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Flue Gas Water Vapor Latent Heat Recovery for Pressurized Oxy-Combustion

DE-FE0025350 Project Kickoff Meeting,
NETL Program Manager: Steve Markovich

Dexin Wang—Principal Investigator
Gas Technology Institute
November 16, 2015

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Flue Gas Water Vapor Latent Heat Recovery for Pressurized Oxy-Combustion

Agenda:

- Technology Development Background
- Project Objectives, and Team Member Responsibilities
- Detailed Project Tasks and Plan
- Risks and Mitigation
- Schedule and Deliverables
- Budget

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Transport Membrane Condenser (TMC) Technology Development Background and its Industrial Applications

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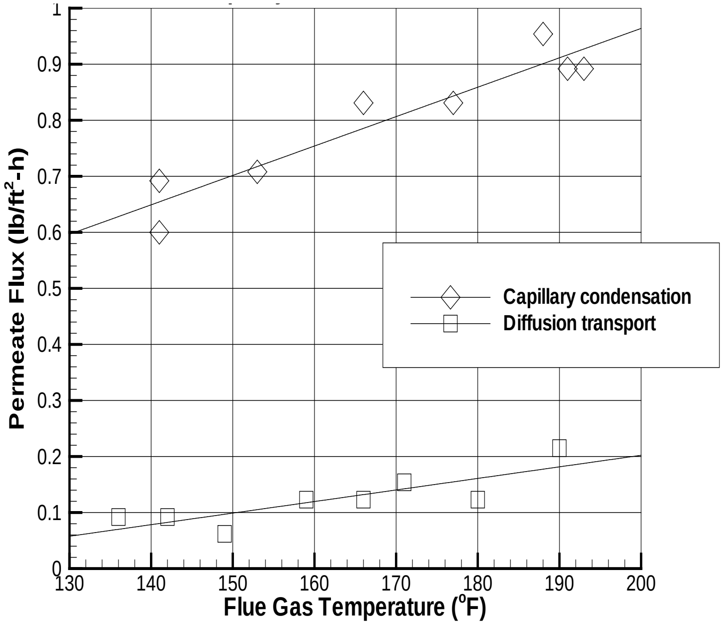
Water Vapor Membrane Separation Study at GTI

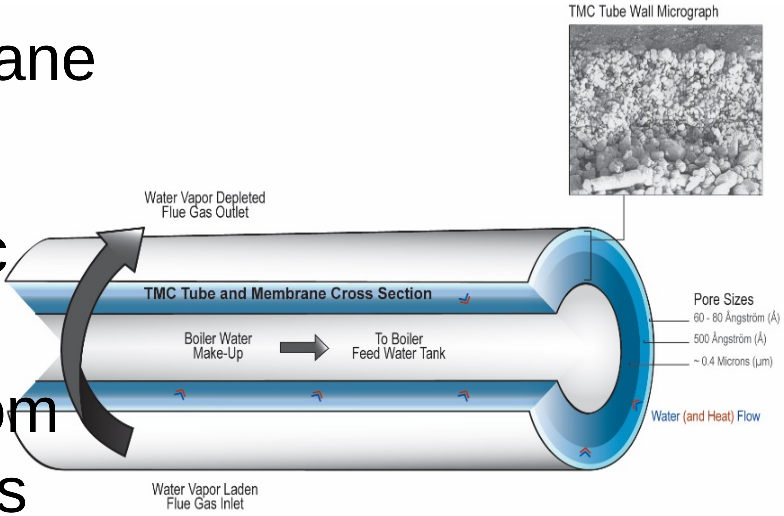
- Extensive study for both porous and non-porous membranes at GTI
- Porous membrane was selected for its potential high water vapor transport flux for industrial uses, and its four vapor separation modes as below:
  - Molecular Sieving
  - Knudsen diffusion
  - Surface diffusion, and
  - Capillary condensation



- Working mode of porous membrane is critical for water vapor transportation.
  - ✓ High permeate flux and high separation ratio could <u>only</u> be achieved in a <u>capillary condensation mode</u> for water vapor.

Simultaneous Water Vapor Latent Heat and Water Recovery from Flue Gases

- GTI developed Transport Membrane Condenser (TMC) technology
- TMC uses a nanoporous ceramic membrane to selectively recover water vapor and its latent heat from natural gas combustion flue gases
  - Increase boiler efficiency and save water, avoids corrosive condensate
- Successfully developed for industrial boilers



TMC tubes in a bundle assembly

TMC Heat/Water Recovery System for Industrial Applications

- TMC modules integrated into a housing to form a TMC unit with controls.
- Boiler feedwater is pre-heated to boost efficiency
- Fresh makeup water requirement is reduced by flue gas water vapor recovery

Cannon Boiler Works Ultramizer®

- Advanced TMC-based heat recovery systems for industrial, large commercial, and institutional boilers commercially available from Cannon Boiler Works
  - Current sizes around 10-20 MMBtu/hr
  - 92-95% efficiency
- Ongoing development to scale-up to larger sizes
  - Over 20 MMBtu/hr

Industrial boiler heat recovery with Ultramizer product at a brewery

TMC Energy and Water Recovery Field Installations for Industrial Boilers

TMC field installation pictures: *left* City Brewing (first commercial unit), *mid* Baxter, *right RBC.*

TMC System Field Demo for a Laundry Steam Tunnel

TMC unit installed on top of the Steam Tunnel stack

The Steam Tunnel stack gas before and after TMC installation

- ✓ Recovered water and heat are used for washing machine hot water, saves energy and water from a steam boiler.

