Scale-Up of High-Temperature Syngas Cleanup Technology

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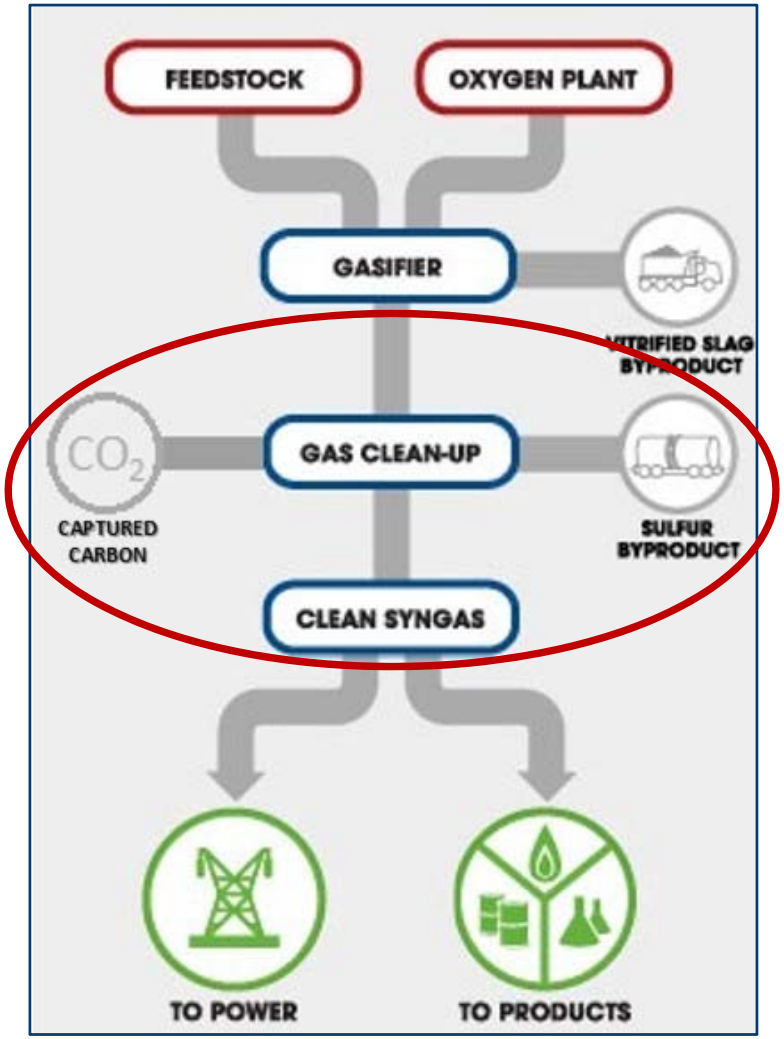
Raghubir Gupta
Vice President, Energy Technology Division, RTI International

Recovery Act: DOE Cooperative Agreement DE-FE0000489

Syngas Cleanup is a Critical Step in the Gasification Process



Graphic: Gasification Technologies Council

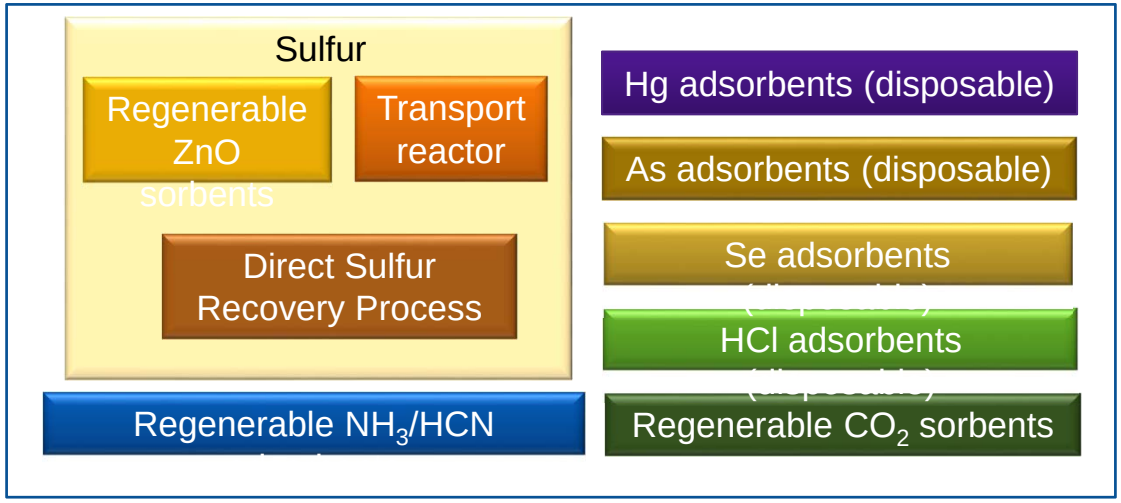
RTI Warm Gas Cleanup Technology

An advanced enabling technology for other downstream technologies, such as novel hydrogen enrichment, syngas conversion, WGS, warm CO_2 capture.

RTI INTERNATIONAL

RTI Warm Syngas Cleanup Technology Platform

RTI PILOT PLANT TEST UNITS AT EASTMAN COAL GASIFICATION PLANT



PRE-COMMERCIAL DEMO PROJECT w/CC UNDERWAY AT TAMPA ELECTRIC SITE

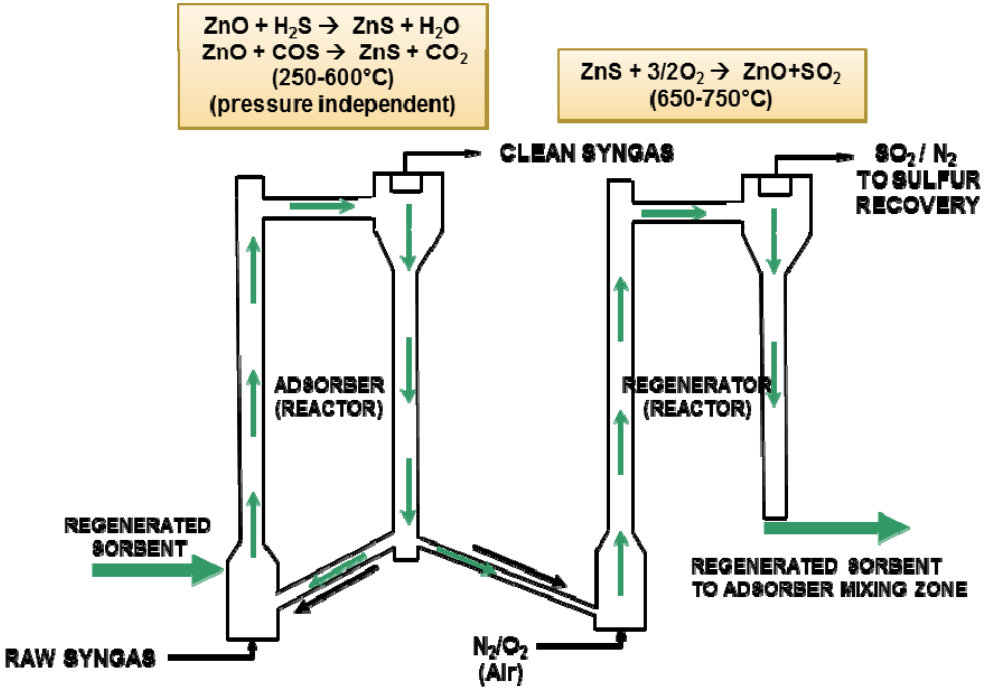
RTI has developed a platform of warm syngas cleanup technologies:

- Increase efficiency and lower costs
- Operate at 250-600ºC
- Pressure independent
- Effective for all forms of sulfur
- Fully compatible with all CO_2 capture
- Flexible modular approach enables specific syngas purity needs to be met
- Systems tested on actual coal-based syngas
- Warm desulfurization process (WDP) now tested through pre-commercial demo scale

RTI Warm Syngas Desulfurization Process (WDP)

A unique process technology based on transport reactor design (related to commercial FCC reactor designs)…

… and on the development of a highly active, attrition-resistant sorbent.

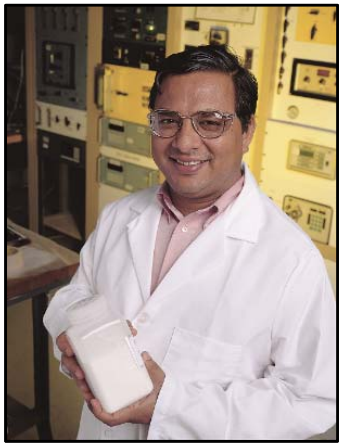


RTI Proprietary Desulfurization Sorbent

- R&D 100 Award
- Unique highly-dispersed nanostructures
- Developed in long-term cooperation with Clariant (~100 tons to date)
- Covered by extensive US & International patents, including several recent improvements

Part of comprehensive high temperature contaminant removal platform.

