RTI Carbon Capture Technology Development

California Energy Commission

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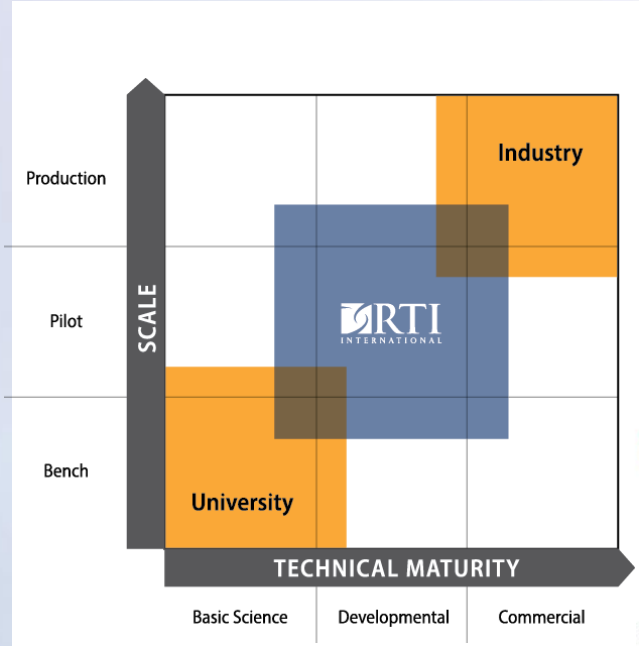
Energy Technology Development with RTI

- RTI is one of the leading global research organizations
- RTI develops advanced process technologies in partnership with leaders in energy
- From concept to large scale demonstration
- Full alignment with industry objectives
  - Defined commercialization pathways
  - Potential leveraging of industrial R&D funding with government provided funding



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Natural Gas

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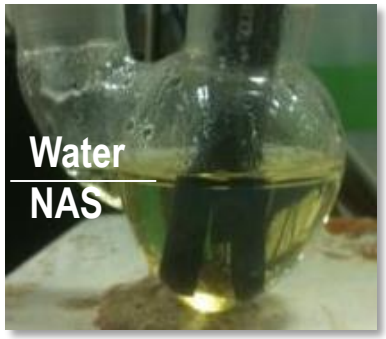
Industrial Water

RTI's Carbon Capture Technologies

Non-Aqueous Solvents



Advanced Solid Sorbents

RTI has more 15 years of continuous involvement in developing CO_2 capture technologies with industrial partners

- Leveraging capabilities in advanced materials and process development
- Technology portfolio comprises:
  - Non-aqueous solvent process
  - Advanced solid sorbent process

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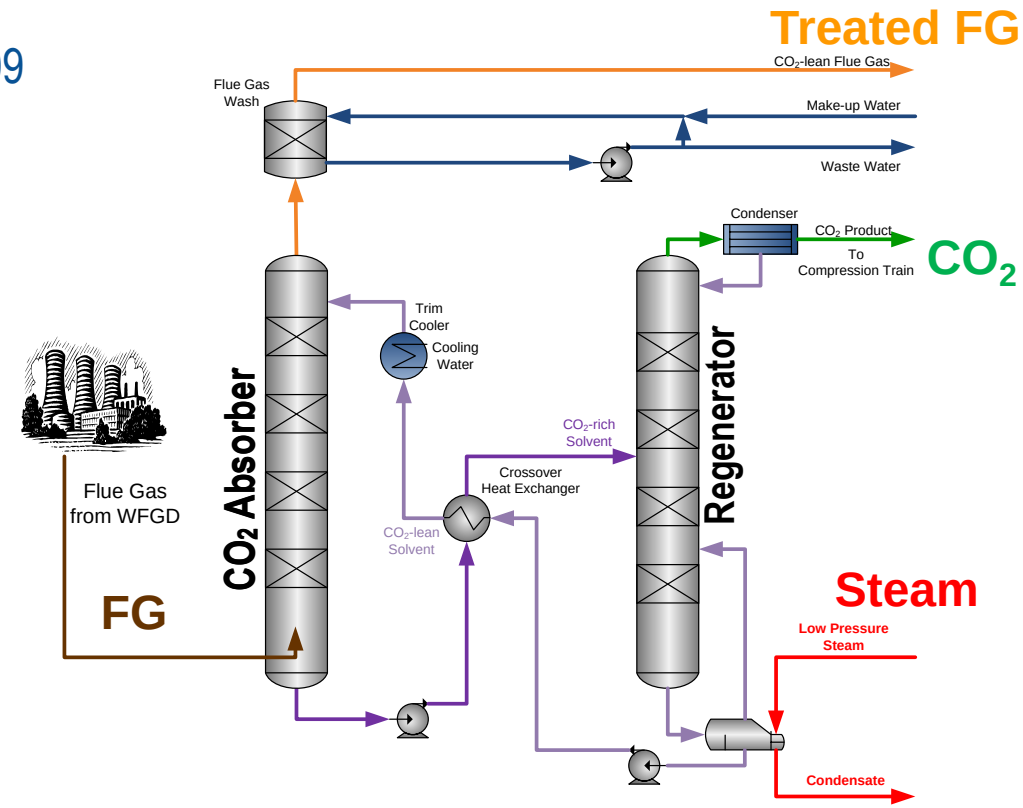
Non-Aqueous Solvent CO_2 Capture Process