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Transport Membrane Condenser for Water and Energy Recovery from Power Plant Flue Gas

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TMC Applications for Water Vapor Recovery from Coal Flue Gases

Advantages:

- Higher moisture content in coal flue gas:
  - With FGD, flue gas dew point 140 to 170°F
  - Compared with natural gas boiler flue gas: 130 to 136°F
- More favorable cooling conditions for TMC:
  - Steam condensate can be one cooling water source for TMC, typically at 90 to 115°F.
  - Cooling water flow rate is typically at 25 times of the boiler feed water flow rate, from 50 to 100°F.
  - Industrial boiler has only 10 to 50% of makeup water, and its steam condensate is at >180°F, can not be used for TMC.

Disadvantages:

- More complicated components in coal flue gas:
  - SO_2, heavy metals, particulate matter, etc.
  - Compare with relatively “clean” natural gas-based flue gas

Pilot scale TMC design and performance testing at GTI

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Pilot scale TMC Field Slip Stream Testing at a Power Plant

Pilot unit test in the field: left shows in installation, right shows in testing with a tent *the Energy to Lead*

New Challenge: Pressurized Oxy-Combustion for Power Generation

Current Project Objectives and SOW

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Project Objectives and Team

- Project Objectives:

Develop and test a high-pressure modular version of the TMC in GTI's pilot-scale pressurized coal combustor to evaluate its performance and analyze the results for future commercial-scale power plants.

- Project Team:

Gas Technology Institute(GTI), Media and Process Technology(M&P), SmartBurn and Florida International University (FIU).

Project Organization Chart

U.S. DOE-NETL
-Federal sponsor-
Technical and administrative oversight

GTI
Not-for-profit R&D organization
-Prime contractor-
Technical & financial management, key technology development and testing

Key personnel:
D. Wang – PM and PI, TMC development and testing
A. Kramer—Pressurized oxy-coal system operation and testing

M&P
-Small manufacturing business-
-cost-*share partner-*
Membrane development and high pressure bundle fabrication and pretest

Key personnel:
R. Ciora

SmartBurn
-Utility Consultant Company-
cost-share partner-
-potential commercializer-
Power plant data and technology integration evaluation for commercial use

Key personnel:
E. Lightbourne

FIU
-University-
Process Modeling, CFD assist design and parameter study

Key personnel:
C. Lin

Project Tasks and Responsibilities

Project RACI Chart

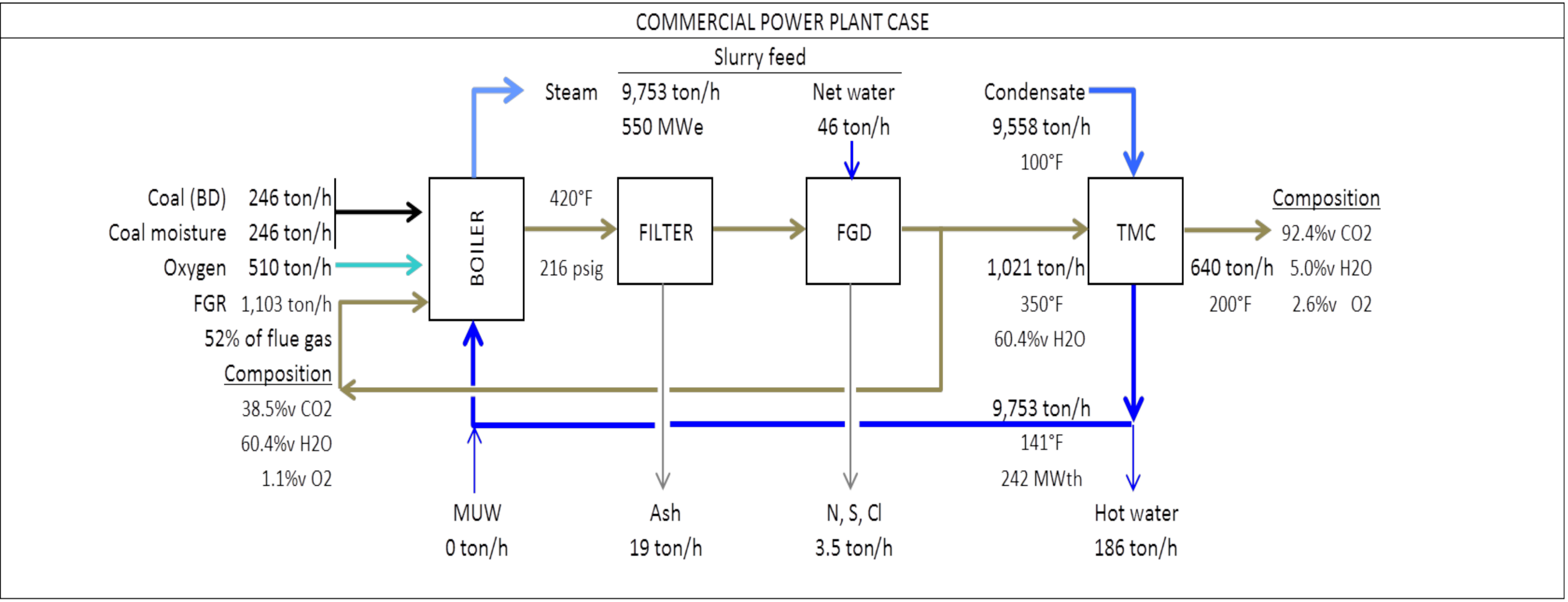
R:	Responsible for (performs) the task
A:	Accountable for the results of the task
C:	Consulted before/during the task
I:	Informed when the task is completed

