Thermal Integration of Closed, Indirect Supercritical CO_2 Brayton Power Cycles with Oxy-Fired Heaters

DE-FE0025959

NETL CO_2 Capture Technology Project Review Meeting

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Project Overview

- Project Objectives
  - Design and cost coal power plants with CO_2 capture and storage (CCS) that combine oxy-combustion with an indirect-fired, supercritical CO_2 (sCO_2) power cycle and compare the benefits against conventional steam-Rankine cycle coal plants with CCS
- Funding
  - Federal Share: $1,838,062; Non-Federal Share: $459,516
- Project Performance Dates
  - 10/1/2015–9/30/2017 (request for 3/31/2018)
- Project Participants
  - **Prime:** Electric Power Research Institute, Inc. (EPRI)
  - **Subs:** Babcock and Wilcox Company (B&W), Doosan ATS America, LLC (Doosan), Dresser-Rand (Siemens), Echogen Power Systems, LLC (EPS); GE Power, Inc., (GE), and Howden Group Ltd. (Howden)

Technology Background

sCO_2 Power Cycle Deployments

Developer	Location	Funding	Size, net MW	Configuration	First Fire
Echogen Power Systems	U.S. (OH)	Private	0.25	Indirect, low temperature	2010
Sandia National Laboratories	U.S. (NM)	Public	0.2	Indirect, low temperature	2011
Bettis Atomic Laboratories	U.S. (PA)	Public	0.15	Indirect, low temperature	2012
Echogen Power Systems	U.S. (NY)	Private	7.3	Combustion turbine bottoming cycle, low temperature	2013
Southwest Research Institute	U.S. (TX)	Public	10	Indirect, high temperature (partial flow)	2017
NET Power	U.S. (TX)	Private	20	Direct, oxy-natural gas, high temperature	2017
STEP Program, Gas Technology Institute	U.S. (TX)	Public	10	Indirect, high temperature	2020

sCO_2 Power Cycle Technology Gaps

MIND THE GAP

- **Big Picture**
  - Overall sCO_2 power cycle design that maximizes efficiency and minimizes cost (dependent on thermal resource used)
  - Field confirmation of sCO_2 power cycle viability
  - Better understanding of operations (e.g., dynamic operation)
- **Can Durable Components Be Built at Acceptable Cost?**
  - Fired heater (interface with thermal resource): pressure drop, corrosion, and high heat fluxes
  - Recuperators (higher duty than fired heater): are printed circuit heat exchangers the answer?
  - sCO_2 turbines: suitable materials for high-turbine inlet temperatures

Fired heater design identified as a major gap; focus of this project

Technical Approach/Project Scope

Task Descriptions

- **Task 1 – Project Management and Planning**
- **Task 2 – Develop Power Block Design Basis and Baseline**
  - Develop design basis and identify baselines for six cases that vary:
    - **Net Power Out:** 550 MWe (oxy-fired) and 90 MWe (air-fired)
    - **Oxy-combustion Technologies:** atmospheric pressure oxy-pulverized coal (PC) and chemical looping combustion (CLC)
    - **Turbine Inlet Temperatures:** 593°C and 730°C
- **Task 3 – Optimize Thermal Integration between Fired Heater and Power Cycle**
  - Develop flow sheets integrating fired heater and sCO_2 power cycle to maximize efficiency
- **Task 4 – Conduct Cost Estimates**
  - Conduct AACE Class-5 cost estimates for each case and compare to base cases
- **Task 5 – Process Design and Cost Review**
  - Review cost estimates to identify high-cost items and assess the impact on plant performance and costs of using a lower-cost item

Test Cases

Case	Net Power, MWe	Coal	Combustion Technology	Base Case/Test Case Turbine Inlet conditions	Base Case Reference
1	550	PRB	Oxy/PC	Base: 593°C / 24.1 MPa Test: 593°C / 24.1 MPa	1
2	550	PRB	Oxy/PC	Base: 730°C / 27.6 MPa Test: 730°C / 27.6 MPa	1
3	550	Illinois Basin	CLC	Base: 593°C / 24.1 MPa Test: 593°C / 24.1 MPa	2
4	550	Illinois Basin	CLC	Base: 730°C / 27.6 MPa Test: 730°C / 27.6 MPa	2
5	90	PRB	Air/PC	Base: 538°C / 10.6 MPa Test: 593°C / 24.1 MPa	3
6	90	PRB	Air/PC	Base: 538°C / 10.6 MPa Test: 730°C / 27.6 MPa	3

References:

1. *Cost and Performance of Low-Rank Pulverized Coal Oxycombustion Energy Plants: Final Report.* DOE/NETL-401/093010. September 2010.
2. *Alstom's Chemical Looping Combustion Technology with CO_2 Capture for New and Retrofit Coal-Fired Power Plants.* Task 2 Final Report, DOE/NETL Cooperative Agreement No. DE-FE0009484. June 2013.
3. B&W internal project files.

