable Study Should Be Performed for New Plant Designs
- There Will Be Additional Savings by Matching Boiler Design, and Mill, Fan, ESP and Scrubber Capabilities to a Lower Moisture As-Fired Fuel.

Coal Creek Station

Water Conserving Steam-Ammonia Power Cycle

Donald C. Erickson
Energy Concepts Co.

Presented at: NETL Water and Power Plants Conference
June 20, 2006

OUTLINE

1. Effects of dry cooling on steam power plants

2. Damp cooling effects

3. Historical search for dry/damp cooling penalty mitigation

4. Steam-Ammonia Power Cycle

Dry Cooling Effects

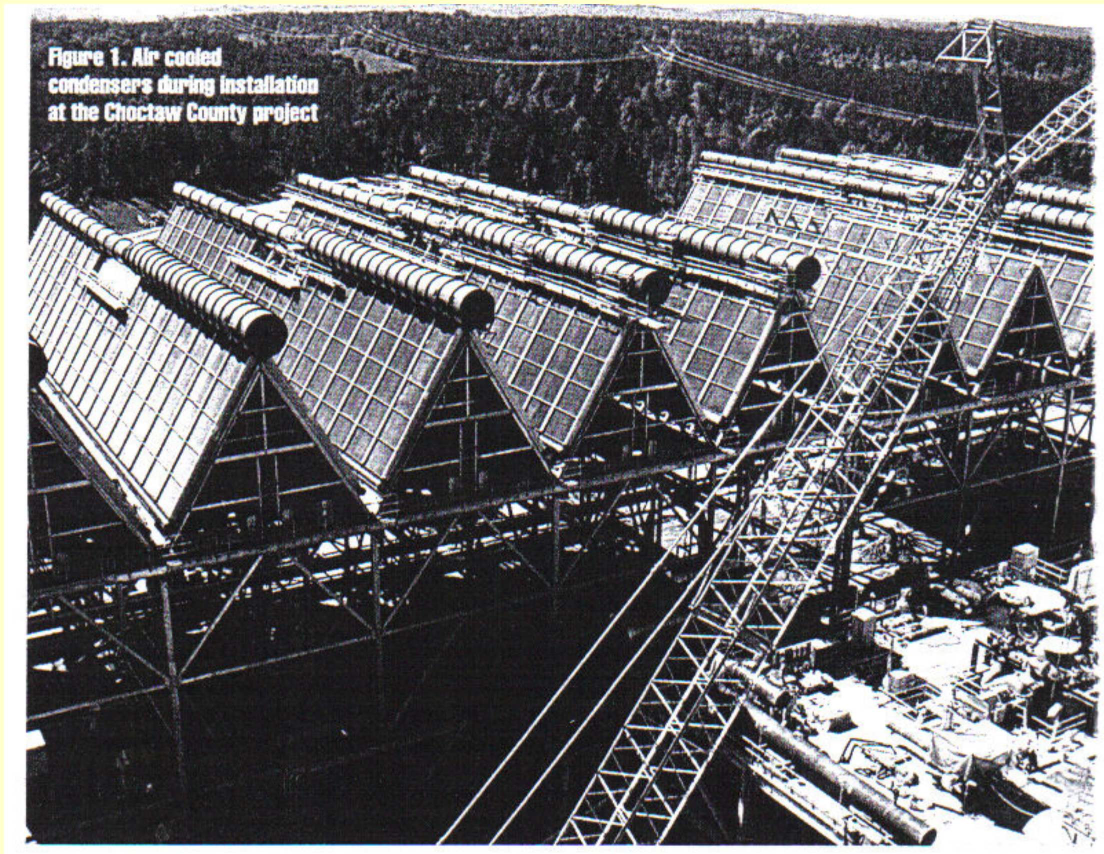
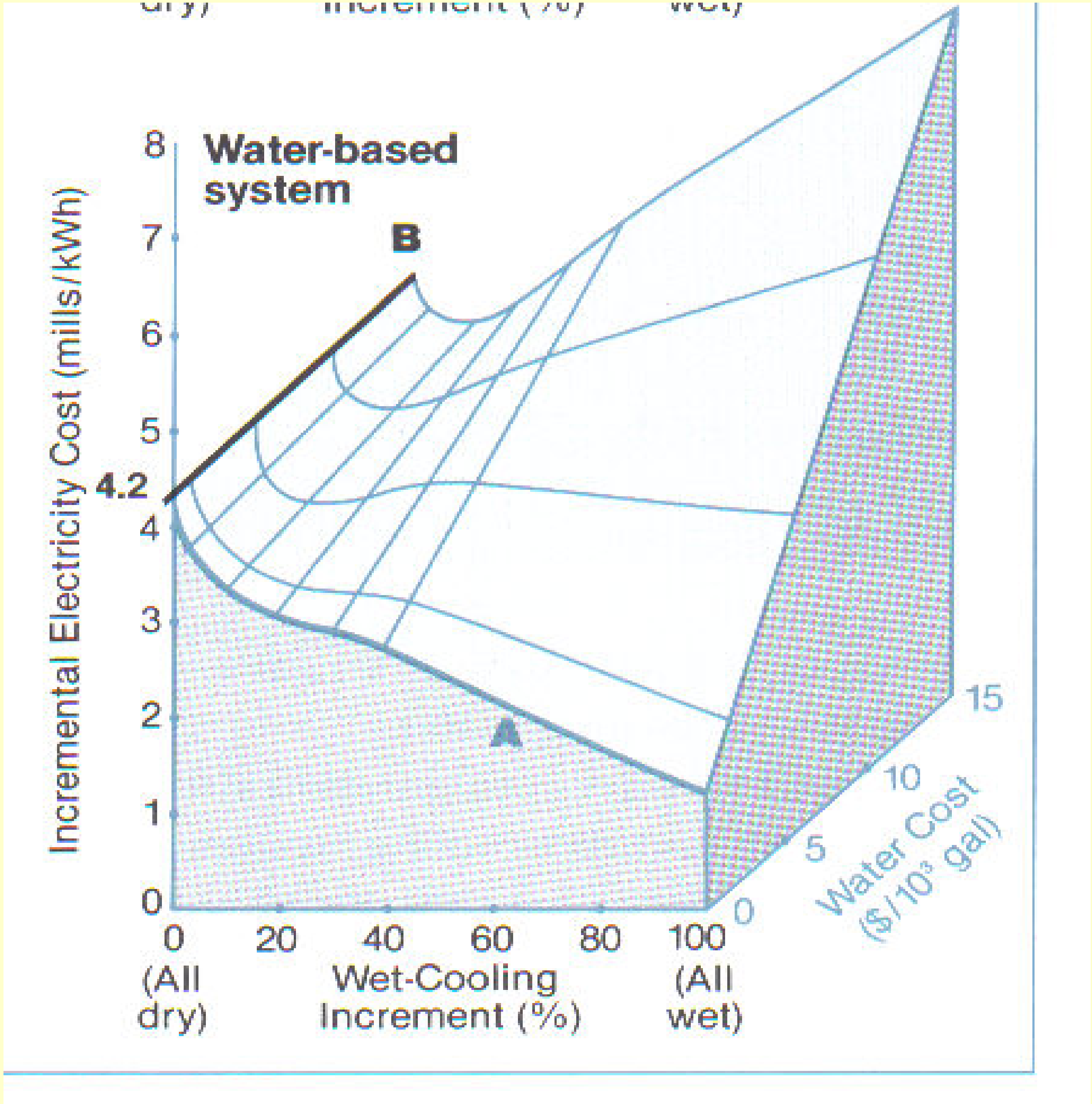


Figure 1. Air cooled condensers during installation at the Choctaw County project

Required Air Movement

- 6x for same condensing pressure
- 3x for max power production
- Coolant glide doubles (40 vs. 20 ΔF)
- ~ 3% penalty on heat rate

Effect of Damp Cooling



Penalty Mitigation From Damp Cooling

Spray Enhancement at Crockett cogeneration plant provides a 7-12 megawatt increase in production on hot days.

Historical Search For Dry/Damp Cooling Penalty Mitigation

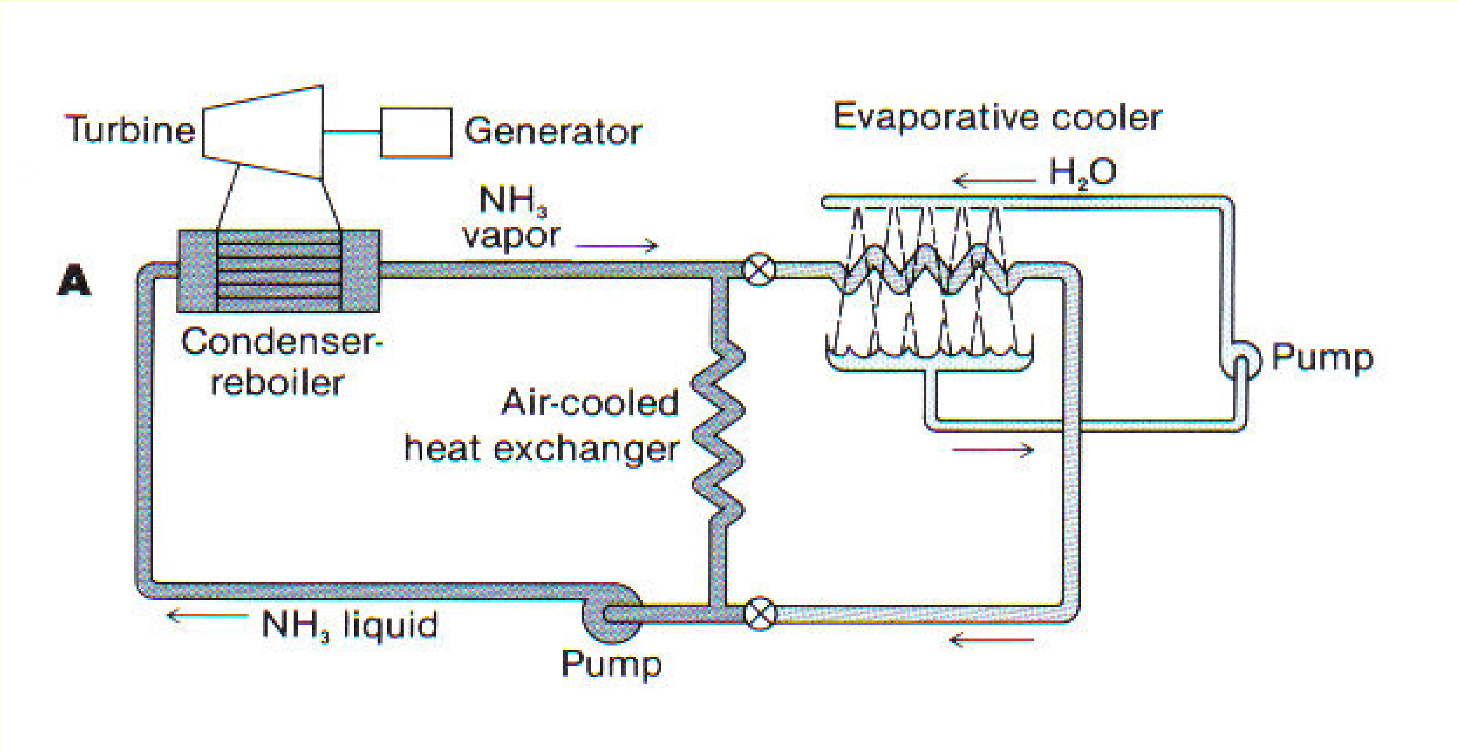
- Advanced Concept Test
  (EPRI, PGE, Union Carbide, Battelle)

- Enhanced ACT (CBI)

- CYBIAM (Electricite de France)

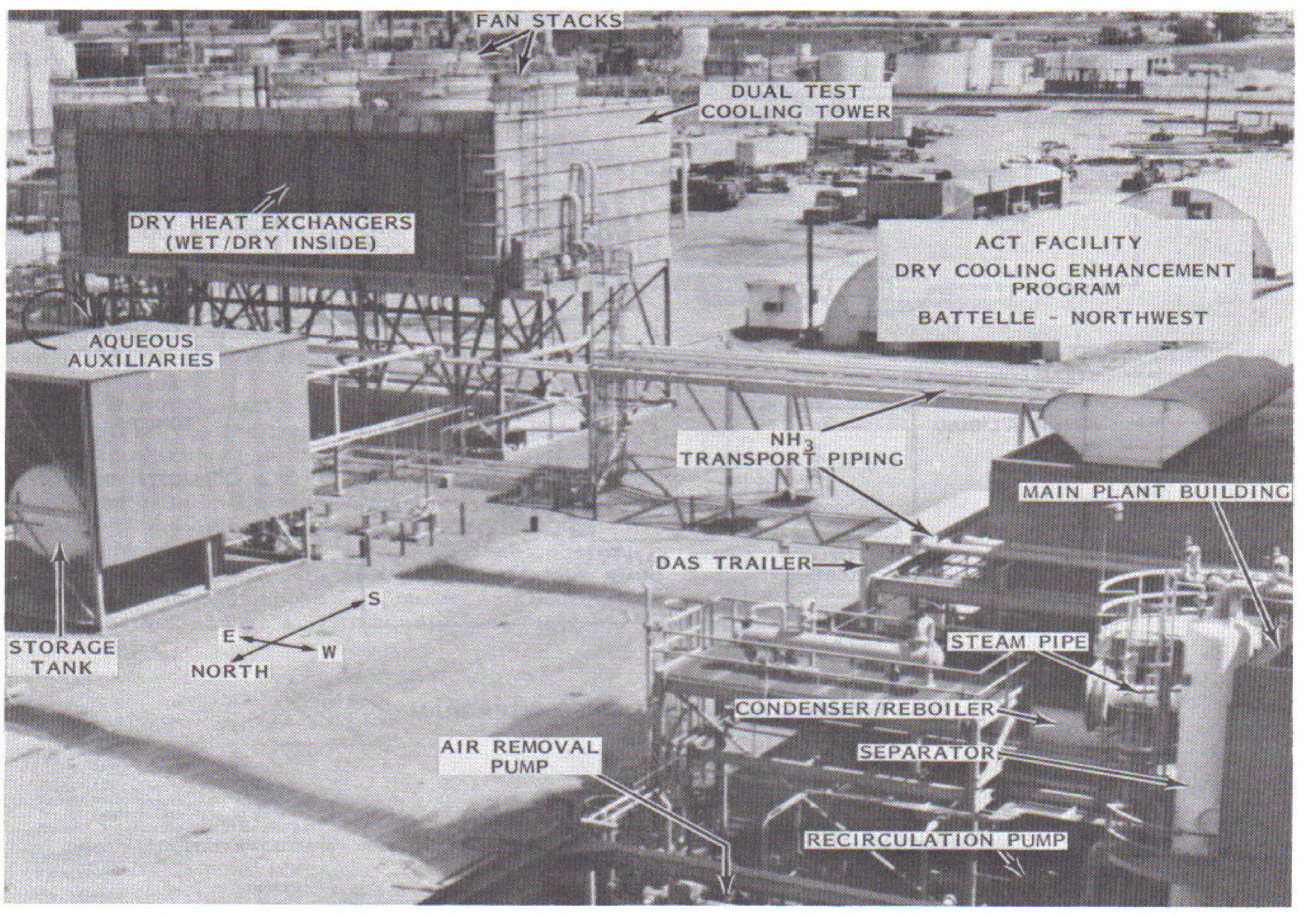
- SAPC

Advanced Concept Test

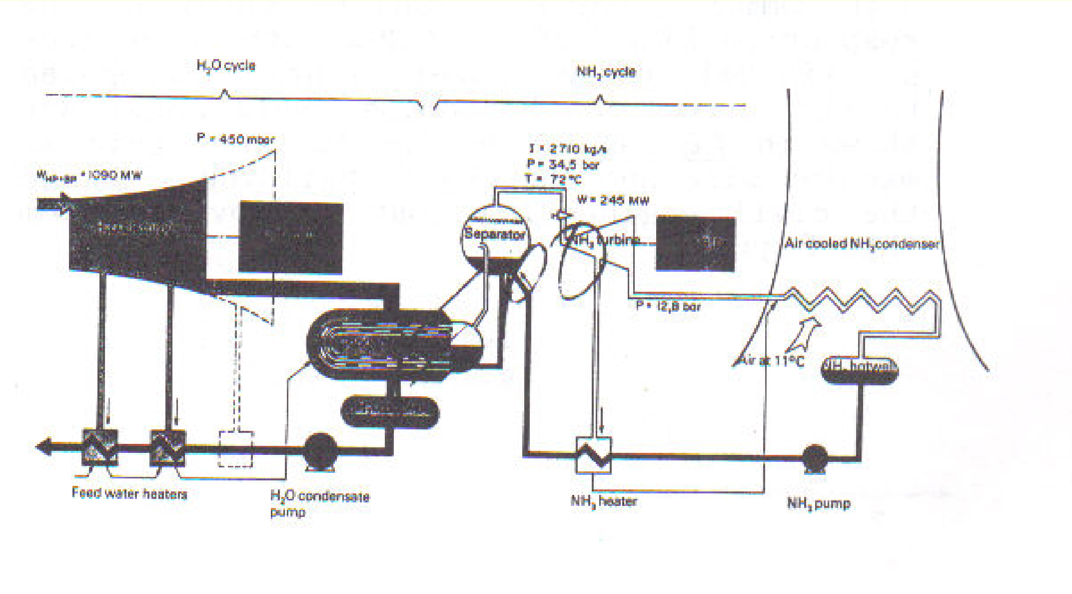


- Steam condenser/ammonia boiler (C/B)
- Eliminates vacuum air coil disadvantage
- Adds C/B disadvantage
- No net gain

Advanced Concept Test Facility

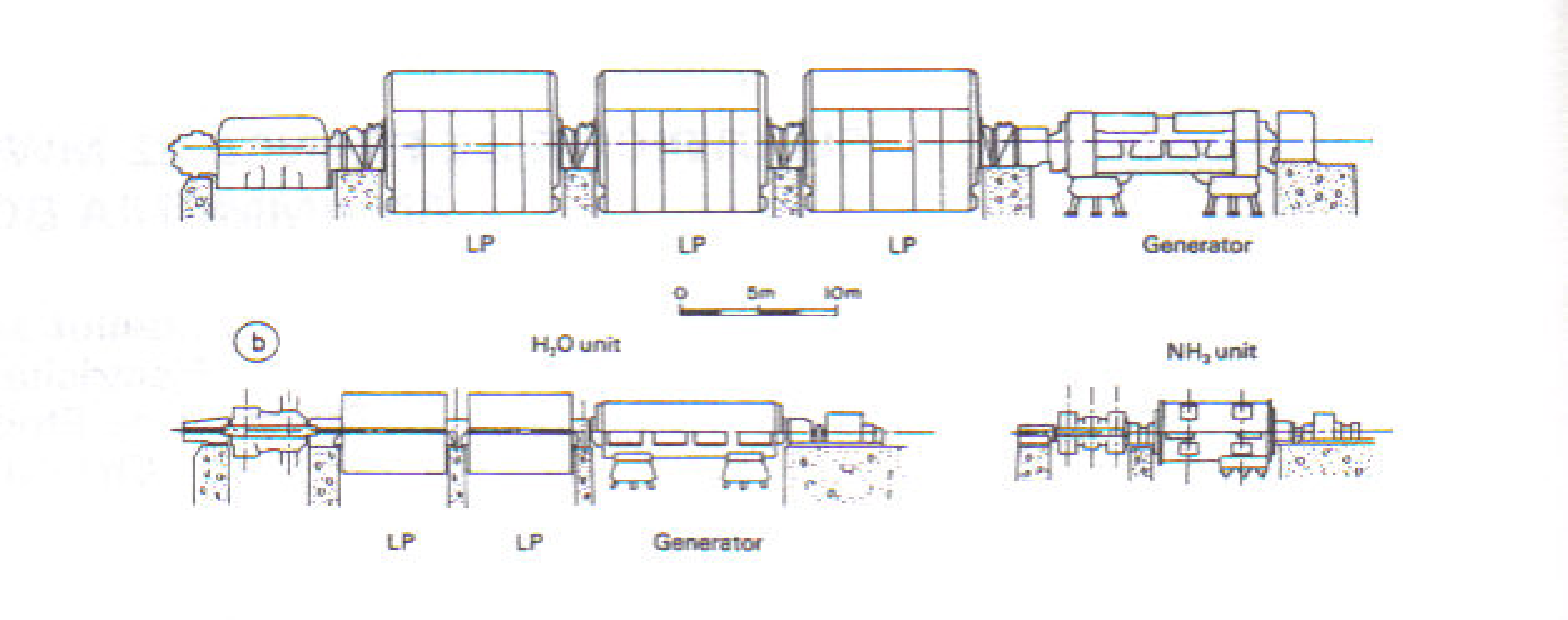


CYBIAM (EdF)



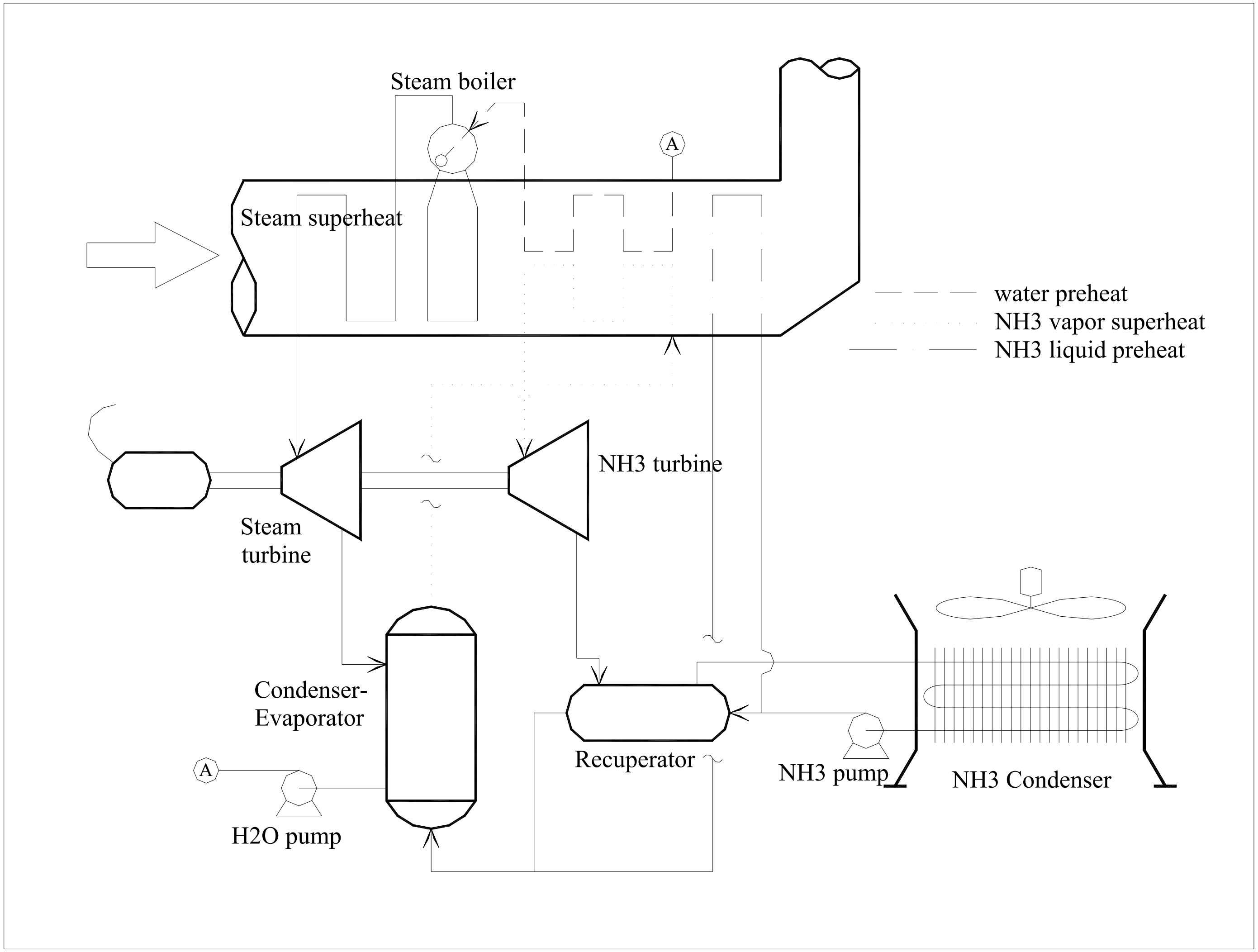
- Adds expander to C/B plus aircoil
- Two Rankine cycles with one inter connection
- Some benefit on capital and heat rate

CYBIAM Capital Advantage

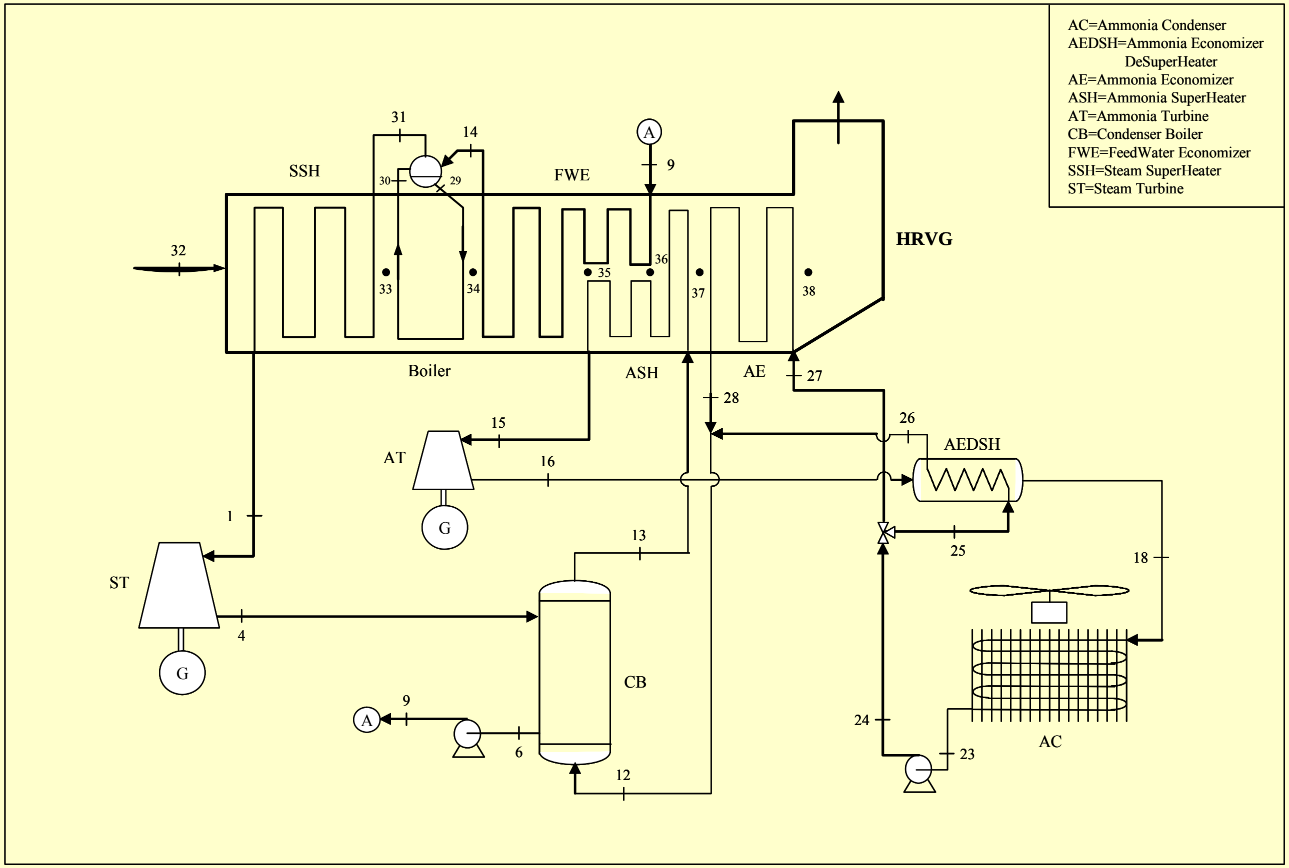


Steam-Ammonia Power Cycle

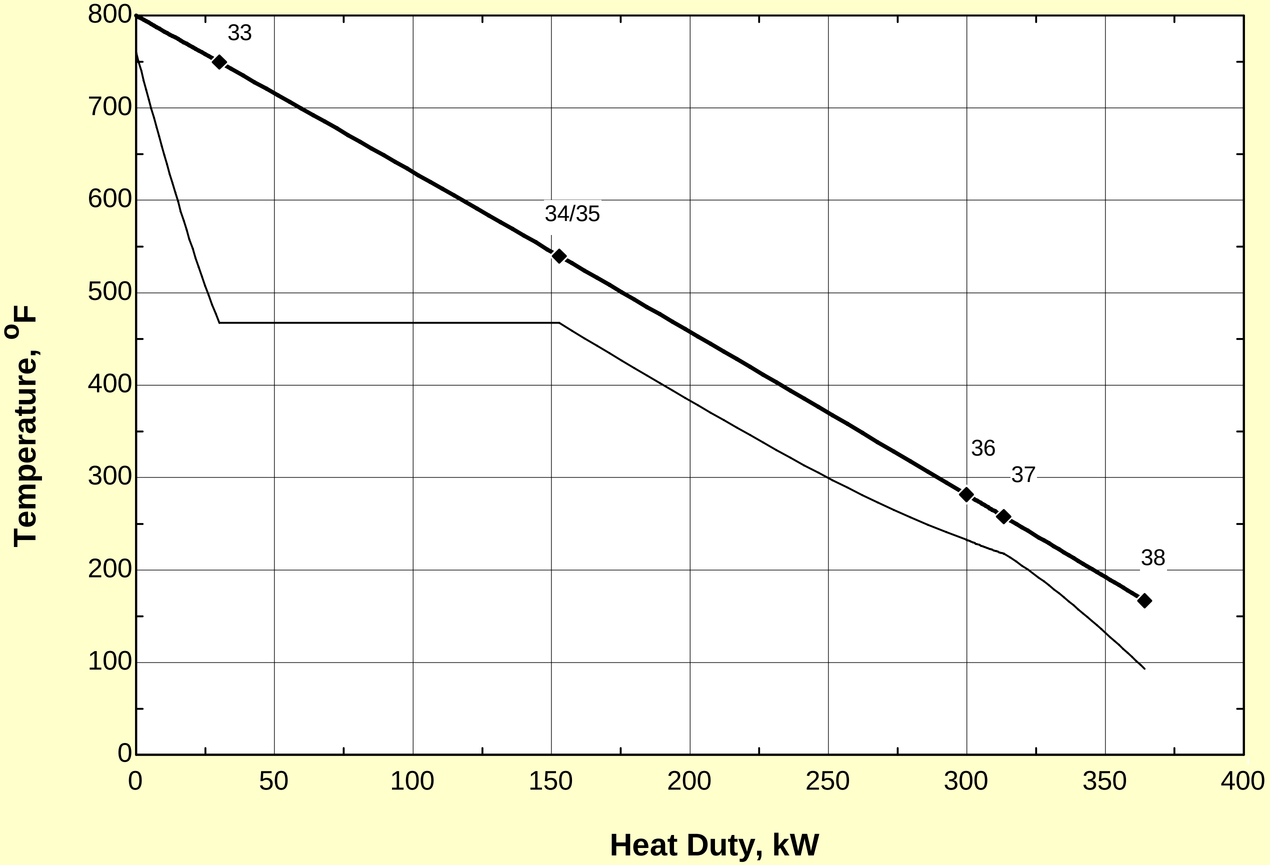
- Two Rankine cycles with two interconnections
- Adds superheater and economizer
- Major system efficiency gain due to glide matching
- Each working fluid stays within its optimum range
- Patented


Steam boiler
A
Steam superheat
water preheat
NH3 vapor superheat
NH3 liquid preheat
NH3 turbine
Steam
turbine
Condenser-
Evaporator
A
H2O pump
Recuperator
NH3 pump
NH3 Condenser

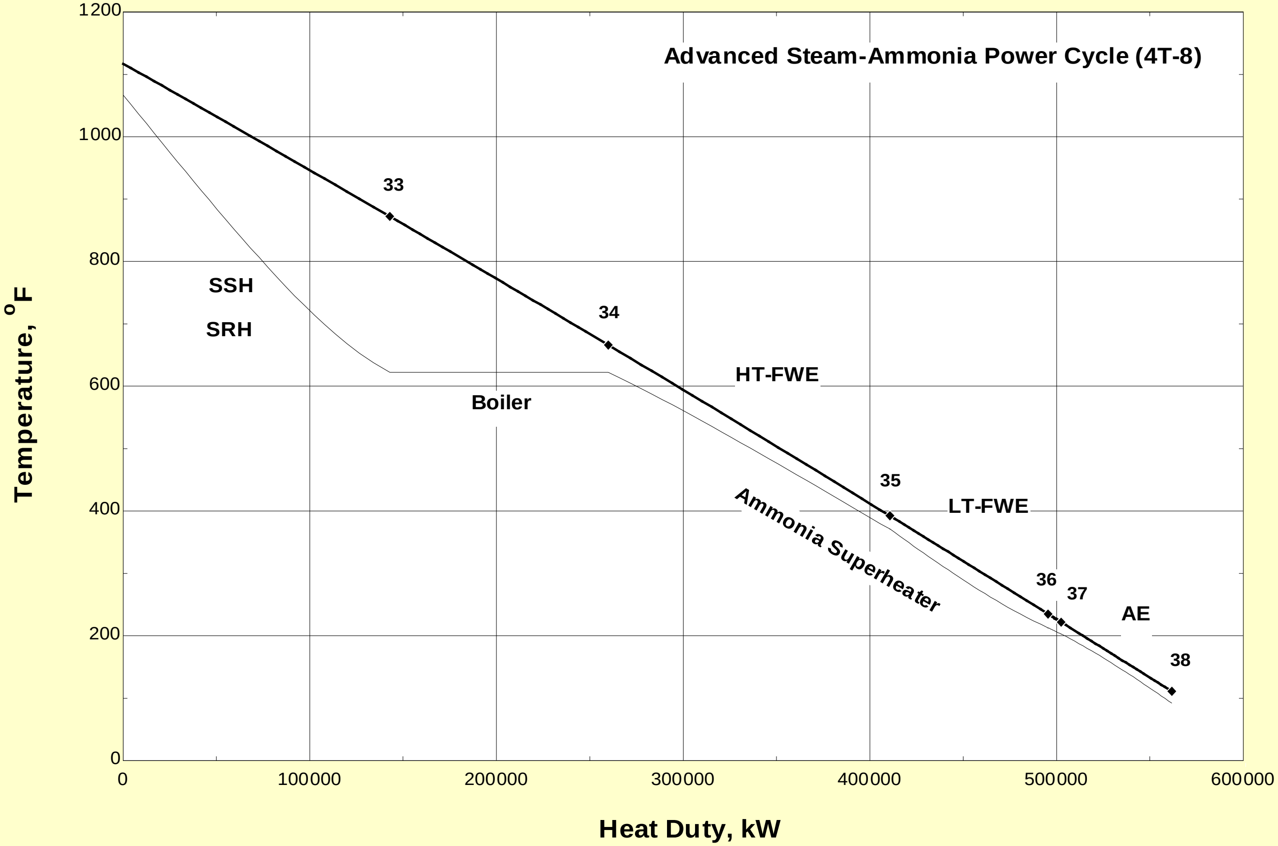
SAPC Flowsheet



SAPC Glide Matching



4 Turbine Cycle Comparison (World Class GTCC)



Development Plans

- Thermodynamic feasibility confirmed
- Need operating prototype
- Sized to fit Phase II budget
- Small size dictates cycle modification, useful in own right

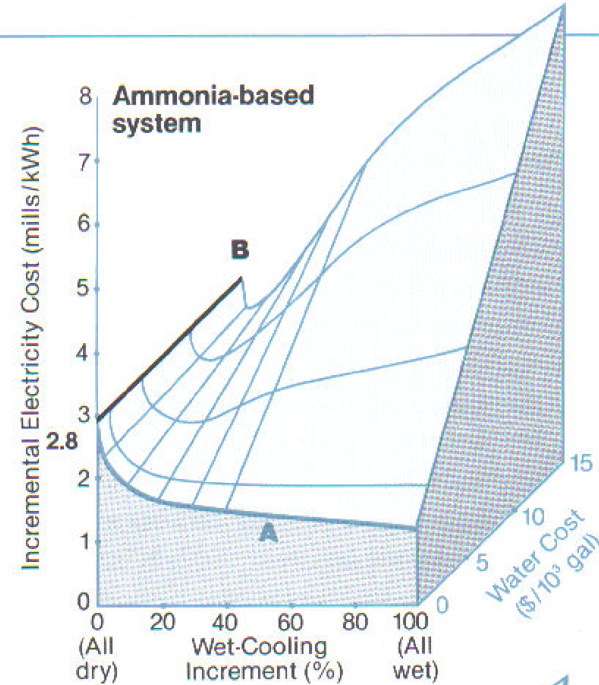
Advantages of Ammonia

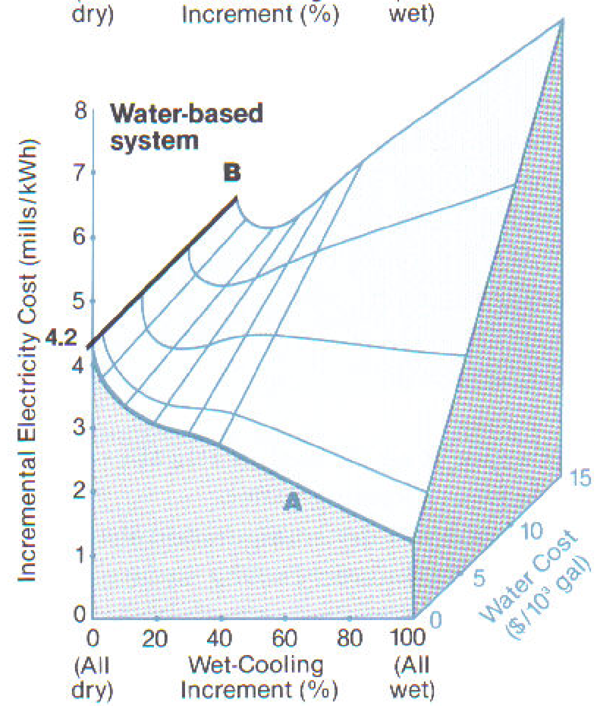
Three-dimensional graphs compare the incremental costs of electricity from power plants that use indirect dry cooling with ammonia (top) and with water (bottom). Sloping surfaces show how the cost varies when dry cooling is gradually replaced by wet (moving from left to right) and when the necessary water becomes more expensive (from front to back).

All-dry cooling is clearly cheaper with an ammonia-filled system (2.8 mills/kWh) than with a water-filled system (4.2 mills/kWh). And the ammonia system remains more economical even when 20–30% wet cooling is introduced at high water cost—as can be seen by comparing the lower elevations at the back of the graphs.

The important messages from these two graphs are that wet cooling is preferable whenever water is plentiful and cheap (low elevations in right foreground, indicated by *A*) and that a small substitution of wet cooling sharply reduces the overall cooling cost even when water is expensive (steep declines in elevation at left rear, indicated by *B*).

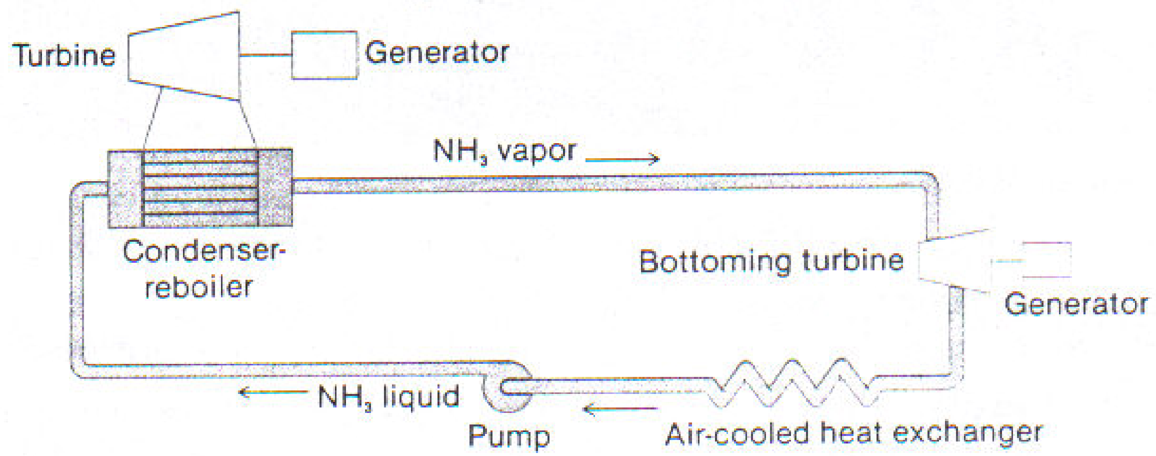
These incremental costs are over and above the base-case cost of electricity from a 500-MW plant (75% capacity factor) that uses once-through wet cooling.





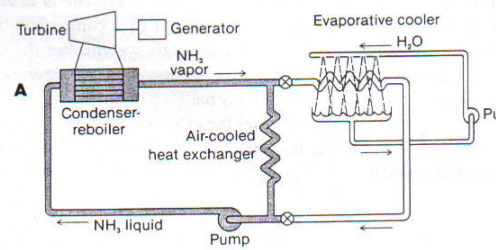
Coolant Vapor Drives Turbine

Ammonia's capacity (per unit volume) for heat exchange when it changes phase is the basis for using ammonia for indirect dry cooling. Its vapor phase can be further exploited by adding a small vapor turbine to the coolant loop, as in this system about to be tested by Electricité de France. Cost projections suggest that the energy from the bottoming turbine (about 25% of the overall output) will largely overcome the high cost of dry cooling.

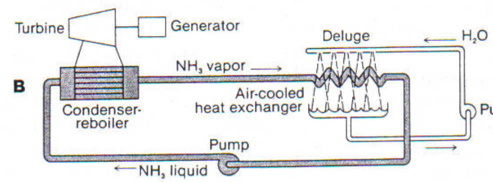


Three Ammonia-Based Systems

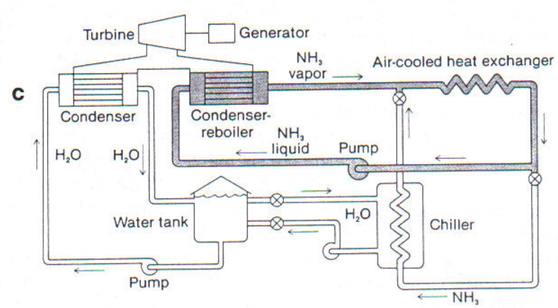
Circulating between a condenser-reboiler and an air-cooled heat exchanger, a closed loop of ammonia is the principal element of three dry-cooling systems developed under EPRI sponsorship.

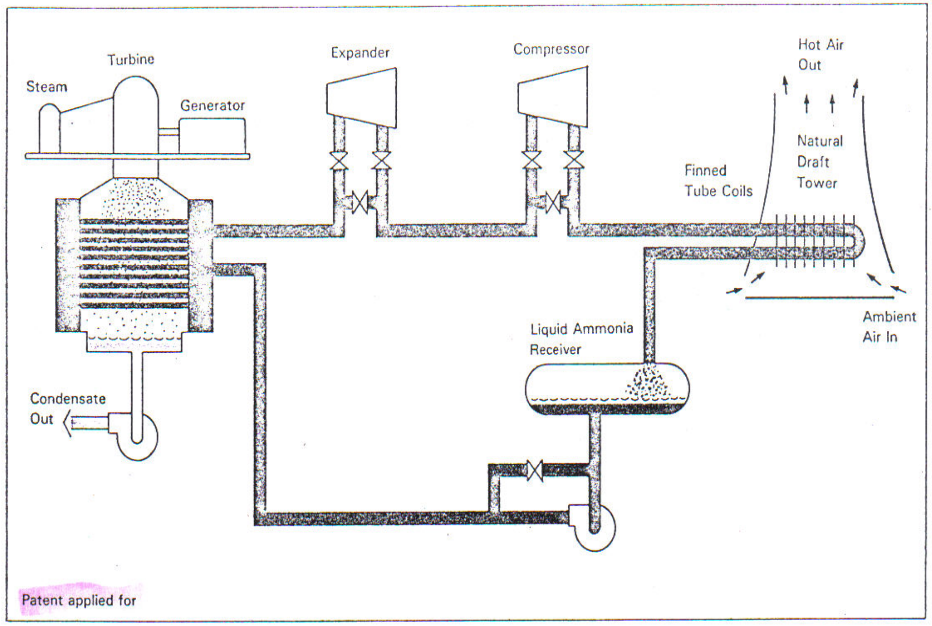


Two of the systems become wet-dry when supplemented by wet cooling. One of them, **A,** uses a small, separate evaporative cooler; the other, **B,** uses a shower of water (a "deluge") directly on the air-cooled heat exchanger.

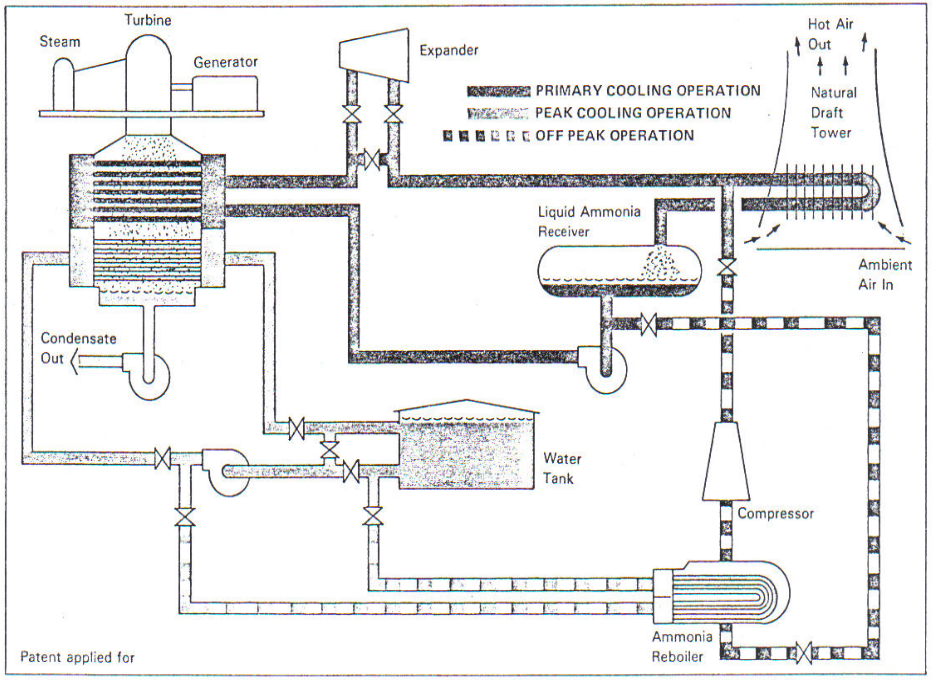


Where supplemental water is out of the question at all times, a system with capacitive cooling, **C,** uses a closed loop of water as an extra heat sink during the day, then cools that water via heat exchange with the ammonia loop at night.





CBI Natural Draft Dry Cooling Tower System with Compressor and Expander



CBI Natural Draft Dry Cooling Tower System with Peak Shaving System and Expander

US006895740B2

(12) **United States Patent**
Erickson

(10) **Patent No.:** **US 6,895,740 B2**
(45) **Date of Patent:** **May 24, 2005**

(54) **STEAM AMMONIA POWER CYCLE**

(75) Inventor: **Donald C Erickson**, Annapolis, MD (US)

(73) Assignee: **Donald C. Erickson**, Annapolis, MD (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/348,392**

(22) Filed: **Jan. 21, 2003**

(65) **Prior Publication Data**

US 2004/0139747 A1 Jul. 22, 2004

(51) **Int. Cl.**[7] **F02C 6/00**; F02G 1/00; F02G 3/00

(52) **U.S. Cl.** **60/39.182**; 60/772; 60/39.181

(58) **Field of Search** .... 60/39.181, 39.182, 60/772, 39.183; 122/7 R

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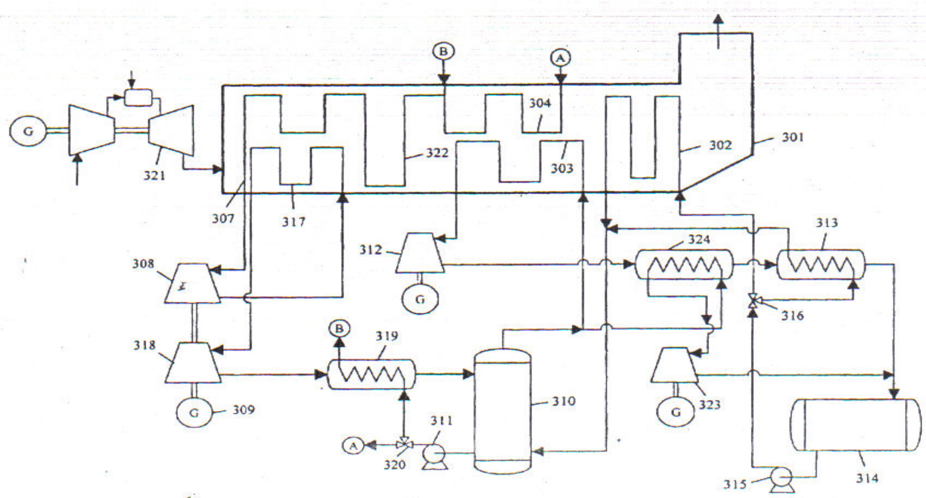
Primary Examiner—Cheryl Tyler
Assistant Examiner—William H. Rodriguez

(57) **ABSTRACT**

An integrated steam-ammonia power cycle is disclosed which achieves a close match to a glide heat source such as exhaust from a gas turbine, and which also eliminates sub-atmospheric pressure operation. With reference to FIG. **1**, the exhaust heats in sequence steam superheater **107**; steam boiler **105**; feedwater preheater **104** plus ammonia superheater **103**; and ammonia preheater **102**. Steam is expanded to at least 17 psia in turbine **108**, then condensed to boil ammonia in boiler **110**. Superheated ammonia is expanded in turbine **112**, and condensed in condenser **114**. Feed ammonia is preheated in at least two parallel preheaters.

22 Claims, 3 Drawing Sheets



Fresh Water Production Using Waste Heat for Distillation

By: James F. Klausner, Yi Li and Renwei Mei
University of Florida

NETL Water and Power Plants Review Meeting

Supported by U.S. Department of Energy, under Award No. DE-FG26-02NT41537.

Motivation for Developing Technology

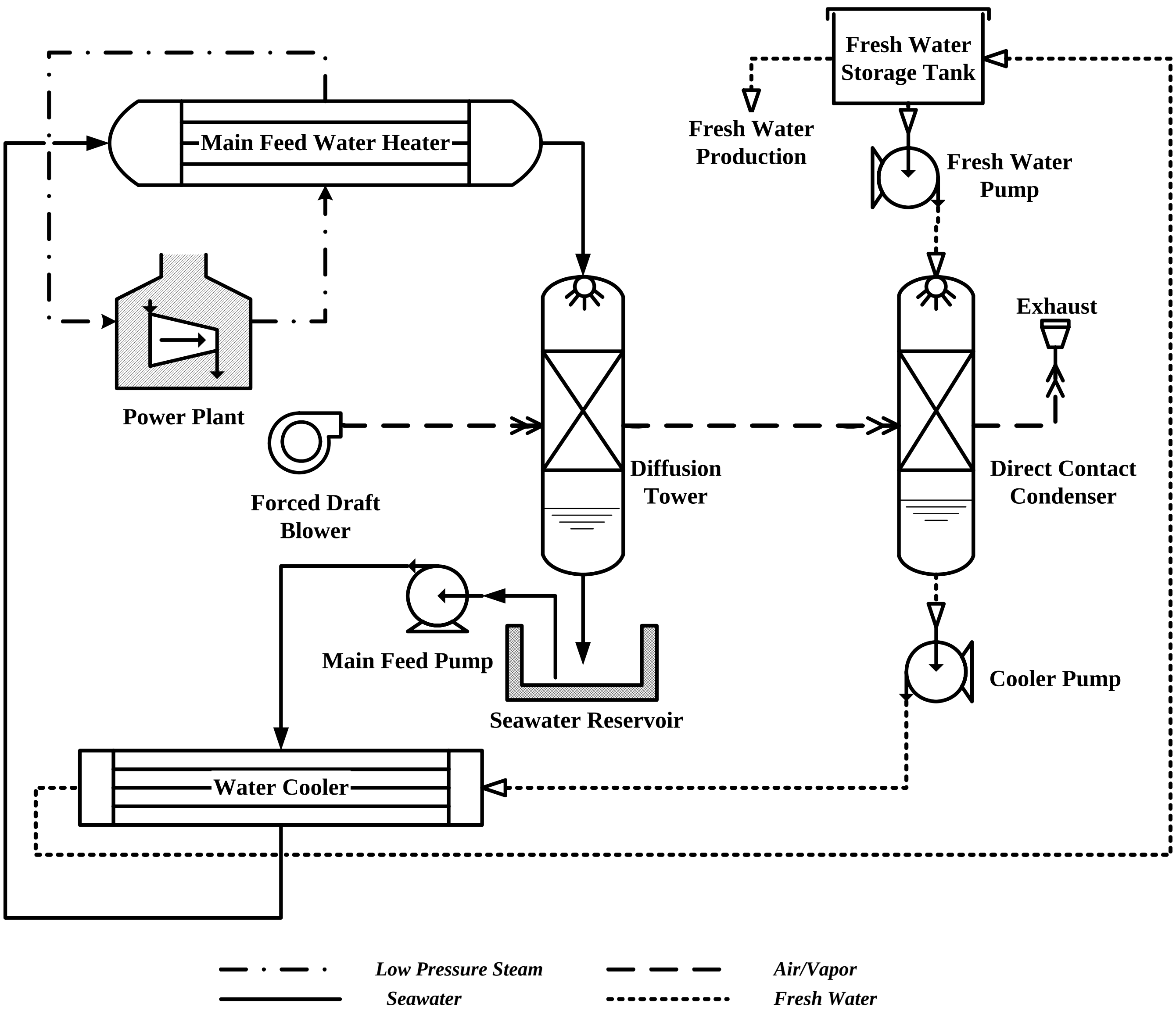
- Fresh water is a commodity in diminishing supply

- Conventional water distillation plants are energy intensive, and fresh water production is expensive

- There exist many industrial processes that produce waste heat that is discarded to the environment; waste heat may be utilized to produce fresh water

- Ideal technology will utilize waste heat to produce fresh water and deliver large production rate with low additional energy consumption

University of Florida Diffusion Driven Desalination Process



Advantages of Diffusion Driven Desalination

- Waste heat may be used to produce fresh water

- Temperature requirement for heated water is as low as 45 C

- Low energy consumption process when integrated with a power plant

- Low temperature and pressure process; inexpensive materials of construction and waste heat from many different sources is useful for fresh water production

- Very large production rates possible; waste heat from a 300 MW power plant can produce 3.1 million gallons of fresh water per day

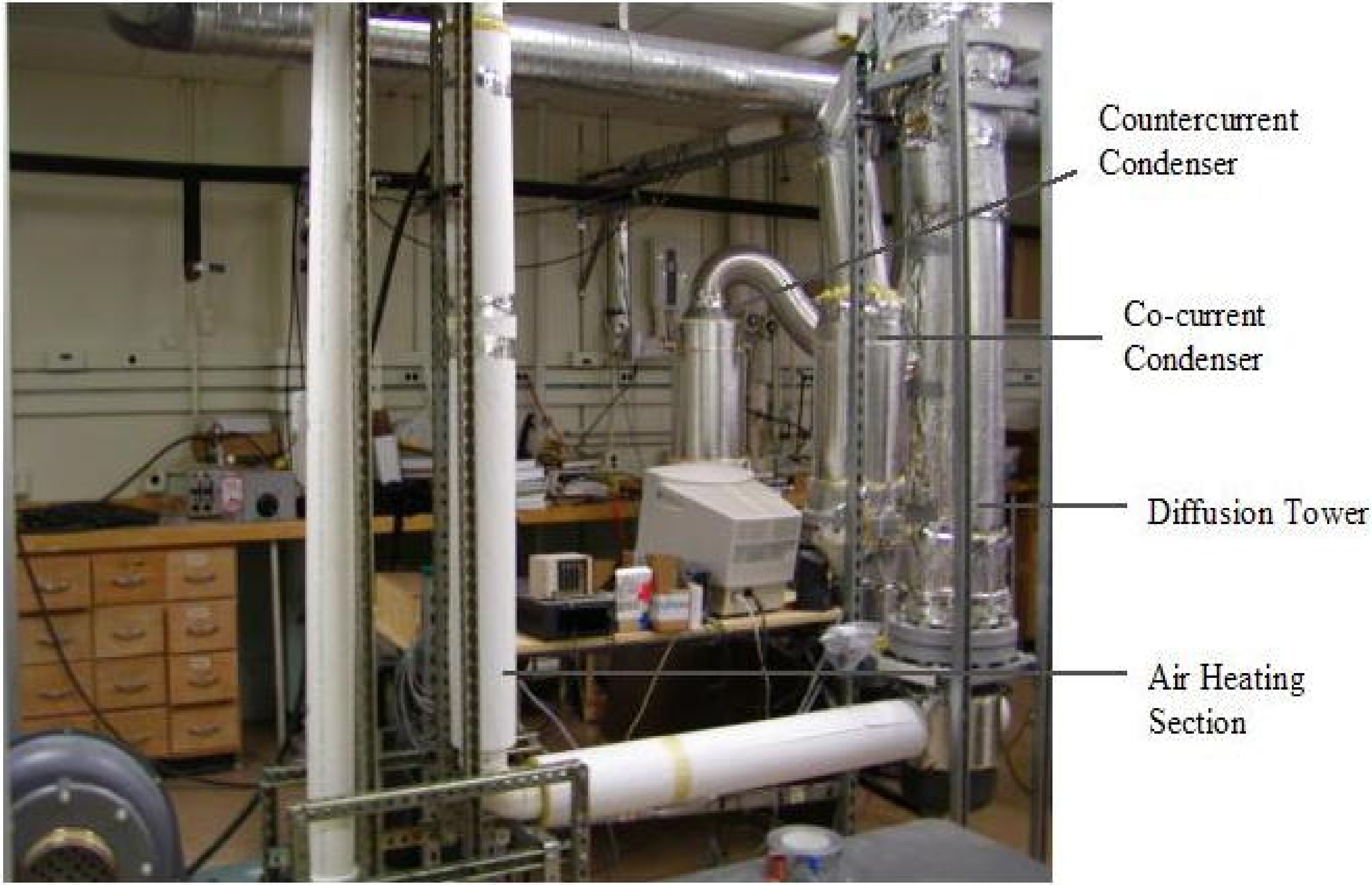
Diffusion Driven Desalination for the Electric Power Industry

Diablo Nuclear Power Plant,
San Luis Obispo

I. Power Plants Coupled With Desalination Plant

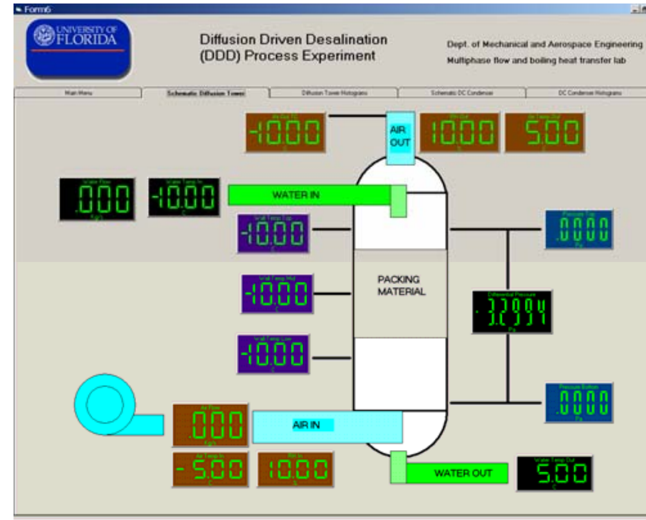
- Many electric power generation plants are sited along the coastline
- Power plants discharge waste heat into the environment via cooling towers or direct discharge into the sea
- Utilize waste heat to produce fresh water

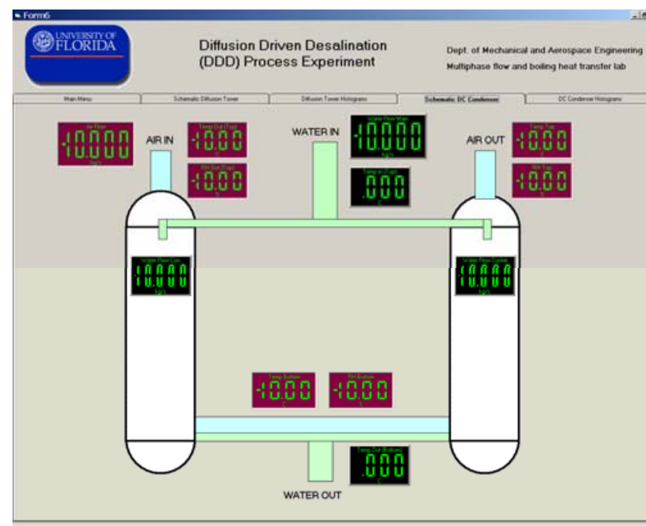
Lab Scale DDD Facility



Packing Material

Data Acquisition





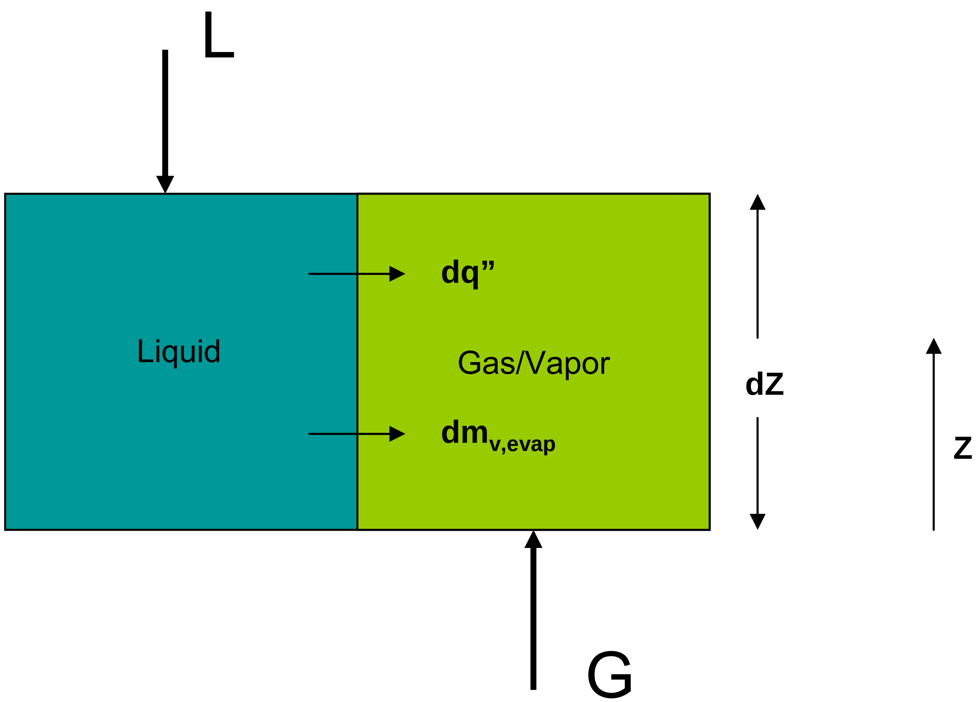
Diffusion Tower Analysis

- First analysis of cooling towers provided by Merkel (1925)

