RTI Warm Syngas Cleanup Operational Testing at Tampa Electric Company's Polk 1 IGCC Site

DOE Cooperative Agreements DE-FE0000489 and DE-FE0026622
Gasification Systems Project Review Meeting
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DOE/NETL Technology Managers: Gary Stiegel, Jenny Tennant, K. David Lyons
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Energy Technologies at RTI International

delivering **the promise of science** for global good

RTI INTERNATIONAL

$885 M
FY2016 Revenue

3,064 Projects (fiscal year 2016)

1,102 Clients (fiscal year 2016)

5,032 Staff Members Worldwide

90 Languages

250 Degree Fields

105 Nationalities

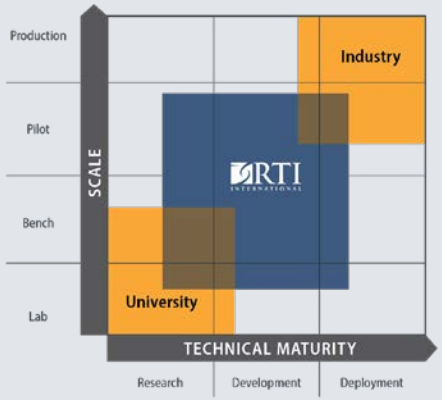
13 U.S. Offices

10 International Offices

ENERGY TECHNOLOGIES

Developing advanced process technologies for energy applications by partnering with industry leaders

Clean Coal / Syngas Processing	Industrial Water Treatment
Carbon Capture & Utilization / Gas Separations	Advanced Materials for Catalysis & Separations
Biomass Conversion	Natural Gas Extraction & Conversion



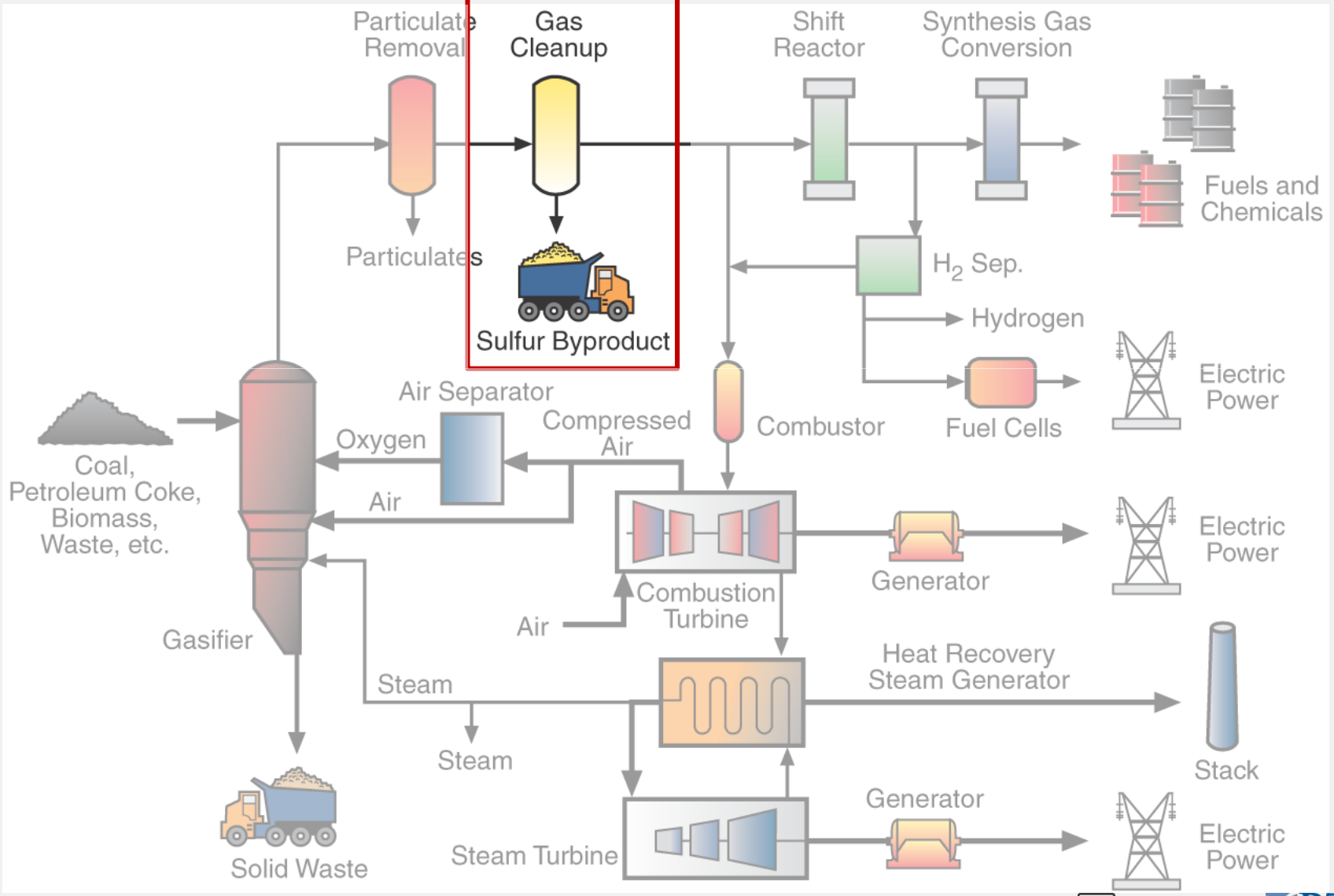
Focused on Applied Research (concept to demonstration) in Partnership with Government Agencies, Academia, and Industry

