Project Kickoff Meeting

DE-FE0031630

ROTA-CAP: An Intensified Carbon Capture System Using Rotating Packed Beds

> December 14th, 2018

Osman M. Akpolat, Howard Meyer - GTI

Will Shimer, Dave Bahr, Dr. James Hall - CCS

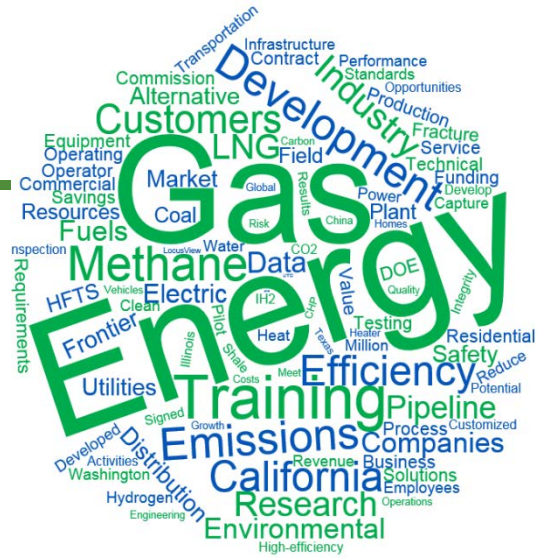
Meeting Objectives

- Introduction of Project Team Members
- Short Background on ROTA-CAP Technology
- Discussion of Technical Aspects of the Project
- Overview of Administrative Efforts
- Comments and Questions

Meeting Agenda

- 8:00 AM Introductions
- 8:10 AM Background Information on Project Team Members
- 8:30 AM Technical Approach Discussion
- 8:50 AM Project Structure / Task description
- 9:10 AM Schedule
- 9:20 AM Budget
- 9:30 AM Comments and Questions
- 10:00 AM Adjourn

