ADVANCED ENERGY TECHNOLOGY DEVELOPMENT AT RTI INTERNATIONAL

2017 Syngas Technologies Conference

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October 16, 2017
Outline of Presentation

- RTI Overview
- Commercial-ready Warm Syngas Cleanup Technology (WDP)
- Breakthrough RTI Microreformer™ Technology
- Novel Carbon Capture and Utilization Technologies
- Modular Oxygen Separation Technology
- Catalyst and Materials Capabilities, including MOFs
- Low-energy Water Treatment Technologies
- Acknowledgements
Energy Technologies at RTI International

$885 M
FY2016 Revenue

3,064 Projects
3,064 Clients
3,064 Staff Members

1,102 Degree Fields
1,102 Languages
1,102 Nationalities

5,032 Worldwide
5,032
5,032

90
90
90

250
250
250

105
105
105

13 U.S. Offices
13 U.S. Offices
13 U.S. Offices

10 International Offices
10 International 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
A unique process technology based on dual transport reactor loops (similar to FCC reactor designs)...

Enables high removal of total sulfur (>99.9%) from syngas at temperatures as high as 650°C.

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

A 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
Construction was achieved on schedule and under budget.
No injuries beyond minor first aids during construction/operation.
Unit performed as expected, replicating all previous scales.
WDP consistently reduced inlet total sulfur by up to 99.9% from as high as 14,000 ppmv inlet (40% over design target).
Clean syngas exiting the carbon capture block was typically lower than 0.5 ppmv sulfur, up to 99.999% total sulfur removal.
Microreactor testing of clean syngas with commercial FT and MeOH catalysts showed no significant signs of deactivation.
Sorbent attrition rate was better (lower) than expected.
Sorbent sulfur capacity was steady - no significant deactivation.
CO₂ capture efficiency was >99%; 90+% total carbon capture.
RTI achieved ~7,000 hours of total syngas operations from our combined pilot and demonstration-scale testing programs.
WDP availability was > 90%; high 90’s% expected commercially.
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 CO₂ capture, and
- A capable and economic syngas cleanup option for all applications:

The WDP demonstration project was a success and the technology is now ready for license from Casale SA!
Breakthrough Alternative to Conventional NG Conversion Technologies

Natural Gas → Synthesis Gas Production → GTL Synthesis → Product Collection → Liquid Product

Utilizes modified stock IC engines to produce syngas from methane

Replaced by:

RTI Microreformer™

Offsetting Economies of Scale with Economies of Mass Manufacture

Traditional NG conversion technologies do not scale down economically, such as for use with stranded/associated gas

RTI Microreformer™

The solution to small-scale (50K+ scfd), modular gas conversion:

1. Small unit size allows for right-in-time deployment
2. Increase the utility of isolated natural gas
3. Low CAPEX and fast replacement times
4. Syngas conversion into value added products
5. Reduce greenhouse gas emissions

- Stranded or associated gas from:
  - Isolated wells
  - Newly drilled wells, lacking pipeline
  - Wells with mature pipeline maxed out
- Coal bed methane
- Biogas / Landfill gas
- Anaerobic WWT off-gas
- Distributed sources
- Distributed modular production of methane conversion products
RTI Microreformer™ Compares Favorably with World-Scale Syngas Production

- Syngas costs from RTI Microreformer™, treating ≥ 50K scfd of NG, compare favorably with conventional methane reformer costs (based on $3/MMBtu NG cost).
- The RTI Microreformer™ can be located at the site of low-cost stranded, associated, or landfill gas, making its potential syngas costs even more competitive.

* Data analysis from manuscript submitted for publication by RTI and Columbia University, references from other cases studies contained in manuscript
50K scfd Microreformer™ Testing at RTI - Key Findings to Date

- Can produce syngas with H₂:CO ratios > 1.5 with greater than 90% O₂ and CH₄ conversions
- Utilizes a standard mass-produced engine/genset with modifications based on available parts
- Has been coupled with a 1-bpd methanol synthesis skid (but enough total syngas for ~10 bpd)
- Pilot testing has revealed key learnings for transition to the next stage - field demonstration:
  - Design and modification of engine hardware components
  - Start-up and shutdown sequence from standard operation to syngas production
  - Key variables to control for system performance
- Current efforts are focused on refining our understanding and optimization of engine operation
- Strong commercial interest and market potentials (seeking partners for field demonstration trials)
RTI is developing innovative solutions for capturing CO₂ from large industrial sources, such as fossil-fuel power, chemical and cement plants, at lower costs and energy.