Apples-to-apples comparison to existing base cases

Progress and Current Status of Project

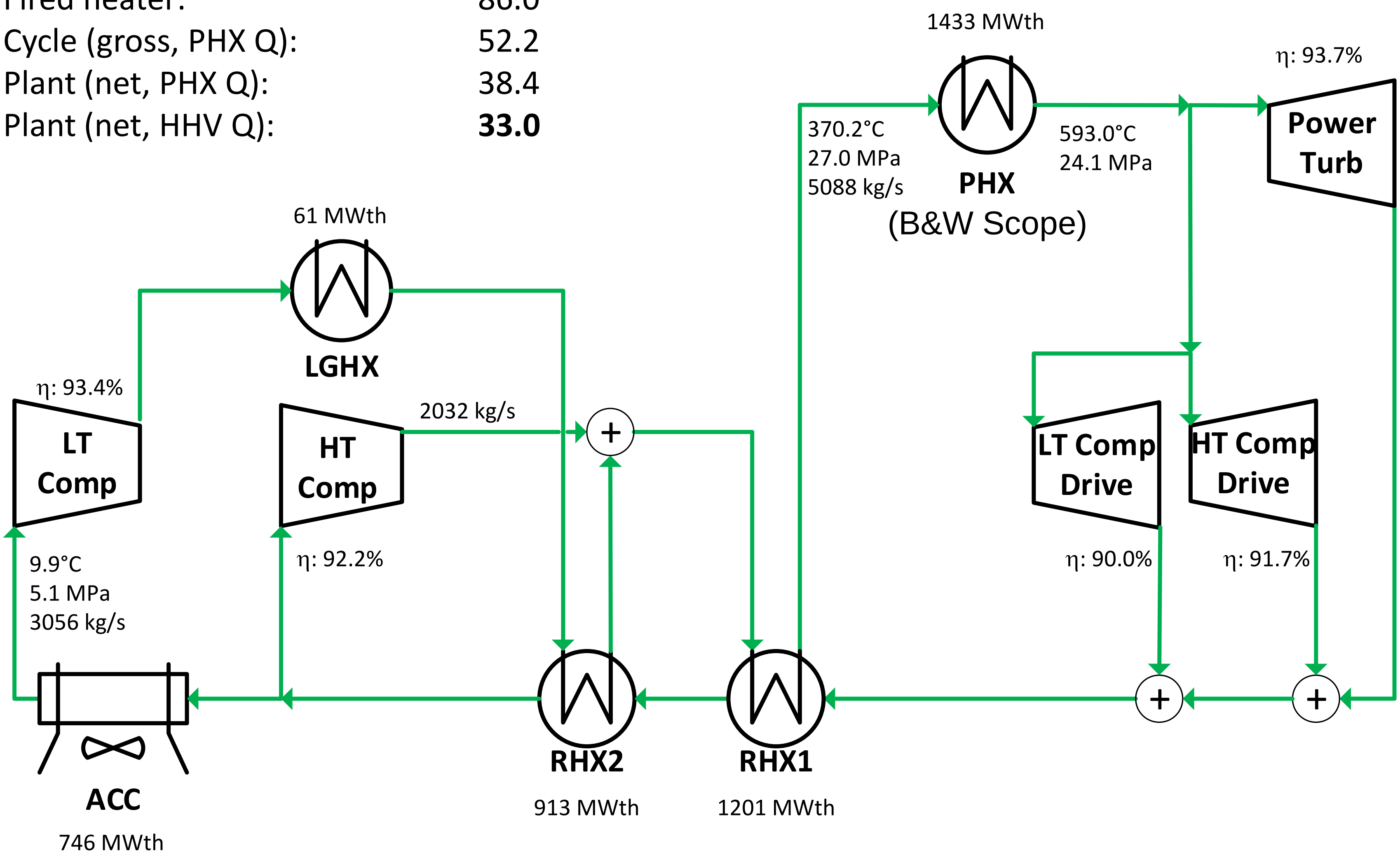
Summary of Progress

- Task Summary
  - Task 2 was completed in May 2016
  - Task 3 was completed in March 2017
  - Task 4 is underway and is scheduled to be completed by December 2017
  - Task 5 will begin in January 2018 and finish in March 2018
- Focus of this presentation will be on Task 3 results, which provide the design for each test case and compare the performance against the base cases

