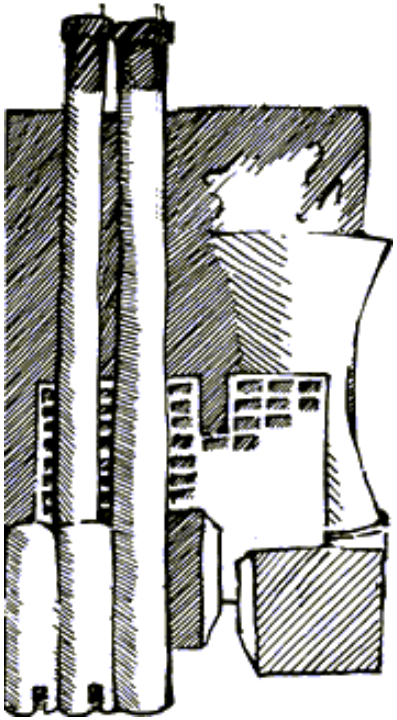
RECOVERY OF WATER FROM BOILER FLUE GAS



Project DE-FC26-06NT42727

Dr. Edward Levy
Dr. Harun Bilirgen
Energy Research Center
Lehigh University

DOE-NETL Water Meeting
Pittsburgh, Pa
October 27, 2008

ACKNOWLEDGEMENTS

Funding also provided by:

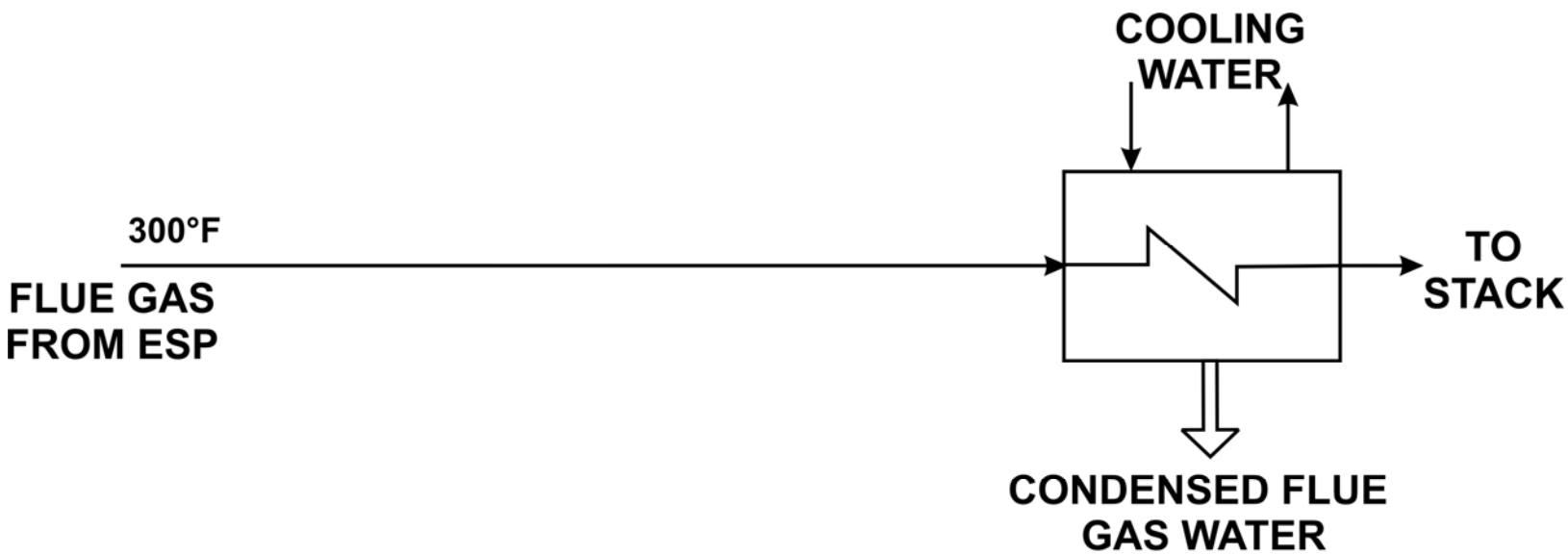
> Alstom Power Company

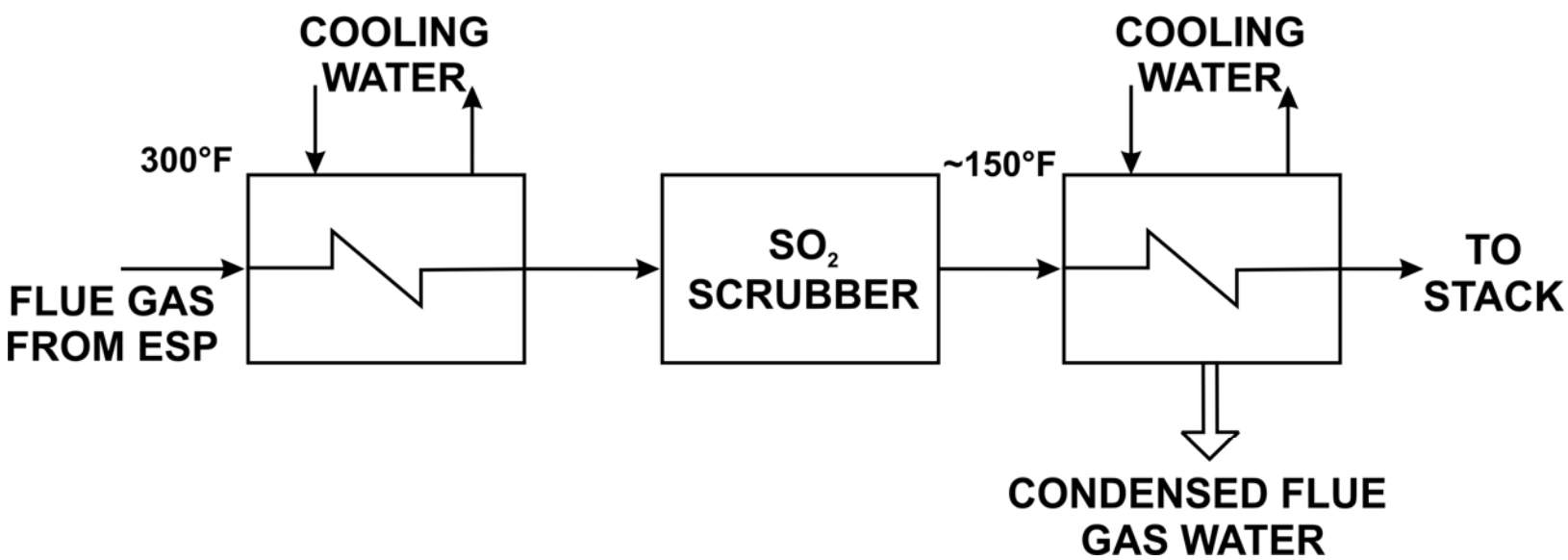
> Pennsylvania Infrastructure Technology Alliance,

> Lehigh University

BACKGROUND

- **Concentrations and Dew Points**
  - **> Water vapor**
    - **6 to 15 vol % …….95 to 130 F**
  - **> Sulfuric acid**
    - **0 to 40 PPM ……..220 to 310 F**
- **Flue Gas Inlet Temperature…….300 F**
- **Cooling Water Inlet Temp……50 to 110 F**


COOLING
WATER
300°F
FLUE GAS
FROM ESP
TO
STACK
CONDENSED FLUE
GAS WATER


COOLING
WATER
300°F
FLUE GAS
FROM ESP
SO_2
SCRUBBER
~150°F
COOLING
WATER
TO
STACK
CONDENSED FLUE
GAS WATER

QUESTIONS

- **How much flue gas moisture can be recovered?**

- **Heat rate Impacts…How large?….Will depend on how much sensible and latent heat can be captured.**

- **Can we control the region over which acid condenses?**

- **Acid corrosion……What heat exchanger designs and tubing materials will be needed to avoid serious acid corrosion problems?**

- **What will be impact on Hg emissions?**

PROJECT OBJECTIVES

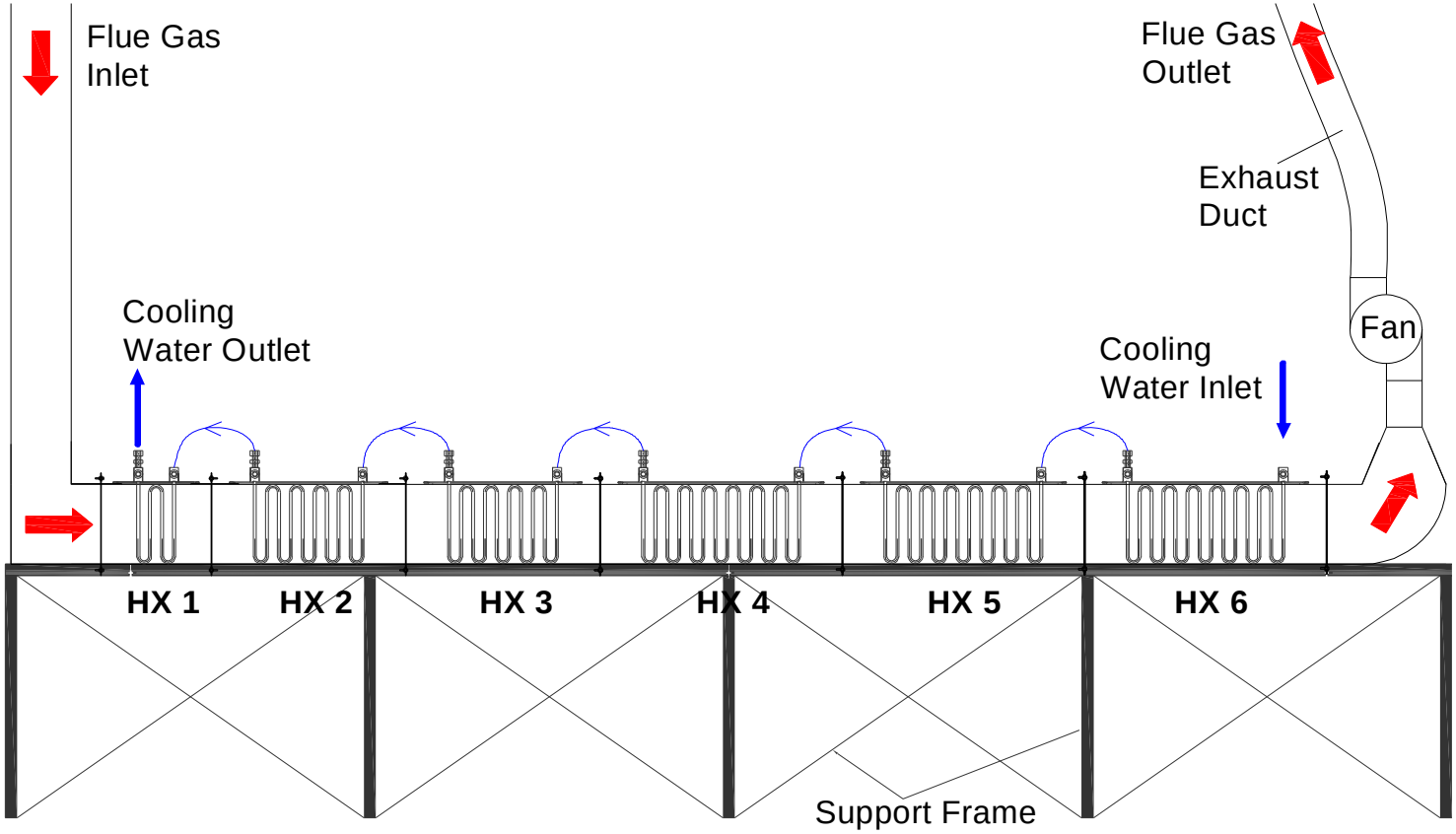
- **Explore technical issues involved in using heat exchangers to condense H_20 from boiler flue gas**
- **Develop new designs for condensing heat exchangers**
- **Perform pilot scale tests and measure acid and water condensation patterns**
- **Determine maximum recoverable water from flue gas**
- **Determine potential heat rate benefits**