77-year History of Turning Raw Technology into Practical Energy Solutions



FOR A BETTER ECONOMY AND A BETTER ENVIRONMENT

SUPPLY	CONVERSION	DELIVERY	UTILIZATION

RESEARCH & DEVELOPMENT

PROGRAM MANAGEMENT

TECHNICAL/ ANALYTICAL

CONSULTING

TRAINING

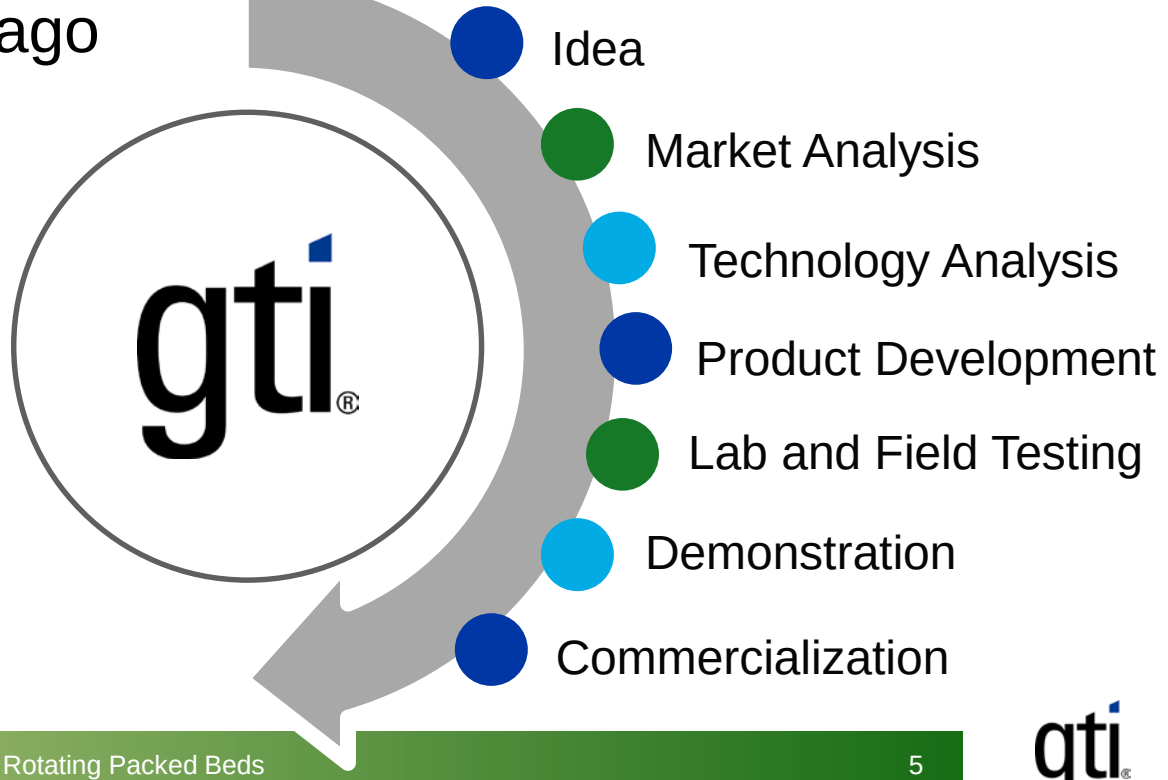
360+ EMPLOYEES

World-class piloting facilities headquartered in Chicago area

gti. 75 YEARS ENERGY EXCELLENCE EST 1941

Introduction to GTI

- Research organization, providing energy and environmental solutions to the government and industry since 1941
- Facilities: 18 acre campus near Chicago



Business Highlights

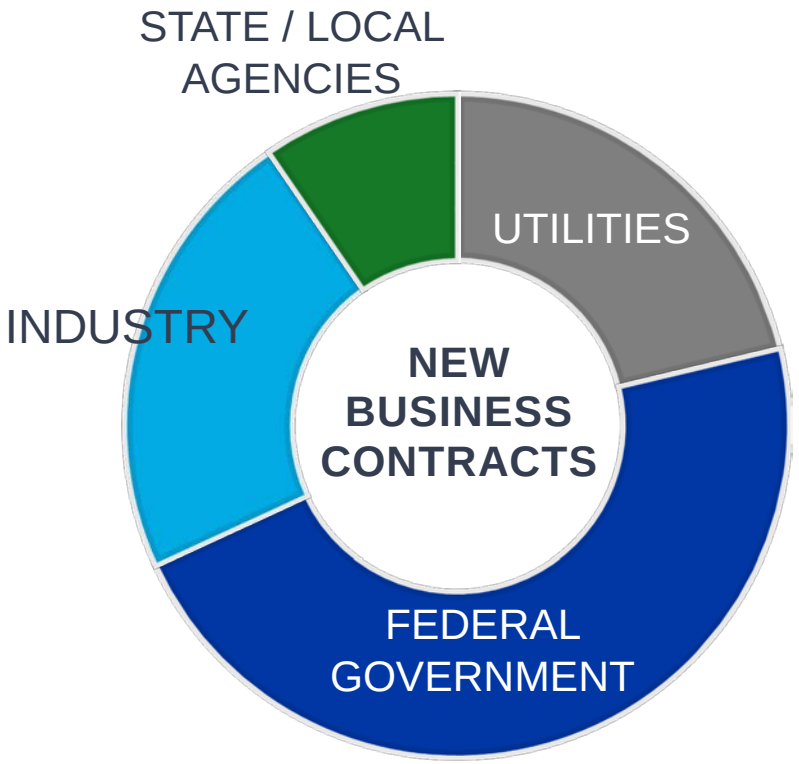
DIVERSE CUSTOMER BASE

GTI provides solutions to clients in the private sector, federal government, and state government agencies

> 300+ active projects

> 14 patents issued

> 10 patent applications



2017 Results

Company History

1940 | 1970 | 1990 | 2000 | 2010

1941
Institute for Gas Technology (IGT) formed at the Illinois Institute of Technology (IIT)

1947
IGT Laboratory
Chicago, Illinois

1967
IGT created and patented the “Eternal Flame” burner for JFK’s Memorial in Arlington National Cemetery.

1970
Blue Flame natural gas powered rocket car sets world land speed record of 630 mph

1973
Oil Crisis

Dr. Henry Linden
GRI President

1976
Federal Power Commission approved surcharge on pipeline transmission for research funding and Gas Research Institute (GRI) formed

1991
GRI sponsored Mitchell Energy’s first horizontal well in the Barnett shale

George Mitchell

1992
FERC Order No. 636, Restructuring Rule mandated unbundling to separate sales from transportation services

1995
U-GAS® Plant
Shanghai, China

2000
GRI and IGT combined to form Gas Technology Institute (GTI)

2009
GTI Pilot-Scale Gasification Campus
Des Plaines, Illinois

2003
Operations Technology Development (OTD) launched to facilitate collaborative gas operations and infrastructure research