Test Case 1 Power Island

Efficiencies, %

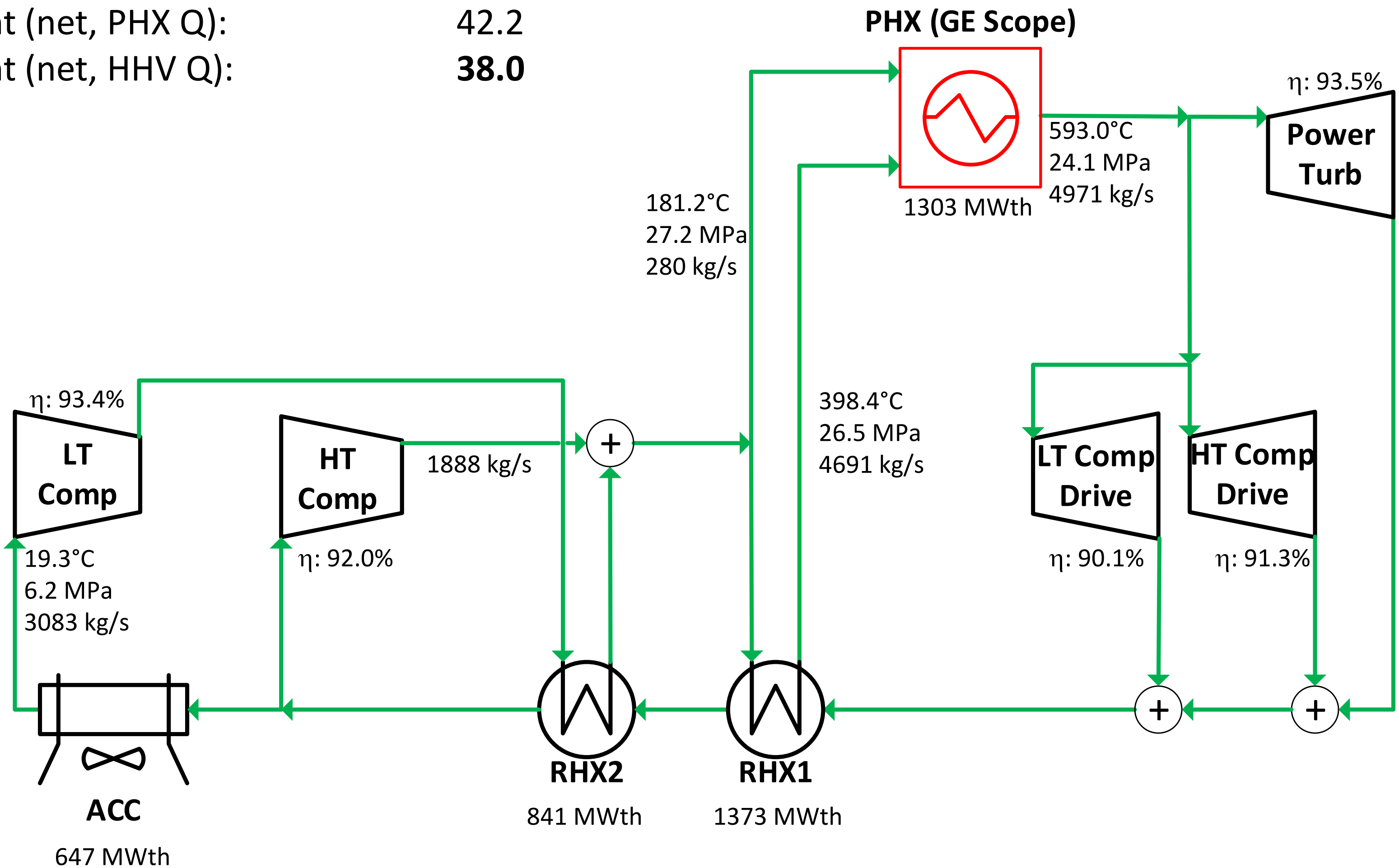
Fired heater:	86.0
Cycle (gross, PHX Q):	52.2
Plant (net, PHX Q):	38.4
Plant (net, HHV Q):	**33.0**



Test Case 3 Power Island

Efficiencies, %

Fired heater:	90.0
Cycle (gross, PHX Q):	50.3
Plant (net, PHX Q):	42.2
Plant (net, HHV Q):	**38.0**



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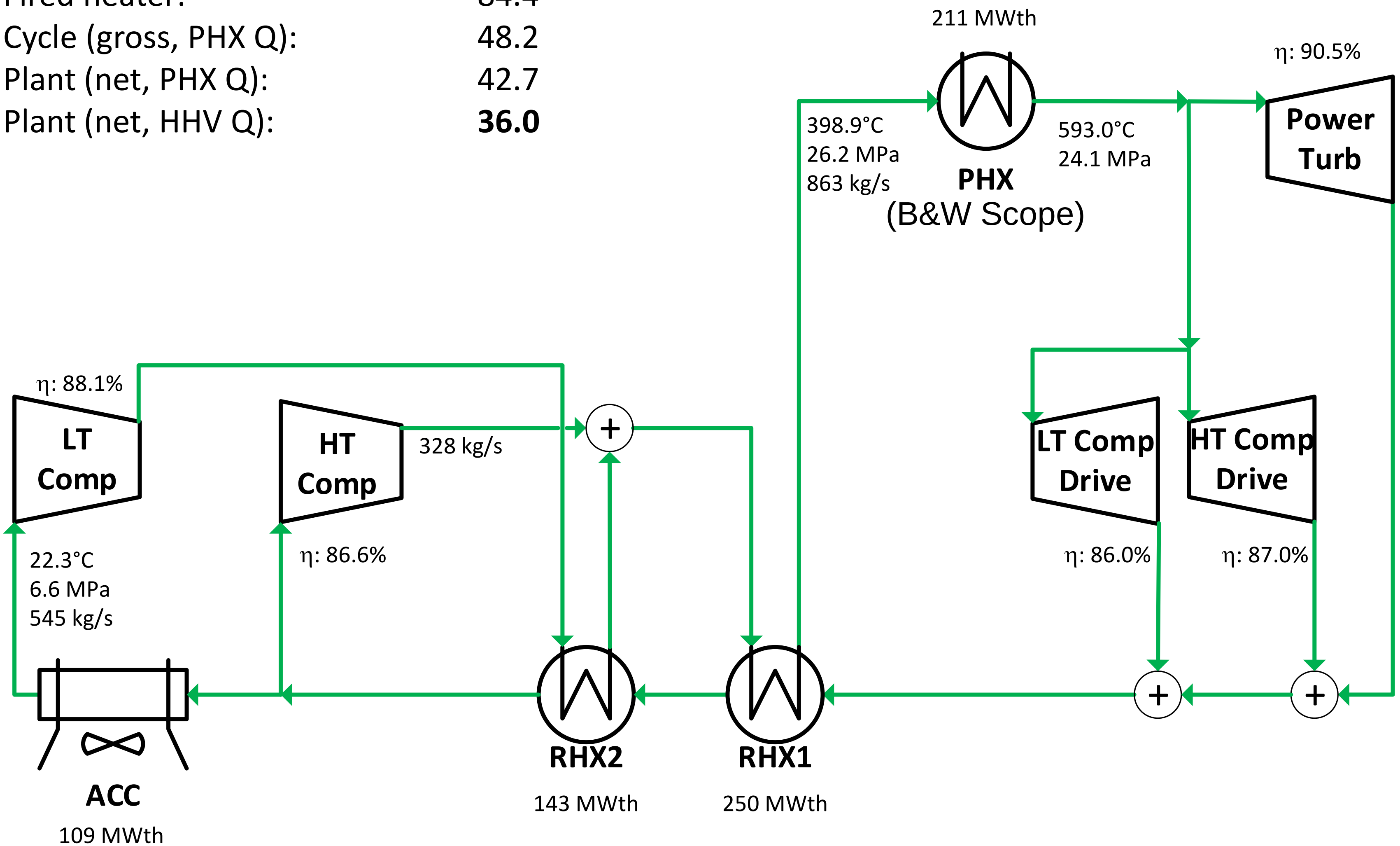
Test Case 5 Power Island