HEAT EXCHANGER SYSTEM DESIGN PHILOSOPHY

> Cool flue gas and condense acids and water in stages

> Condense sulfuric acid in high temperature heat exchangers

> Condense water vapor and other acids in low temperature heat exchangers

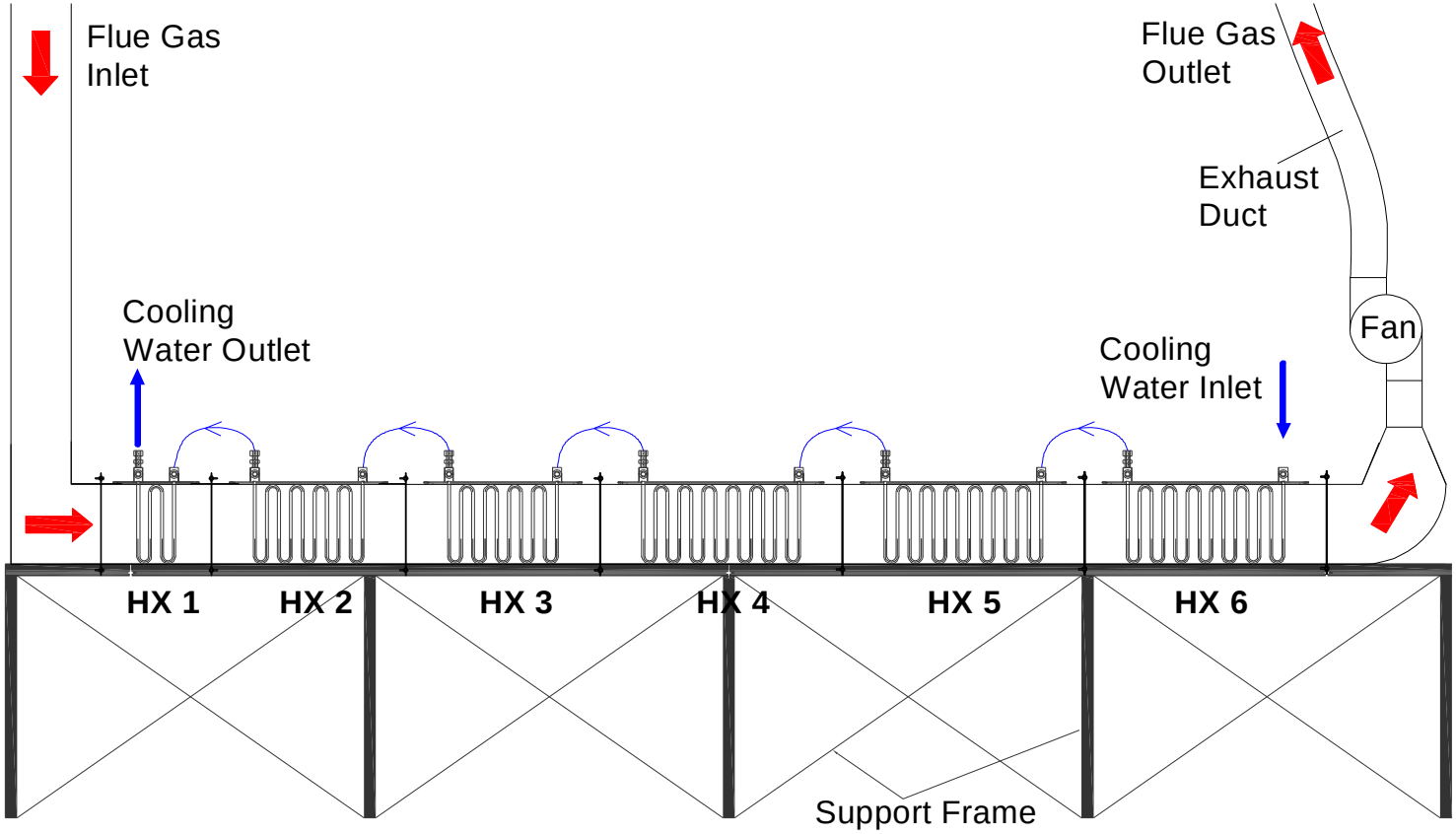

Flue Gas
Inlet
Flue Gas
Outlet
Exhaust
Duct
Fan
Cooling
Water Outlet
Cooling
Water Inlet
HX 1
HX 2
HX 3
HX 4
HX 5
HX 6
Support Frame

PILOT-SCALE TESTS

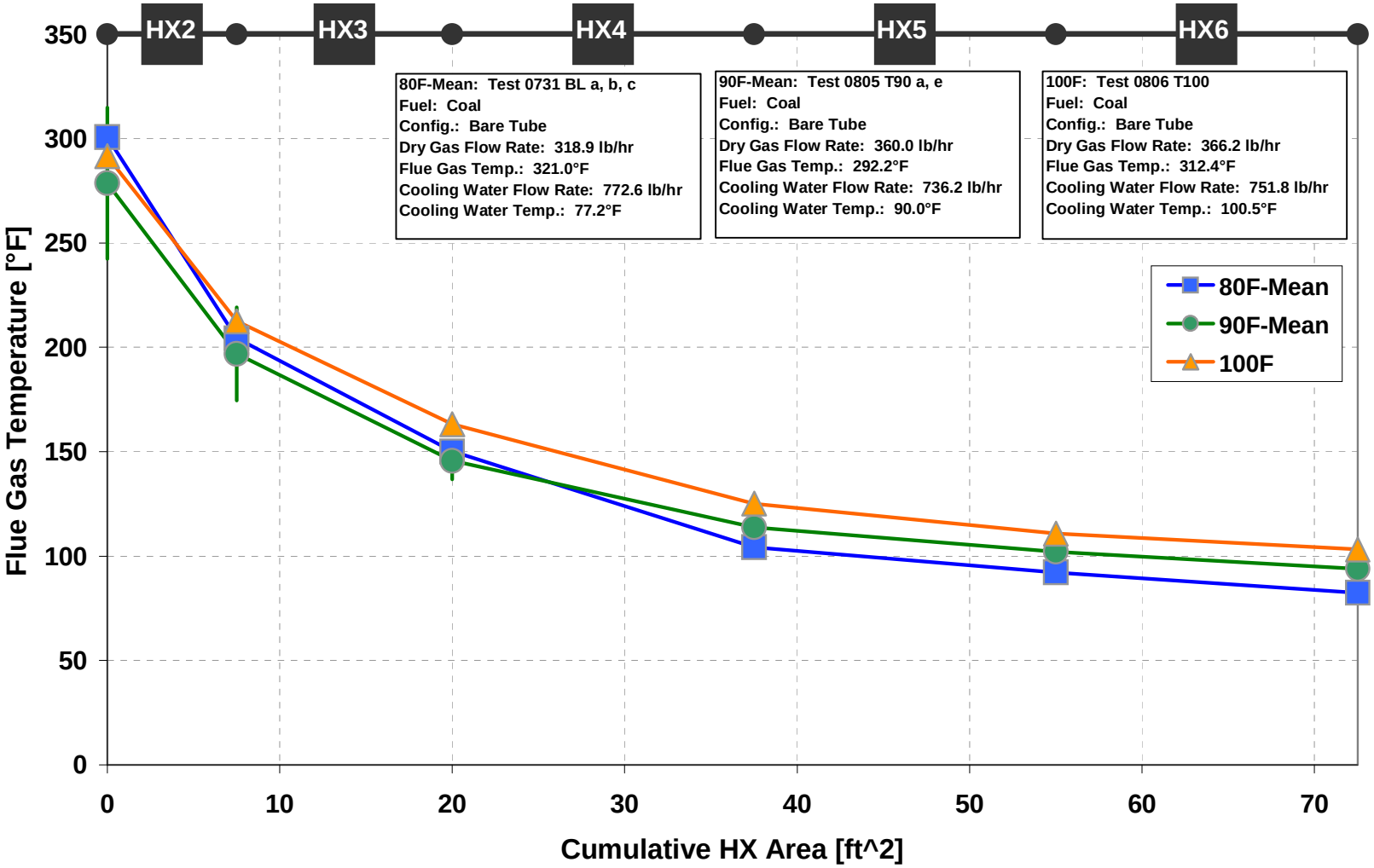
- **Lehigh University Boiler**
  - > #6 fuel oil and natural gas
  - > flue gas slip stream after economizer

- **Coal-Fired Power Plant**
  - > high moisture coal
  - > flue gas slipstream after ESP

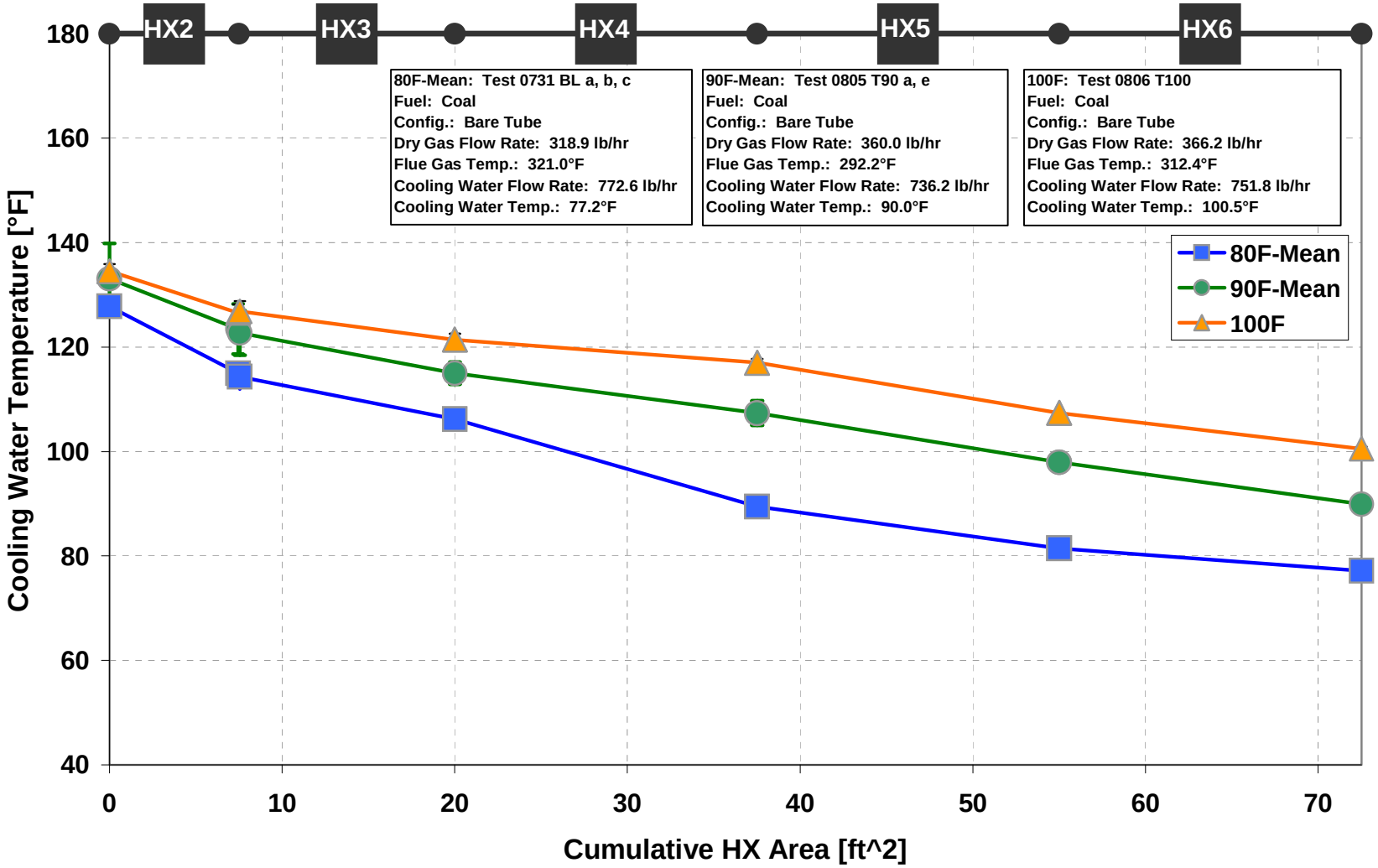
CAE
ACE
ardware


Flue Gas
Inlet
Flue Gas
Outlet
Exhaust
Duct
Fan
Cooling
Water Outlet
Cooling
Water Inlet
HX 1
HX 2
HX 3
HX 4
HX 5
HX 6
Support Frame

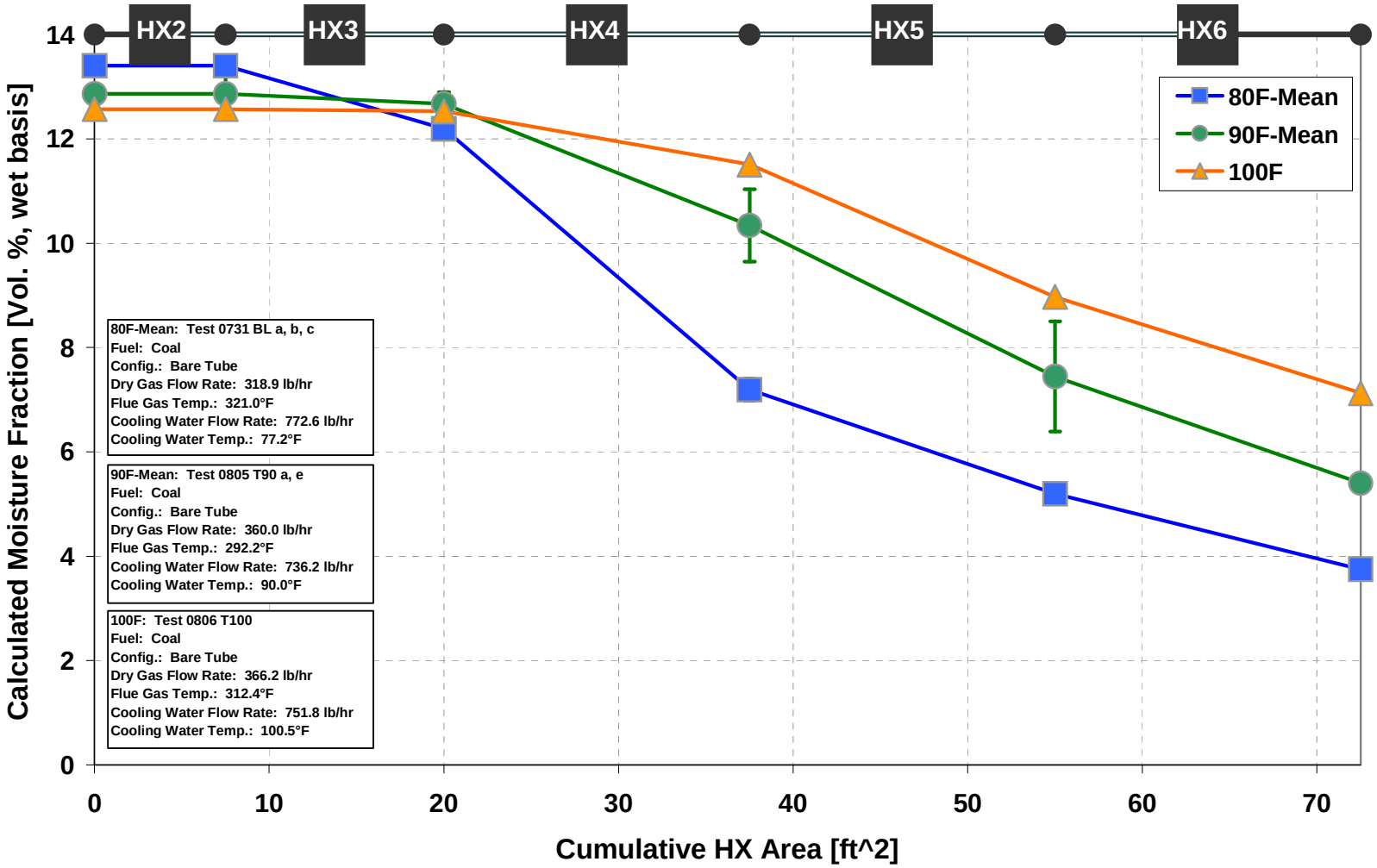
AXIAL VARIATIONS OF FLUE GAS TEMPERATURE