2004
Utilization Technology Development (UTD) initiated to address end use issues of interest to the gas industry

2015
GTI acquired Aerojet Rocketdyne’s fossil energy business

2017
GTI International subsidiaries combined to form energy efficiency and alternative transportation services firm Frontier Energy

CCSL - Introduction

We've made industrial decarbonisation a commercial reality

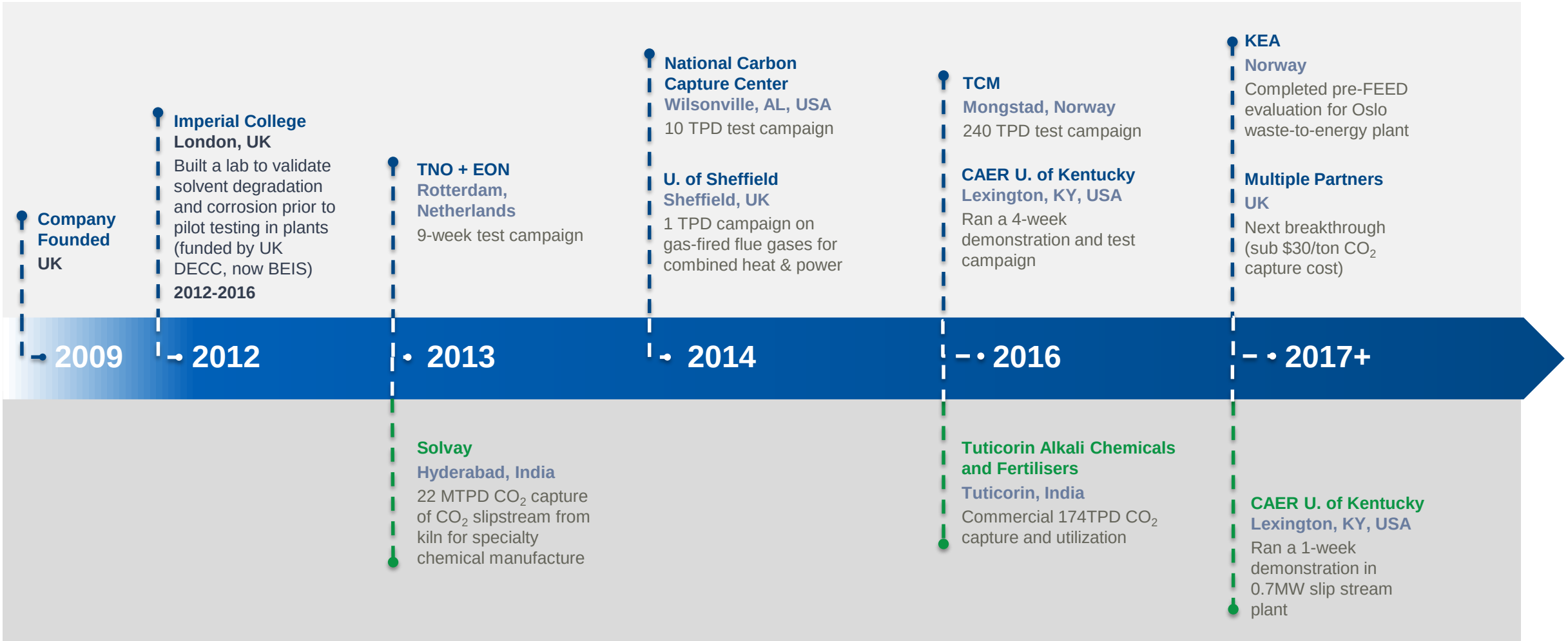
Carbon Clean Solutions is an established global leader in providing CO_2 capture technology.

Our advanced technology is proven to dramatically reduce to the cost of carbon capture – enabling industrial emitters to reduce CO_2 emissions.

Mission and Focus

- Our focus is on providing the most cost-effective CO_2 capture and separation technology
- A Flexible business models help to drive projects at a local level
- Our patented chemistry and engineering know-how is proven at 30+ sites globally
- Our advances in technology will enable a $1 trillion/yr CO_2 reuse market