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY | U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy BIOENERGY TECHNOLOGIES OFFICE | U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy ADVANCED MANUFACTURING OFFICE | arpa·e | EMISSIONS REDUCTION ALBERTA | GASSNOVA | CASALE | CLARIANT | BASF We create chemistry

SINTEF | HALDOR TOPSOE | VEOLIA | Masdar | THE LINDE GROUP | BERKELEY LAB | MIT | CLEMSON UNIVERSITY | NC STATE UNIVERSITY | STANFORD UNIVERSITY | Duke UNIVERSITY | UC RIVERSIDE

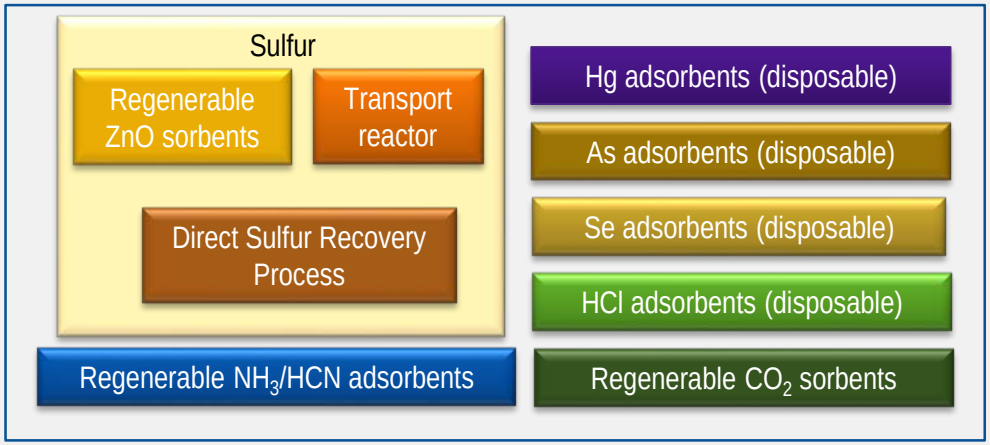
NATIONAL ENERGY TECHNOLOGY LABORATORY | RTI INTERNATIONAL

Integrated Gasification Combined Cycle – Syngas Cleanup



RTI Warm Syngas Cleanup Technology Platform

RTI PILOT PLANT TEST UNITS AT EASTMAN COAL GASIFICATION PLANT



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

RTI has developed a platform of warm syngas cleanup technologies that:

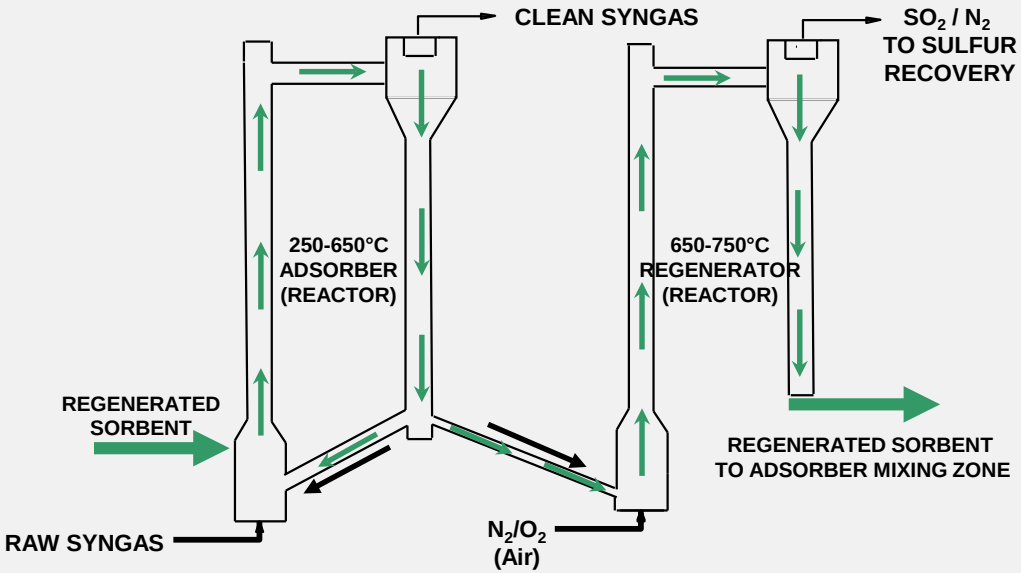
- Increase efficiency and lower costs,
- Operate at 250-600ºC (maximum temperature varies with specific contaminants),
- Have been tested on actual coal-based and petcoke-based syngas,
- Are fully compatible with CO_2 capture technologies, and
- Enable specific syngas purity needs to be met via a flexible modular approach.

RTI Warm Gas Desulfurization Process (WDP) - Overview

Enables high removal of total sulfur (≥99.9%) from syngas at temperatures as high as 600°C.

A unique process technology based on dual transport reactor loops (similar to FCC reactor designs)…

… and on a regenerable, high-capacity, rapid acting, attrition-resistant sorbent.



