Results and Future Perspective of RTI's Advanced Solid Sorbent Project

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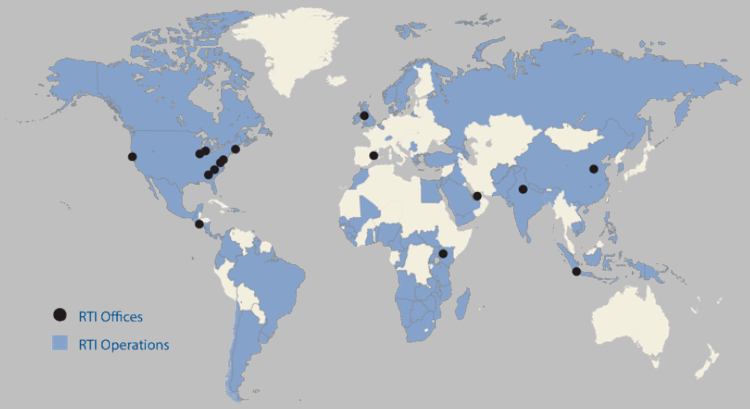
Discussion Outline

- Introduction to RTI
- Solid sorbent technology background
- Project background and scope
- Phase I project results
- Phase II project overview and path forward

Energy Research at RTI International

RTI International

Turning Knowledge Into Practice



One of the world's leading research organizations

3,700 staff
Work in 75 countries

1,800+
Active RTI projects

scientific staff
Highly qualified with tremendous breadth

$780 million
Research budget

Energy Technologies

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

Biomass and Biofuels

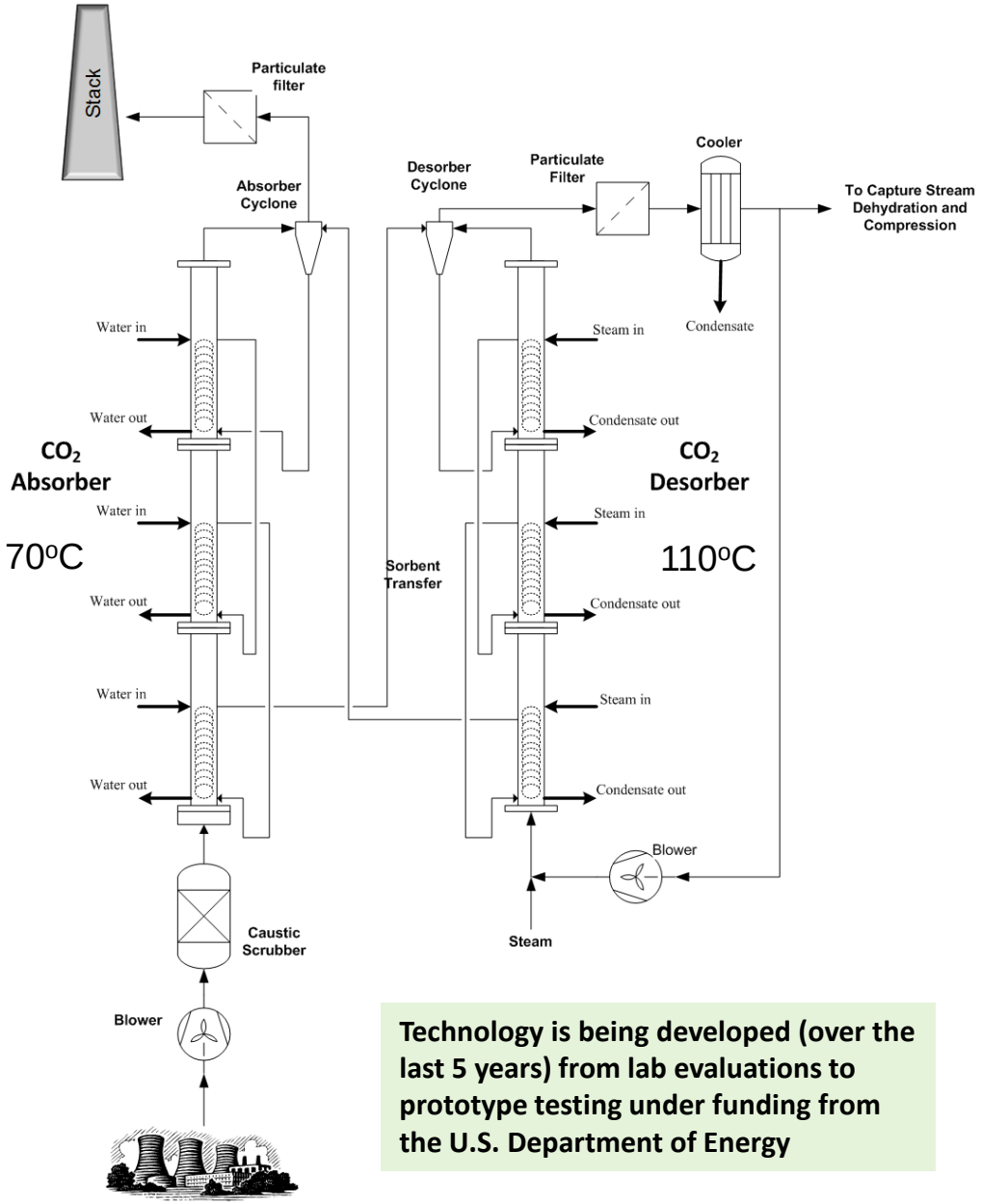
Natural Gas

Carbon Capture

Industrial Water

Syngas

Solid Sorbent CO_2 Capture Technology



Technology is being developed (over the last 5 years) from lab evaluations to prototype testing under funding from the U.S. Department of Energy