RTI is developing a NAS CO_2 capture process for post-combustion applications that has the potential to reduce the regeneration energy penalty to < 2.0 GJ_t / tonne CO_2 (~40% < state-of-the-art solvents).

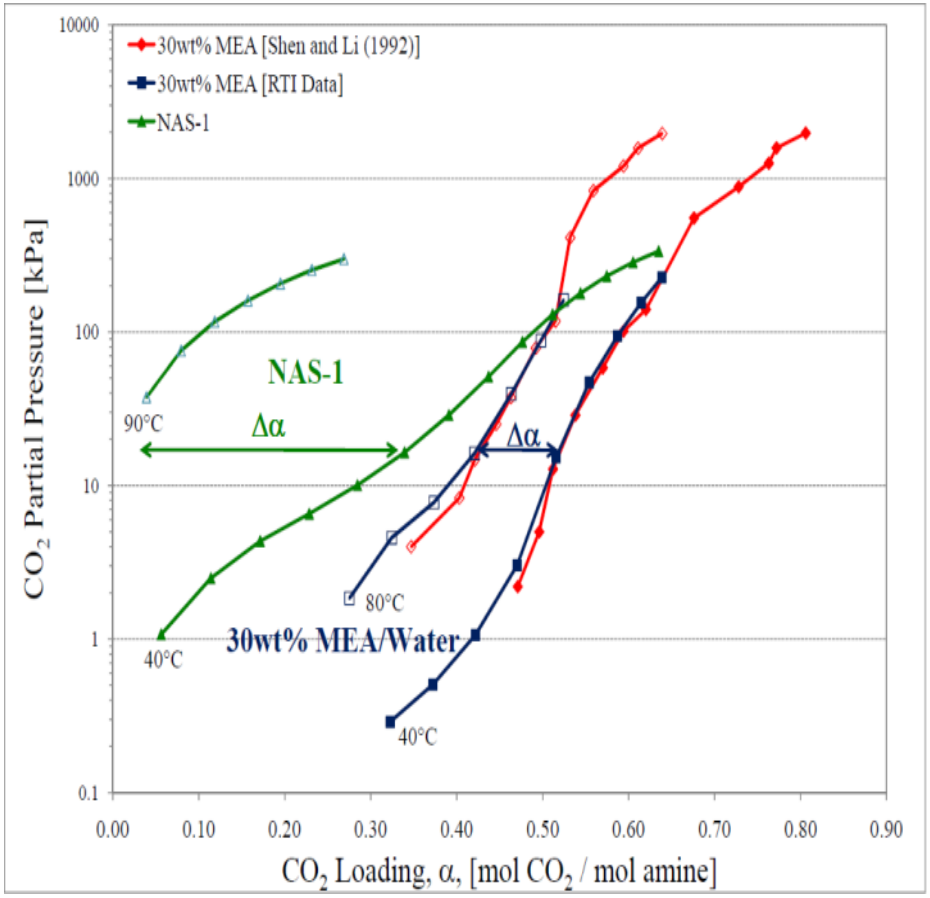
- Technology in development at RTI since 2009
- Strong partnerships with government and industrial partners