RTI Warm Gas Desulfurization Process (WDP)

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

Successful WDP Scale-up from Lab to Large-Scale Pre-Commercial Testing

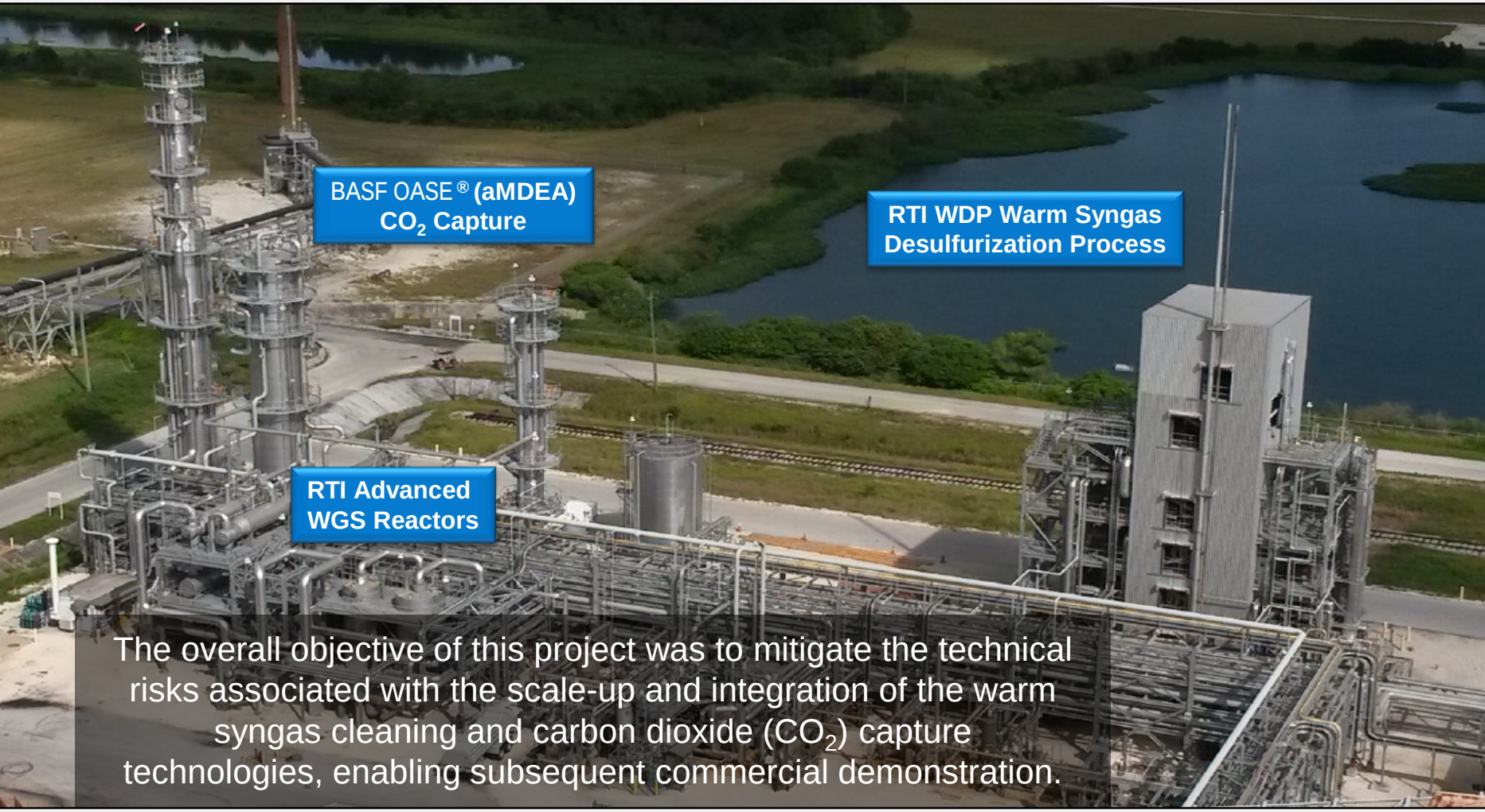
Invention (2001)
- Proprietary RTI sorbent
- High attrition resistance
- Lab production

Lab/bench testing (2001-2003)
- RTI International, NC
- Simulated syngas
- Extensive bench scale testing (operating conditions, syngas composition and regeneration gas)
- Largest lab production

Pilot testing (2006-2008)
- Eastman Chemical Co., TN
- >3,000 hr, coal syngas
- Parametric testing of operating conditions (pressure and temperature)
- Pilot batch production