**Technologies (pre- and post-combustion):**
- Non-Aqueous Solvents
- Solid Sorbents
- Chemical Looping Systems
- Membranes
- Hybrid Systems

**Benefits:** Substantial improvements to the cost and energy demands of CO₂ capture and utilization compared to conventional technologies
- Regeneration energy reduced by as much as 40-50% (compared to MEA)
- Overall cost of electricity reduced ~10-12% for powergen (compared to a DOE baseline study)
- Capex of carbon capture block reduced by up to 50%

Source: Norcem
A number of novel non-aqueous solvents have been developed and tested by RTI.

Projected technology benefits of NAS systems:
- Don’t absorb water like conventional amine systems
- Reduce regeneration energy penalty ~40% lower than MEA solvents (and better than state-of-the-art systems)
- Reduce the increase in cost of electricity associated with CO₂ capture
- Substantially reduce capital costs for carbon capture

Scale-up testing underway at SINTEF pilot facility:
- Successful cooperation between RTI, Linde, and SINTEF (Scandinavia’s leading research organization)
- Testing is confirming the excellent performance benefits we projected from our smaller-scale testing.
Technology Roadmap: RTI Novel Non-Aqueous CO₂ Solvents (NAS)

- **Lab-Scale Development & Evaluation (2010-2013)**
  - Solvent screening
  - Lab-scale evaluation of process

- **Large Bench-Scale System (RTI facility, 2014-2016)**
  - Demonstration of key process features (≤ 2,000 kJ/kg CO₂)

- **Pilot Testing at Tiller Plant (Norway, 2016-2018)**
  - Demonstration of all process components at pilot scale (~60 kWe)

- **Future Demonstration (2018+)**
  - Pre-commercial Demo Testing at Technology Centre Mongstad (~1-10 MWe) or in the U.S.
  - Planning and pre-qualification ongoing (will test range of flue gases – coal, NG, etc.)

Source: SINTEF
Source: Technology Centre Mongstad
Applicability of RTI NAS for Gasification Syngas Carbon Capture

Since syngas is at pressure, we expect the NAS to work even better for syngas-based carbon dioxide capture than in the flue gas case, but they may need to be coupled with upstream sulfur removal (such as RTI’s WDP warm gas desulfurization process).

- NAS behaves as both a chemical solvent and a physical solvent.
- Thus at higher pressures, the overall absorption of CO$_2$ should be enhanced.
- Pre-combustion testing has been started and preliminary results are encouraging.
Advanced Solid Sorbent CO₂ Capture

**Technology Features**

- **Sorbent**: supported polyethyleneimine (PEI)
- **Process**: fluidized, moving-bed

**Advantages**

- Potential for substantially reduced energy and CAPEX/OPEX
- High CO₂ loading capacity (8-9 wt%)
- Low heat of absorption; no heat of vaporization penalty
- Avoidance of evaporative emissions

**Challenges**

- Heat management / temperature control
- Solids handling / solids circulation control
- Physically strong / attrition-resistant
- Stability of sorbent performance

**Technology Development**

- Long-term testing on actual flue gas at Norcem cement plant validated the performance of the solid sorbent.
- Sorbent was stable; retained capacity after 6 months testing.