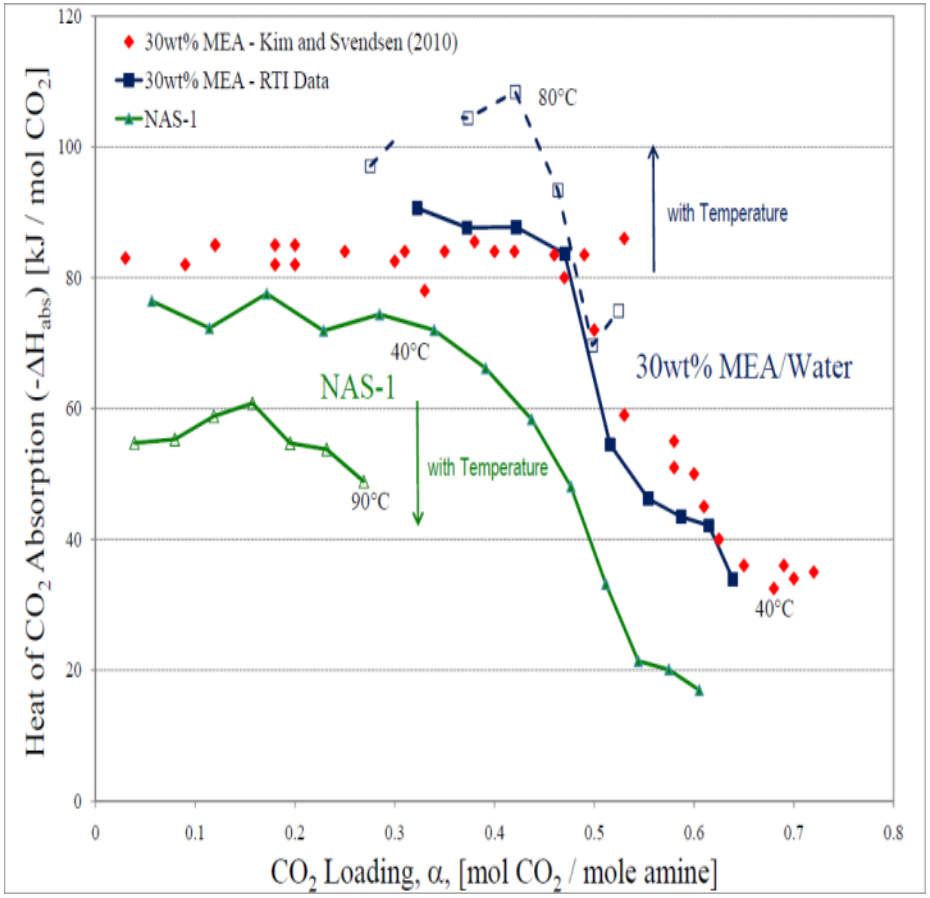
Why are RTI's NASs so promising?

Superior Thermodynamic Properties

CO_2 Isotherms



Heat of Absorption

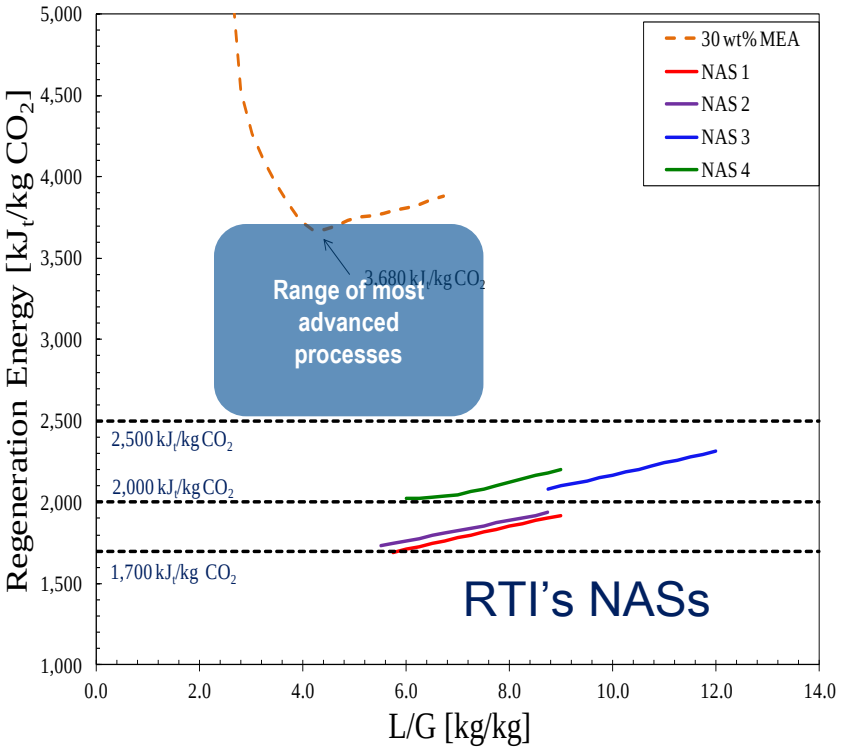


- NASs achieve larger dynamic capacities ($\Delta\alpha$) with smaller ΔTs
- CO_2 pressure of > 2 bar can be achieved around 90°C