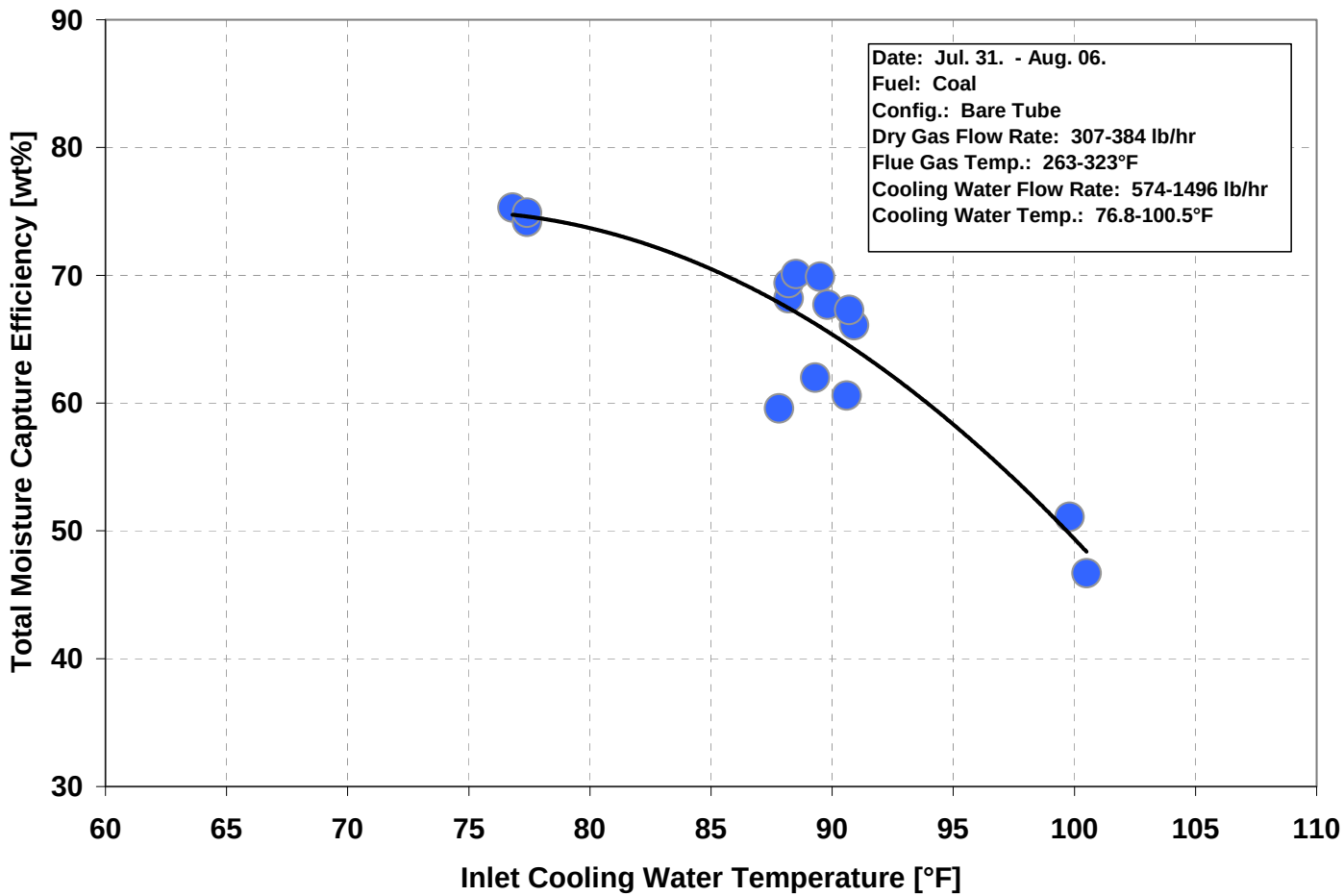
AXIAL VARIATION OF COOLING WATER TEMPERATURE



AXIAL VARIATIONS OF FLUE GAS MOISTURE CONCENTRATION



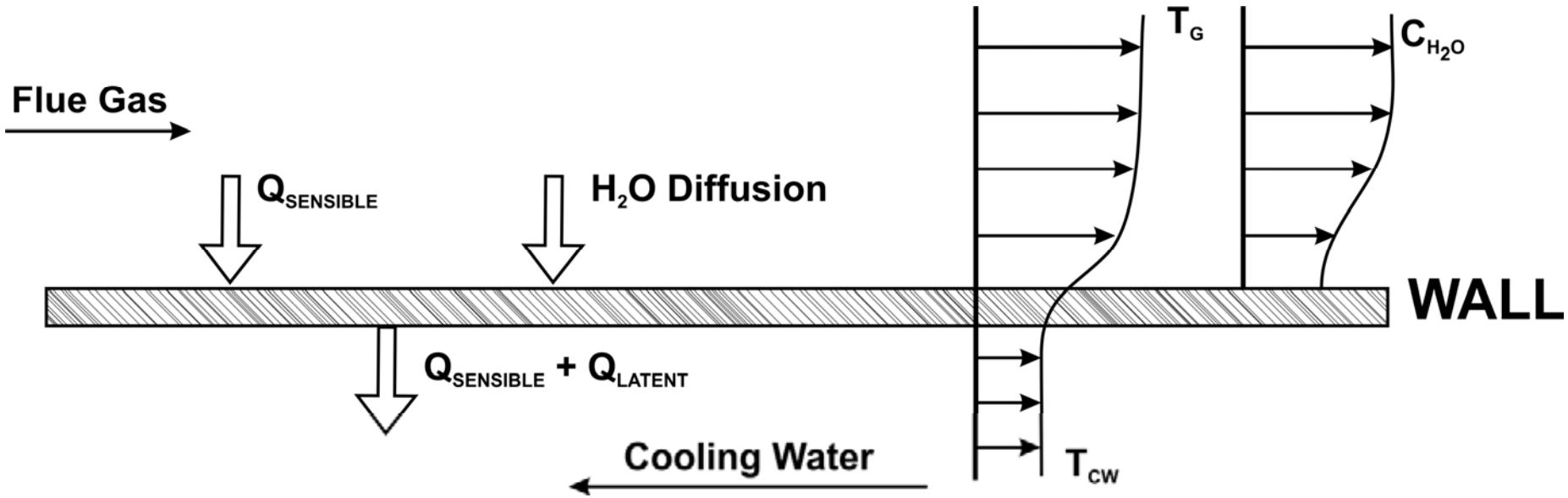
MOISTURE CAPTURE EFFICIENCY VS INLET COOLING WATER TEMPERATURE



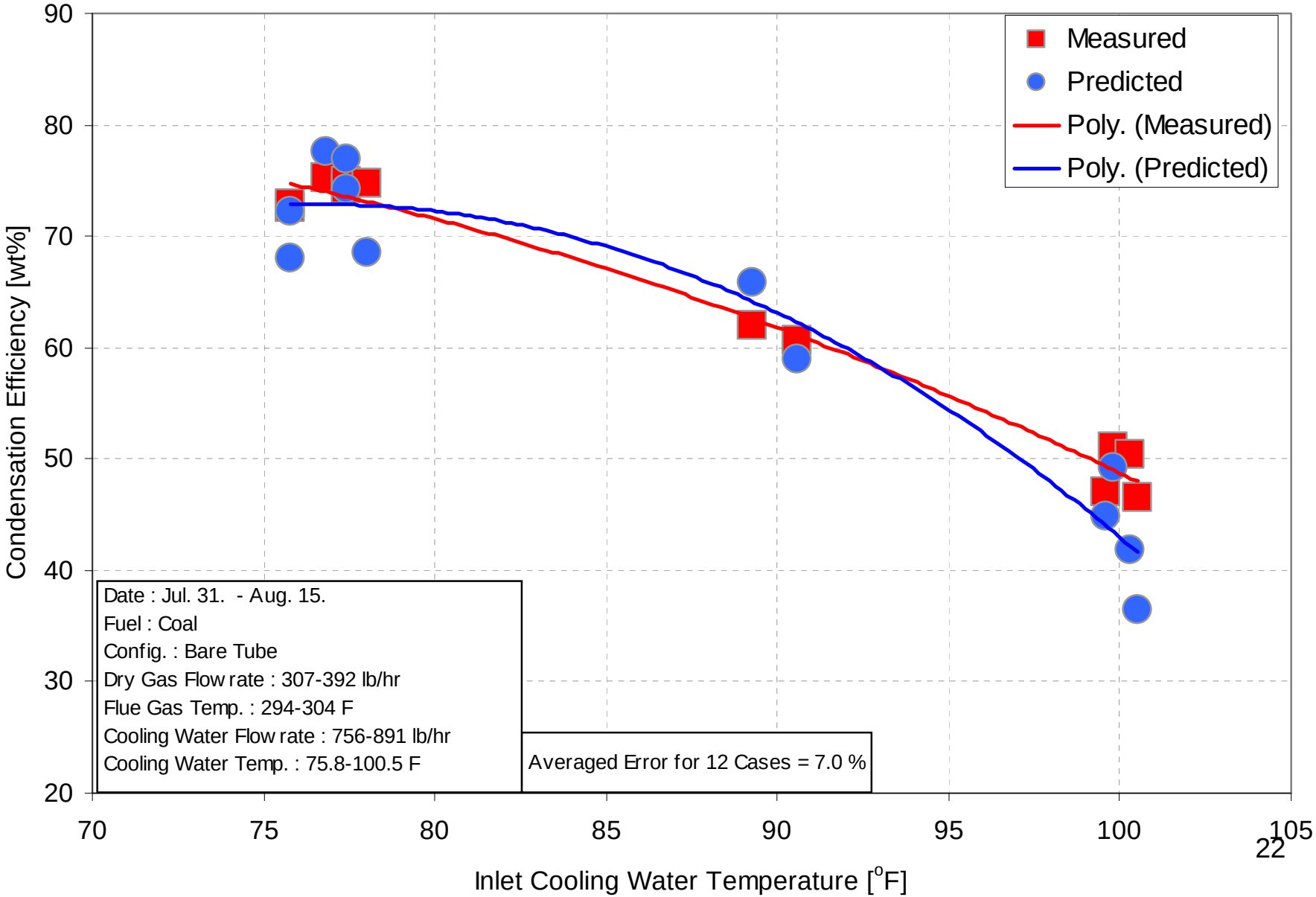
COMPARISONS BETWEEN

PILOT- SCALE WATER CONDENSATION DATA

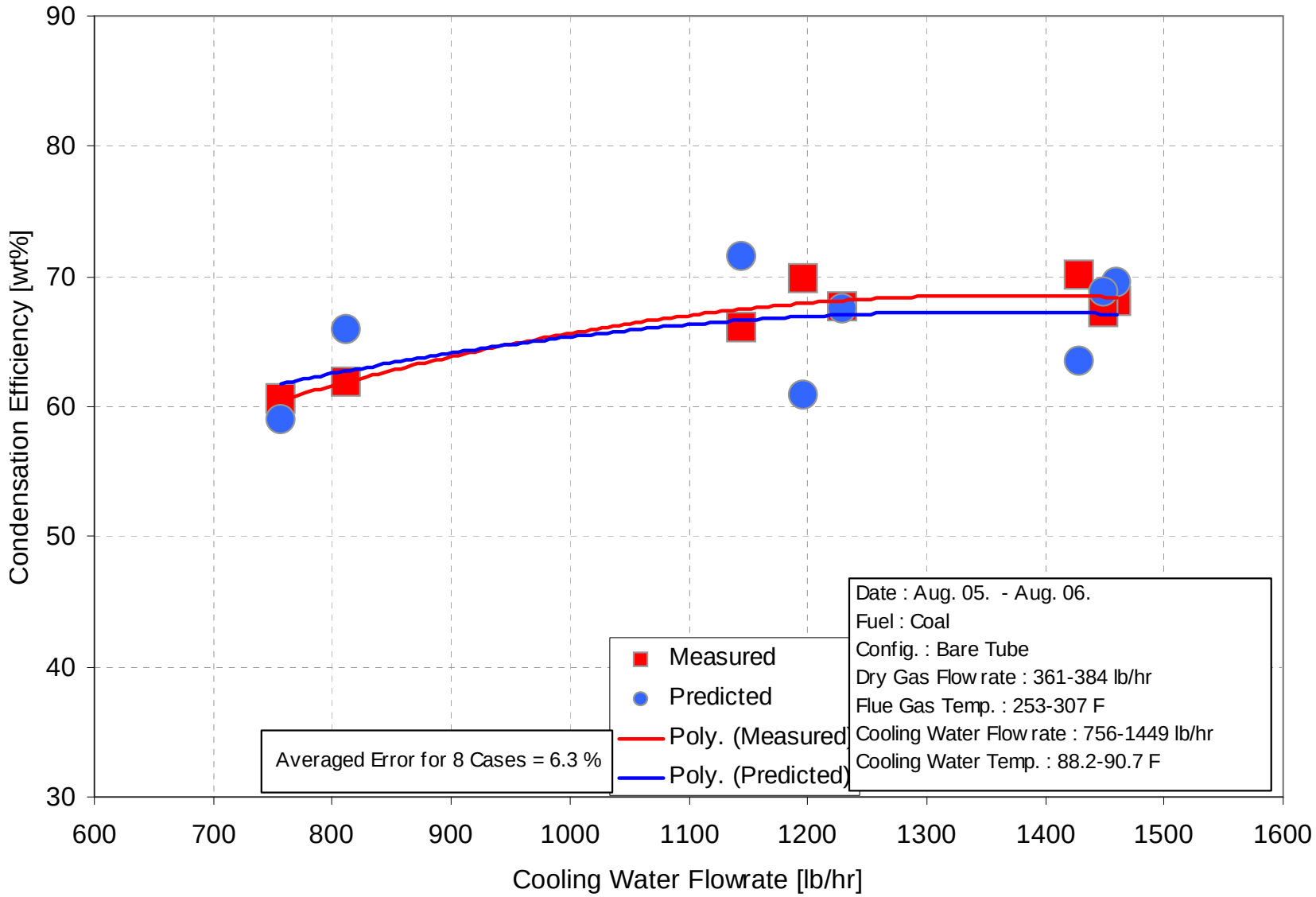
AND HEAT AND MASS TRANSFER MODEL


Flue Gas
$Q_{SENSIBLE}$
H_2O Diffusion
T_G
C_{H_2O}
WALL
$Q_{SENSIBLE} + Q_{LATENT}$
Cooling Water
T_{CW}