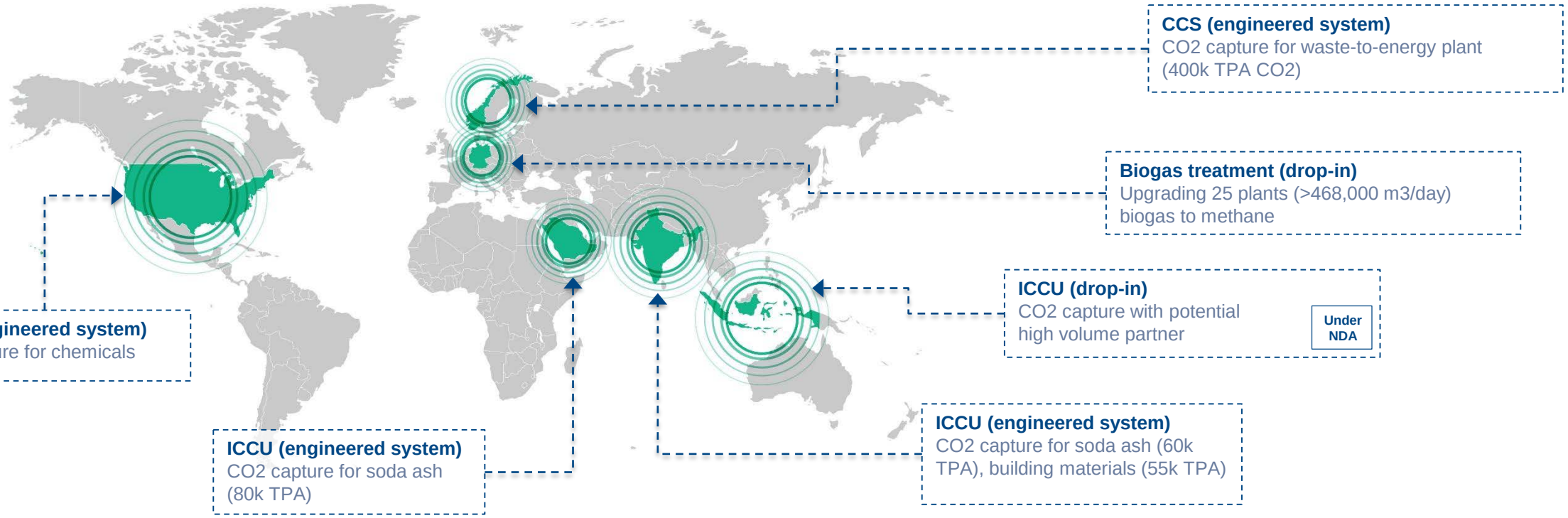
CCSL - Experience



CCSL - Commercial Partnerships

> We have global reach with delivery support

> Extensive demonstration of our technology and knowhow



CCSUS, Inc.

- Headquartered in Chicago, IL
- Incorporated 2013
- Wholly owned subsidiary of CCSL
- Executed projects with:
  - NCCC
  - CAER U. of Kentucky
  - Major oil and gas company

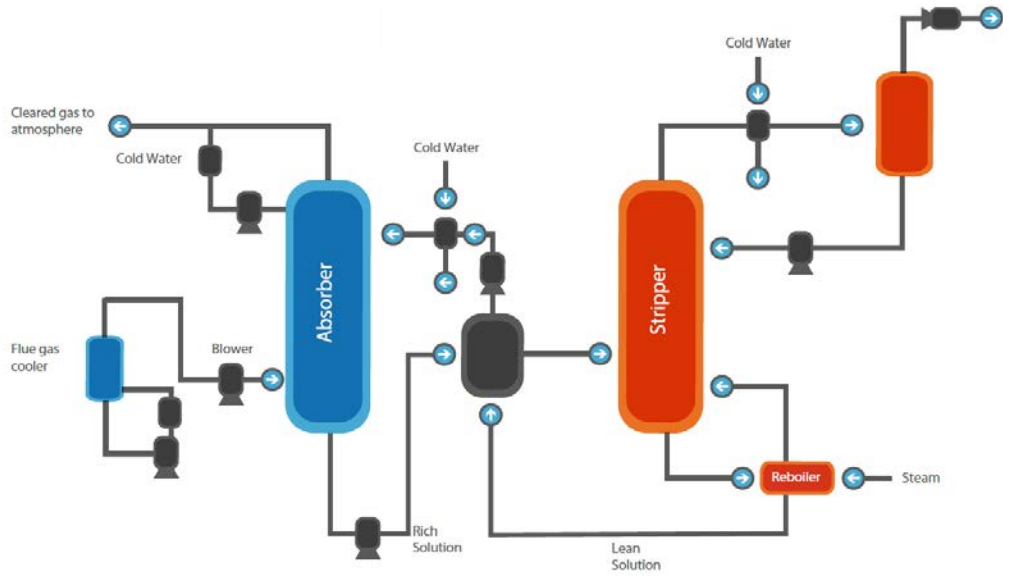
Mission: Further develop technology and expand partnerships in the Americas