- Heat of absorption ranging from 55 to 75 kJ/mol CO_2
- Specific heat capacity of 1.2 to 1.5 kJ/kg K

Regeneration Energy & Technical Assessment

Thermal Regeneration Energy



- RTI non-aqueous solvents have potential to achieve regeneration energies < 2.0 GJ_t / tonne CO_2

Process modeling to estimate parasitic power load

CO_2 Capture Process	Net Power [kWe]	Net Efficiency [%]	Efficiency Point Loss
No Capture*	784,700	39.3	-
Fluor Econamine FG+*	549,970	28.4	10.9
RTI's NAS Process	652,079	32.7	6.6

* Cost and Performance Baseline for Fossil Energy Power Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity (Nov 2010)

- NAS CO_2 capture process has potential to reduce parasitic power load by ~ 40% compared to MEA-based process
- NAS Process requires lower quantity and quality of steam for solvent regeneration
  - *40% less steam; up to 30°C cooler steam*

NAS Process Development Status

- Inventor of non-aqueous CO_2 solvent chemistry
- Lead bench-scale testing campaign to optimize process performance

- Global leader in gas separations & purifications solutions
- Expertise in the design, engineering, and operation of gas treatment processes
- Techno-economic and EH&S assessments of novel processes

- Extensive experience in amine degradation & amine plant emissions

- Demonstrated stability of non-aq. solvents in a representative process arrangement
- Demonstrated key process concepts specific to non-aqueous solvent process
- Compared performance of the NAS process and 30 wt% MEA-H_2O
  - Prelim. data verifies 30-40% reduction in thermal regeneration energy
- Evaluated the effect of long-term (>500 h) exposure to common flue gas contaminants.
- Detailed solvent degradation and emission studies, lower emissions profile than MEA.
- Currently operating small pilot unit under simulated flue gas conditions.

NAS CO_2 Capture Process: Technology Roadmap

	Previous Work			DOE ARPA-E Project		DOE NETL Project (Current)		Future Development	
Yr	2009-10			2010-13		2014-15		2016-20	2020+
TRL	1	2	3	4	5		6	7	8 & 9
	Proof of Concept/Feasibility								Pre-Commercial Demonstration

Lab Scale Development (*Previous*)

- Solvent screening to identify promising solvent formulations
- Lab-scale evaluation of NAS Process
- Preliminary technical and economic assessments

Small Pilot System / Relevant Environment Testing (*Current*)

- Bench-scale testing with in a process unit with major process components
- Demonstrate ≤ 2 .0 GJ/tonne CO_2 using bench-scale system
- Address process, environmental, and economic challenges
- Detailed solvent degradation and emissions studies
- Detailed Techno-Economic & EH&S Assessments

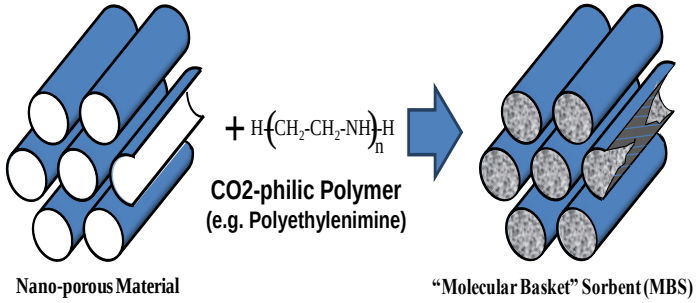
Pilot-scale prototypical system demonstrated in a relevant environment (*Future*)

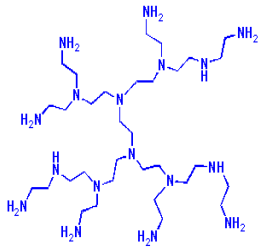
- Pilot system, using real flue gas and a complete process unit
- Collect critical process information to support detailed T&E assessments and scale-up efforts

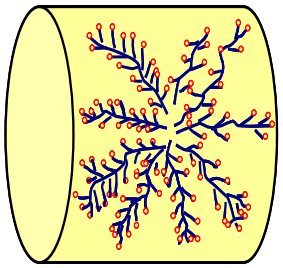
RTI Solid Sorbent CO_2 Capture Process

RTI is developing a sorbent-based CO_2 capture process for post-combustion applications (power and industrial installations):

- supported, polymeric amine sorbent
- fluidized-bed process arrangement.