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**Promising sorbent chemistry**

- CO₂-philic polymer (e.g., polyethylenimine)
- Immobilize polymer into nano-porous material

**RTI bench-scale unit**

**Norcem Testing**

*Photo Source: Norcem*
RTI Prototype Testing at Norcem

- Completed engineering, construction, shipment, installation, commissioning
- Sorbent production scaled up to 1,000 kg
- Baseline and parametric testing completed
- Updated techno-economic analysis
Long-term Performance Testing of Solid Sorbents for CO$_2$ Capture

**Long-term testing**
- 100+ hr continuous testing, stable operation maintaining performance target of 90% CO$_2$ capture
- Robust nature of system proven

**Sorbent Performance**
- Attrition-resistance of sorbent demonstrated
- Sorbent maintains excellent hydrodynamic / fluidization properties and stable CO$_2$ capacity (8.5 – 9.0 wt% CO$_2$ capacity) even after 6 months of testing
RTI Solid Sorbent Based CO₂ Capture Technology Development

1st and 2nd Generation Sorbents

Initial Sorbent Discovery
2011 – 2015

- Demonstrated > 25% reduction in cost of CO₂ capture
- ~10 wt% CO₂ loading capacity
- Sorbent production scaled up to 1,000 kg

NORCEM Cement Plant Pilot Testing
2013 – 2016

- Demonstrated the technical and economic feasibility of RTI's solid sorbent CO₂ capture process in an operating cement plant
- Pilot unit captured >100 kg/day CO₂

3rd Generation Sorbents

3rd Generation Sorbent Development
2015 – 2017

- Metal organic framework and dendrimer based, fluidizable sorbents
- Higher CO₂ capacity and sorbent stability and attrition resistance
- Tunable pore sizes
- Exceptionally high surface areas
RTI’s Novel Catalytic Platform for CO₂ Utilization

CONCEPT

Selective oxidation with CO₂ for large value chemical applications

INNOVATION

- Utilizes CO₂ as oxidant instead of O₂
- Based on novel catalysts that can extract an oxygen atom from CO₂ at moderate temperatures, coproducing CO, while driving reactions such as dry methane reforming or oxidations such as ethylene to ethylene oxide.

![Diagram showing the process and products](attachment:diagram.png)
Comparison to Conventional Ethylene Epoxidation

- Conventional ethylene epoxidation has been practiced for many years.
- RTI’s catalysts achieve similar yields with CO₂ as oxidant as developmental Ag-based catalysts that use O₂.
Application Example: Ethylene Oxide Production

- RTI's technology is based on a novel catalyst
  - Extracts O from CO₂ and transfers to ethylene at low energy threshold
  - Coproduces EtO and CO, in a relatively simple process

- Enables EtO + CO process simplification and CAPEX reduction
  - Removes need for energy intensive air separation unit
  - Eliminates CO₂ emissions from EtO process
  - Eliminates CO production by methane reforming plus its CO₂ emissions

- Enables safer operation
  - Changes highly exothermic process to moderately endothermic
  - Removes explosion potential of conventional EtO production

- Acceptable economics (at current EtO prices >$1,200/tonne)
  - Potential for < $800/tonne EtO production cost
  - Penalty for CO₂ use offset by process simplification & CAPEX reduction
  - Byproduct CO is also a valuable chemical intermediate

- Reduces CO₂ emissions
  - >2.8 net tons of CO₂ reduction per ton of EtO product
  - 350 Kta EtO plant could reduce CO₂ emissions 1 Mta
Benefits of RTI’s Novel CO$_2$ Utilization Technology Approach

- Uses CO$_2$ as the oxidant, as opposed to high-purity O$_2$ (avoids ASU)
- Creates a safer operating environment compared with oxidation with O$_2$
- Produces CO as a valuable by-product that can be used as a chemical feedstock or for power or thermal energy needs
- Reduces greenhouse gas emissions through utilization of CO$_2$ and reductions in its production versus alternative conventional routes
- Reduces CAPEX and OPEX costs by removing the need for air separation and methane reforming
- Enables economic utilization of CO$_2$ without a carbon tax or subsidies
- RTI is seeking partners interested in CO$_2$ utilization for a variety of high value chemical applications.
• RTI has developed biomimetic materials (mimicking the oxygen binding capability of hemoglobin) that selectively adsorb and bind oxygen for use in oxygen separation.

• Vacuum-pressure-swing adsorption (VPSA) can be effectively used with the oxygen sorbents we have developed.

• Our process produces a high-purity oxygen product stream, with high oxygen recovery rate.

• There is no need to treat the larger stream of nitrogen as with conventional nitrogen selective adsorbents.