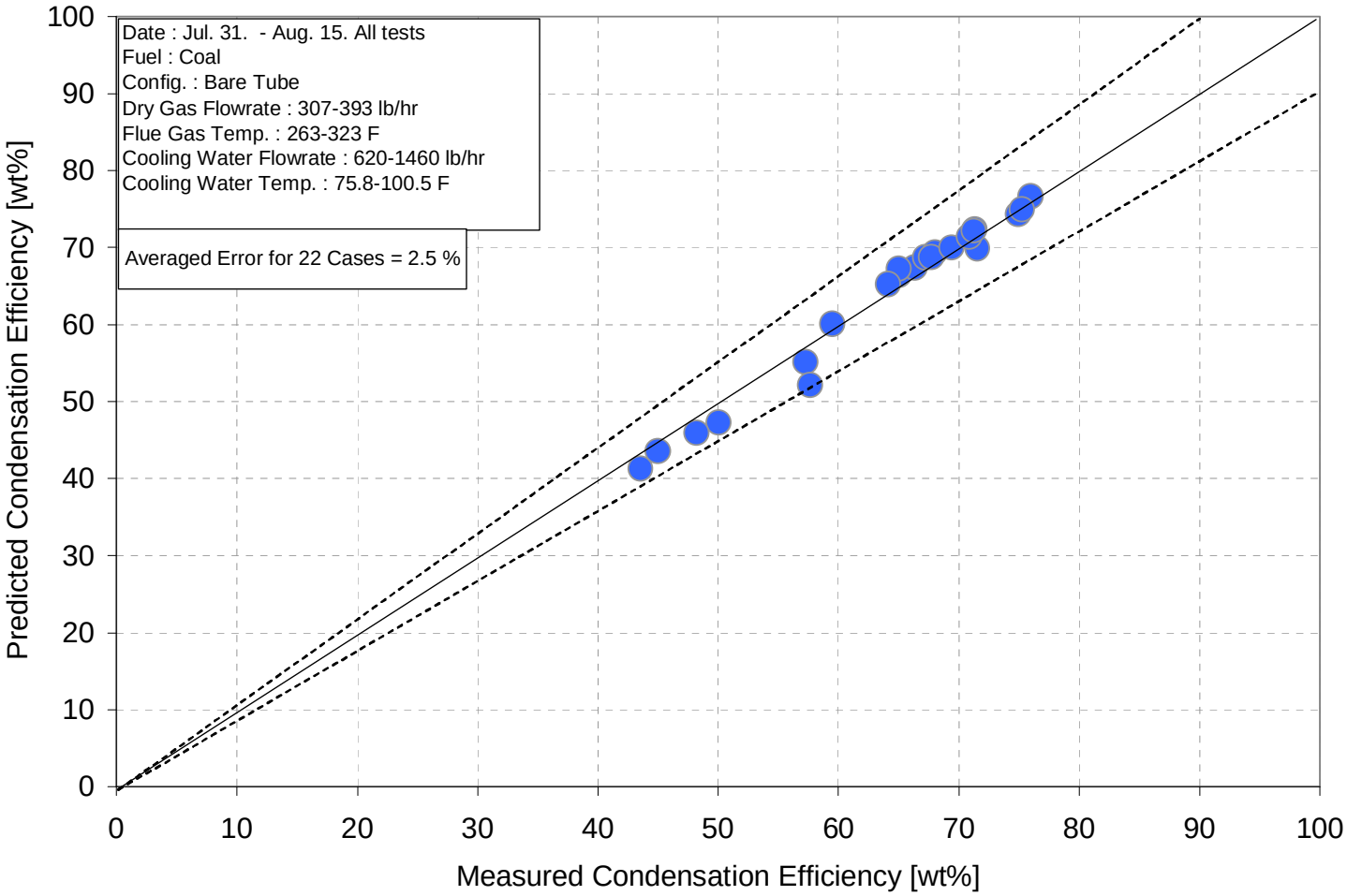
EFFECT OF INLET COOLING WATER TEMPERATURE



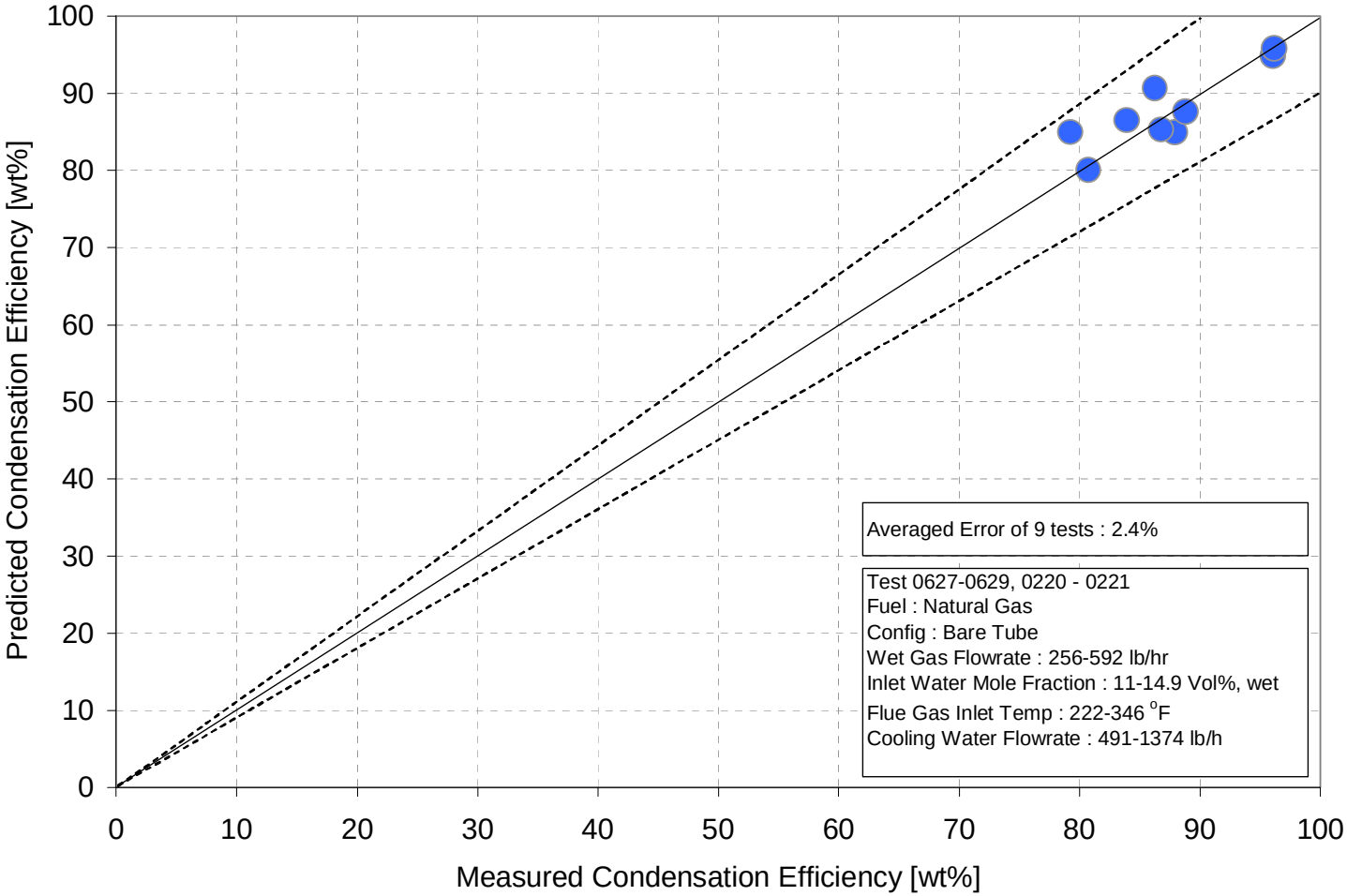
EFFECT OF COOLING WATER FLOW RATE



COAL DATA


Date : Jul. 31. - Aug. 15. All tests
Fuel : Coal
Config. : Bare Tube
Dry Gas Flowrate : 307-393 lb/hr
Flue Gas Temp. : 263-323 F
Cooling Water Flowrate : 620-1460 lb/hr
Cooling Water Temp. : 75.8-100.5 F
Averaged Error for 22 Cases = 2.5 %
Predicted Condensation Efficiency [wt%]
Measured Condensation Efficiency [wt%]
0
10
20
30
40
50
60
70
80
90
100

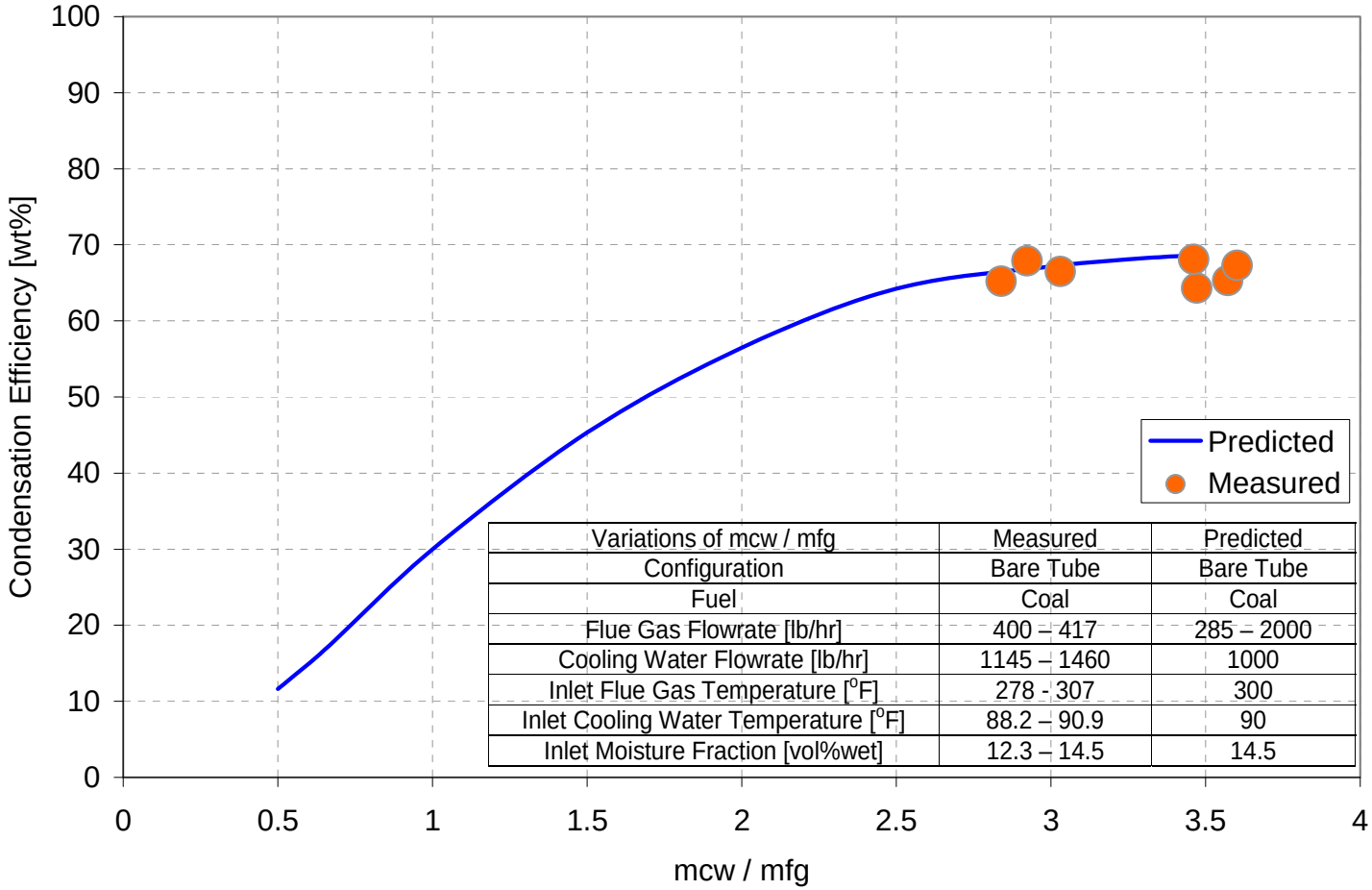
NATURAL GAS DATA



WATER CAPTURE EFFICIENCY

- **Results suggest that water capture efficiencies greater than 70 percent will be possible for some process conditions.**
- **However, for other combinations of process conditions, much lower water capture efficiencies are to be expected.**