- Strong partnerships with government and industrial entities

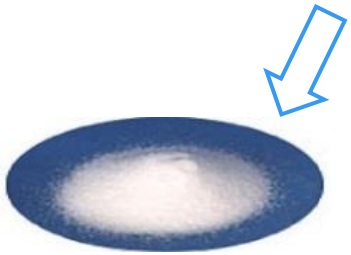
NETL

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

PENNSTATE 1855

Masdar A MUBADALA COMPANY

- Masdar is evaluating the process for NGCC applications (interest in EOR)



Promising sorbent chemistry

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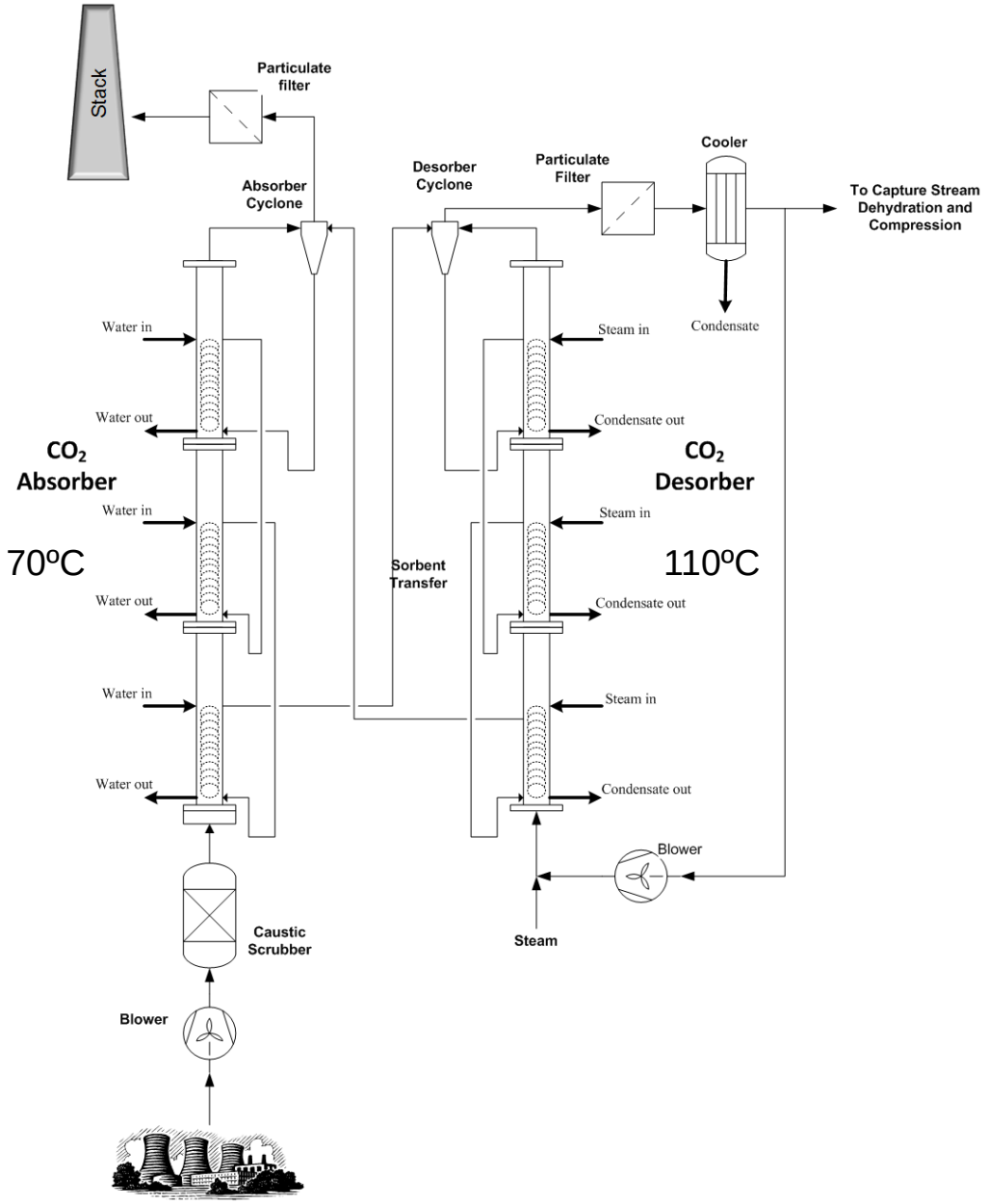
RTI Solid Sorbent CO_2 Capture Process