Efficiencies, %

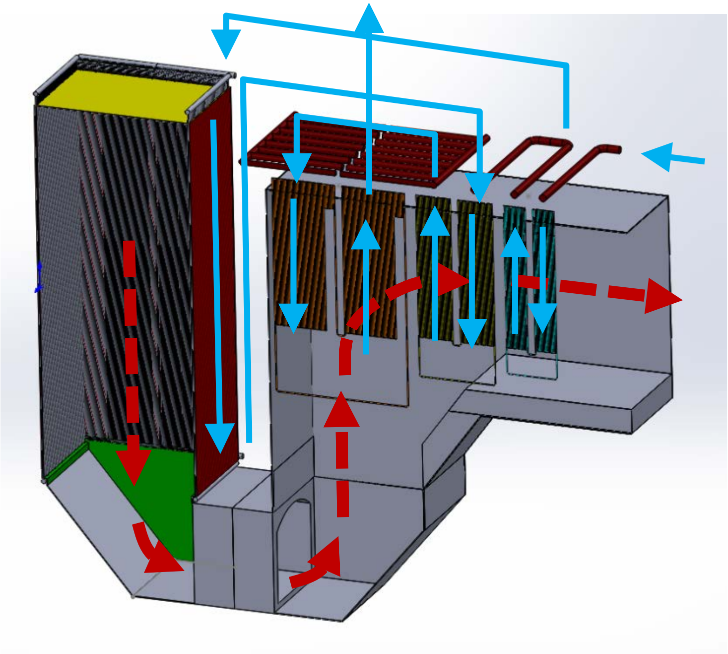
Fired heater:	84.4
Cycle (gross, PHX Q):	48.2
Plant (net, PHX Q):	42.7
Plant (net, HHV Q):	**36.0**



Test Cases 1, 2, 5, and 6 Fired-Heater Design

- B&W completed the design of four (4) PC-fired heater concepts: Test Cases 1 and 2 (oxy) and 5 and 6 (air)

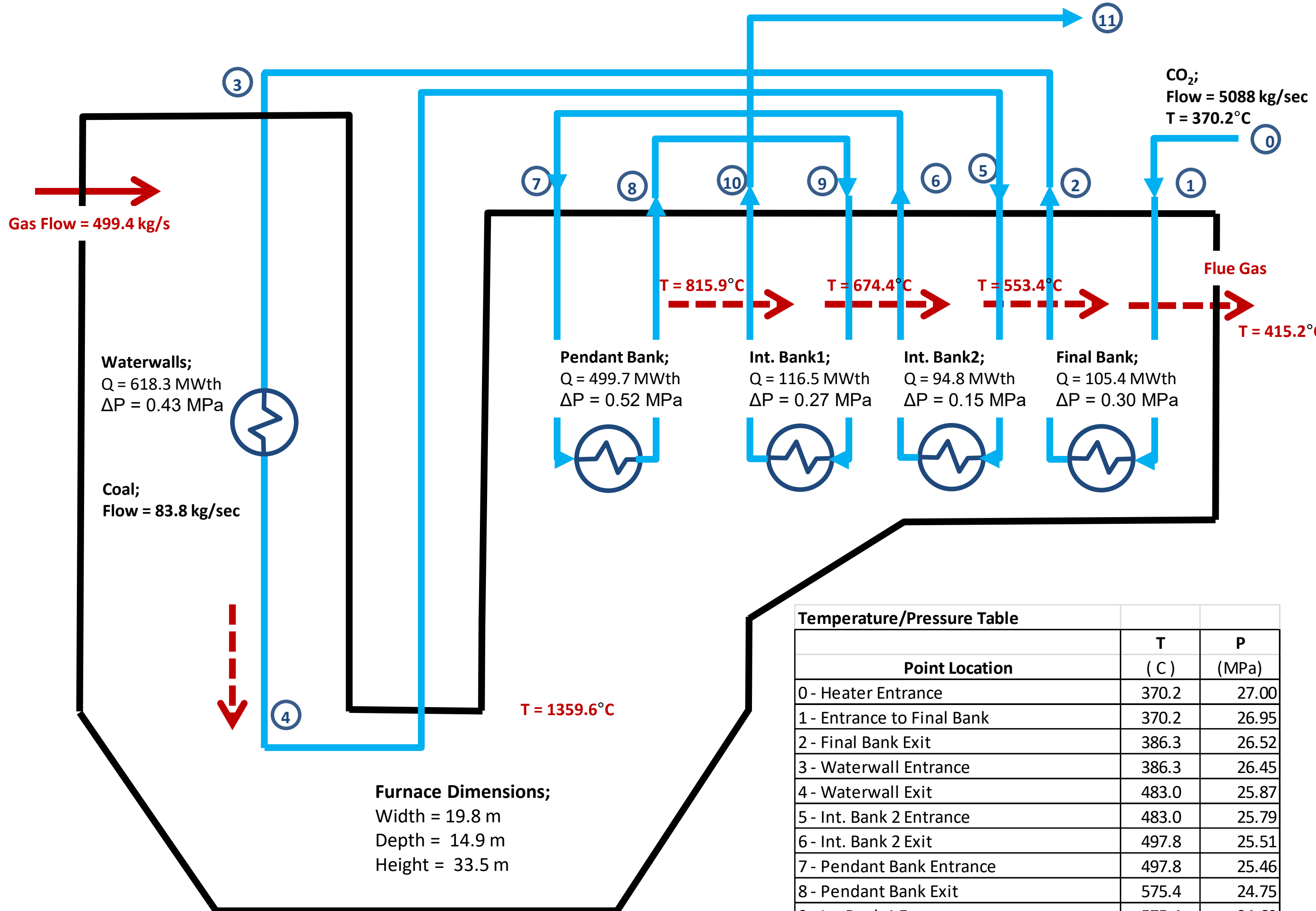
- All concepts based on inverted heater configuration
  - Minimizes pipe lengths to/from upstream/downstream equipment
  - Reduces pipe lengths from convection banks to radiant platen and furnace tube arrays
  - Improvement in particle removal