Key assumptions: 1) Water mass loss is negligible and
2) the Lewis number is unity

- Merkel analysis not suited for diffusion tower design

Two Film Theory Used to Derive Governing Equations



Governing Equations

Conservation of Energy--Liquid

$$\frac{dT_L}{dz} = \frac{G}{L}\frac{d\omega}{dz}\frac{(h_{Fg} - h_L)}{Cp_L} + \frac{Ua(T_L - T_a)}{Cp_L L}$$

Conservation of Energy--Gas/Vapor

$$\frac{dT_a}{dz} = -\frac{1}{1+\omega}\frac{d\omega}{dz}\frac{h_L(T_a)}{Cp_G} + \frac{Ua(T_L - T_a)}{Cp_G \cdot G(1+\omega)}$$

Mass Transfer

$$\frac{d\omega}{dz} = \frac{k_G a_w}{G}\frac{M_V}{R}\left(\frac{P_{sat}(T_i)}{T_i} - \frac{\omega}{0.622+\omega}\frac{P}{T_a}\right)$$

Problem Encountered

- **Three coupled ODE's; use Runge-Kutta and march in z-direction to solve for TL , Ta , and ω; equations require closure:**
  - Gas side mass transfer coefficient, k_G, must be specified, correlations in dimensional form are not useful
  - Overall heat transfer coefficient, U, must be specified, but we cannot directly determine the liquid and gas heat transfer coefficients from measured data
  - Interfacial temperature, T_i, required, but We cannot measure the interfacial temperature

Determination of Heat and Mass Transfer Coefficients

- **Onda et al. (1968) correlation used to evaluate liquid and gas mass transfer coefficients; widely tested**

$$k_L = 0.0051 \mathrm{Re}_{Lw}^{2/3} Sc_L^{-0.5} (ad_p)^{0.4} \left[\frac{\mu_L g}{\rho_L} \right]^{1/3}$$

$$k_G = 5.23 \mathrm{Re}_{GA}^{0.7} Sc_G^{1/3} (ad_p)^{-2} aD_G$$

$$^{\#}a_w = a\left\{1 - \exp\left[-2.2\left(\frac{\sigma_c}{\sigma_L}\right)^{3/4} \mathrm{Re}_{LA}^{1/2} Fr_L^{-0.05} We_L^{1/5}\right]\right\}$$

This equation was slightly modified from its original form

$$\mathrm{Re}_{LW} = \frac{L}{a_w \mu_L} \qquad \mathrm{Re}_{GA} = \frac{G}{a\mu_G} \qquad \mathrm{Re}_{LA} = \frac{L}{a\mu_L}$$

$$Sc_G = \frac{\mu_G}{\rho_G D_G} \qquad Sc_L = \frac{\mu_L}{\rho_L D_L} \qquad We_L = \frac{L^2}{\rho_L \sigma_L a} \qquad Fr_L = \frac{L^2 a}{\rho_L g}$$

Determination of Heat and Mass Transfer Coefficients

•**Heat and mass transfer analogy used to evaluate heat transfer coefficients:**

$$\frac{Nu_L}{\Pr_L^{1/2}} = \frac{Sh_L}{Sc_L^{1/2}} \quad \text{and} \quad \frac{Nu_G}{\Pr_G^{1/3}} = \frac{Sh_G}{Sc_G^{1/3}}$$

Liquid side heat transfer coefficient

$$U_L = k_L \left(\rho_L C_{pL} \frac{\kappa_L}{D_L} \right)^{1/2}$$

Gas side heat transfer coefficient

$$U_G = k_G \left(\rho_G C_{pG} \right)^{1/3} \left(\frac{\kappa_G}{D_G} \right)^{2/3}$$

Determination of Interfacial Temperature

Interfacial Energy Balance

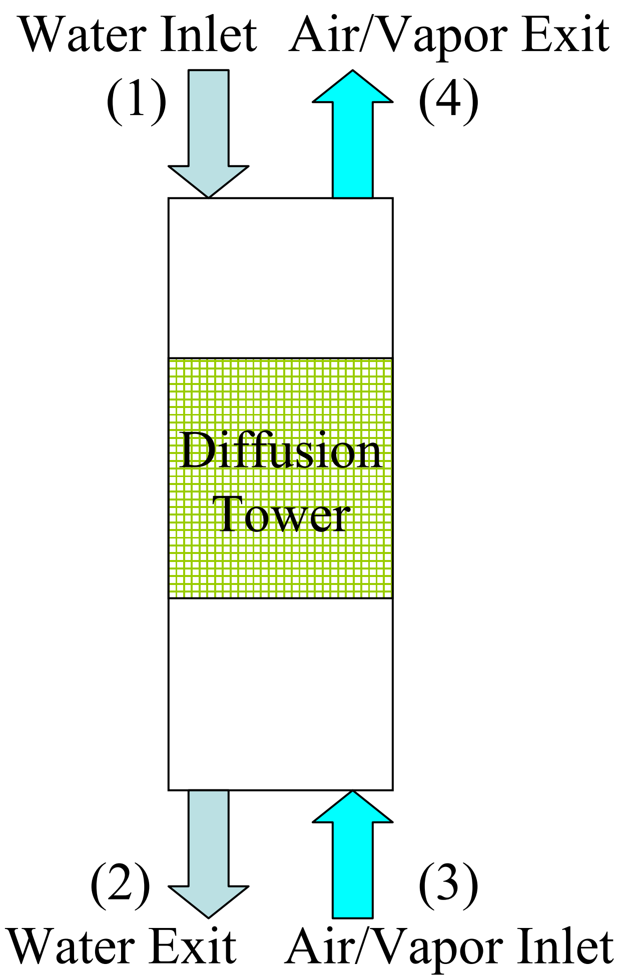
$$U_L(T_L - T_i) = U_G(T_i - T_a)$$

Evaluation of Interfacial Temperature

$$T_i = \frac{T_L - {U_G}/{U_L}\, T_a}{1 + {U_G}/{U_L}}$$

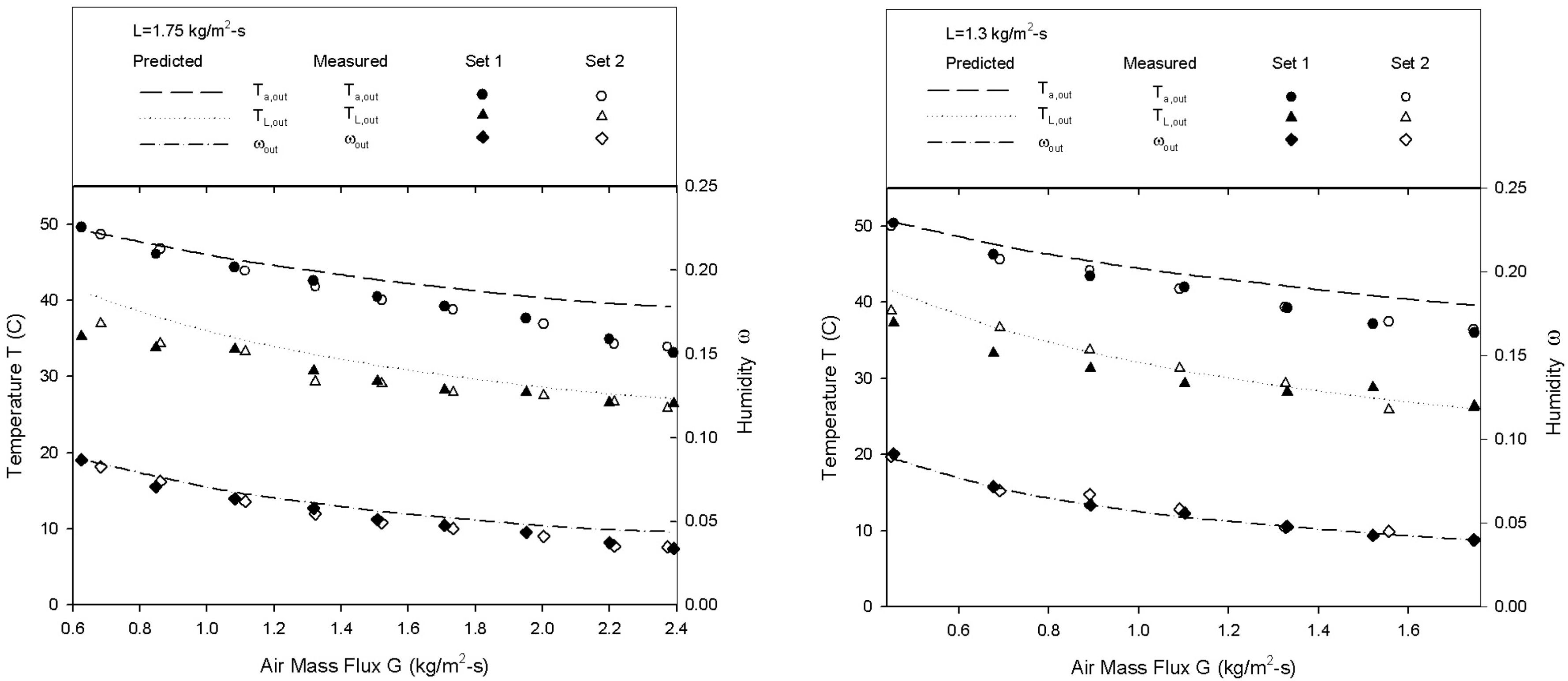
- **In practice we find T_i~T_L**

Diffusion Tower Design and Analysis



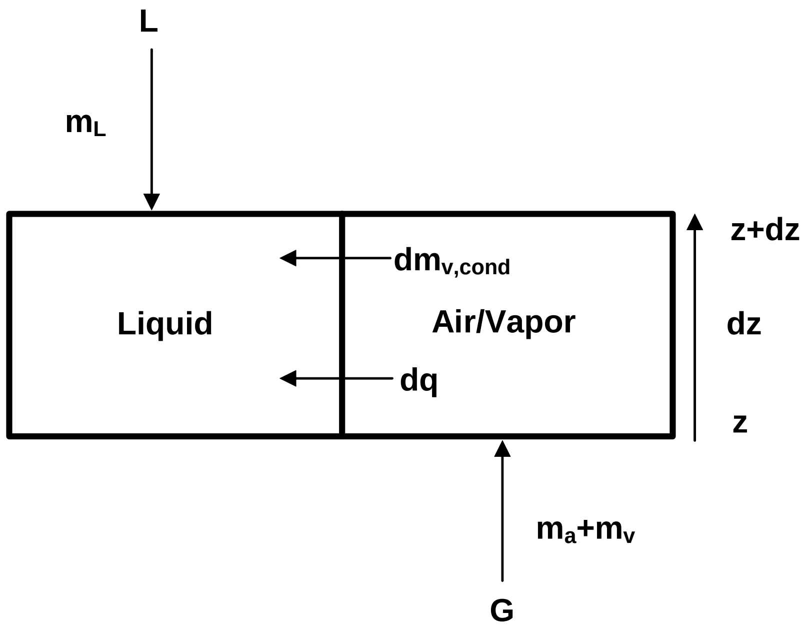
- **Specify inlet conditions**
  - Inlet water mass flux,temperature
  - Inlet air mass flux, temperature and relative humidity
- **Guess water exit conditions**
  - exit water temperature
- **Apply conservation of mass and energy to liquid and gas/vapor mixture**
  - Use explicit marching scheme
  - Stop computation when water temperature reaches specified inlet water temperature

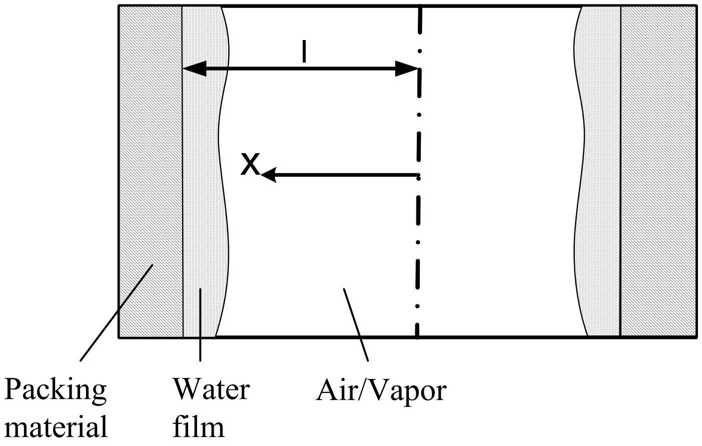
Experiment Validation of Diffusion Tower Model



Direct Contact Condenser Analysis

- Two film theory used to derive governing equations
- Non-uniform distribution of the air temperature in the transverse direction, the mean humidity is used in the one dimensional conservation equations





Governing Equations

Conservation of Energy--Liquid

$$\frac{dT_L}{dz} = \frac{G}{L}\frac{d\omega}{dz}\frac{(h_{Fg} - h_L)}{Cp_L} + \frac{Ua(T_L - T_a)}{Cp_L L}$$

Conservation of Energy--Gas/Vapor

$$\frac{dT_a}{dz} = -\frac{1}{1+\omega}\frac{d\omega}{dz}\frac{h_L(T_a)}{Cp_G} + \frac{Ua(T_L - T_a)}{Cp_G \cdot G(1+\omega)}$$

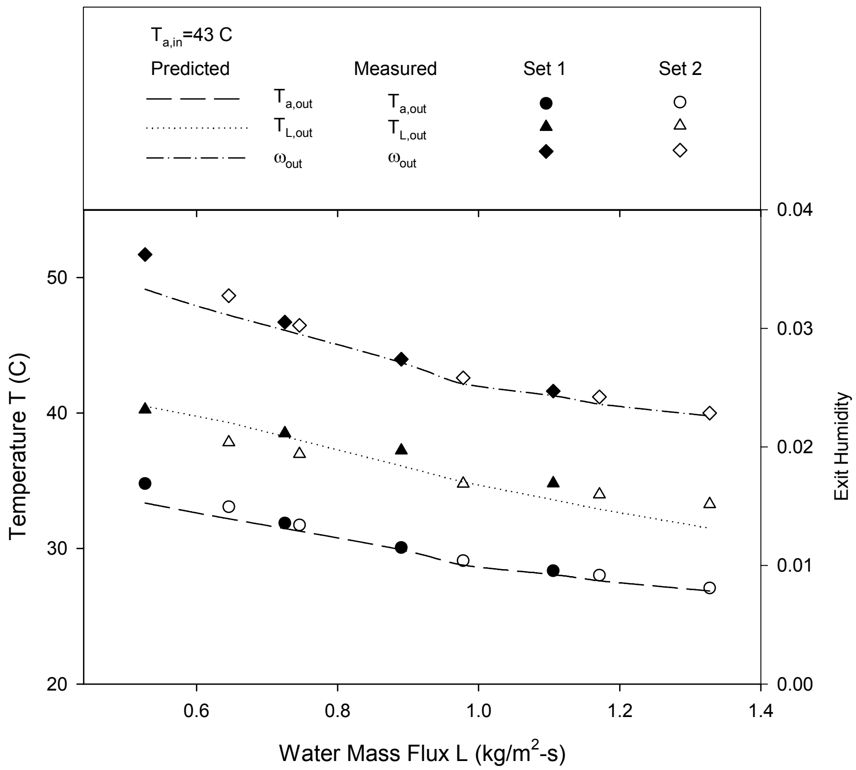
Mass Transfer

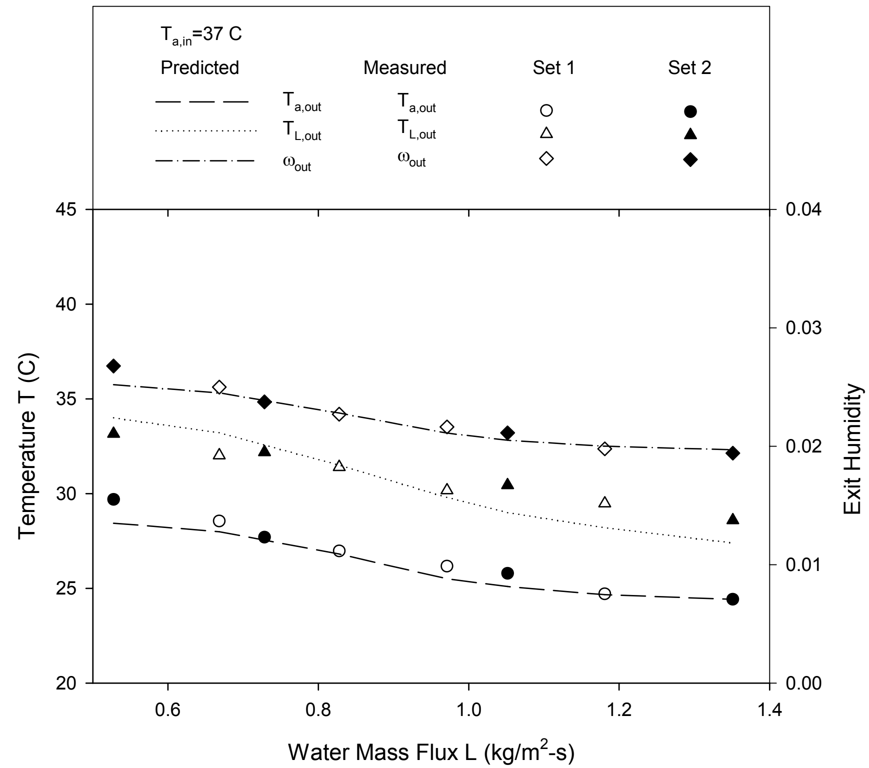
$$\frac{d\omega}{dz} = \frac{dT_a}{dz}\frac{P}{P - P_{sat}(T_a)}\omega(b - 2cT_a + 3dT_a^2)$$

Condenser Design and Analysis

- **Specify inlet conditions**
  - Inlet water mass flux,temperature
  - Inlet air mass flux, temperature and relative humidity
- **Guess water exit temperature**
- **Compute the mean humidity**
- **Compute the temperatures and humidity at this height**
- **Proceed to a new height, compute the temperatures and humidity until the exit air temperature is minimum**
- **Check whether the computed inlet water temperature reaches specified inlet water temperature;**
- **Stop computation when agreement is reached; otherwise guess a new exit water temperature and cycle through compution again.**

Experiment Validation of Counter Current Condenser Model





Electric Power Consumption

Pressure drop on water side

$$\Delta P_L = \rho_L g h$$

Fresh water production rate

$$m_f = GA(\omega_{out} - \omega_{in})$$

Pressure drop on gas side

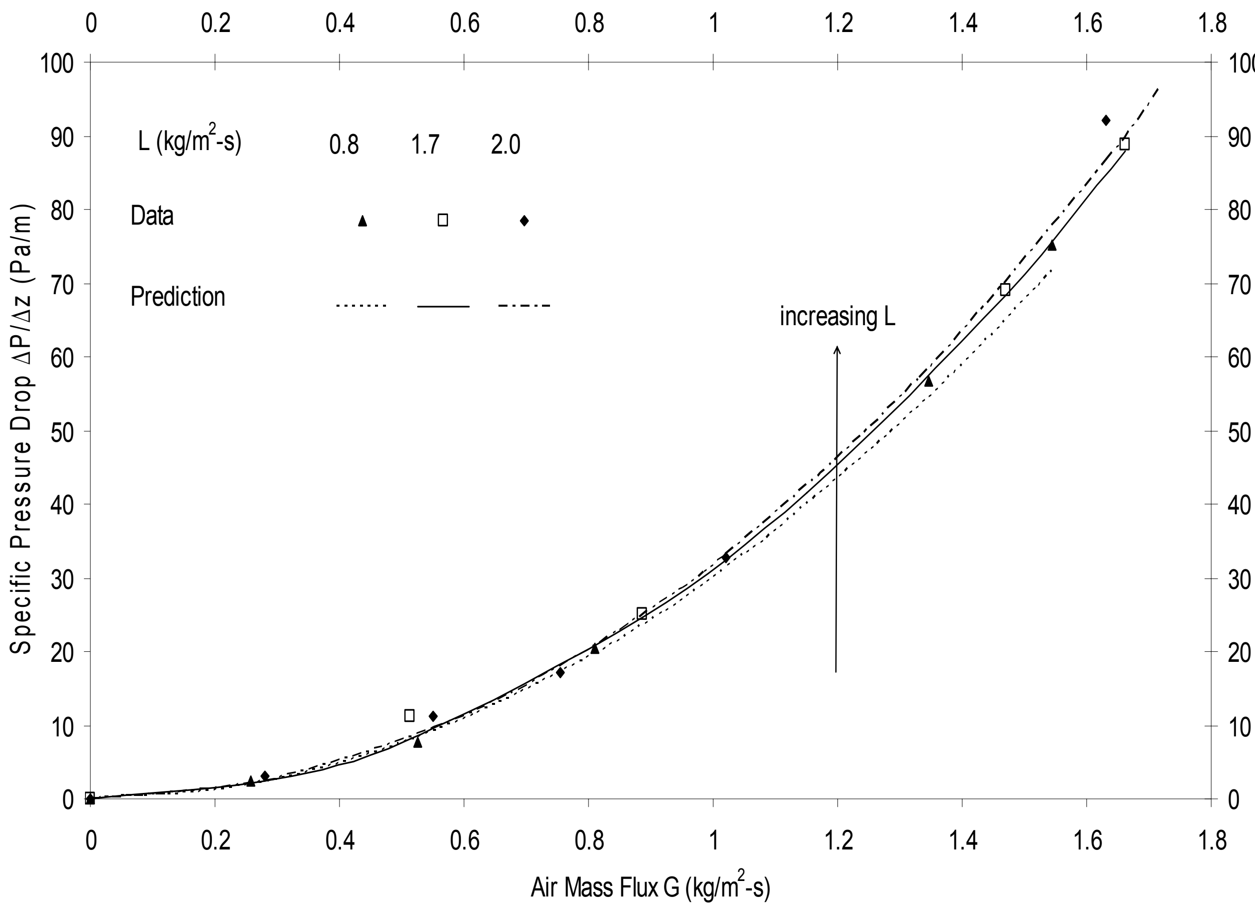
$$\frac{\Delta P_G}{z} = \frac{G^2}{\rho_G}[0.0354 + 5.05 \times 10^{-5}(\frac{L}{\rho_L})^2 + 7.0 \times 10^{-8}(\frac{L}{\rho_L})^4 \frac{G^4}{\rho_G^2}]$$

Energy consumption rate

$$E_{total} = \frac{LA}{\rho_L}\Delta P_L + \frac{GA}{\rho_g}\Delta P_g$$

$$E_{fw} = \frac{E_{total}}{m_{fw}}$$

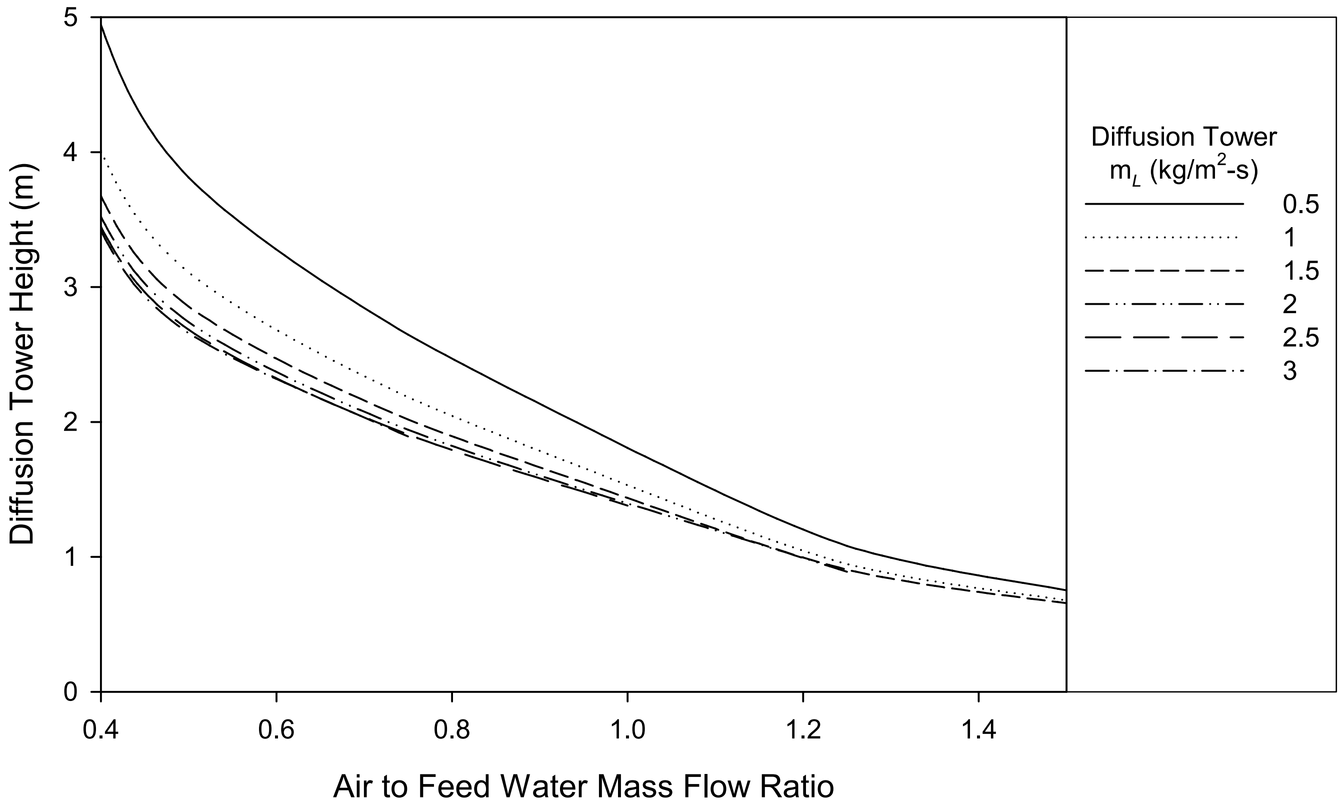
Experiment Validation of the Pressure Drop through the Packing



Parametric Study of DDD Performance

- Compute required tower height
- Compute total pumping power for system
- Examine optimum air to water flow ratio
- Estimate cost of fresh water production

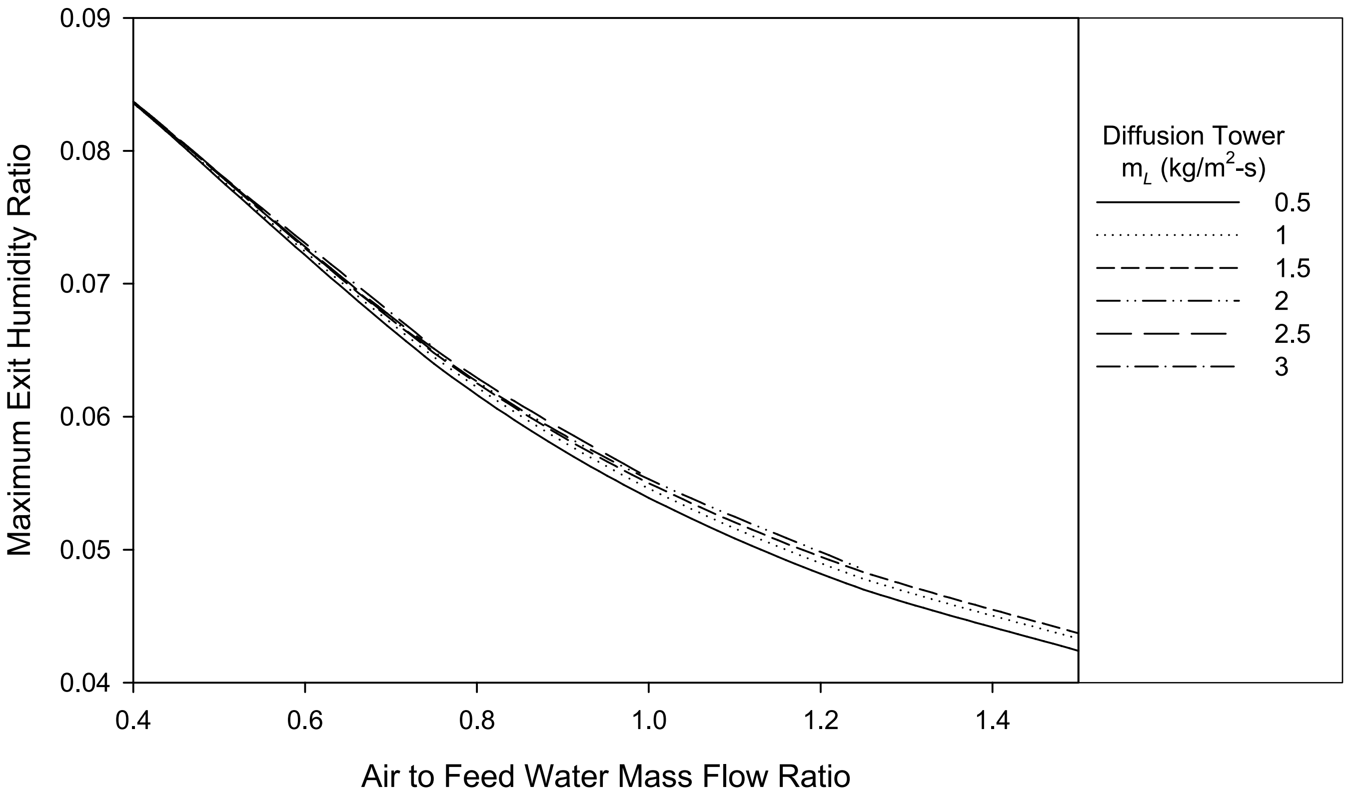
Diffusion Tower Computational Results



Required tower height for $T_{w,l}$=50 C at different water mass flux and air/water flow ratio

- **Required tower height increases with decreasing G/L**

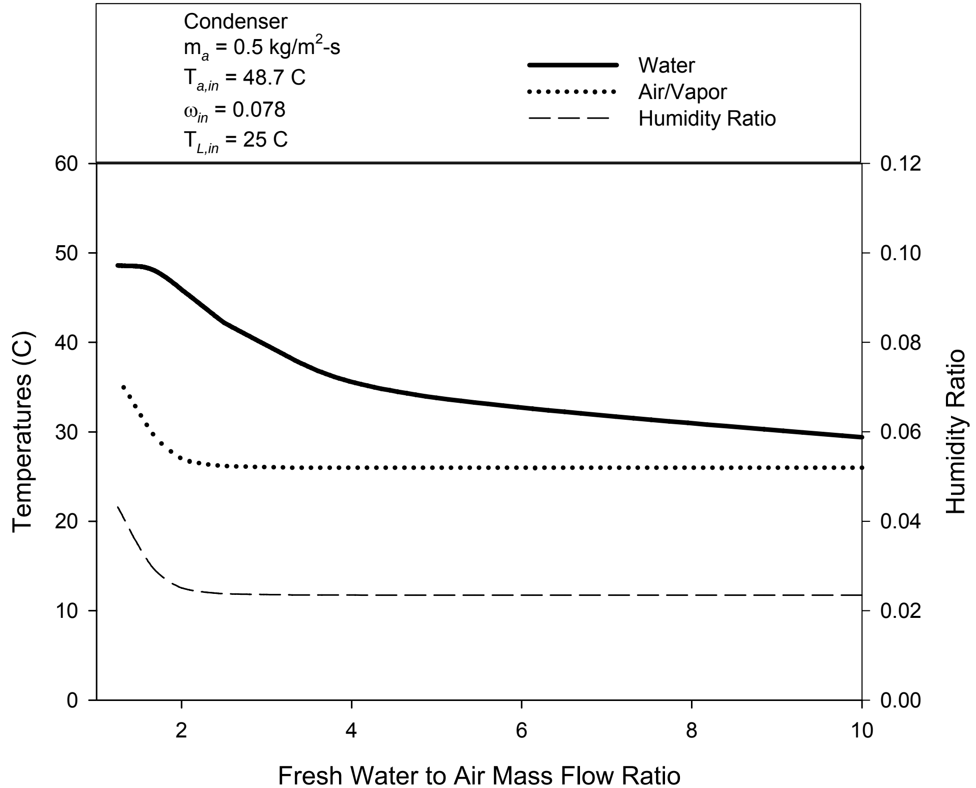
Diffusion Tower Computational Results



Maximum outlet humidity ratio for $T_{w,I}$=50 C at different air/water flow ratio and water mass flux

- **Maximum outlet humidity ratio governed by air/water flow ratio**

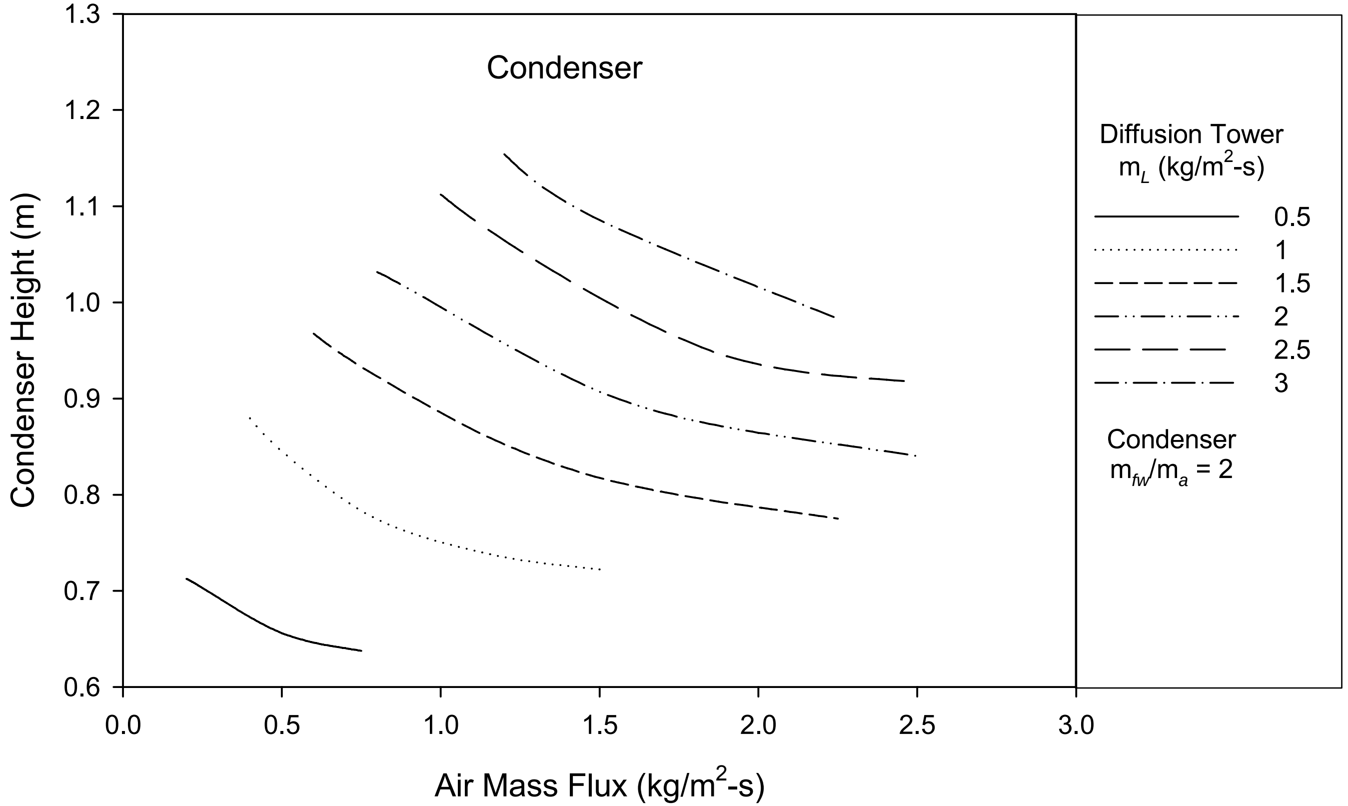
Condenser Computational Results



Condenser temperature and humidity ratio variation with fresh water to air mass flow ratio

- **Minimum exit humidity ratio is observed when the fresh water to air mass flow ratio is 2.**

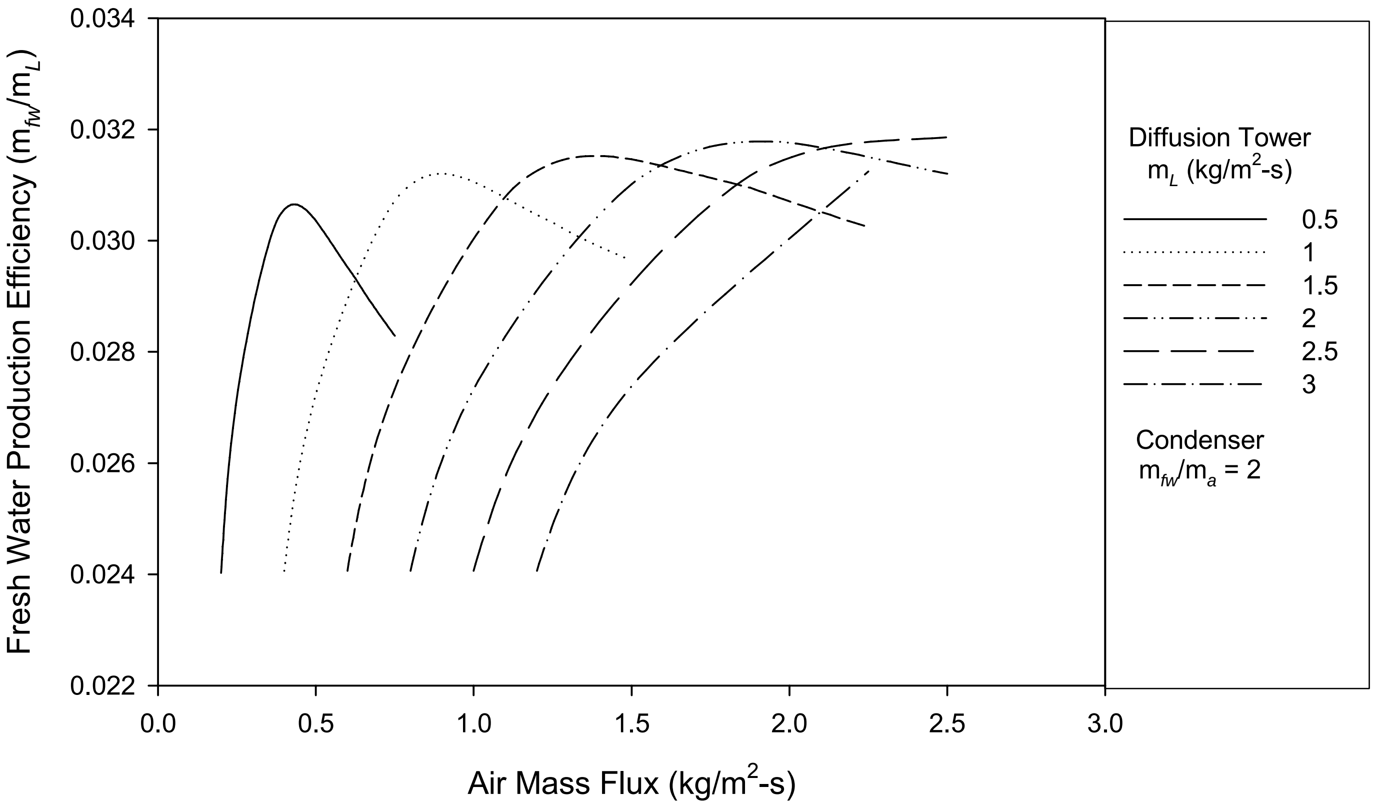
Condenser Computational Results



Required direct contact condenser height with variations in air mass flux (counter current only)

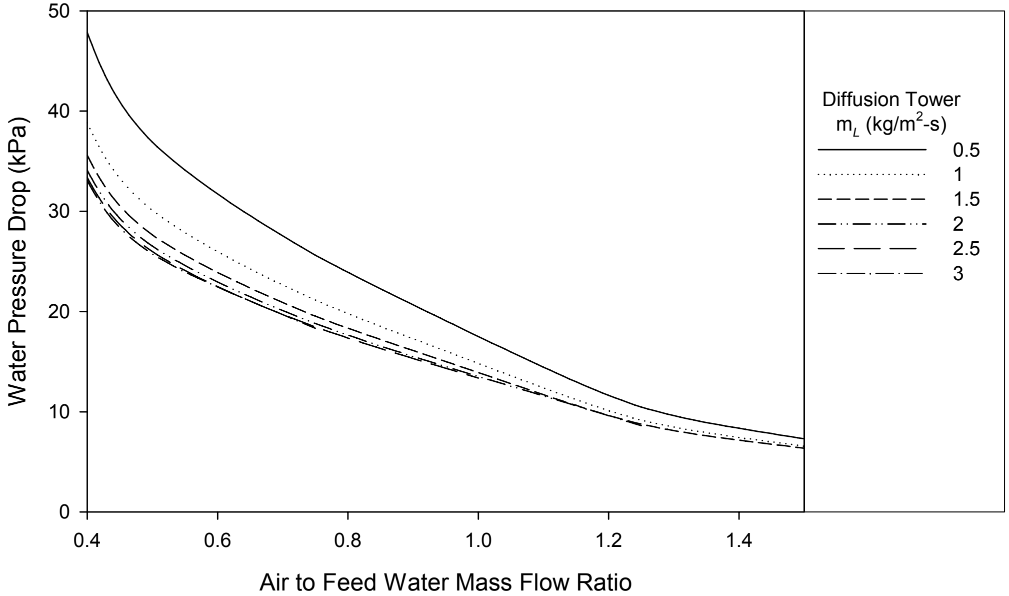
- **Condenser height follows the same trend as the diffusion tower exit air temperature**

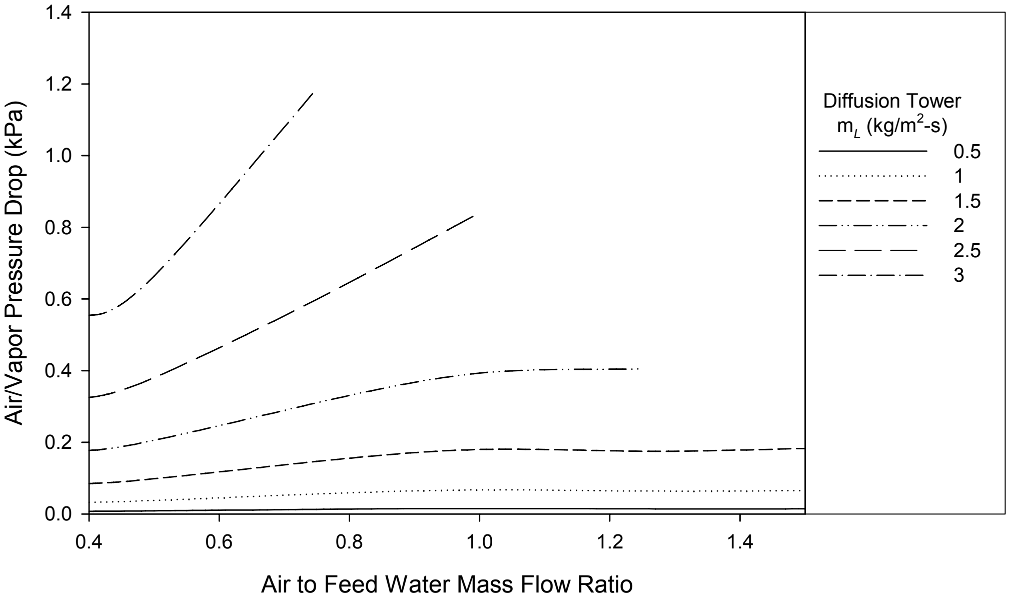
Fresh Water Production Efficiency



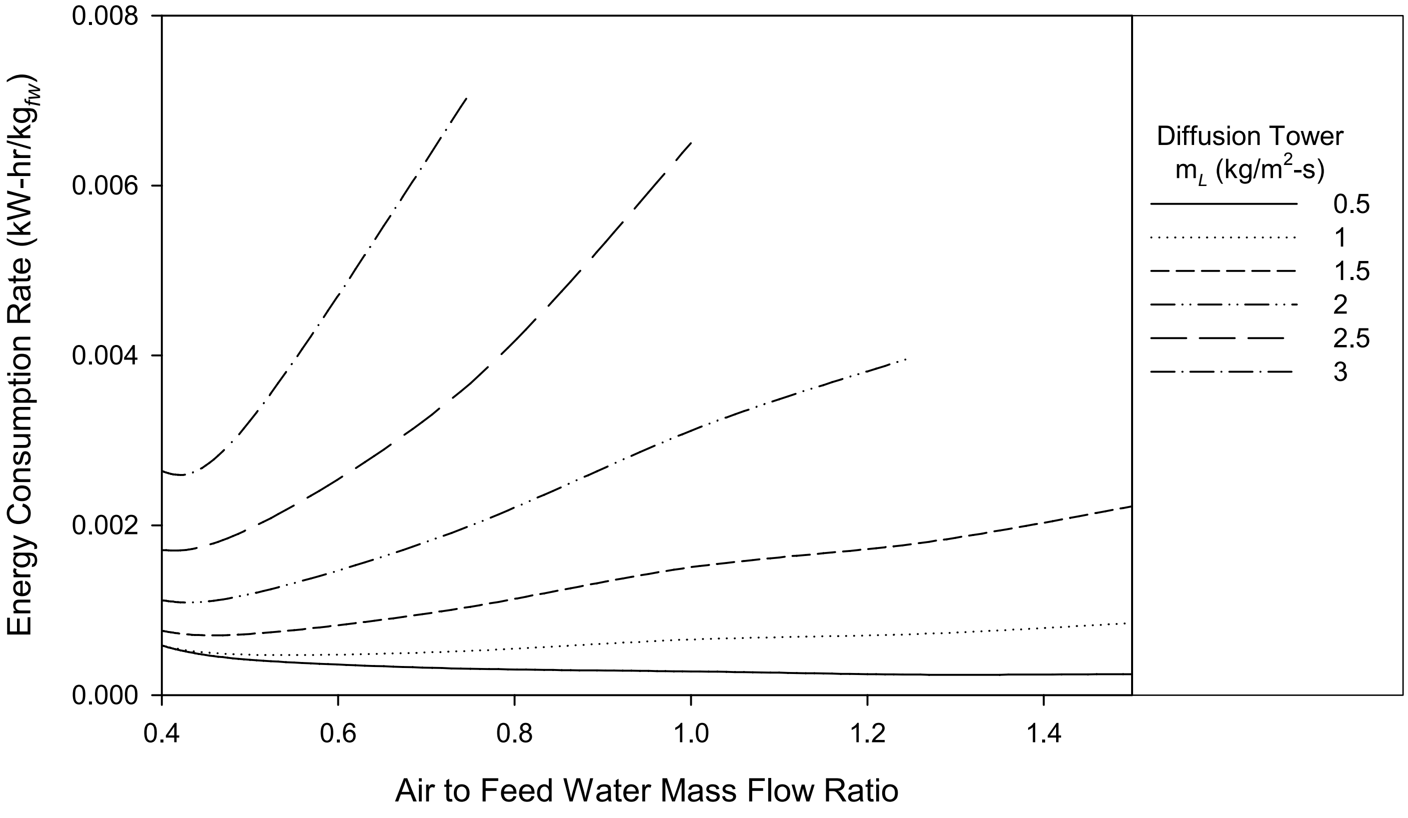
- **The maximum fresh water production efficiency tends to approach a value of 0.032**
- **It is largely controlled by the ratio of the diffusion tower inlet water temperature to the sink temperature**

Pressure Drop

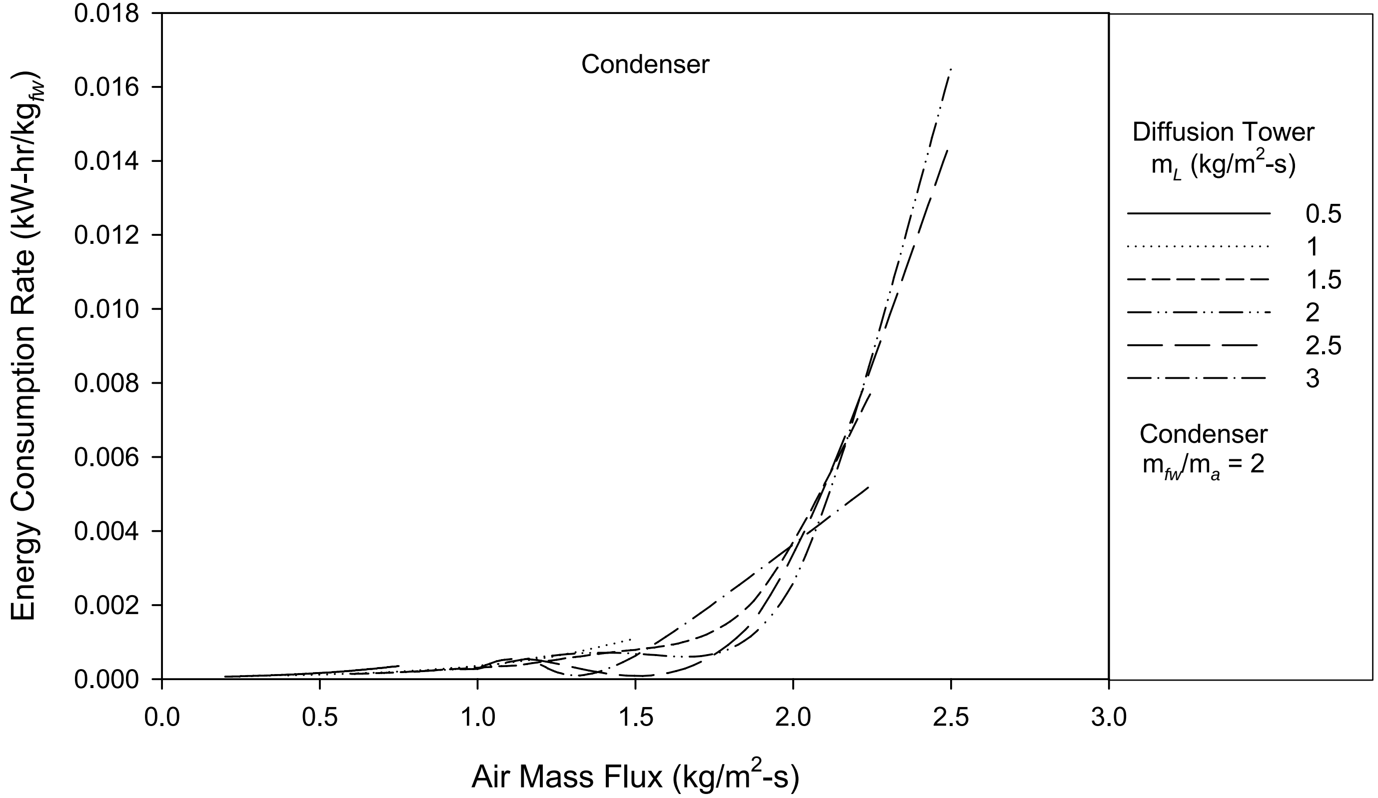




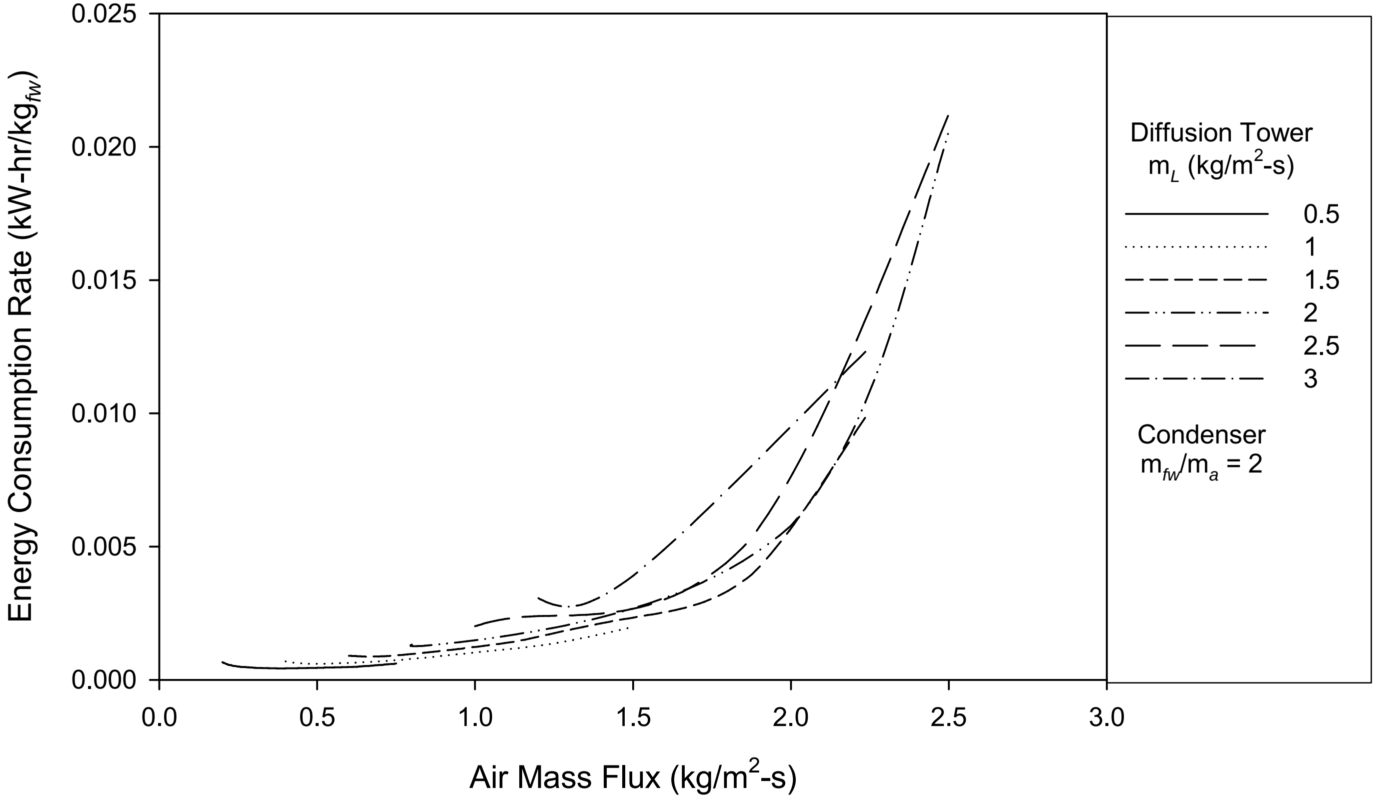
Diffusion Tower Electric Energy Consumption Rate



Condenser Electric Energy Consumption Rate

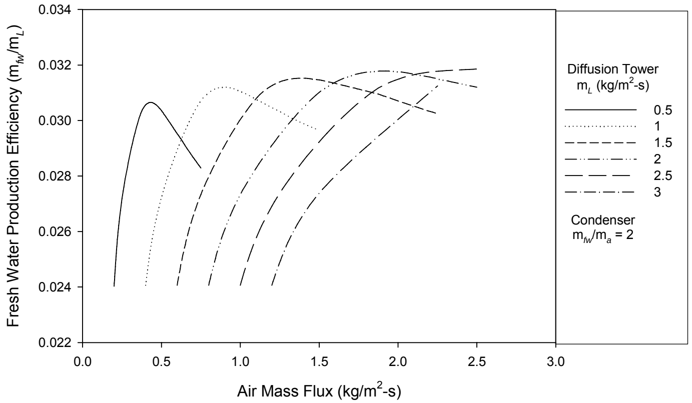


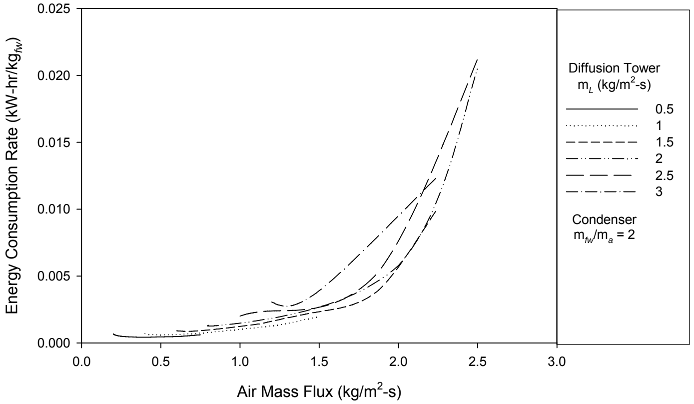
Total DDD Electric Energy Consumption Rate



- The minimum shown in this figure, 0.00043 kW-hr/kgfw, occurs when the air mass flux is 0.375 kg/m2-s, air to feed water mass flow ratio is 0.75, and fresh water to air mass flow ratio is 2.
- This minimum is about an order of magnitude less energy consumption than reverse osmosis.

Optimization of the DDD Process





The optimum operating conditions of the system should satisfy competing requirements:

•high fresh water production efficiency

•low energy consumption rate

Based on data presented in Fig. 14 and Fig. 17 in the paper, a reasonable optimum operating condition:

•air mass flux of 1.5 kg/m^2-s,

•air to feed water mass flow ratio of 1,

•fresh water to air mass flow ratio of 2.

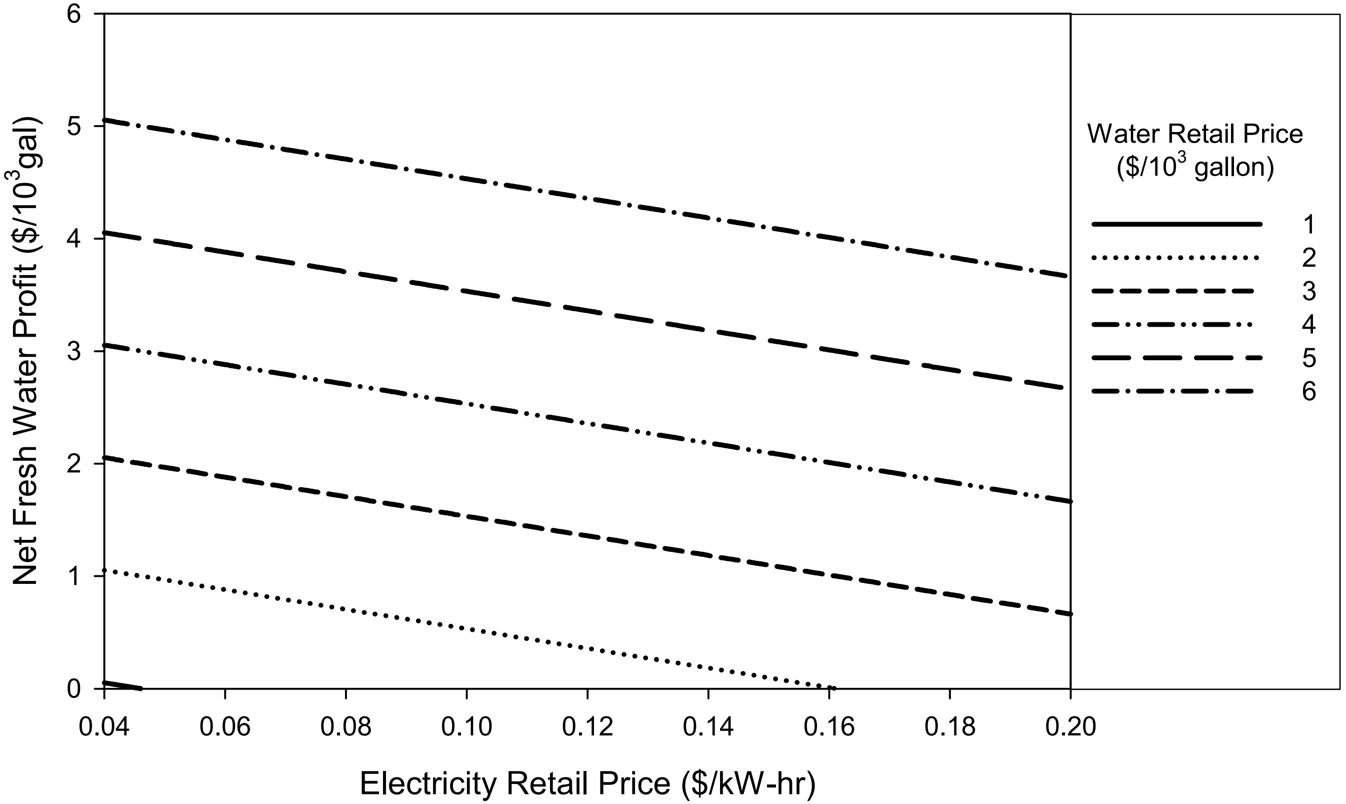
These conditions can yield fresh water production efficiency of 0.0314 and energy consumption rate of 0.0023 kW-hr/kgfw.