Technical Advantages

- Potential for reduced energy loads and lower capital and operating costs
- High CO_2 loading capacity; higher utilization of CO_2 capture sites
- Relatively low heat of absorption; no heat of vaporization penalty (as with aqueous amines)
- Avoidance of evaporative emissions
- Superior reactor design for optimized gas-solid heat and mass transfer and efficient operation

Economic Advantages

- RTI's technology represents > 25% reduction in cost of CO_2 capture, with > 40% reduction possible with advances in sorbent stability and reactor design
- ~ 40% reduction in energy penalty
- The total capture plant capital cost for our technology is significantly lower than state-of-the-art amines

Sorbent Chemistry

- Polyethyleneime (PEI)

Primary: $CO_2 + 2RNH_2 \rightleftarrows NH_4^+ + R_2NCOO^-$

Secondary: $CO_2 + 2R_2NH \rightleftarrows R_2NH_2^+ + R_2NCOO^-$

Tertiary: $CO_2 + 2R_3N \rightleftarrows R_4N^+ + R_2NCOO^-$

RTI's Project Overview

Objective

Demonstrate the technical and economic feasibility of RTI's advanced, solid sorbent CO_2 capture process in an operating cement plant

Period of Performance:

- 5/1/2013 to 10/31/2016

Location:

- Norcem's cement plant in Brevik, Norway

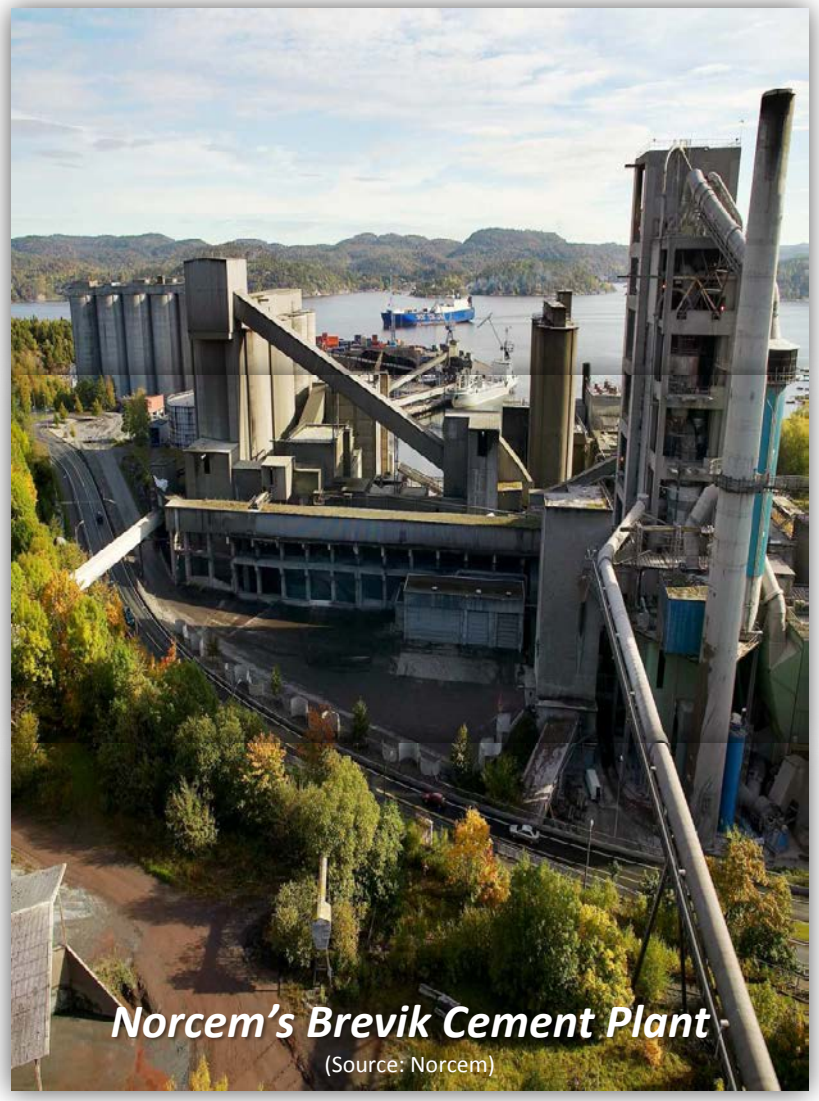
Project is structured in two phases:

Phase I

- Evaluate sorbent performance using simulated and actual cement plant flue gas (testing in Norway)
- Prove economic viability of RTI's technology through detailed economic analyses
- Develop commercial design for cement application