From Lab to Large Scale Demonstration



Invention (2001)
- Proprietary RTI sorbent
- R&D 100 Award (2004)

Lab/bench testing (2001-2003)
- RTI, NC
- Concept proven & modeled

Pilot testing (2006-2008)
- Eastman Chemical Co., TN
- 3000 hr, coal-derived syngas

Demonstration (2010-2015): Syngas cleanup / carbon capture
- Tampa Electric Co., Polk 1 IGCC Plant, FL
- 50 MW_e equivalent scale, coal/petcoke-derived syngas

Installed Pilot Plant Systems (2006-2008)

Eastman's Kingsport, TN, Coal Gasification Facility

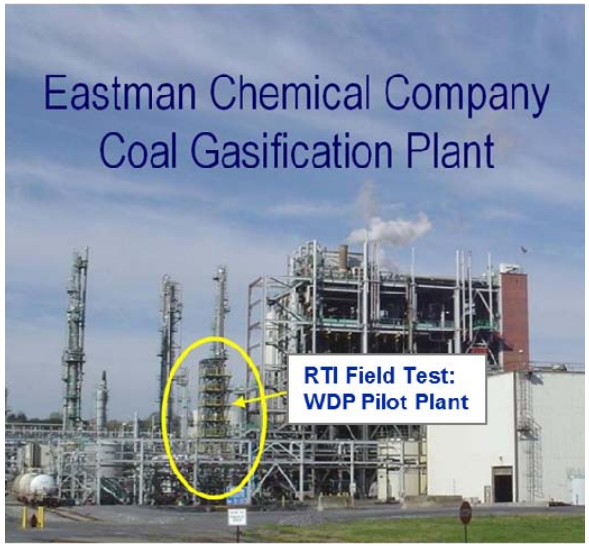
Warm Desulfurization Process (WDP)

Multi-contaminant Control Test System (MCC)

Direct Sulfur Recovery Process (DSRP)

RTI Warm Desulfurization Process (WDP) Pilot Plant Testing at Eastman Chemical Company Coal Gasification Plant (2006-2008)

More than 3,000 hours of total syngas operation. Consistent high performance across a wide pressure range.			
Pressure	20 bar	30 bar	40 bar *
Inlet Sulfur Concentration (avg.)	8,700 ppmv	7,000 ppmv	8,400 ppmv
Effluent Sulfur Concentration (avg.)	5.9 ppmv	10.7 ppmv	5.7 ppmv
% Total Sulfur Removal (avg.)	99.9%	99.8%	99.9%

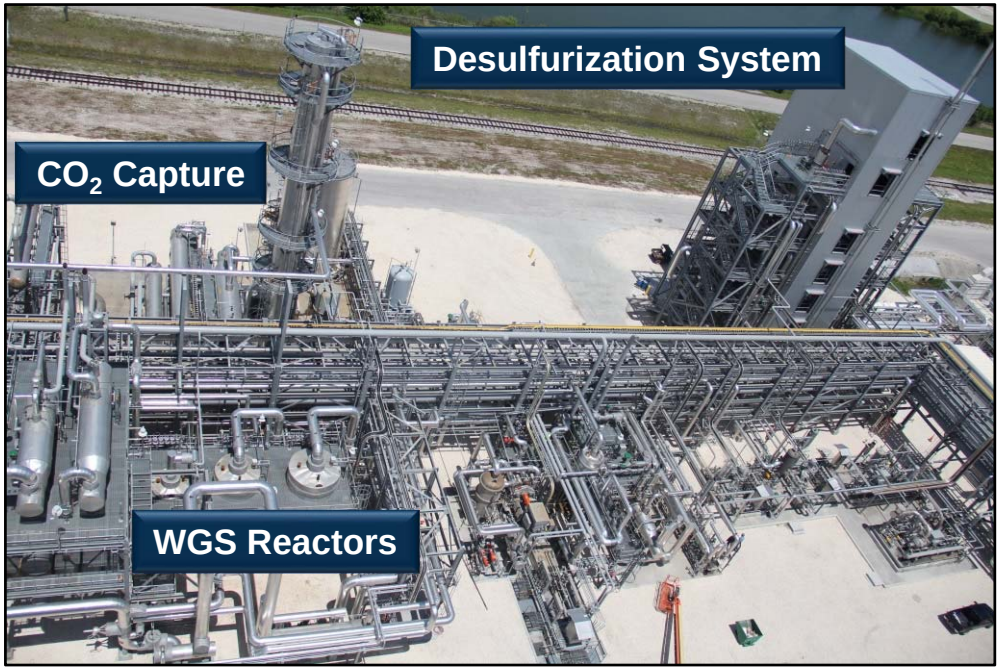


Picture Source: Eastman Chemical Company

Observed attrition rate was lower than commercial FCC catalysts.

* Same pilot unit was tested to 80 bar at ChevronTexaco R&D site with similar (~99.9%) S removal.

RTI Warm Syngas Desulfurization Demonstration Project



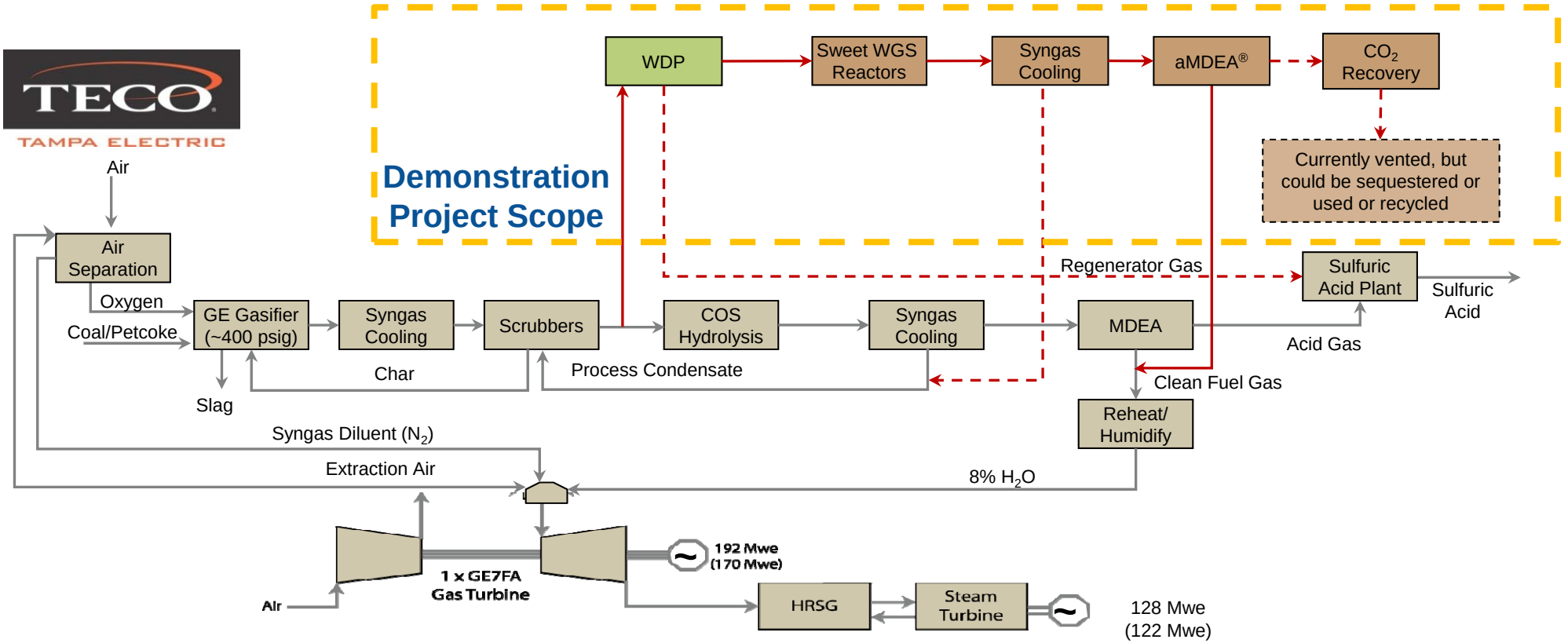
Project Detail: Combined syngas cleanup / water-gas-shift / carbon capture demonstration

- $168.8M DOE ARRA funding to design, construct, operate
- 50 MW_e equivalent scale; captures > 90% of CO_2

Demonstration Project Team	Role
RTI	Project management; technology developer
Tampa Electric (TEC)	Host site and operations support
Shaw Group, AMEC	Engineering (Shaw - FEED, AMEC - EPC)
CH2M Hill	Owner's engineer
BASF	Technology (aMDEA®) for CO_2 capture
Clariant	Produces sulfur sorbent & WGS
Eastman Chemical	Development partner; technical support

Project Objective: Demonstrate RTI's warm syngas cleanup technology with integrated carbon capture at pre-commercial scale at an operating gasification plant.