Comparing Desalination Technologies‡

‡Averaged data obtained from California Coastal Commission Report, 1992

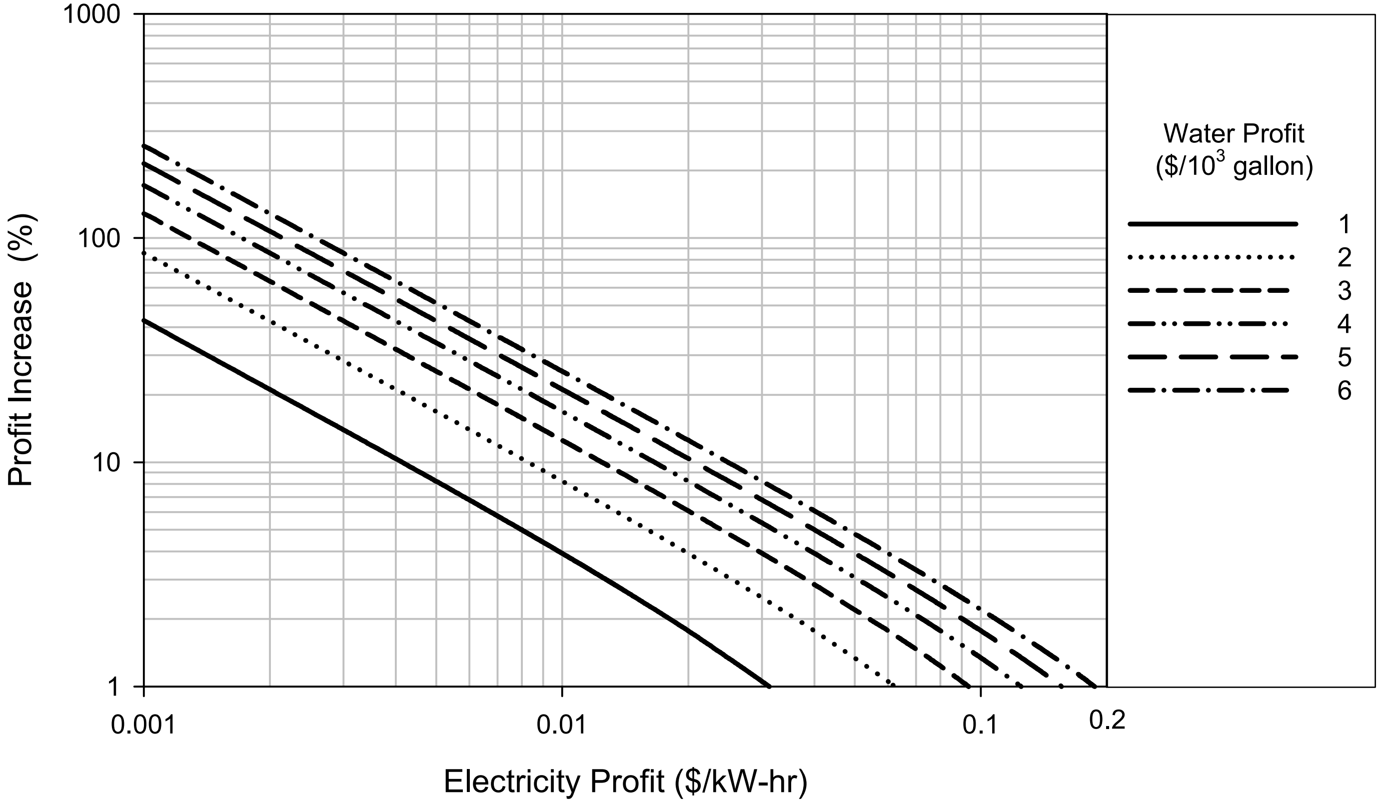
Technology	Energy Consumption Rate (kW-hr/kg_{fw})		
	Mechanical	Thermal	Total
DDD	0.002-0.0053	0.75 (free)	0.002-0.0053
MSF	0.004 - 0.006	0.008-0.018	0.012 – 0.024
RO	0.005 - 0.007	NA	0.005 – 0.007

Net Fresh Water Profit with Electricity Retail Price



- **Consider the DDD facility is independent from the power plant**
- **The fresh water production cost, not including electricity costs, is 0.6 $/1000gal.**

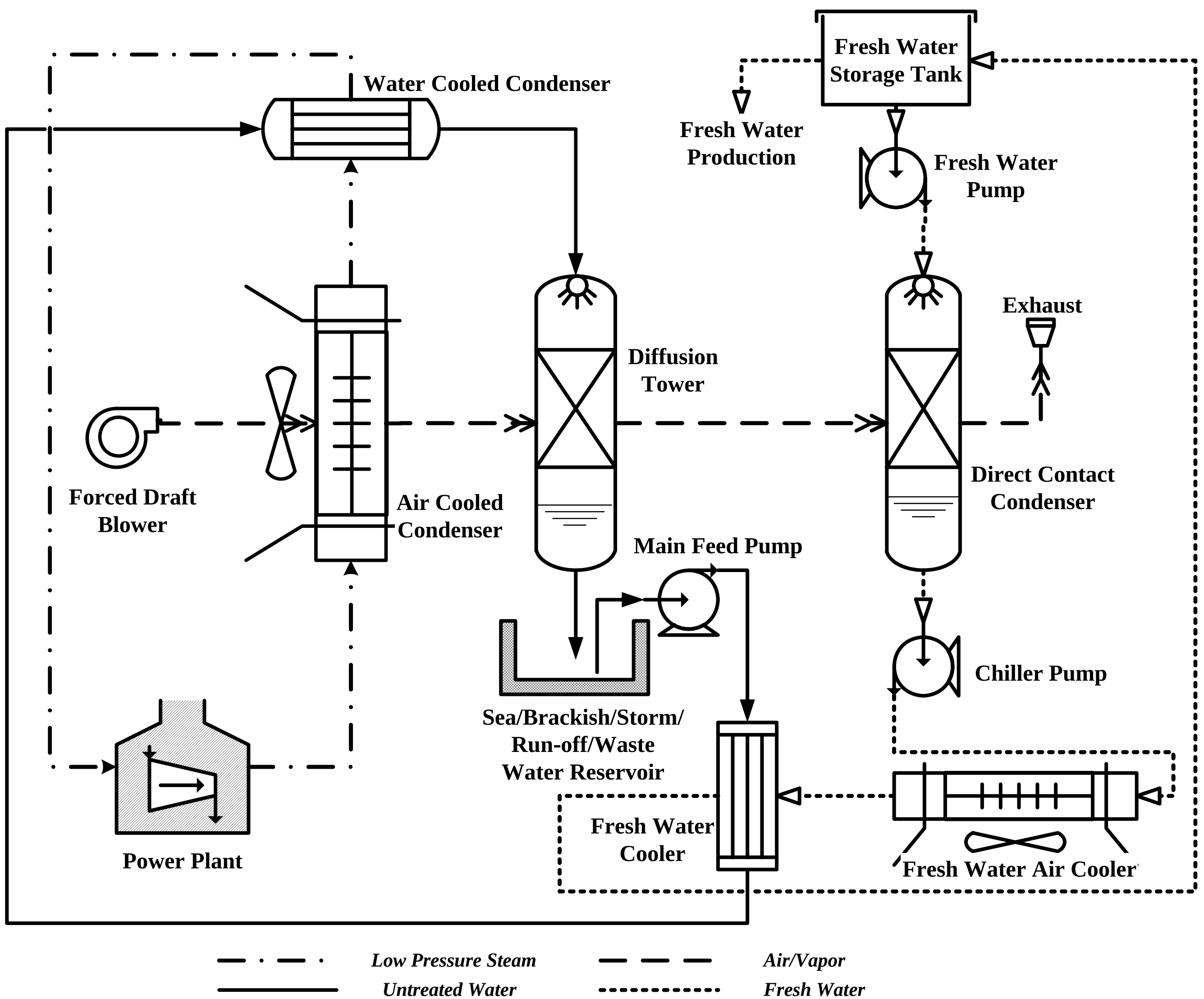
Percent increase in profit with electricity profit



- **Consider the DDD facility is combined with the power plant**

Technology	Advantages	Disadvantages
DDD	•Low energy consumption and low cost water production •Waste heat utilized •Low salinity concentration discharge-minimal environmental impact •Low maintenance required •Low temperature operation--low cost of construction and packing replacement	•Lower conversion efficiency •Requires waste heat •Requires large land footprint
RO	•Feed water does not require heating •Lower energy requirements •Removal of unwanted contaminants such as pesticides and bacteria	•High maintenance required •Performance degrades with time •High salinity concentration discharge-environmental impact •High cost of filter replacement •Generates waste from pretreatment and backwash
MSF	•Large production rates and economies of scale •Continuous operation without shutting down	•Large energy consumption •High cost of water production

Distillation Process Driven by Air Heating



Conclusion

•A process has been identified that allows the distillation of brackish and seawater at low temperatures

•A design procedure for the DDD system has been presented

•For a given feed water flowrate there exists an air to seawater flow ratio that maximizes the fresh water production efficiency

•For a given feed water flow rate there exists an water to air flow ratio that minimizes the energy consumption rate

•Diffusion towers and Condensers are small enough that they may be manufactured off-site and delivered on site

EERC Technology… Putting Research into Practice

Water Extraction from Coal-Fired Power Plant Flue Gas

NETL Water and Power Plants
June 20, 2006, Review Meeting
Pittsburgh B922 Rooms A & B

Bruce Folkedahl
Energy & Environmental Research Center
University of North Dakota

John Copen
Terry Sullivan
Phil Deen
Siemens Power Generation

NATIONAL ENERGY TECHNOLOGY LABORATORY

SIEMENS

Presentation Outline

- Background
- Project outline
- Process description
- Pilot plant test results
- Commercial plant evaluations
- Conclusions

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Water Permit Denied !
Power Project Cancelled

Water Is the Next Regulatory Frontier !

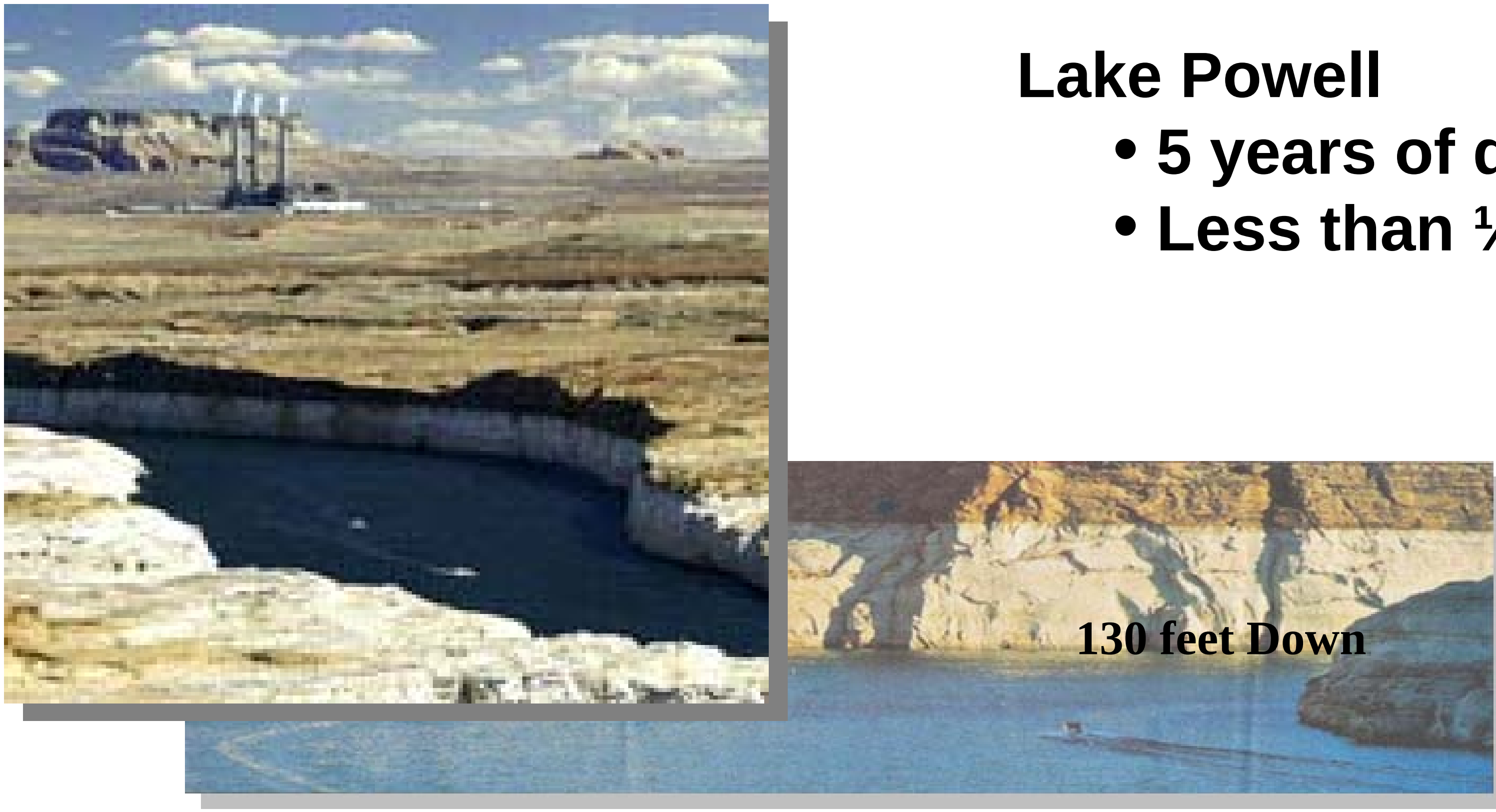
"The global water picture is bleak. Water use spiraled six-fold in the last century, more than twice the rate of population growth, and there is little prospect of a slow-down. Per capita supply is expected to drop by a third in the next two decades."

Richard Collins on the 3rd World Water Forum in Kyoto, 2003

USGS identifies power industry as one of the largest users and consumers of water resources.

Estimated Use of Water in the United States, USGS 1990

Water – The Next Scarce Resource



Lake Powell

- **5 years of drought**
- **Less than ½ full**

Source: USA Today 9/30/04

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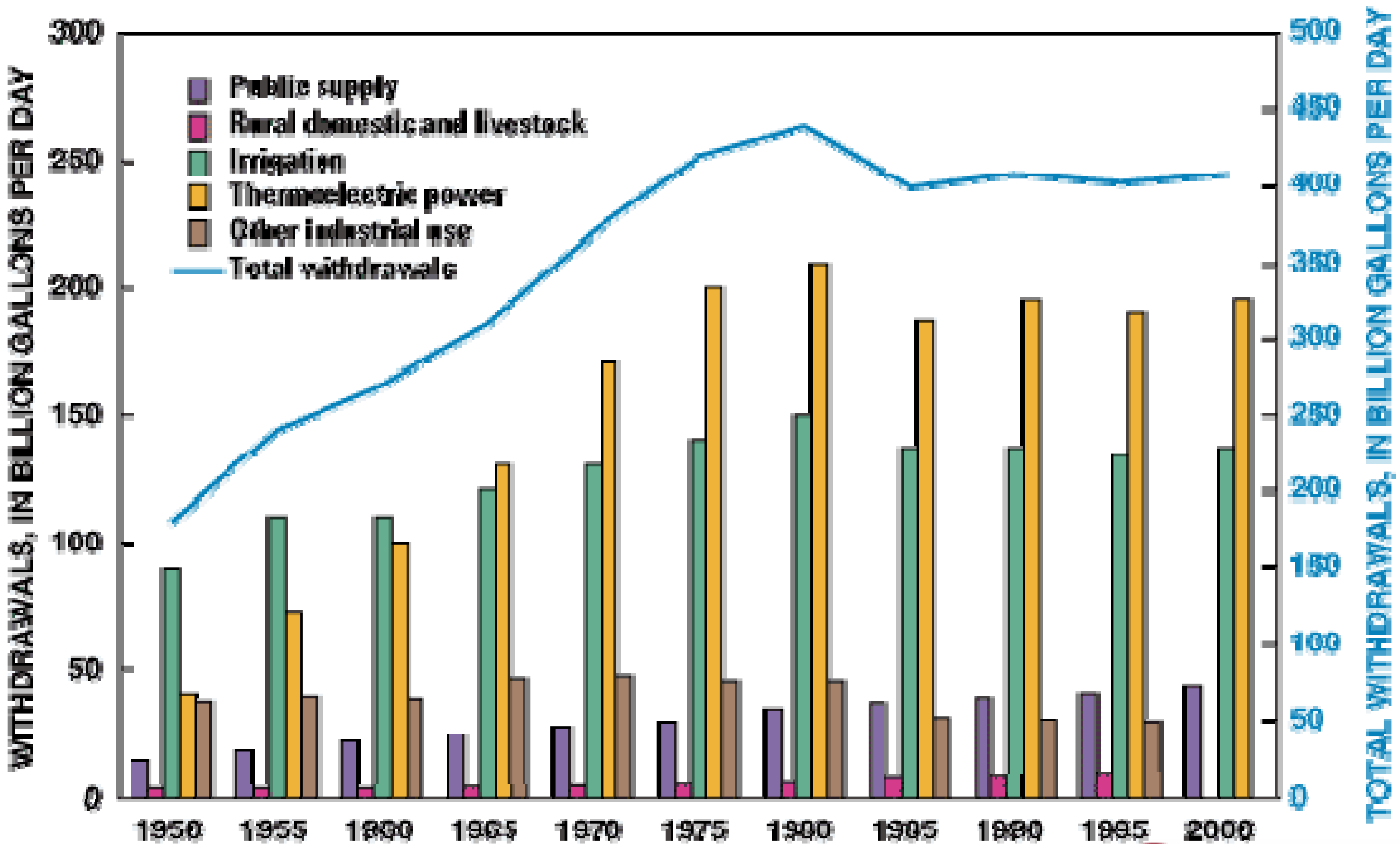
Power Plants Are Among the Largest Consumers of Water in the United States



Source: USGS 2000

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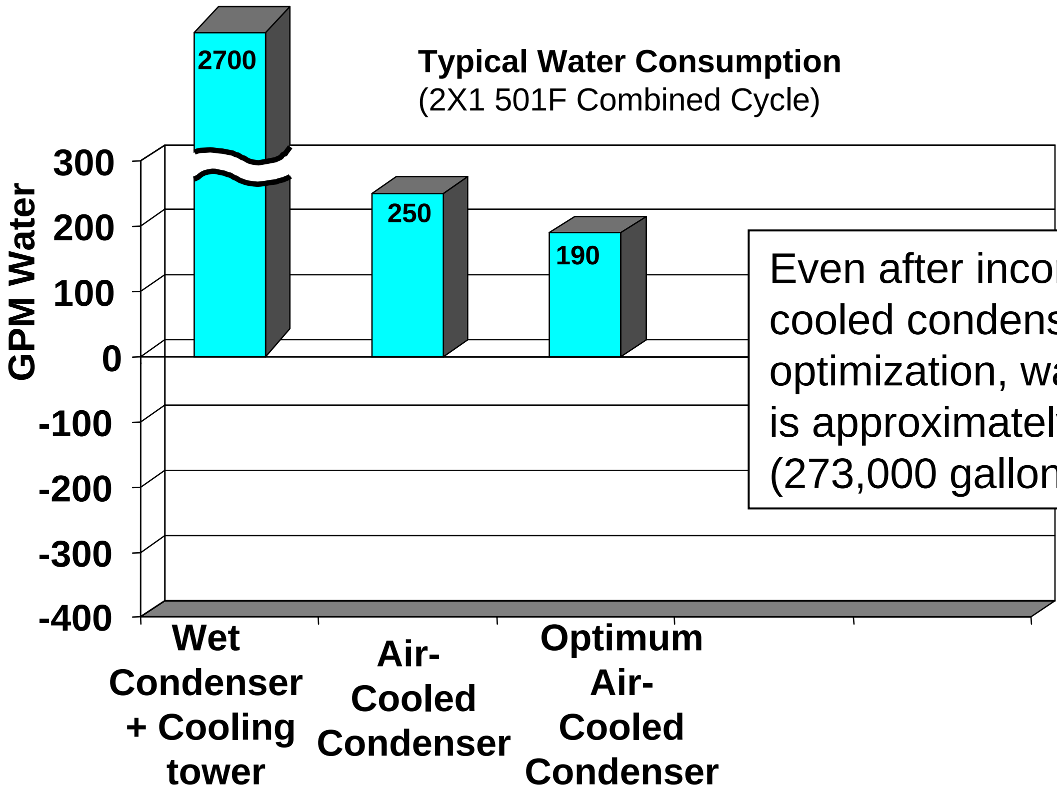
Current State of the Art Technology



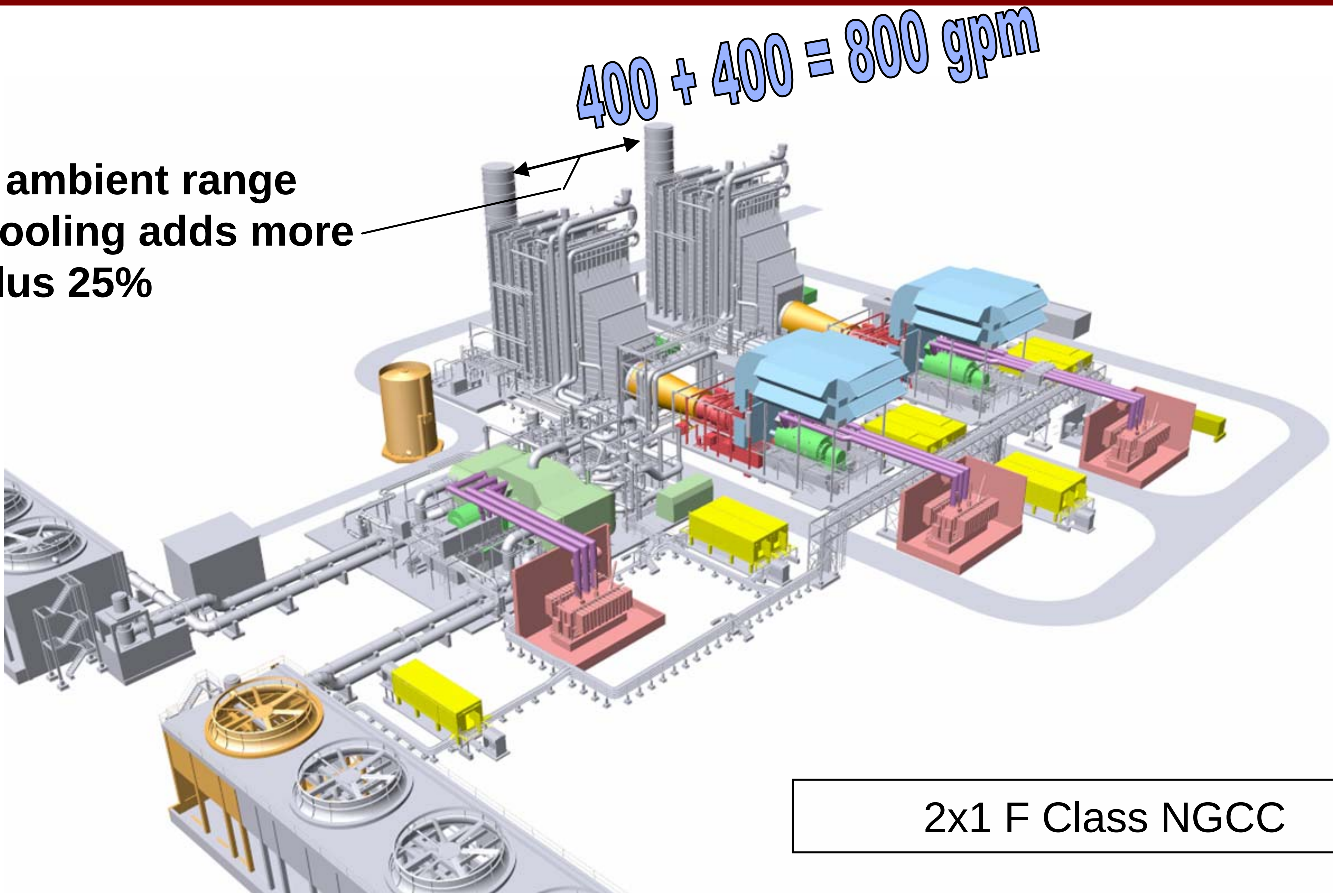
Even after incorporating an air-cooled condenser with usage optimization, water consumption is approximately 190 gpm (273,000 gallons per day)

Can Water Consumption Be Reduced to Zero?

Are There Alternative Sources of Water?

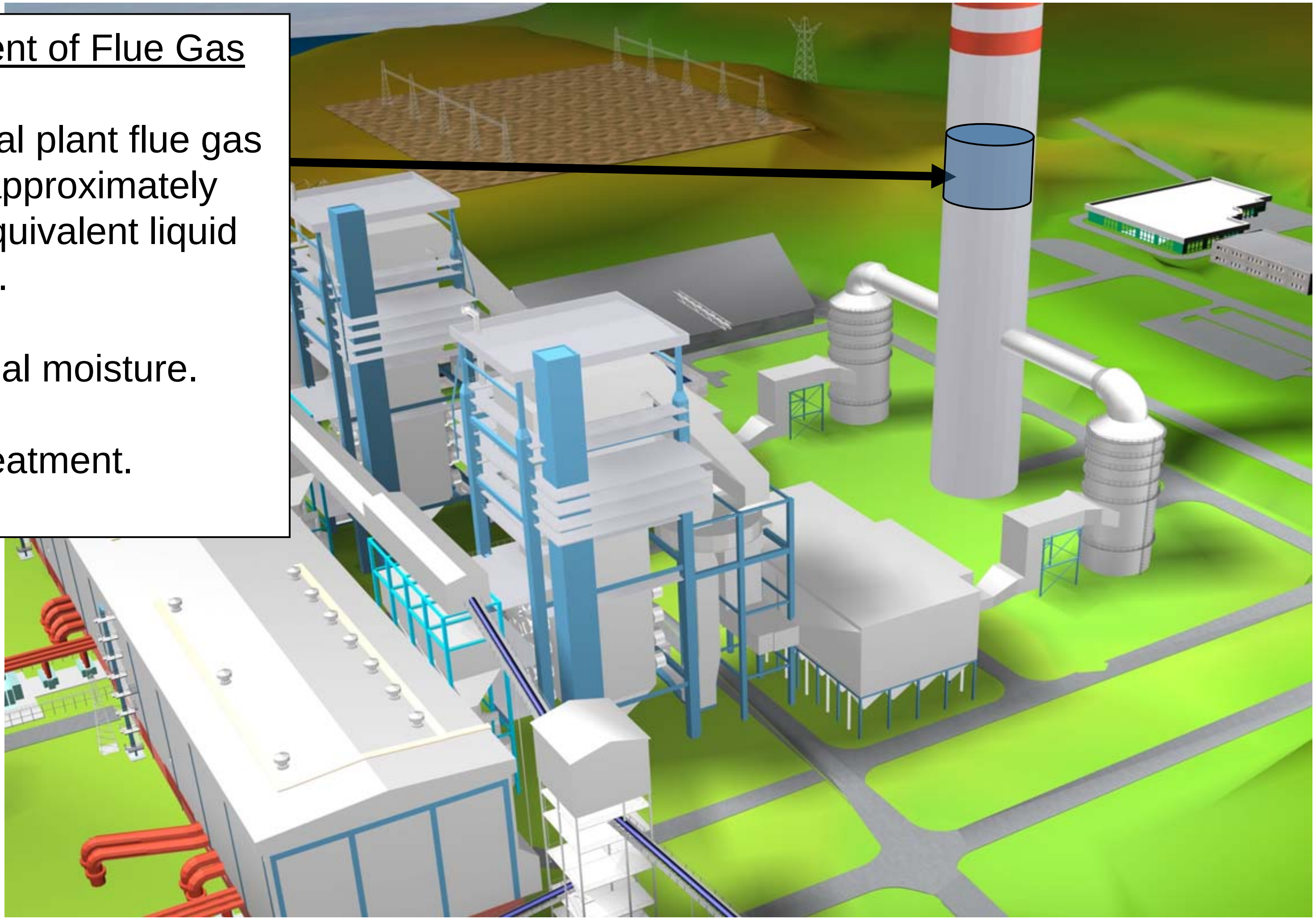
Alternative Water Source – Gas-Fired Plants

- **Across ambient range**
- **Evap. cooling adds more**
- **IGCC plus 25%**



2x1 F Class NGCC

Potential Water Available (Coal)



Water Content of Flue Gas

A 700-MW coal plant flue gas may contain approximately 1000–2400 equivalent liquid GPM of water.

Varies with coal moisture.

Varies with treatment.

What Can Be Done?

WETEX™

Water Extraction from Turbine Exhaust

- Flue gas water recovery system
- Desiccant based
- Power plants can reduce or eliminate water from outside sources
- Fitted on any power plant that burns carbonaceous or hydrogeneous fuels
- Retrofit and greenfield applicable

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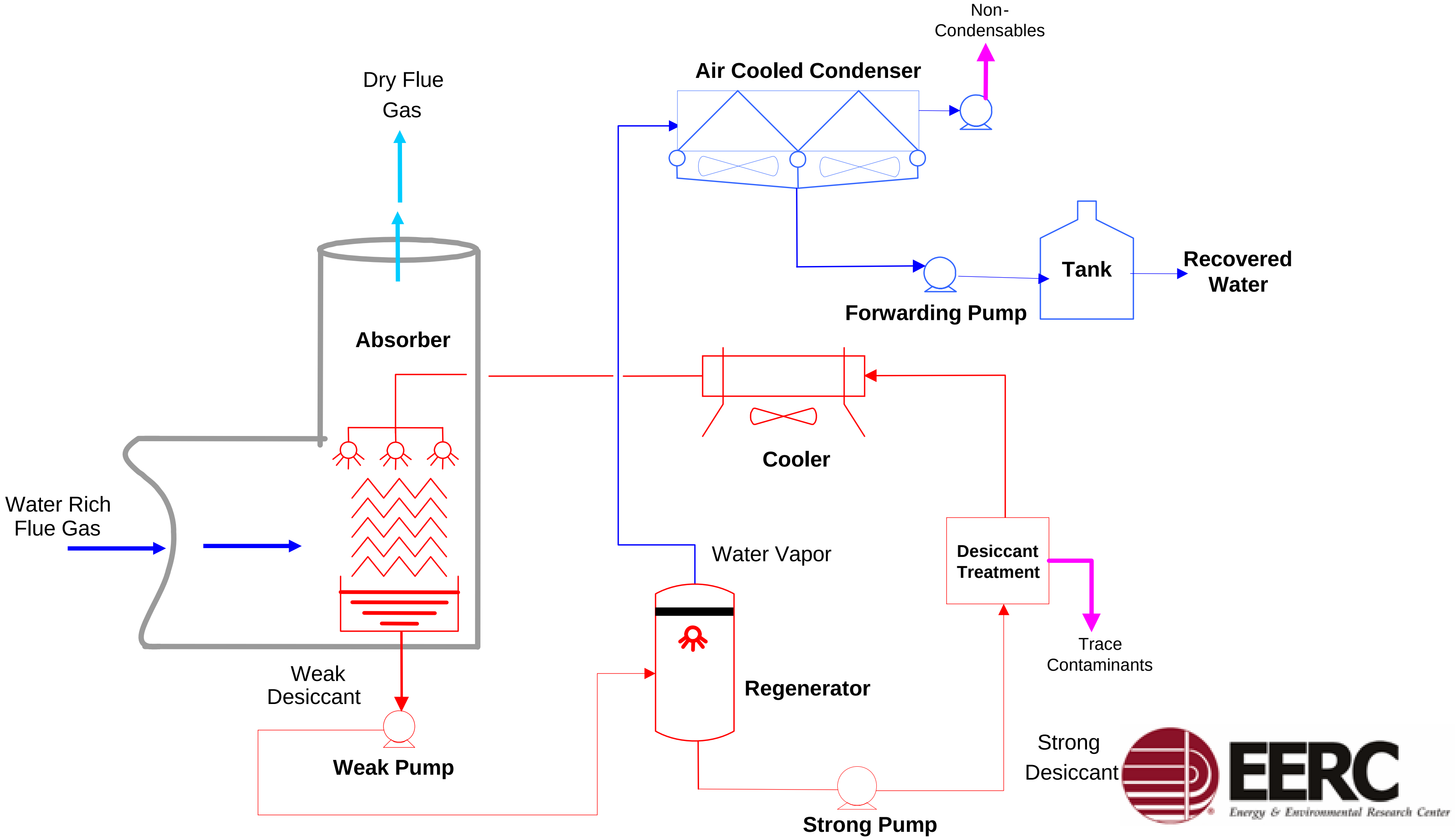
The WETEX™ Process



DOE Program Task List

- Task 1 – Desiccant Selection
  - Report by Desiccant Expert Dr. Keith Herold
- Task 2 – Desiccant Laboratory Test Evaluation
- Task 3 – Test Plan Development
- Task 4 – Test Facility and Equipment Design
- Task 5 – Equipment and Materials Procurement
- Task 6 – Test Equipment Installation
- **Task 7 – Testing**
- **Task 8 – Test Data Evaluation**
- **Task 9 – Commercial Power Plant Evaluation**
- Task 10 – Program Management

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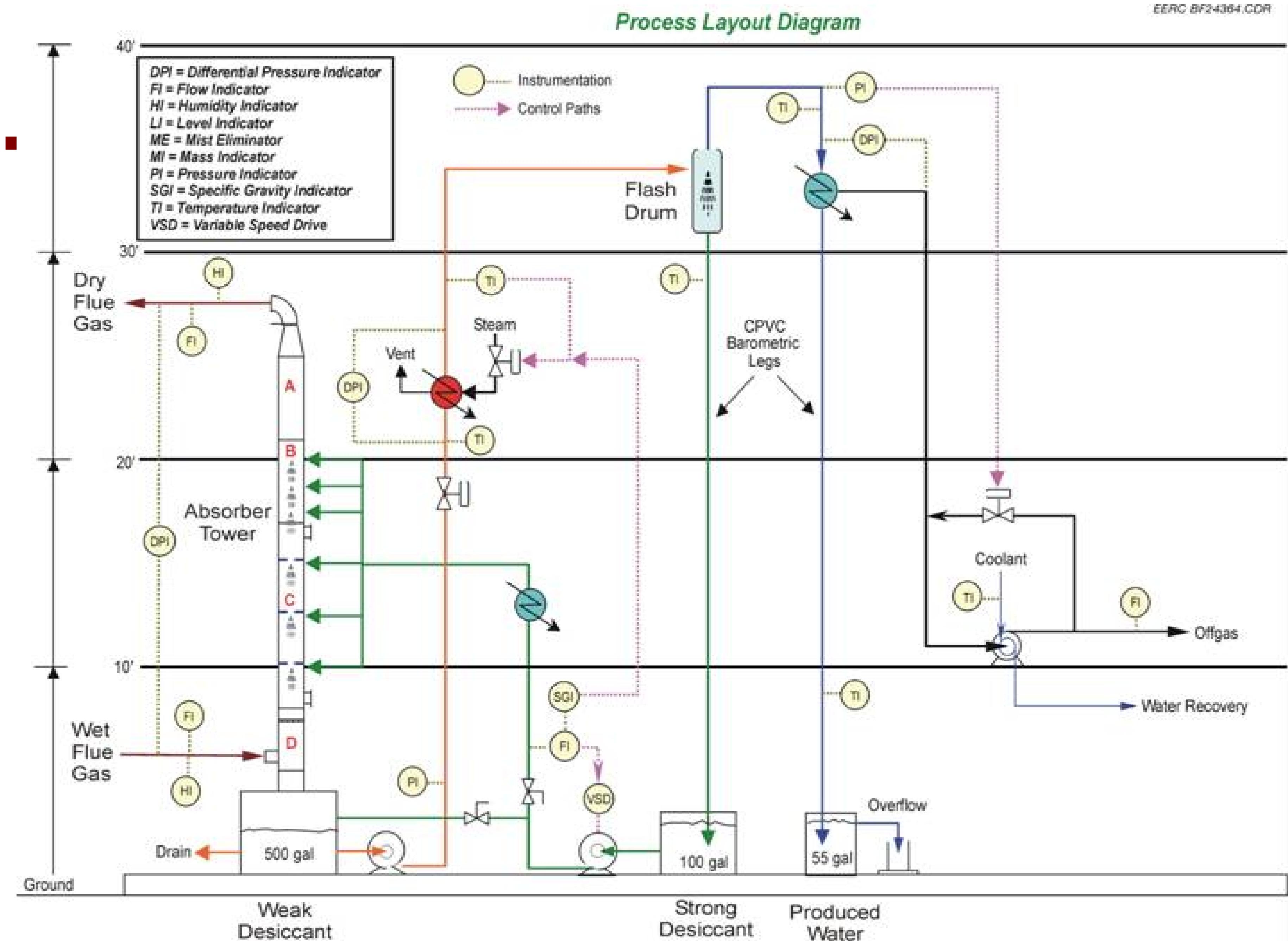
WETEX™ Pilot Test System Layout



Absorber Tower and Tank

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Absorber Tower

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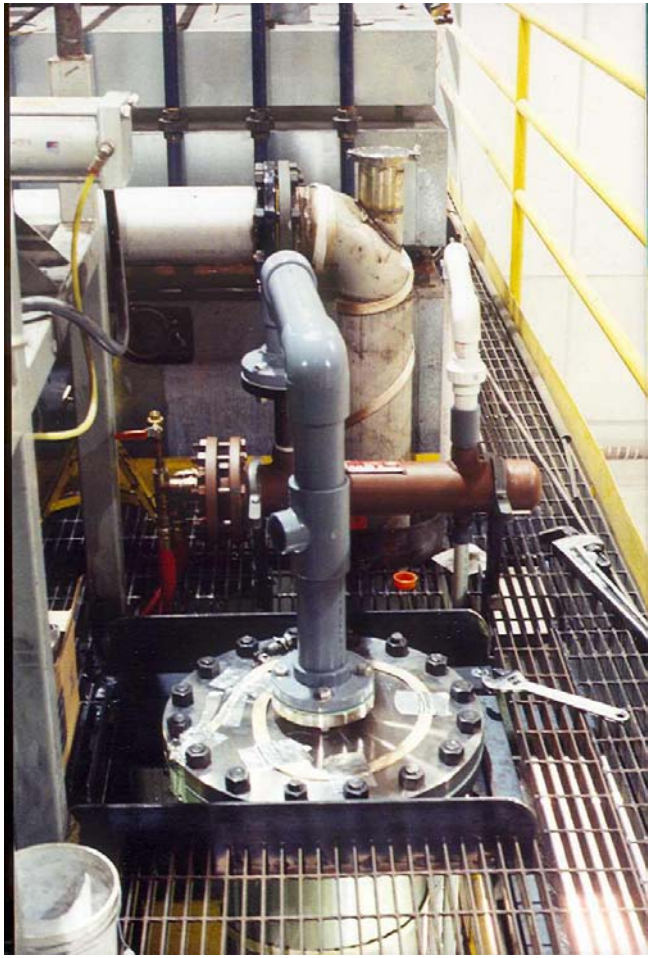
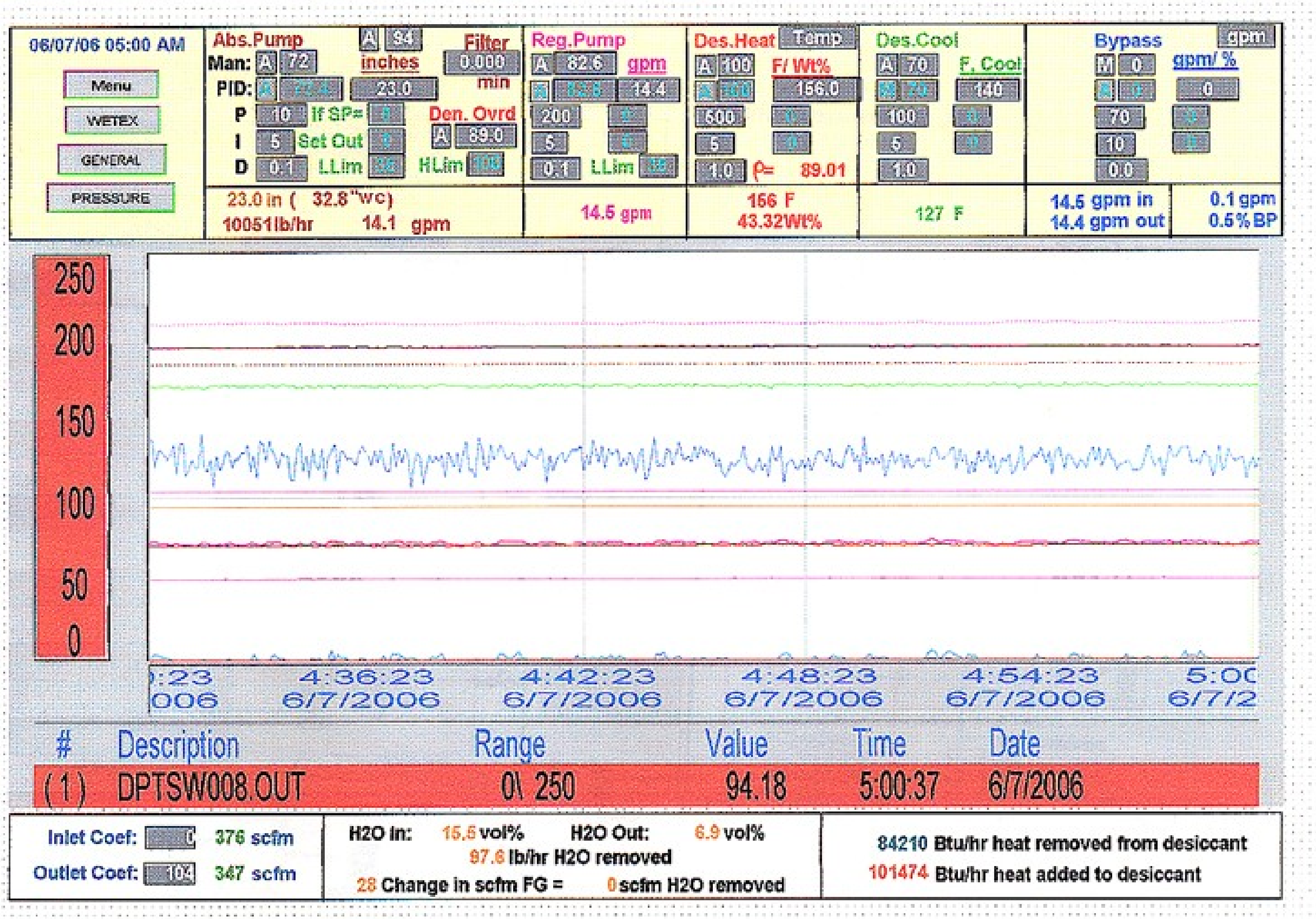
Flash Drum

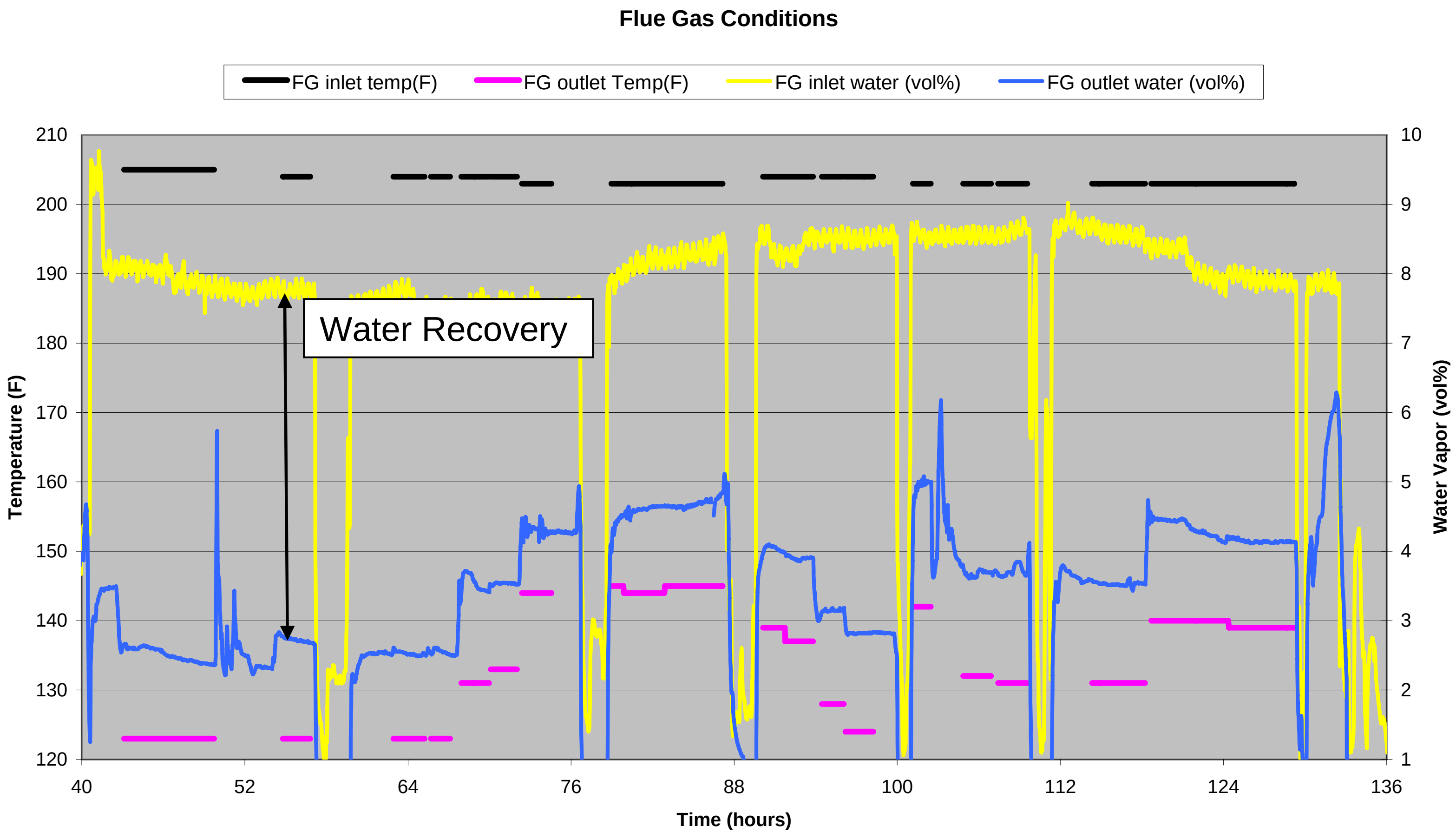
Flash Drum and Condenser



Process Flow Pilot-Scale Test



WETEX™ Pilot Test Results



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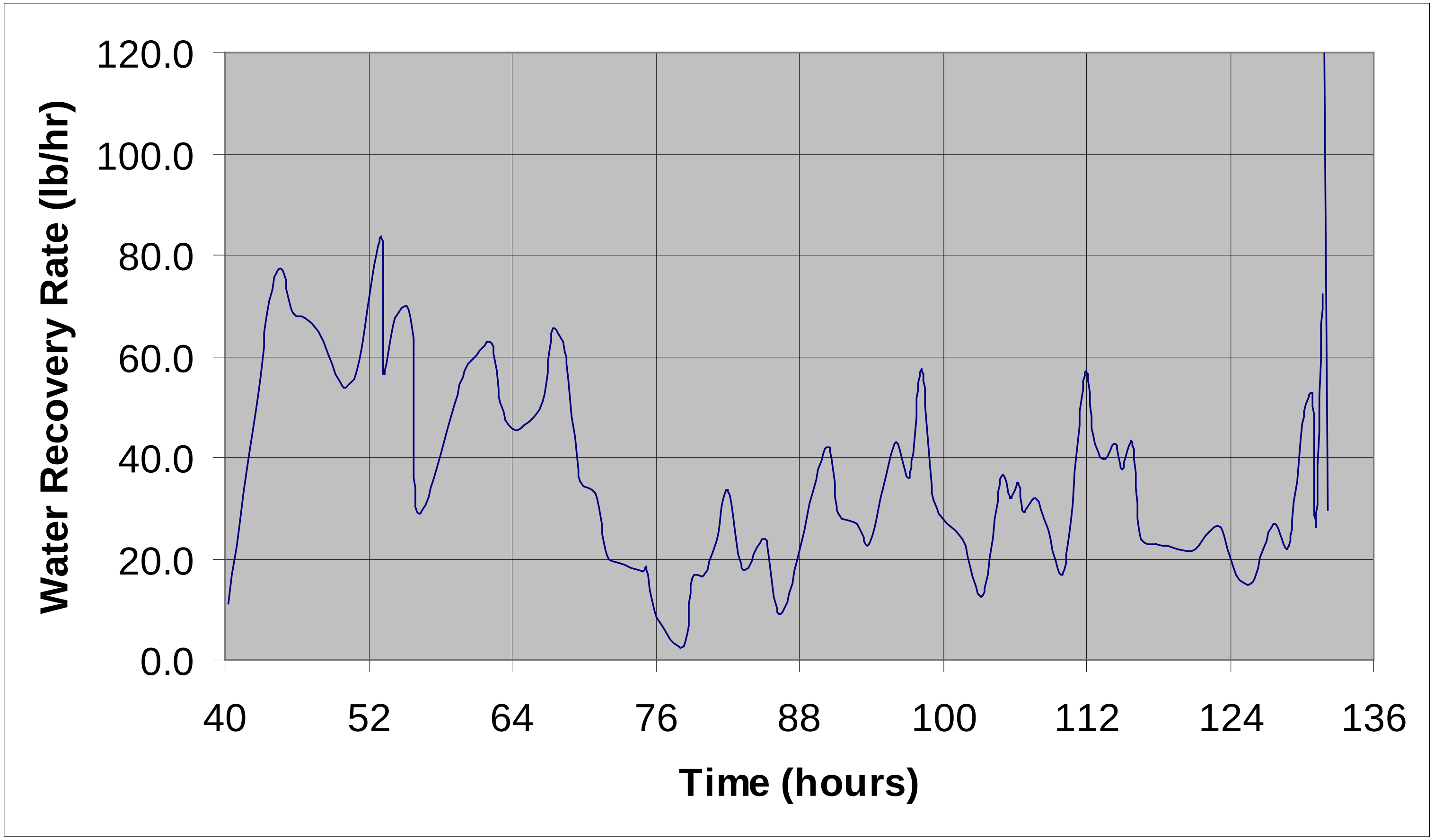
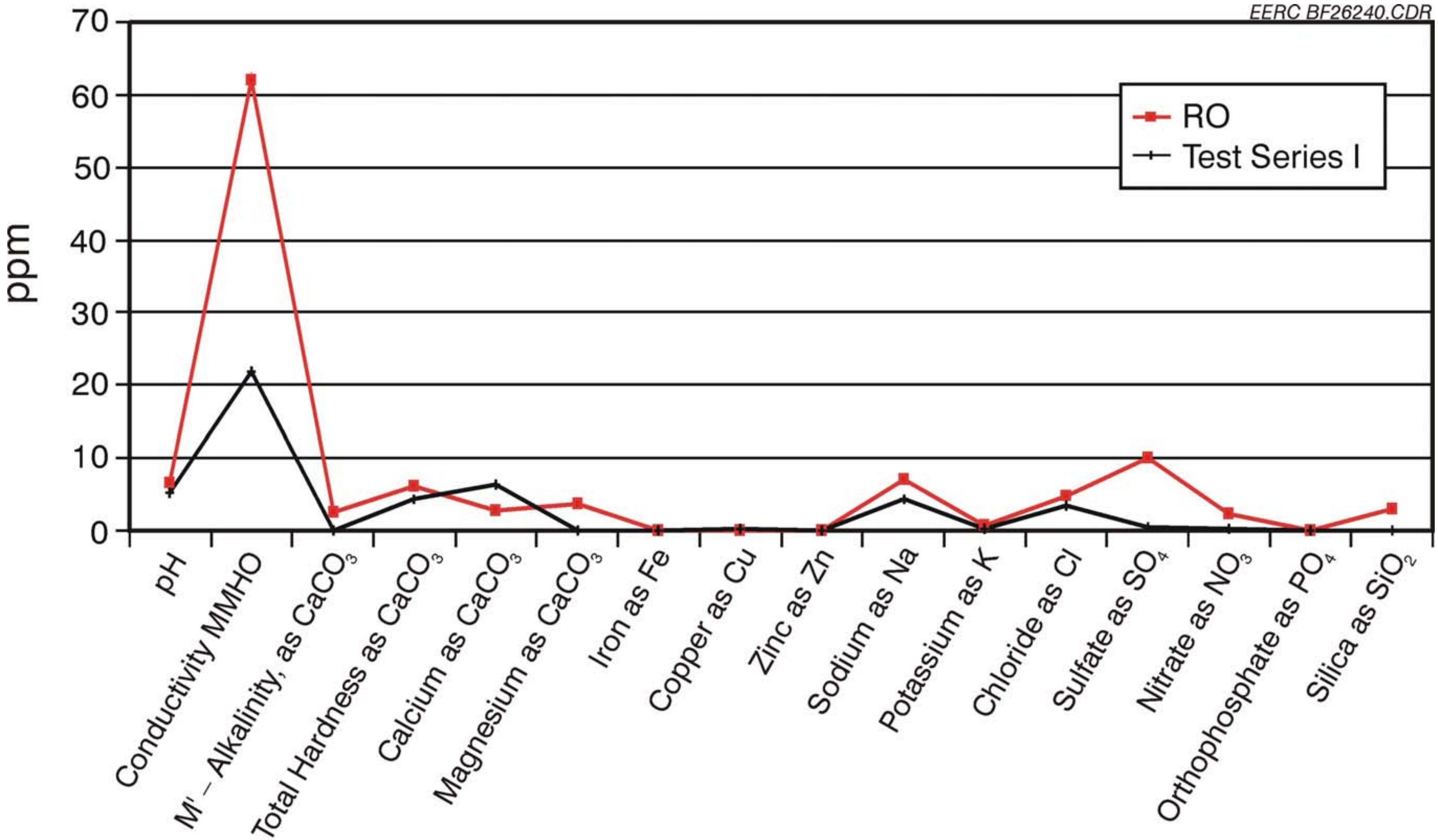
WETEX™ Pilot Test Results



WETEX™ Pilot Test Results



WETEX™ Pilot Test Results

Summary Pilot Test Results

✓ Complete system with regeneration – demonstrated

✓ Natural gas and coal – demonstrated

✓ System stability – automatic operation demonstrated

✓ Desiccant carryover – undetectable

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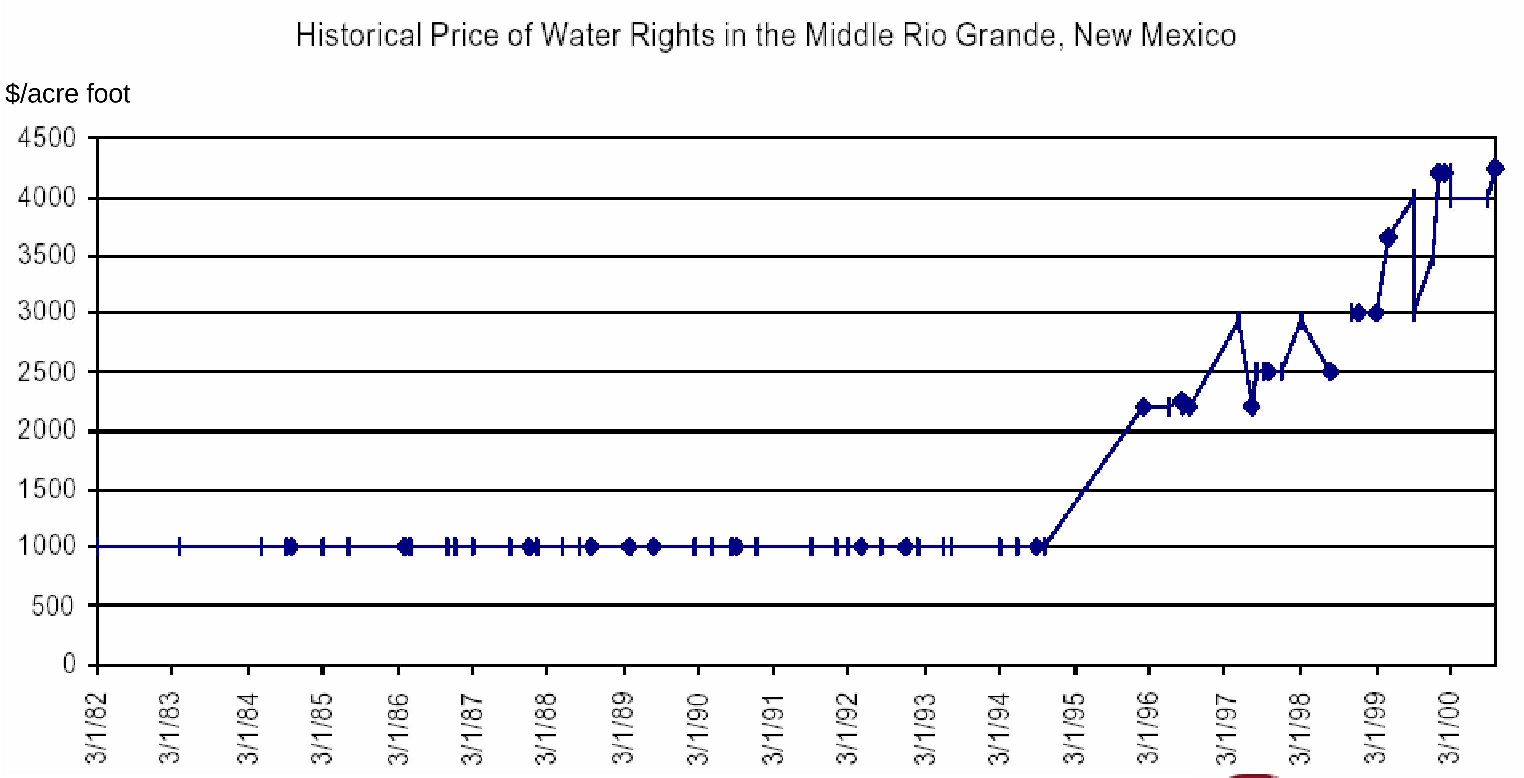
Water Prices Are Rising Example: Rio Grande

Is WETEX ™ Economically Viable?



Source: University of New Mexico

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Costs of Substitute Technologies Conservative Assumptions

SYSTEM	Δ Capital Expense	Δ Water Cost	Total
Wet Cooling Tower	BASE	BASE	BASE
Dry Cooling Tower	$26.6	-$27	-$0.4
Air-Cooled Condenser	$14.3	-$27	-$12.7
WETEX with ACC	$25.3	-$46	-$20.7

- In millions of dollars
- NPV using today's prices, 3.5% inflation, 10% discount
- 25-year plant life
- Wet cooling tower cost is $4 million
- Wet cooling tower water cost NPV 25 years $46 mill.
- Water cost $0.003/gal for raw water, $0.05/gal for demin. water
- WETEX enables $18 Mill. Savings on demin. water

Using Rio Grande prices, the savings from WETEX with ACC would be **$127 mill.**

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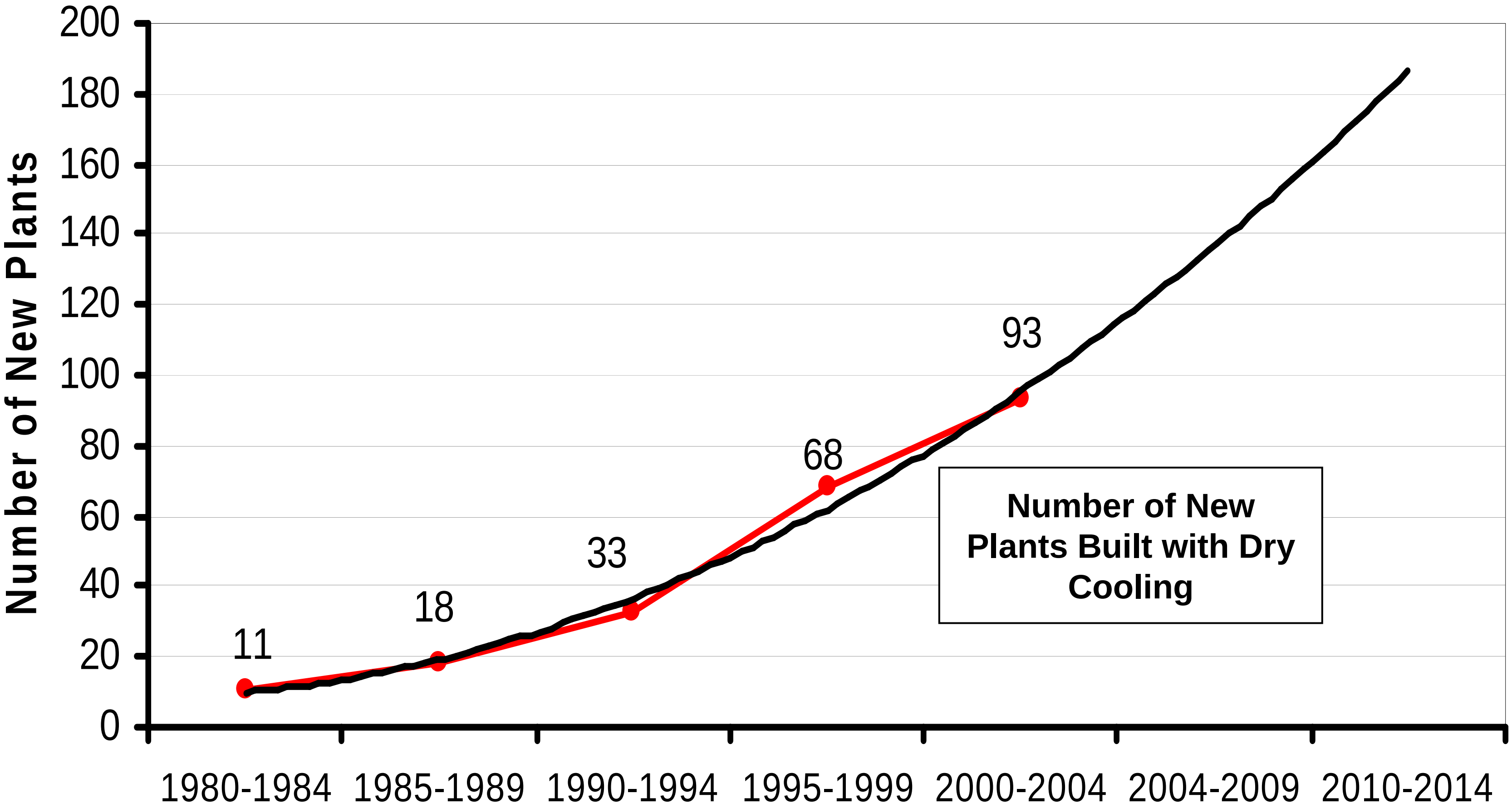
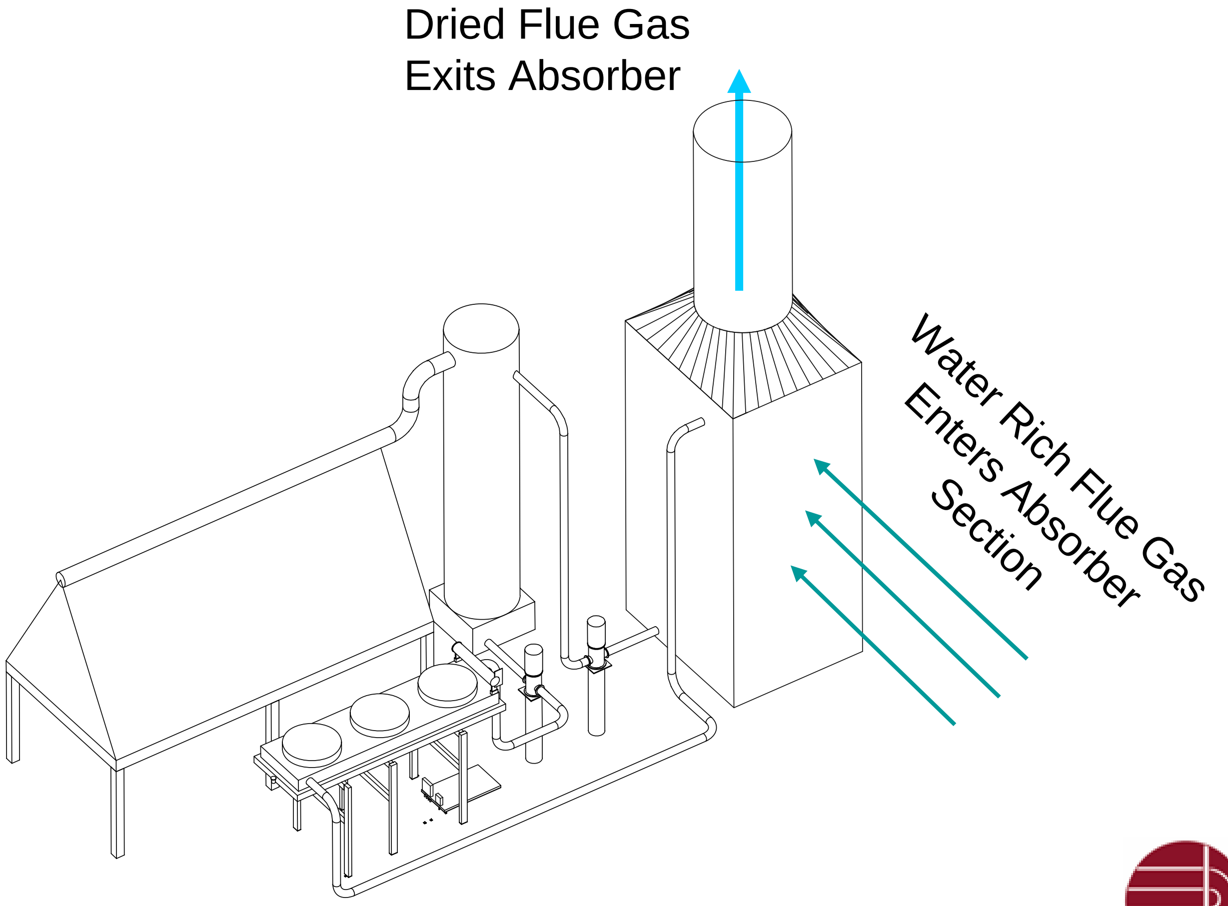
WETEX™ Commercial Market Vision

New Air Cooled Power Plants World Wide



SIEMENS Market Research

WETEX™ Commercial Configuration



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Conclusions

- 30% water recovery is achievable/50% is feasible.
- Potential for gas-, coal-, and syngas-fired plants
- Equipment can be designed and operated to meet variable performance and cost targets
- Water quality is exceptional, similar to R.O. outlet
- Extended operation testing currently under way to verify longer-term behavior
- Emissions impact study being planned

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Summary

WETEX is…..