TASK	TASK DESCRIPTION	GTI	M&P	SmartBurn	FIU
1.0	Project Management & Planning	R / A	C	C	C
2.0	Process Modeling & Design Evaluation				
2.1	Process Modeling for System Design	R / A	C	C	C
2.2	CFD Simulation to Define TMC System Parameters	A	C / I	I	R / A
3.0	TMC Unit Design, Fabrication, and Assembly for High Pressure				
3.1	Spaced Tube Bundles Design, Fabrication and Testing	C / I	R / A	I	I
3.2	High Pressure Bundle Housing Design, Fabrication and Testing	C / I	R / A	I	I
3.3	TMC Unit Assembly and System Control Setup	R / A	C / I	I	I
4.0	Pressurized Oxy-Coal Pilot Test System Preparation and Modifications				
4.1	Feedstocks and Raw Material Preparation	R / A	I	I	I
4.2	Test System Modifications	R / A	C / I	I	I
4.3	Test Plan	R / A	C / I	C / I	I
5.0	Overall Test System Installation and Shakedown				
5.1	TMC System Installation and Control Integration with Oxy-Coal Test Rig	R / A	C / I	C / I	I
5.2	System Shakedown	R / A	C / I	C / I	I
6.0	System Performance Testing for Latent Heat Recovery				
6.1	TMC Performance Test #1	R / A	C / I	C / I	I
6.2	TMC Performance Test #2	R / A	C / I	C / I	I
6.3	Result Summary and Future Development Directions	R / A	R / I	R / I	R / I
7.0	Scale-Up and Integration Evaluation for Commercial Scale Power Plant	A	C / I	R / A	C / I

Task 2: Process Modeling and Design Evaluation

❑Task 2.1: Process Modeling for System Design and Operation.

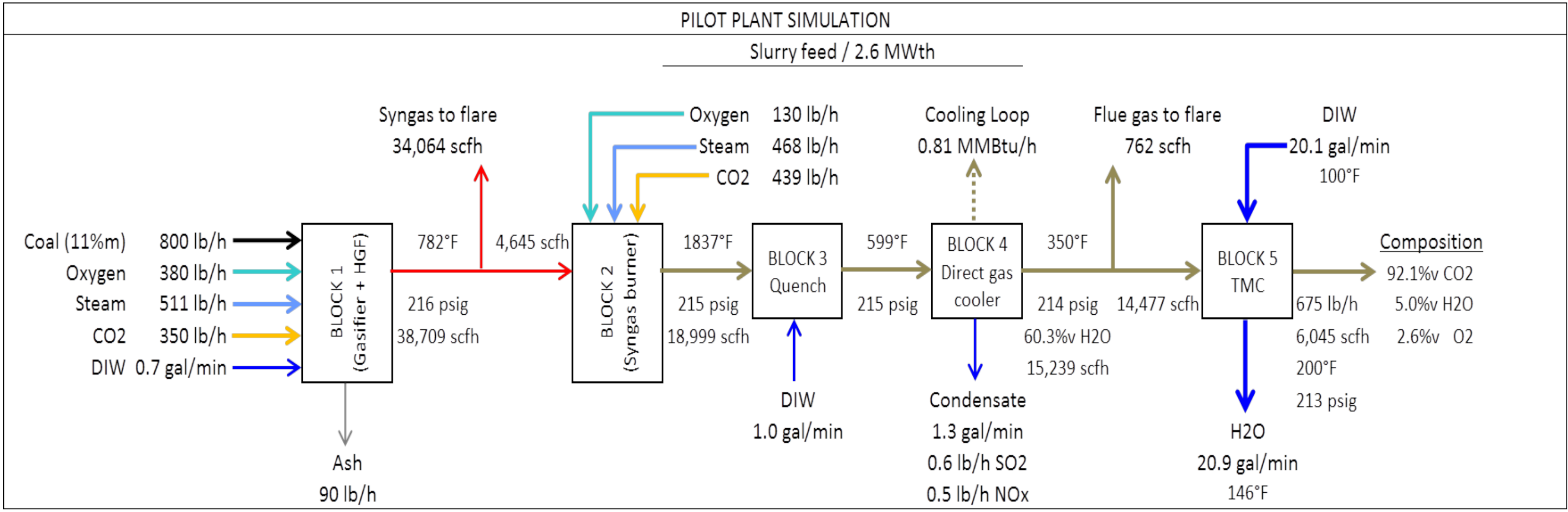
– Commercial scale power plant simulation with flue gas recirculation to see how TMC can be fitted into the system and its impacts on system efficiency and water recovery



Task 2: Process Modeling and Design Evaluation

❑Task 2.1: Process Modeling for System Design and Operation.