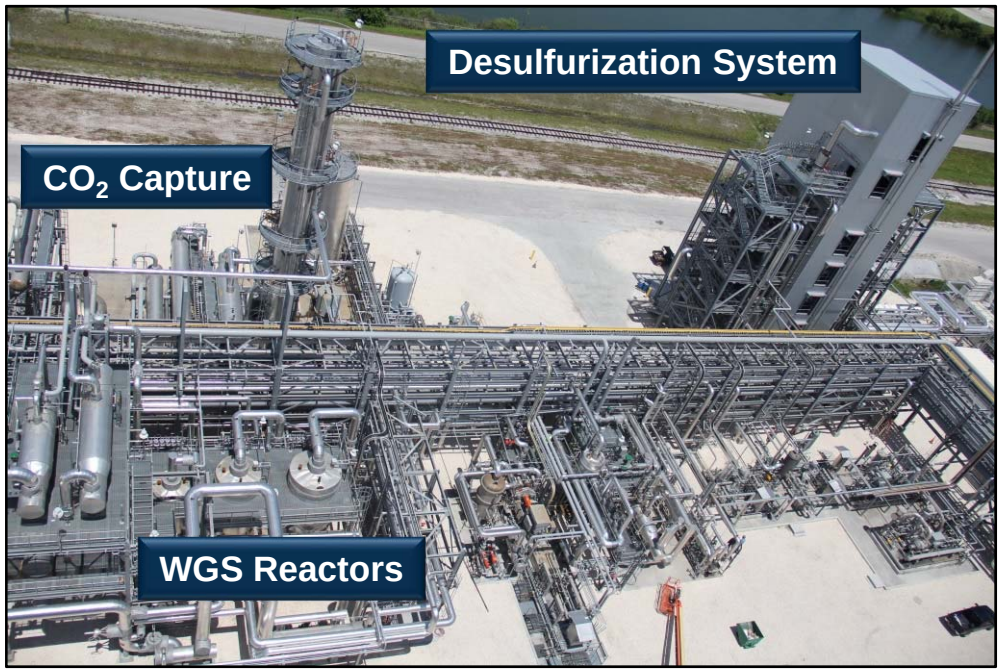
Integration of Syngas Cleaning and Carbon Capture Systems at Tampa Site



20% slipstream test (~50 MW_e) enables direct commercial scale-up from this demonstration scale. The demonstration plant cleans ~2MMscfh of raw syngas from the TECO gasifier.

RTI WDP Demonstration Project Objectives

- Demonstrate RTI WDP technology's ability to reduce capital costs, improve efficiency, and lower carbon footprint for gasification
- Mitigate design and scale-up risks
- Verify capital and operating costs
- Integrate RTI warm syngas cleanup technology with carbon dioxide capture



WDP Scale-Up Factors

	EMN Pilot Plant	Demonstration	Commercial
Size (MWe)	**0.3**	**50***	**600****
Gas Flow (KSCFH)	8	2,000	24,000
Footprint (ft^2)	260	1,100	3,000
Adsorber Mixing Zone Riser	 15'H x 2.5"ID 40'H x 1.5"ID	 16'H x 54"ID 50'H x 28"ID	 16'H x 15'ID 50'H x 8'ID
Regenerator Mixing Zone Riser	 10'H x 1.5"ID 20'H x 1"ID	 21'H x 14"ID 44'H x 8"ID	 21'H x 4'ID 44'H x 2.5'ID

* About half the size of commercial industrial gasification systems which are typically ~100 MWe.

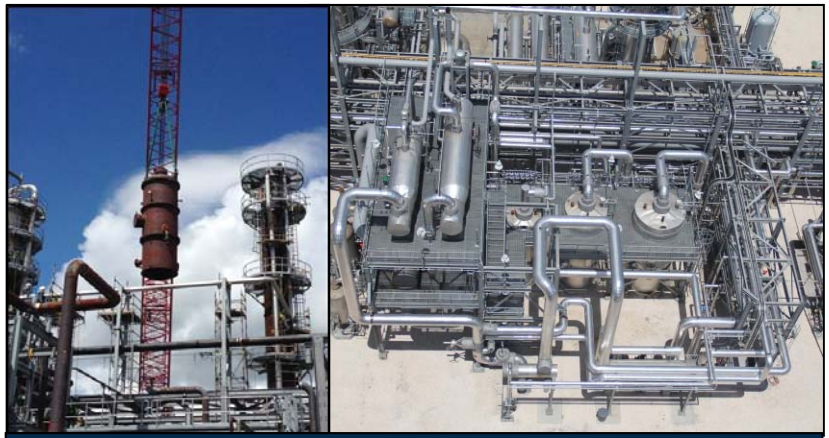
** Approximately the size of current state-of-the-art IGCC reference plants (~600 MWe)