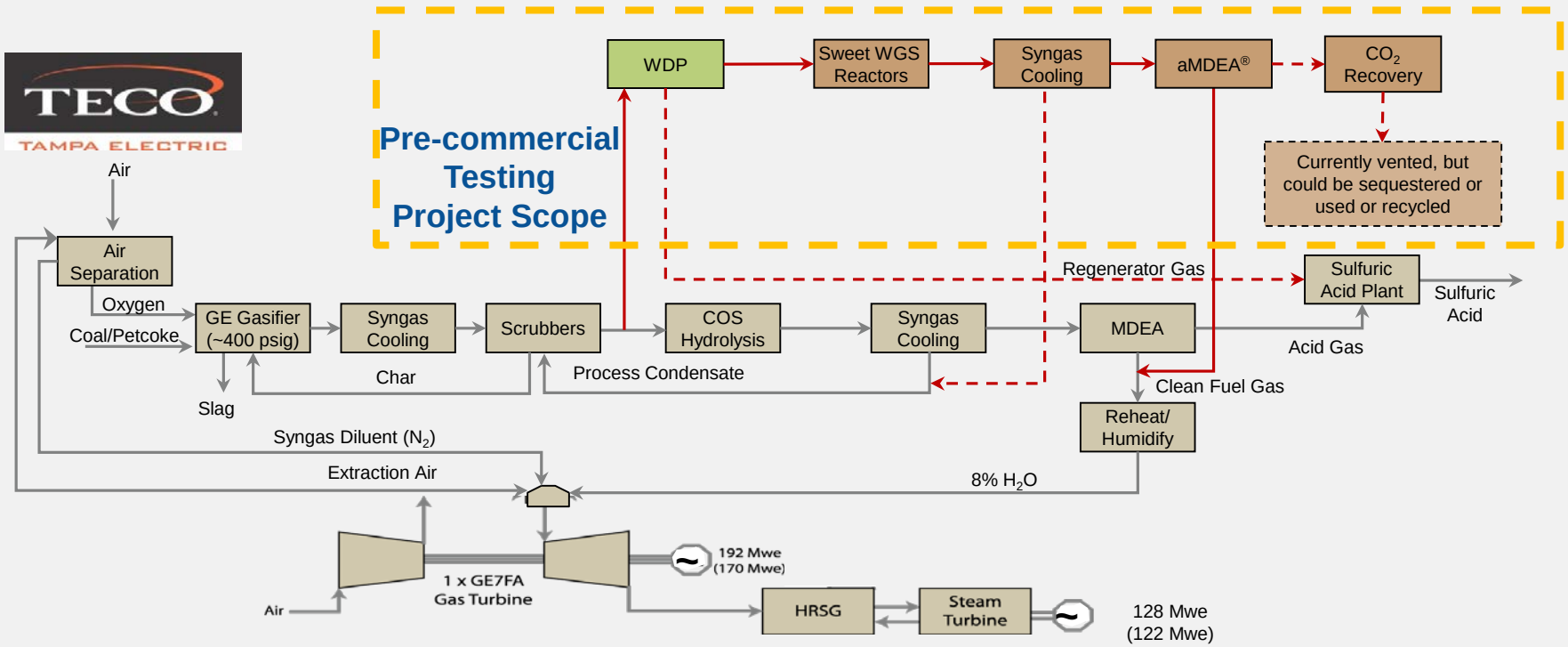
Pre-Commercial – Syngas Cleanup & CO_2 Capture (2010-2016)
- Tampa Electric Co., Polk 1 IGCC Plant, FL
- 50-MW_e scale, >3,500 hr, coal/petcoke-derived syngas
- Commercial scale equipment
- Fully integrated with operating plant (upstream and downstream)
- Commercial sorbent production

RTI Warm Syngas Desulfurization: 50-MW_e Pre-Commercial Testing Project at Tampa Electric Company's Polk 1 IGCC Site



The overall objective of this project was to mitigate the technical risks associated with the scale-up and integration of the warm syngas cleaning and carbon dioxide (CO_2) capture technologies, enabling subsequent commercial demonstration.

Integration of Warm 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.

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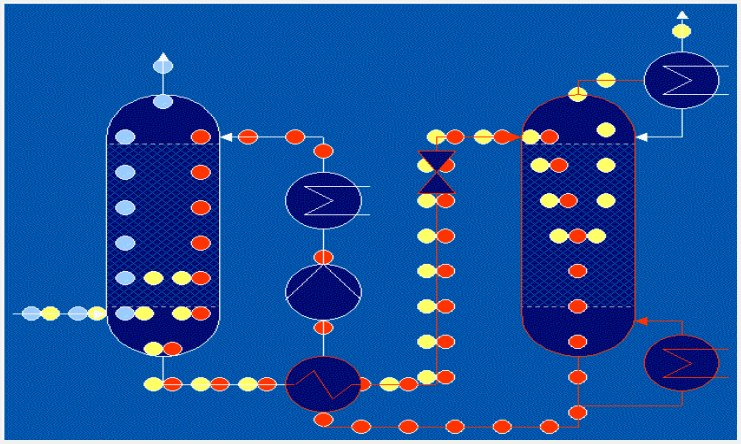
RTI INTERNATIONAL

CO_2 Capture: BASF OASE® Activated Amine Process



Source: BASF

OASE® has the lowest specific energy consumption of any standard amines for acid gas removal.

OASE® 's higher absorption kinetics and capacity reduce equipment size resulting in lower capex and opex.

OASE® is chemically and thermally stable, non-corrosive, non-toxic, and readily biodegradable.

But, exploiting OASE® for CCS in IGCC requires upstream selective sulfur removal technology for syngas.

Design rate ~1200 tpd of carbon dioxide captured by RTI demonstration plant

RTI WDP Pre-commercial Demonstration Project Team

Project Team	
RTI INTERNATIONAL	Overall project management responsibility, engineering, day-to-day operations oversight, and laboratory support
TECO TAMPA ELECTRIC	Provision of the site, syngas slipstream feedstock, demonstration unit product/by-product off-takes, process operators, and operations and maintenance support
amec foster wheeler	EPC, operations and maintenance support, on-site process engineers, safety and an experienced site manager
CLARIANT	Sorbent and catalyst supply
BASF The Chemical Company	Activated amine supply and process license
U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY	Funding agency; project consultation

RTI WDP Demonstration Project Performance – Construction and Initial Operation Period (ARRA Funding)

DOE/RTI/TECO/Clariant Team

- Construction achieved on schedule & under budget
- >500,000 total labor hours with no significant injury
- Unit performed as expected
- ~99.9% total sulfur removal from RTI WDP step
- Up to 99.999% total sulfur removal with WDP + aMDEA® (sub-ppmv levels of total sulfur in syngas)
- Sorbent attrition rate in line with design expectations
- Sorbent sulfur capacity steady - no deactivation
- Successful operation below and above design rate
- Unit was down for an unexpectedly long period of time in 2015 due to host site problems, resulting in need for extension of the operational testing period.

Primary Need and Goals - Post-ARRA Operational Testing

- **Need:**
  - Testing through ARRA funding showed that WDP technology had great potential to provide clean syngas from coal and petcoke-based gasification at increased efficiency and at lower capital and operating costs than conventional syngas cleanup technologies.
  - The unexpectedly long host site outage in spring/summer of 2015 sacrificed operational time needed to fully address all critical technical risks before the technology could be deemed ready for scale-up to a full commercial demonstration.