…a viable technology

…part of the solution for power generation water use

…has potential of a positive net present value over the life of the plant

"We never know the worth of water till the well is dry."

\- French Proverb

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CARBON FOAM AIR COOLED CONDENSER HEAT EXCHANGERS

Funded under DOE Contract DE-FG02-03ER83627
Presented at NETL Water and Power Plants Review Meeting
June 20, 2006

CONTRACTOR
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INTEGRATION PARTNER
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a SPX Company
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Outline

- Problem and Application Review
- Material Property Review
- Design Review
- Bench Top Testing Results
- Future Work

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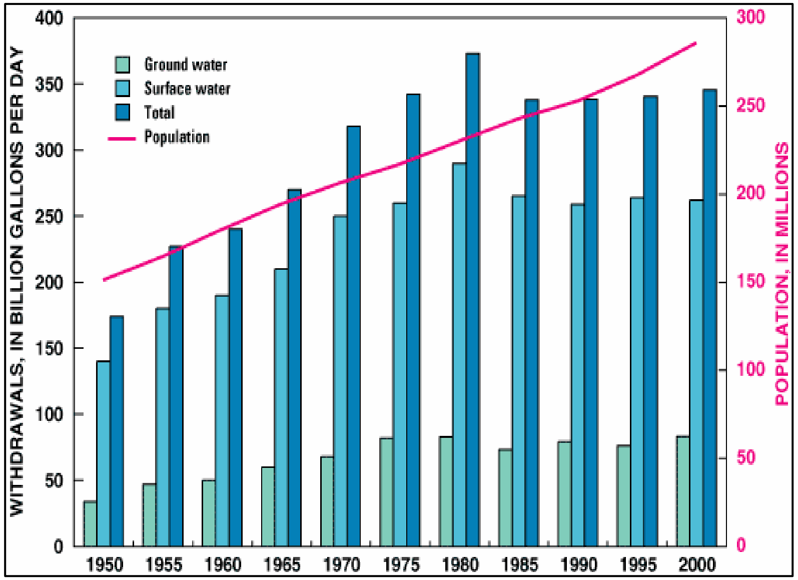
DOE Area of Concern

- Electricity production requires water, accounting for 39 percent of freshwater withdrawals
- 195 billion gallons per day in 2000
- Water is impacted by thermoelectric plants before returning to the environment
- Local discharge of warm water alters the natural habits of many species, the gathering of manatee at power plant cooling water discharge locations is a commonly noted example.
- Solution: Replace water with more efficient air cooled condensers



Trends in population and freshwater withdrawals by source, 1950-2000.

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Program Vision

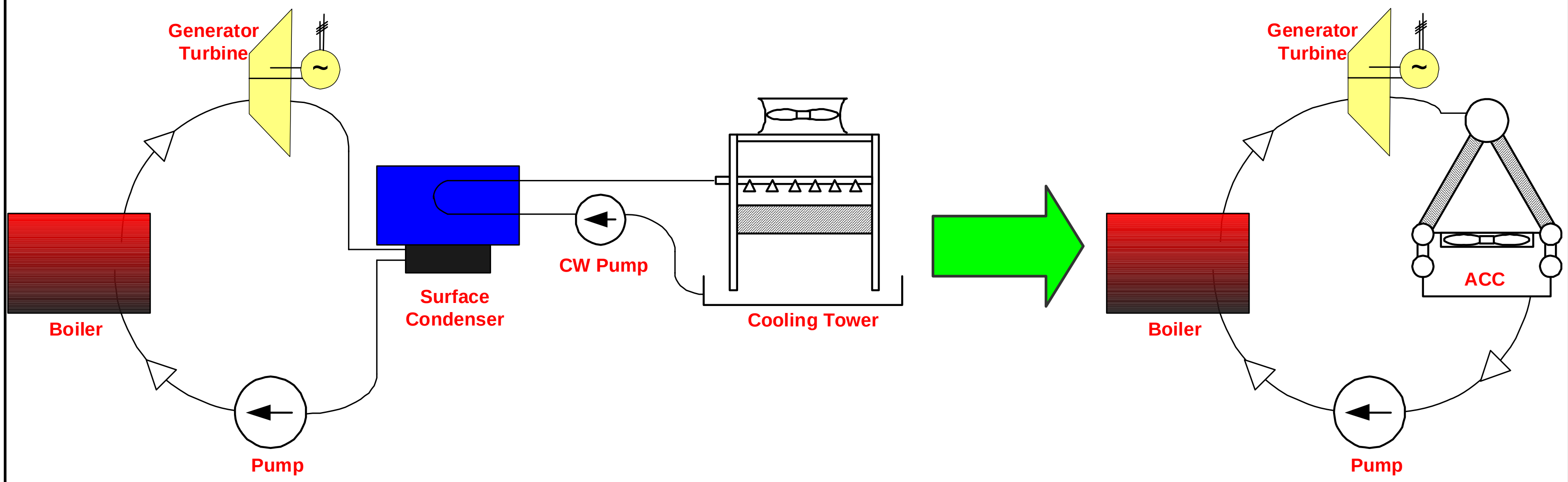

Figure 1: The vision is replacement of the water cooling loop with carbon foam enabled air-cooled condenser.

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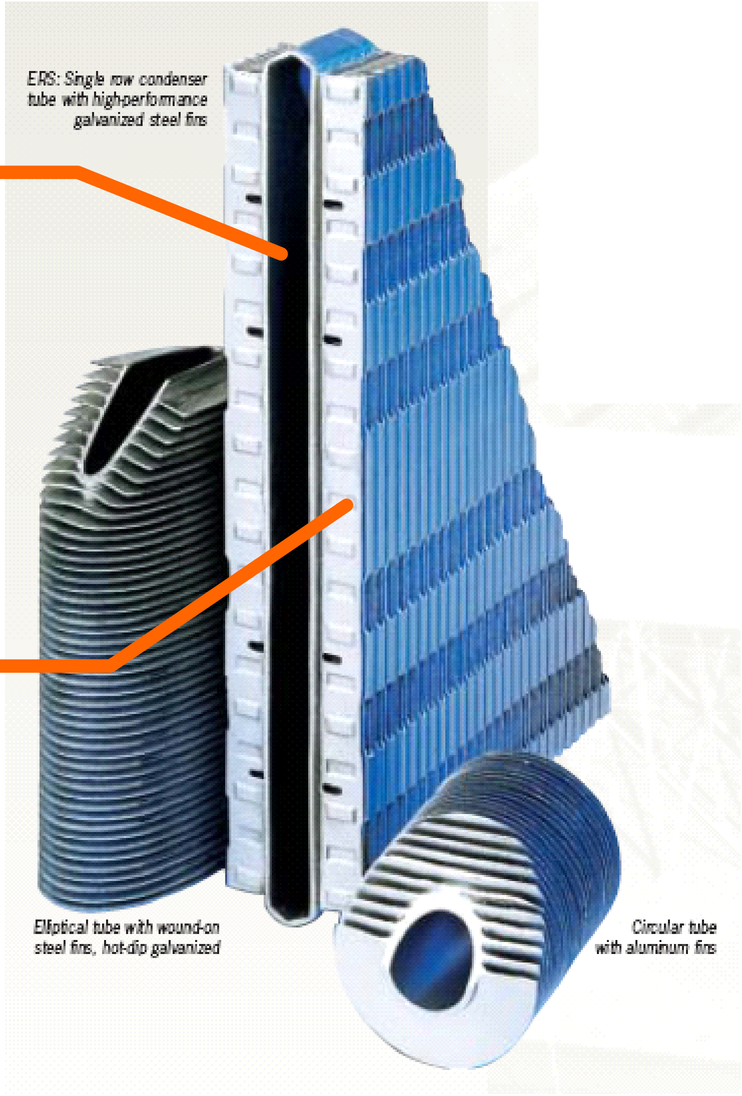
Steam tube

Metal fins to be replaced with

Carbon foam



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DOE Application: Power Plant Cooling Towers

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Approach

- Purchase POCO HTC billets
- Structurally Enhance
- Design Heat Exchanger Fins
  - Flow by rather than flow-through design
- Machine
- Bond to Plenums
- Test
- Economic Benefit Analysis

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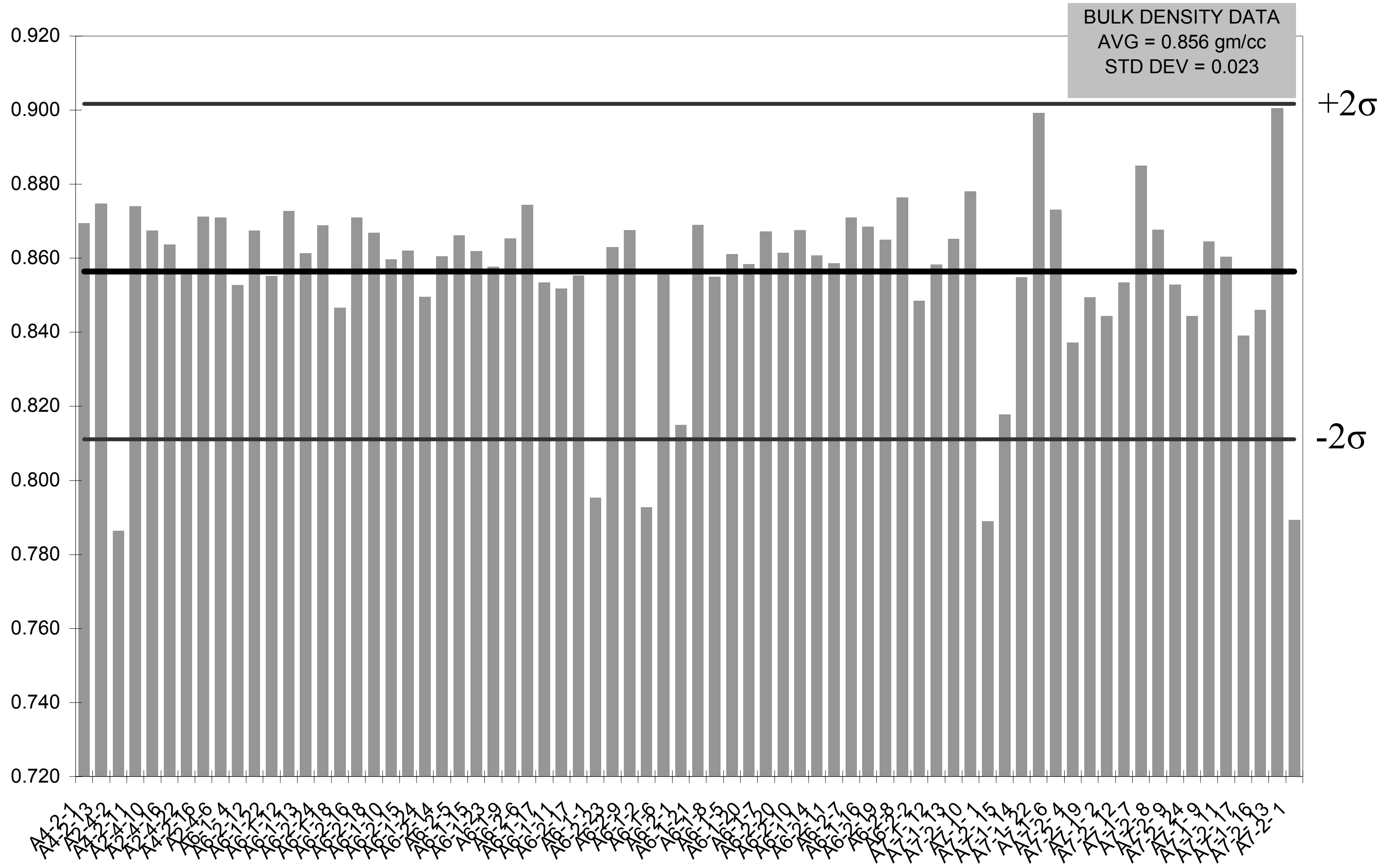
Bulk Density Data for 72 POCO HTC Billets



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Density Data From Within Billets

A4-2-1

0.883	0.882	0.887	0.894
0.876	0.859	0.868	0.887
0.867	0.857	0.864	0.886
0.875	0.869	0.878	0.889

Average 0.876
Std Dev 0.011

A2-4-2

0.815	0.780	0.790	0.815
0.766	0.768	0.776	0.800
0.763	0.764	0.773	0.802
0.774	0.776	0.785	0.810

Average 0.785
Std Dev 0.018

A2-4-11

0.888	0.879	0.882	0.899
0.881	0.860	0.863	0.880
0.880	0.861	0.859	0.873
0.895	0.872	0.869	0.884

Average 0.877
Std Dev 0.012

A2-4-10

0.866	0.844	0.851	0.874
0.859	0.842	0.842	0.872
0.859	0.844	0.849	0.872
0.886	0.870	0.870	0.888

Average 0.862
Std Dev 0.015

A2-4-13

0.868	0.867	0.886	0.883
0.871	0.865	0.882	0.901
0.884	0.901	0.900	0.877
0.882	0.910	0.899	0.926

Average 0.887
Std Dev 0.018

-2σ -1σ avg -2σ -2σ

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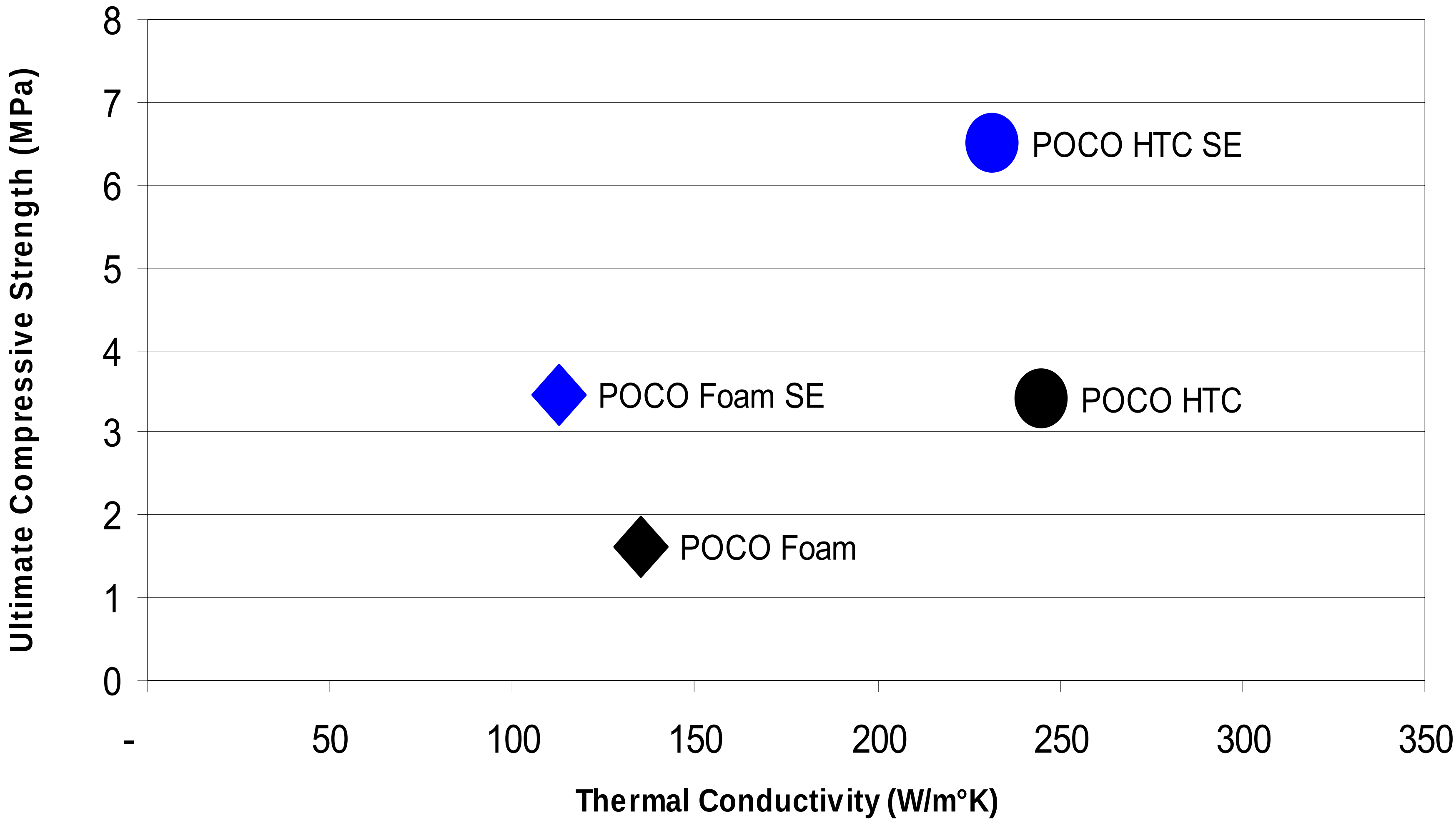
Structurally Enhanced Carbon Foam Will Handle the Physical Requirements of the Application



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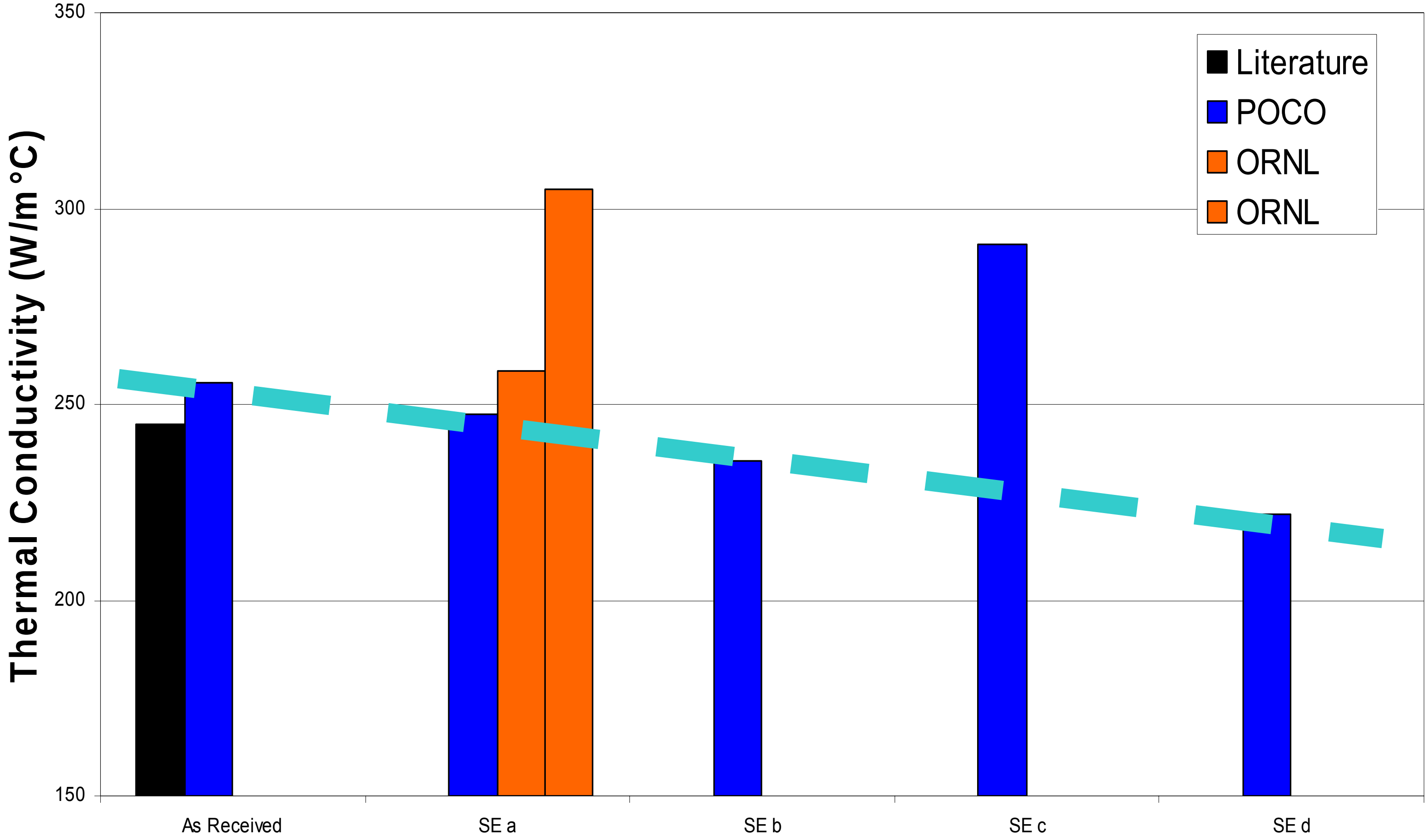
Thermal Conductivity Data of POCO HTC SE

out of plane, room temperature, blind testing



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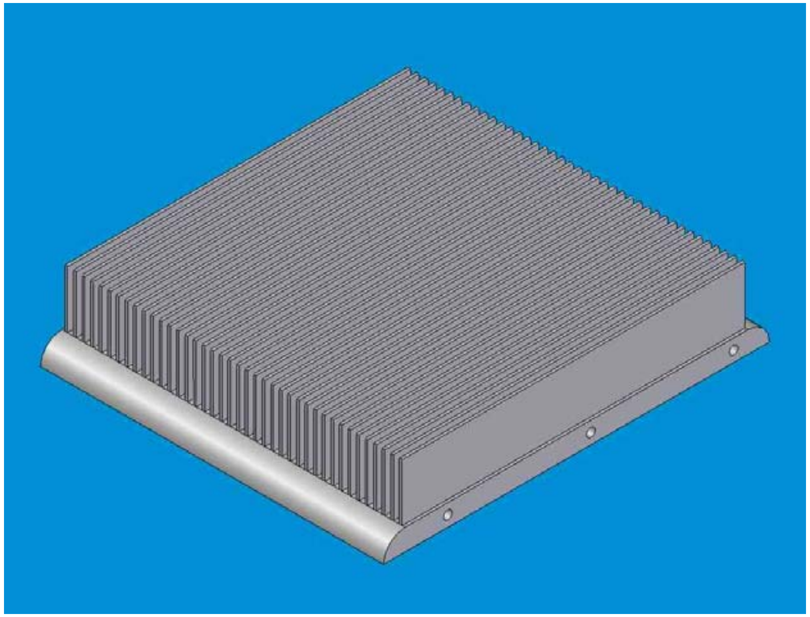
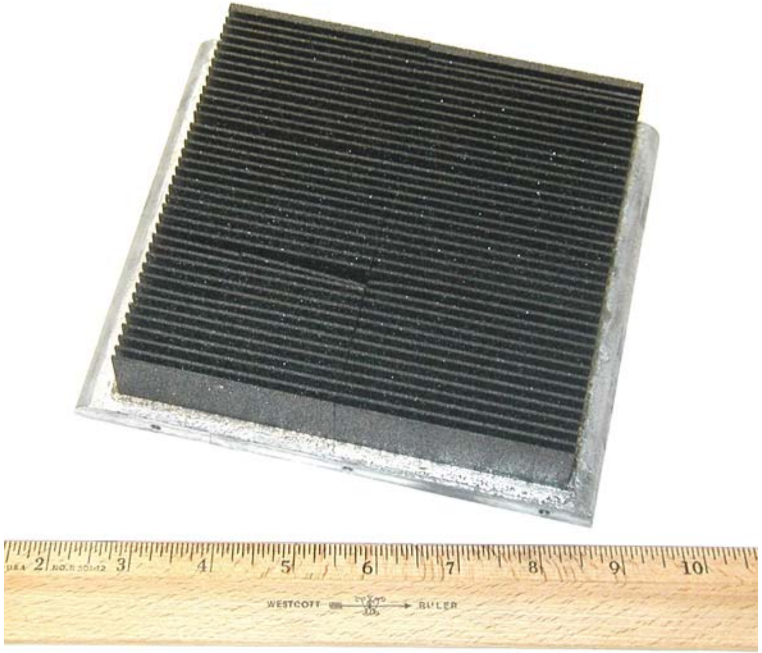
Design – Straight Fin





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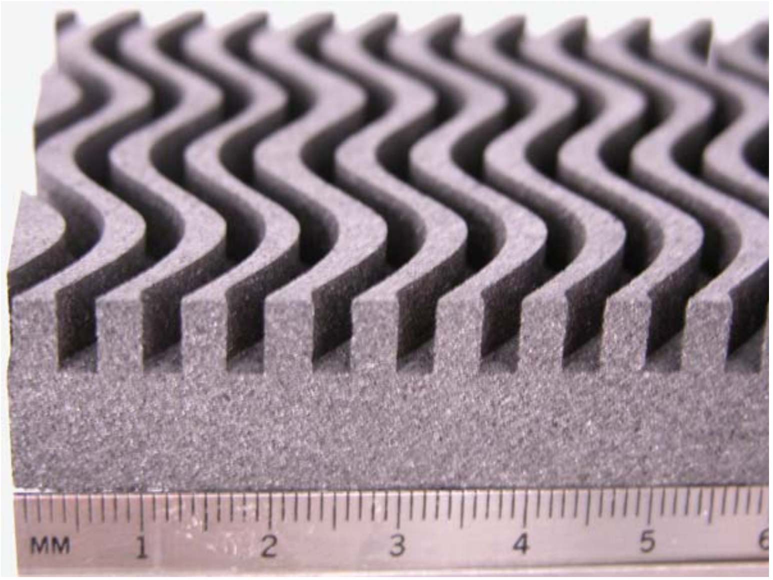
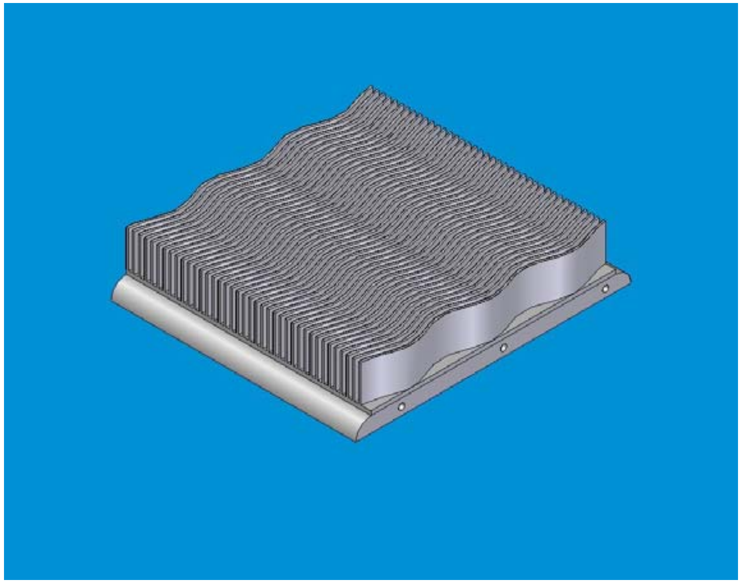
Design – Wavy Fin

Touchstone Research Laboratory CFoam®
Air-to-Air Heat Exchanger
Wavy Fin Configuration

Ceramic Composites Inc.
Steam-to-Air Heat Exchanger
Wavy Fin Configuration





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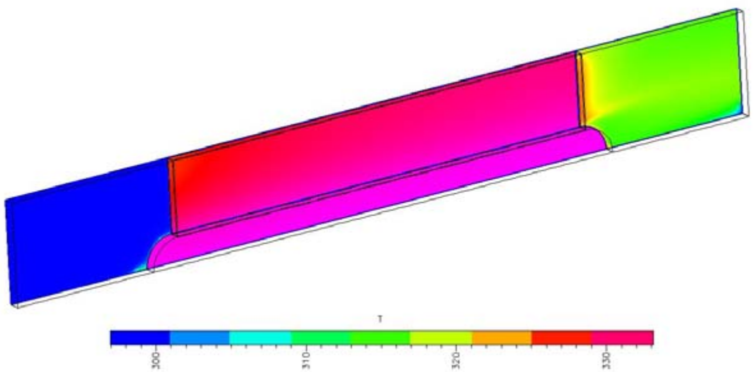
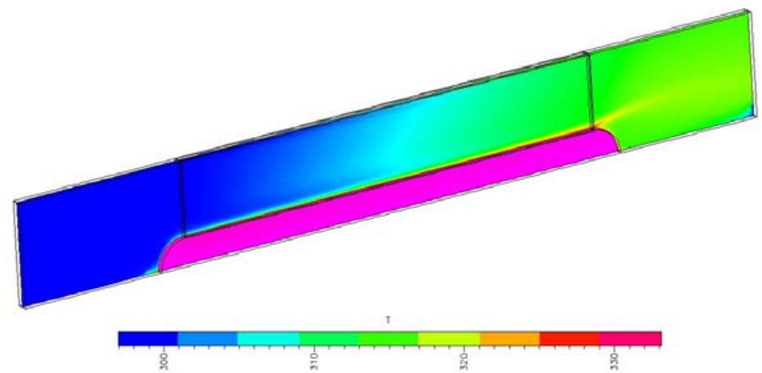
Predicted Fin Performance

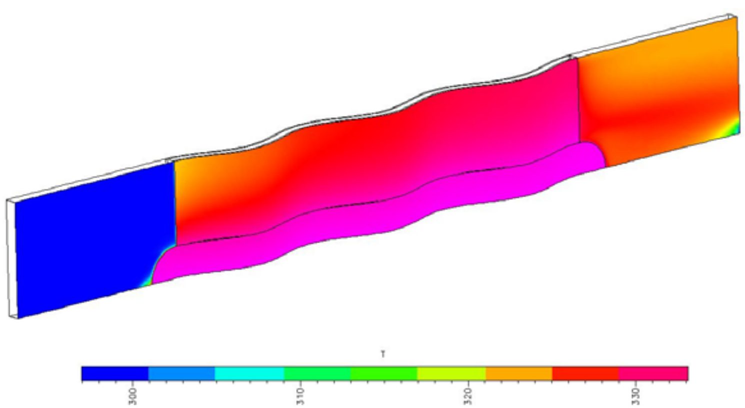
Mid-Fin

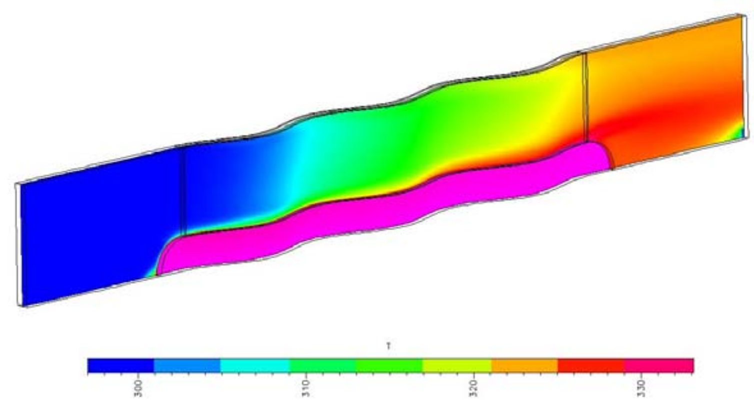
Mid-Channel





WAVY FIN IS 2X MORE EFFICIENT THAN STRAIGHT FIN DESIGN





140°F base temperature, 75°F inlet air at 1000 ft/m

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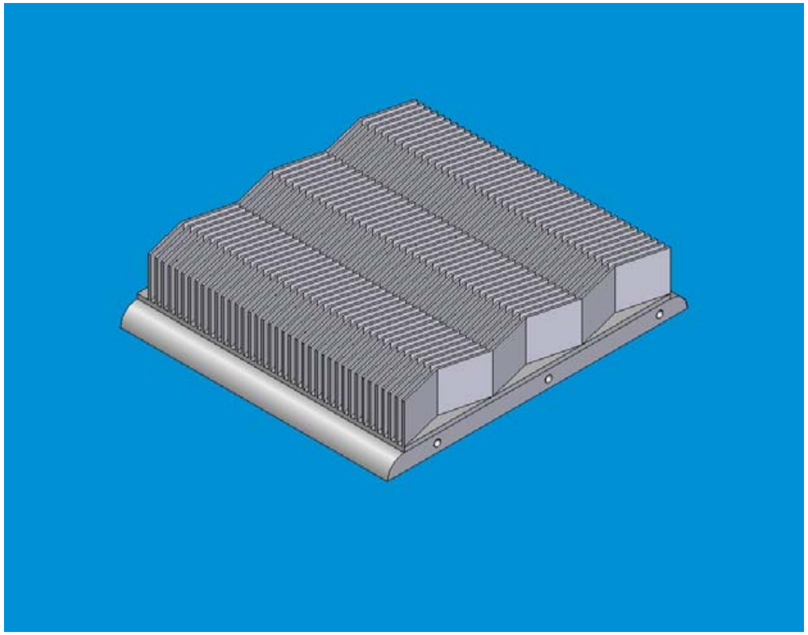
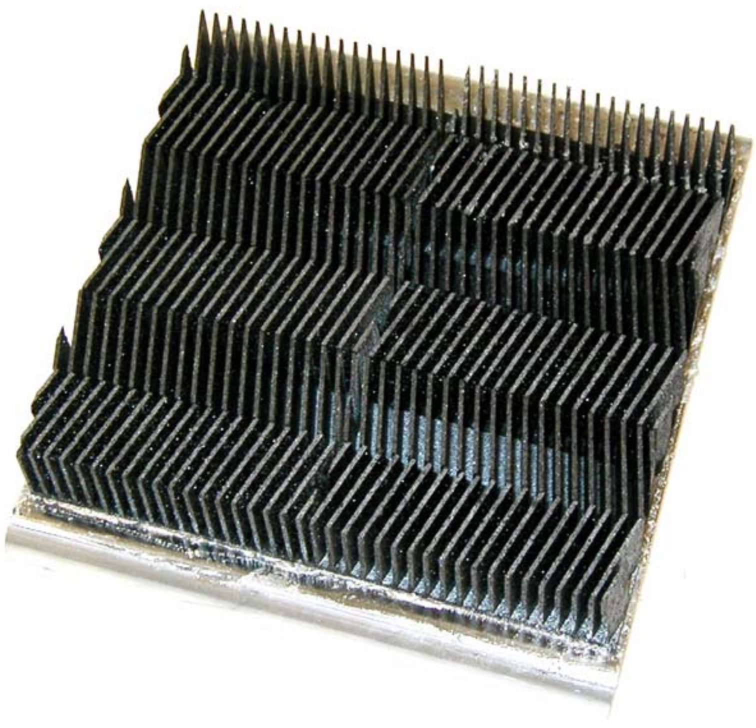
Design – Chevron Fin





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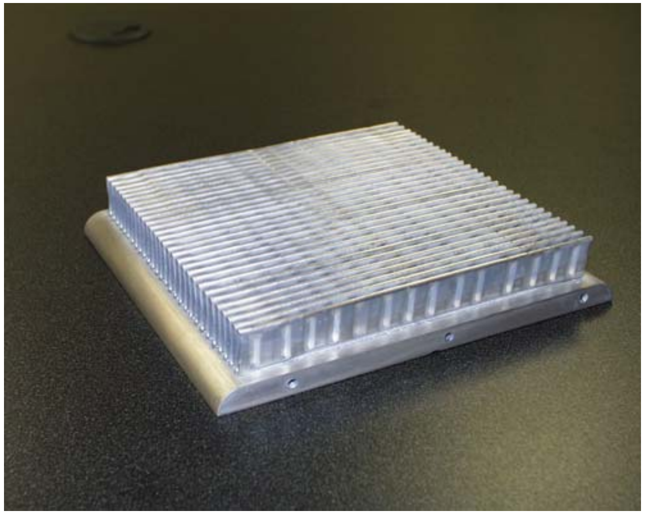
6” x 6” Air Cooled Heat Exchanger



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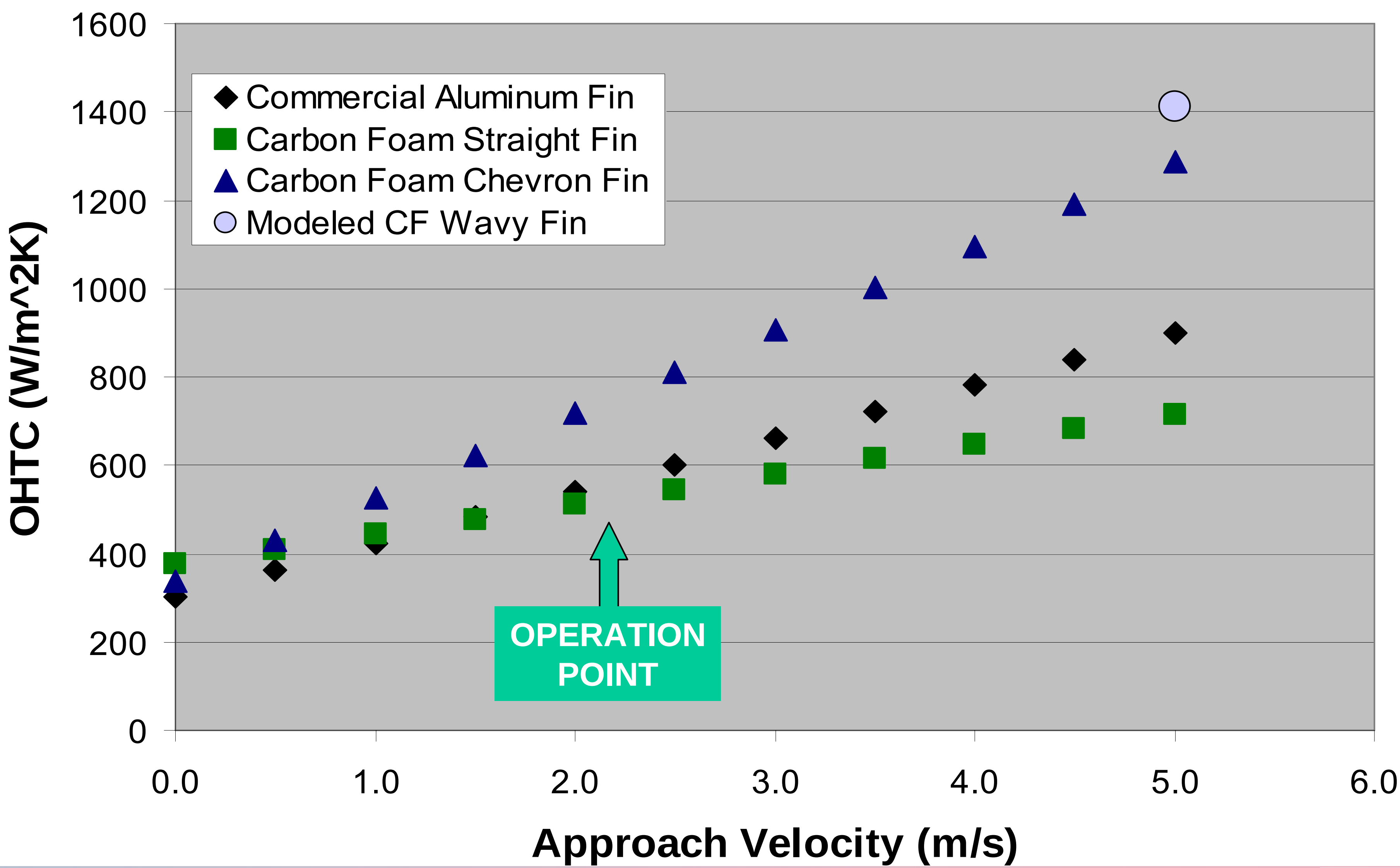
Overall Heat Transfer Coefficient versus Approach Velocity



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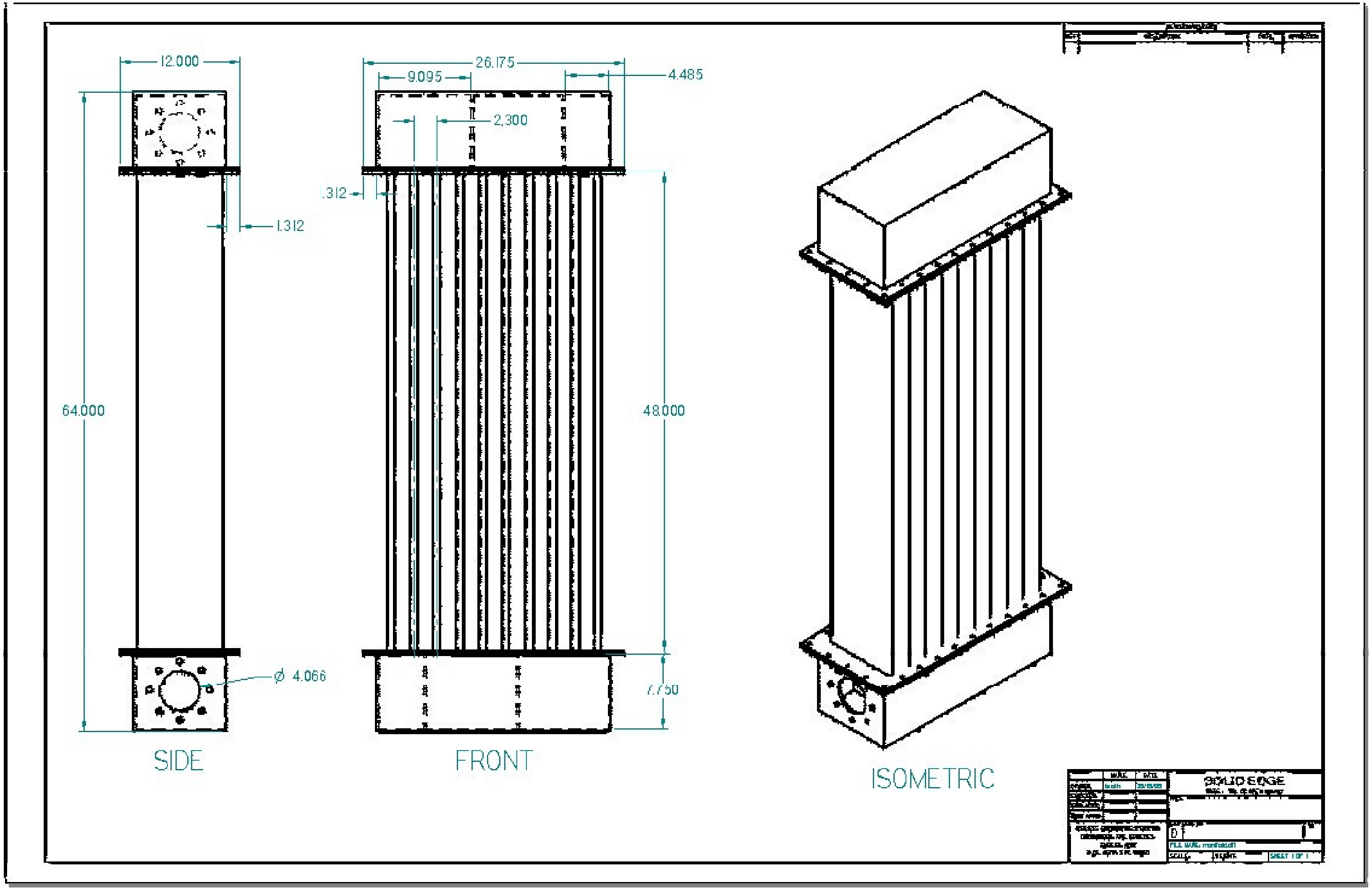
DOE Phase 2 Deliverable: 1 x ½ meter HX



Marley will test the performance of this HX in their research laboratory

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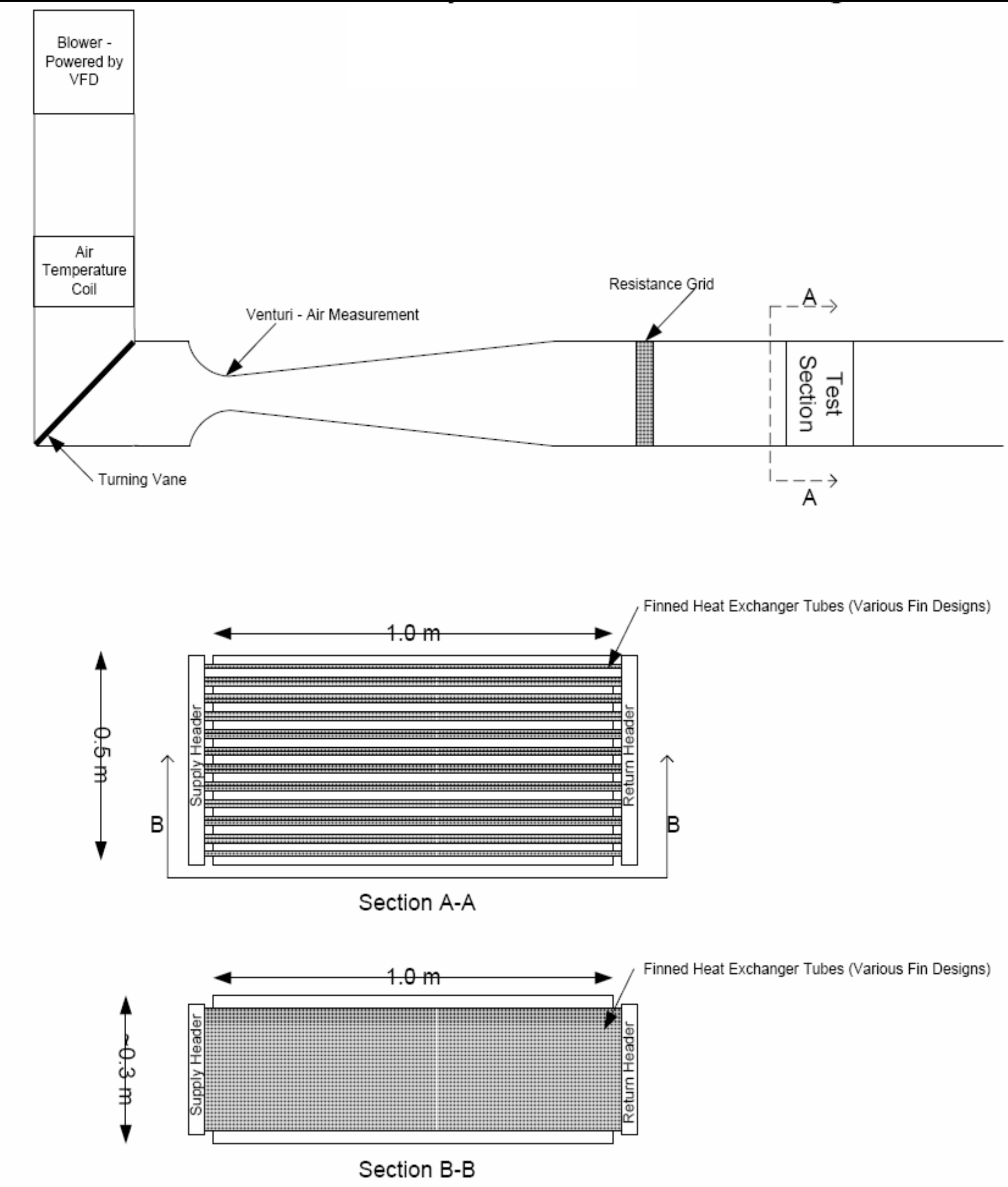
SPX HEAT EXCHANGER TEST FACILITY



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Summary of Program Status

- Structural Enhancement Technology Characterized
- Designs nearing completion
- Machining cost is big concern
- Bonding brought in-house
- Manifolds nearing completion
- Economic study about to start

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A Future Carbon Foam Application?

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REUSE OF INTERNAL OR EXTERNAL WASTEWATERS IN THE COOLING SYSTEMS OF COAL-BASED THERMOELECTRIC POWER PLANTS

Radisav Vidic
University of Pittsburgh

David Dzombak
Carnegie Mellon University

June 20, 2006

OVERVIEW

- Project goal
- Background
- Nontraditional sources of cooling water
- Project tasks
- Project schedule
- Summary

PROJECT GOAL

- Assess potential of three different impaired waters for use in recirculating cooling water systems
  - secondary-treated municipal wastewater
  - passively-treated coal mine drainage
  - ash pond effluent

BACKGROUND

- About 50% of coal-fired power plants in the U.S. employ recirculating cooling water systems
- Increasing federal, state, and community interest in expanding use of recirculating cooling water systems to limit use of freshwater resources
- Large-flow impaired waters are available in some locations

NONTRADITIONAL SOURCES OF COOLING WATER: TREATED MUNICIPAL WASTEWATER

- 11.4 trillion gallons of municipal wastewater collected and treated annually in U.S.
- Experience with use of treated municipal water for power plant cooling in arid west; e.g., Burbank, Las Vegas, Phoenix
- Significant additional treatment beyond secondary treatment (e.g., clarification, filtration, N and P removal)

NONTRADITIONAL SOURCES OF COOLING WATER: PASSIVELY-TREATED AMD

- Significant flows of abandoned mine drainage (AMD) in coal mining regions
- NETL has confirmed magnitude and reliability of AMD as source of cooling water
- Adequate treatment (to raise pH, remove dissolved solids and metals) prior to use is largest concern
- Passive treatment systems offer potential for inexpensive source of cooling water

NONTRADITIONAL SOURCES OF COOLING WATER: ASH POND EFFLUENT

- Water-ash slurry systems used commonly to remove bottom ash and fly ash
- Slurry is directed to ponds where settling of ash particles occurs
- Slurry water is often discharged
- Potential to reuse the slurry water in the slurry system and as cooling system makeup water

PROBLEMS WITH USE OF IMPAIRED WATERS

- Precipitation and scaling
- Accelerated corrosion
- Biomass growth

RESEARCH TASKS

- Task 1: Assess quantities and availability of impaired waters and proximity to power plants
- Task 2: Assess relevant regulations and permitting issues related to use of impaired waters
- Task 3: Characterize impaired waters from 3 sites
- Task 4: Construct and test model cooling tower
- Task 5: Field tests with model cooling tower with impaired waters at 3 sites

RESEARCH TASKS (cont)

- Task 6: Develop mathematical model for water quality characteristics in cooling systems with the 3 impaired waters
- Task 7: Assess treatment needs for cooling tower blowdown
- Task 8: Progress reports and final report

RESEARCH TASK 1

- Identify 12 coal-based power plants spanning different geographic regions of U.S.
- Identify sources of impaired water within 20-mile radius of each plant, and characteristics of sources (distance from plant, average flow, water characteristics)
- Resources
  - USGS topographic and other available maps
  - personnel at each plant
  - local or state regulatory personnel

RESEARCH TASK 2

- Identify range of air quality, water quality, and other regulations that pertain to use of each of the three impaired waters
  - Potential for aerosolization of pathogenic microorganisms in the cooling tower
  - Possible deleterious effects of removing discharges due to the resulting reduction in minimum stream flows
  - Transport of impaired waters over political and administrative boundaries

RESEARCH TASK 3

- Three test sites included in this study
  - Secondary treated municipal wastewater (Franklin Township Municipal Sanitary Authority, Murrysville, PA)
  - Passively treated mine water (St. Vincent College, Latrobe, PA)
  - Ash pond water (Cheswick Thermoelectric Plant, Springdale, PA)

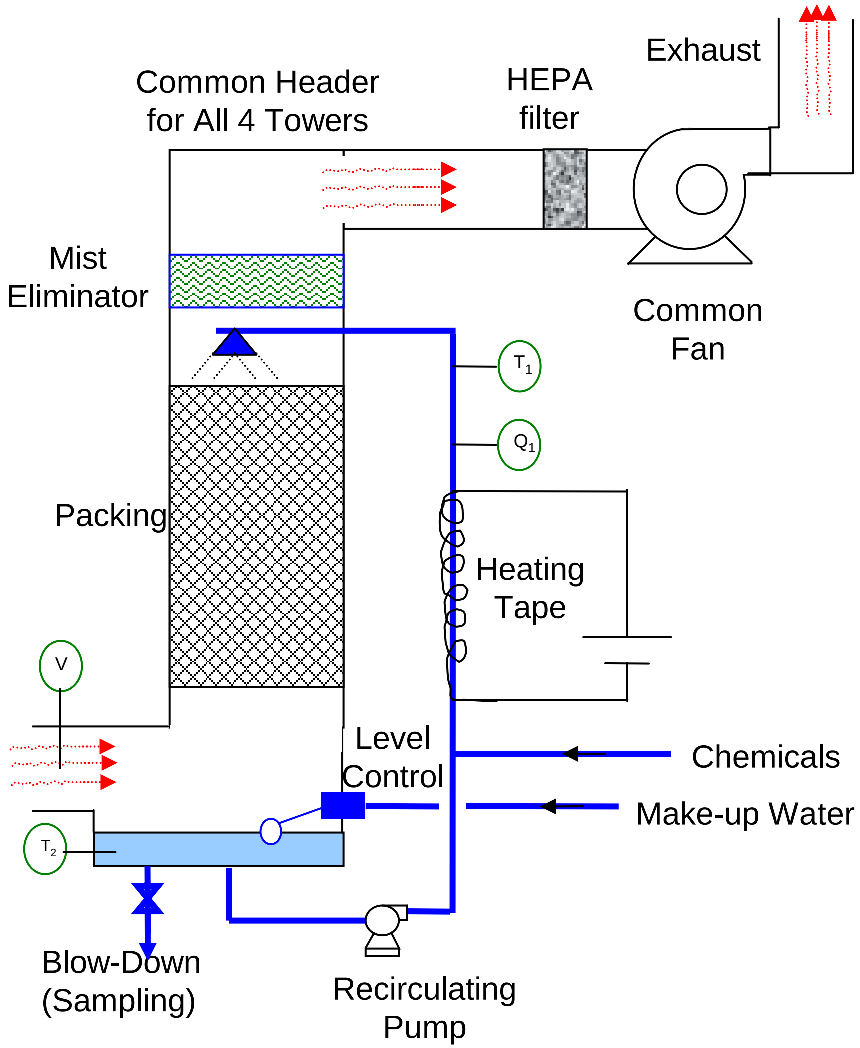
RESEARCH TASK 3

- Characterize general water quality for each site included in this study
  - Basic water quality parameters (pH, TDS, TSS, conductivity, alkalinity, major cations and anions)
  - Organic carbon content (DOC, TOC)
  - Selected metals (Al, Fe, Mn, Zn)
  - Nutrients (N, P)

RESEARCH TASK 4

- Build pilot-scale system comprising four counter-flow cooling towers with common air handling unit
  - galvanized steel with counter-flow packing
  - control and measurement equipment
  - anti-corrosion and anti-scaling treatment program
  - 2 to 6 cycles of concentration
  - corrosion monitoring with steel and copper coupons

RESEARCH TASK 4



RESEARCH TASK 4

RESEARCH TASK 5

- Field-scale testing
  - One tower operated as control with tap water
  - Vary cycles of concentration with impaired waters
  - Anti-corrosion and anti-scaling chemicals
  - Evaluate water quality, including biological quality and precipitation potential
  - Evaluate corrosion potential

RESEARCH TASK 6

- Chemical equilibrium program MINEQL+
- EPRI cooling water chemistry model ChemExpert
- Provide fundamental insight into:
  - scale-producing reactions
  - corrosion chemistry and its inhibition
  - potential chemistries that could be exploited to remove target species in cooling system sidestream treatment

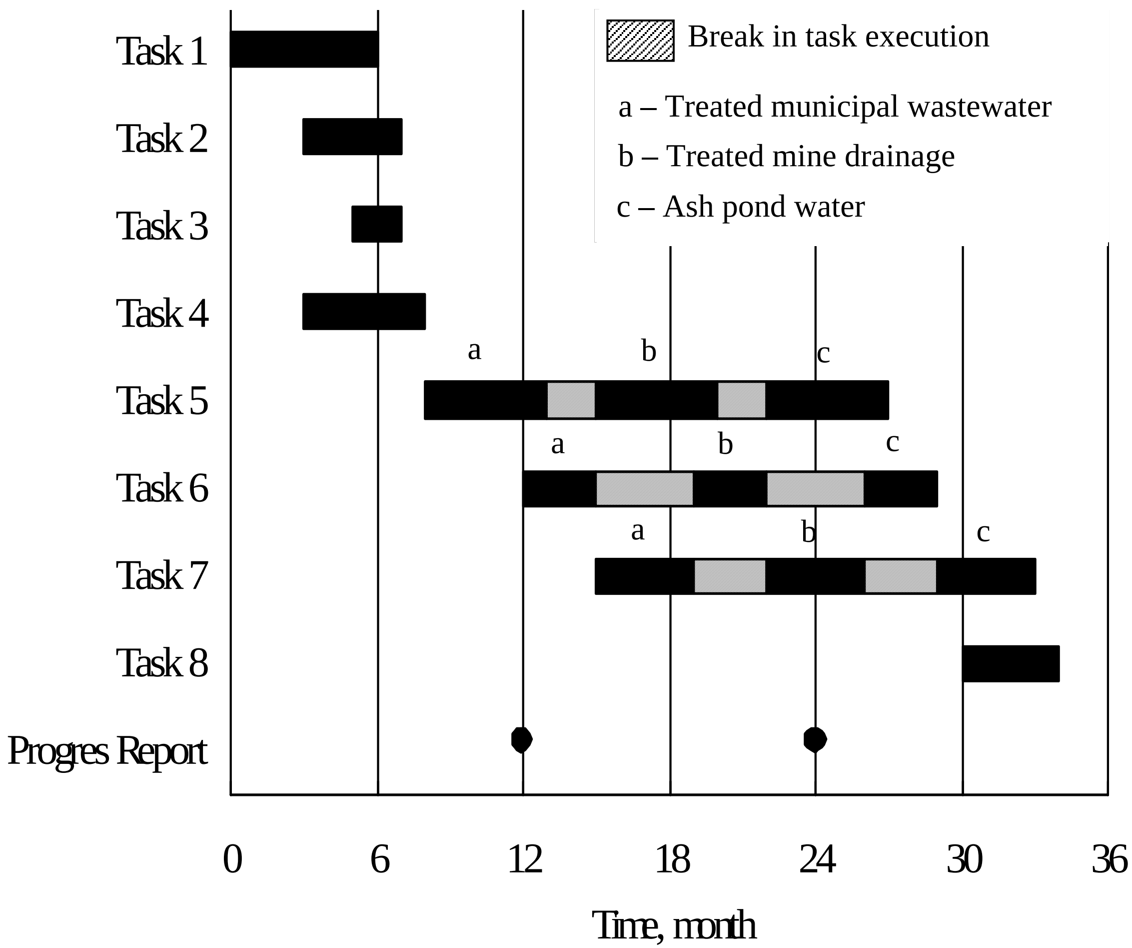
RESEARCH TASK 7

- Blowdown from the highest cycle of concentration for each impaired water will be evaluated for treatment needs
  - Characterization
  - Modeling
  - Bench-scale testing (e.g., softening, reverse osmosis, ion exchange)

RESEARCH TASK 8

- All reports will be in compliance with the reporting requirements of DOE
- Research accomplishments and results
- Recommendations regarding the key parameters influencing operational characteristics of cooling towers for selected impaired water sources
- Practical utility of the mathematical model developed in this study
- Refereed journals and professional meetings

PROJECT SCHEDULE



SUMMARY

- Assess potential of three different impaired waters for use in recirculating cooling water systems
- Impaired waters: treated municipal wastewater, passively-treated AMD, ash transport water
- Project will involve laboratory testing, field evaluations with a model cooling tower, and modeling of cooling water chemistry evolution

Development and Demonstration of a Modeling Framework for Assessing the Efficacy of Using Mine Pool Water for Thermoelectric Generation

Prepared for:

USDOE

National Energy Technology Laboratory

Water and Power Plants Review Meeting

June 20, 2006

Paul Ziemkiewicz

WV Water Research Institute

WV-232

Objective

- Develop and demonstrate a computer based design aid around the Beech Hollow Power Plant (300MW) that can be used by developers in evaluating the hydrologic, chemical, engineering, environmental benefits and costs of using mine pool water as an alternative to traditional supply

- Need 3,000 gpm

Location of Beech Hollow Power Plant

Task 1.1 – Identify Mine Water Sources

- Literature search and field investigation will be used to identify potential mine water sources within 6 miles of the Beech Hollow Power Plant .
- Both above drainage and below drainage mines will be considered.
- Several wells will be drilled to intercept below drainage mines.