CCSUS - Technology / Technical approach

We combine licensed technologies with performance chemistry to deliver cost-effective process solutions

LICENSED TECHNOLOGIES

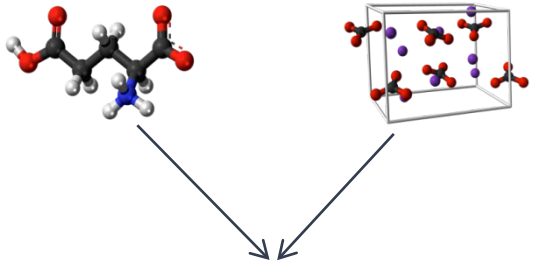
Our process technology generates transformational results for the capture and recovery of CO_2.



PERFORMANCE CHEMISTRY

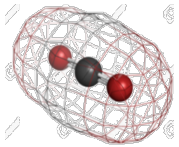
Our advanced solvents (Amine Promoted Buffer Solutions or APBS) remove CO_2 from a variety of gas streams – for use in new and existing industrial facilities.

SOLVENTS:
Fast reaction,
High energy



SALTS:
Slow Reaction,
Low energy

Advanced Solvents



Technical Approach Discussion

ROTA-CAP: An Intensified Carbon Capture System Using Rotating Packed Beds

- **Sponsor**

DE-FE0031630

- **Funding**: $2,784,222 DOE ($698,000 co-funding), Duration 30 months

- **Objective**: The objective of this project is to develop and validate a transformational carbon capture technology—ROTA-CAP to meet DOE's cost target of ≤$30/tonne CO_2, 90% capture rate, and product CO_2 purity target of ≥95 %.