Demo to Full Commercial Scale is Straight-forward Scale-up

Demonstration Plant Site Location Pre-Construction

RTI 50-MWe Warm Syngas Cleanup Demonstration Project - Construction

Warm Syngas Desulfurization Process (WDP) Equipment



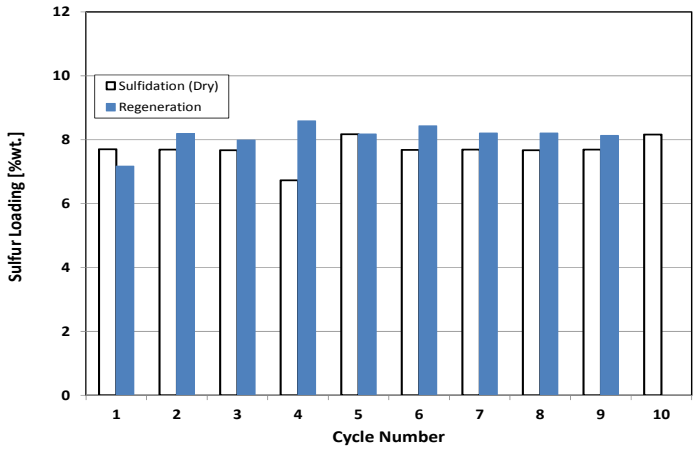
Water-Gas-Shift (WGS) Reactors

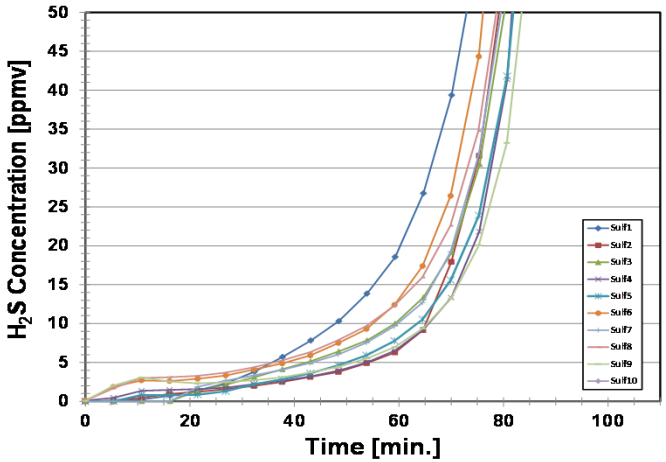
aMDEA Carbon Capture Unit

Completed Construction – 50-MWe Demonstration Project

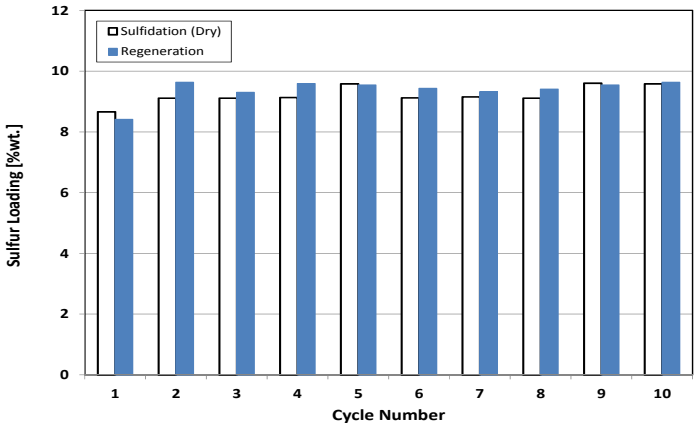
Ribbon-Cutting Ceremony
April 9, 2014

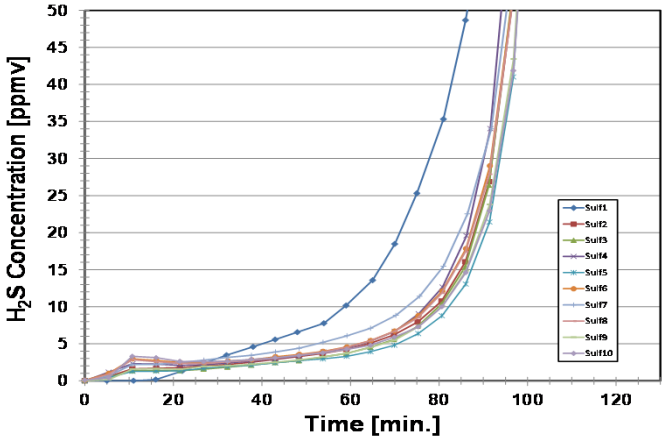
Bench-scale Testing of RTI-3 Shows Good Performance