EFFECT OF LOW COOLANT FLOW RATE ON CAPTURE EFFICIENCY

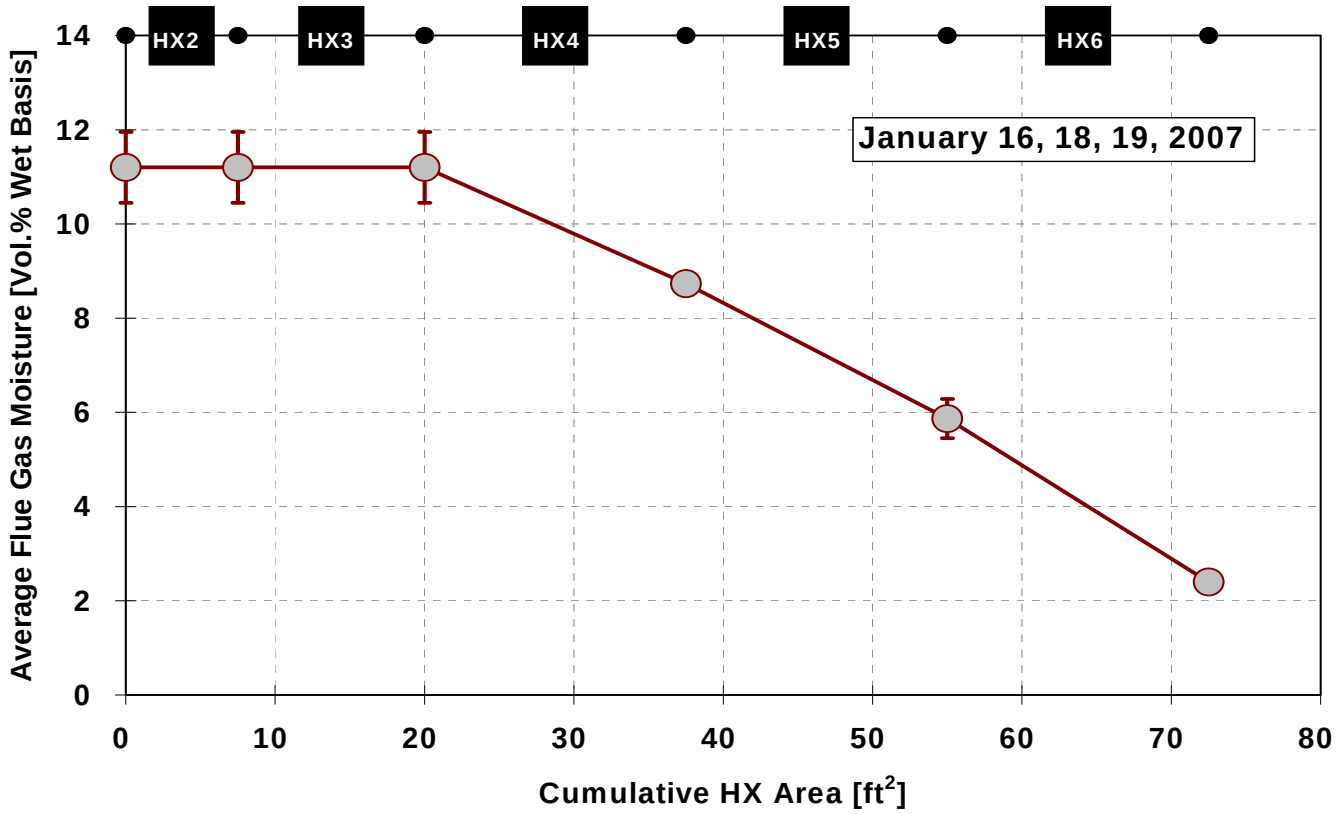


Variations of mcw / mfg	Measured	Predicted
Configuration	Bare Tube	Bare Tube
Fuel	Coal	Coal
Flue Gas Flowrate [lb/hr]	400 – 417	285 – 2000
Cooling Water Flowrate [lb/hr]	1145 – 1460	1000
Inlet Flue Gas Temperature [^{o}F]	278 - 307	300
Inlet Cooling Water Temperature [^{o}F]	88.2 – 90.9	90
Inlet Moisture Fraction [vol%wet]	12.3 – 14.5	14.5

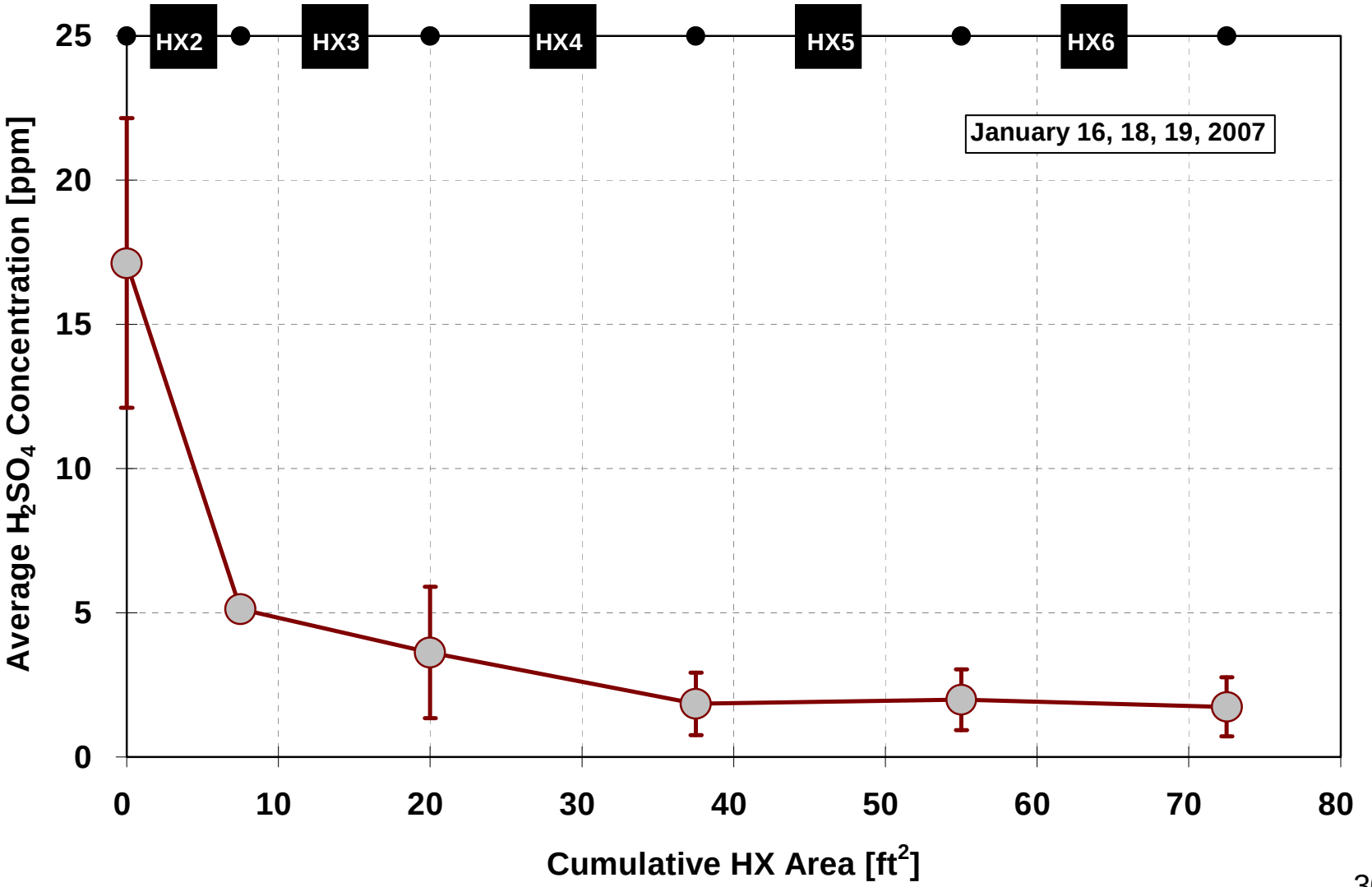
SULFURIC ACID MEASUREMENTS

- **Flue gas--Controlled Condensation Method**
- **Condensed water-- Laboratory analysis of acid concentrations**

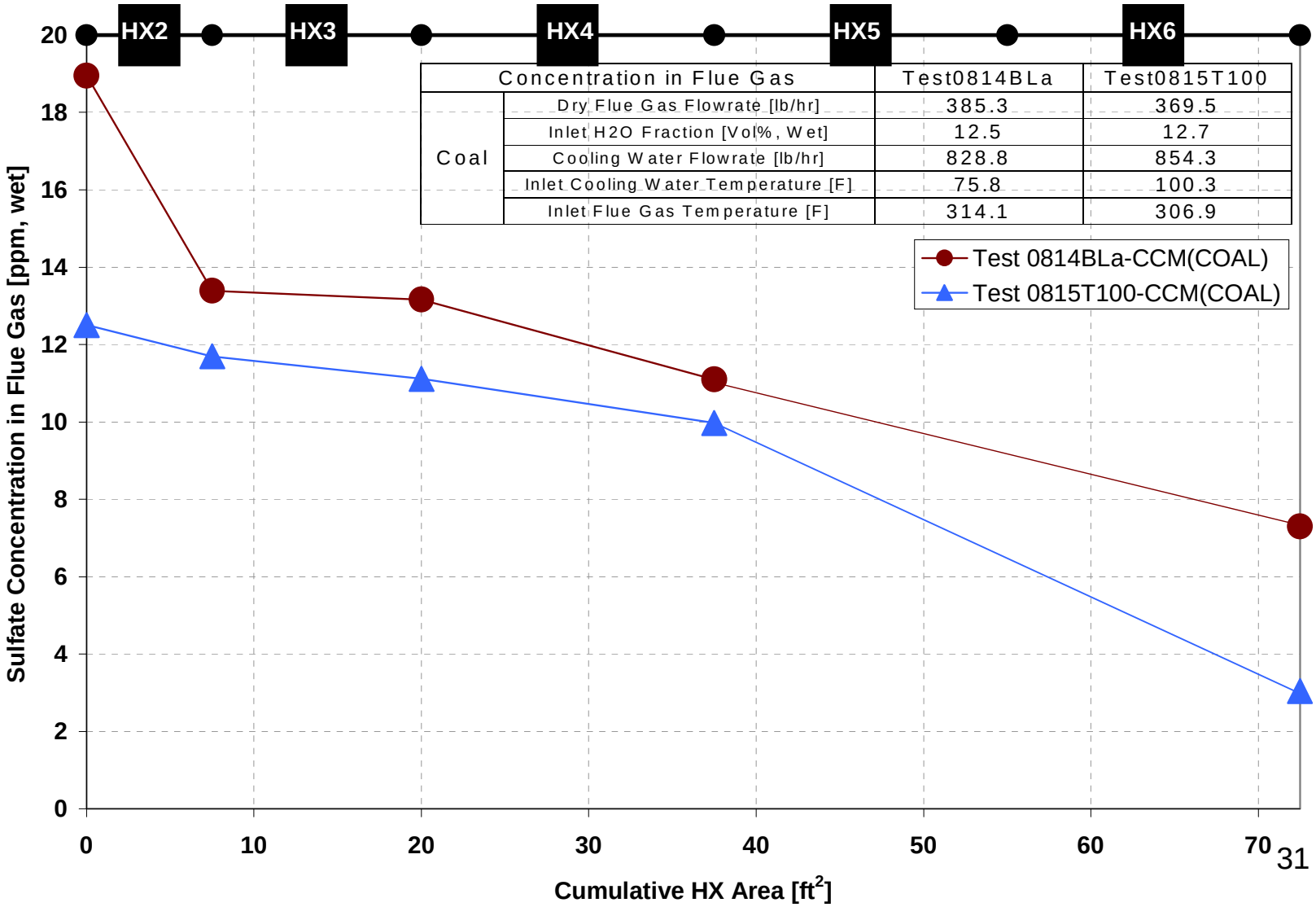
OIL DATA….WATER VAPOR CONDENSATION PATTERN



OIL DATA…H2SO4 CONDENSATION PATTERN



COAL DATA…H2SO4 CONDENSATION PATTERN



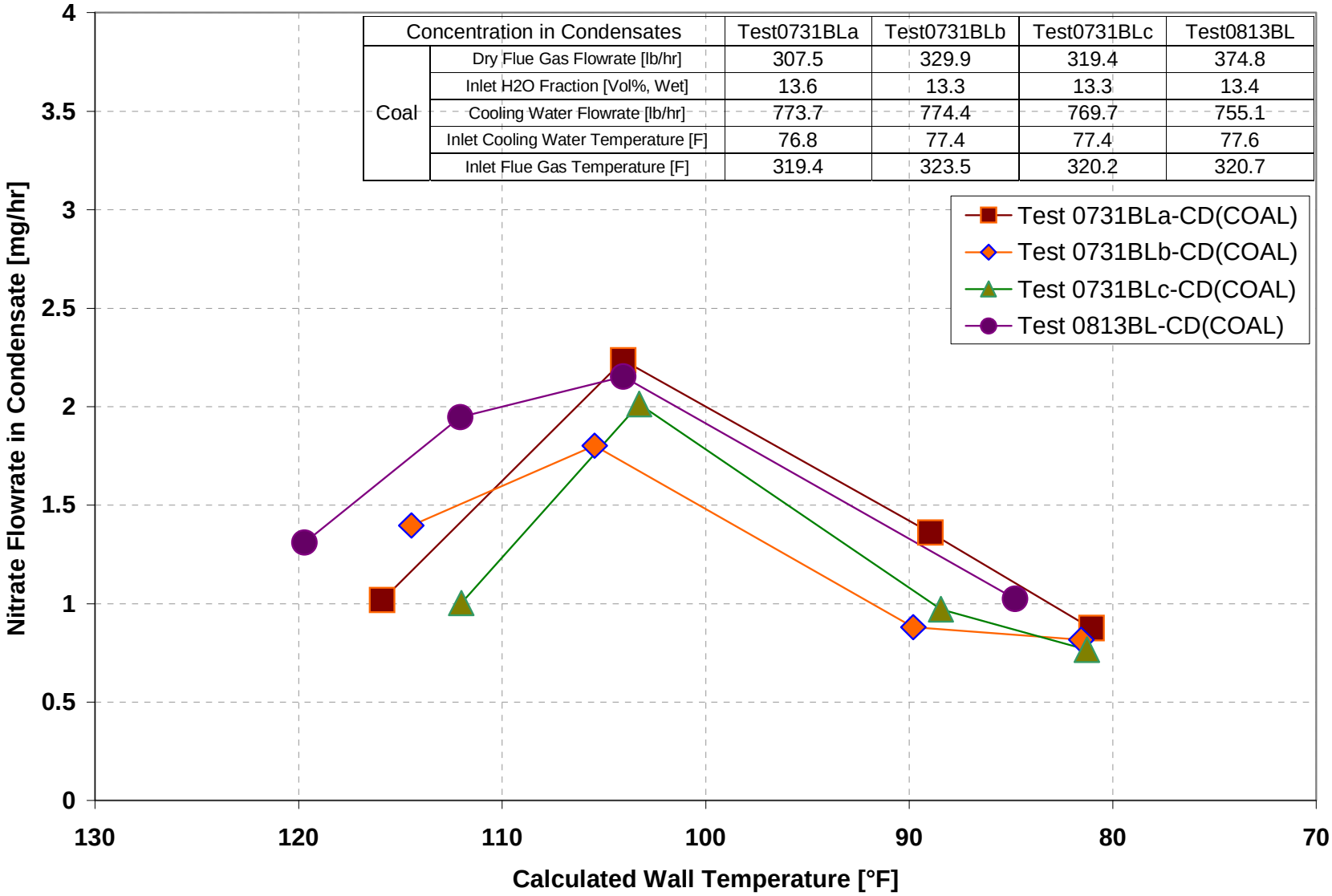
Concentration in Flue Gas		Test0814BLa	Test0815T100
Coal	Dry Flue Gas Flowrate [lb/hr]	385.3	369.5
	Inlet H2O Fraction [Vol%, Wet]	12.5	12.7
	Cooling Water Flowrate [lb/hr]	828.8	854.3
	Inlet Cooling Water Temperature [F]	75.8	100.3
	Inlet Flue Gas Temperature [F]	314.1	306.9