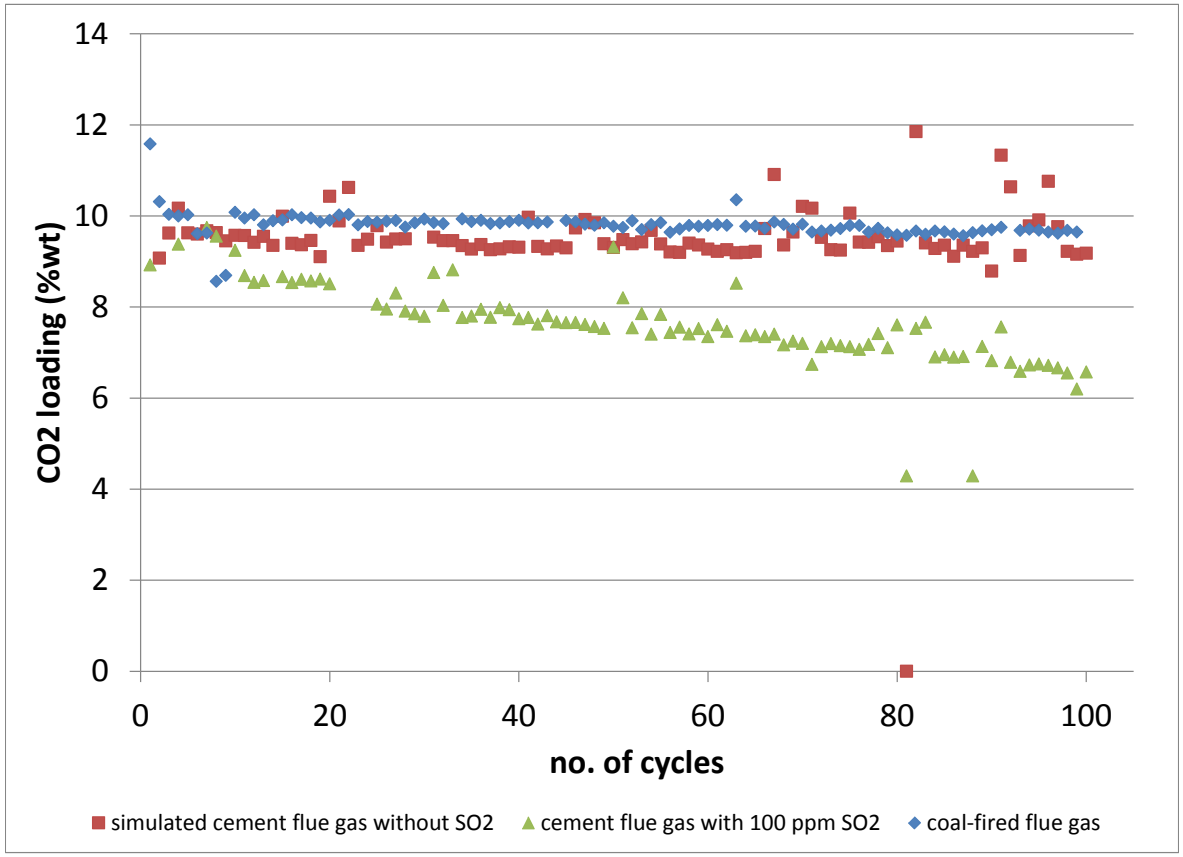
Phase II

- Design, build, and test a pilot-scale system of RTI's technology at Norcem's Brevik cement plant
- Demonstrate long-term stability and effective CO_2 capture performance
- Update economic analyses with pilot test data



Norcem's Brevik Cement Plant
(Source: Norcem)

Simulated Cement Flue Gas Testing at RTI



Component	"Clean" cement flue	Simulated cement flue gas (with SO_2)	Simulated coal-fired flue
CO_2 (%)	18	18	14.8
H_2O (%)	12	12	5.7
O_2 (%)	9.2	9.2	2.6
N_2 (%)	Balance	Balance	Balance
SO_2 (ppm)	0	100	0

- Testing condition:
  - Absorption at 70 °C
  - Regeneration at 110 °C
  - GHSV = 3,500-5,000 h^{-1}
  - Reactor size: 0.5” ID, 8” L
- High water and oxygen content did not impact sorbent performance
- Presence of SO_2 causes rapid performance drop
- Spent sample after SO_2 run exhibits discoloration
- Gas pre-treatment is needed for economical operation