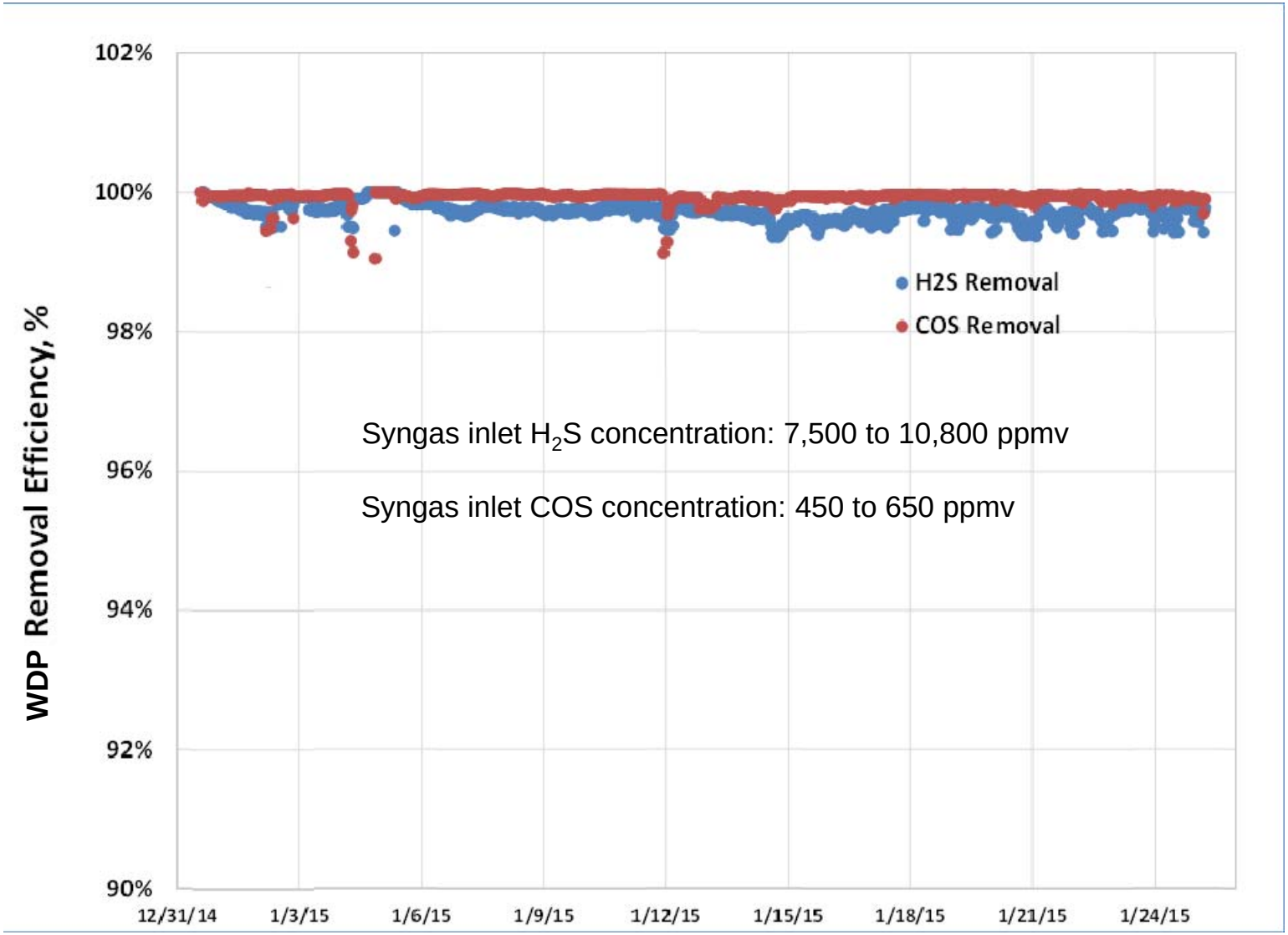
Initial production



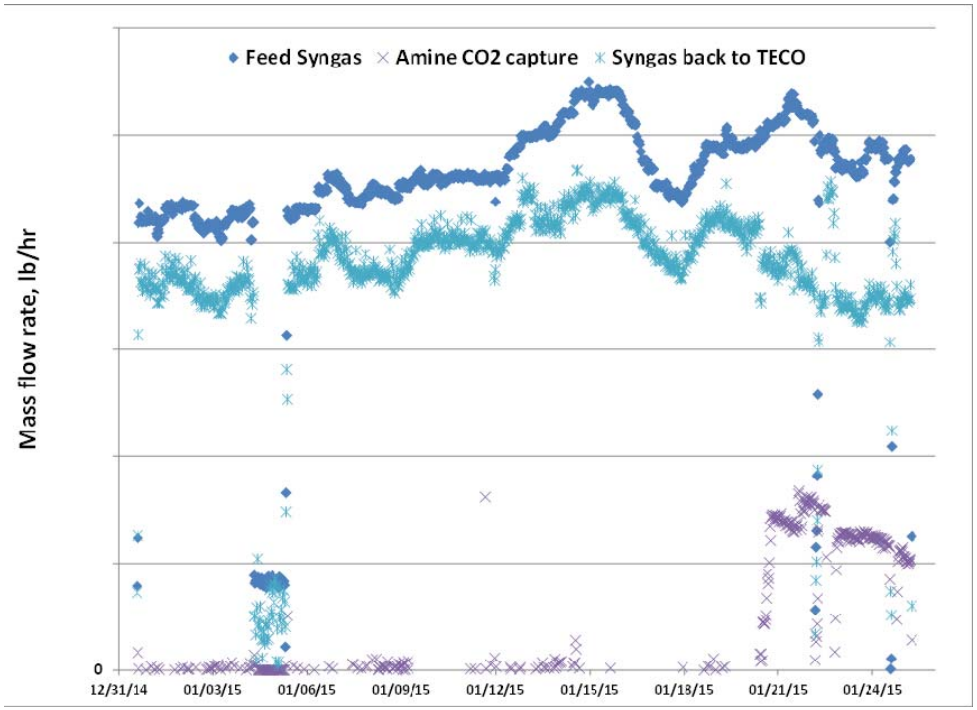


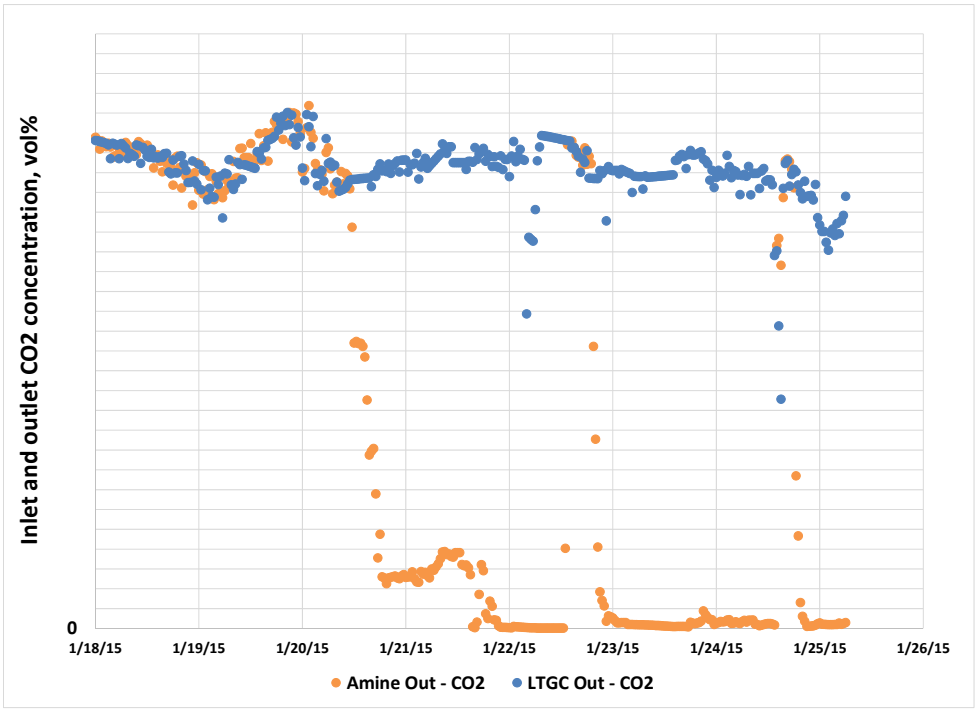
Optimized production

Demonstration Plant Results: High Total S Removal

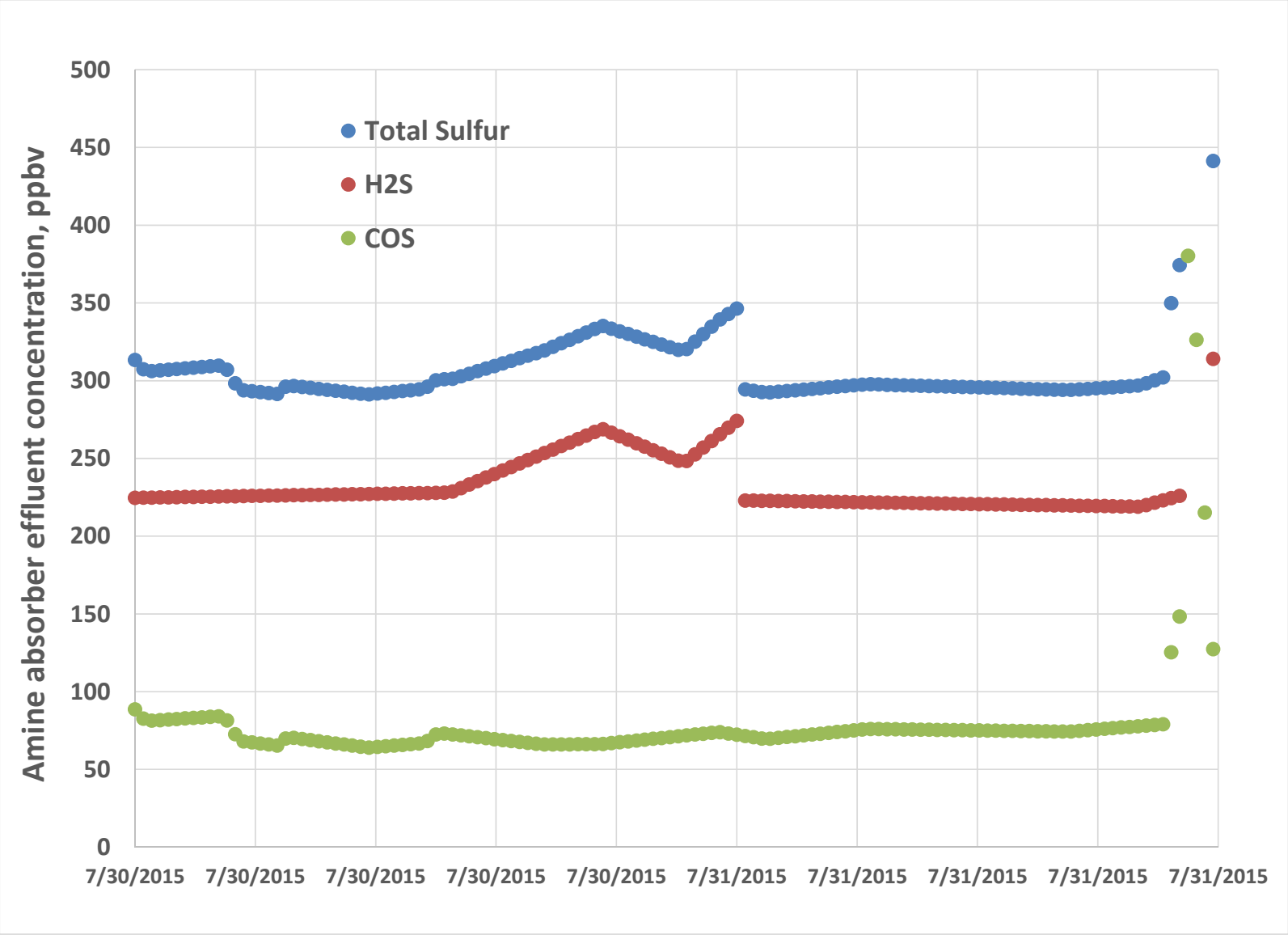


Demonstration Plant: Gas Mass Flow Rates for Syngas



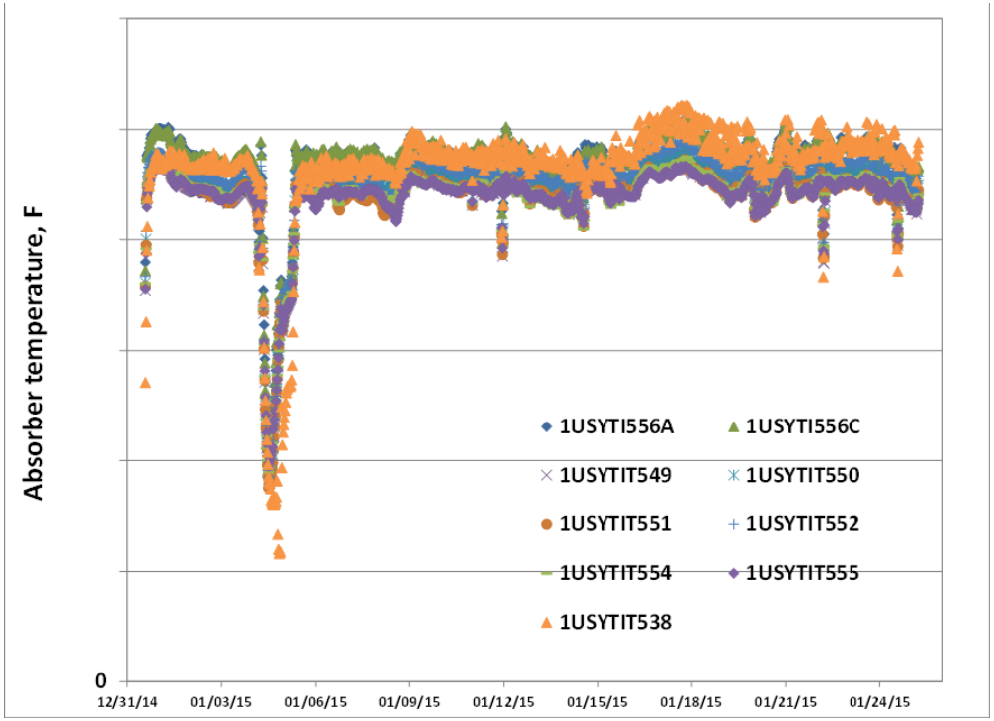


Sulfur Concentration Downstream of the aMDEA

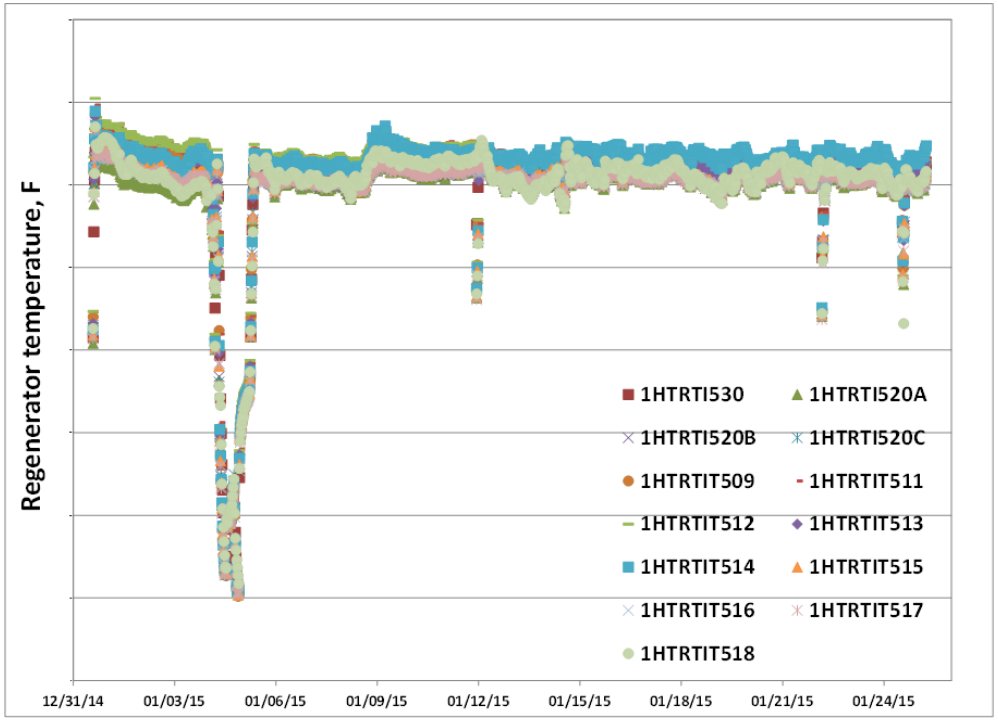


Demonstration Plant: Temperature Profile

Adsorber



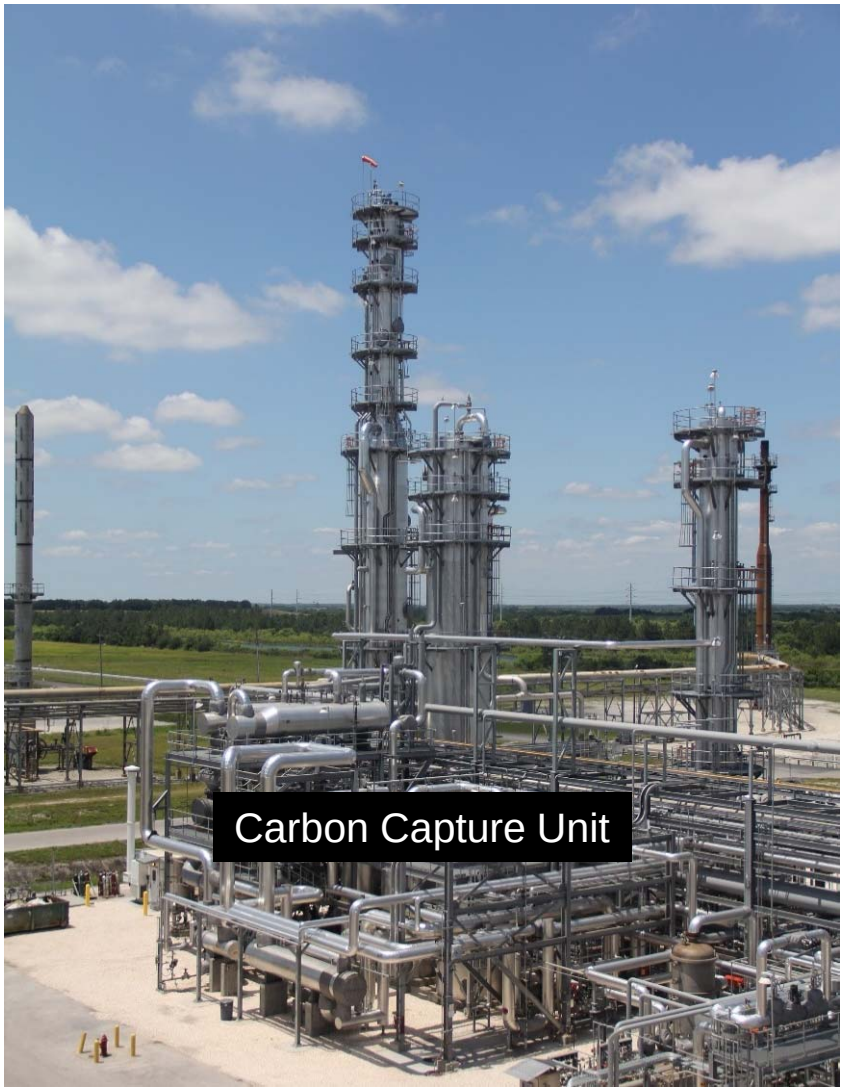
Regenerator



RTI Warm Gas Cleanup (WDP) Demonstration Project Performance

- Construction achieved on schedule and under budget
- > 500,000 total labor hours with no significant injury (other than minor first aid)
- Unit performing as expected with >1,200 syngas operation hours to date
- 99.7-99.9% total sulfur removal from RTI WDP step
- >99.99% total sulfur removal achieved WDP + aMDEA® (sub-ppmv levels of total sulfur in cleaned syngas)

RTI Warm Gas Cleanup (WDP) Demonstration Project Performance



- Sorbent attrition rate significantly lower compared to the design value
- Sorbent sulfur capacity steady - no sign of deactivation
- Successful operation both below and above design syngas flow rate
- Demonstration testing continuing with goal to achieve at least 5,000 total syngas operation hours
- Now seeking suitable partner(s) to help RTI commercially deploy the technology

Competitive Position of RTI Warm Syngas Cleanup Technology

A previous 2007 study by Nexant* indicated significant (10-15% or more) advantages of RTI's warm syngas cleanup technology for IGCC applications without carbon capture. This study was based upon data from the 3000+ hrs of pilot testing at Eastman Chemical Company. The Nexant studies were also independently verified by a separate study commissioned by DOE-NETL with Noblis.

RTI Technology Benefits – IGCC w/o CC

- **Increases overall IGCC efficiency ~10%**
- **Dispatches ~10% more power**
- **Reduces IGCC capex/KW ~15%**
- **Reduces LCOE ~10%**
- **Reduces water consumption ~25%**
- **Reduces wastewater ~60%**
- **Reduces high-pressure N_2 used by ~40%**