- **Goals of Extended Operational Testing:**
  - Operate the WDP unit up to an additional **3,000 hours** to allow adequate time to mitigate remaining technical risks for WDP scale-up.
  - Target achieving **1,000** of those hours via continuous operation of the integrated pre-commercial demonstration system (WDP+WGS+aMDEA) to mitigate any risks of integrating WDP with WGS and carbon capture.

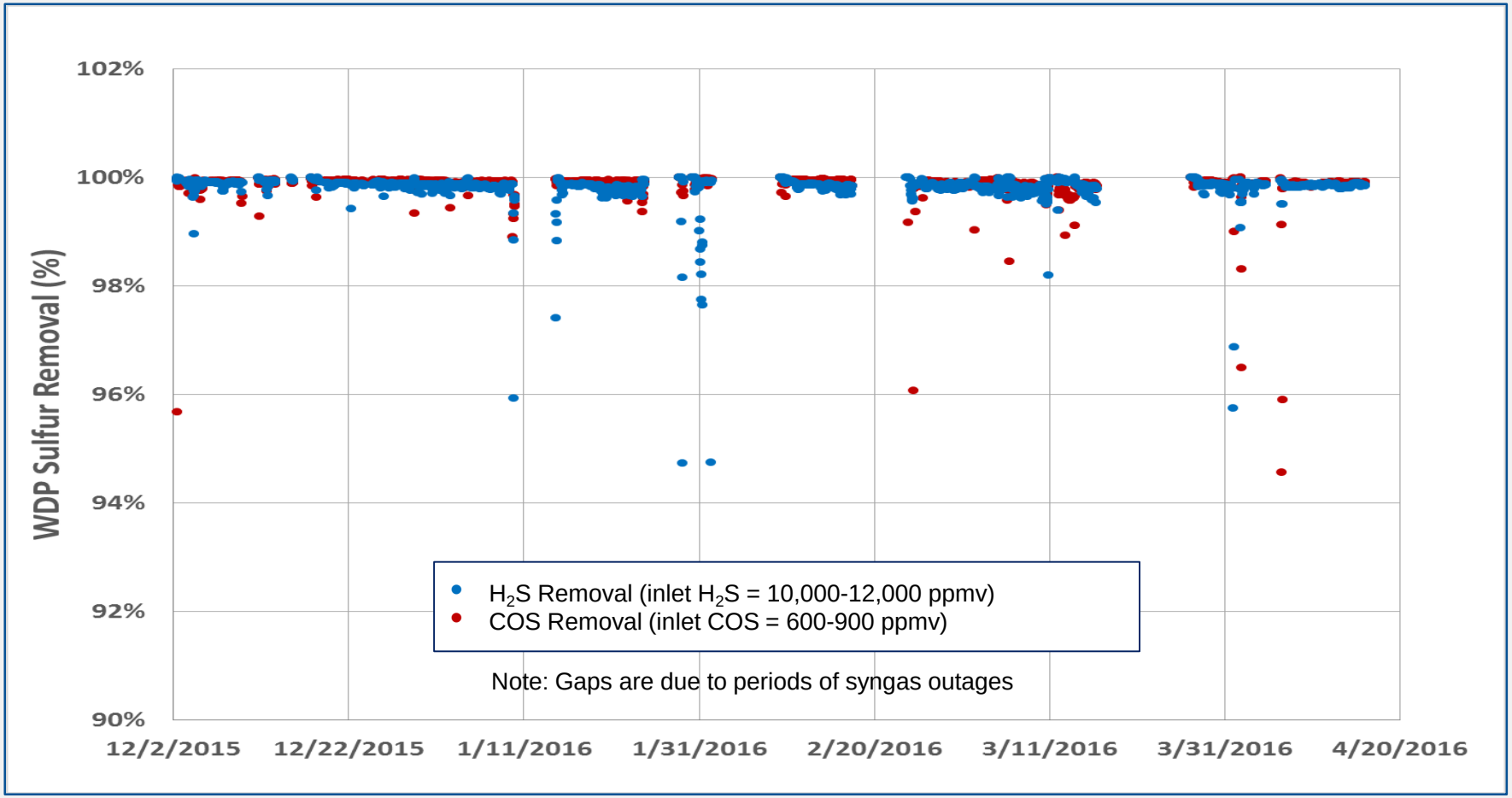
RTI WDP Pre-Commercial Testing Project Performance - Post-ARRA Operations Summary Results

- WDP consistently reduced inlet total sulfur ~99.9%.
- Clean syngas exiting the carbon capture block was as low as 99.999% total sulfur removal (< 0.5 ppmv total sulfur).
- Post operation inspections demonstrated that acceptable materials of construction had been ultimately identified for heat exchangers and refractory.
- Microreactor testing of the cleaned syngas showed no significant signs of methanol or F-T catalyst deactivation.
- Achieved >3,500 total syngas operation hours on WDP, >2,000 hrs on WDP+aMDEA®, and ~700 total integrated hours on WDP+WGS+aMDEA® (had to stop testing in April, 2016 due to host site cooling water system switchover).
- We achieved ~7,000 hours of total syngas operations from the combined pilot and pre-commercial demonstration testing programs.
- WDP availability at the end of testing was as high as 93%, with identified new design improvements that should enable availabilities in the high 90's% for future commercial units.