—Pilot plant simulation to define system modification and feed stock needs, and provide parameters for TMC design work

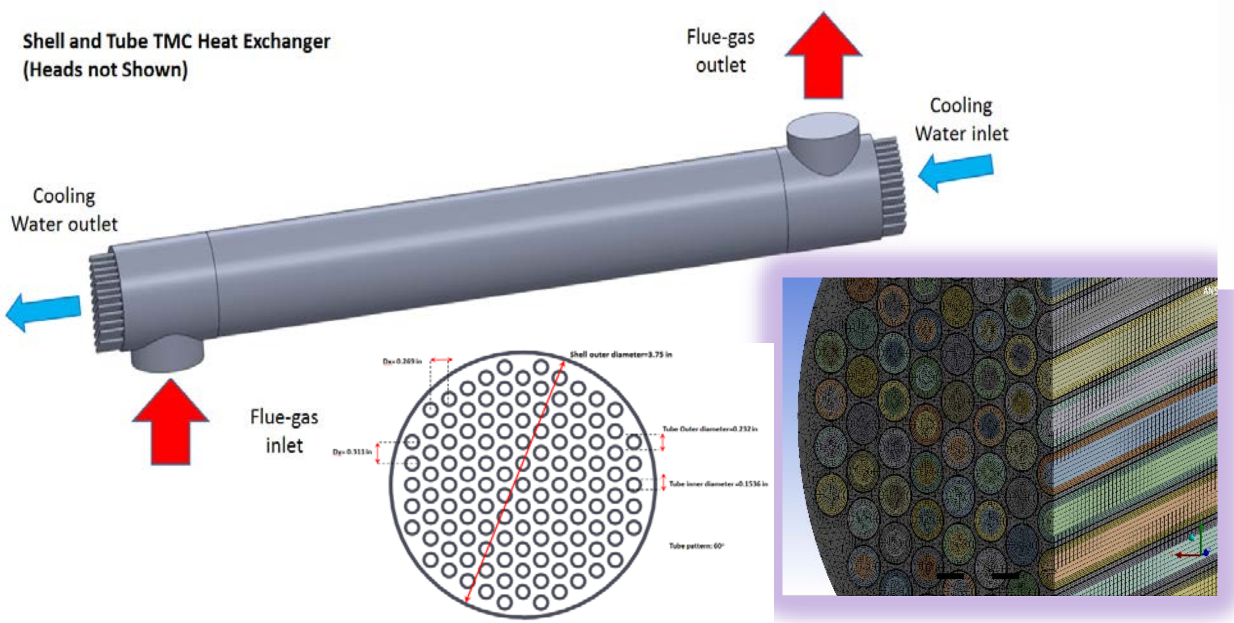


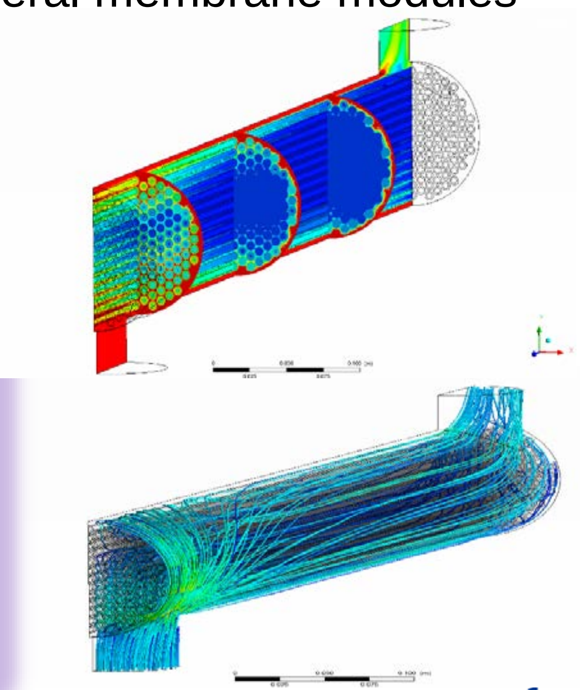
Task 2: Process Modeling and Design Evaluation

❑Task 2.2: CFD Simulation to Define TMC Design Parameters.

1. Define design parameters for a single membrane module, such as spacing between membrane tubes in a fixed housing volume to provide the optimum heat/mass transfer performance with reasonable pressure drop.

2. Simulate TMC unit performance, which may include several membrane modules arranged in different configurations (in series and parallel).





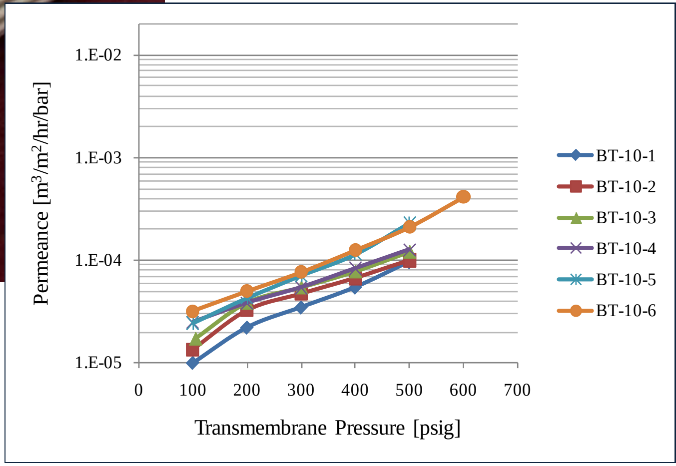
Task 3: TMC Unit Design, Fabrication and Assembly

- Task 3.1: Spaced Tube Bundle Design, Fabrication and Testing.

—design and test new membrane bundles for 20 bar pressure and up to 200ºC, with adequate spacing between the tubes to allow optimum heat/mass transfer.