Design Highlights

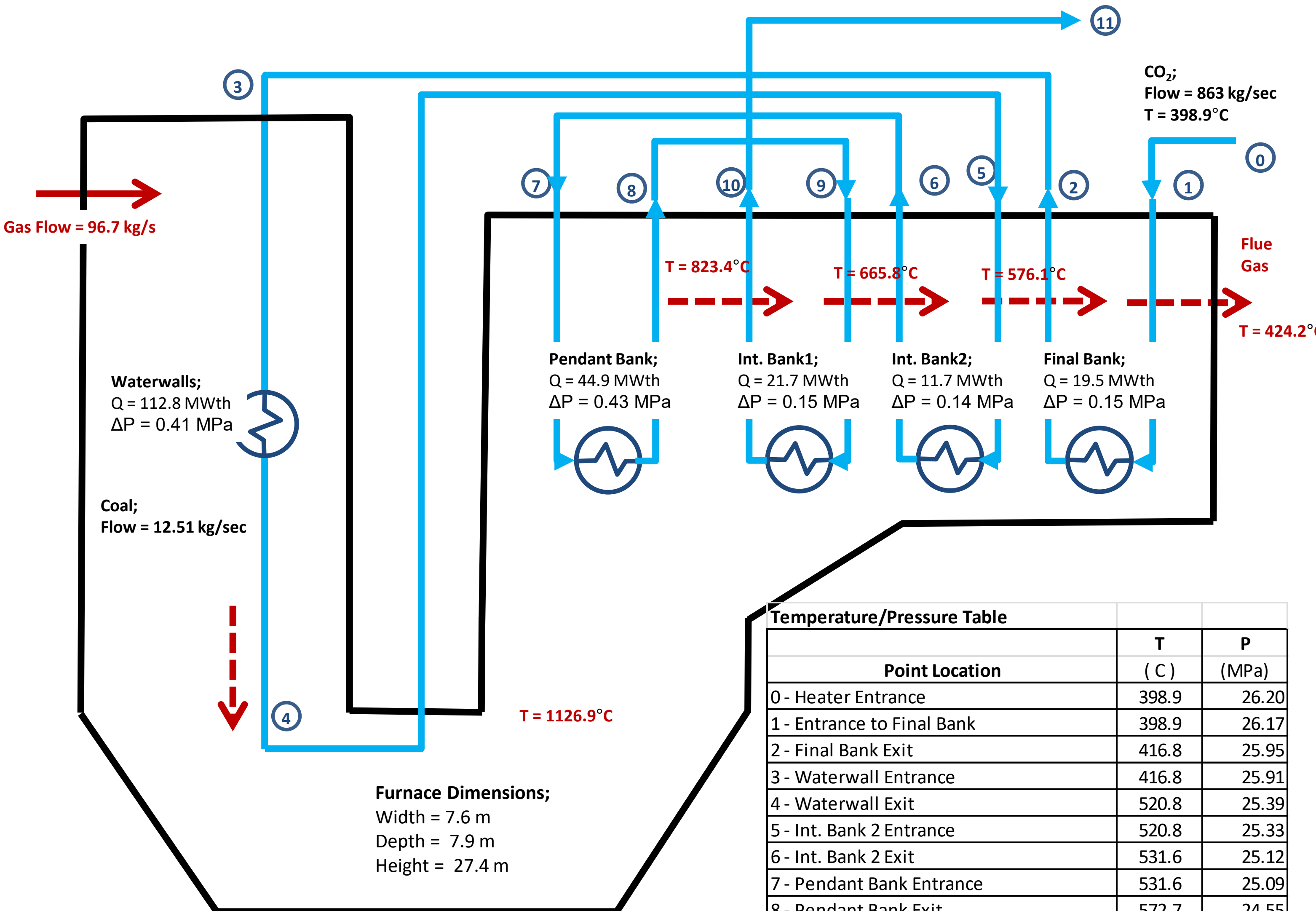
- Low sCO_2-Side Pressure Drop Requirement
  - sCO_2 volumetric flows 4–6 times higher than equivalent steam systems
  - High sCO_2 pressure drop decreases cycle efficiency
  - Results in deep tube banks with many tubes and lower CO_2 mass fluxes
- High sCO_2 Inlet Temperature
  - sCO_2 inlet temperature 28–56°C higher than equivalent steam systems for Test Cases 1 and 5; 140–195°C higher for Test Cases 2 and 6
  - Higher sCO_2 temperatures result in high tube temperatures, limiting material choices
- Potential design measures to address high tube temperatures
  - Tighter control on CO_2 fluid temperatures
  - Use of higher strength materials
  - Use of additional flue gas recycle
  - Combination of different measures