Actual cost data from the demo plant indicate that these previously estimated cost benefits are conservative. A new Nexant study is now underway (including CC) based upon results from our demonstration testing at Tampa Electric Company.

* http://www.netl.doe.gov/File%20Library/Research/Coal/energy%20systems/gasification/pubs/090520-Nexant-RTI-Rpt-_Public_.pdf

Competitive Position of RTI Warm Syngas Cleanup Technology

Ongoing RTI techno-economic 3rd-party validated studies also show potential for significant advantages of RTI's warm syngas cleanup technology for chemicals/fuels applications

RTI Technology Benefits – Chemicals

- **Substantially reduces capex for AGR/SRU**
- **Decouples S and CO_2 removal, with benefits**
- **Integrates with most CO_2 capture processes to achieve S reductions adequate for use in chemicals/fuels applications at lower costs & higher overall process efficiencies**
- **Reduces overall water footprint**
- **Increases efficiency in coal usage - same product volumes with less feedstock**

RTI WDP Technology Can Expand Markets for Conventional Acid Gas Removal (AGR)

Typical/Suitable Applications	Amines	Selexol®	Rectisol®	RTI WDP + CC (e.g., aMDEA®)
IGCC (without CC)	✓	✓	✗ (too expensive)	✓
IGCC (with CC)	✓	✓	✗ (too expensive)	✓
H_2 or NH_3/Urea	✗ (not capable)	✓	✓	✓
Chemicals (e.g., MeOH, F-T, SNG)	✗ (not capable)	✗ (not capable)	✓	✓

RTI WDP + aMDEA® works economically across the whole spectrum of applications

* CC = Carbon dioxide capture

Techno-Economic Analyses: Gasifier Design Basis

- Shell solids-fed type gasifier
- Coal – PRB or Shenhua Mix* coal (~0.6-0.7% sulfur in coal)
  (~2,000-3,000 ppmv total sulfur in raw syngas)
- Syngas flow-rate equivalent to two large gasifiers (each ~300 MW_e)
  (combined ~33,000 lbmoles/hr of CO + H_2)
- Raw syngas pressure ~ 600 psia, Temperature ~ 600°F

* Representative of the most common type of coal in China

Techno-Economic Analyses: Syngas Cleanup Design Cases

Base Case for Chemicals (e.g., Methanol):

Sour WGS + Syngas Cooling + Rectisol® AGR + Claus/SCOT® SRU

Base Case for IGCC Power Generation with CC:

Sour WGS + Syngas Cooling + Selexol® AGR + Claus/SCOT® SRU

(dual-stage Selexol® for IGCC with CC)