Primrose Discharge

(flow avg.= 80 gpm)

Task 1.2 – Quantify Water Volume and Water Quality

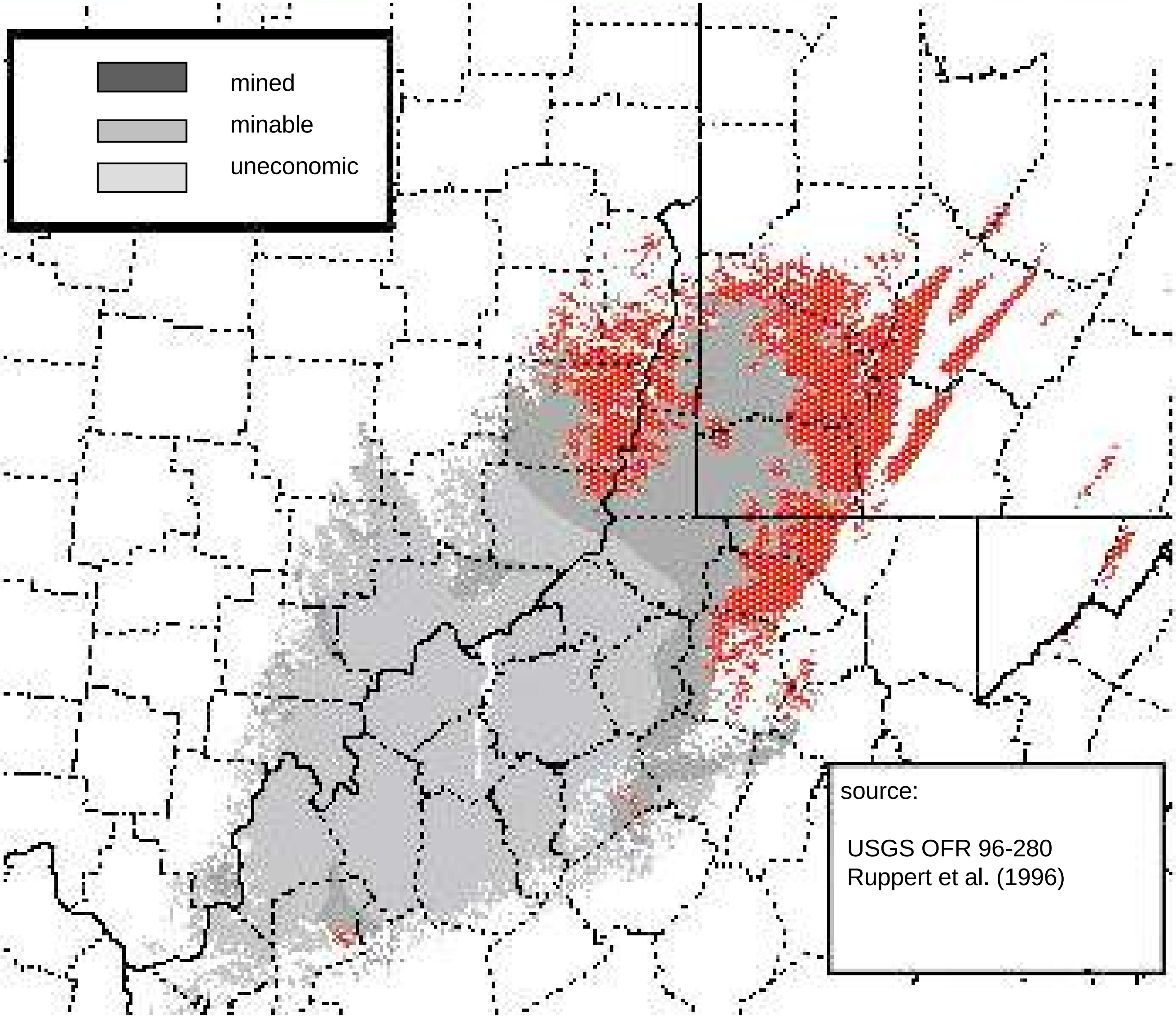
- Promising discharges will be equipped with primary flow measuring devices and pressure transducers.
- Water quality from these discharges will be evaluated monthly over a one year period.
- One well will be fitted with a pressure transducer to record water level fluctuation.

JB-1 with H-Flume

pH 5.3, Fe 47 mg/L , Flow 953 gpm

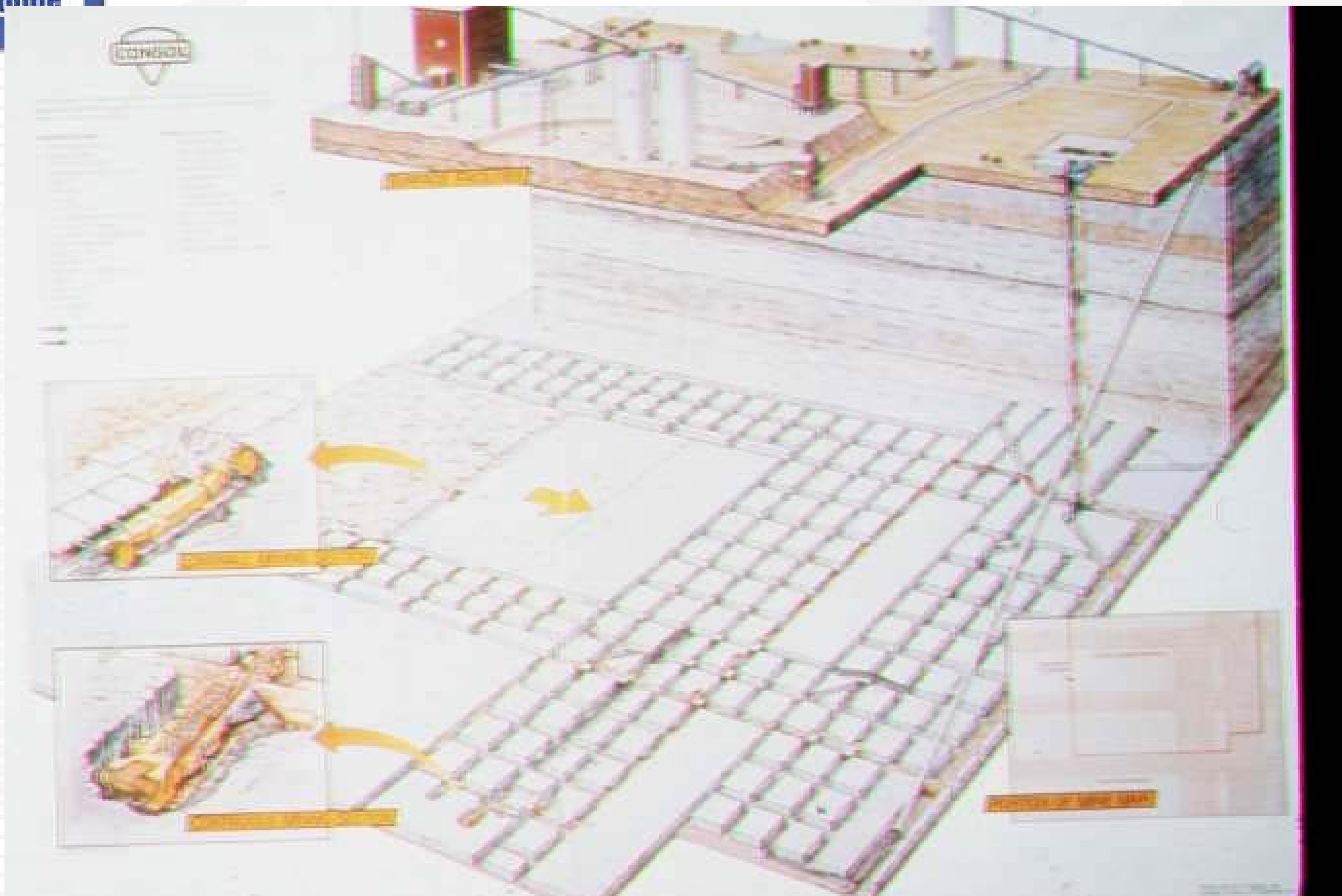
Task 1.3 – GIS Mapping

- High resolution mine maps will be sought for the mine discharges previously identified.
- These maps will be scanned and geo-referenced for use in the engineering design analysis.
- The mapping will also be used to identify the areas of contribution to the mine discharge.



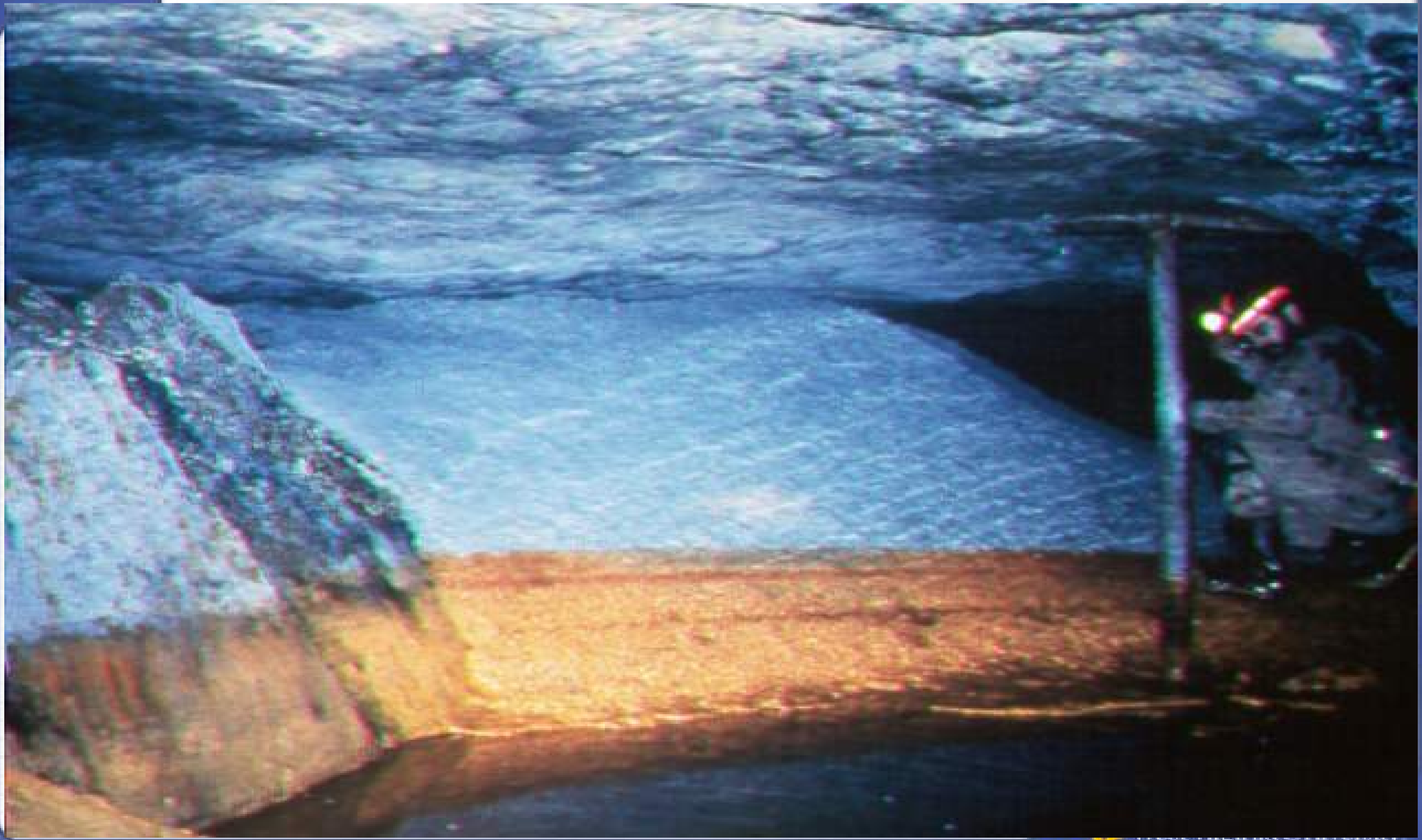
The Pittsburgh coal basin

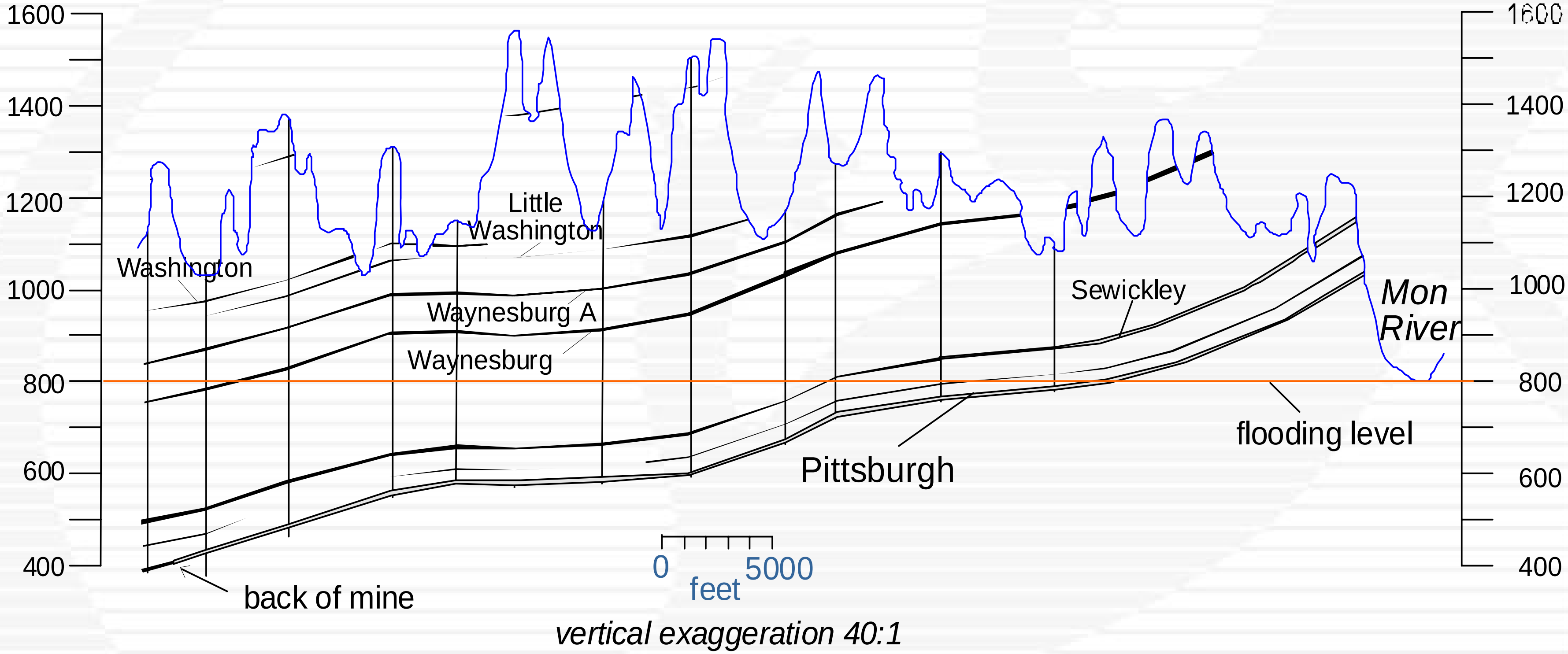
Layout of Typical Underground Coal Mine



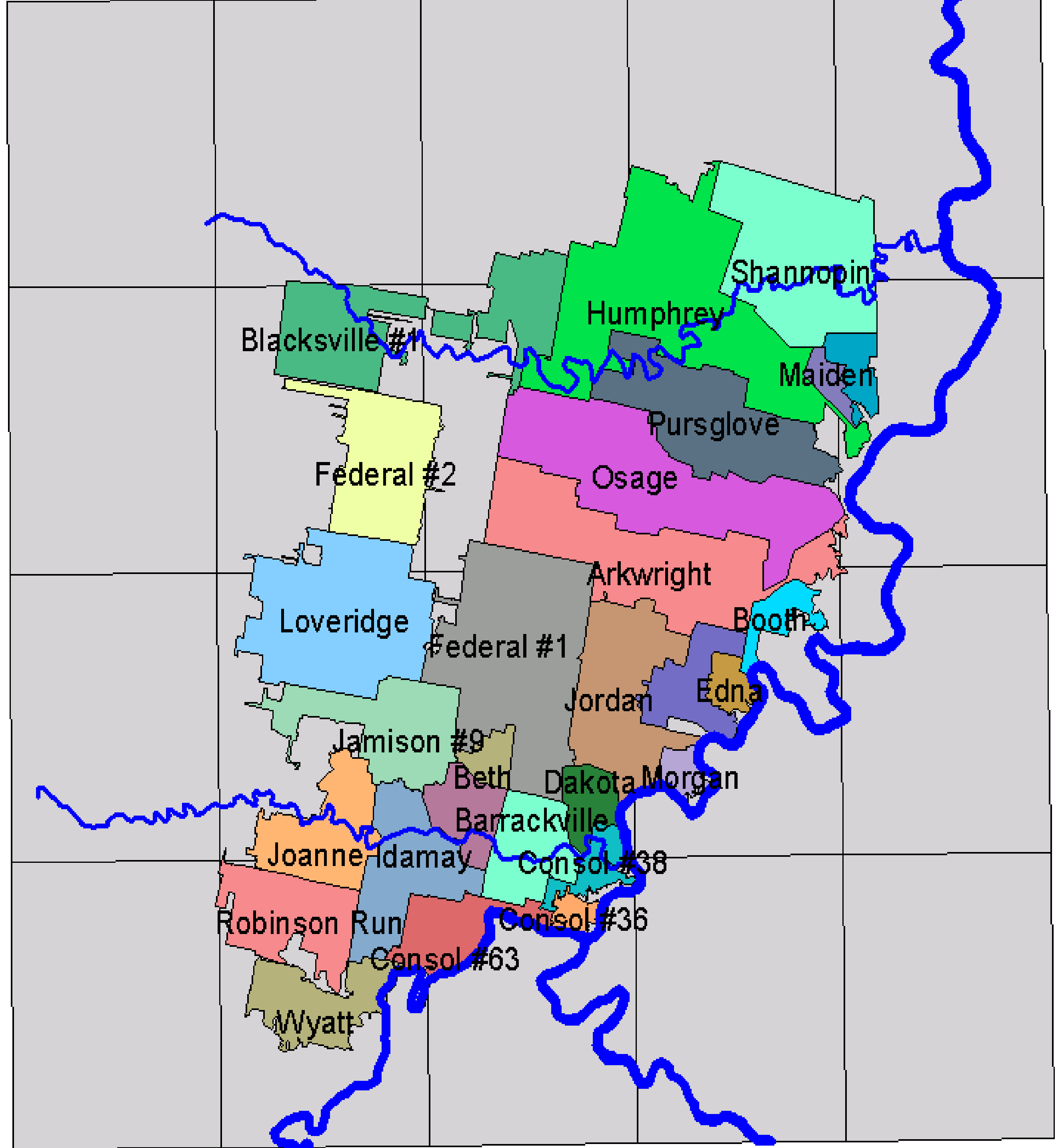
Underground Coal Mine Void

Partially Flooded Mine





Schematic cross section of geology in the eastern portion of the Pittsburgh coal basin.



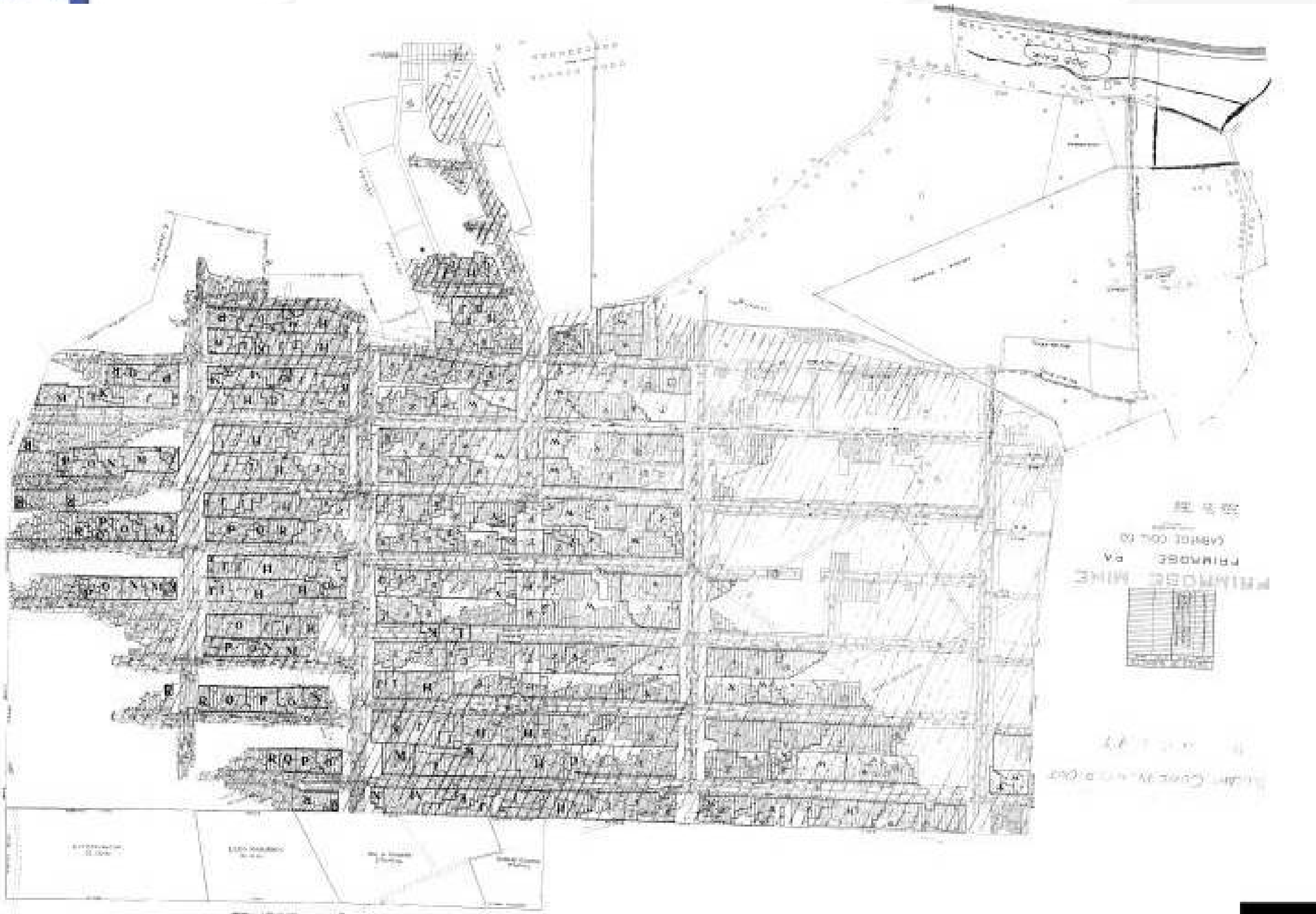
Underground Mines in Monongahela Basin

Below Drainage

Pittsburgh Coal Basin Water Resources

- Water Production:
  - 92,000 GPM
  - 205 CFS
- Capacity 11,409 MW:
  - 12 -15 600 MW units
  - 60 200 MW FBCs

Primrose Mine



Task 1.4 - Mine Discharge Selection

- Meteorologic records and flow rate data from identified mine discharges will be used to derive a regression formula for estimating mine discharge flow rate from observed precipitation rates.
- Regression formula will be employed to project the 10 year, low flow mine discharges.
- Mine water treatment requirements will be a function of power plant water quality needs.
- Mine discharge water quality.

Task 1.5 – Collection and Treatment System design

- A collection system will be designed to supply the mine water to the power plant.
- Based on power plant requirements, a treatment system will be designed using initial hydrated lime treatment.
- Anticipated capital and operating costs will be generated.

Task 2.1 - General Information Module

- Module will query the user for:
  - Site information.
  - Owner information.
  - Anticipated construction date.
  - If the mine water will provide: makeup water or both makeup water and heat rejection.
- User will specify the inflation rate.
- Design program will consist of a Microsoft Excel spreadsheet with Visual Basic for Applications (VBA) modules.

Task 2.2 - Water Source Module

- Module will query for:
  - Mine discharge flow rate.
  - Water quality.
  - Distance from the source to the treatment plant.
  - Elevation of mine water.
  - Elevation of mine water pump.
  - Elevation of treatment plant.
  - Maximum elevation of the pipeline.

Task 2.2 - Water Source Module

- Module will recommend:
  - Three different pipeline diameters.
  - Estimated installed cost for each option.
- Module will calculate:
  - Low flow discharge rate for above drainage mines.
  - Sustainable yield for below drainage mines.
- Module will accept multiple water source inputs.

Task 2.3 - Water Treatment Module

- User will have the option of forcing the module to minimize mine water temperature.
- Module will size the treatment plant equipment based upon:
  - Water treatment volume.
  - Raw water chemistry.
- Module's calculations will assume that:
  - Hydrated lime will be the neutralization regent.
  - Either air or hydrogen peroxide will be oxidant.

Task 2.4 - Cost Module

- Cooler summer makeup water temperatures may result in a equipment size reduction at the power plant.
- If the user elects to use mine makeup water, module will calculate:
  - Overall capital cost savings.
  - Overall operational cost savings.

Task 2.5 - Module Integration

- VBA modules will be integrated into a design aid.
- Calculations and the user interface of the design aid will be extensively tested.
- Design aid will incorporate a users manual that will explain the application of the design aid and basic cost data.

Design Aid Requirements

- Using the design Aid will require:
  - 90 MHz Pentium Computer.
  - Microsoft Windows 2000 or XP.
  - 48 MB RAM.
  - Microsoft Office 2000.
- Design aid and users manual will be available via the WV Water Research WWW site.

Application of pulsed electrical fields for advanced cooling in coal-fired power plant

"Advanced Technologies and Concepts
to Minimize Freshwater Use in Coal-Based Thermoelectric Power Plants"
Topic 2: Advanced Cooling Technology
U.S. DEPARTMENT OF ENERGY
National Energy Technology Laboratory

Drexel University

Y. Cho, A. Fridman, and A. Gutsol

June 20, 2006

Goal of the project

To develop a scale prevention technology based on integrated system of physical water treatment (PWT) and a novel filtration method.

To significantly reduce water blowdown, which accounts approximately 30% of water loss in a cooling tower.

Specific Target

To increase COC from 3-4 to a higher COC (8-10)

How?

To continuously convert dissolved calcium ions in water to calcium particles (PWT technology)

To continuously remove them

What is COC?

$$COC = \frac{X_{\text{Circulating water}}}{X_{\text{Make-up water}}}$$

Mass balance

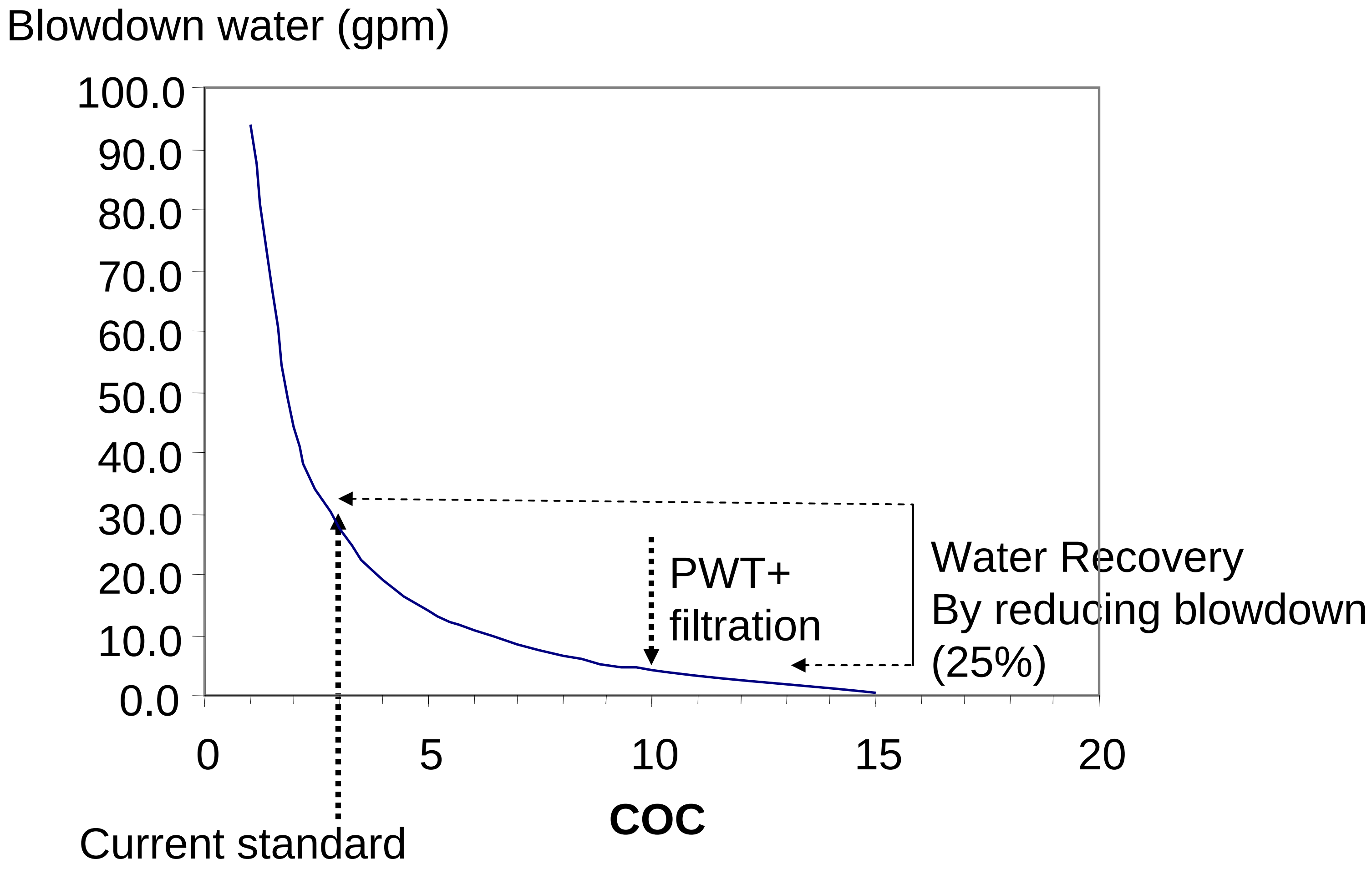
Make up = Evaporation + Blow Down + Wind Loss

Ion balance

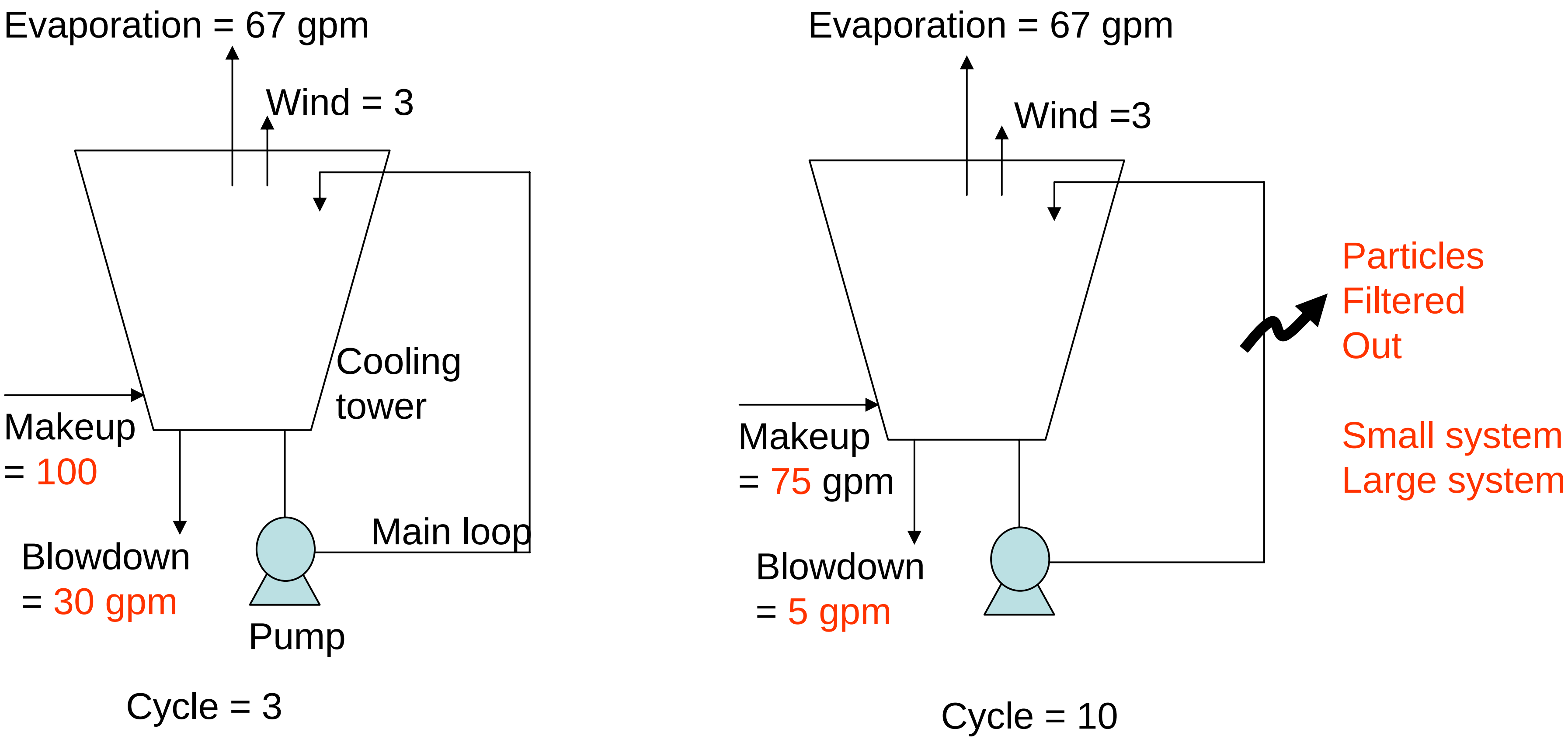
$$M\,X_{\text{Make-up}} = (B+W)\,X_{\text{Circulating}}$$

$$COC = \frac{M}{B+W}$$

If Makeup water is 100 gpm,



If Makeup water is 100 gpm,



(A) Existing technology

(B) Proposed technology
(Maintain high COC)

Why fouling?
- cooling tower application

- Evaporation of pure water leaves calcium ions behind.

- Water becomes hard → scaling takes place.

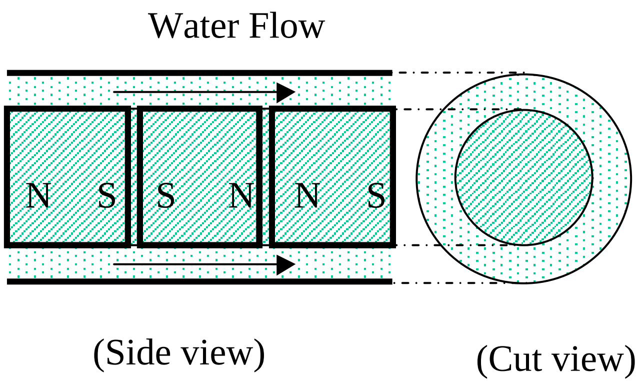
Cooling tower water analysis

(from our previous study)

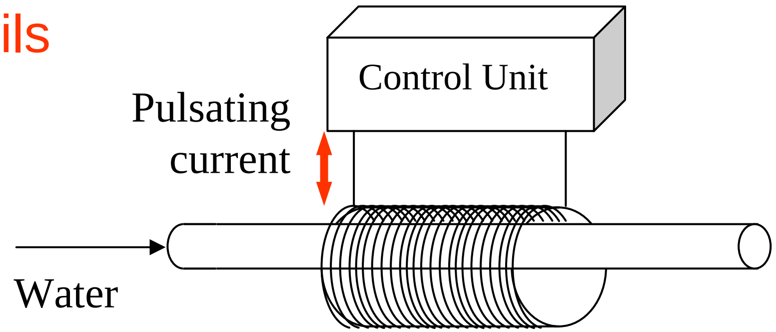
	Make-up	5 COC
Conductivity (μS/cm)	450	2040
pH	7.2	8.1
Calcium (mg/L)	150	520
Magnesium (mg/L)	50	244
Total Hardness (mg/L)	200	764
Total alkalinity (mg/L)	78	176
Chloride (mg/L)	73	382
Langelier Saturation Index (at 59 ^{o}C)	0.36	2.02

PWT devices

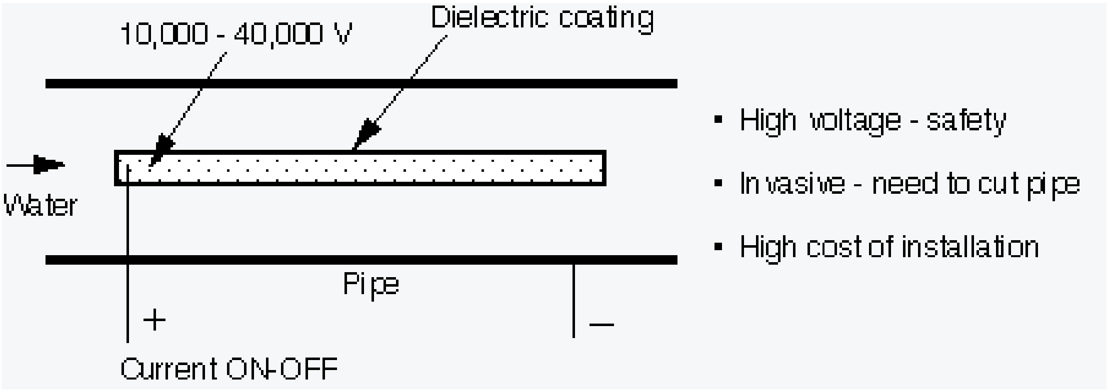
Permanent magnets



Solenoid-coils



Electrostatic device



No treatment

→ Crystallization Fouling ($CaCO_3$ reaction)

→ Hardened scale deposits

Mechanism of PWT

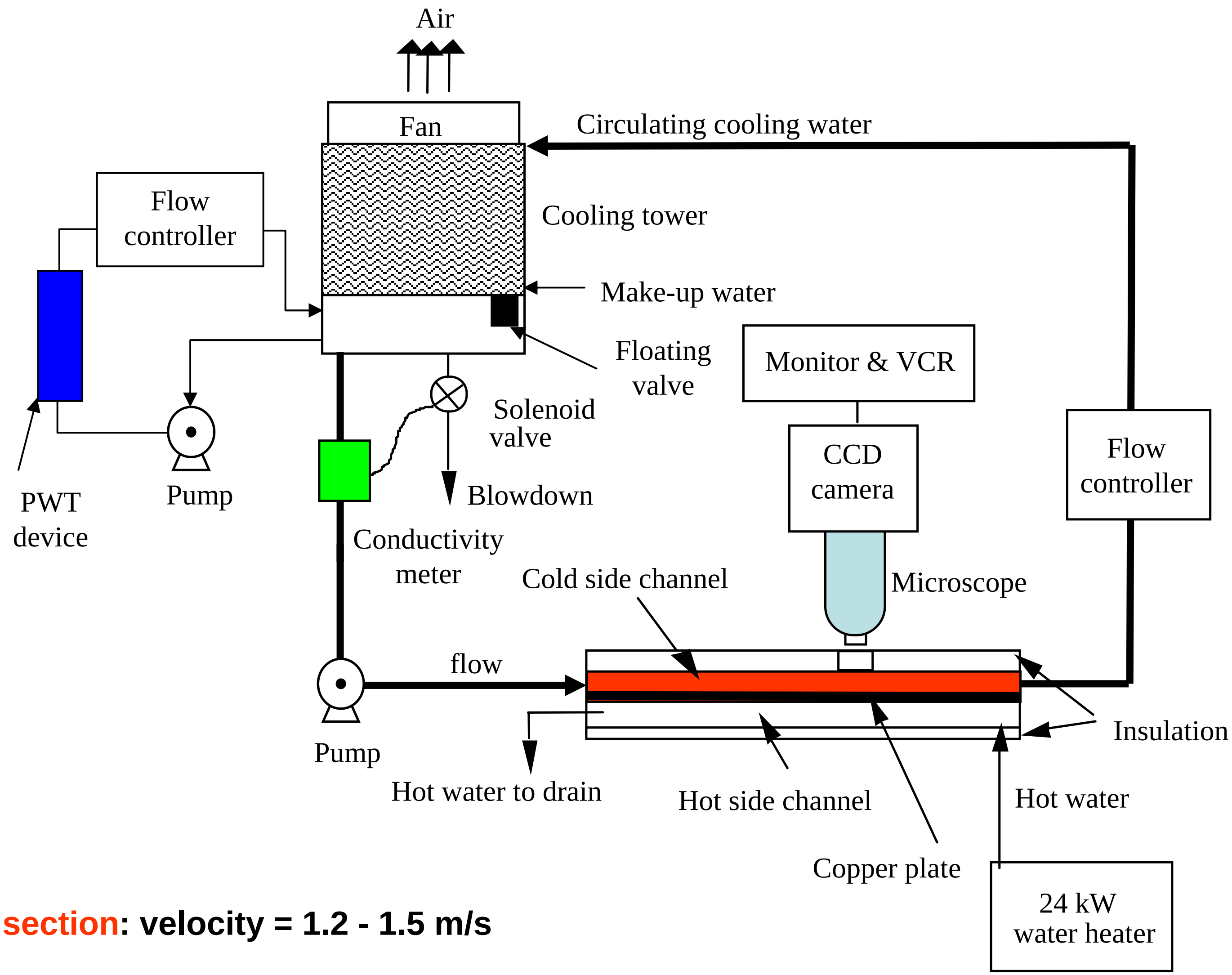
Bulk precipitation

→ Particulate Fouling

→ Soft sludge scales

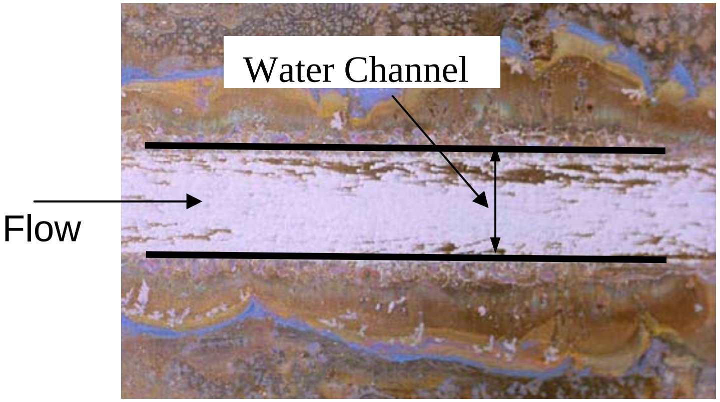
→ Removed by shear force

Fouling Research at Drexel Univ.

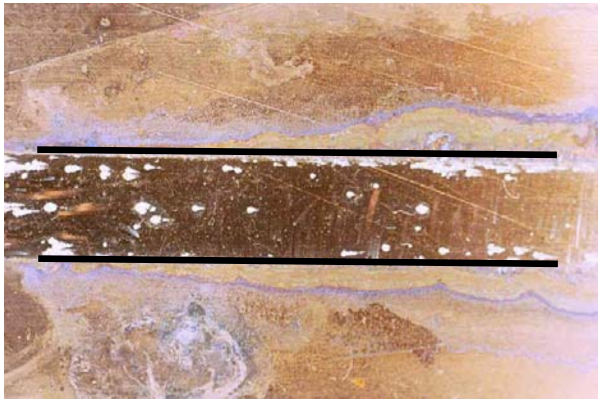


HT test section: velocity = 1.2 - 1.5 m/s

Fouled surfaces with and without PWT



No- treatment



PM-2.3 m/s

Calculation of Fouling Resistance

Fouling resistance

$$\mathrm{R_f} = \frac{1}{\mathrm{U_{fouled}}} - \frac{1}{\mathrm{U_{ini}}}$$

Overall heat transfer coefficient

$$U = \frac{\dot{Q}}{A \Delta T_{lm}}$$

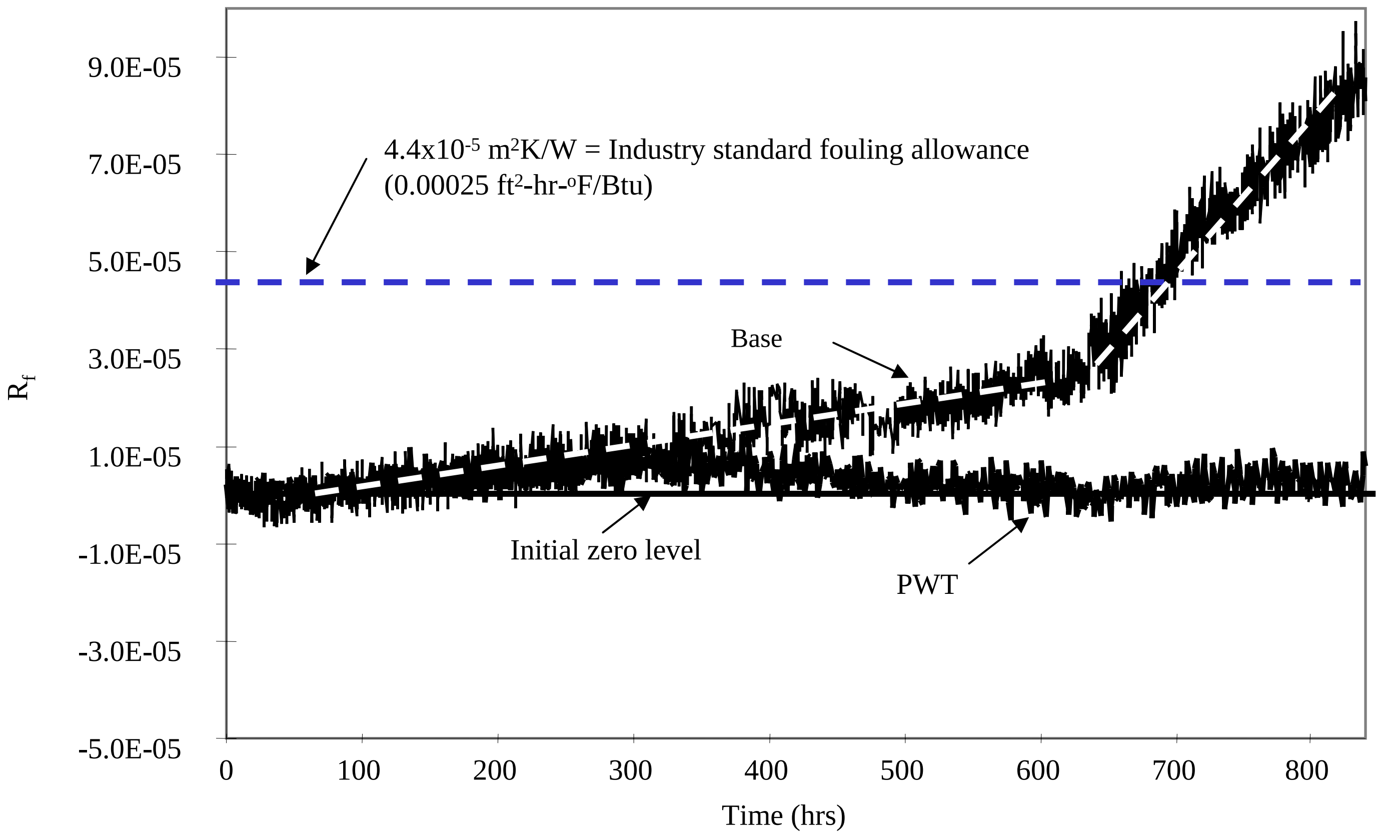
Log-mean-temperature-difference

$$\Delta T_{lm} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln\left[\frac{(T_{h,i} - T_{c,o})}{(T_{h,o} - T_{c,i})}\right]}$$

Energy balance

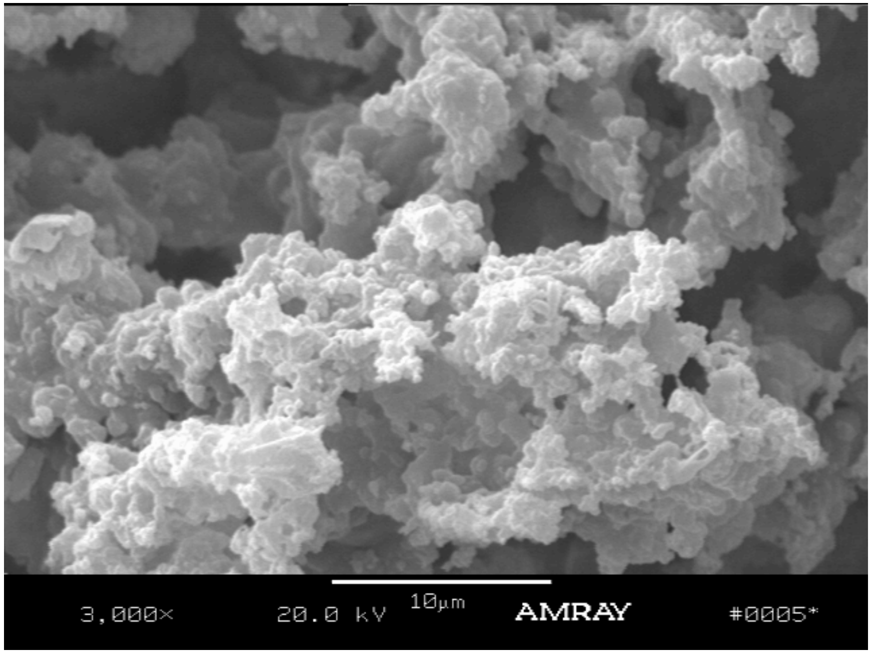
$$\dot{Q} = [\dot{m} c_p (T_i - T_o)]_h = [\dot{m} c_p (T_o - T_i)]_c$$

Solenoid-coil device for fouling mitigation



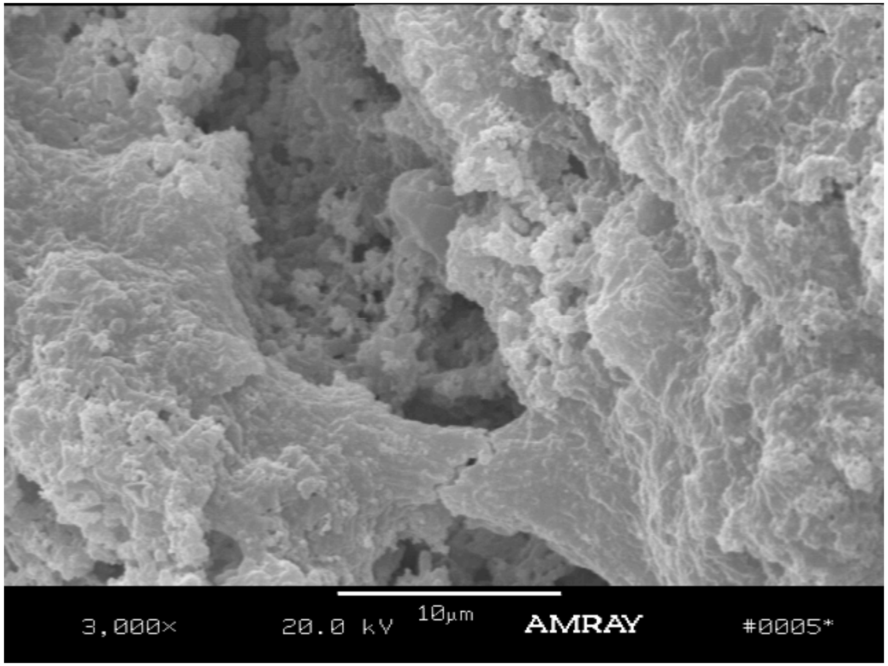
Y. Cho, J. Lane, and W.T. Kim., Pulsed-power treatment for physical water treatment,
Int. Comm. Heat Mass Transfer, Vol. 32, pp.861-871 2005

SEM photographs: 3000x

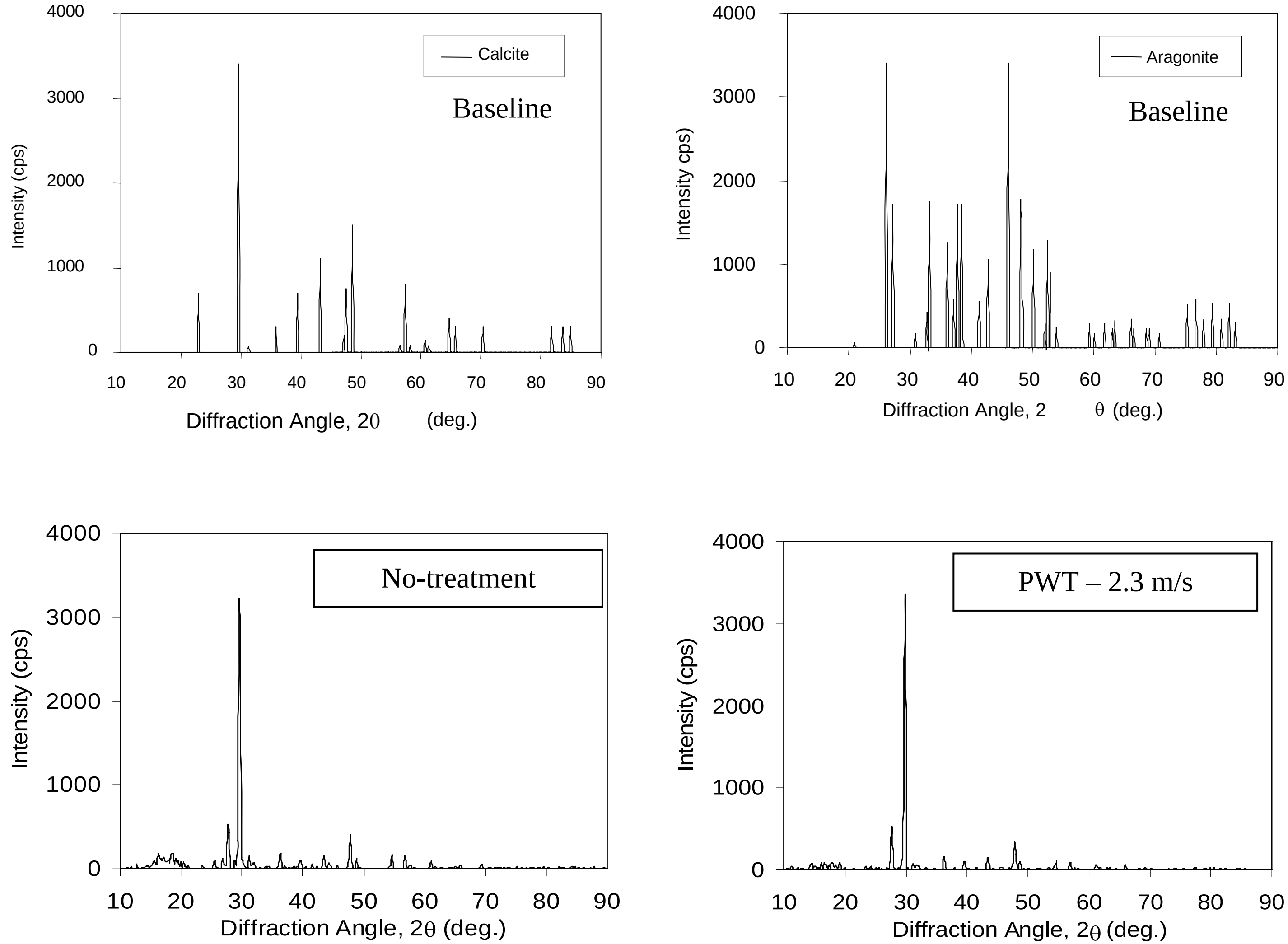


No Treatment

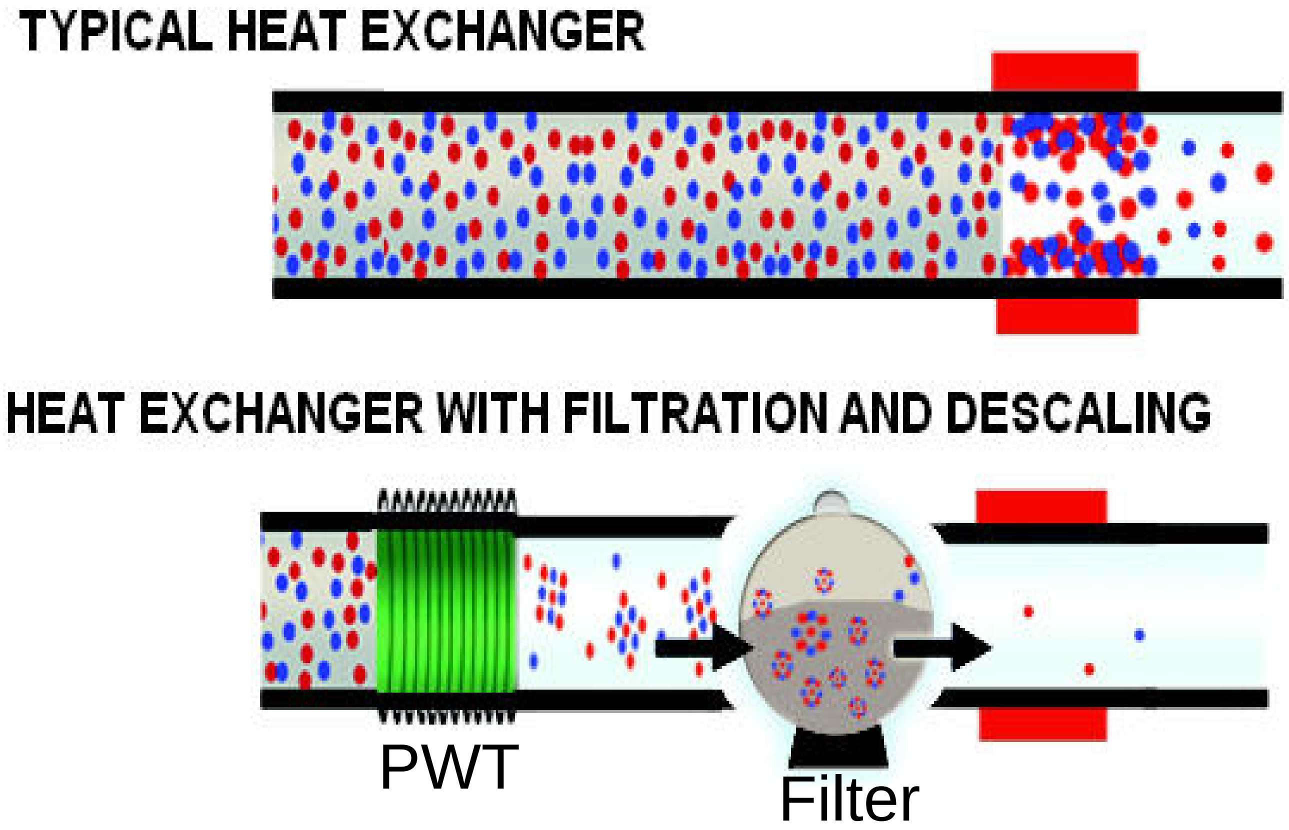
Tests with PWT - PM-2.3 m/s



X-ray diffraction measurements of scale deposits

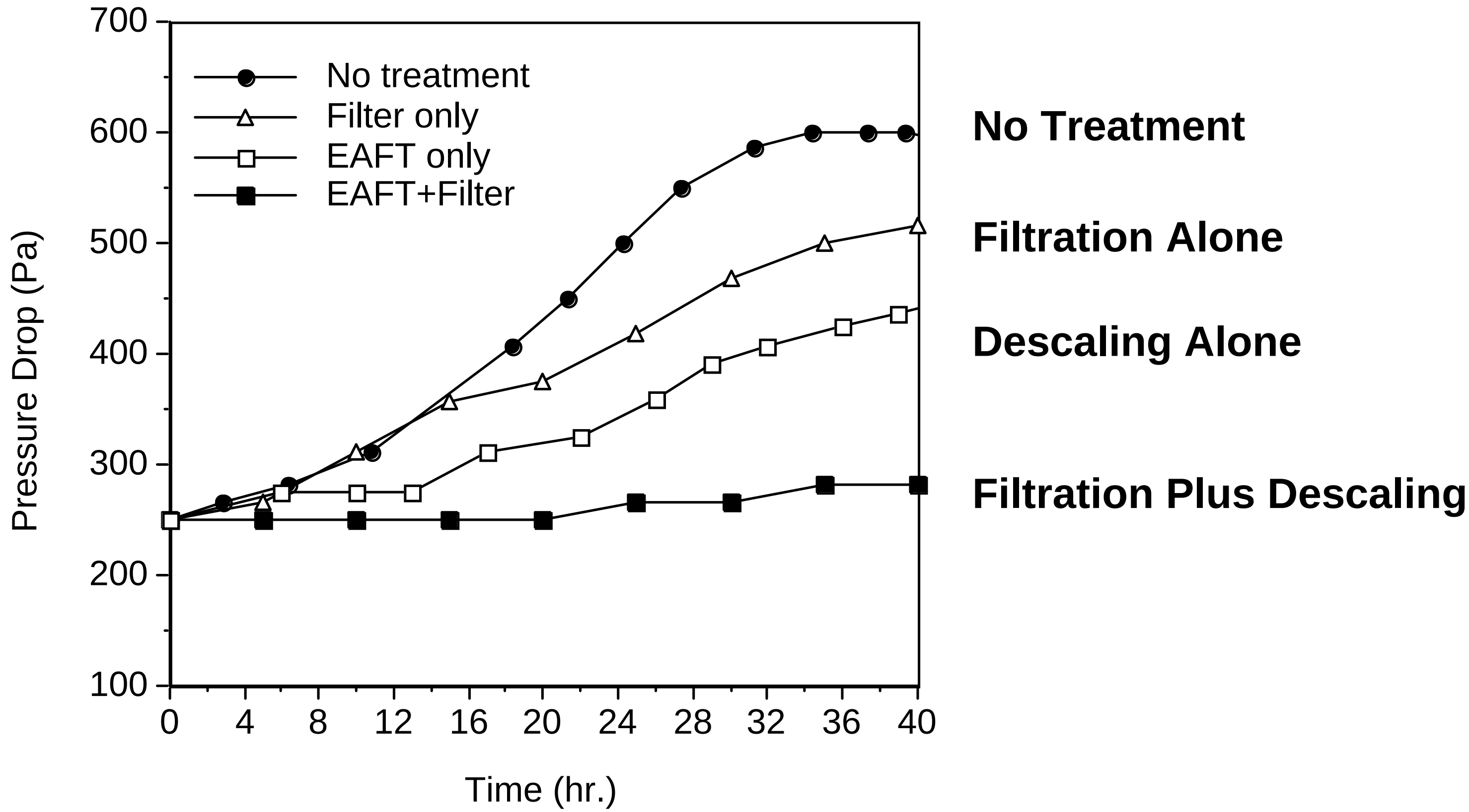


Synergy of PWT and Filtration



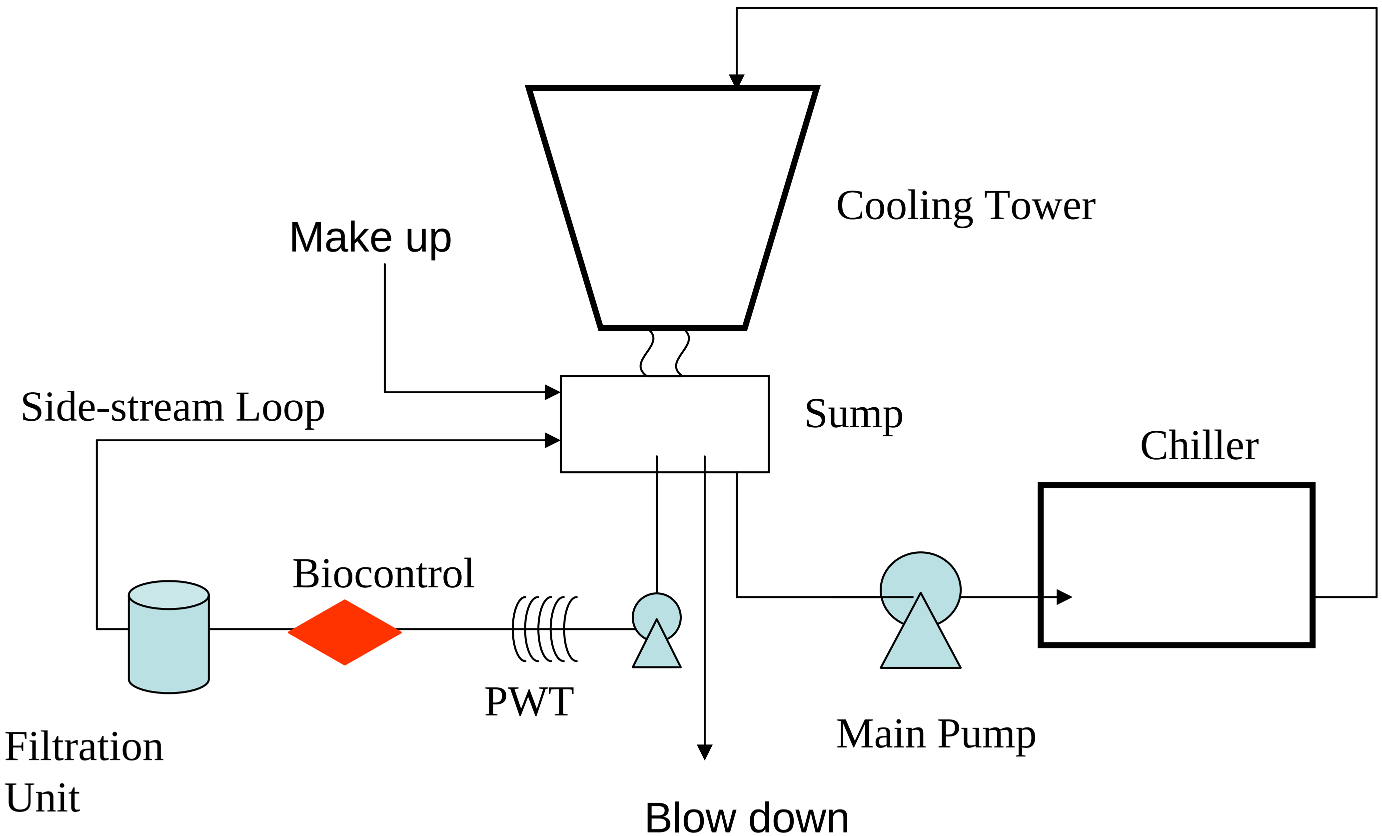
Benefit of Filtration plus PWT

for fouling mitigation

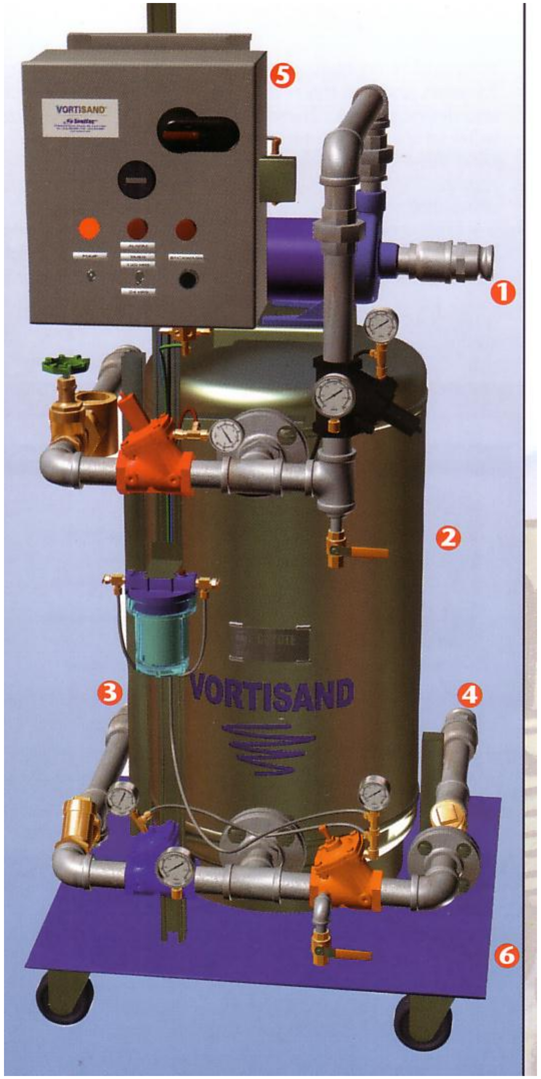


Cho et al. Use of Electronic Anti-Fouling Technology with Filtration to Prevent Fouling in a Heat Exchanger, Int. J. Heat Mass Transfer, Vol.41, pp.2961-2966, 1998.