Test Case 1 Fired-Heater Design



Temperature/Pressure Table		
	T	P
Point Location	(C)	(MPa)
0 - Heater Entrance	370.2	27.00
1 - Entrance to Final Bank	370.2	26.95
2 - Final Bank Exit	386.3	26.52
3 - Waterwall Entrance	386.3	26.45
4 - Waterwall Exit	483.0	25.87
5 - Int. Bank 2 Entrance	483.0	25.79
6 - Int. Bank 2 Exit	497.8	25.51
7 - Pendant Bank Entrance	497.8	25.46
8 - Pendant Bank Exit	575.4	24.75
9 - Int Bank 1 Entrance	575.4	24.69
10 - Int Bank 1 Exit	593.0	24.26
11 - Heater Exit (to Turbine)	593.0	24.19

Test Case 5 Fired-Heater Design



Temperature/Pressure Table		
	T	P
Point Location	(C)	(MPa)
0 - Heater Entrance	398.9	26.20
1 - Entrance to Final Bank	398.9	26.17
2 - Final Bank Exit	416.8	25.95
3 - Waterwall Entrance	416.8	25.91
4 - Waterwall Exit	520.8	25.39
5 - Int. Bank 2 Entrance	520.8	25.33
6 - Int. Bank 2 Exit	531.6	25.12
7 - Pendant Bank Entrance	531.6	25.09
8 - Pendant Bank Exit	572.7	24.55
9 - Int Bank 1 Entrance	572.7	24.51
10 - Int Bank 1 Exit	593.0	24.28
11 - Heater Exit (to Turbine)	593.0	24.24

Test Cases 1, 2, 5, and 6 – Summary

- In all cases, nickel alloys were used for the furnace, platens, and first intermediate banks, stainless steel for the second intermediate banks, and croloy steel for the final bank

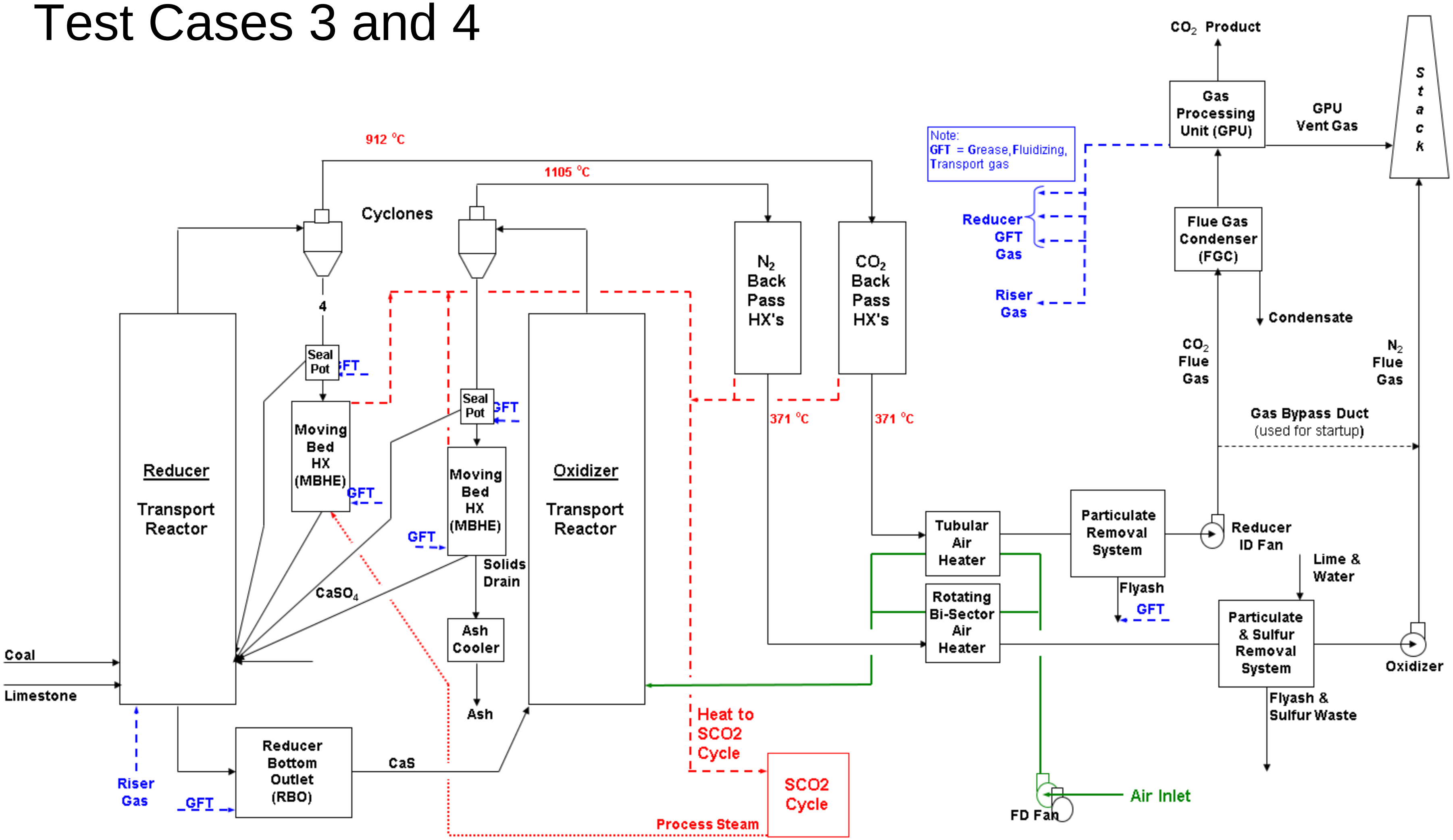
Test Case	Coal	Fuel Rate, kg/sec	Furnace Dimensions, m	Heat Transferred to CO_2, MWth	Total Pressure Drop, MPa[1]	Heater Efficiency, %[2]
1	Rosebud Powder River Basin	83.8	19.8 x 14.9 x 33.5	1433	2.81	86.0
2		72.6	18.3 x 13.7 x 33.5	1261	3.83[3]	87.1
5		12.5	7.6 x 7.9 x 27.4	211	1.96	84.4
6		11.0	7.6 x 7.9 x 27.4	187	2.65[3]	85.2