Low Pressure Bundle

High Pressure Bundle



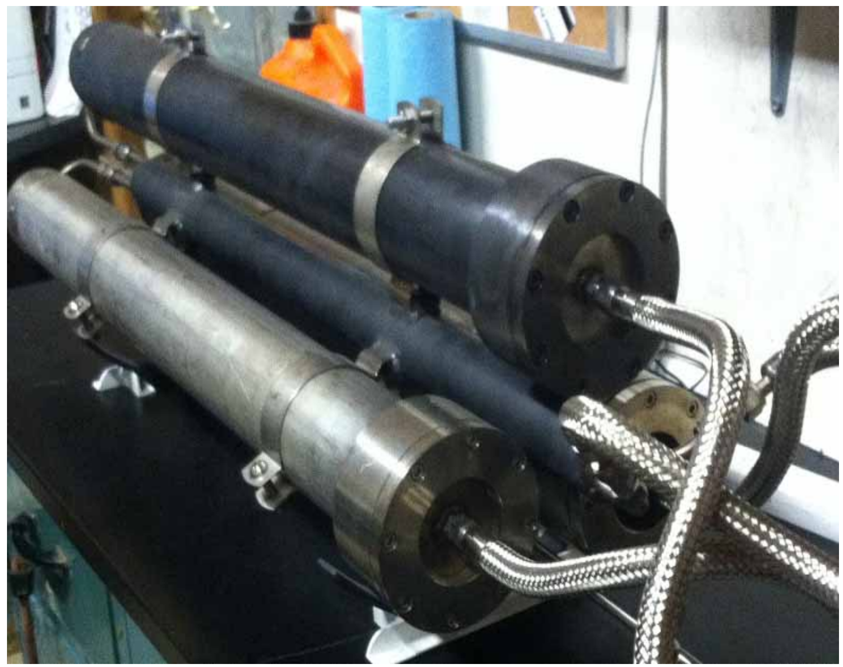
High Pressure Bundle Performance

Task 3: TMC Unit Design, Fabrication and Assembly

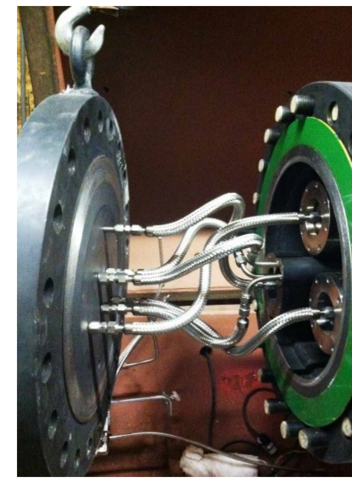
- Task 3.2: High Pressure Bundle Housing Design/Fabrication/Testing.

—design and test new membrane bundle housing for 70 bar pressure and up to 300ºC.

Low Pressure Module



High Pressure Modules



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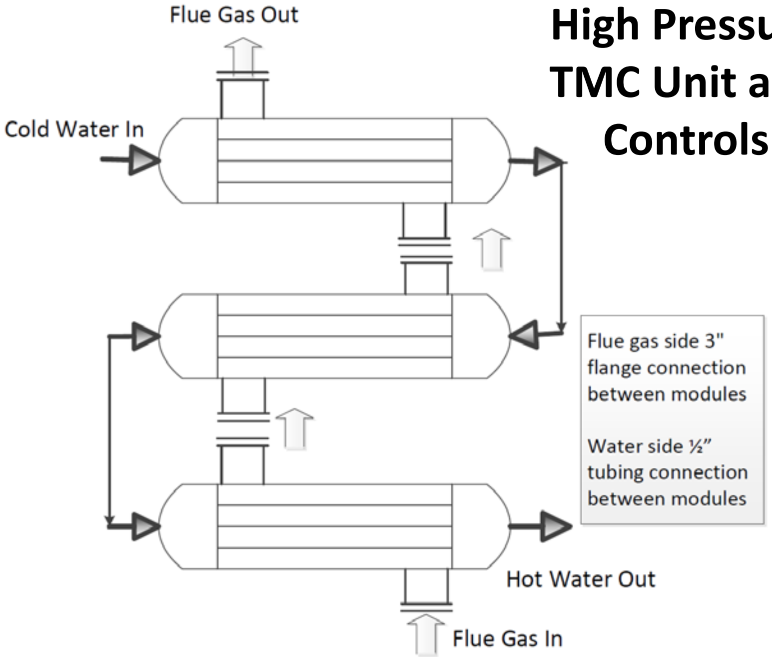
Task 3: TMC Unit Design, Fabrication and Assembly

❑ Task 3.3: TMC Unit Assembly and System Control Setups.

—design and configure the new TMC unit with control system to allow its integration with the pilot plant, and operate automatically and respond well with parameter changes during the pilot testing.

Low Pressure TMC Unit and Controls

High Pressure TMC Unit and Controls



New TMC Design for High Pressure Flue Gas

Task 4: Pilot Test System Preparation and Modifications

- Task 4.1: Feedstocks and Raw Material Preparation

—GTI shall obtain a sufficient supply of pulverized, sized, and dried Powder River Basin coal for the test campaign, estimated at about 18 metric tons, assuming 15% moisture at 0.84 x 6-mm particle size. For startup, GTI anticipates using metallurgical coke prior to feeding coal, subject to further consultation with suppliers, and will obtain that material as required. GTI shall also contract for deliveries of the required cryogenic oxygen, cryogenic CO2, and nitrogen to support startup and operation throughout the test campaign.