Flue gas from coal and oil had:

- **Similar inlet vapor H_2SO_4 concentrations**
- **Similar H_2SO_4 concentrations in condensed water**
- **Radically different flue gas H_2SO_4 profiles**
- **The reasons for these differences are under investigation.**

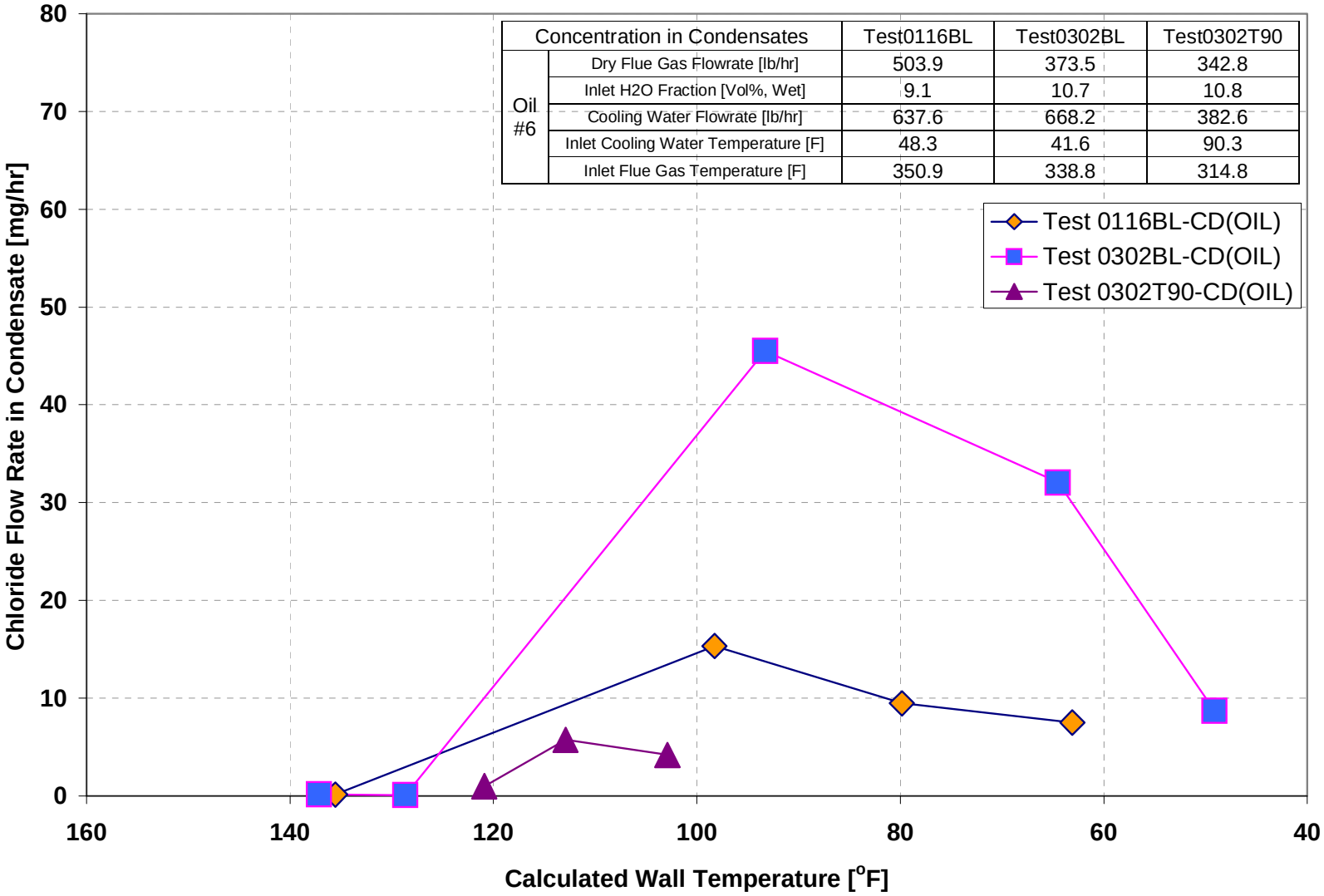
Hydrochloric and nitric acids condense in same temperature range as water vapor

NITRIC ACID



Concentration in Condensates		Test0731BLa	Test0731BLb	Test0731BLc	Test0813BL
Coal	Dry Flue Gas Flowrate [lb/hr]	307.5	329.9	319.4	374.8
	Inlet H2O Fraction [Vol%, Wet]	13.6	13.3	13.3	13.4
	Cooling Water Flowrate [lb/hr]	773.7	774.4	769.7	755.1
	Inlet Cooling Water Temperature [F]	76.8	77.4	77.4	77.6
	Inlet Flue Gas Temperature [F]	319.4	323.5	320.2	320.7

HYDROCHLORIC ACID



Concentration in Condensates		Test0116BL	Test0302BL	Test0302T90
Oil #6	Dry Flue Gas Flowrate [lb/hr]	503.9	373.5	342.8
	Inlet H2O Fraction [Vol%, Wet]	9.1	10.7	10.8
	Cooling Water Flowrate [lb/hr]	637.6	668.2	382.6
	Inlet Cooling Water Temperature [F]	48.3	41.6	90.3
	Inlet Flue Gas Temperature [F]	350.9	338.8	314.8

FLUE GAS MERCURY MEASUREMENTS

Used sorbent traps at flue gas inlet and at exit of condensing heat exchanger system.

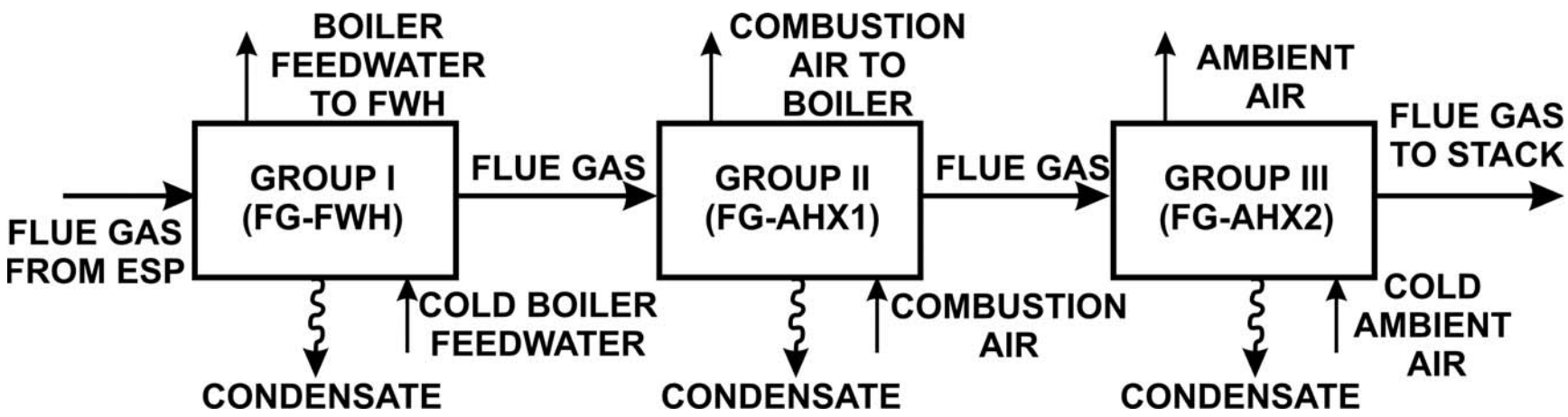
Vapor phase mercury was reduced by 60 percent.

ENHANCING WATER CAPTURE EFFICIENCY AND UNIT HEAT RATE

Analyses performed to determine:

- **> Maximum recoverable flue gas water vapor**
- **> Maximum unit heat rate improvement**

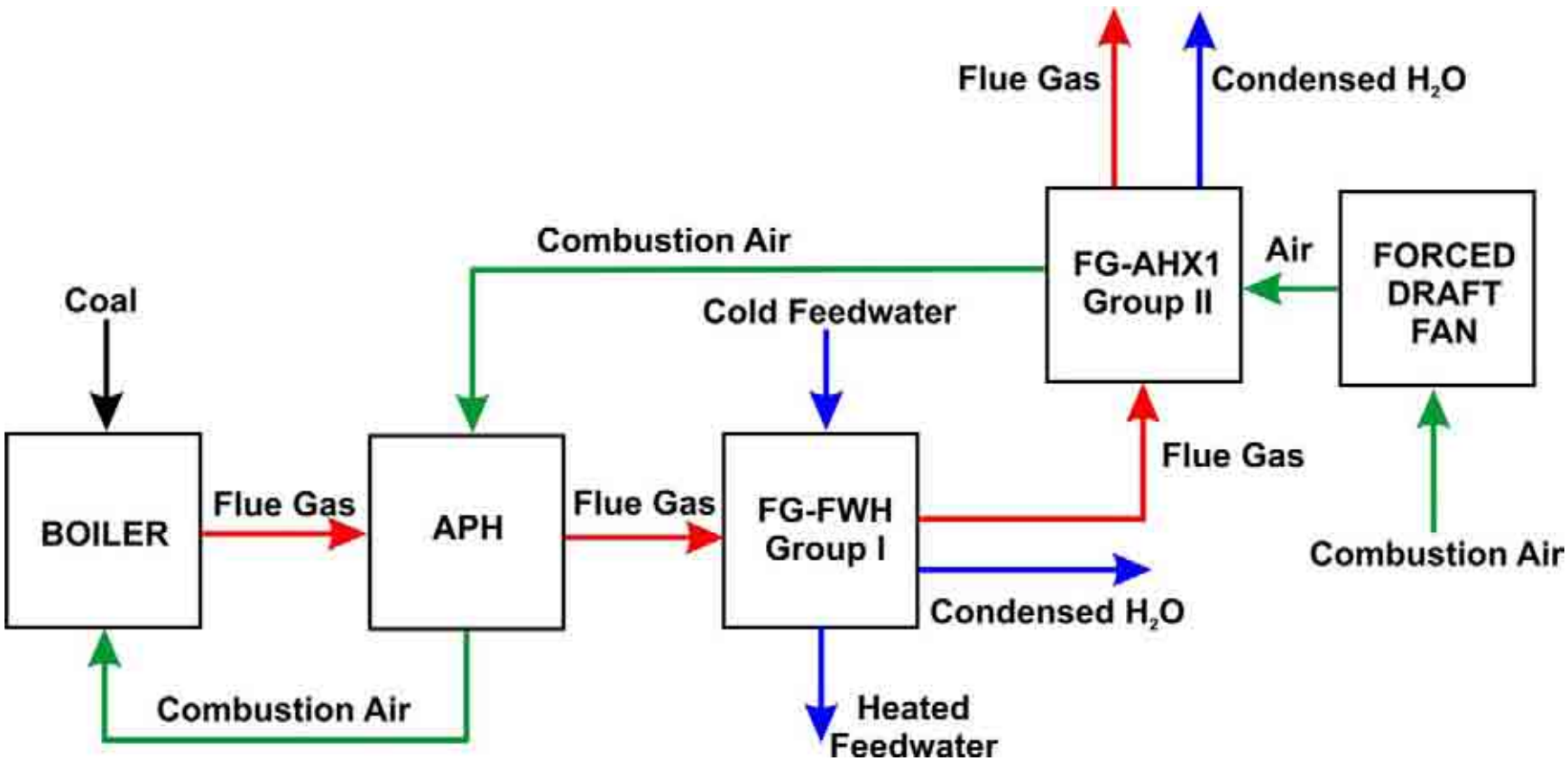
SEPARATE HEAT EXCHANGERS INTO THREE GROUPS