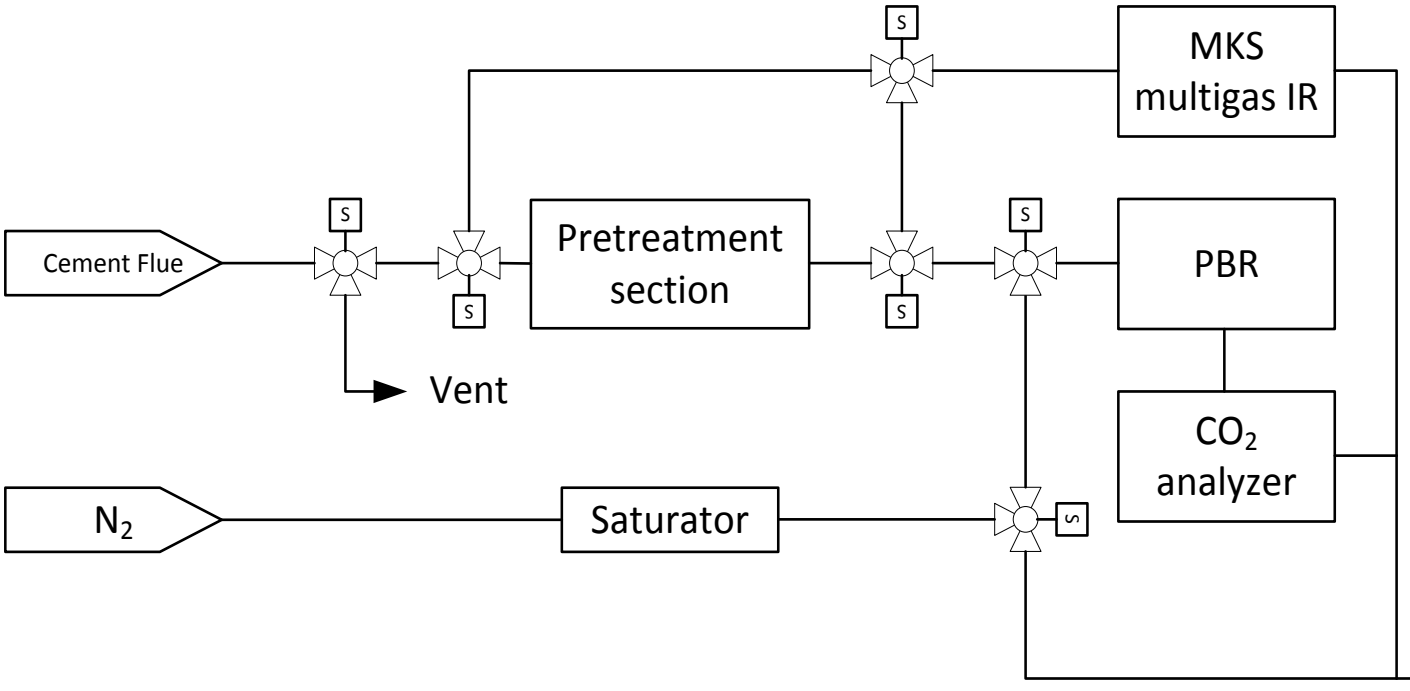
Sorbent Exposure Testing at Norcem

Objective

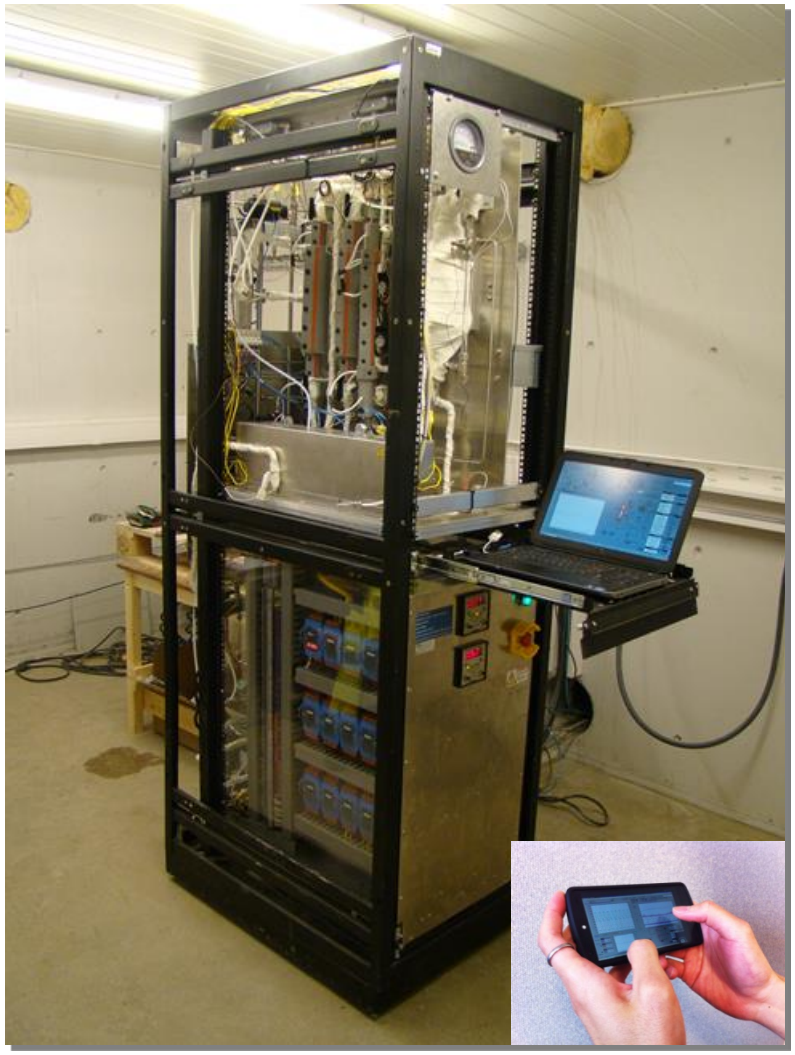
Conduct small-scale field exposure testing of RTI's solid sorbents at Norcem's cement plant utilizing a flue gas slipstream taken from the actual plant exhaust.