Task 4: Pilot Test System Preparation and Modifications

❑Task 4.2: Test System Modifications

GTI will test the TMC technology by using its existing pressurized oxygen-blown fluidized-bed gasifier and associated feeding, gas conditioning, and control systems. The following is the procedure:

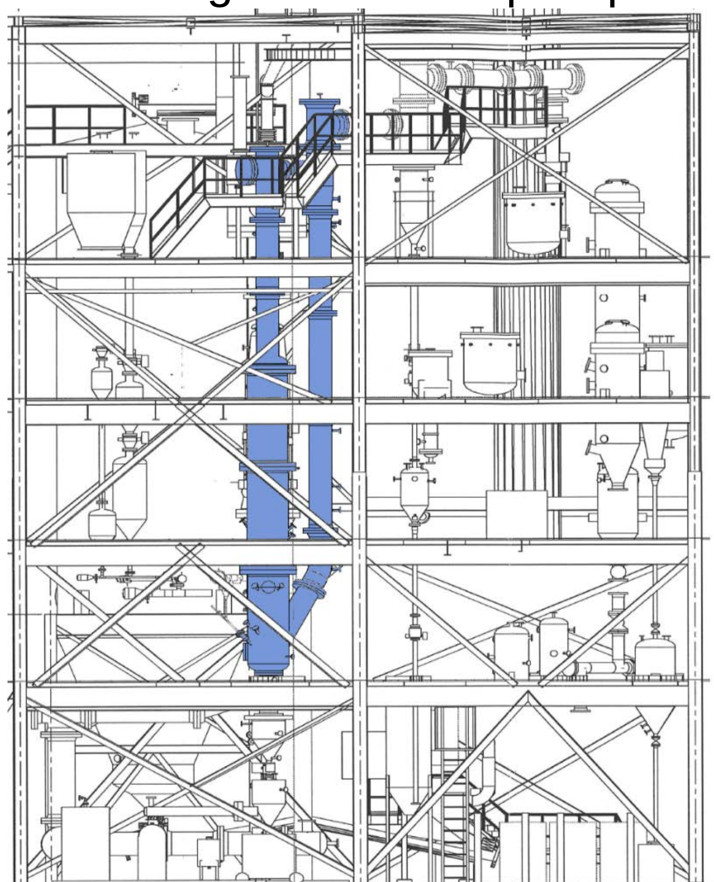
1. Gasify coal in existing pilot-scale gasifier
   - Pressurized fluidized bed
   - Feeds coal, O_2, steam, and CO_2
   - Generates syngas
2. Gas cleanup
   - Ash removal from syngas in hot gas filter
3. Combustion
   - Convert tar reformer to pressurized syngas burner
   - Combust syngas with additional O_2, steam, and CO_2
   - Cool the flue gas with direct water injection and indirect heat removal
4. Flue gas conditioning
   - Scrub out at least 90% SO2 and NOx by caustic injection in the direct cooler to simulate FGD outlet flue gas conditions, ready to feed into the TMC.

Task 4: Pilot Test System Preparation and Modifications

❑ Task 4.2: Test System Modifications

The following pictures show the existing items in the pilot plant

FlexFuel pilot-scale pressurized fluidized-bed gasifier at GTI



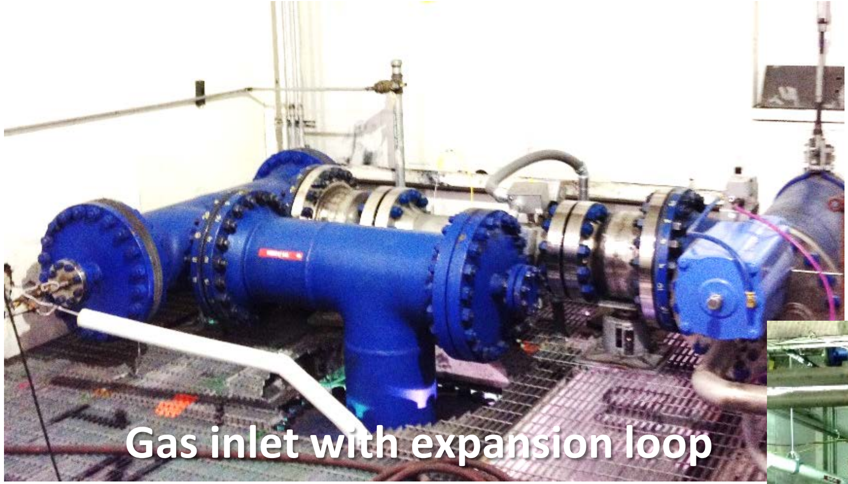
Gasifier installed in process building at GTI