Comprehensive Cooling Water Treatment Program

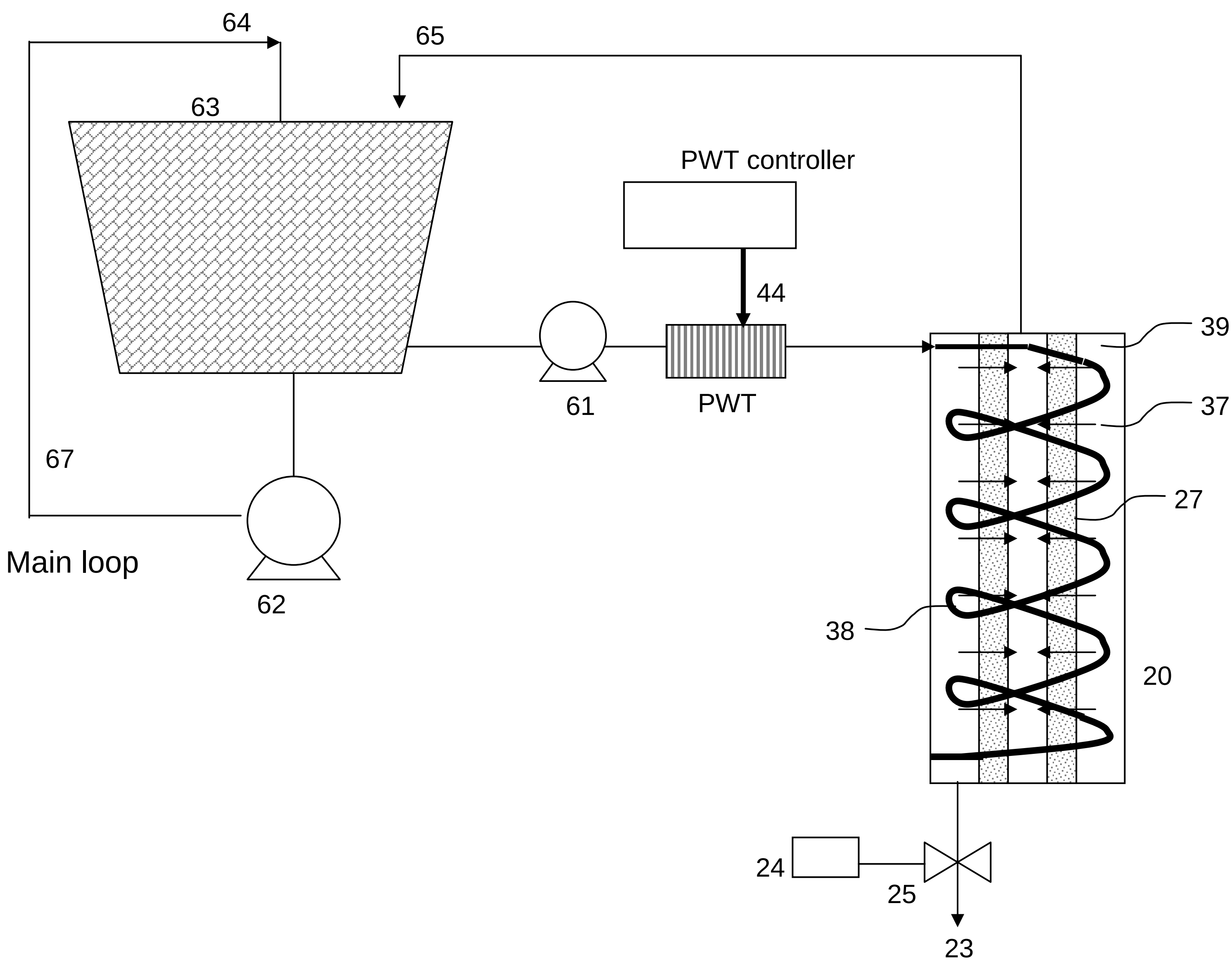


Backwash-filtration system for small cooling towers (for water-cooled chiller:)



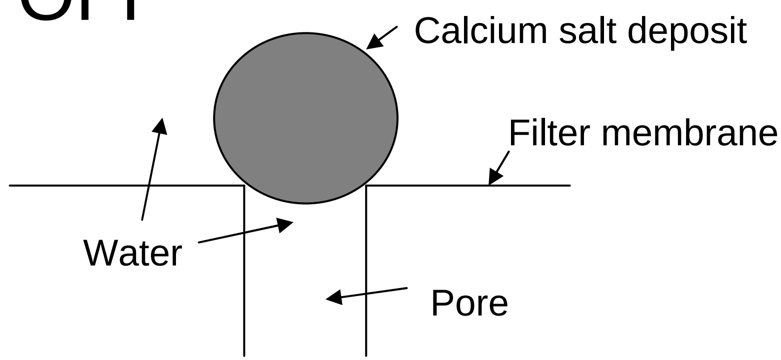
Sand filter
0.5 micron
with backwash

Synergy between PWT and high-shear filter membrane to remove soft sludge from particulate fouling (2002)

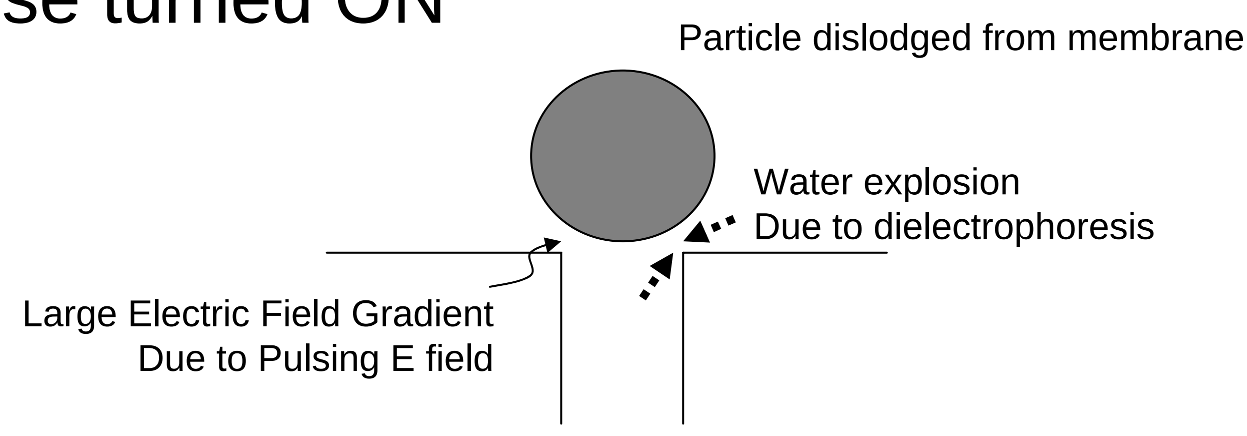


Self-cleaning Filter
- Dielectrophoresis principle

Pulse turned OFF



Pulse turned ON



Self-cleaning Filter
- Dielectrophoresis principle

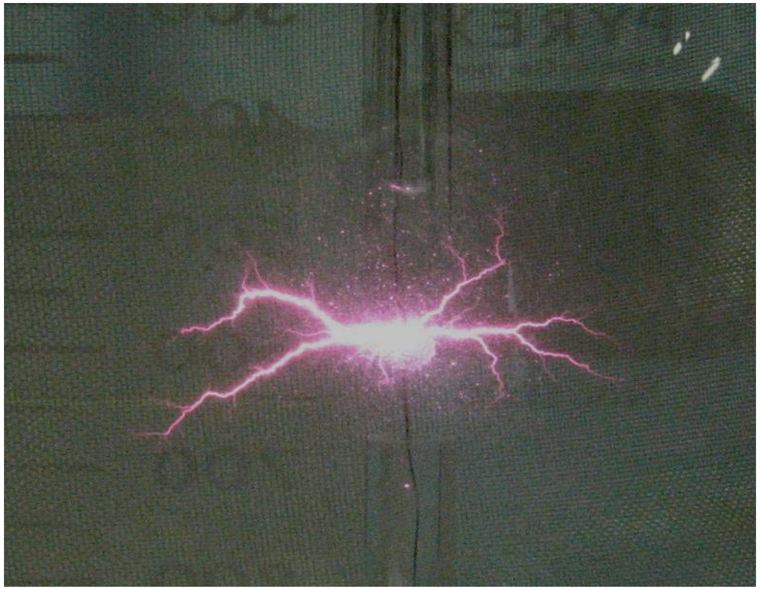
Electrical shocks of 200 ns with high voltage (~40 kV).

The mechanism:

- The electrical pulse rapidly polarizes water molecules.
- Water molecules are literally pulled to the membrane corner.
- Attached scaling particles are pushed out.

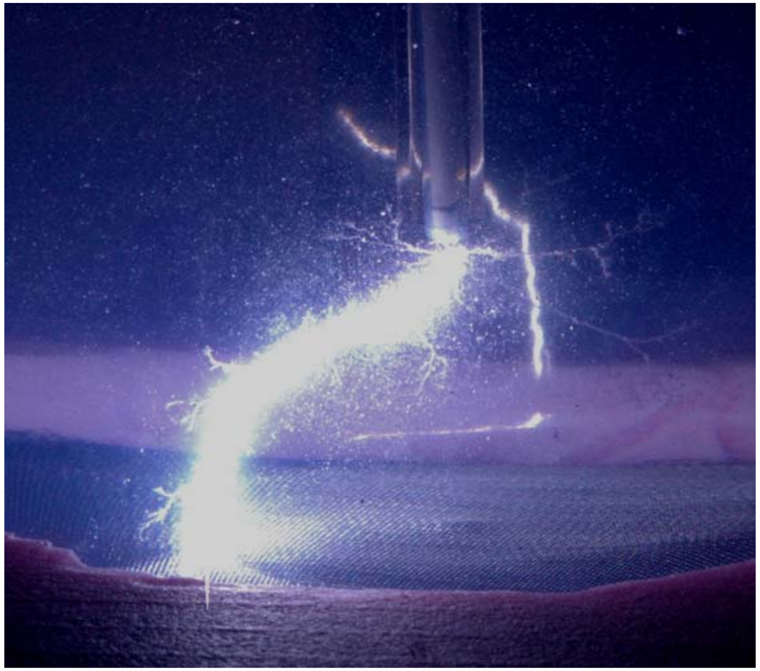
Why? dielectric constant of water molecules (~ 80)
calcium carbonate deposits (~ 6)

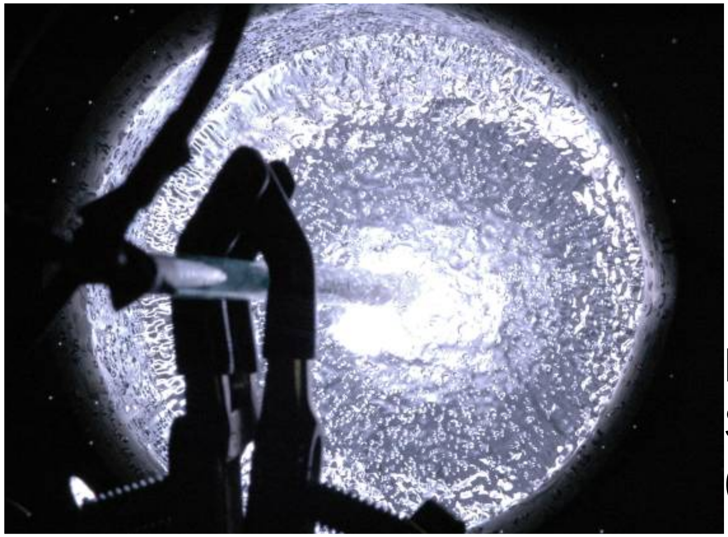
Alternative methods:
Pulsed techniques allow to avoid electrolysis influence and to generate direct plasma discharge in water



Pulsed Corona
in water (4-06 DU)

Pulsed Spark
in water (6-06 DU)





Pulsed Spark
Shockwaves
(6-06 DU)

Full scale analysis

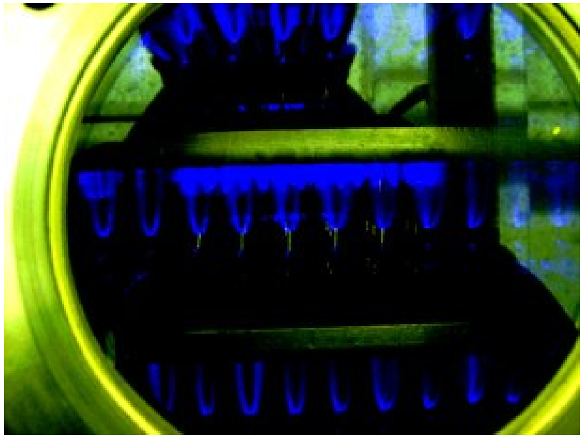
1,000-MW fossil plant, 3 COC

Main circulating loop: 760,000 gpm
Make-up water: 7500 gpm
Side-stream loop: 38,000 gpm

When we improve COC from 3 to 10,

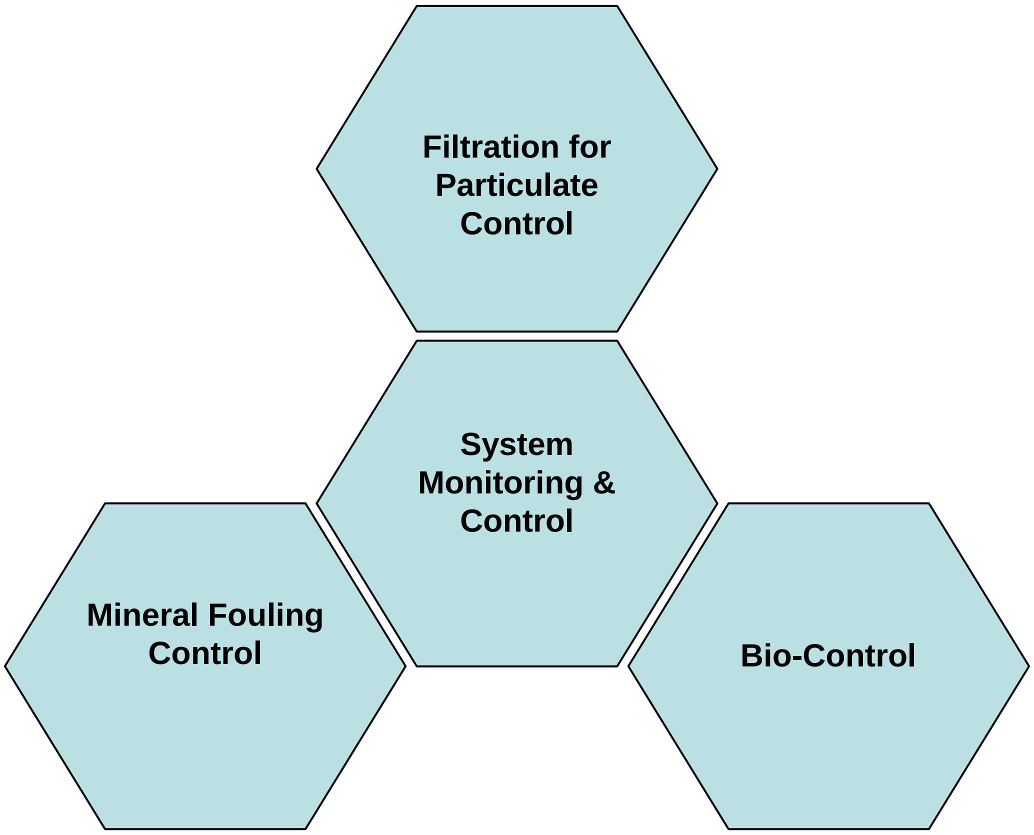
Solid removal rate = 53 g/s = 4 tons/day
Filter surface area = 640 m^2
Deposition rate on filter membrane = 30 nm/s
Pulse rate = 40 s (One pulse every 40 s)

Drexel Plasma Institute



Pulsed corona technique allows
to avoid spark formation in water spray
during plasma generation (2005)

Green Water Treatment Technology



Delivery

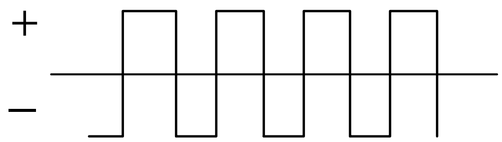
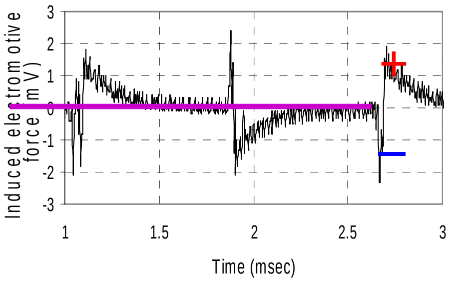
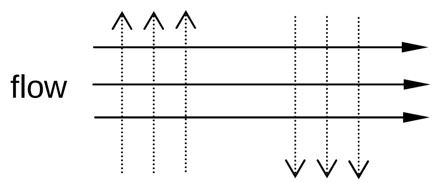
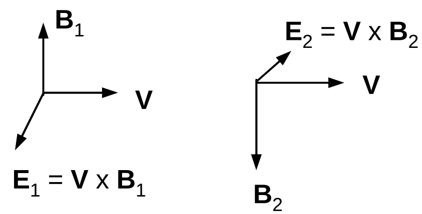
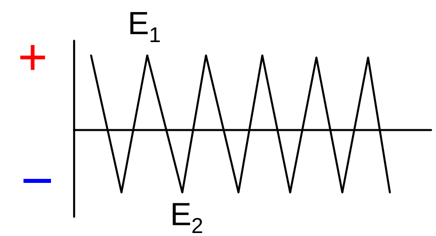
The project will deliver
a self-cleaning membrane filter system complete
with a power supply generating high voltage pulses.

Fouling Costs for Several Countries

Country	Fouling in costs (million U.S. dollars)	1992 GNP (billions U.S. dollars)	Fouling as % of GNP
United States	14,175	5,670	0.25
Japan	10,000	4,000	0.25
Germany	4,875	1,950	0.25
United Kingdom	2,500	1,000	0.25
Australia	463	309	0.15
New Zealand	64	43	0.15

Data from www.cpe.surrey.ac.uk/dptri/hms/fouling.htm

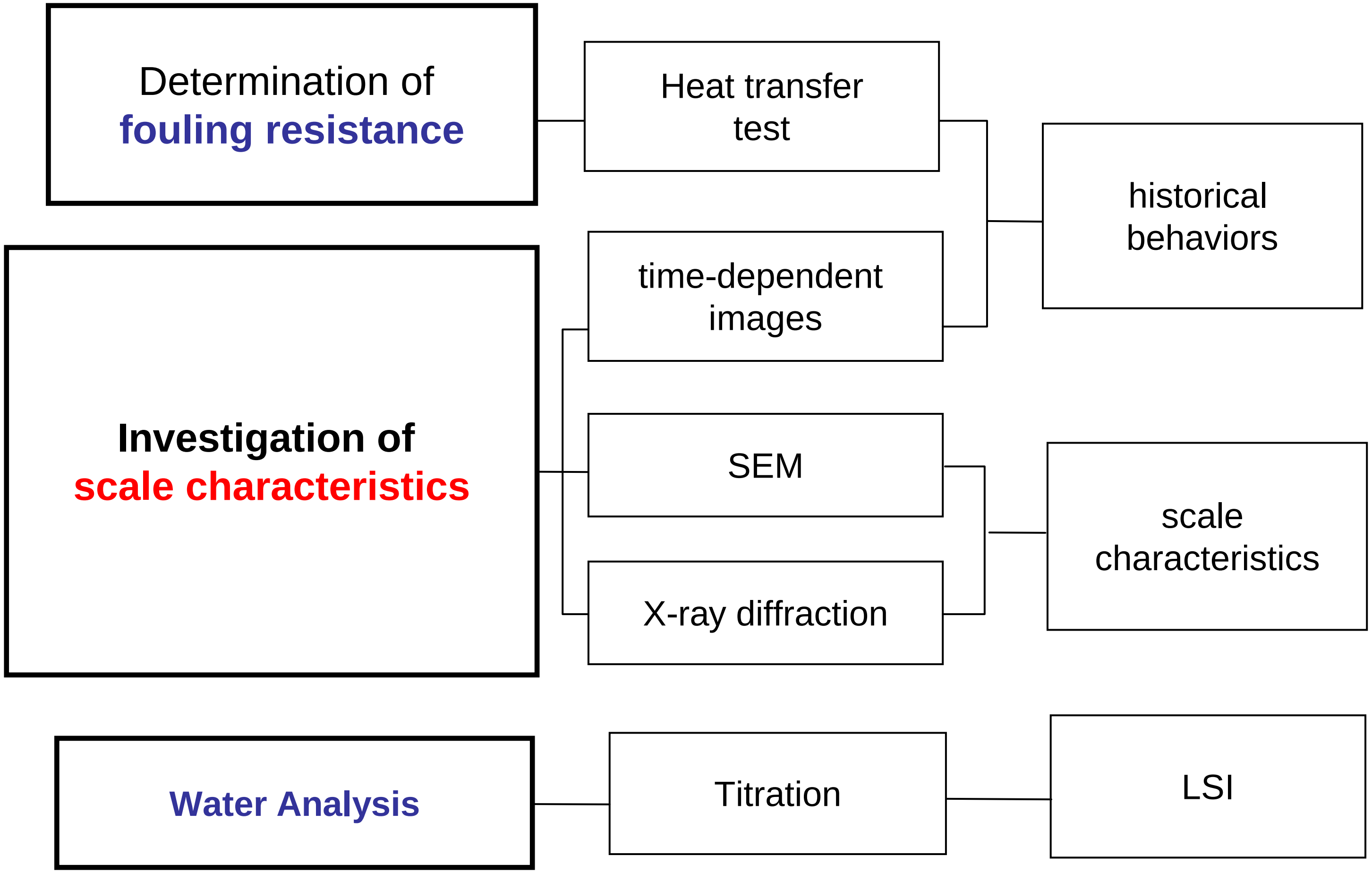
Physics behind PWT devices

Solenoide coils	 Square wave current	$\int \mathbf{E} \cdot d\mathbf{s} = -\frac{\partial}{\partial t} \int \mathbf{B} \cdot d\mathbf{A}$ Faraday's law	
Permanent Magnets	magnetic field changes direction  magnetic field perpendicular to flow	**E** = **V** x **B** Lorentz force 	

Physical water treatment research
at Drexel University
(Mineral fouling mitigation - since 1990)

- Permanent magnets
- Solenoid coils
- Electrostatic device
- Catalytic alloys
- Others
  – (sudden ΔP, vortex flows, ball, brush)

The scope of the research

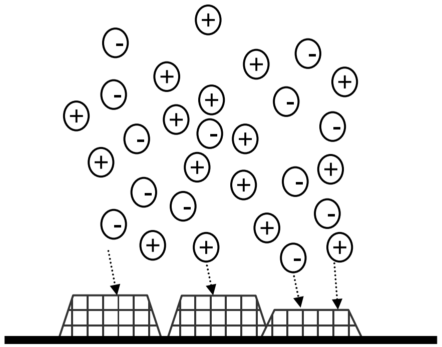


All tests were conducted with a biocide.

Hard and soft scale deposits

Crystallization Fouling

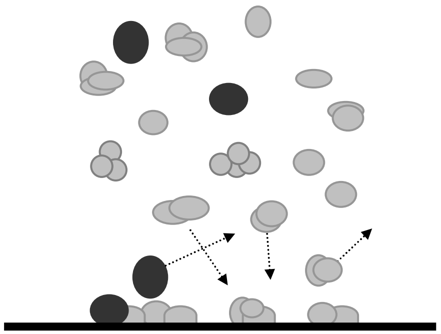
- Produce hardened scale deposits
- Difficult to remove; need acid wash.



Hard scale

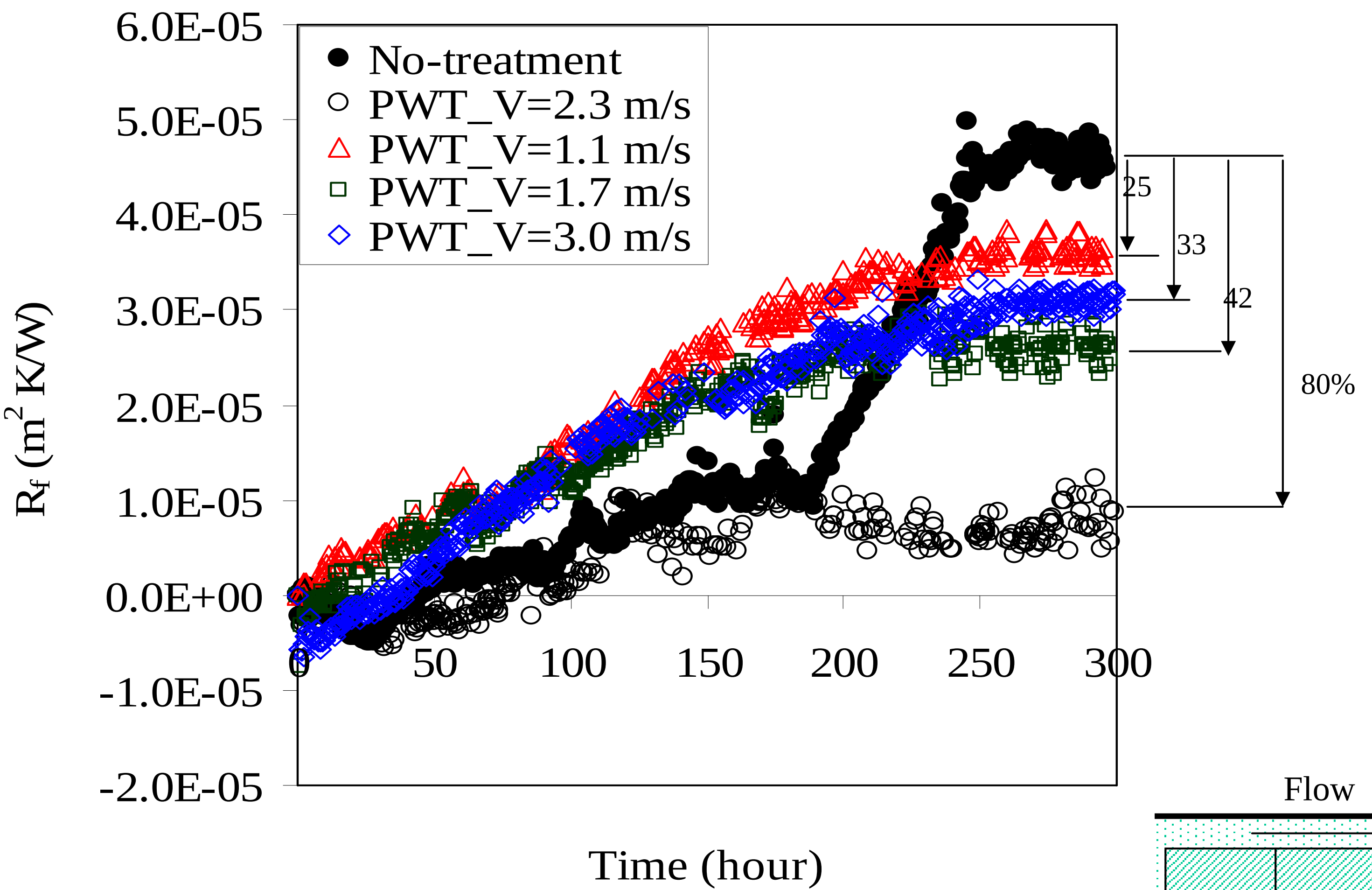
Particulate Fouling

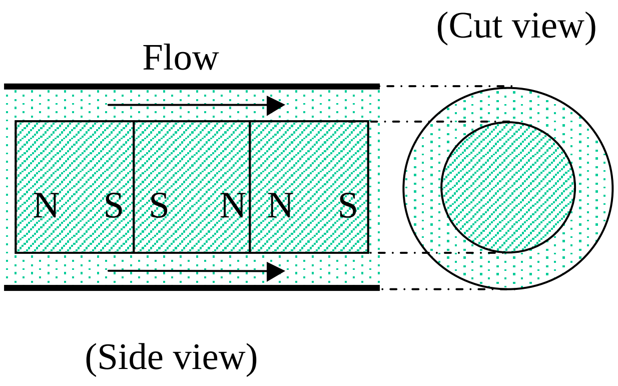
- Produces soft sludge scale coating
- Can be removed if flow velocity is large.



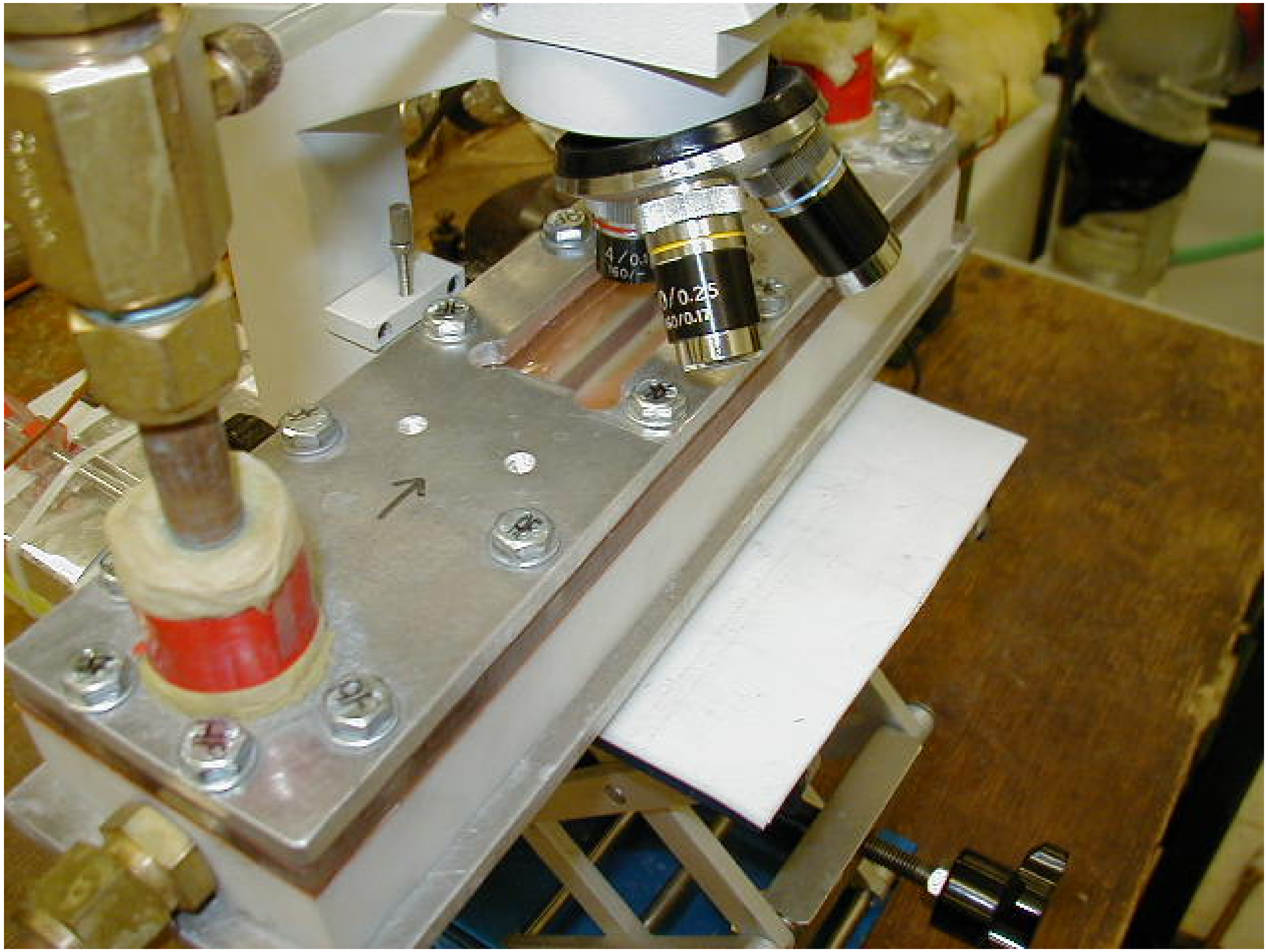
Soft scale

Fouling resistance R_f (permanent magnet-1)



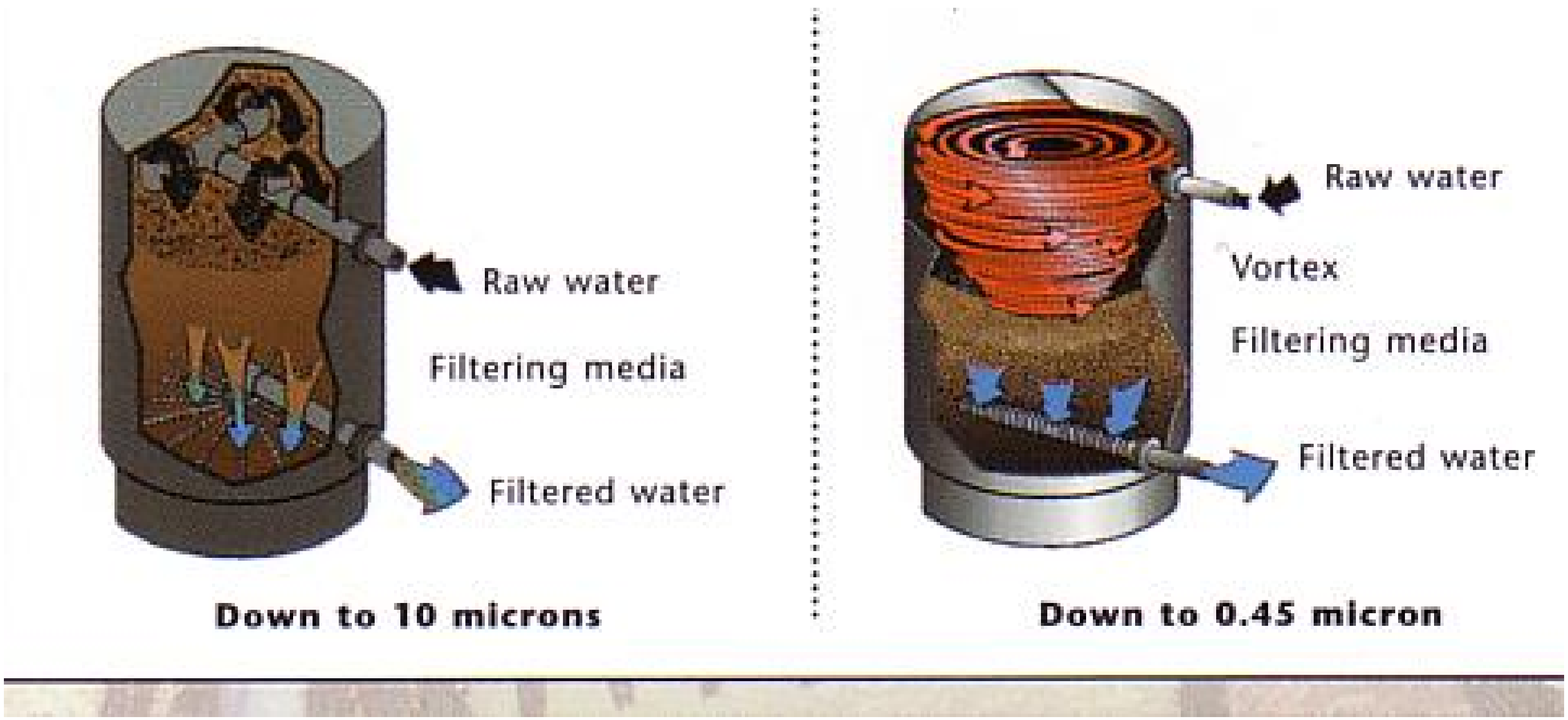


Heat transfer test section

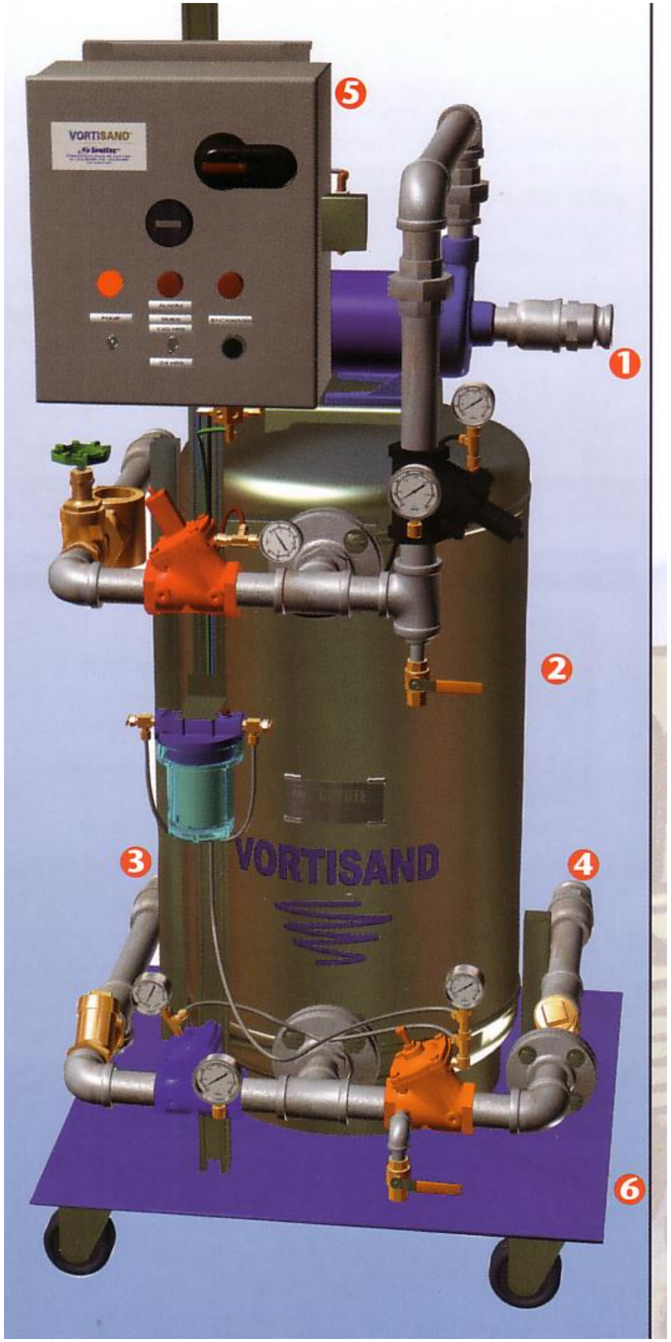


Sand Filter

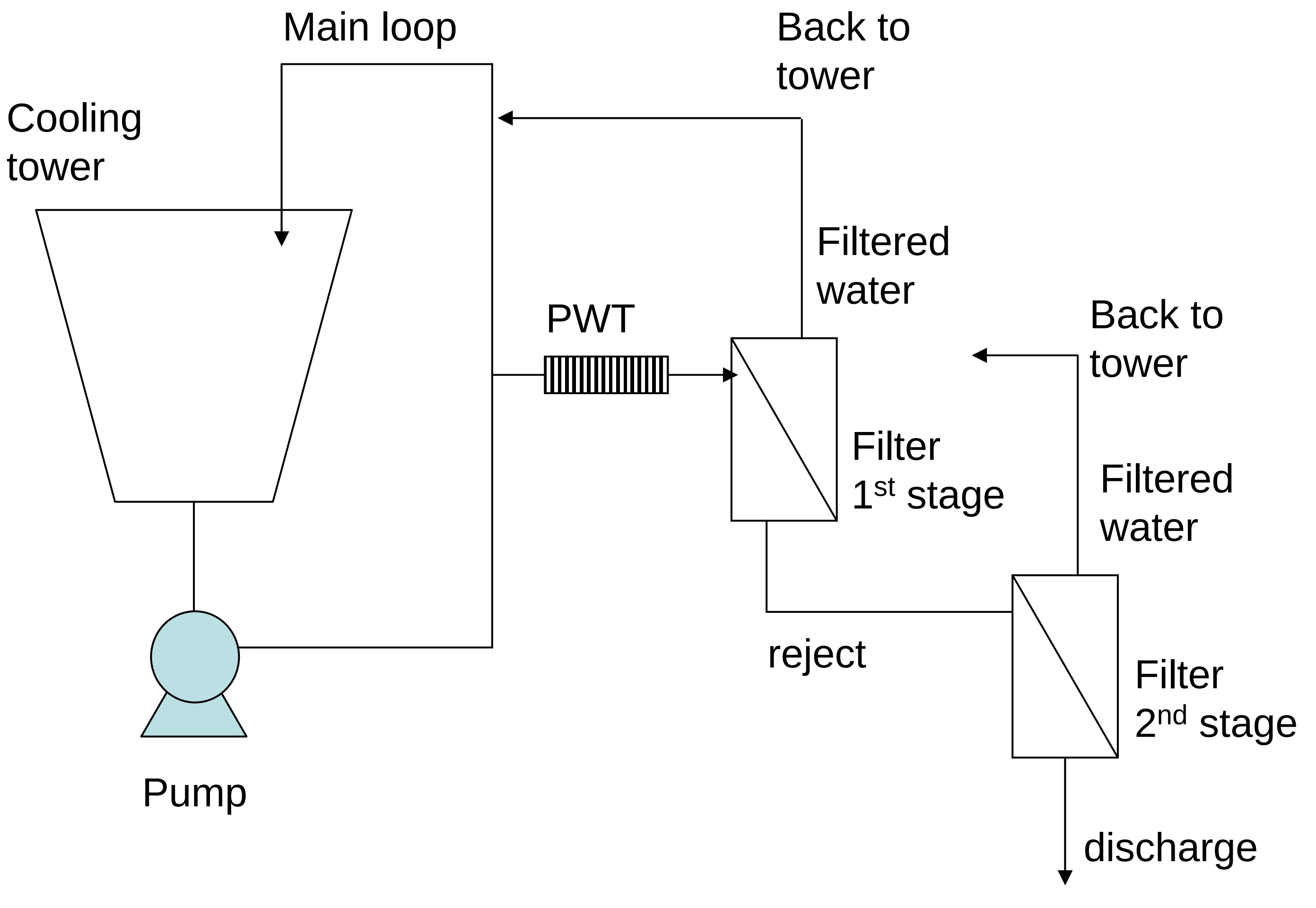
Sane filter with tangential entry



Sand filter
0.5 micron
with backwash



Two-stage filtration system – side stream loop



A Synergistic Combination of Advanced Separation and Chemical Scale Inhibitor Technologies for Efficient Use of Impaired Water as Cooling Water in Coal-Based Power Plants

NALCO

Nalco Company and Argonne National Laboratory

NETL Water and Power Plants Program 2006 Review Meeting

June 20, 2006, Pittsburgh, PA

NALCO

Outline

- Introduction
- Technical Approaches
- Task Plan
- Progresses to Date
- Next Steps

Nalco Company Overview

- Nalco Company is a leader in water treatment with more than 60,000 customers worldwide
- Three business units
  - Industrial and Institutional
  - Paper
  - Energy
- Nalco produces & supplies chemicals, equipment and service for a wide range of customers including power plants

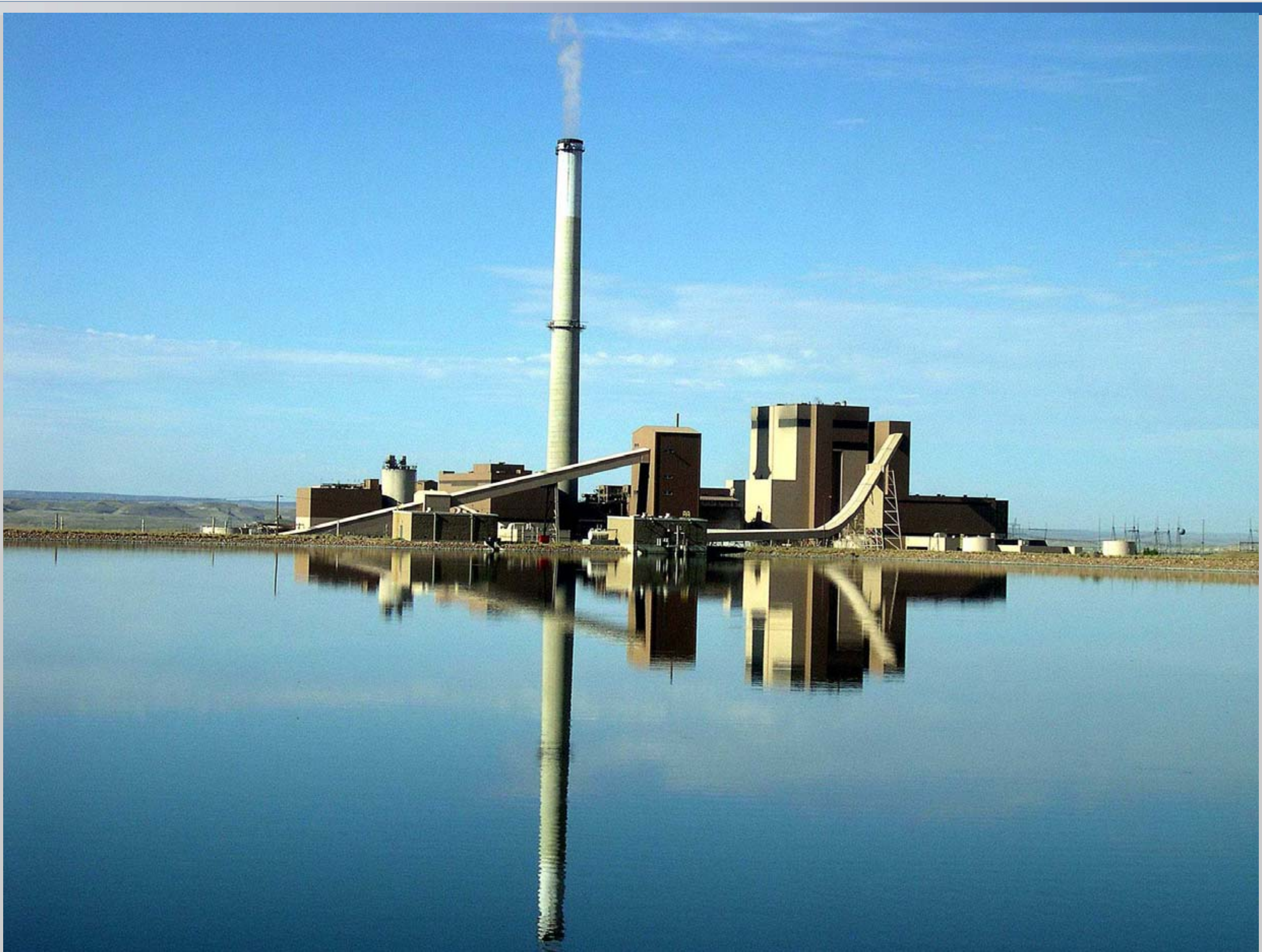
Project Overview

- Participants
  - Nalco Company, LEAD
  - Argonne National Laboratory, via CRADA
- Duration
  - 41 months (March 31, 2006 to August 30, 2009)
- Goal
  - To minimize fresh water use by using impaired water for cooling
- Technology needs
  - Scale control technologies for impaired water in recirculating cooling water systems at high cycles of concentrations
- Approach
  - Synergistic combination of physical and chemical technologies
    - Separation processes to reduce the scaling potential
    - Scale inhibitors to extend the safe operating range

Background

- Once-through, closed loop vs. open re-circulating
- 3 major issues: corrosion, biofouling and scaling
- Recirculating cooling systems
  - Limited cycles
    - Due to quality of water causing scaling
    - Discharge limits for blow down due to pH, TSS, etc.
  - ZLD systems
- Scaling is caused by evaporation and exceeding mineral equilibrium solubility
- Scaling potential limits the reuse of water and it depends on quality of water and operating conditions

Desert Power – Bonanza Power Plant



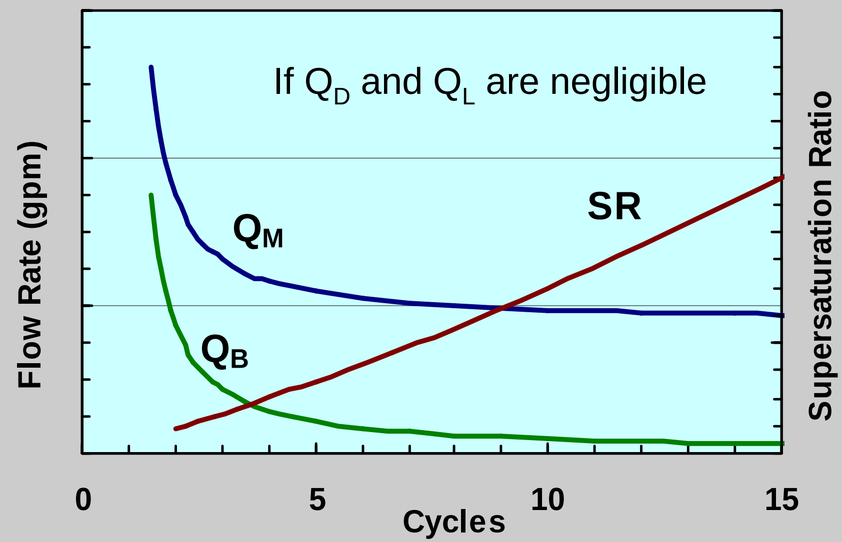
Bonanza Power Plant

- 450 MW net coal-fired power generation station
- Total system volume: 4.3 MM gallons
- Water recirculating rate
  - 216,000 GPM with 2 pumps
  - 126,000 GPM with 1 pump
- Make-up water source: Green River
- Automated blow down based on conductivity and calcium level at a rate of 280-312 GPM (average)
- 11-12 cycles of concentration
- Holding time index (HTI): 168 hours
- High efficiency fill

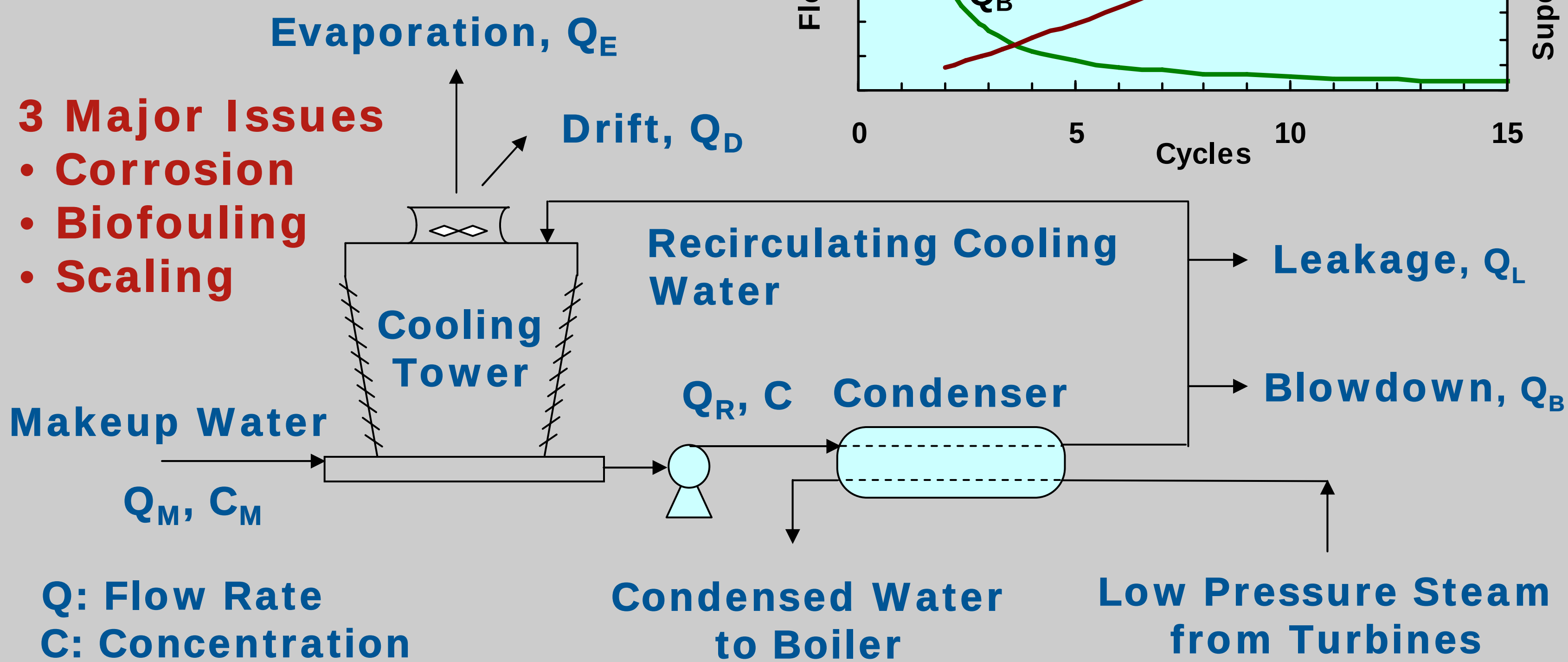
Open Re-circulating Cooling Water System

Cycles of concentration
$= 1 + Q_E / (Q_B + Q_D + Q_L)$

Scaling potential exists, if supersaturation ratio > 1



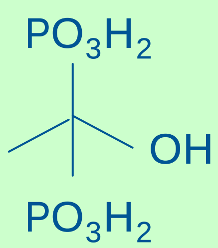
3 Major Issues
- **Corrosion**
- **Biofouling**
- **Scaling**



Scale Inhibitors

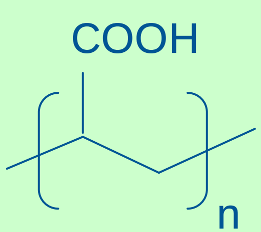
Chemistry

- Phosphonates



HEDP

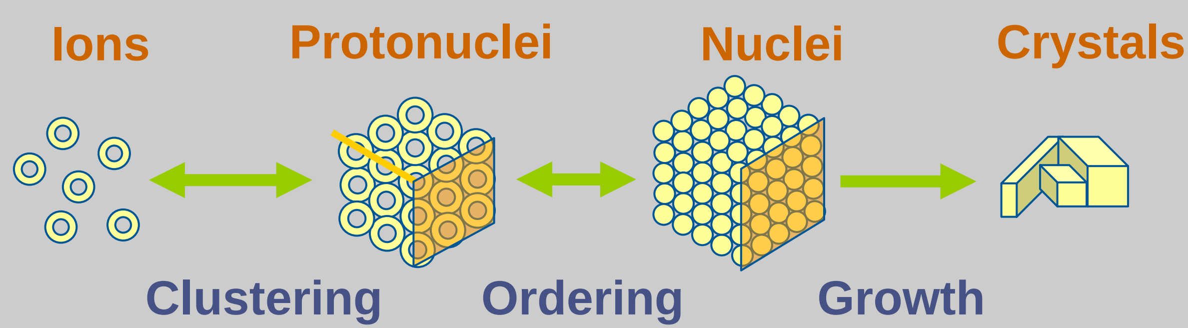
- Polymers



Polyacrylic Acid

Mechanisms

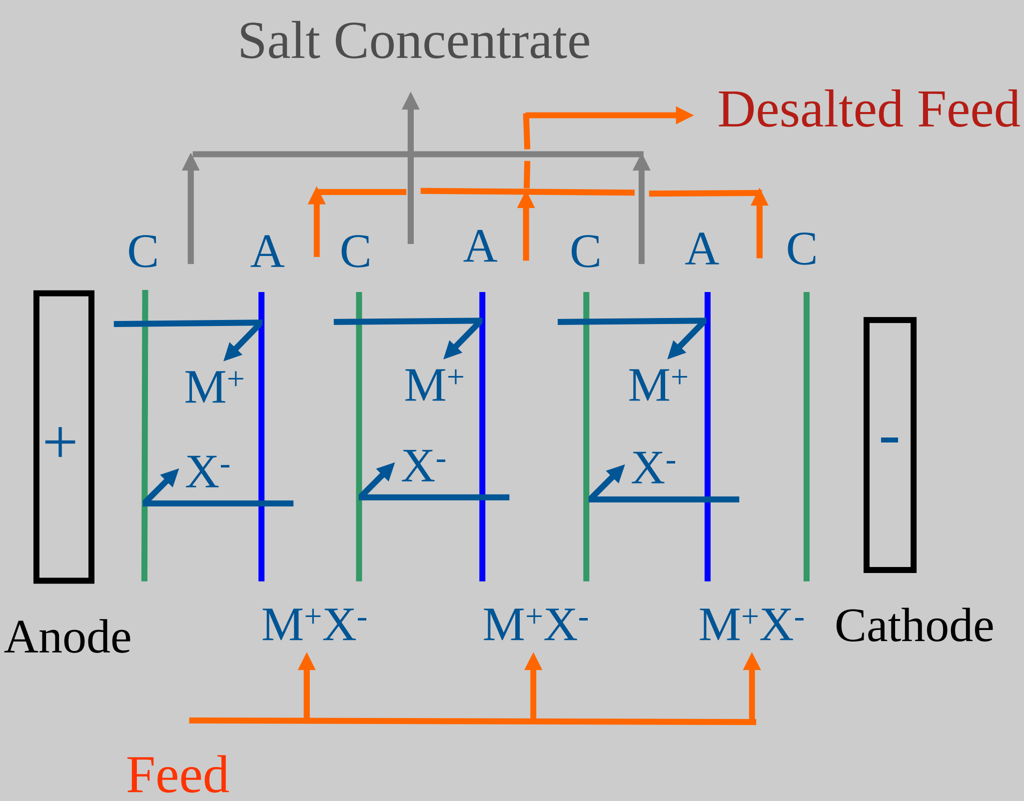
- Threshold Inhibitors
  - Delay the ordering process
- Crystal Modifiers
  - Form irregular crystals that are less adhering
- Dispersants
  - Keep crystals suspended in water