Approach

Design, fabricate construct, deliver, install, commission, and test a lab-scale system – the Automated Sorbent Test Rig (ASTR) – at Norcem's cement plant.



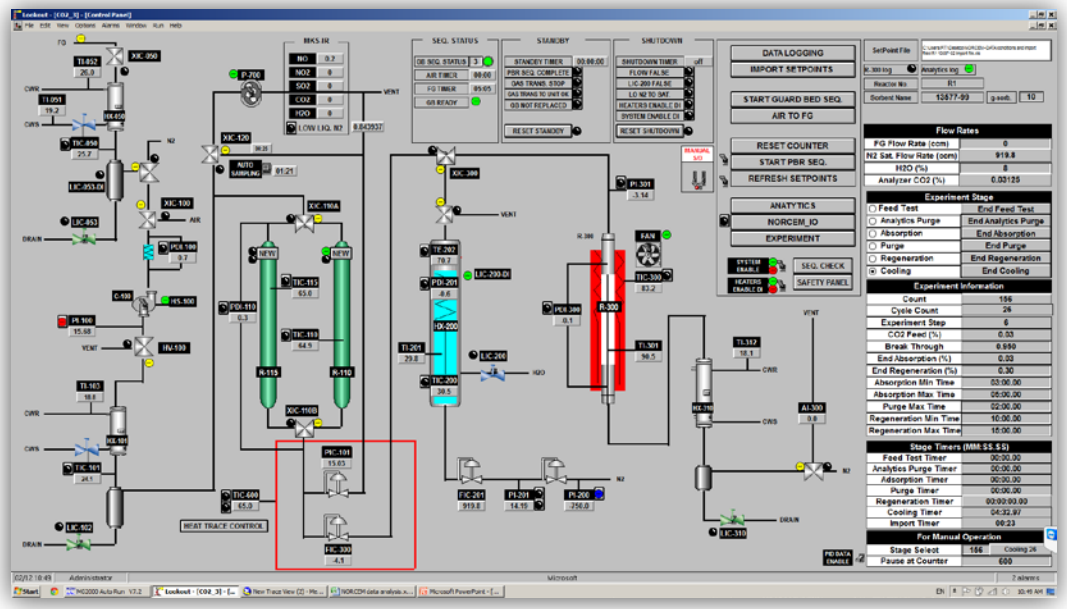
Sorbent Exposure Testing at Norcem



RTI's Automated Sorbent Test Rig (ASTR) installed at Norcem's cement production plant in Brevik, Norway

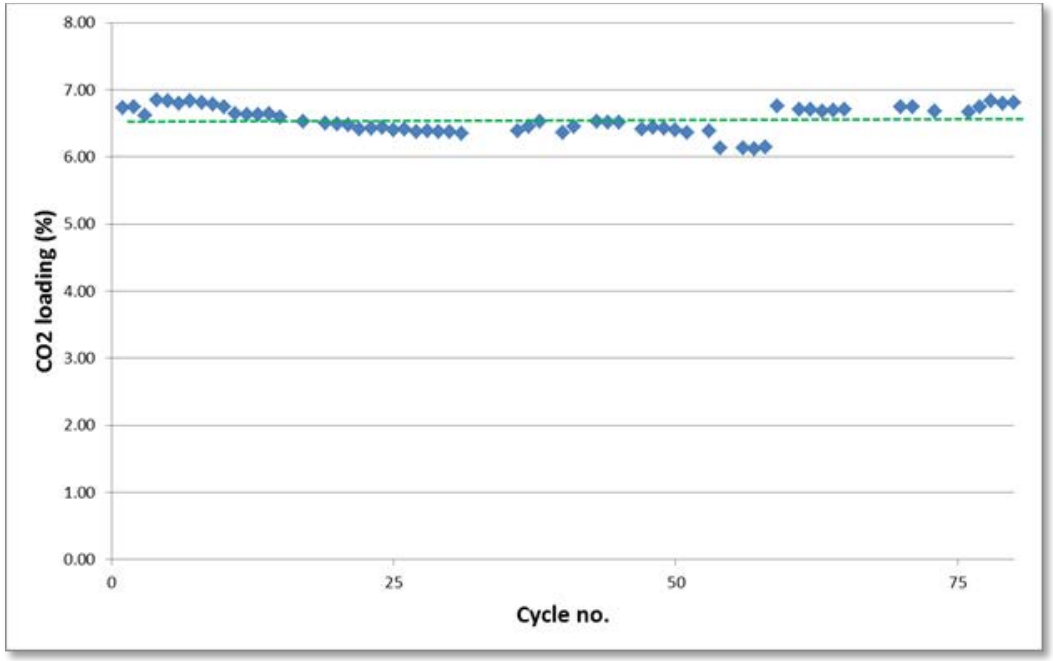
Specific Goals:

- Evaluate sorbent performance under actual cement flue gas conditions.
- Evaluate sorbent stability and contaminant tolerance.
- Determine if sorbent exhibits any critical performance failure due to exposure to real cement flue gas.
- Gain experience installing and commissioning a research unit in an industrial setting and prove that the system can operate in a stable manner.