Hot gas filter candles

Task 4: Pilot Test System Preparation and Modifications

- Task 4.2: Test System Modifications

More pictures show the existing items in the pilot plant

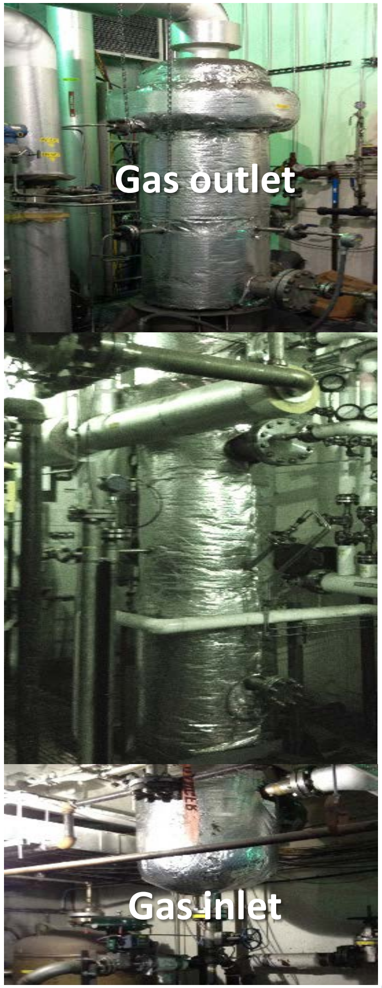


Tar reformer repurposed as syngas burner with oxygen, steam, and CO_2 inputs

Task 4: Pilot Test System Preparation and Modifications

❑Task 4.2: Test System Modifications

More pictures show the existing items in the pilot plant



Direct gas cooler & condenser using circulating countercurrent water spray

Task 4: Pilot Test System Preparation and Modifications

- Task 4.3: Test Plan

Develop and draft a Test Plan to be followed in the test campaigns during Budget Period II. The Test Plan will be based on coal combustion in the gasifier/combustor with oxygen, steam, and CO2 input to simulate the final flue gas composition from an oxy-coal power boiler with flue gas recirculation. At least two TMC configurations, comprising different arrangements of six TMC modules, will be included. Preliminary test conditions are estimated to be 2.6 MW_{th} total thermal input to the gasifier/combustor at 14-16 bar, with a final flue gas available to the TMC equivalent to that coming out from a **1.0 MW_{th}** total thermal input oxy-boiler at approximately 14 bar, 150-180°C, humidity near saturation, and SO2 and NOx content similar to those expected from a commercial power plant after a FGD unit.

Task 5: Overall Test System Installation and Shakedown

- Task 5.1 TMC System Installation and Control Integration

  - ✓ Heat/water recovery: Install the TMC system in the pilot plant facility, and integrate the new instrumentation and controls with the existing gasification pilot plant Distributed Control System.
  - ✓ Gasifier: Install and pre-test coal feed system and CO_2 supply system
  - ✓ Gas cleanup: Install existing ceramic filter candles and CO_2 pulse system
  - ✓ Combustion: Install steam feed to syngas burner and update controls
  - ✓ Operational: Conduct HAZOP analysis, and develop startup plan

Task 5: Overall Test System Installation and Shakedown

- Task 5.2 Pilot Test System Shakedown

For the first TMC configuration, test out the control system to ensure that parameters can be varied according to the Test Plan, verify that the direct gas cooler caustic injection system is operational, verify that all existing control loops and monitoring functions are working properly, commission all new or modified equipment items, and conduct a pre-test pressure test. The newly installed TMC shall be commissioned at cold conditions using nitrogen at desired flow conditions with flow and pressure control and TMC water recycle. Then initiate a hot shakedown test including feeding and firing coal in the gasifier/combustor under planned conditions to confirm that flue gas can be generated at the composition and conditions dictated in the Test Plan.

Task 6: System Performance Testing for Latent Heat and Water Recovery

❑Task 6.1: TMC Performance Test #1

The first test campaign is designed to obtain detailed performance data for the first TMC configuration, analyze its latent heat recovery and pressure drop data, and define steps needed for improvement. It will comprise coal combustion in the gasifier/combustor under conditions specified in the Test Plan. Variations in test parameters will include, but not necessarily be limited to, TMC transmembrane pressure drop, water inlet temperature, and water inlet flow rate. If possible, Test #1 shall be initiated at the conclusion of the Shakedown Test without system shutdown. Test #1 shall continue for approximately 48 hours following the establishment of steady-state conditions as defined by flue gas temperature, flow, and composition.

Task 6: System Performance Testing for Latent Heat and Water Recovery

❑Task 6.2: TMC Performance Test #2

Based on the first TMC configuration test results and analysis, set up at least one more new TMC configuration to test for performance improvements. GTI shall then conduct the second test campaign as described in the Test Plan. This test campaign will comprise coal combustion and flue gas compositions similar to those in Test #1, however will be mainly aimed at evaluating the TMC performance in the second configuration. Test #2 shall continue for approximately 48 hours following establishment of steady-state conditions as defined by flue gas temperature, flow, and composition.

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Task 6: System Performance Testing for Latent Heat and Water Recovery

- Task 6.3: Results analysis and future development directions

Analyze the performance test results for different TMC configurations and operating parameters, and FIU shall use simulation tools to evaluate more TMC design options to complement the test results. Based on these results, point out directions for future TMC development, and formulate the optimum TMC design and operating conditions for future commercial and pilot unit development.