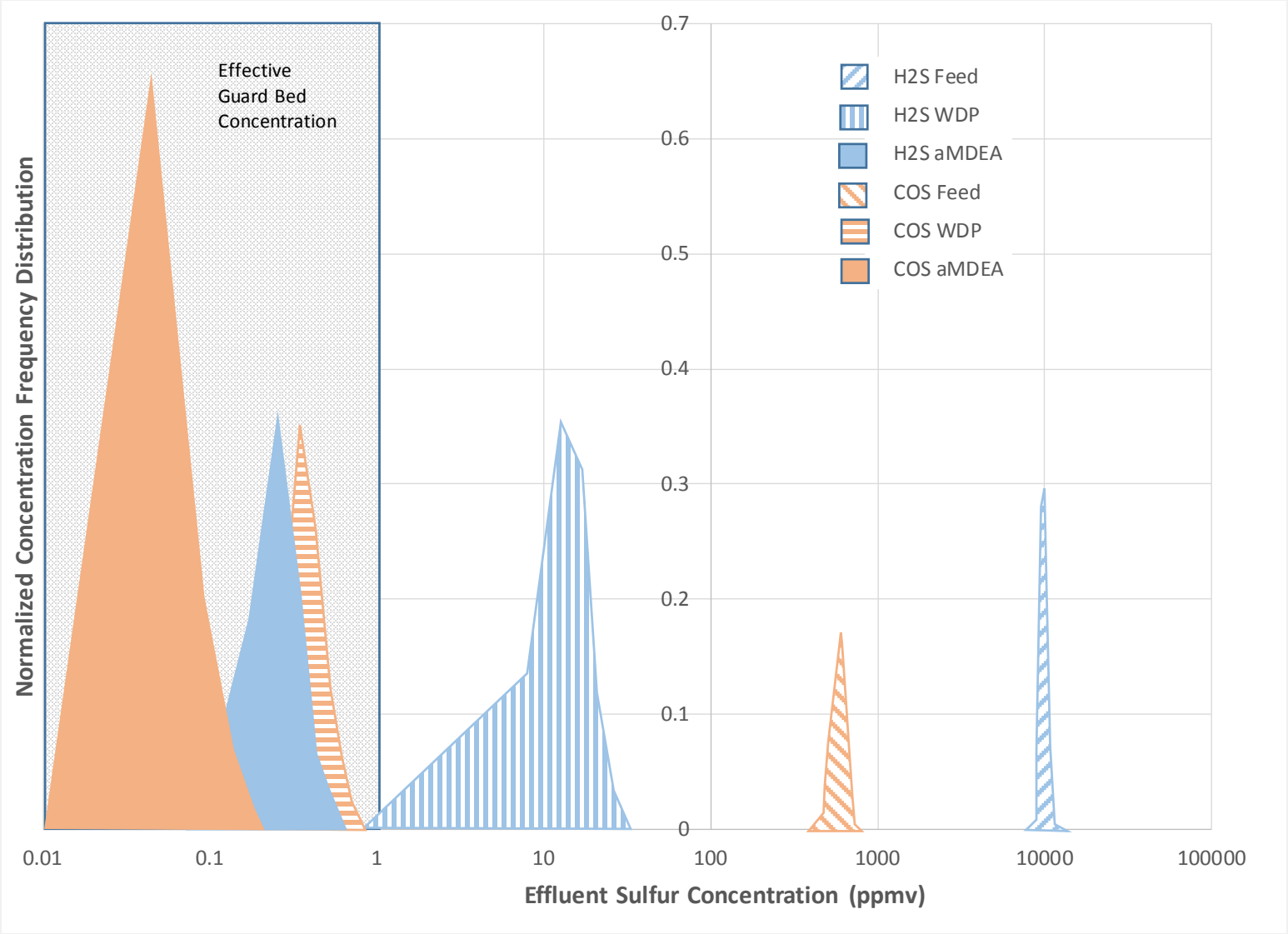
aMDEA® = activated amine carbon capture process of BASF
WGS = water gas shift process

Pre-commercial Demonstration Test Plant Results: Consistently High Total Sulfur Removal from WDP Alone (both H_2S and COS)