ASTR Human-Machine Interface

Sorbent Exposure Testing at Norcem



Component	Cement flue gas
CO_2 (%)	18-22
H_2O (%)	2-4
O_2 (%)	6-10
NO (ppm)	0-5
NO_2 (ppm)	0-20
N_2 (%)	Balance
SO_2 (ppm)	0-20

Testing conditions

- Absorption temperature: 60 ^oC
- Regeneration temperature: 120 ^oC
- GHSV = 3,500-5,000 h^{-1}

Phase I Objective	Results and Conclusions
Build and install a lab-scale process unit and test sorbent performance on real flue gas at Norcem's Brevik cement plant	• Designed, built, delivered, installed, and commissioned a fully functioning Automated Sorbent Test Rig (ASTR) at Norcem • In total, **roughly 300 absorption/regeneration test cycles** were performed with CO_2 capture loading typically in the range of 5 to 7 wt% loading • RTI sorbent **exhibited no critical failure in CO_2 capture performance** • Low water content in flue gas did have some impact on CO_2 loading • RTI's **ASTR system was commissioned in 5 days** and maintained stable operation in Norway during intermittent testing over 4 months.

Economic Analysis

Objective

Deliver a preliminary technical and economic feasibility analysis of RTI's novel solid sorbent CO_2 capture technology installed at a commercial cement plant

Case Studies

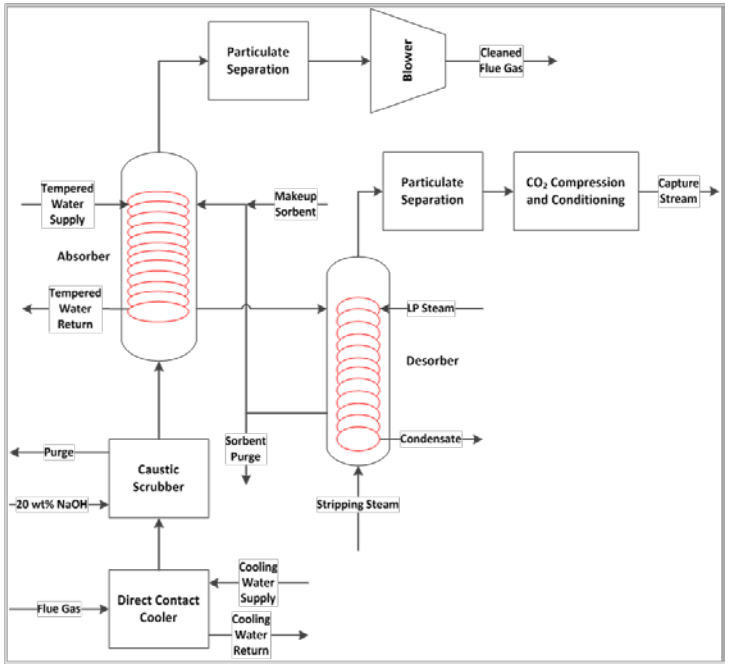
- *Case 1 (reference):* Full-size cleaning (minimum 85 % CO2 capture), no waste heat available
- *Case 2:* Full-size cleaning (minimum 85 % CO2 capture), waste heat available
- *Case 3:* Reduced-size cleaning, based on a cost-optimal utilization of waste heat available

Approach:

- Followed guidelines of "Benchmark Indicator Report"
- Developed commercial design, sizing, and Aspen simulations for 3 case studies using reasonable technology assumptions
- Quantitative assessments for primary economic indicators:
  - capital and operating cost, cost per CO_2 avoided, energy consumed
- Qualitative assessments for other technology factors:
  - performance under varying conditions, health/safety risks, environmental risks, technology improvements

Results:

- Economic indicators of 38 – 46 €/t-CO_2 avoided show RTI's technology is economically competitive with conventional/next generation technologies
- RTI's technology is a good candidate for waste heat utilization
- Conditions at a cement plant require RTI's technology to include a steam boiler, pretreatment system, and waste heat recovery



Category / Economic Contribution	Case 1	Case 2	Case 3
Steam contribution (%)	41%	30%	0%
Electricity contribution (%)	29%	33%	36%
Other variable/fixed OPEX contribution (%)	11%	12%	23%
CAPEX contribution (%)	19%	25%	41%
Normalized cost per mass of CO_2 avoided	**1.00**	**0.89**	**0.84**