Economics

- RTI's technology represents > 25% reduction in cost of CO2 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

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

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Process Development Status

Objective

Design, build, and test a bench-scale system to evaluate optimal fluidized-bed reactor design and demonstrate long-term performance stability of PEI-based CO_2 sorbents.

Status

- *Process design screening:* initial process design screening, heat transfer tests, and engineering evaluation, resulting in fluidized moving-bed design.
- *Fluidized-bed reactor model:* developed a FB reactor model to simulate performance.
- *Bench-scale / small pilot system:* developed a detailed engineering design package and test unit to evaluate effectiveness of proposed reactor designs for CO_2 removal from flue gas.
- *Operation:* ongoing at RTI, >90% CO_2 capture on simulated flue gas.

Cement Application – Ongoing Demo in Norway

NORCEM
HEIDELBERGCEMENT Group

Objective: Demonstrate RTI's advanced, solid sorbent CO_2 capture process in an operating cement plant and evaluate economic feasibility

Norcem's Cement Plant – Brevik, Norway

Photo Source: Norcem

RTI's Lab-scale Sorbent Test Unit

Photo Source: Norcem

Phase I – *Complete*

- Performed sorbent exposure testing with real cement flue gas using lab-scale test unit
- Performed techno-economic study

Phase II – *Ongoing* (July '14 to June '16)

- Pilot field testing of RTI's technology at Norcem's Brevik cement plant
- Modular test unit

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Solid Sorbent Technology Development Roadmap

Previous Work	Current Project	Future Development		
< 2011	2011-15	2015 - 19	2019-22	> 2022
Proof-of-Concept / Feasibility		Pilot	Demo	Commercial
		1 - 5 MW (eq)	~ 50 MW	

Laboratory Validation (2011 – 2013)

Economic analysis
- Favorable technology feasibility study

Sorbent development
- Successful scale-up of fluidized-bed sorbent

Process development
- Working multi-physics, CFD model of FMBR
- Fabrication-ready design and schedule for single-stage contactor

Prototype Testing (2014 – 2015)

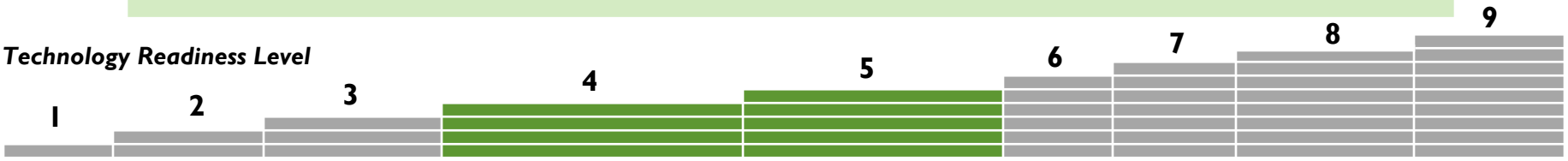
Field Testing of Prototype Unit
- Operational FMBR prototype capable of 90% CO_2 capture
- Completion of 1,000 hours of parametric and long-term testing

Updated Economics
- Favorable technical, economic, environmental study (i.e. meets DOE targets)

Relevant Environment Validation (2013 – 2014)

Process development
- Fully operational bench-scale FMBR unit capable of absorption / desorption operation
- Fabrication-ready design and schedule for high-fidelity, bench-scale FMBR prototype

Sorbent development
- Successful scale-up of sorbent material with confirmation of maintained properties and performance



Summary

- RTI is leading the development of two advanced CO_2 capture technologies:
  - Non-aqueous solvent (NAS) process
  - Advanced solid sorbent process
- Both technologies can substantially lower the energy penalty compared to conventional capture technology at attractive process economics.
- Additional advantages:
  - NAS process:
    - Water balance can be controlled to lower or eliminate evaporative water losses, potentially making the process attractive for water stressed environments
  - Solid sorbent process:
    - Inherently low evaporative emissions of organic compounds
    - Currently being assessed for NGCC application