RTI WDP Cases:

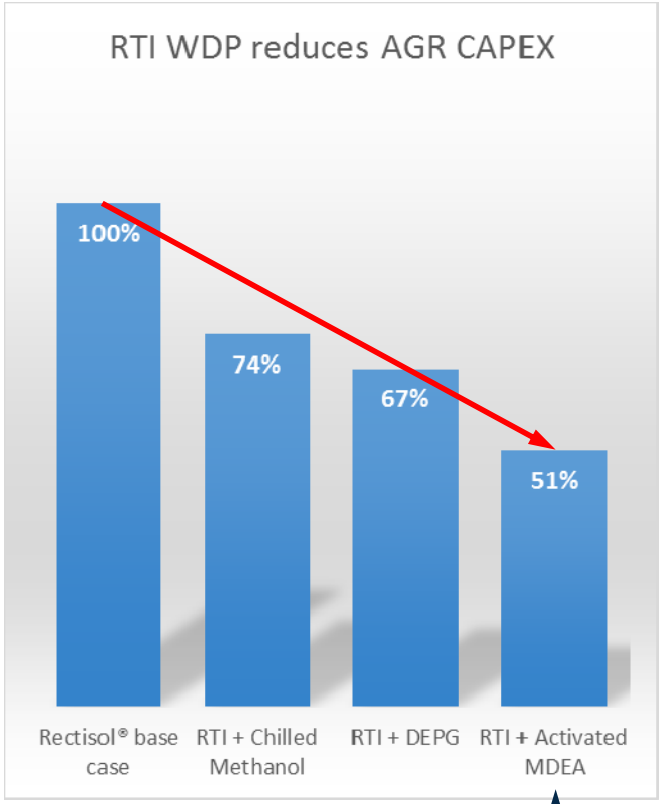
WDP + Sweet WGS + Syngas Cooling + CC* + Modified Claus/DYNAWAVE® SRU

* CO_2 capture (CC) options for WDP Cases:

- Rectisol® (chilled methanol; Linde/Lurgi)
- Selexol® (DEPG solvent; UOP)
- Activated amines (e.g., BASF aMDEA®)

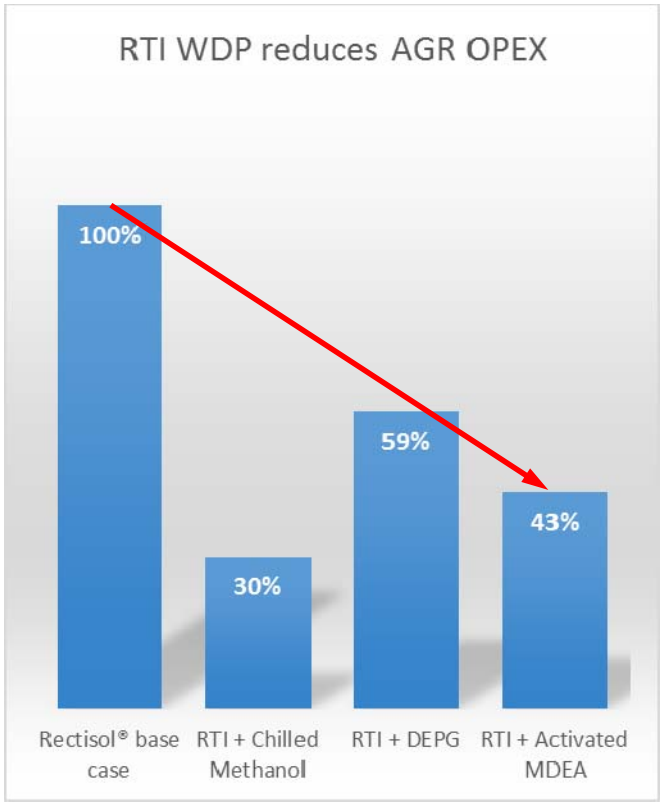
Acronyms:
AGR = acid gas removal
CC = carbon capture
WGS = water gas shift
SRU = sulfur recovery unit

TEA: Coal to Methanol Comparisons



Technology used in RTI Demo Plant

RTI WDP improves economics for all CC cases!

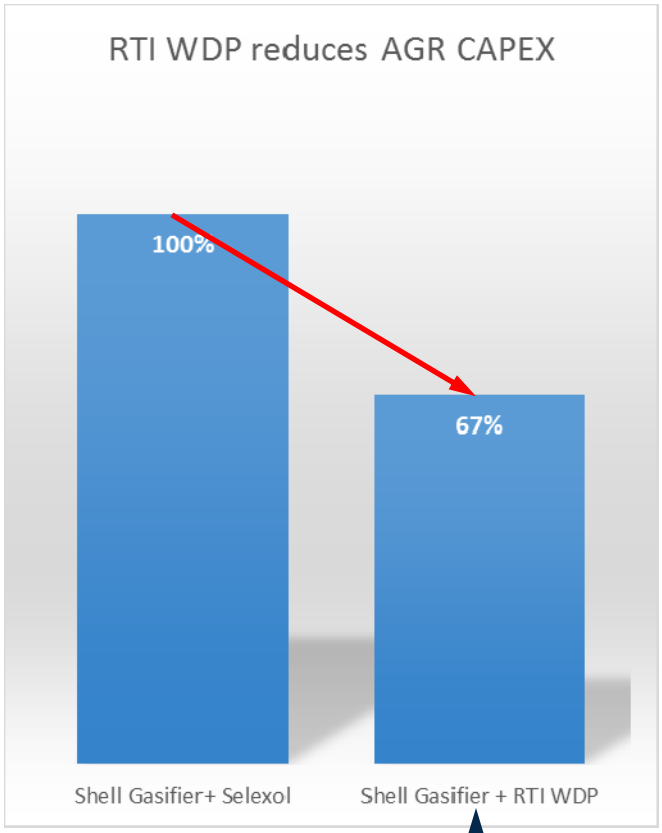


Non-labor, non-feedstock operating costs

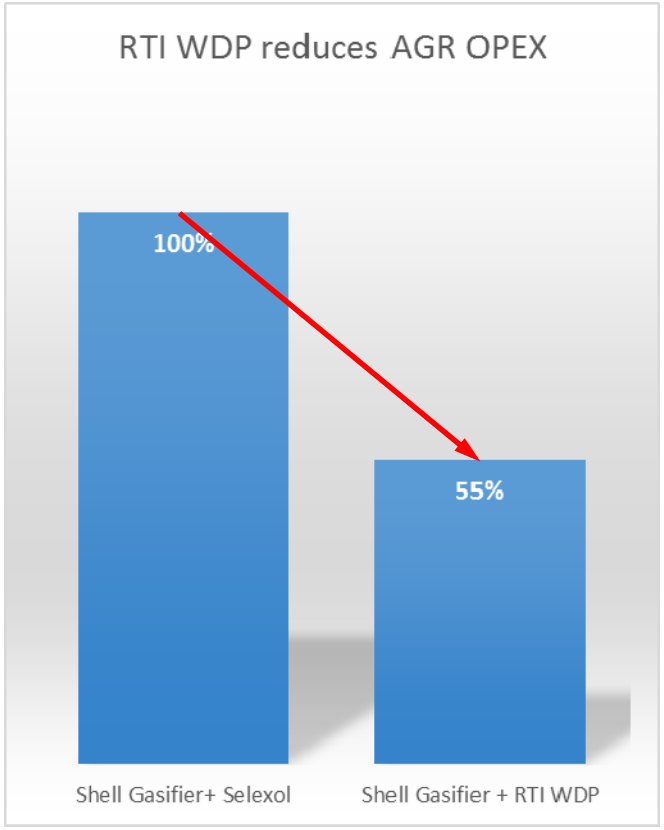
NOTES:

- Cost savings indicated are across the entire block from raw warm syngas exiting the gasifier block through cleaned syngas feed to the methanol conversion step, including the SRU.
- These analyses do not include additional benefits to the entire plant that might occur from overall efficiency savings. Nexant is currently performing a detailed analysis to determine these overall system benefits.

TEA: IGCC (power gen) with CO_2 Capture



Technology used in RTI Demo Plant



Non-labor, non-feedstock operating costs

NOTES:

- Cost savings indicated are across the entire block from raw warm syngas exiting the gasifier block through cleaned syngas feed to the syngas turbine step, including the sulfur recovery unit.
- These analyses do not include additional benefits to the entire IGCC plant that might occur from overall efficiency savings, such as higher net power generation per ton of coal. A new Nexant study is providing an indication of these additional overall system benefits, which are substantial.