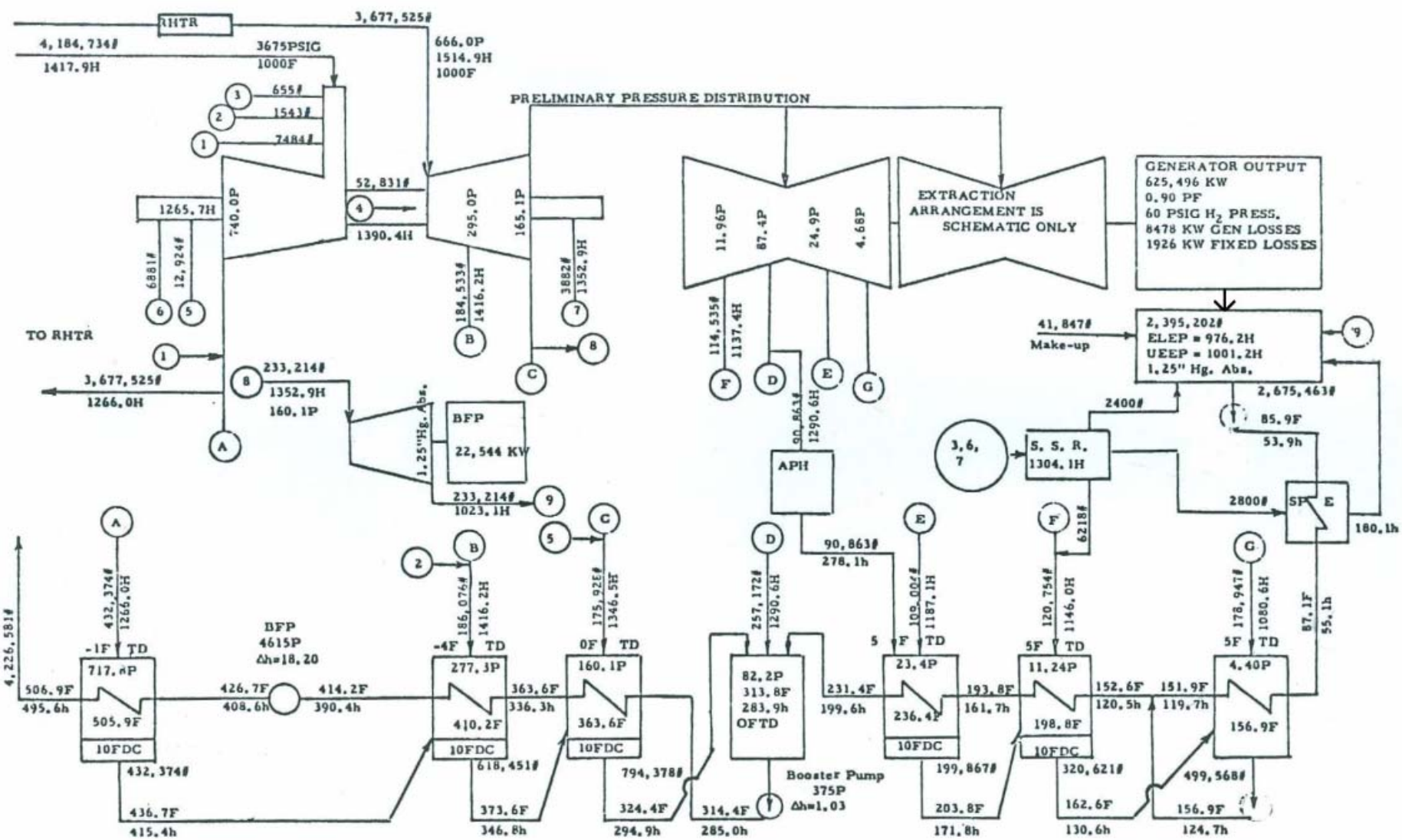


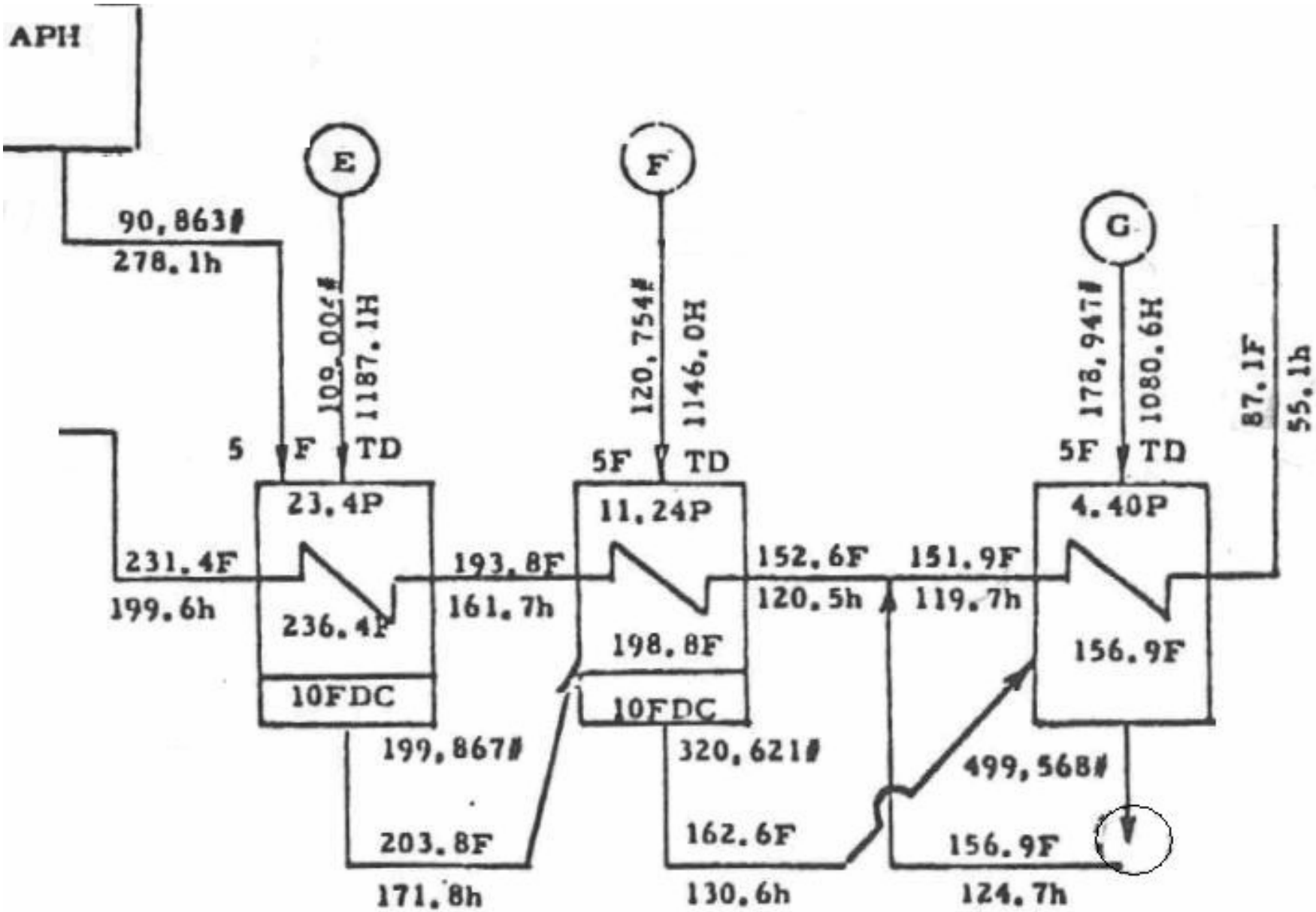
Descriptions of HX Groups

Group	Heat Sink	Water Capture	Heat Rate Decrease
I	Boiler Feedwater	Yes	Yes
II	Combustion Air	Yes	Yes
III	Ambient Air	Yes	No

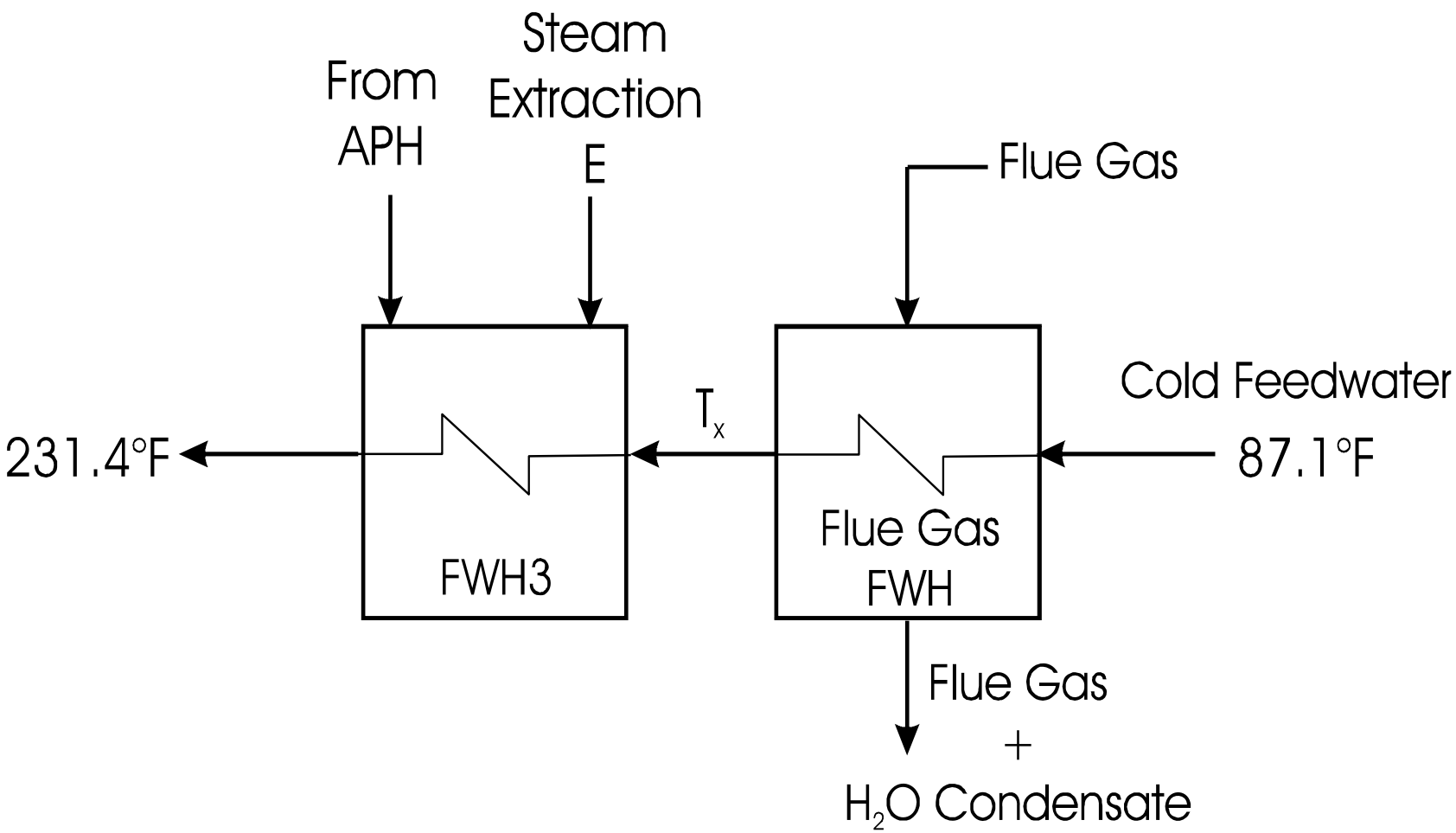
COMBINED ANALYSES OF BOILER & TURBINE CYCLE




RHTR
3,677,525#
4,184,734#
1417.9H
3675PSIG
1000F
666.0P
1514.9H
1000F
PRELIMINARY PRESSURE DISTRIBUTION
655#
1543#
7484#
1265.7H
740.0P
52,831#
1390.4H
295.0P
165.1P
6881#
12,924#
184,533#
1416.2H
3882#
1352.9H
11.96P
87.4P
24.9P
4.68P
EXTRACTION ARRANGEMENT IS SCHEMATIC ONLY
GENERATOR OUTPUT
625,496 KW
0.90 PF
60 PSIG H2 PRESS.
8478 KW GEN LOSSES
1926 KW FIXED LOSSES
TO RHTR
3,677,525#
1266.0H
233,214#
1352.9H
160.1P
114,535#
1137.4H
41,847#
Make-up
2,395,202#
ELEP = 976.2H
UEEP = 1001.2H
1.25" Hg. Abs.
2,675,463#
2400#
85.9F
53.9h
1.25"Hg. Abs.
BFP
22,544 KW
90,863#
1290.6H
APH
3,6,
7
S. S. R.
1304.1H
233,214#
1023.1H
2800#
SP
E
180.1h
6218#
90,863#
278.1h
4,226,581#
432,374#
1266.0H
186,076#
1416.2H
175,925#
1346.5H
257,172#
1290.6H
109,007#
1187.1H
120,754#
1146.0H
178,947#
1080.6H
87.1F
55.1h
BFP
4615P
Δh=18.20
-1F TD
717.8P
506.9F
495.6h
505.9F
10FDC
426.7F
408.6h
414.2F
390.4h
-4F TD
277.3P
410.2F
363.6F
336.3h
10FDC
0F TD
160.1P
363.6F
10FDC
82.2P
313.8F
283.9h
OFTD
231.4F
199.6h
5 F TD
23.4P
236.4F
193.8F
161.7h
10FDC
5F TD
11.24P
198.8F
152.6F
120.5h
10FDC
5F TD
4.40P
156.9F
151.9F
119.7h
432,374#
436.7F
415.4h
618,451#
373.6F
346.8h
794,378#
324.4F
294.9h
314.4F
285.0h
Booster Pump
375P
Δh=1.03
199,867#
203.8F
171.8h
320,621#
162.6F
130.6h
499,568#
156.9F
124.7h


APH
E
F
G
90,863#
278.1h
109,005#
1187.1H
120,754#
1146.0H
178,947#
1080.6H
87.1F
55.1h
5 F TD
5F TD
5F TD
23.4P
11.24P
4.40P
231.4F
199.6h
236.4F
193.8F
161.7h
152.6F
120.5h
151.9F
119.7h
198.8F
156.9F
10FDC
10FDC
199,867#
203.8F
171.8h
320,621#
162.6F
130.6h
499,568#
156.9F
124.7h

Captured Sensible and Latent Heat Preheat Cycle Feedwater



- **Use captured sensible and latent heat to preheat cycle feedwater**
- **CHX reduces need for steam turbine extractions, increases MW output, and improves heat rate**
- **Preheating combustion air improves boiler efficiency**

GROUP I & II RESULTS

- **Flue gas water capture efficiency and heat rate depend on coal moisture content, inlet feedwater temperature, HX effectiveness, and ambient air temperature**
- **Heat rate reduction:**

  2.6 to 3.8 % (winter)

  1.8 to 3.1 % (summer)