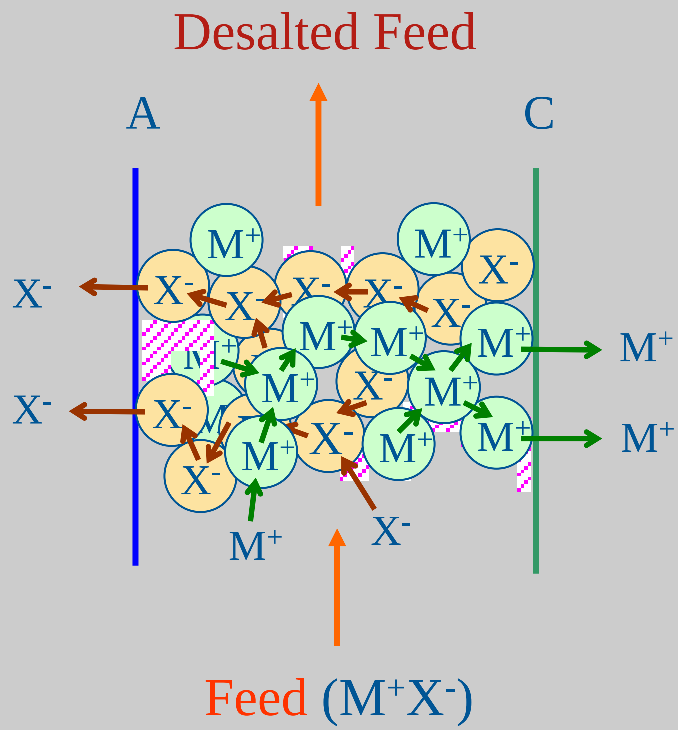
Stages of Crystallization

Electrodialysis and Electrodeionization

Electrodialysis



Electrodeionization



M^+X^-: ionized salt

A: anion-exchange membrane

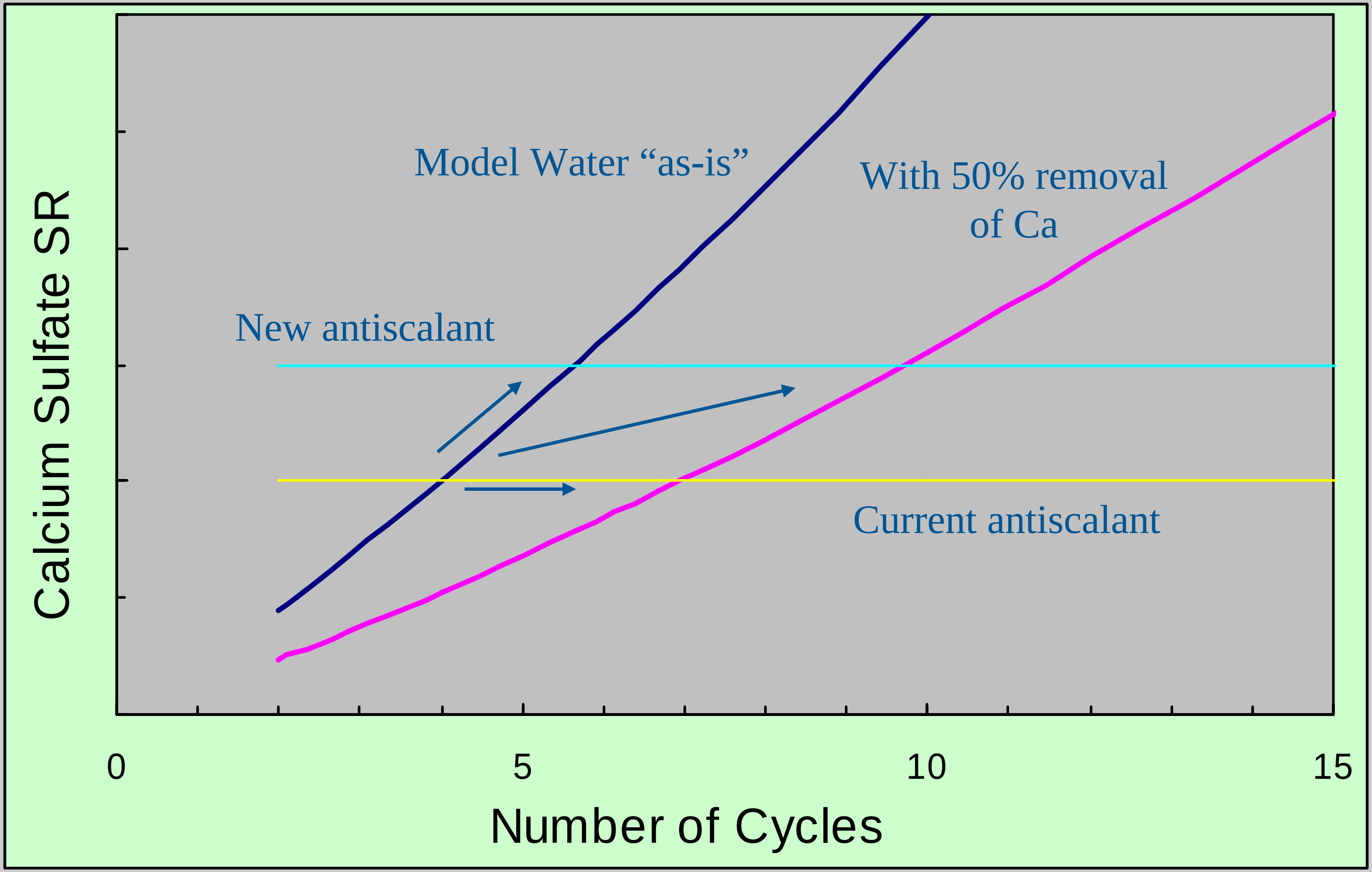
C: cation-exchange membrane

anion-exchange resin

cation-exchange resin

Synergy of Separations and Scale Inhibitors

Model Water: Agricultural Drainage Water in California (EPRI and CEC, 2003)



Task Plan

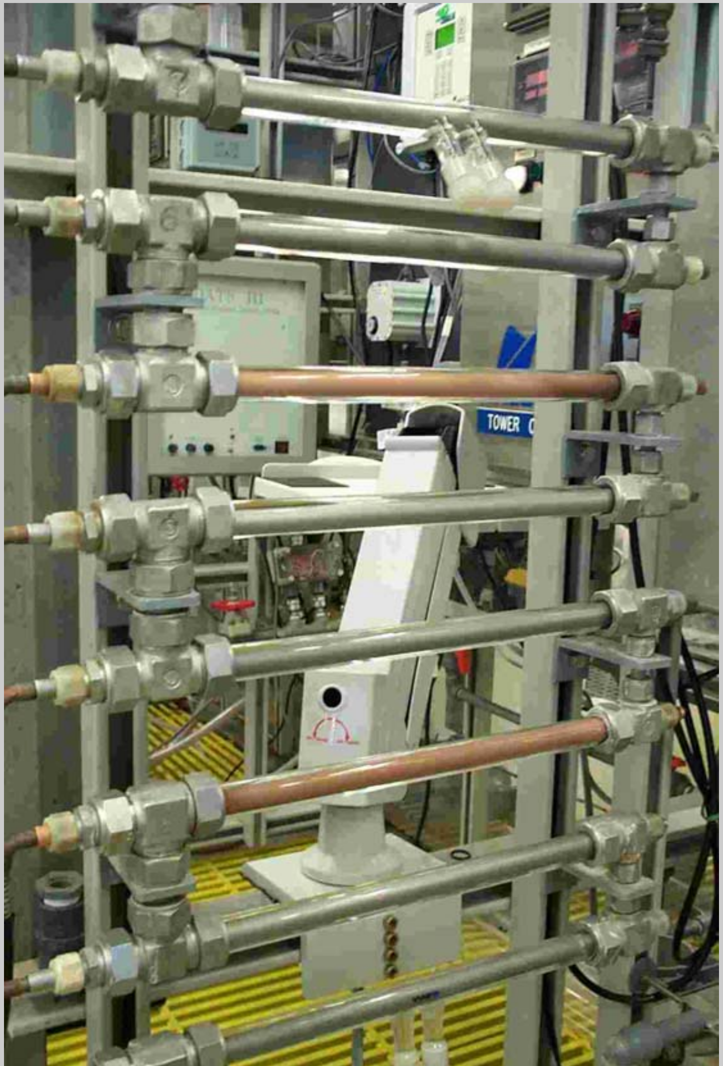
- Phase 1: Technical Targets and Proof of Concept (Years 1 & 2)
  - Task 1: Identify Limiting Factors for High Cycles and Quantify Technical Targets (Months 1-12)
  - Task 2: Develop High Stress Calcite and Silica Scale Control Chemistries (Months 1-18)
  - Task 3: Develop Advanced Membrane Separation Technologies and Processes (Months 2-18)
- Phase 2: Technology Development and Integration (Years 2 and 3)
- Phase Three: Technology Validation (Years 3 and 4)

NALCO

Task Plan (cont'd)

- Phase 1: Technical Targets and Proof of Concept (Years 1 & 2)
- Phase 2: Technology Development and Integration (Years 2 and 3)
  - Task 4: Develop Additional Novel Scale Control Chemistries (Months 19-30)
  - Task 5: Develop and Integrate Separation Processes (Months 19-30)
- Phase Three: Technology Validation (Years 3 and 4)
  - Task 6: Pilot Technology Demonstration (Months 30-41)
  - Task 7: Prepare Final Report (Months 40-41)

Pilot Cooling Towers



Simulation of cooling towers using synthetic or actual make-up water

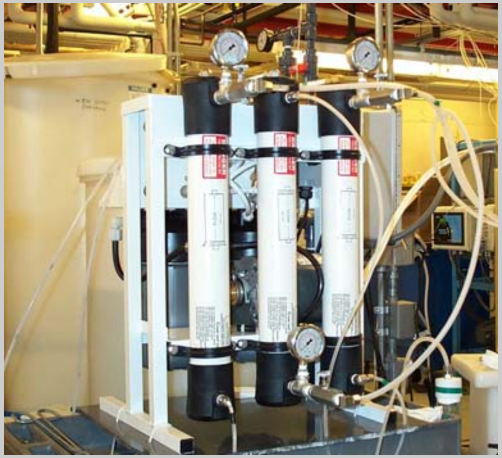
Studies of scaling, biofouling and corrosion using heat exchanger tubes of different metallurgies

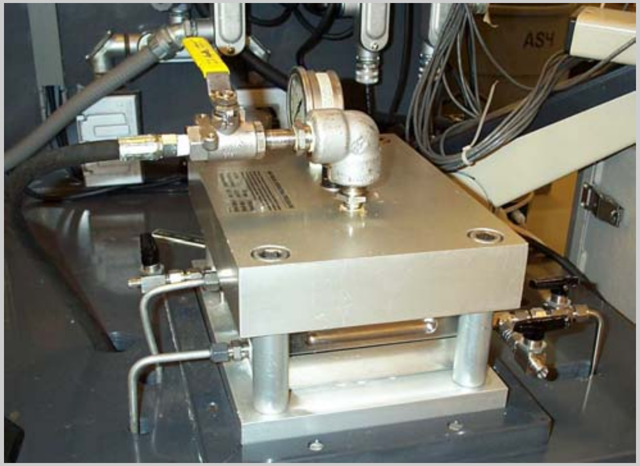
NALCO

Membrane Separation Systems

ED/EDI

RO/NF





Task 1 Progress Update

- Literature and existing Nalco data on characteristics of impaired waters are being collected and reviewed
  - Produced water
  - Municipal secondary effluent
- Additional target impaired waters are being identified and samples will be obtained for analysis
- Calculations of scaling limitations of impaired waters on-going

Typical Produced Water Characteristics

Reference	Tsai (1995)		Nalco	EPRI & CEC (2003)	EPRI (2004)	
Location	Site B	Site C	Gillette, WY	Central Valley, CA	McGrath, NM	Fairway, NM
Type		CBM	CBM	Oil Well	Mixed	CBM
pH	7.6	7.2	8.1	7.9	7.1	8.0
TDS, mg/L	8,000	14,700	4,000	3,879	12,714	12,236
Na, mg/L	2,640	6,200	870	982	4,149	3,620
Ca, mg/L	18.9	22.1	44	40	143	31.0
Ba, mg/L	10.1	27.2	1.5		3.1	25.1
Fe, mg/L	3.87	3.16	0.6		41	4.87
Cl, mg/L	18.9	1,920	25	920	6,298	2,018
SO4, mg/L	6.9	10.6	0	110	544	4.3
HCO3, mg/L	1,976	11,700	2,684	1,100	765	6,381
SiO2, mg/L			15	120	18.5	21.4

Typical Municipal Secondary Effluent Characteristics

Reference	Nalco			EPRI & CEC (2003)
Location	OCWD, CA	DDSD, CA	Naperville, IL	Bay Area, CA
pH	7.8	8.0	7.9	7.0
TDS, mg/L	940	1190	555	869
Na, mg/L	230	248.3	88.0	76
Ca, mg/L	82.0	52.1	64.0	76
Fe, mg/L	0.55	0.19	0.08	
Al, mg/L		0.4		
Cl, mg/L		290.5	120	102
SO4, mg/L		220.8	60	68
PO4, mg/L	2.5	0.6	2.0	6.0
HCO3, mg/L		305	171	1100
SiO2, mg/L	26.0		8.3	17

Scaling Limitations – Preliminary Findings

- Common cycle-limiting species
  - Calcium carbonate
  - Silica/silicate
  - Calcium sulfate
    - Often due to sulfuric acid for pH control
  - Calcium phosphate (municipal effluent)
    - With co-presence of high silica
  - Barium sulfate (produced water)
  - Iron and aluminum
- Challenges vary for each impaired water and power plant

Proposed Technical Strategy

Universal methodology to develop case-specific solutions

- Recognize and address interdependence of scaling/corrosion/biofouling
- Use model to select and control operating conditions, such as pH and cycles of concentration
- Address scale control and blowdown management simultaneously
- Use combination of different technologies for scale control, including scale inhibitors, separation technologies and cooling tower operations
  - Need a well-equipped technology tool box

Task 2 Progress Update

- Scale control chemistries for high stress calcite and silica control
- Silica/silicate
  - Laboratory screening of candidate chemistries started
  - Initial tests showed promising results compared with benchmark (a current commercial silica control product)
- Calcite
  - Candidate chemistries identified
  - Laboratory screening to be started in July

Silica/Silicate Control

- Silica/silicate-based scale forms a very hard tenacious deposit and creates an extremely high barrier to heat transfer
  - Amorphous silica as a result of polymerization
  - Silicates of calcium, magnesium, iron or aluminum
  - Co-precipitation on other mineral scales
- Approaches
  - Inhibitors
    - Silica polymerization control
    - Silica dispersants
  - Selective removal by separations
- Silica/silicate solubility is strongly affected by pH, temperature and presence of some metal ions

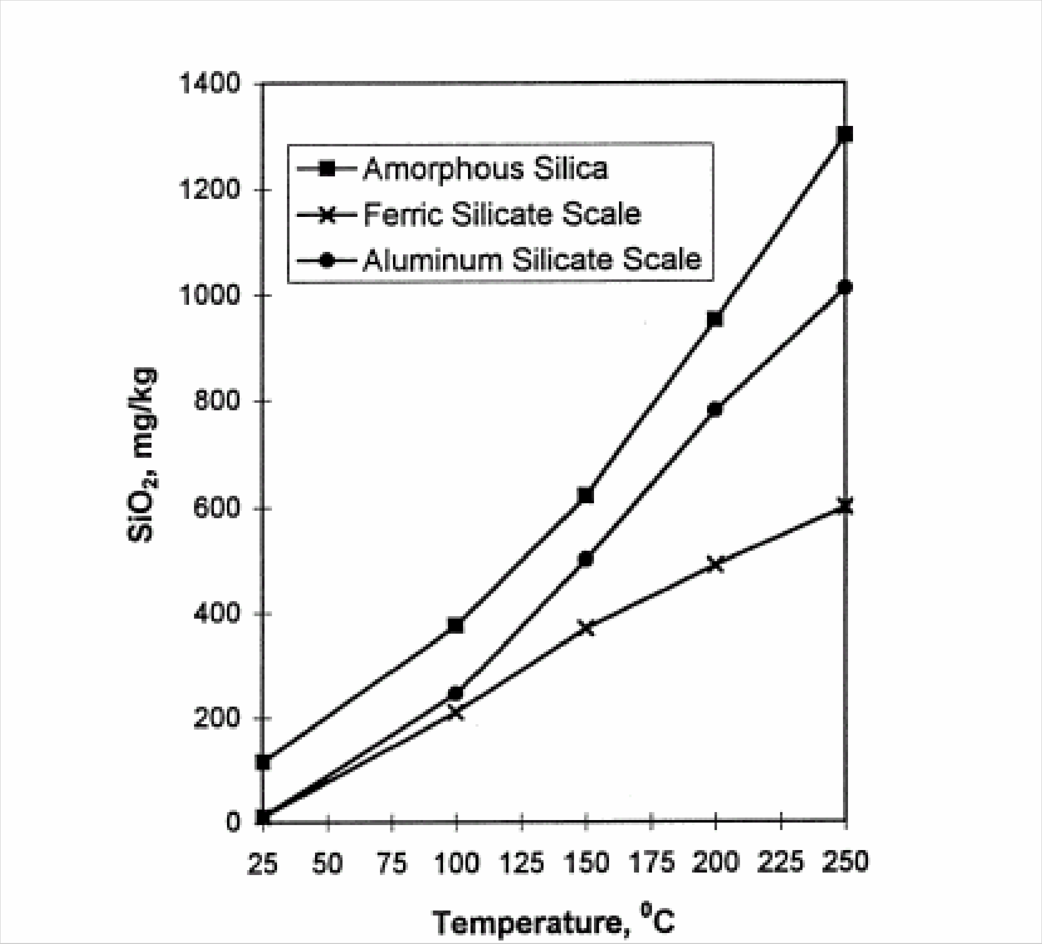
Silica/Silicate Solubility

Silica Solubility: pH effect

pH mg/L

SiO_2 at 25 degrees C

pH	mg/L
6-8	120
9	138
9.5	180
10	310
10.6	876



Task 3 Progress Update

- Feasibility of membrane separation technologies
  - Electrodialysis and electrodeionization (Argonne lead)
  - Nanofiltration (Nalco lead)
- Task to be started when CRADA with Argonne is signed
  - Drafting of CRADA in progress
- Key technical issues
  - Selectivity
  - Energy consumption
  - Flux
  - Scale control

Year One Milestone Status

- Milestone 1 (July 30, 2006)
  - Three impaired waters identified and water quality analyzed
  - On-time completion expected
- Milestone 2 (September 30, 2006)
  - Scaling limitations determined for three impaired waters
  - On-time completion expected
- Milestone 3 (March 30, 2007)
  - Technical targets identified for separation processes and scale inhibitors to relieve scaling limitations to high-cycle cooling water operations using impaired water
  - On-time completion expected

Other Programmatic

- Patent Waiver pending
  - Petition submitted April 20, 2006
- Request for Reimbursement
  - First request (April-June 2006) to be submitted in July
- Funding

	DOE Share		Nalco Share	Total
	to ANL	to Nalco		
Year 1	$80,000	$113,499	$93.493	$286,992
Year 2	$100,000	$135,203	$112,261	$347.464
Year 3	$120,000	$289,054	$327.486	$736,540
Total	$300,000	$537,756	$533.240	$1,370,996

Plans for Year One

- Continue to collect water quality data for impaired waters and assess scaling limitations
  - Run pilot cooling towers for selected target impaired waters
- Continue to evaluate new antiscalant(s) for silica/silicate control
- Begin to evaluate new antiscalants for calcite control
- Sign CRADA with Argonne and start Task 3
- Begin to plan for dissemination of project information at meetings and conferences

"Use of Air2Air™ to Recover Fresh Water in Evaporative Cooling at Coal Based Thermoelectric Power Plants"

Presented at NETL
Pittsburgh - June 20, 2006

Water in Western US

SPX Cooling Technologies
Balcke | Hamon Dry Cooling | Marley

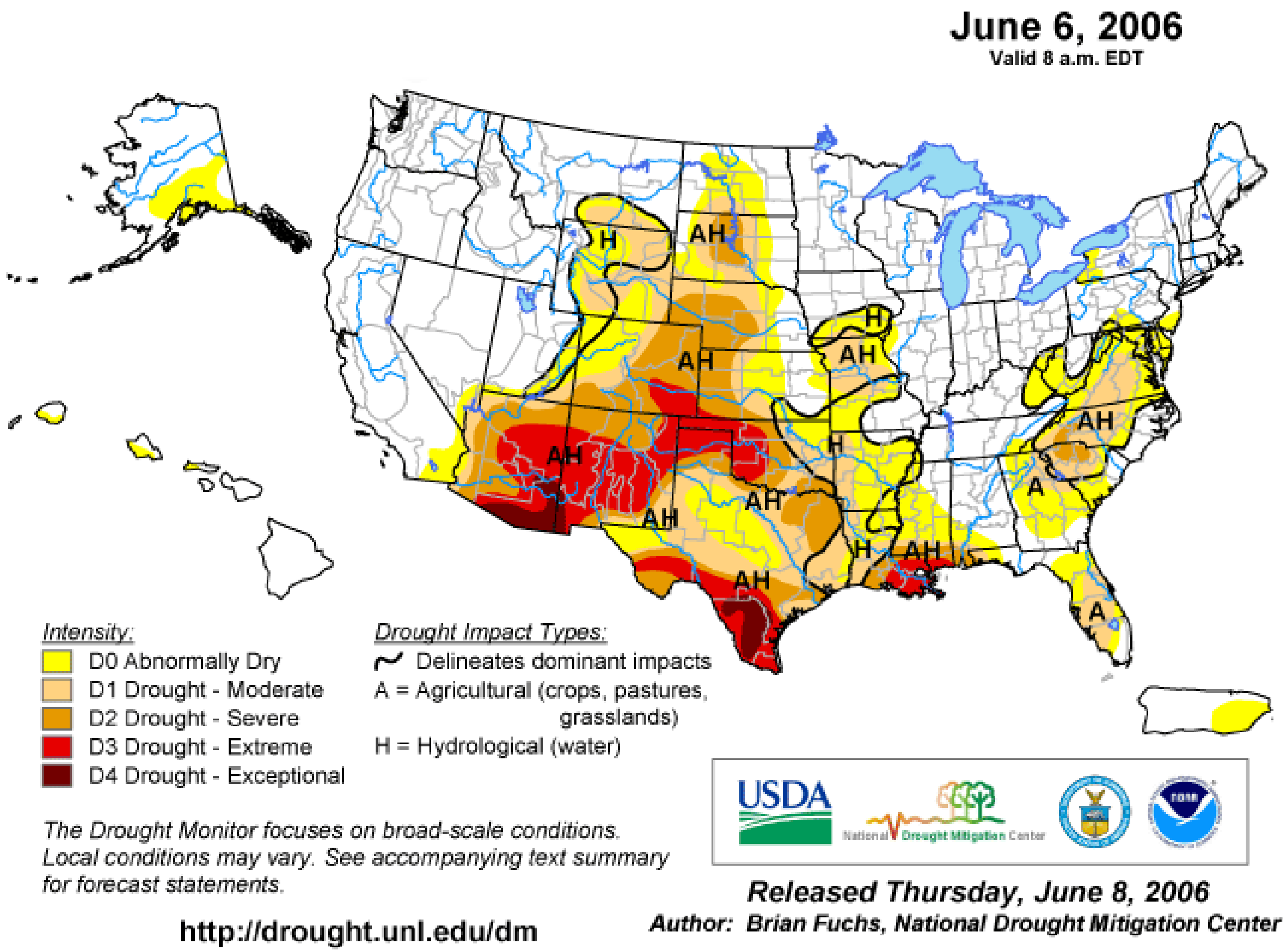
"Unlimited growth is not sustainable ...unless there's ….balancing of new development with water use and recycling"

Charles Goldman, Professor
University of California-Davis

"Lake Mead is lower than it has been in 40 years." "Lake Powell Reservoir is over 100 feet below its normal level."

National Park Service 2003/2005

US Drought Monitor



Water Use in the US

- **Agriculture, Livestock and Irrigation**
- **Fossil Fuel Power Generation**

Source: USGS Circular 1268, 2004

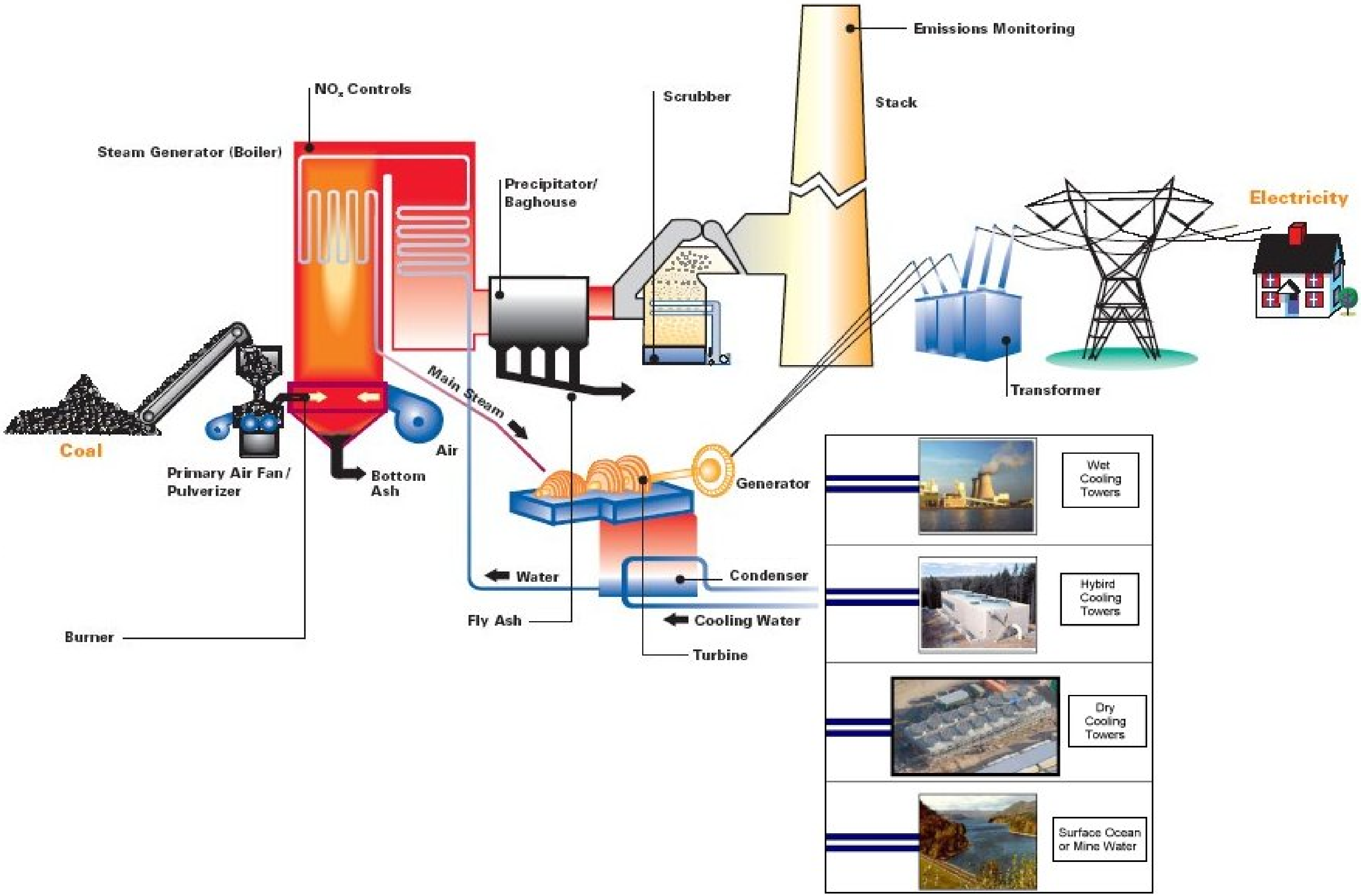
Cooling towers represent substantial water usage at power plants

"Producing a kilowatt-hour of electricity… takes about 3/5ths of a gallon of water"

Joey Bunch, Environmental Writer
Denver Post

Water at Power Plants

SPX Cooling Technologies
Balcke | Hamon Dry Cooling | Marley



Adapted from http://www.eei.org/industry_issues/environment/air/New_Source_Review/coal1.pdf

Air2Air

Innovative Water Conservation

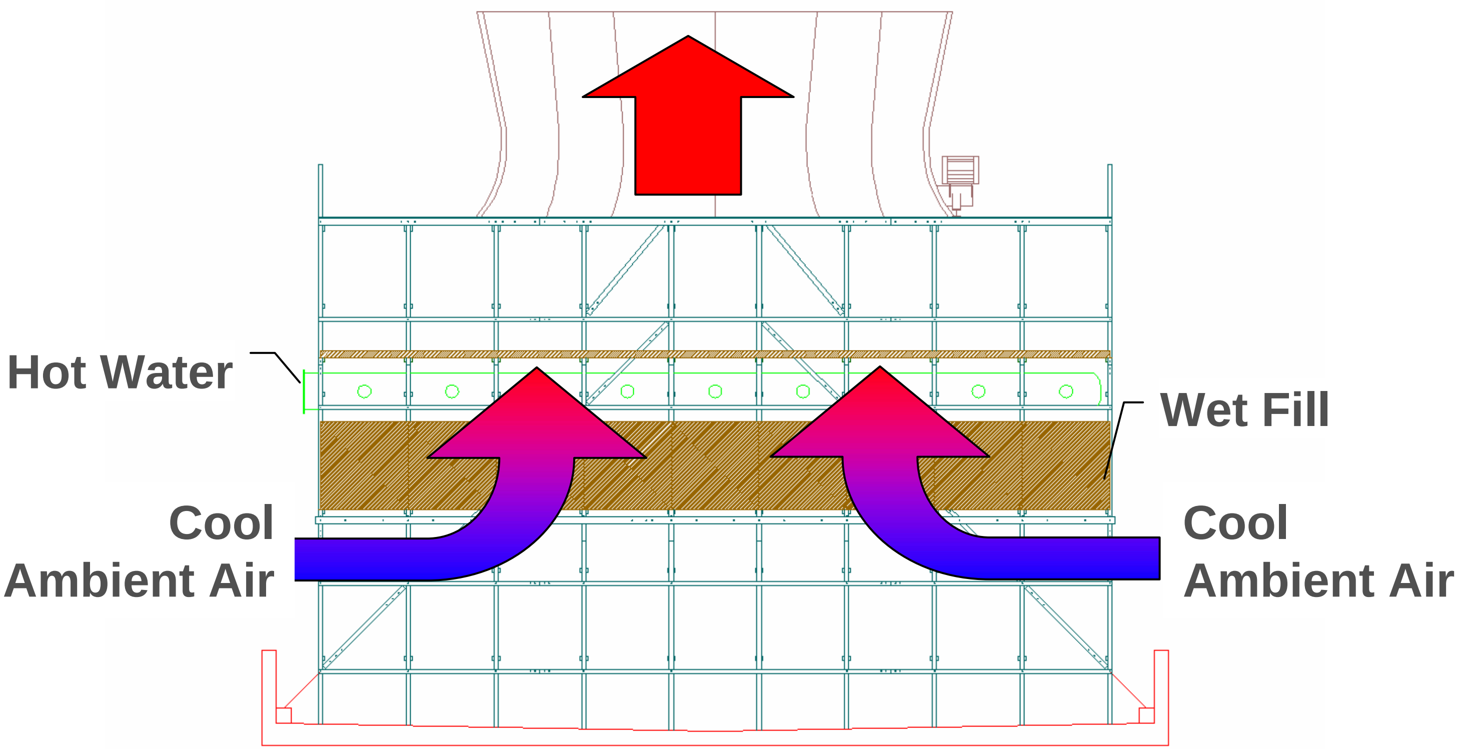
R&D Needs

SPX Cooling Technologies
Balcke | Hamon Dry Cooling | Marley

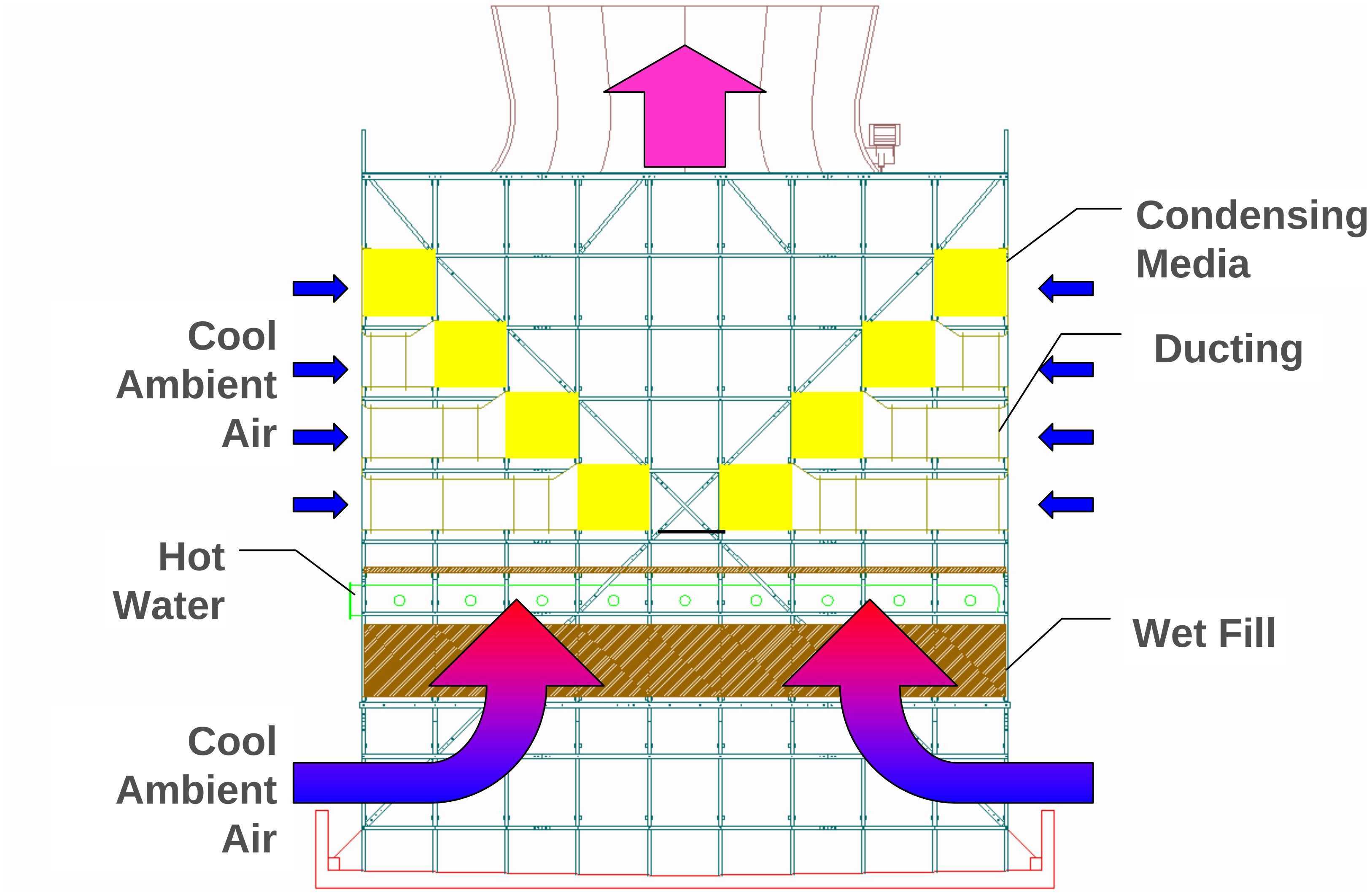
"…(C)ollaborative approaches and market-based transfers can ...meet emerging needs. Federal investment in R&D can provide more affordable water treatment technologies, such as desalination, to increase water supplies in critical areas."

Gail Norton, U.S. Secretary of the Interior
Water 2025 Report, May 2, 2003

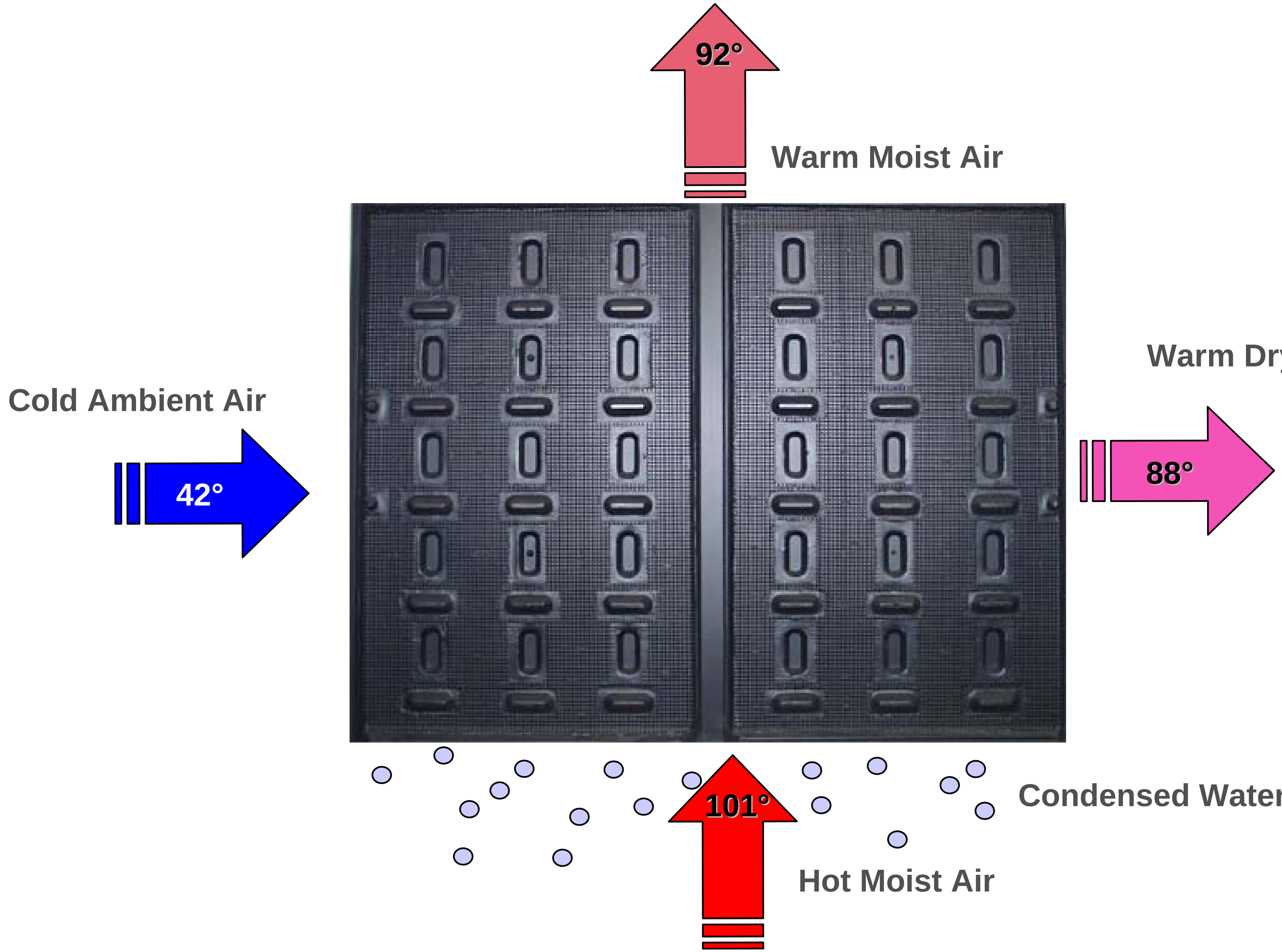
Conventional Cooling Tower



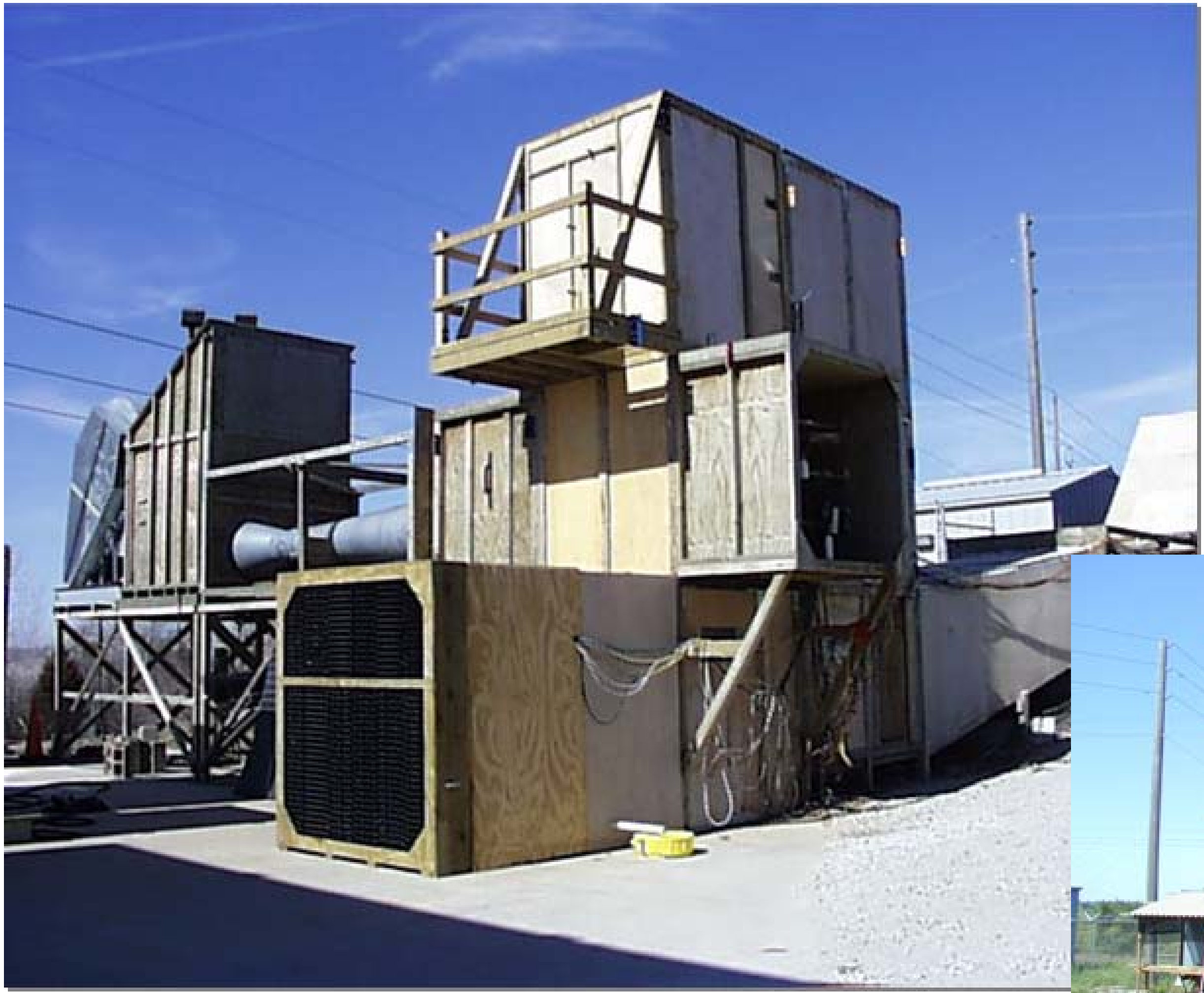
Air2Air Technology



Condensing Module



Test Cell and Mock-up



Water Return Data

Test	Season	Ambient WB/DB, (°F) Temperature	Mass Balance Condensation, GPM	Volumetric Condensation, GPM	Agreement of Methods
AAHE14-2	Spring	65.8/73.1	0.578	0.573	99.1%
AAHE14-6	Spring	71.0/85.4	0.408	0.399	97.8%
AAHE14-20	Spring	74.6/84.5	0.525	0.506	96.3%
AAHE14-27	Summer	57.6/68.4	0.605	0.615	101.6%

Recovery Potential:

162,420 GPD

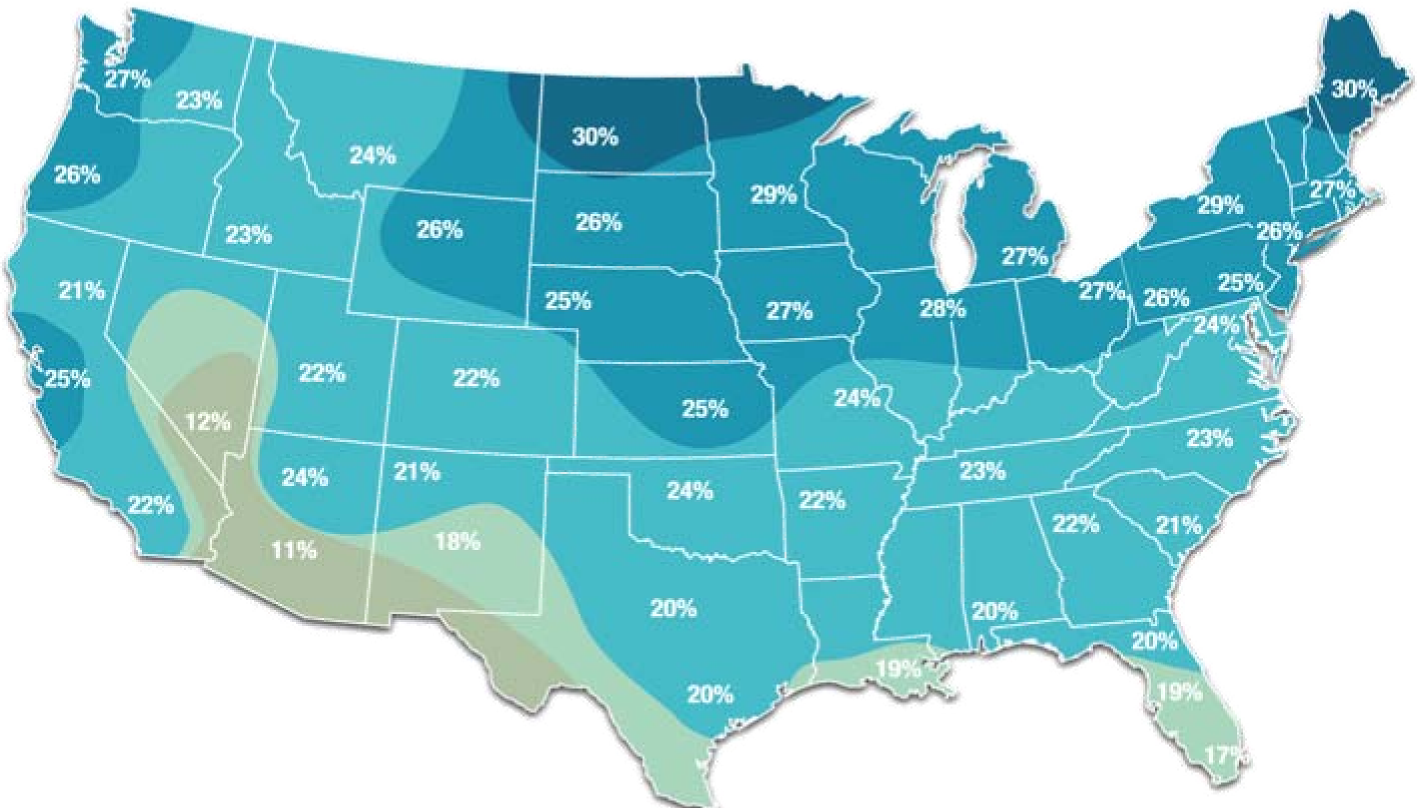
- Average Industrial/Power Tower: 58,000GPM @ 18.7degF Range
- GPM_{evap} = GPM_{fl} X Range degF X 0.0008 X 65% Load Factor
- $GPM_{watersavings}$= 20% X GPM_{evap}

188M GPD in California for:
2.6M residents

- 1156 Industrial/Power installations in California; 188MGD/71GPD/Prs

Water Savings–Gallons / Day

SPX Cooling Technologies
Balcke | Hamon Dry Cooling | Marley



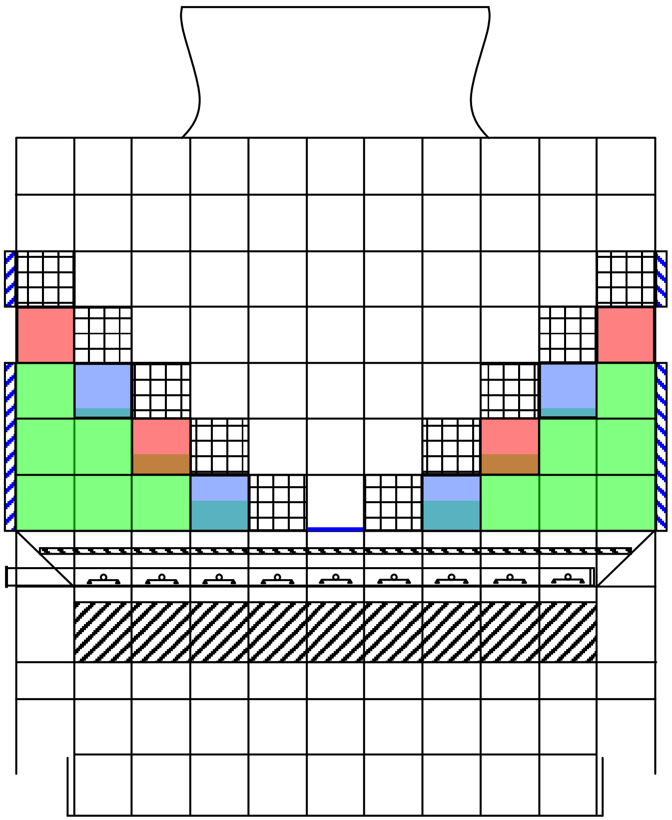
A typical 500 MW combined cycle power plant			
	12%	18%	21%
	345,000	515,000	600,000
	24%	27%	30%
	685,000	770,000	865,000

High Quality Condensed Water

- Low TDS < 10 ppm
- Low Hardness $\leq$ 1ppm
- Low Chlorides < 1 ppm
- Low Organics $\leq$ 5 ppm
- pH, 7.2 to 7.6
- Moderate Biological Entrainment, 6700-12000 cfu/ml [HPC]

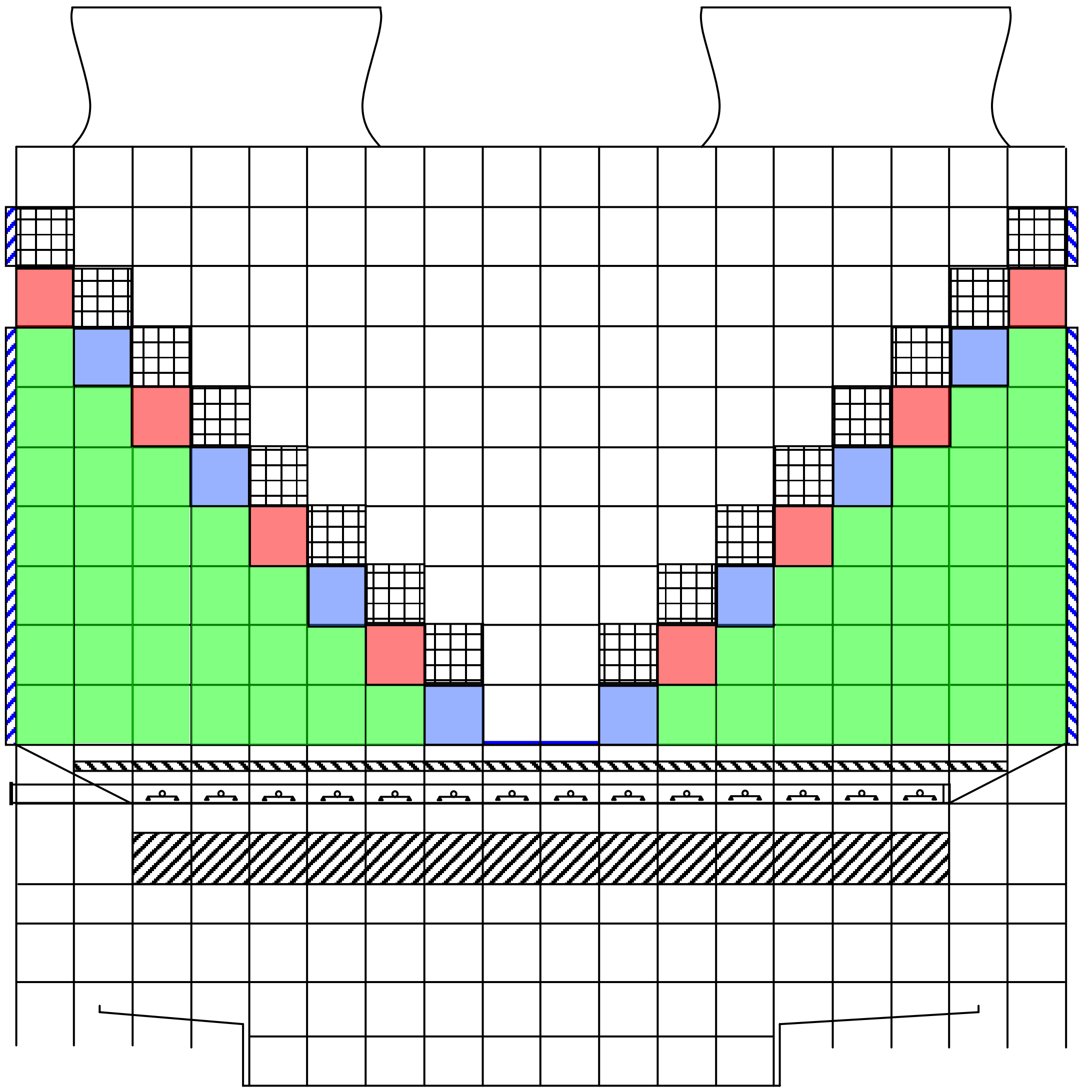
Validation Design

- Water Savings =18-19%
- Adds Cell Length at Equal Capacity
- Adds Horsepower

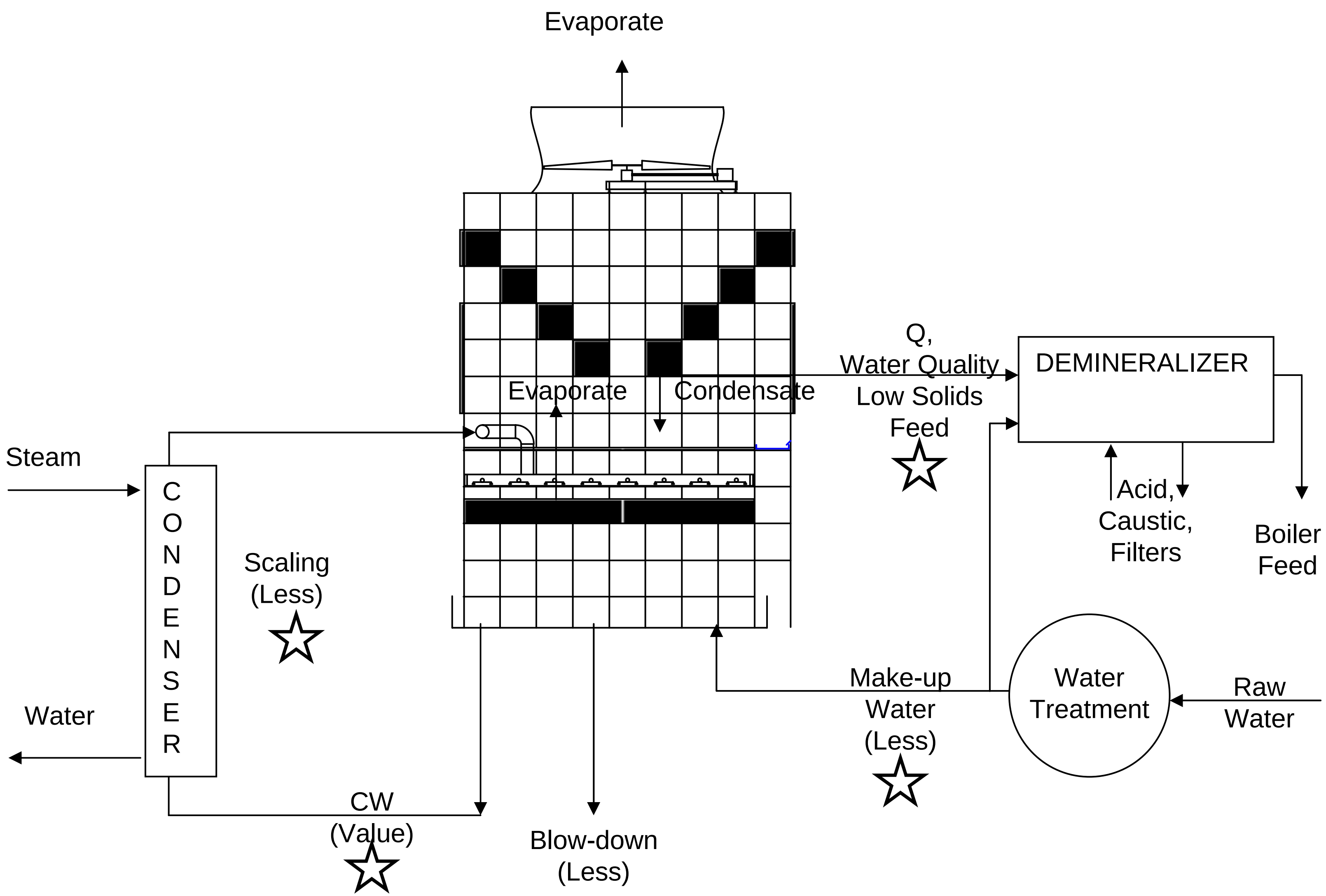


Alternate Type Design

- Water Savings =19%
- Adds Cell Width at Equal Capacity
- Adds More Horsepower with 2 fans/cell



Site Water Flows



Progress Summary

SPX Cooling Technologies
Balcke | Hamon Dry Cooling | Marley

1. *DOE Award - complete*
2. *Host Agreement – being finalized*
3. *Milestones, as follows:*

Milestone Description – DE-FC26-06NT42725	Year	Dates
1. Finalize Host Site Agreement with Power Company 2. Design & Procure Materials of Construction for the Air2Air Test Cell	1	6/30/06 12/31/06
1. Finish Construction of the Air2Air Test Cell 2. Finish Testing of Summer and Fall Operation	2	6/30/07 12/31/07
1. Finish Testing of Winter and Spring Operation 2. Final Report drafted	3	6/30/08 12/31/08

Benefits

Water Conservation

- Less make-up
- Less blow-down
- Less chemical treatment

Compared to ACC

- Colder Water
- Less Parasitic Power
- Lower Capital Cost

Possible Collection/Use - High Quality Condensate
Reduced Plume - Lowers Actual Humidity of Exit Air

Discussion - Questions

SPX Cooling Technologies
Balcke | Hamon Dry Cooling | Marley

Reduction of Water Use in Wet FGD Systems

Milton Owen
URS Corporation

NETL Project DE-FC26-06NT42726
COR: Sara Pletcher

Introduction

- **Project Goal** – Demonstrate the use of heat exchange to reduce flue gas temperature and evaporative water consumption in wet FGD systems. Additional potential benefits for new and retrofit applications:
  - Improve ESP performance: reduced gas volume & improved ash resistivity
  - Reduced gas volume results in smaller FGD system and stack requirements
  - Control SO_3 emissions through condensation on ash
  - Avoid need to install wet stacks or provide flue gas reheat
  - Potential to use recovered heat to increase turbine output (alternative)
  - Potential to increase Hg removal across ESP and FGD system
- **Technical Approach** – Conduct pilot scale tests of integrated air pollution control (APC) system, determine heat exchanger corrosion rates in long-term tests, and assess benefits and costs.
- **Expected Benefits** – Reduced FGD system water consumption, improved APC performance, and reduced capital and O&M costs.