Notes:

1. **Total pressure drop includes estimate of header pressure losses.**
2. **Heater efficiency defined as heat input to CO_2 divided by fuel heat input on an HHV basis.**
3. **Current design does not fully address local tube temperature variations in furnace and platens. Measures necessary to address local tube temperatures may increase pressure drop above the cited values.**

Test Cases 3 and 4 Fired-Heater Design

- GE completed the design of 2 CLC fired-heater concepts: Test Cases 3 and 4



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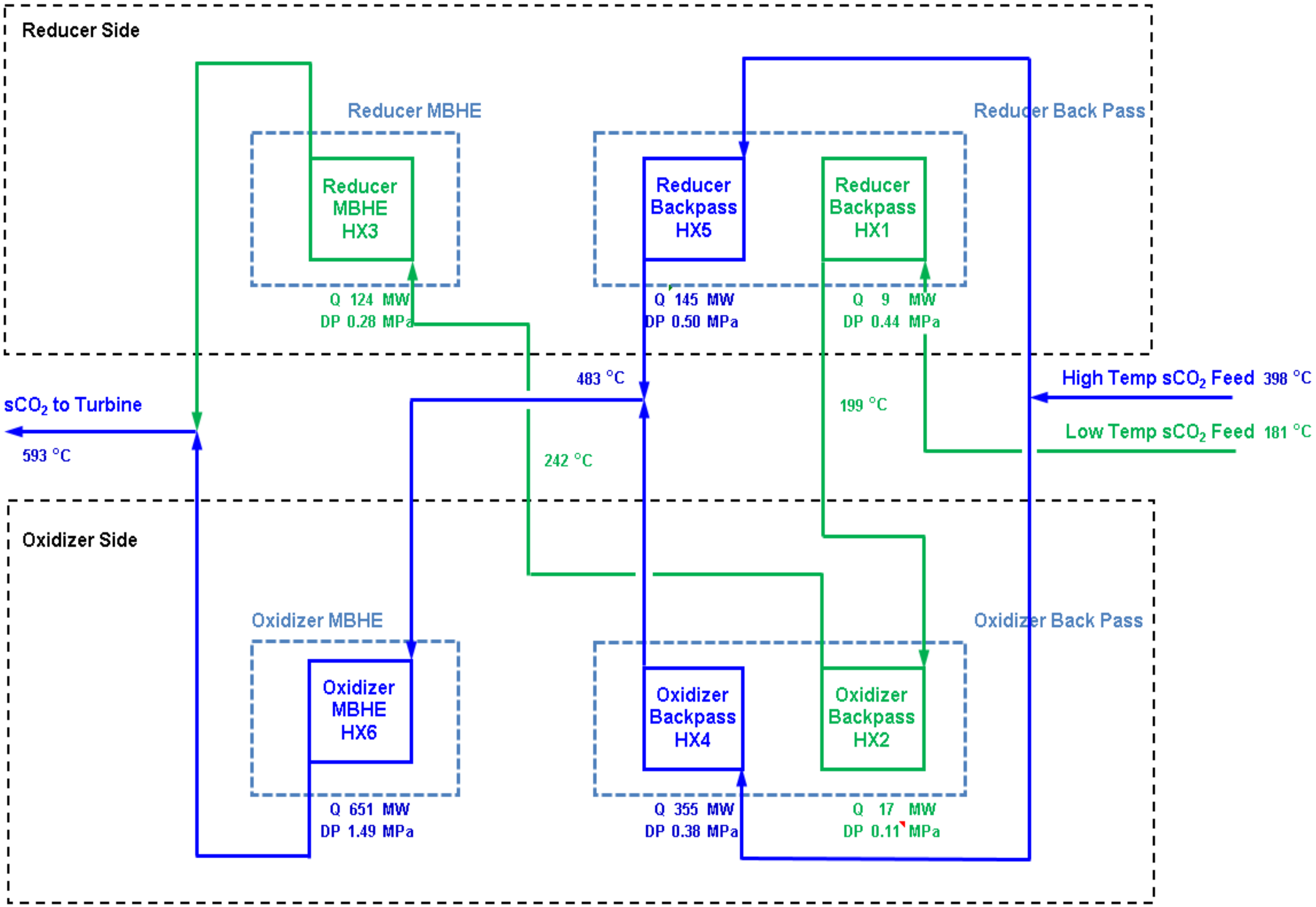
Design Highlights

- CLC fired heater is comprised of transport reactors, cyclones, convective backpasses, and external moving-bed heat exchangers (MBHEs), but the sCO_2 heat exchanger tube bundles are only arranged in the latter two locations
- Finishing sCO_2 heater section is at a lower elevation to shorten piping length to the turbine, saving material cost
- As pressure drop is the most significant parameter impacting efficiency, the design minimized pressure drop by:
  - Using refractory-lined, instead of fluid-cooled, walls
  - Designing tube bundles wider with more assemblies
  - Selecting larger tubing sizes
  - Selecting higher-grade materials to reduce tubing wall thickness