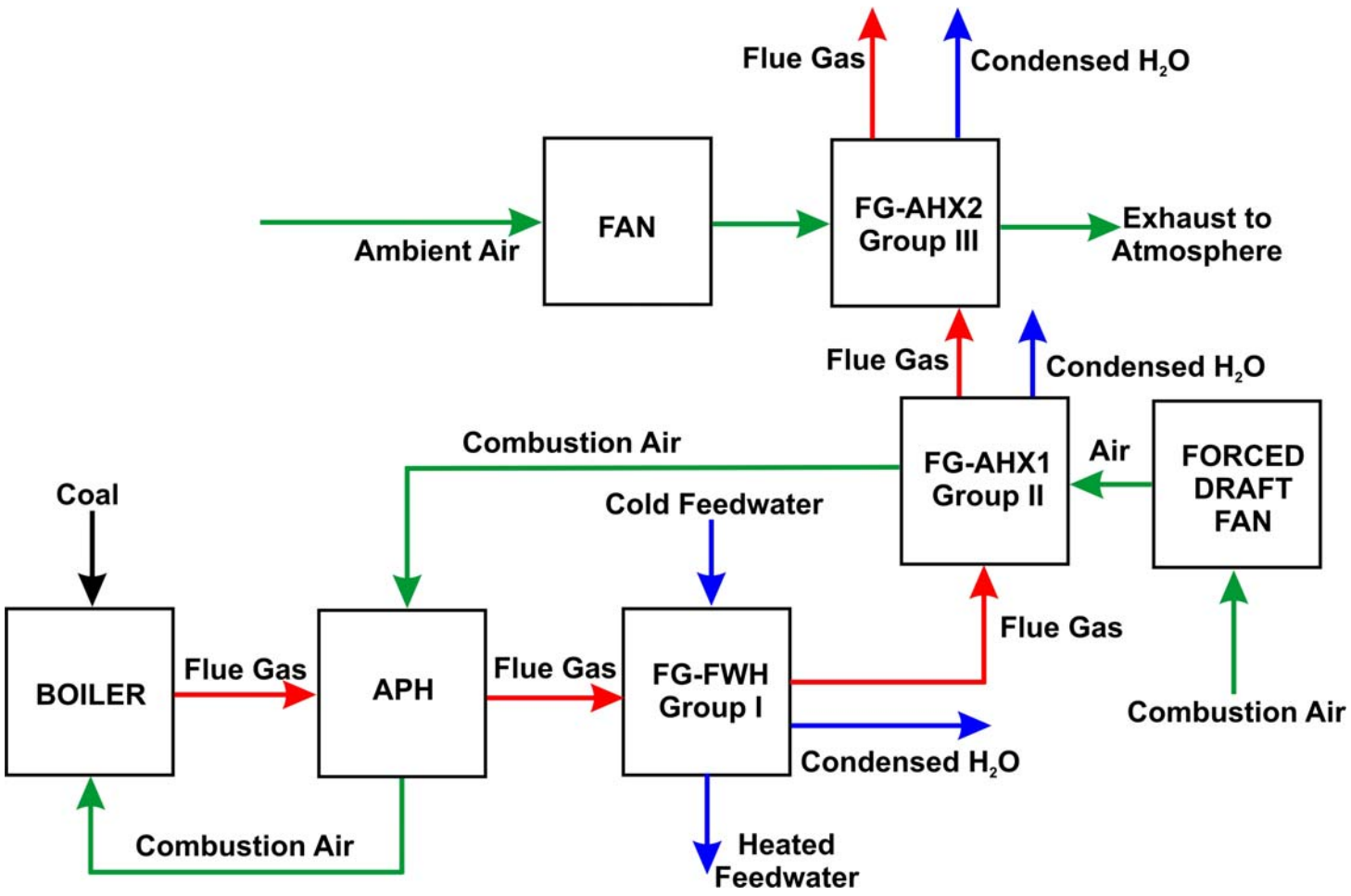
GROUP I & II RESULTS (continued)

- **Water capture efficiency:**

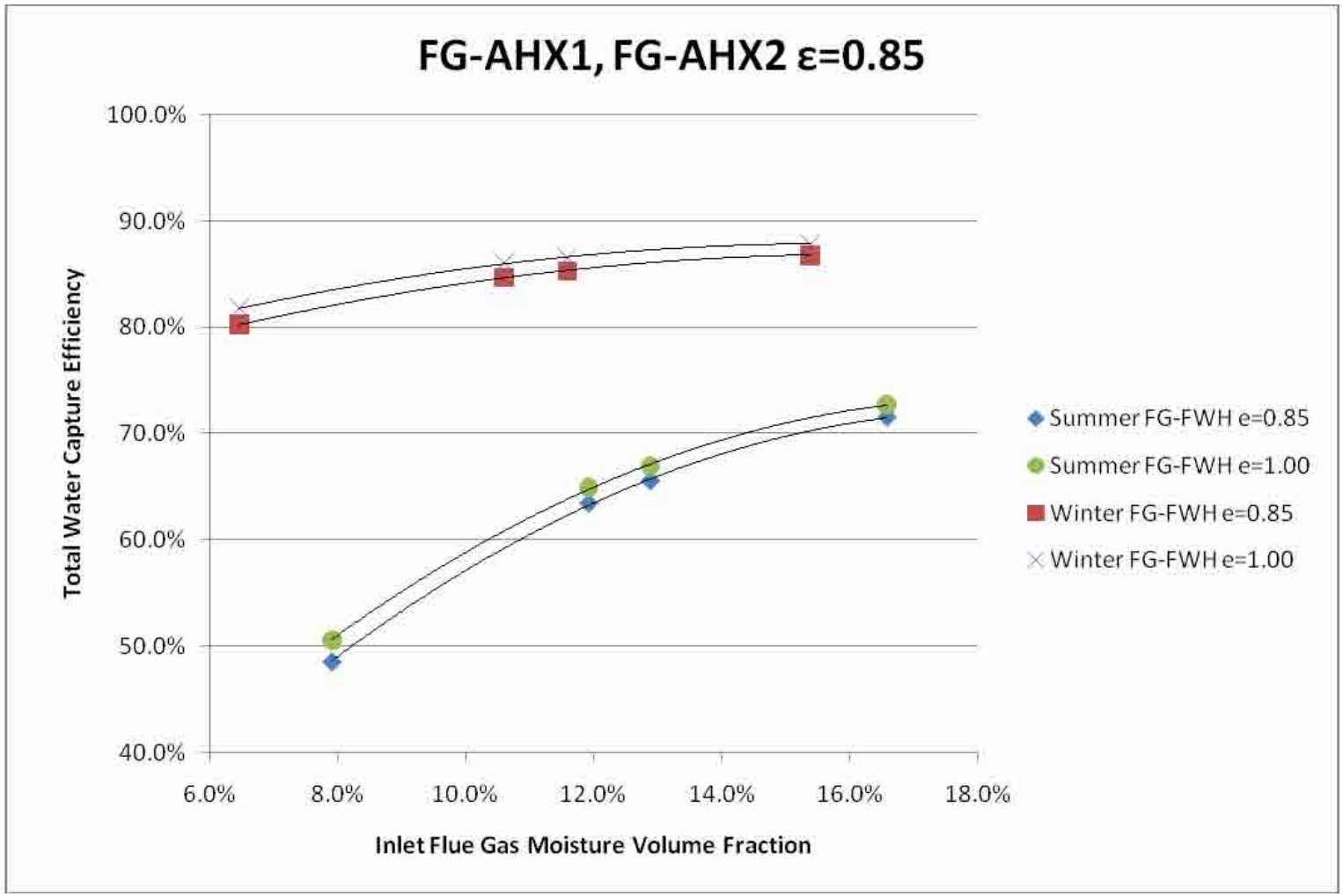
  21 to 34 % (winter)

  10 to 26 % (summer)

COMBINED ANALYSIS OF GROUPS I, II, & III



TOTAL WATER CAPTURE EFFICIENCY



INTERPRETATION OF RESULTS

- **Flue gas water capture efficiency increases greatly with addition of Group III HX, and it is strong function of coal moisture content and ambient air temperature.**
- **Water capture efficiency:**

  50 to 72 % in summer (77 F air)

  81 to 88 % in winter (33 F air)

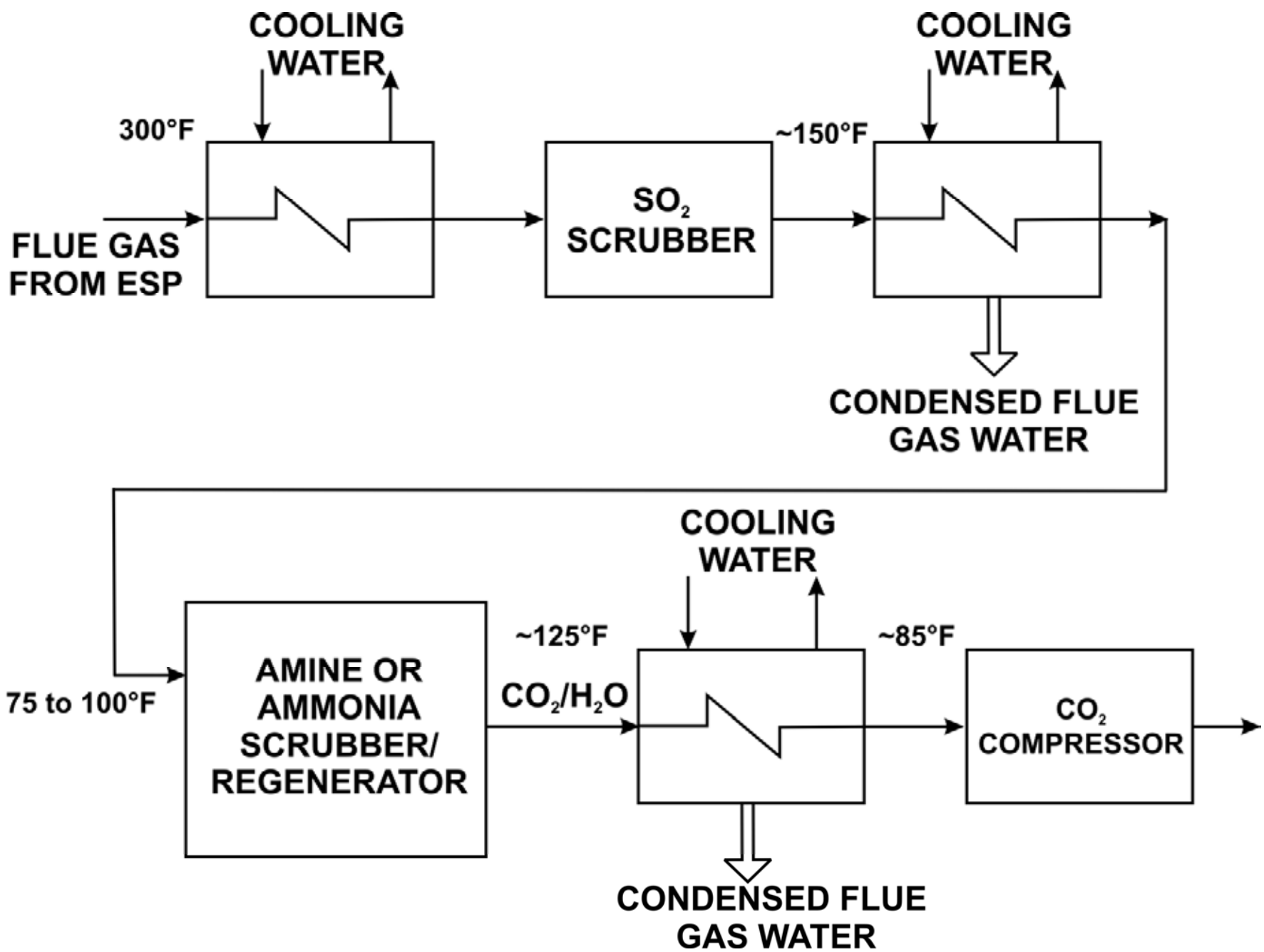
TOTAL MOISTURE RECOVERY AS PERCENT OF COOLING TOWER MAKEUP WATER

	Percent
Low Moisture Bituminous	6.4 to 8.5
PRB	14.1 to 16.5
High Moisture Lignite	22.2 to 24.8

POTENTIAL APPLICATIONS IN CARBON CAPTURE SYSTEMS

- **Reduce flue gas temperature, moisture content and acid concentrations ahead of amine or ammonia scrubbers**

- **Reduce moisture content of CO2/H2O mixture entering CO2 compressor**


COOLING WATER
300°F
FLUE GAS FROM ESP
SO2 SCRUBBER
~150°F
COOLING WATER
CONDENSED FLUE GAS WATER
COOLING WATER
75 to 100°F
AMINE OR AMMONIA SCRUBBER/ REGENERATOR
~125°F
CO2/H2O
~85°F
CO2 COMPRESSOR
CONDENSED FLUE GAS WATER

WHAT'S NEXT?

- **Project DE-NT0005648**
- **Recovery of Water from Boiler Flue Gas Using Condensing Heat Exchangers**
- **Funds also provided by Southern Company and Lehigh University**

TASKS

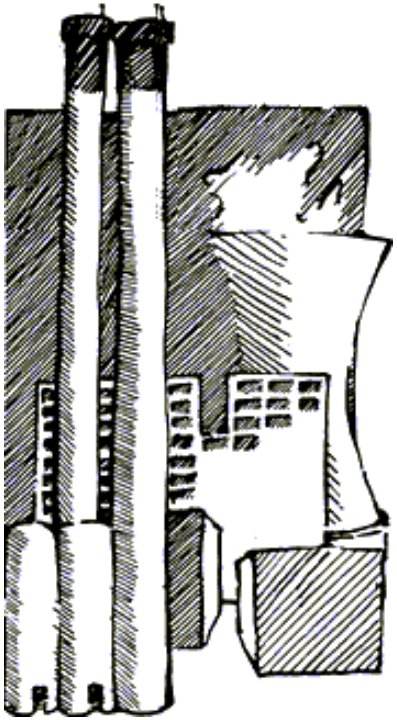
- **Develop techniques to enhance H_2SO_4 capture at high temperature end of CHX**
- **Perform additional field tests for H_2O, H_2SO_4 , HCl, HNO_3 and mercury capture.**
  - **> Unit with high sulfur coal and FGD**
  - **> Unscrubbed unit firing PRB**
- **Determine corrosion resistance of available corrosion resistant materials**
  - **> Laboratory corrosion tests**

WHAT'S NEXT (cont.)

- **Scale up heat exchanger design for commercial-size units**
- **Estimate capital costs**
- **Determine condensed water treatment needs**

POTENTIAL BENEFITS

- **Water recovery**
- **Heat rate improvement**
- **Acid capture**
- **Hg removal**
- **Technology useful in CO_2 capture systems**



THANK YOU!!!

QUESTIONS?