Presentation Outline

- Background on FGD water consumption
- Effects of lower gas temperature on APC system
- Project team
- Technical approach
  - Pilot Testing of Integrated APC systems
  - Pilot Testing of Corrosion in Heat Exchanger
  - Assess Benefits and Costs of Regenerative Heat Exchange
- Schedule

Background – Water Consumption in FGD Systems

- Most water consumed in coal-fired power plants by evaporative losses
  - Cooling towers- 90%
  - Wet FGD systems- 10%
- Recent EPA regulations- CAIR
  - Add 82-GW of FGD capacity by 2020
  - Added FGD capacity will consume 120 MGD
    - Enough to satisfy water needs for 1 million people
    - Or total water demands for 7-GW of new capacity

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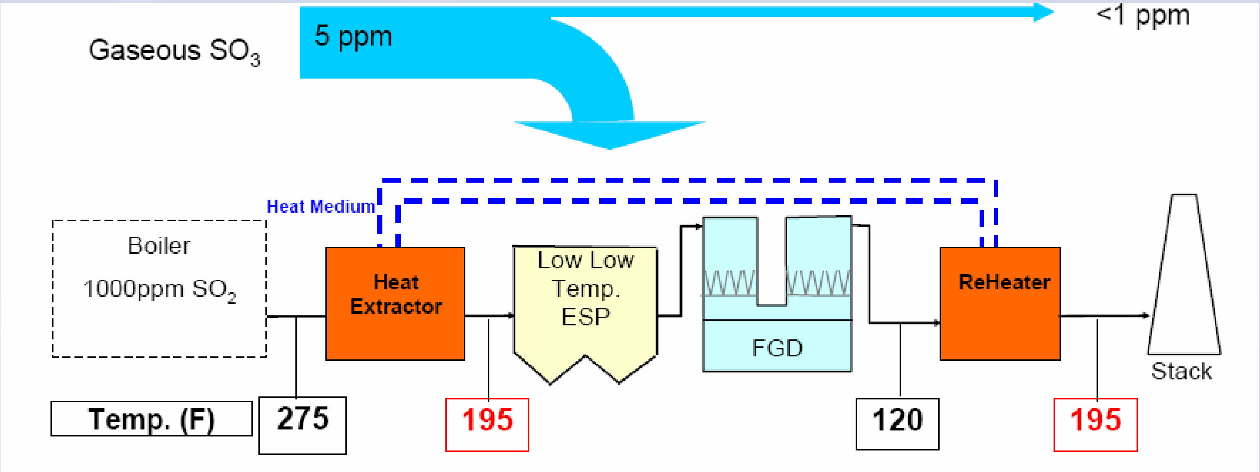
Effects of Lower Flue Gas Temperature

- Regenerative heat exchange used in Europe and Japan
- Mitsubishi Heavy Industry (MHI) High Efficiency System in Japan (US Patents 5282429 & 6149713)



Effects of Lower Flue Gas Temperature- Continued

- Potential benefits
  - Lower water consumption in FGD system
  - Control of SO_3 by condensation on ash
  - Improved particulate control by ESP due to reduced gas volume and lower ash resistivity
  - Avoided costs for flue gas reheat or wet stacks
  - Potential reduction in native Hg removal in ESP
- Not demonstrated commercially in US
  - Concerns on cost effectiveness, and
  - Potential increased corrosion rates

Effects of Lower Flue Gas Temperature- Continued

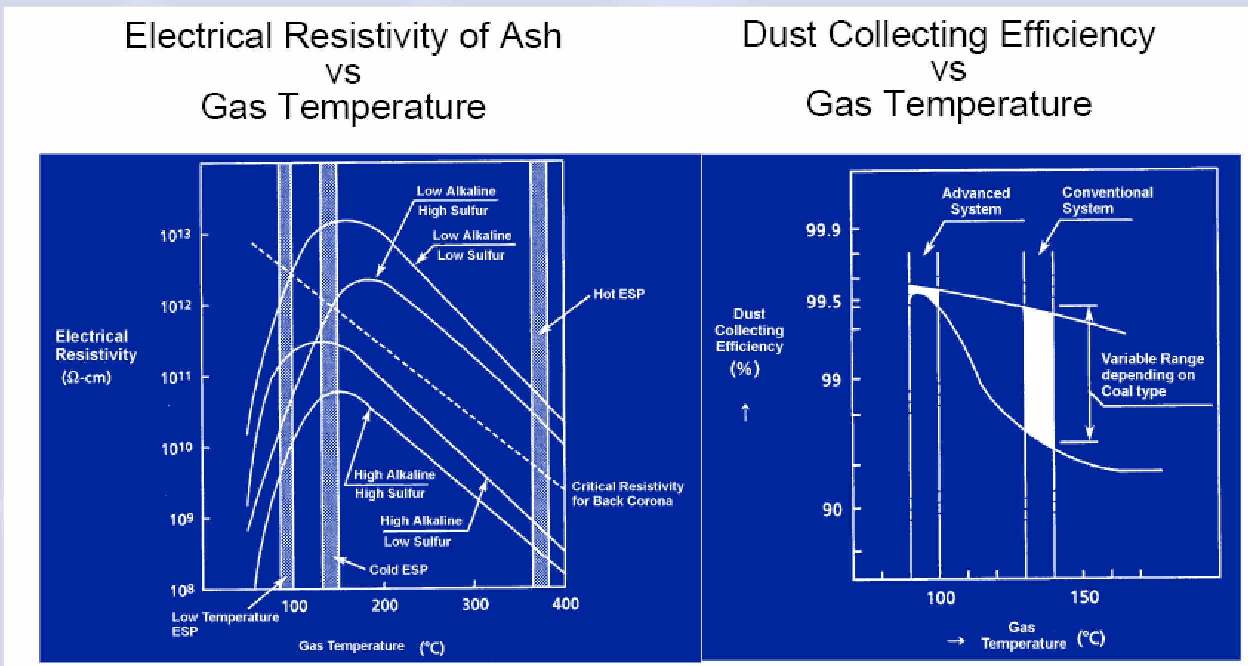
- Minimum flue gas temperature ~120°F (FGD outlet) eliminates water evaporation
- Practical limit to reduction of FGD evaporation
  - ESP performance (re-entrainment)
  - Cost of regenerative heat exchanger
    - Materials of construction (carbon steel)
    - Larger size required to lower temperature
- May limit flue gas temperature reduction to ~200°F or reduce water consumption by half
- Trade-offs will be investigated in this project

Effects of Lower Flue Gas Temperature- Continued

- Condensation of SO_3 on fly ash
  - Avoid opacity problems
  - Reduce SO_3 without additives or stand-alone controls
  - Inhibit corrosion rates in SO_3 dew point environment
  - Carbon steel heat bundle can be used
- Corrosion tests to be conducted in pilot program to collect corrosion data

Effects of Lower Flue Gas Temperature- Continued

- Improved ESP performance at lower temperature
  - Lower gas velocity and higher specific collection area
  - Lower fly ash resistivity



Effects of Lower Flue Gas Temperature- Continued

- Theoretical ESP performance
  - Particulate collection could improve in retrofit applications
  - Greatest benefit could be for low-sulfur coals which typically have higher resistivity ash
- Non-ideal ESP Performance (Cannot be modeled)
  - Re-entrainment of fly ash at lower resistivity
    - Flue gas flow “scrubbing” collected particles from plates
    - Re-entrainment during rapping
    - Ash resistivity below “ideal” range

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Project Team

- URS Corporation- Prime Contractor
- Southern Company
- Electric Power Research Institute
- Tennessee Valley Authority
- Mitsubishi Heavy Industry
- Southern Research Institute

Presentation Outline

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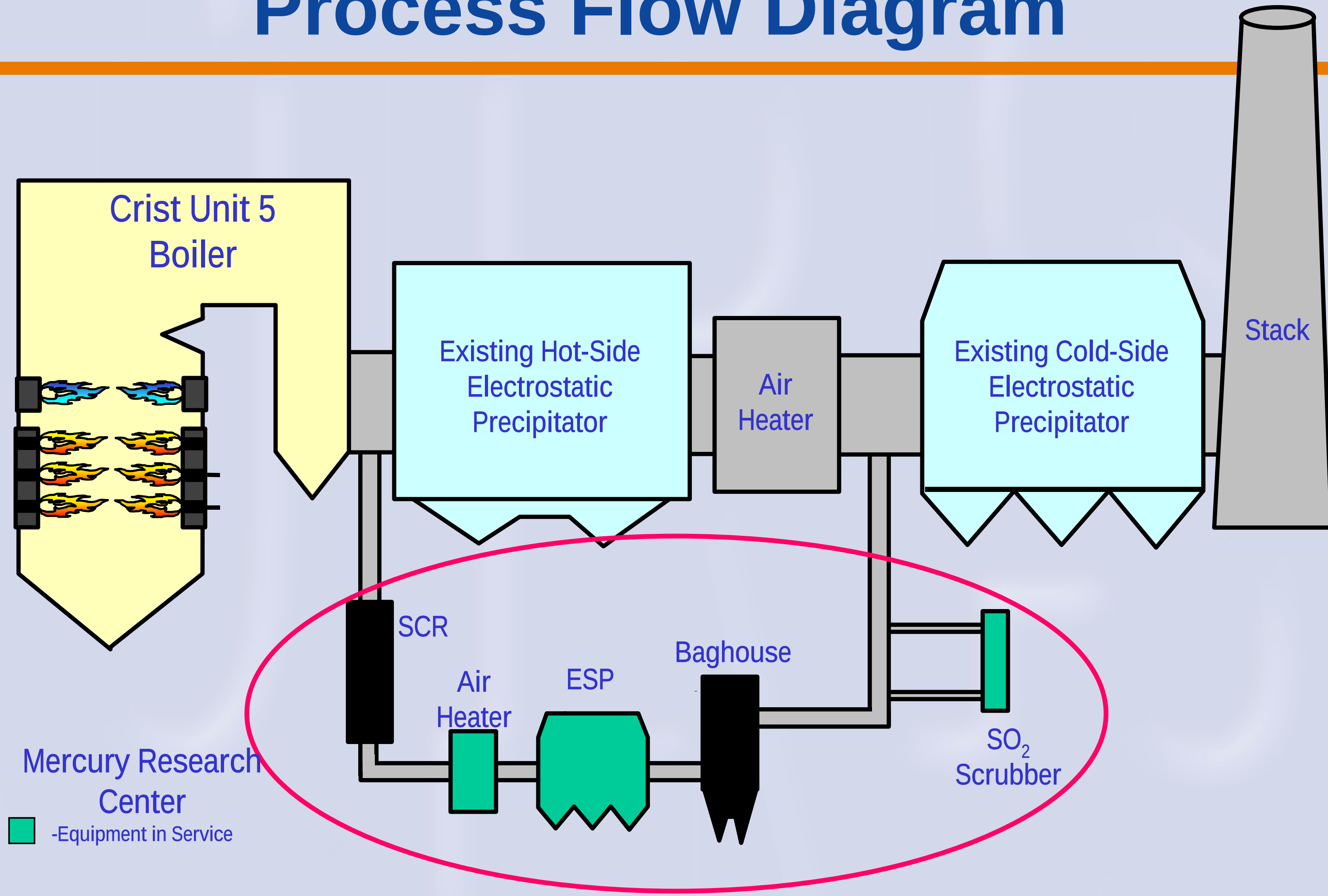
Project Technical Approach

- Pilot Testing to be conducted at Southern Company's Mercury Research Center (MRC)
  - Located at Gulf Power's Plant Crist near Pensacola, FL
  - Operated by SRI
- MRC processes flue gas slipstream from Unit 5
  - Firing low-sulfur bituminous coal
  - Flue gas flow rate 50,500 lb/hr (5-MW)
  - Ljungstrom air heater
  - Four-field ESP
  - Wet FGD
  - Capability to Inject SO_3 (simulate high-sulfur operation)
- Construct smaller skid-mounted heat exchanger for long-term corrosion tests (3,600 lb/hr)

Mercury Research Center Process Flow Diagram



Mercury Research Center Pilot Unit

Integrated Pilot Tests

- Baseline tests at typical flue gas temperature
- Parametric tests
  - Vary flue gas temperature
  - Spike SO_3 up to 30 ppm
  - Assess impacts
    - FGD system evaporation rates
    - ESP performance- particulate and Hg removal
    - Simulate operation for higher sulfur coal or plants with SCR
- Select conditions for optimum operation
  - Without SO_3 spiking- minimize FGD water consumption
  - With SO_3 spiking- maximum acceptable SO_3 level

Pilot Measurements

Measurements	Location
FGD evaporative water consumption	Make-up water rates and measurements of liquid levels in reagent and slurry tanks during the duration of each test.
SO_3 concentrations (CCS)	AH and ESP outlets
Particulate loading (M17)	AH and ESP outlets
Total Hg concentrations	AH and ESP outlets by carbon tube (screen overall Hg removal); coal (baseline only), ash & FGD solids and liquids (verify mass balance)
LOI of ash	ESP ash
Fly ash resistivity	ESP inlet

Corrosion Tests

- Small pilot heat exchanger- carbon steel
- Long-term test- 6 months
- Select test conditions from Integrated Tests
- Determine if corrosion rates are excessive at low flue gas temperatures
- Collect data on corrosion rates and SO_3 levels

Assess Benefits and Costs

- Estimate water use reduction for existing and future FGD systems
- Investigate commercial alternatives for heat exchanger and associated costs
- Estimate ESP performance in retrofit applications
- Determine if additional SO_3 control is required
- Evaluate impacts on Hg removal
- Compared cost to flue gas reheat and wet stacks
- Collect data on corrosion rates and SO_3 levels
- Estimate potential application to population of existing boilers

Presentation Outline

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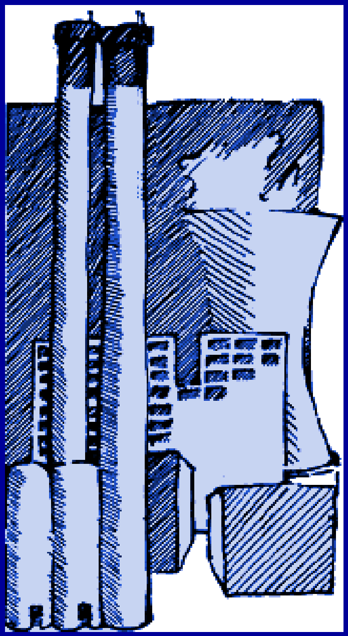
Project Schedule

Task	Schedule
1- Project Planning	July-September, 2006
2- Pilot Plant Assembly	October 2006- July 2007
3- Integrated Pilot Tests	August 2007- November 2007
4- Corrosion Tests	December 2007- May 2008
5- Cost/Benefit Analysis	February 2008-August 2008
6- Management and Reporting	July 2006- August 2008

RECOVERY OF WATER FROM BOILER FLUE GAS

DOE Project DE-FC26-06NT42727



Edward K. Levy

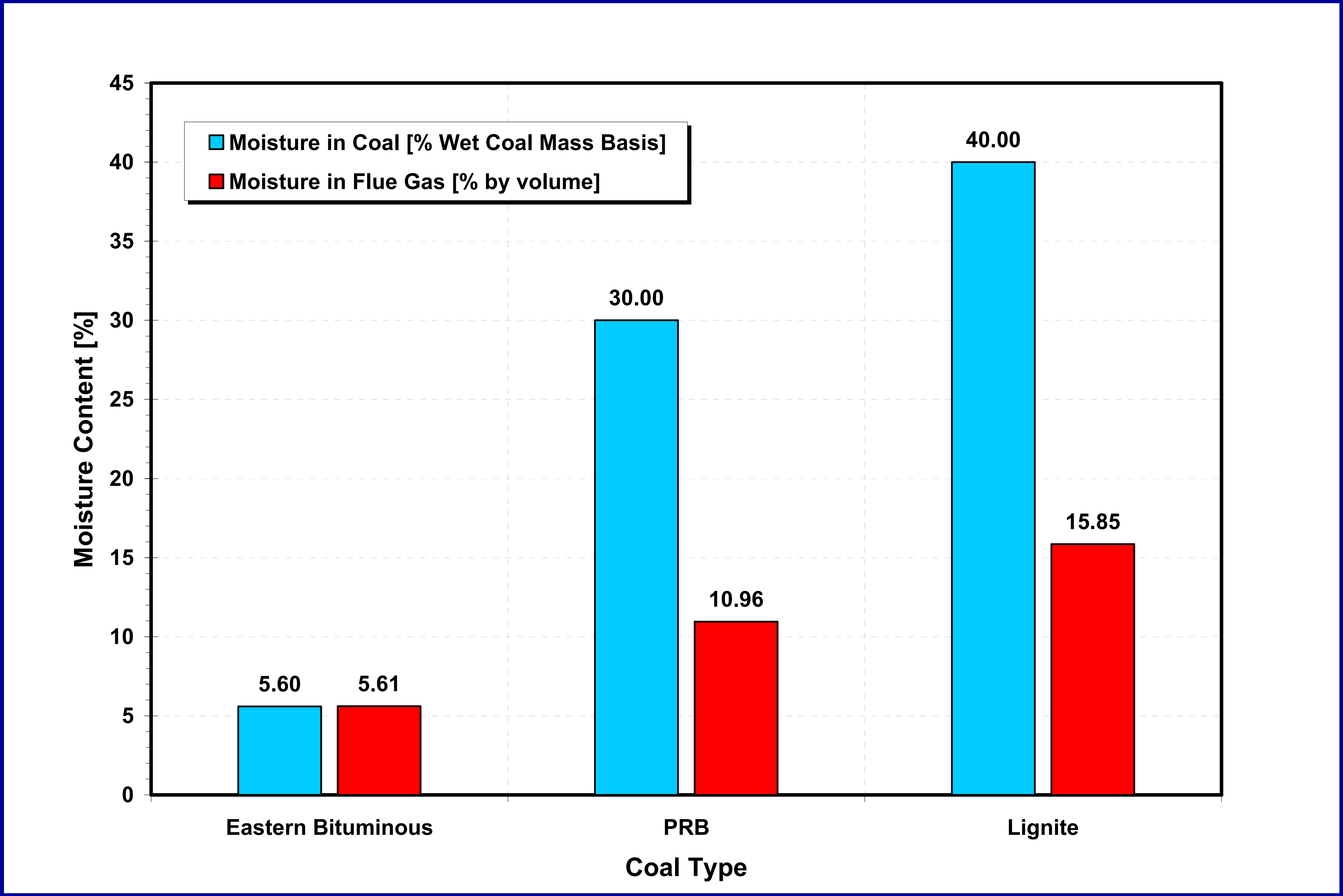
Energy Research Center
Lehigh University
117 ATLSS Drive
Bethlehem, Pennsylvania 18015

LEHIGH

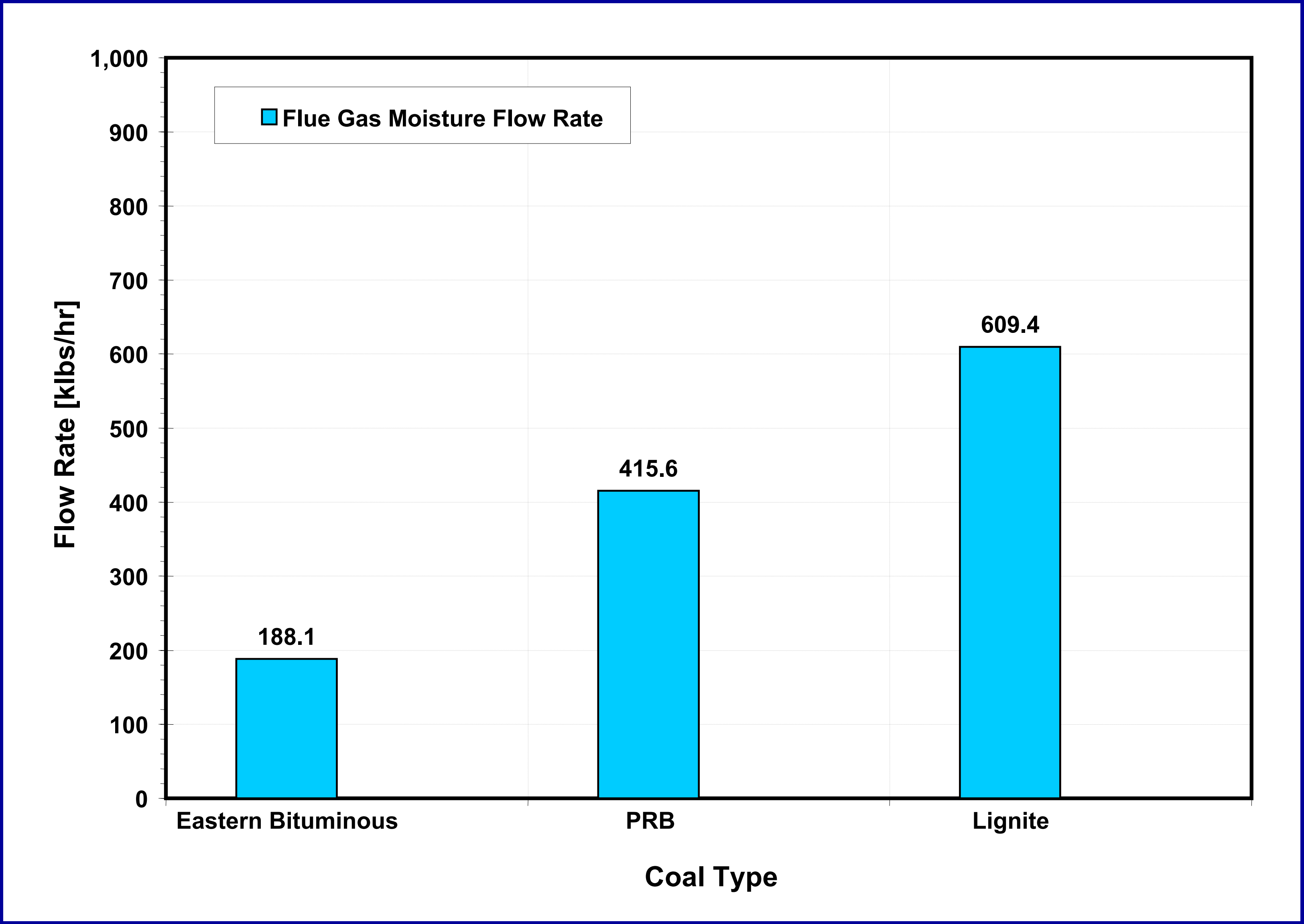
NETL Water Program Review Meeting, June 20, 2006, NETL Pittsburgh Site

MOISTURE IN BOILER FLUE GAS

- Fuel Moisture
- H_2O From Oxidation of Fuel Hydrogen
- Water Vapor in Combustion Air



Effects of Coal Rank on Coal Moisture and Flue Gas Moisture



Typical Coal and Flue Gas Moisture Flow Rates for 600 MW Power Plants

- **FLUE GAS MOISTURE FLOW RATE IN 600 MW UNIT**

  0.2 to 0.6 x 10^6 lbm/hr

- **TYPICAL COOLING TOWER WATER EVAPORATION RATE**

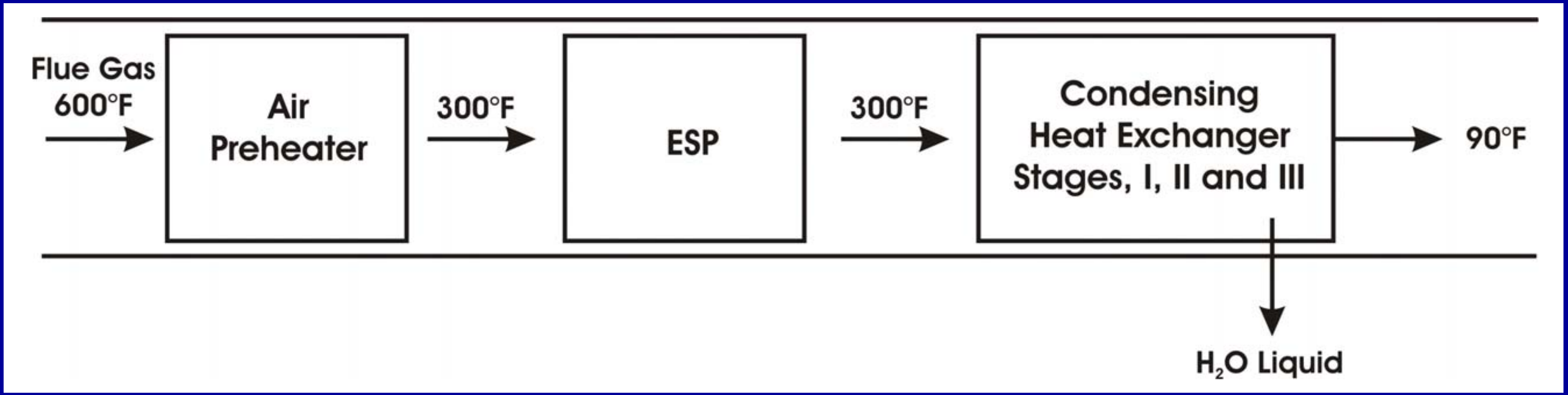
  1.6 x 10^6 lbm/hr

- **IF COULD EXTRACT ALL THE FLUE GAS MOISTURE AND USE IT FOR COOLING TOWER MAKEUP**

	% of Cooling Tower Makeup
PRB	25
Lignite	37

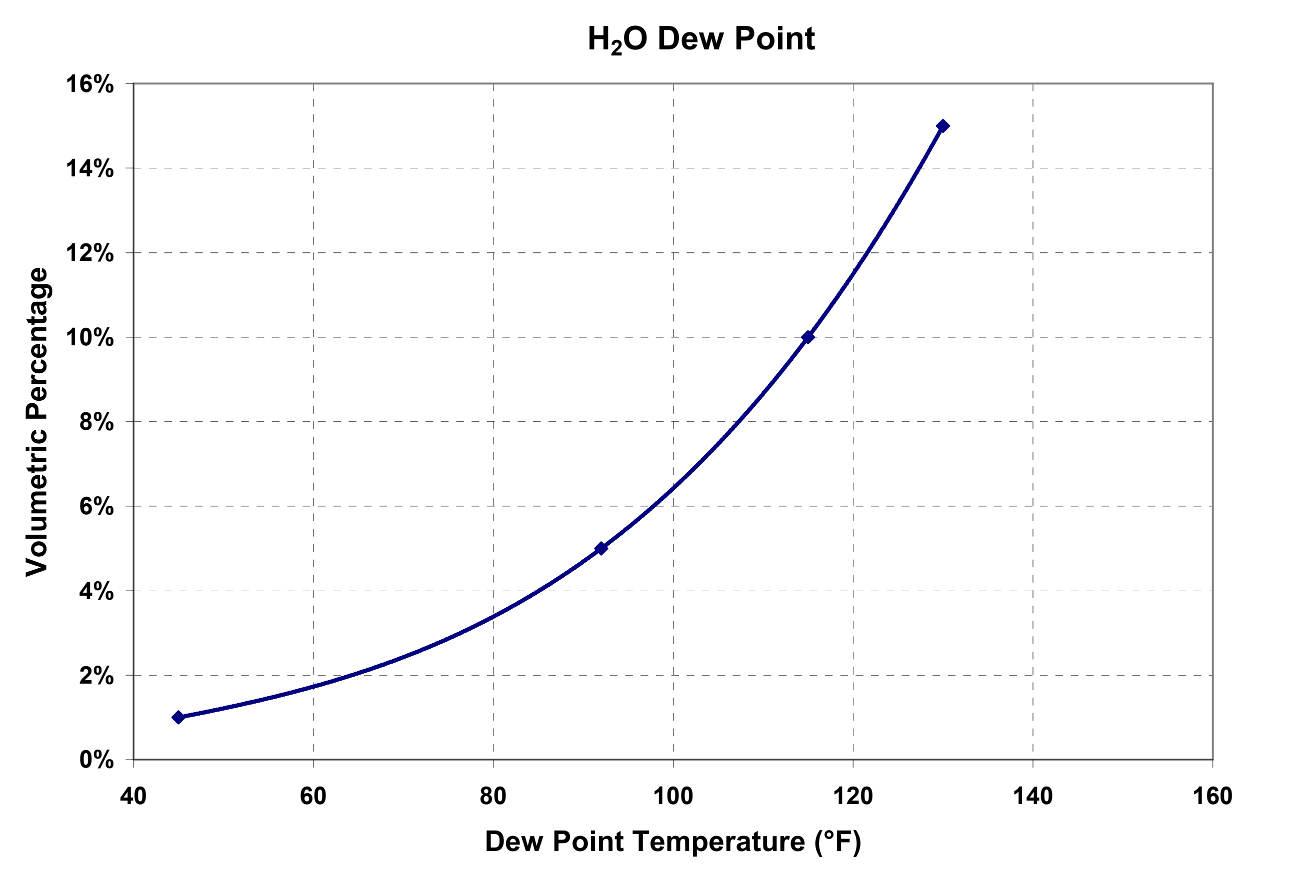
APPROACH

Use Condensing Heat Exchangers to Separate H_2O From Flue Gas



Condensing Heat Exchanger System Located Downstream of ESP

DEW POINTS



Dew Point of Water as Function of Volumetric Percentage of Water in Flue Gas

FLUE GAS ALSO CONTAINS H_2SO_4, HCl AND HNO_3 VAPORS

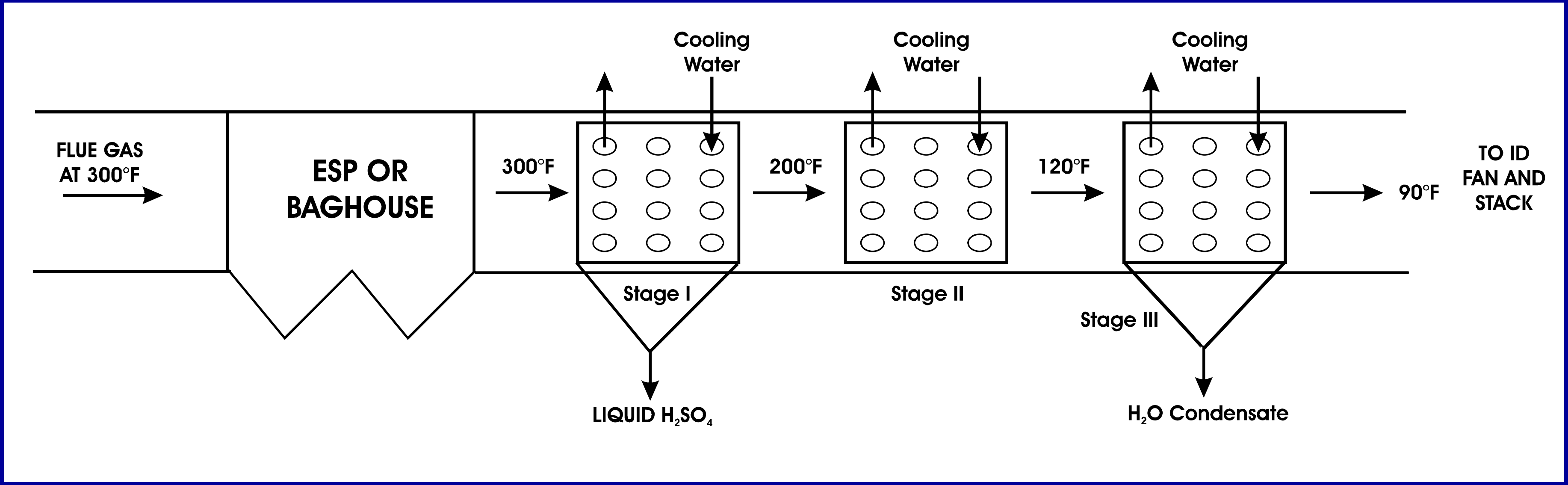
H_2SO_4 Condenses 200 to 320°F

HCl Condenses 80 to 130°F

HNO_3 Condenses 50 to 120°F

PROCESS DESCRIPTION

- **Multistage Heat Exchangers Separately Condense H_2SO_4, H_2O and HCl From Flue Gas**



BENEFITS

- Multistage Approach Minimizes Overall Cost of Heat Exchanger System
- Recovered Water Will Supply Up to 25% (for PRB) to 37% (for lignite) of Cooling Tower Makeup Water

HEAT RATE IMPROVEMENT

Boiler Efficiency Calculation – Heat Loss Method

	Stack Temperature	
	300°F	90°F
Heat Loss Due to Dry Gas (%)	6.00	0.60
Heat Loss Due to Moisture in Fuel (%)	0.37	0.15
Heat Loss Due to H_2O From Fuel Hydrogen (%)	3.81	1.80
Heat Loss Due to Unburned Carbon (%)	0.26	0.26
Radiation Loss (%)	0.16	0.16
TOTAL LOSSES	10.60	2.97
Boiler Efficiency (%)	89.40	97.03

$$\text{UNIT HEAT RATE} = \frac{HR_{CYCLE} \times P_g}{\eta_{BOILER}\left(P_g - P_{ss}\right)}$$

- **Increased Boiler Efficiency Yields Reduced Heat Rate**

CO-BENEFITS

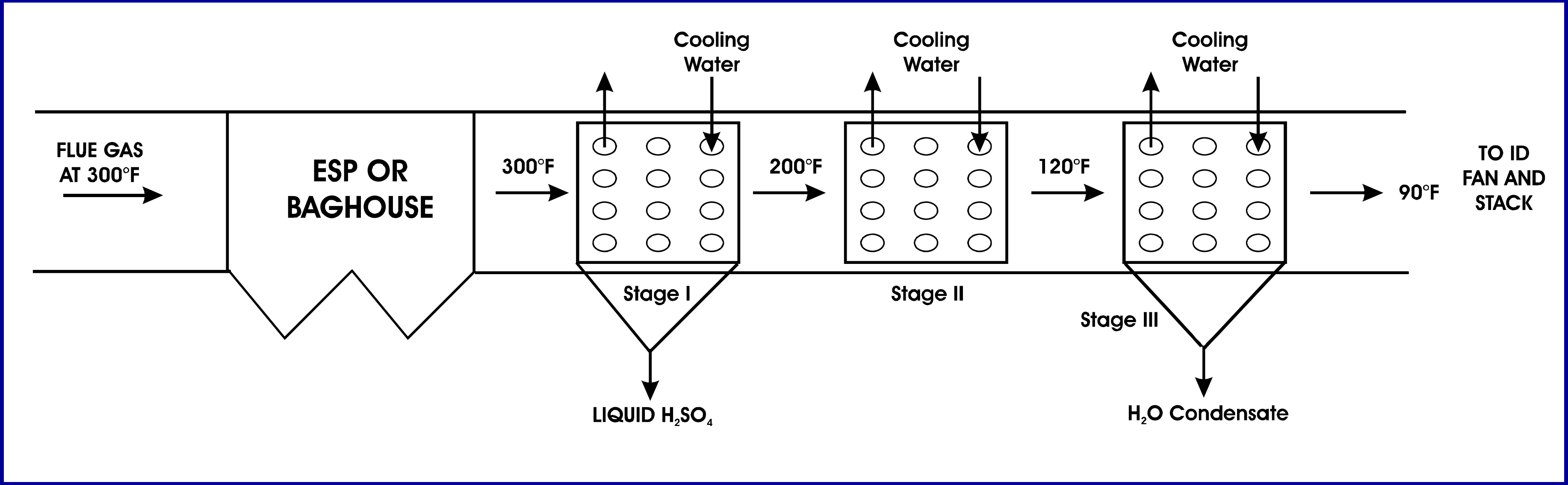
- Unit Heat Rate Reduced By Up to 7% By Recovering Sensible and Latent Heat
- Lower Heat Rate Results in Reductions of CO_2, NO_x, SO_2, and Hg Emissions
- Process Eliminates Acid Plume Problem

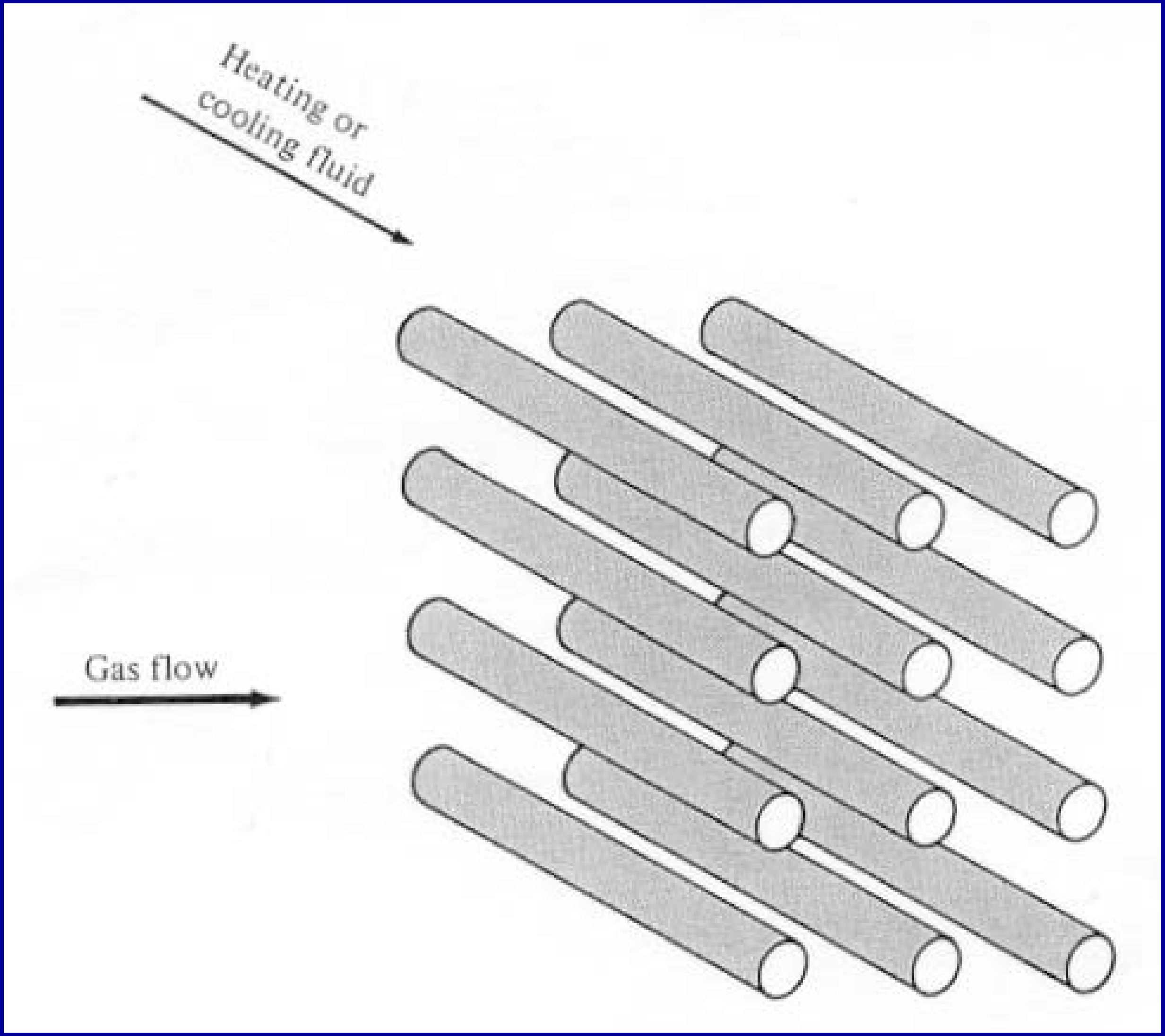
PROJECT OBJECTIVES

- Determine the Extent to Which Removal of Acid Vapors From Flue Gas and Condensation of H_2O Vapor Can Be Achieved in Separate Heat Transfer Sections
- Estimate Potential Heat Rate Reduction

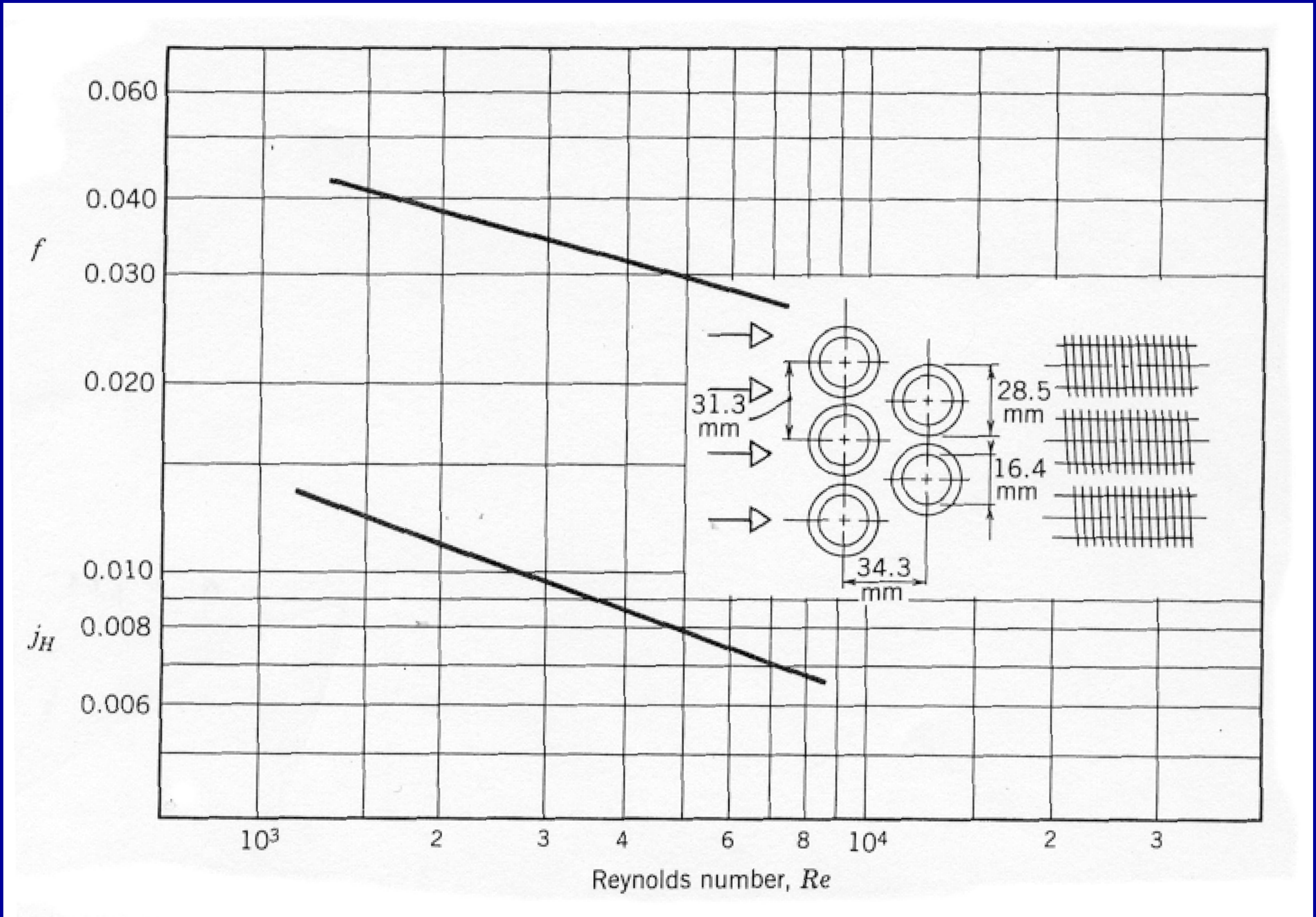
PROCESS DESCRIPTION

- Multistage Heat Exchangers Separately Condense H_2SO_4, H_2O and HCl From Flue Gas

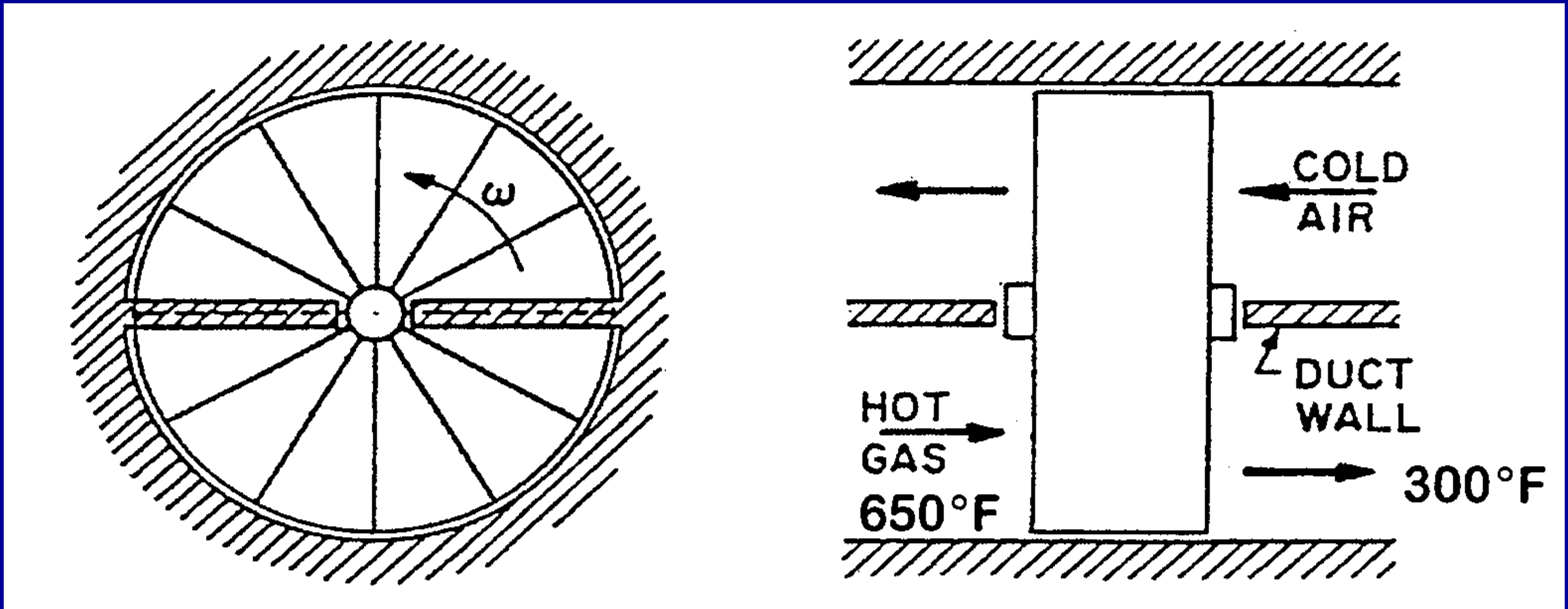




Array of Smooth Wall Circular Tubes in Cross-Flow



Data From Kays and London Showing Heat Transfer and Friction Factors for a Bundle of Circular Tubes with Circular Fins



A Ljungstrum Air Preheater Transfers Heat From Hot Flue Gas to Cool Incoming Air By Way of a Rotating Metal Matrix.

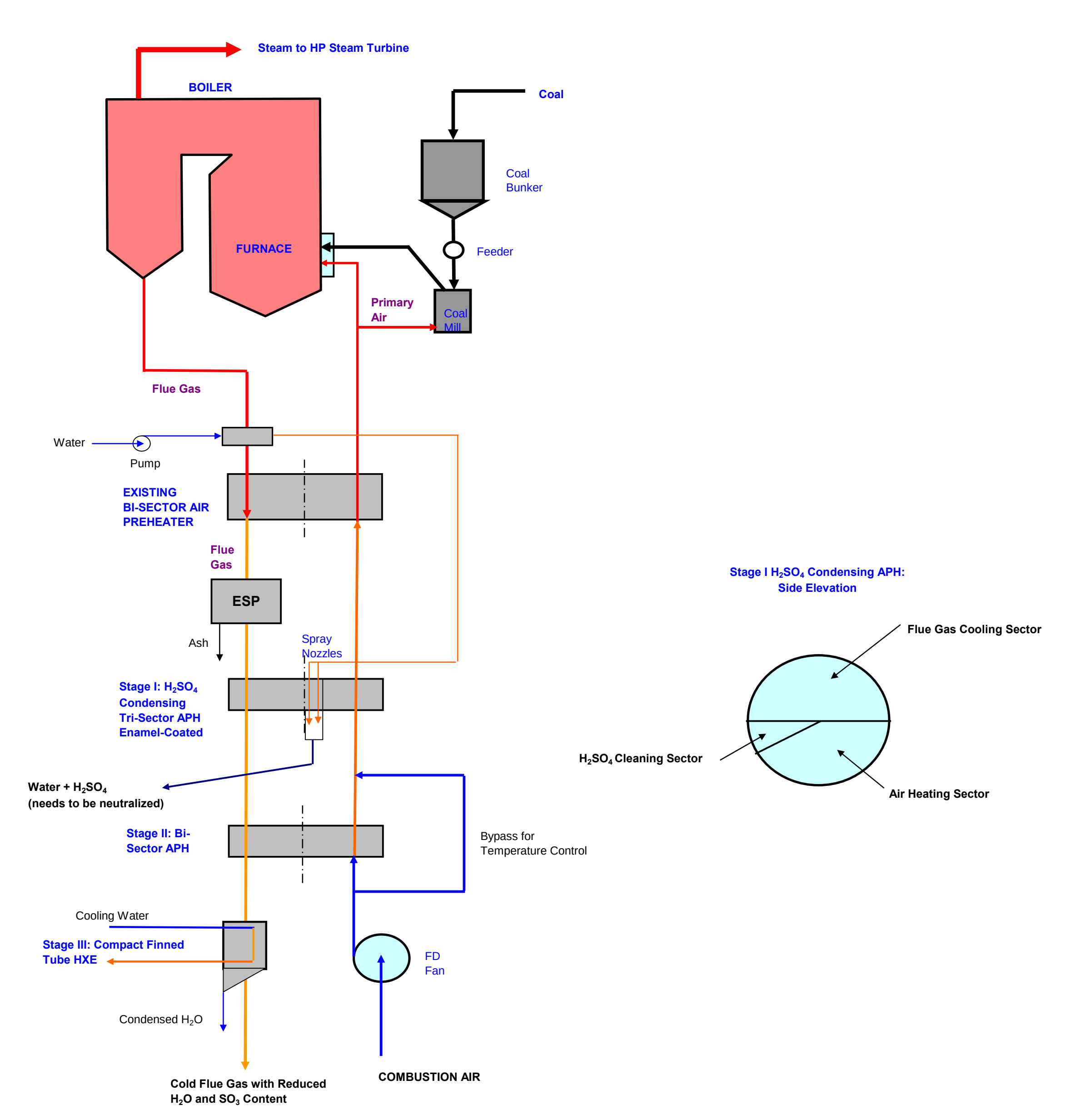
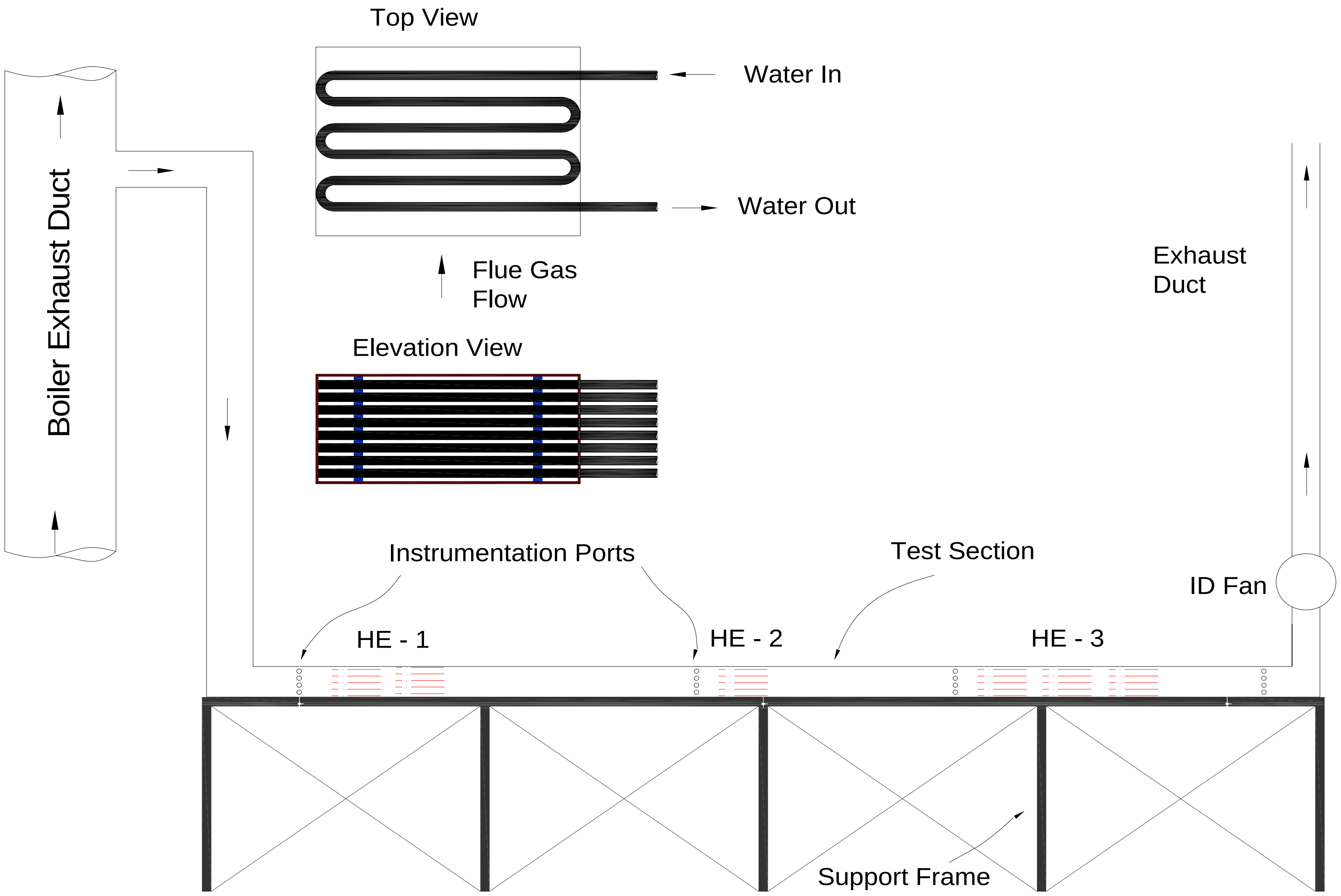


Diagram Showing Ljungstrum Heat Exchanger for Stages I and II

TASKS

1. Design, Fabricate and Assemble Heat Transfer Test Apparatus
2. Experiments at an Oil-Fired Boiler
3. Experiments at a Coal-Fired Boiler
4. Perform Cycle Analyses of Heat Rate Impacts

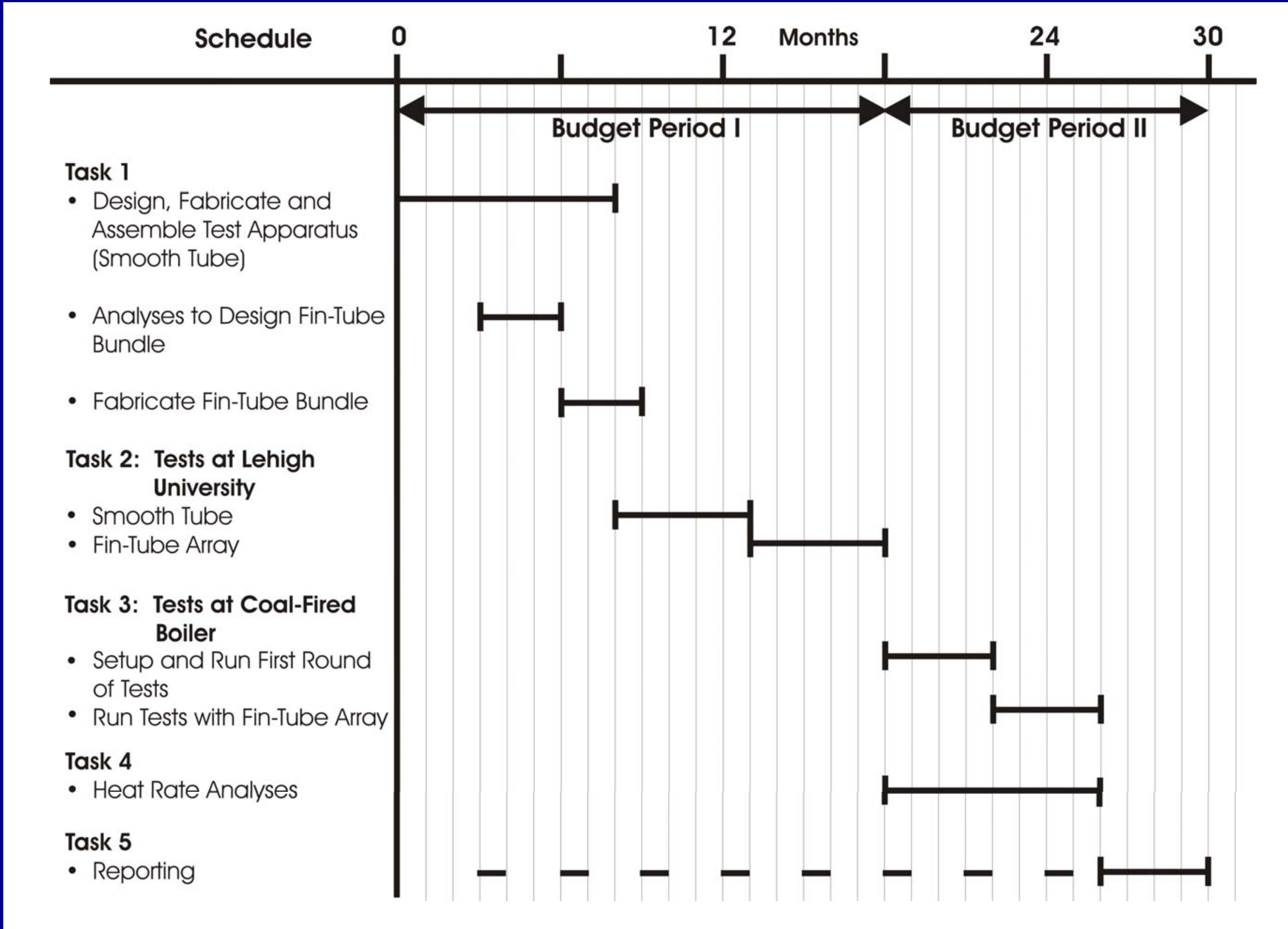

Top View
Water In
Water Out
Boiler Exhaust Duct
Flue Gas
Flow
Exhaust
Duct
Elevation View
Instrumentation Ports
Test Section
ID Fan
HE - 1
HE - 2
HE - 3
Support Frame

INSTRUMENTATION

- Flue Gas Flow Rate (S-Probe Traverses)
- Cooling Water Flow Rates (Rotameters)
- Water and Flue Gas Inlet and Outlet Temperatures (Thermocouples)
- Tube Wall Temperature (Thermocouple)
- Moisture Condensation Rate (Bucket, Stopwatch and Scale)
- H_2SO_4 and HCl Gas-Phase Concentrations (Controlled Condensation)
- Sulfate, Chloride and Nitrate Concentrations in Water

PILOT PLANT FACILITIES

- Oil-Fired Boiler at Lehigh University in Bethlehem, Pennsylvania
- Coal-Fired Boiler at Alstom Power in Windsor, Connecticut


Schedule
0
12
Months
24
30
Budget Period I
Budget Period II
Task 1
• Design, Fabricate and Assemble Test Apparatus (Smooth Tube)
• Analyses to Design Fin-Tube Bundle
• Fabricate Fin-Tube Bundle
Task 2: Tests at Lehigh University
• Smooth Tube
• Fin-Tube Array
Task 3: Tests at Coal-Fired Boiler
• Setup and Run First Round of Tests
• Run Tests with Fin-Tube Array
Task 4
• Heat Rate Analyses
Task 5
• Reporting

PROGRESS TO DATE

- Completed Design of Multi-Stage Heat Exchanger Using Smooth Wall Tube Bundles
- Solicited Bids for Fabrication of System Components
- Beginning to Issue PO’s
- Begin Design and Analysis Work on a Finned-Tube Bundle for Low Temperature Heat Exchanger
- Expect to Connect to Boiler and Begin Testing in September 2006

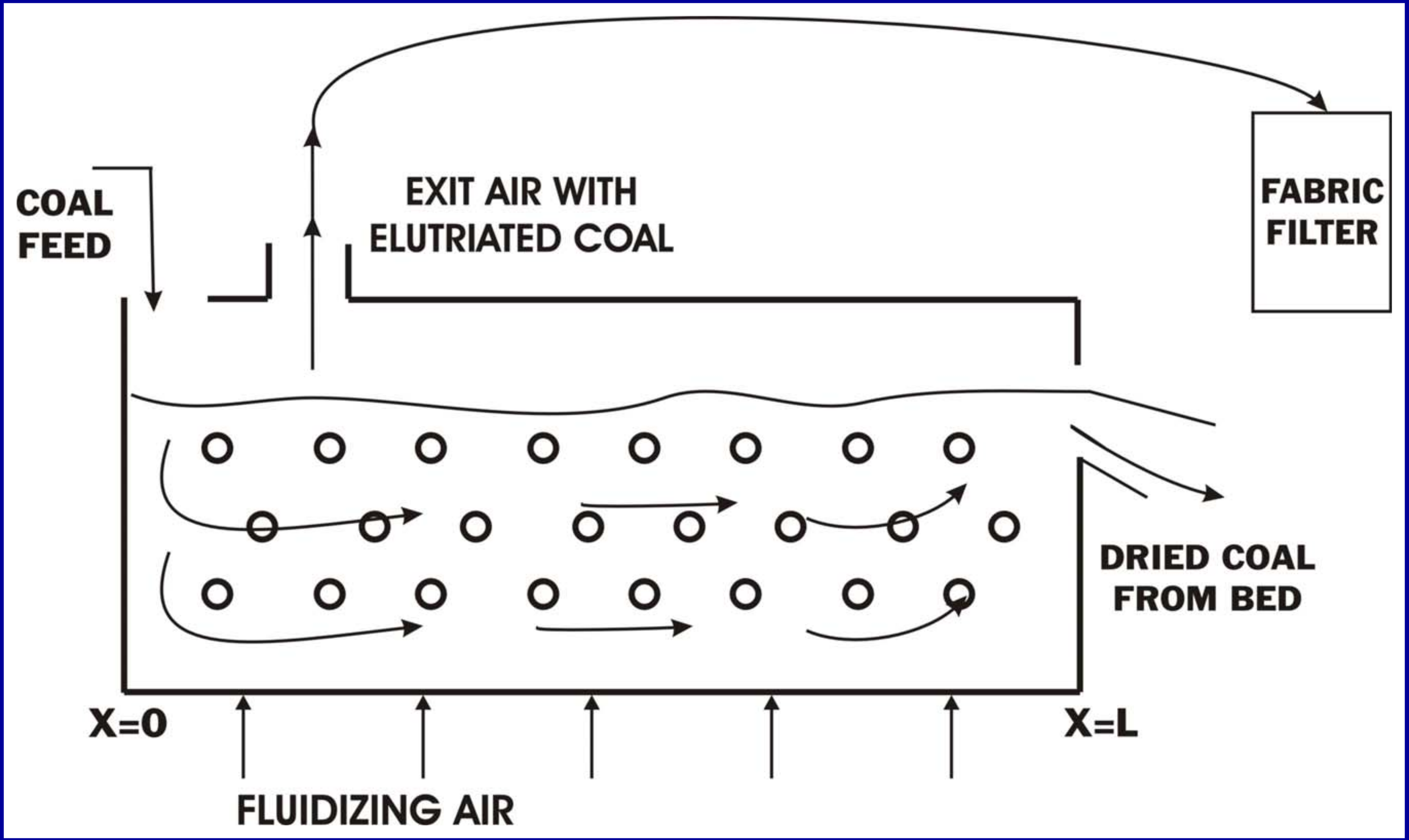
PROJECT TEAM

- Lehigh University, Energy Research Center
- Alstom Power Company

SOME OTHER APPLICATIONS OF CONDENSING HEAT EXCHANGERS

- **Oxygen-Fired Coal Combustors – Separate H_2O From CO_2**
- **IGCC With Oxygen Blown Gasifier – Separate H_2O From CO_2**
- **Recover H_2O From Moist Air Streams From Coal Dryers**

COAL CREEK STATION



Sketch of Continuous Flow Dryer

EVAPORATED COAL MOISTURE DISCHARGED INTO THE ATMOSPHERE

QUESTIONS?