• It is possible with our system to simultaneously produce pure nitrogen and oxygen product streams.
<table>
<thead>
<tr>
<th>Sorbent Working Capacity (wt%)</th>
<th>BSF (lb sorbent/TPD O₂)</th>
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<tbody>
<tr>
<td>0.5</td>
<td>556</td>
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<tr>
<td>1</td>
<td>278</td>
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<tr>
<td>2</td>
<td>139</td>
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<td>92.8</td>
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<td>4</td>
<td>69.6</td>
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<tr>
<td>1.3*</td>
<td>850</td>
</tr>
</tbody>
</table>

*State-of-the-art N₂ selectivity sorbent

Our goal is to achieve a working capacity of ≥ 0.5 wt% O₂ (enables substantially lower BSF than SOTA nitrogen selective sorbents)

BSF = Bed Size Factor for PSA-based system
Status of Our Oxygen Sorbent Development Efforts

• RTI has developed multiple routes for O$_2$ binding solid materials.
• Our target was to achieve a working capacity of > 0.5 wt% O$_2$ to exceed performance of state-of-the-art N$_2$-selective sorbents.
• Progress to date has shown:
  • High O$_2$ capacity – several materials identified with >1.0 wt% capacity
  • Rapid O$_2$ adsorption
  • Enhanced O$_2$ binding reversibility
  • Improved material stability
  • Efficient economic synthesis routes

O$_2$ uptake and release by as-synthesized materials over 4 consecutive cycles at 298 K.
• O$_2$ adsorption performed in pure O$_2$ at 298 K and 1 atm for 400 min;
• O$_2$ desorption performed by heating sample in Ar to 393 K for 60 min.
An industrial PSA oxygen generation system based on nitrogen selectivity adsorbents

- Produces 90 to 95% pure O₂
- 1 TPD unit size: 40 x 80 x 100 inch (W x D x H), 4,700 lbs total weight

The advanced sorbents from RTI based on oxygen selective materials can potentially reduce PSA system size to one quarter of the current commercial system size.
Challenge
Enable novel conversion and separation processes

What We Do
- Core competence in materials development
- Catalyst and sorbent development
  - Fixed-bed applications
  - Fluidizable materials (highly attrition resistant and active) – world class competence of RTI
- Metal organic frameworks
- Novel absorption solvents
- Membrane development
- Ability to scale to levels adequate for effective transfer to commercial vendors

Applied Strengths
Fluidizable Particle Synthesis | Proprietary Scalable Synthesis Methods for MOFs | Experience Working with Catalyst Manufacturers
Metal Organic Frameworks (MOFs)

- MOFs are a new class of materials with a wide platform potential for catalytic and separation applications.
- RTI is experienced in designing, modeling, and developing MOFs for process technology applications, including comprehensive characterization and evaluation.
- We have perfected optimization, scale-up, densification, and characterization at milligram-to kilogram-scale quantities, including solid-state synthesis of MOFs.
- We maintain a portfolio of MOFs prepared from various organic linkers and metal salts.
- RTI can even grow MOFs inside porous supports and membranes.
- Example: development of a MOF-based ammonia synthesis catalyst enabling operation at substantially lower temperatures and pressures.
RTI is employing hybrid membrane systems to address and reduce water and wastewater treatment costs in industrial and municipal applications.

**Technologies:**
- Hybrid Forward Osmosis/Membrane Distillation Technology
- Electrically-conductive Membranes (reduce fouling)
- Novel Membrane Development
- Environmental Biotechnology

**Benefits:**
- Reduce energy consumption by 30% and cost by 20% for water treatment and desalination
- Provide clean water sources for industrial processes
- Recover up to 50% of waste organics (converted to methane) from water production from gas, oil and power processes
Mobile Water Treatment Lab (500-GPD Pilot FO/MD Unit)

Potential future deployment at sites with high-TDS wastewaters.
Acknowledgements

- RTI-ETD Team and Contributors
- United States Department of Energy – Funding Partner
  - DOE-NETL
  - DOE Fossil Energy
  - ARPA-E
- Industrial/Commercial Partners
  - Cost Share Partners
  - Licensing Partners
- Academic Partners
- Consulting Partners
RTI’s Energy Technology Team – See us at Exhibit Booth # 3

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Talented staff produce novel technologies from ideation to pilot-scale to commercial systems