Phase II Overview

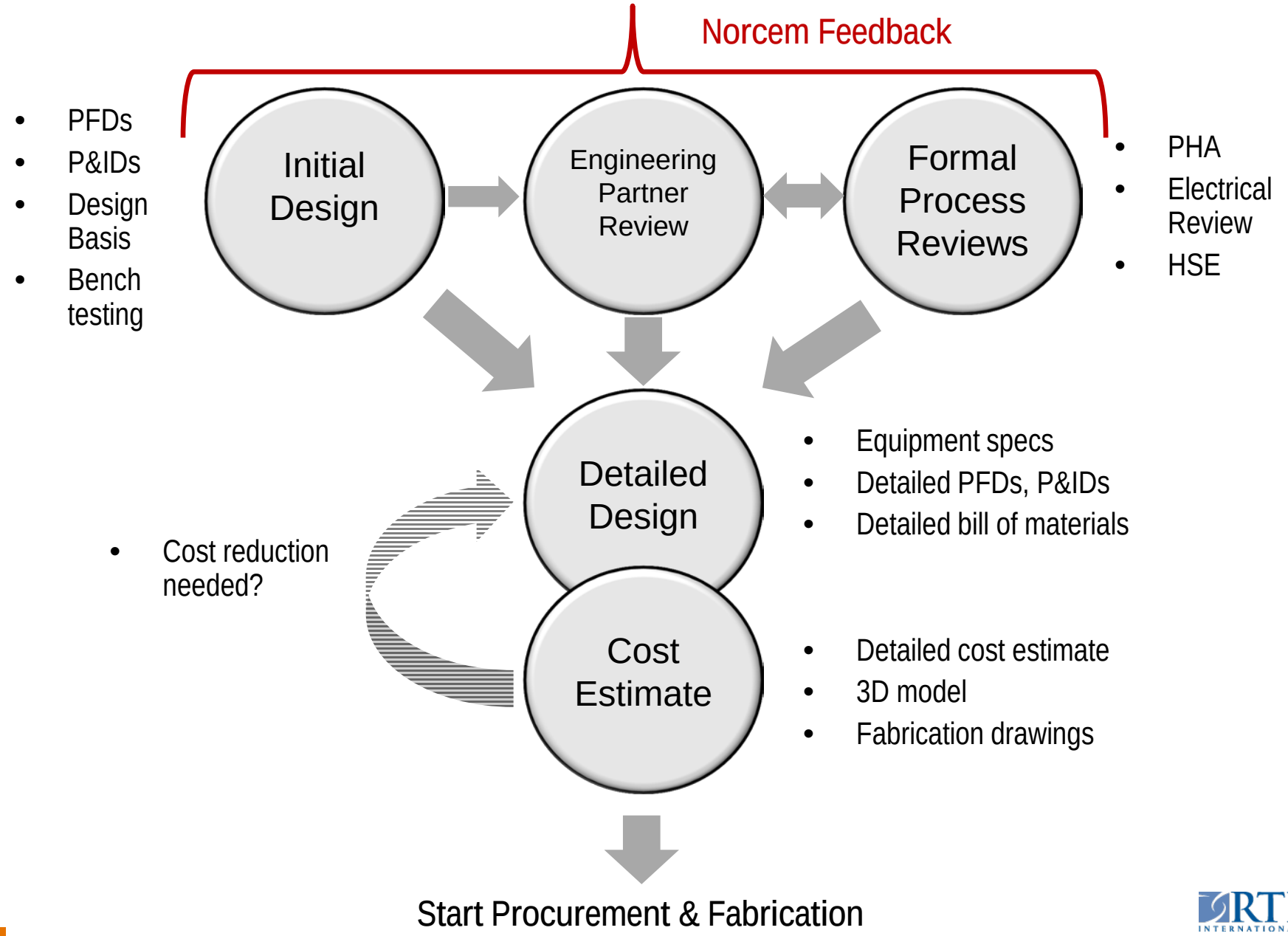
RTI's Bench-scale Prototype System in USA

Objective

Demonstrate, on a pilot-scale, the effective and continuous removal of CO_2 from Norcem's cement plant flue gas using RTI's solid sorbent technology.

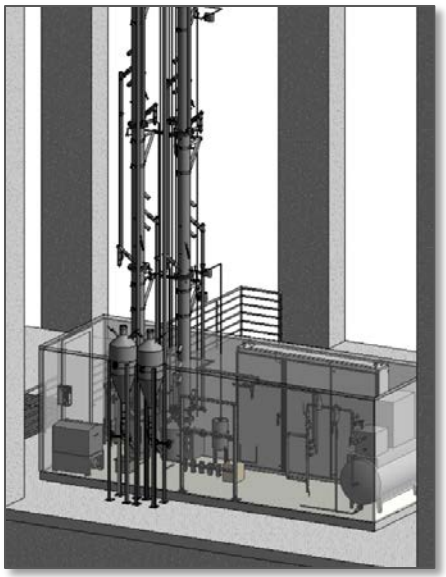
Task Description	Goals / Current Progress
Simulated cement flue gas testing using RTI's existing bench-scale prototype	• Utilize RTI's existing bench-scale system to simulate cement FG and collect additional process design data. • Higher CO_2 content exhibits more driving force for CO_2 separation in flue gas. • *Progress*: Bench-scale operation providing lessons for pilot system.
Field testing of RTI's pilot system at Norcem's Brevik plant	• Design, build, and test a pilot system at Norcem's Brevik plant – demonstrating long-term stability and viable CO_2 capture and regeneration performance. • Testing in Norway to consist of parametric and long-term testing campaigns. • *Progress*: Near completion of detailed design and engineering phase.
Updated economic analyses	• Update the economic analysis with pilot test data – further evaluating the technology's economic viability. • Updates to 31 benchmark economic indicators expected based on data from pilot testing. • *Progress*: some updates made to original economic analysis report based on Tel-Tek feedback.