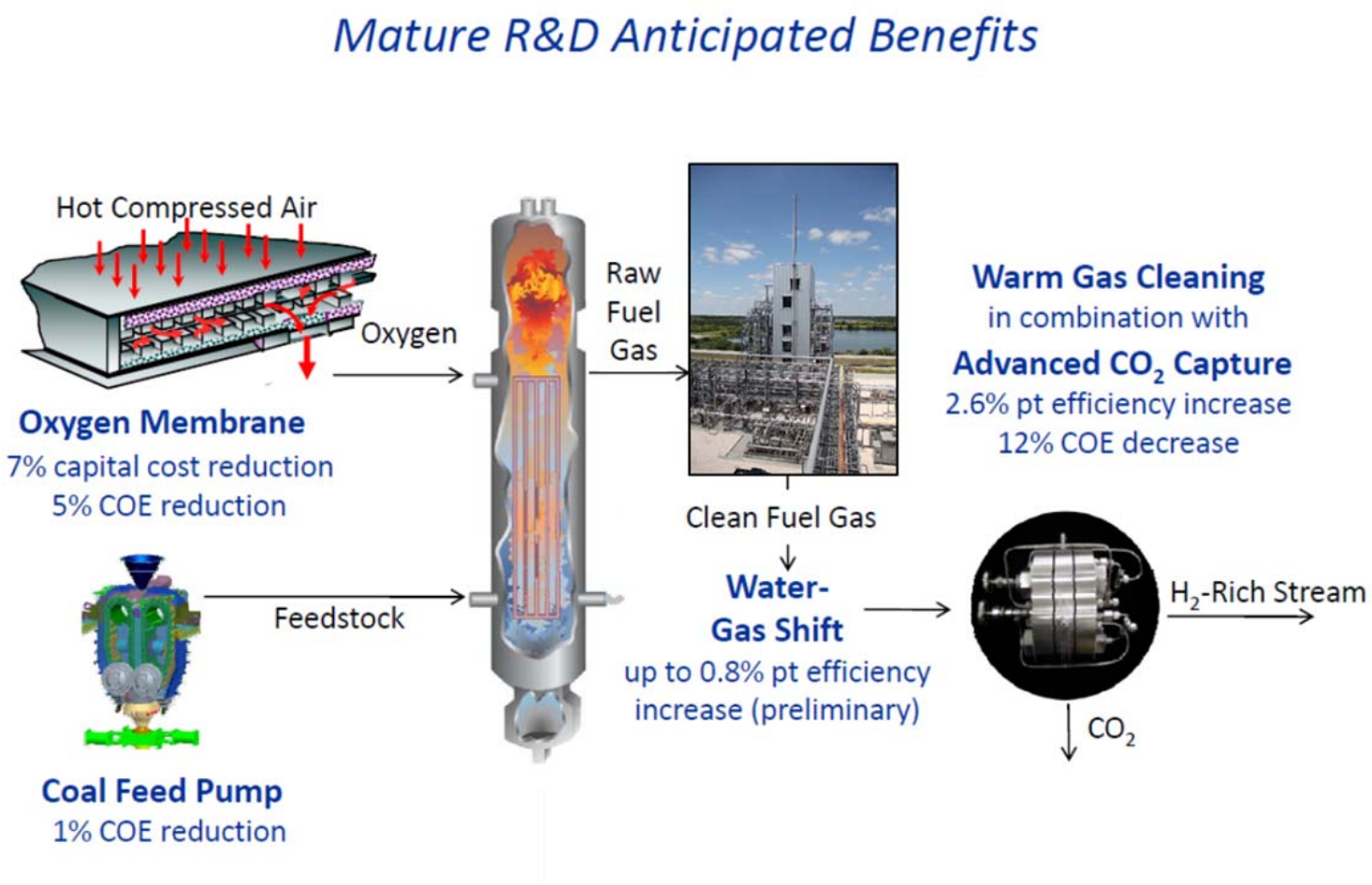
Benefits of RTI WDP Technology

- Rectisol® and Selexol® (solvent-based sorbent systems that operate at sub-ambient temperatures) dominate the current coal to chemicals market.
- RTI WDP is a unique differentiated warm-temperature, solid-sorbent based syngas cleanup system that simultaneously offers:
  - Lower capital costs (20-50% less),
  - Lower non-labor, non-feedstock operating costs (up to 30-50+% less),
  - Improved overall process efficiency (up to 10+% better),
  - Improved process flexibility by decoupling sulfur removal and carbon dioxide capture, and
  - A capable and economic syngas cleanup option for all applications.

Ancillary R&D to Support this Project

- Trace Contaminant Removal Process (TCRP) Technology: warm-temperature (250-600°C) sorbents for other trace contaminants in syngas such as Hg, As, Se, HCN, NH_3, HCl.
- Direct Sulfur Recovery Process (DSRP) Technology: alternative to Claus/SCOT for elemental sulfur recovery
- Advanced Water-Gas-Shift (WGS) Technology: improves efficiency and reduces the cost of WGS
- Warm-temperature CO_2 Capture Technology: enables full efficiency potential of WDP by avoiding downstream syngas cooldown for carbon capture
- Micro-reactor Testing: testing of syngas from RTI's WDP demonstration facility to determine its suitability for chemicals and fuels conversion

Key DOE-NETL Gasification Systems R&D Program Areas



RTI Warm Gas Cleanup Technology

An advanced enabling technology for other downstream technologies, such as novel hydrogen enrichment, syngas conversion, WGS, warm CO_2 capture.

Integration with Other DOE Supported Projects

RTI WDP technology is a key enabler and a complement for a number of other DOE-supported technologies including:

- Advanced gasification technology such as the Aerojet Rocketdyne (now GTI) compact gasifier and dry solids pump:
  - New Nexant studies (soon to be released) show that integration of this advanced gasifier technology with RTI WDP provides significant reductions in overall capital cost, operating cost, and cost of CO_2 avoided and a significant improvement in overall efficiency for both power generation and chemicals production.
- Warm-temperature CO_2 Capture Technology:
  - Enables full efficiency potential by avoiding substantial syngas cooldown
- Advanced WGS:
  - Enables advanced WGS for either sweet or sour WGS systems to help optimize overall process design, cost, and efficiency
- RTI WDP is viable across a wide spectrum of sulfur concentrations and species in syngas, across a wide range of pressures (pressure-independent), and can couple with almost any downstream carbon capture technology, making it suitable and beneficiary for integration with almost any advanced gasification process design, including hybrid coal-biomass and coal-NG systems.

Summary

- RTI has developed and is now demonstrating at near-commercial scale an advanced warm syngas desulfurization process (WDP) at temperatures as high as 600°C.
- WDP technology alone can achieve up to 99.9% total sulfur (S) removal from syngas and when coupled with a carbon capture technology, such as activated amines, can achieve >99.99% total S removal (sub-ppmv levels, suitable for most chemicals/fuels).
- Key to the technology is a proprietary regenerable sorbent that can be used in a very rapid, small footprint transport reactor system with excellent attrition resistance.
- RTI WDP is a unique differentiated syngas cleanup technology system that can:
  - Improve process flexibility by decoupling sulfur removal and carbon dioxide capture,
  - Integrate synergistically with most CO_2 removal technologies to enable them to meet syngas purity requirements for ultra-clean power and chemicals/fuels applications,
  - Provide reduced capital costs for syngas cleanup (20-50% lower than conventional technologies) in either a standalone or integrated approach,
  - Provide reduced overall non-labor, non-feedstock operating costs (30-50+% less), and
  - Provide higher overall process efficiencies (up to 10+% better).
- The WDP technology will be ready for commercial deployment in 2016 and RTI has launched a significant effort to identify and engage the best commercial partner(s).

Acknowledgements

- RTI Contributors: Brian Turk, Ben Gardner, David Denton, J.P. Shen, Atish Kataria, Gary Howe, John Albritton, Vijay Gupta, Himanshu Paliwal, Pradeep Sharma, Markus Lesemann, Jason Norman, Justin Farmer, Caroline Ball
- DOE/NETL: Jenny Tennant, David Lyons, Regis Conrad, Bhima Sastri, Sam Tam, Peter Rozelle, Gary Stiegel
- Development and Project Partners:
  - Tampa Electric Company
  - Eastman Chemical Company
  - Technip (formerly Shaw)
  - AMEC Foster Wheeler
  - CH2M Hill
  - BASF
  - Clariant (formerly Sud Chemie)

QUESTIONS?

Contact: Raghubir Gupta
Vice President
Energy Technology Division
RTI International
gupta@rti.org
919-541-8023