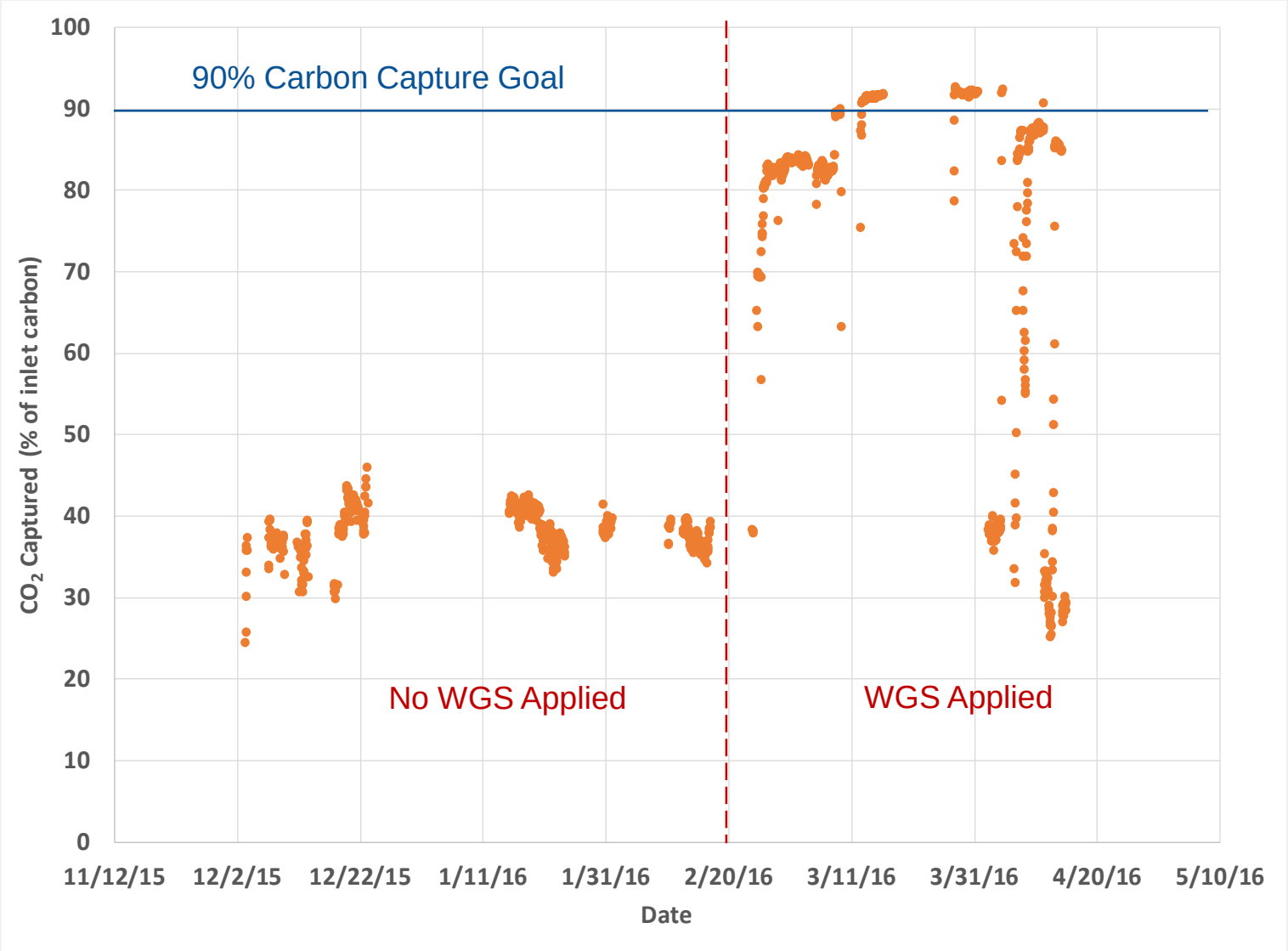
Data from Four Months of WDP Operations



Effluent Syngas Concentrations



90% Carbon Capture Goal Was Achieved



Follow-up Testing Needs Identified

A few data gaps were identified from the lessons learned workshops, particularly related to operation and control when using low sulfur coals (about half of coal reserves in the U.S.). These data gaps can and should be addressed by additional hot and cold flow testing.

Hot Flow Test Unit

Cold Flow Test Unit

Operational Testing Summary

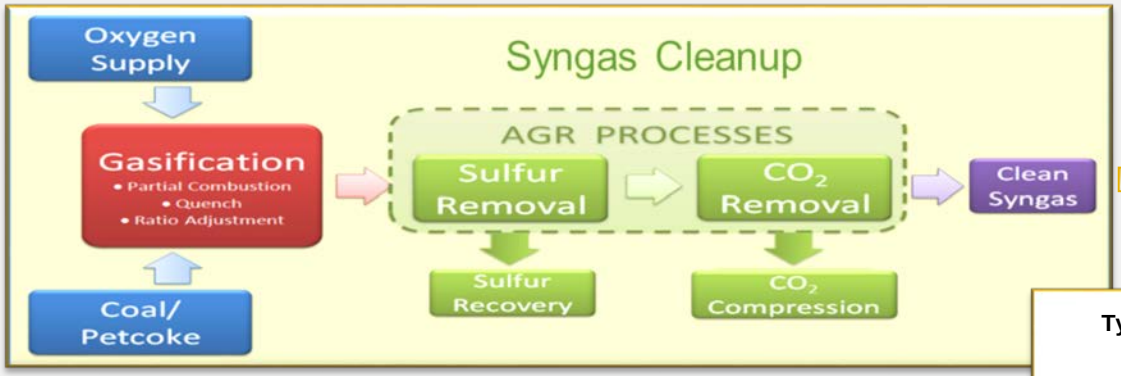
- The operational phase of this project was very successful in its primary goal of reducing technical risks associated with commercial deployment of WDP:
  - Demonstrated that available knowledge and expertise for transport reactor systems from fluid catalytic crackers could be effectively leveraged for high-pressure operations and WDP. This eliminated a number of technical risks for scale-up and deployment.
  - Stable and continuous desulfurization was achieved in just two reactors using near commercial-scale equipment.
  - The desulfurization sorbent consistently demonstrated ability to remove 99.8%-99.9% of both H_2S and COS from syngas.
  - Attrition resistance of the sorbent actually improved with use and actual attrition losses were substantially below design estimates.
  - Sorbent capacity was stable, showing no significant loss in sulfur capacity over >3,500 hours of operation.

Operational Testing Summary (continued)

- Stable, continuous desulfurization of syngas was demonstrated during extended integrated runs with an availability of >90% for the WDP block.
- No evidence was observed of deterioration of new metallurgy installed in the syngas interchanger and the regenerator heat exchanger.
- Refractory remained in good shape in spite of multiple start/stop events with maintenance limited to field installed sections. Refractory is expected to achieve satisfactory commercial lifetimes.
- The aMDEA® system, when coupled with WDP, enabled highly selective removal of both sulfur and CO_2 achieving up to 99.999% total sulfur removal (sub-ppmv levels) and ~98% CO_2 removal. AECOM stream analysis showed essentially no trace contaminants in final syngas.
- WDP, WGS, and aMDEA® were successfully integrated and operated for extended hours while generating a H_2-rich syngas stream and capturing >90% of the system carbon.