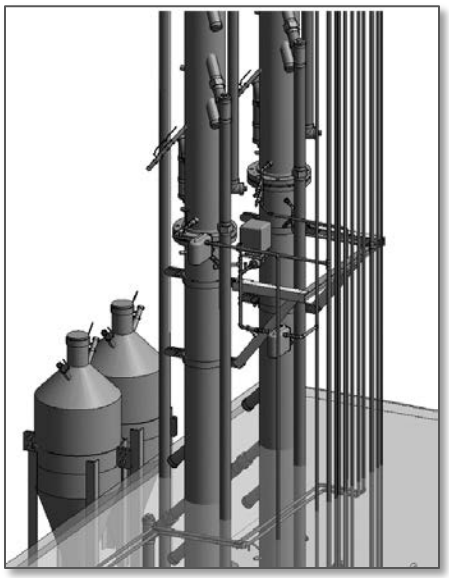
Pilot System Design and Engineering

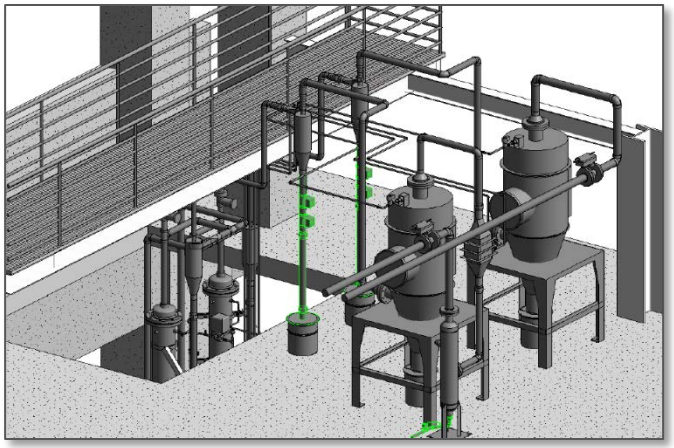


Pilot System Design and Engineering

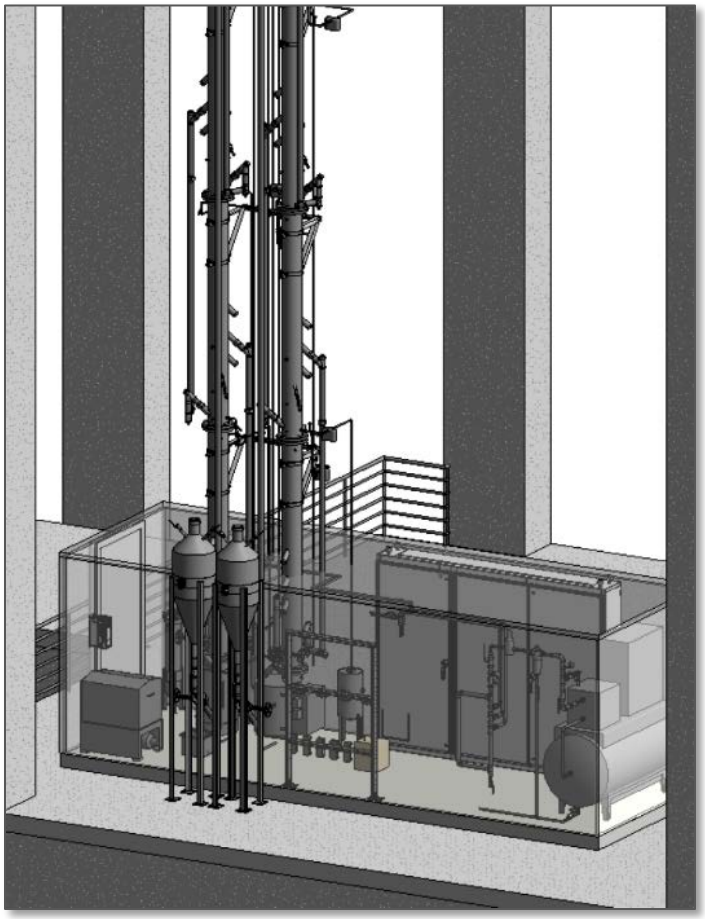
Norcem test site







Pilot System Design, Build, and Testing



Initial pilot system specifications:

- Design based on RTI's bench-scale system
- Footprint: ~ 7.5m X 4m
- Height: ~ 13m
- Flue gas throughput: ~ 600 to 1,600 SLPM
- Sorbent inventory: ~ 300 kg
- Power: ~ 60 to 90 kWe
- Cooling water: 250 to 650 kg/h
- Additional utilities:
  - Low-pressure steam; compressed air; waster disposal

Pilot system activities (Present → October 2016):

- Procurement, fabrication, construction of pilot system in US.
- Production of pilot-scale sorbent inventory.
- Shakedown of RTI's pilot system in US.
- Shipping and delivery of RTI's pilot system to Norcem.
- Commissioning and training of Norcem operational staff.
- Early-stage parametric testing of RTI's pilot system at Norcem.
- Long-term performance stability testing of RTI's pilot system at Norcem.
- RTI pilot system decommissioning:

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RTI Team

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