Test Case 3 Fired Heater Design



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Test Cases 3 and 4 – Summary

- Test Case 3 is designed with conventional austenitic and ferritic materials
- Test Case 4 has nickel-based alloy in the oxidizer MBHE (tubing, outlet header, and piping)

Parameter	Test Case 3	Test Case 4
CO_2 Total Heat Absorption, MWth	1302	1164
Coal Flow, kg/s	53.37	47.73
Fuel Heat Input, MWth HHV	1447	1294
CLC Fired Heater Island Efficiency, % HHV	90	90
CLC sCO_2-side HT Feed DP, MPa	2.4	2.4
CLC sCO_2-side LT Feed DP, MPa	3.1	3.1
Final sCO_2 Delivery Temperature, °C	593	730

Summary of Results

Case	Type	Net Power, MWe	Test (sCO_2) Case		Base Case	Improvement, % points
			Turbine Inlet Conditions, °C / MPa	Net Plant Efficiency, % HHV	Net Plant Efficiency, % HHV	
1	Oxy	550	593 / 24.1	33.0	31.0	2.0
2	Oxy	550	730 / 27.6	38.0	34.3	3.7
3	CLC	550	593 / 24.1	38.0	35.8	2.2
4	CLC	550	730 / 27.6	42.5	40.0	2.5
5	Air	90	593 / 24.1	36.0	33.0	3.0
6	Air	90	730 / 27.6	41.0	33.0[1]	8.0

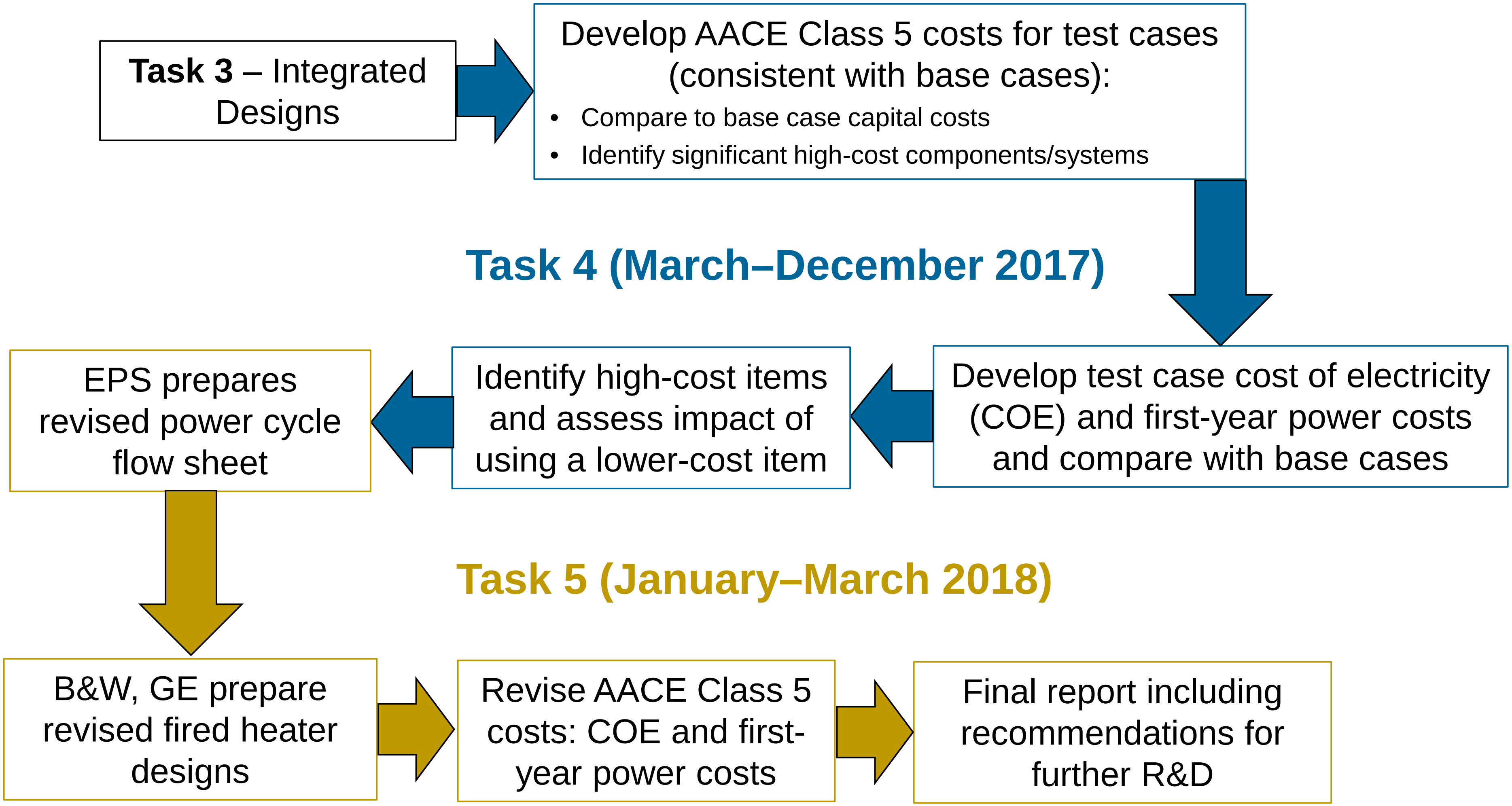
Notes:

1. Base Case 6 efficiency was not updated since the steam cycle employed represents common commercial practice for this size power plant.

Further improvements in efficiency possible, but might be costly

Future Plans

Next Steps: Tasks 4 and 5



sCO_2 power cycle costs look promising, but fired heaters are expensive

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