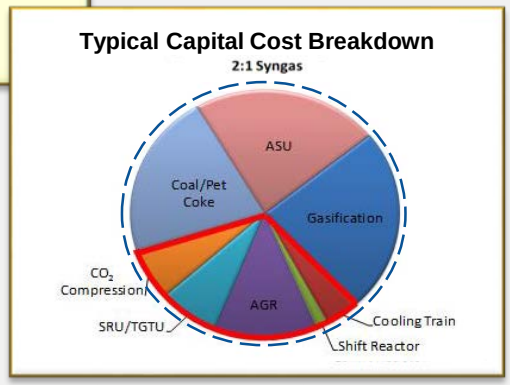
This project has been one of the most successful DOE-NETL projects.

Value Drivers of RTI Warm Syngas Cleanup Technology



Graphics Source:
Eastman Chemical Co.

Conversion to clean power, DRI, or chemicals/fuels



Syngas Cleanup is a Major Cost Driver

Efficiency Improvements Reduce All Elements of Cost

RTI Technology Reduces Cost and Improves Efficiency!

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Benefits of RTI WDP Technology

- 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 CO_2 capture, and
  - A capable and economic syngas cleanup option for all applications:

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)	✓	✓

CC = Carbon Capture

WDP Pre-commercial Testing Video (optional)

RTI Team

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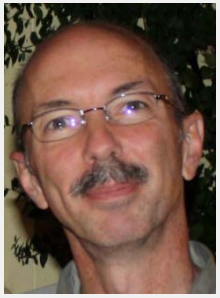

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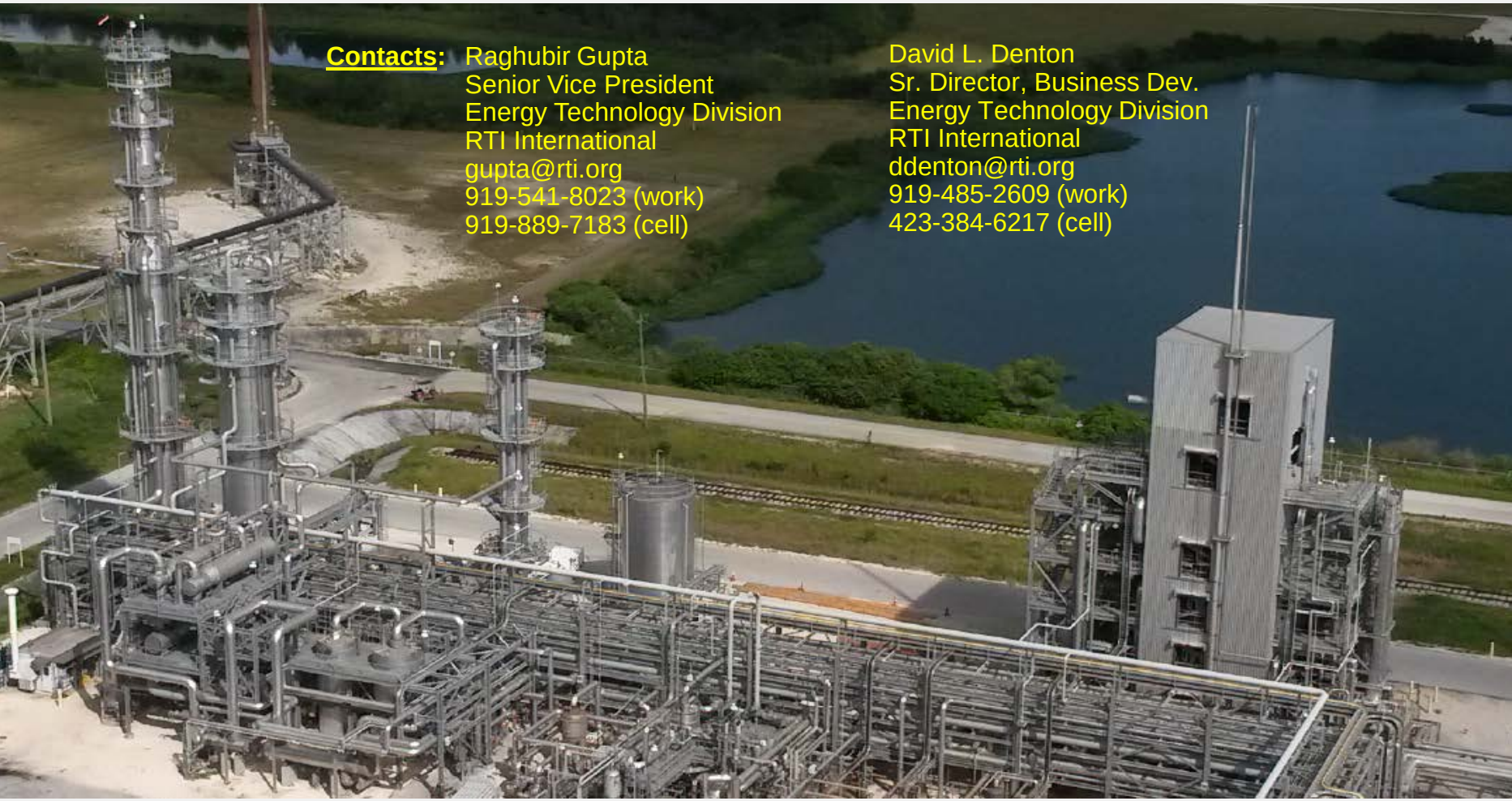
  - Tampa Electric Company
  - Eastman Chemical Company
  - Shaw Energy & Chemicals (now Technip)
  - AMEC Kamtech, Inc. (now Amec Foster Wheeler)
  - CH2M Hill
  - BASF
  - Clariant

QUESTIONS?



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