Task 7: Scale-Up and Integration Evaluation for Commercial Scale Power Plant

- Task 7: Scale-Up and Integration Evaluation for Commercial Scale

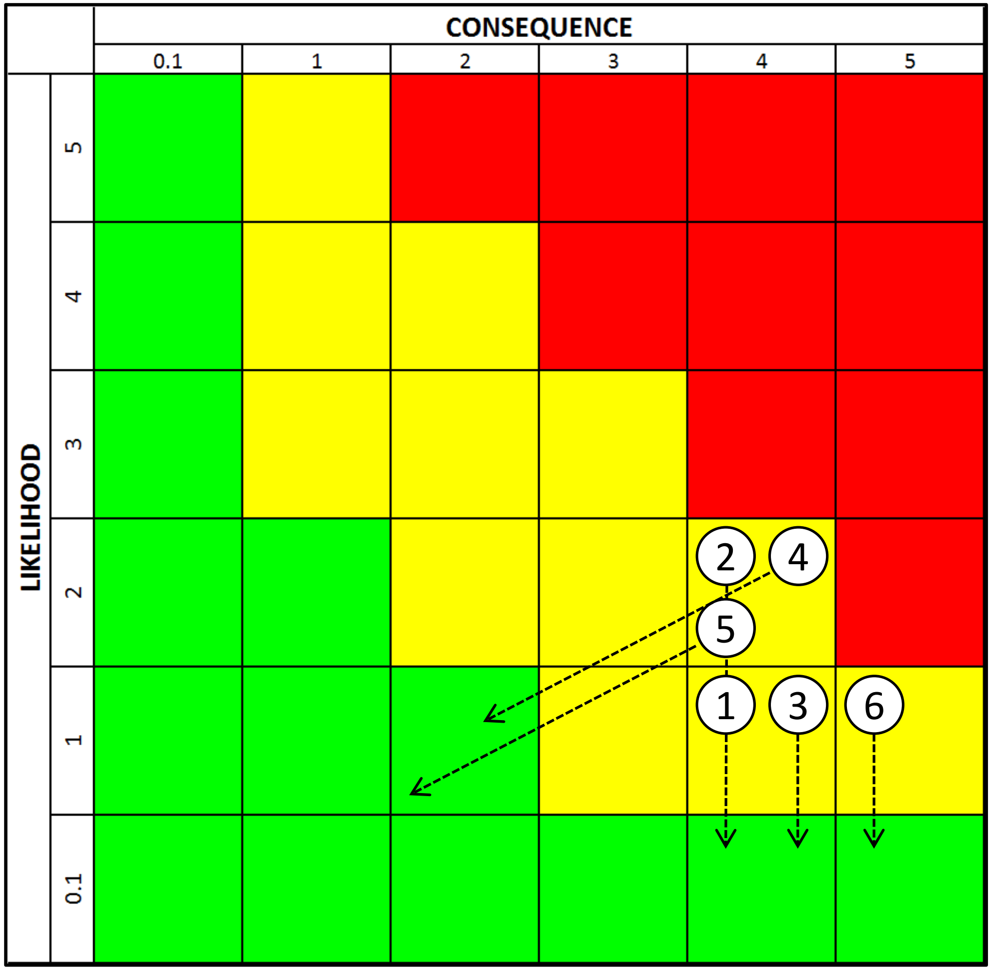
Analyze the pilot-scale test data and derive the basic sizing parameters in terms of membrane surface, pressure drop, temperature gradients, and integration with the plant heat and water management system. Preliminary scale-up design optimizing the TMC unit size and geometry for a 550-MW_e unit shall be developed by using Aspen and other tools developed for the TMC. GTI will work with SmartBurn and M&P to identify potential commercialization paths for this technology to meet the needs of utility customers. Solicit input from utility equipment suppliers and industry groups to guide the commercialization efforts. Cost benefit analysis will be performed and presented. SmartBurn shall lead with participation from GTI and M&P for this task.

Project Milestones

No.	Budget Period	Task/ Subtask	Milestone Description	Planned Completion	Actual Completion	Verification Method
M1	1	1.0	Updated Project Management Plan	11/30/2015	9/30/2015	PMP file
M2		1.0	Budget Period I Progress Report	09/15/2016		Report file
M3	2	5.1	Test Readiness Report	12/31/2016		Report file
M4		1.0	Final Report w/Patent & Property Certification	09/15/2017		Report file

Risk mitigation tracking

1. Pilot plant availability
   - Schedule and coordinate with other tests
2. Subcontractor/vendor delays
   - Formalize deadlines, biweekly update
3. Labor cost exceeds estimates
   - Forecasting, contract labor
4. Steam supply
   - Dedicated steam generator for syngas burner
5. Tar reformer untested as burner
   - CFD modeling, HP burner experience, earlier start
6. TMC pressure seal & control
   - New high-pressure seal design, delta-P control



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Project Funding and Costing Profile

Project Funding Profile	Budget Period 1 9/01/2015 - 08/31/2016		Budget Period 2 9/01/2016 - 08/31/2017		
	Gov't Share	Cost Share	Gov't Share	Cost Share	Total
GTI (Applicant)	$483,530	$128,044	$1,196,303	$457,615	$2,265,492
M&P (Sub)	$144,164	$36,041	$5,798	$1,450	$187,453
SmartBurn LLC (Sub)	$50,000	$20,000	$30,000	$6,000	$106,000
FIU (Sub)	$50,000	$0	$40,000	$0	$90,000
Total	$727,694	$184,085	$1,272,101	$465,065	$2,648,945
Cost Share	79.8%	20.2%	73.2%	26.8%	

Project Costing Profile								
Baseline	Budget Period 1				Budget Period 2			
Reporting	9/01/2015 - 08/31/2016				9/01/2016 - 08/31/2017			
Quarter	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Baseline Cost Plan								
Federal	$123,470	$129,921	$117,378	$356,925	$141,869	$706,351	$373,118	$50,763
Non-Federal	$10,000	$14,000	$20,021	$140,064	$33,240	$291,704	$134,534	$5,587
Total	$133,470	$143,921	$137,399	$496,989	$175,109	$998,055	$507,652	$56,350
Cumulative Baseline Cost Plan								
Federal	$123,470	$253,391	$370,769	$727,694	$869,563	$1,575,914	$1,949,032	$1,999,795
Non-Federal	$10,000	$24,000	$44,021	$184,085	$217,325	$509,029	$643,563	$649,150
Total	$133,470	$277,391	$414,790	$911,779	$1,086,888	$2,084,943	$2,592,595	$2,648,945

Project Timeline

	BUDGET PERIOD I												BUDGET PERIOD II											
	2015				2016												2017							
Tasks	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
1.0 Project Management and Planning		*M1*										*M2*												*M4*
2.0 Process Modeling and Design Evaluation																								
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To Date

Thanks!

Questions?