BP1: 10/1/2018 – 3/31/2020 BP2: 4/1/2020 – 3/31/2021

ROTA-CAP: An Intensified Carbon Capture System Using Rotating Packed Beds

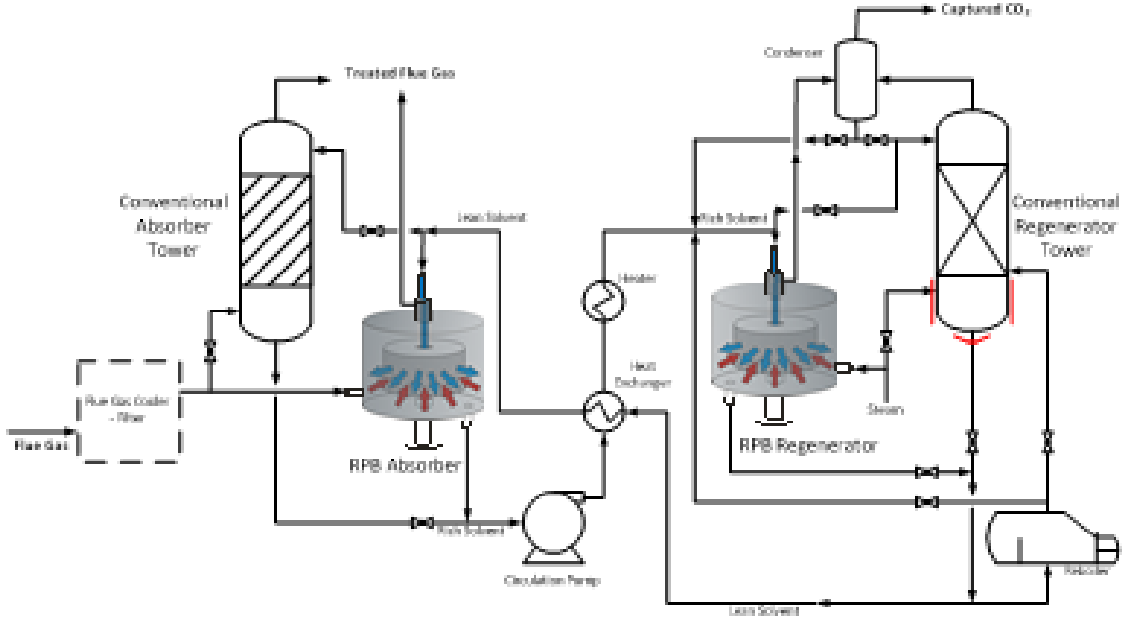
- **Team:**

Member	Expertise
gti	• GTI has expertise is in bench-scale and pilot-scale research and development (R&D) plus scoping economic analysis. We bring over 75 years of performing applied R&D for DOE and other governmental agencies as well as industry and bringing technology to the market to the effort.
CCS Carbon Clean Solutions	• CCSUS is an early stage process technology venture with commercially proven products and process licensing with technologies for industrial decarbonization, while reducing the environmental impact of man-made emissions. Their focus is to provide the most cost-effective CO_2 capture and CO_2 treating technology with patented chemistry and engineering know-how. Currently CCSUS operate at more than 30 sites globally.
NC NATIONAL CARBON CAPTURE CENTER	• NCCC specializes in evaluation of developing technologies using coal-derived gas with the concomitant impurities, providing critical information on material and process suitability for scale-up to commercial applications.

Project Objectives

The objective of this project is to develop and validate a transformational carbon capture technology, ROTA-CAP

ROTA-CAP uses rotating packed bed (RPB) absorbers and regenerators for contacting flue gas with CCSUS's solvent for carbon capture



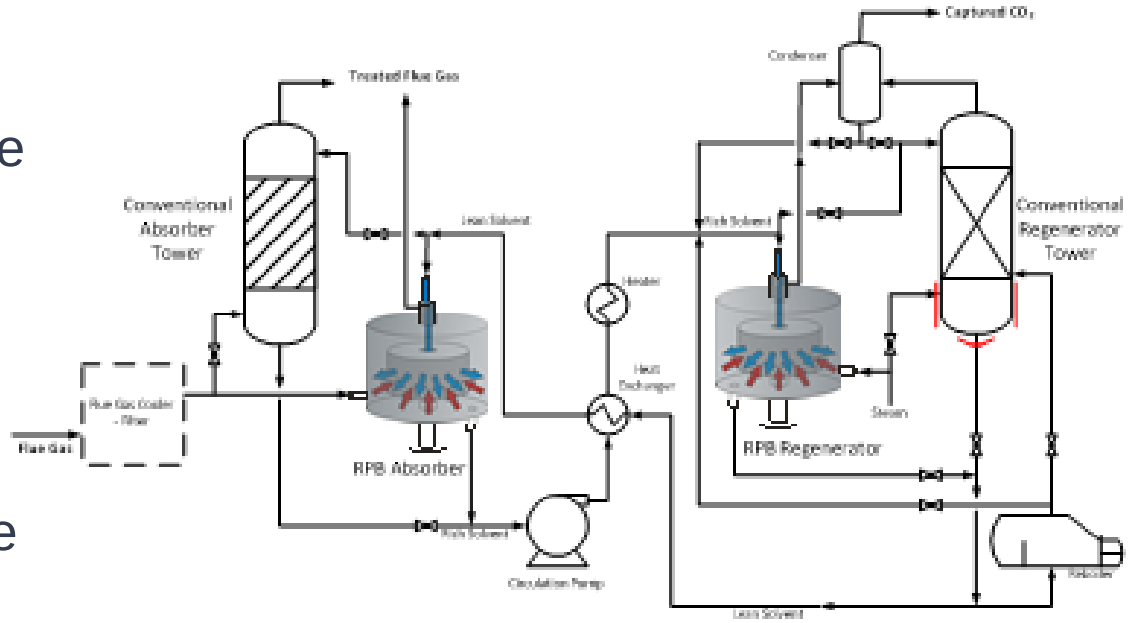
Simplified ROTA-CAP flow diagram

Project Objectives (cont.)

BP	Objectives
1	• Design, Construct and commission ROTA-CAP equipment at GTI. • Develop a preliminary process model and perform an initial fabrication feasibility study for commercial process. • Test with simulated flue gases and natural gas burner flue gas at GTI to determine key operating parameters • Calibrate process model and measure solvent carry over.
2	• Perform long-term reliability and operability testing at NCCC on SCPC flue gas source. • Verify process model. • Determine scale-up challenges, solvent degradation, and aerosol formation. • Complete high-level techno-economic analysis.

Innovation: Process Intensification (PI) by Using Rotating Packed Bed Reactors to Replace Conventional Absorber and Regenerator

- Design, construct, test and model novel rotating packed bed (RPB) absorbers and regenerators
- Assess the performance of the integrated hardware and solvent under a range of operating conditions
- Test with simulated flue gas and GTI's natural gas burner flue gas
- Long term test with coal-fired flue gas testing at the National Carbon Capture Center (NCCC)



Simplified ROTA-CAP flow diagram

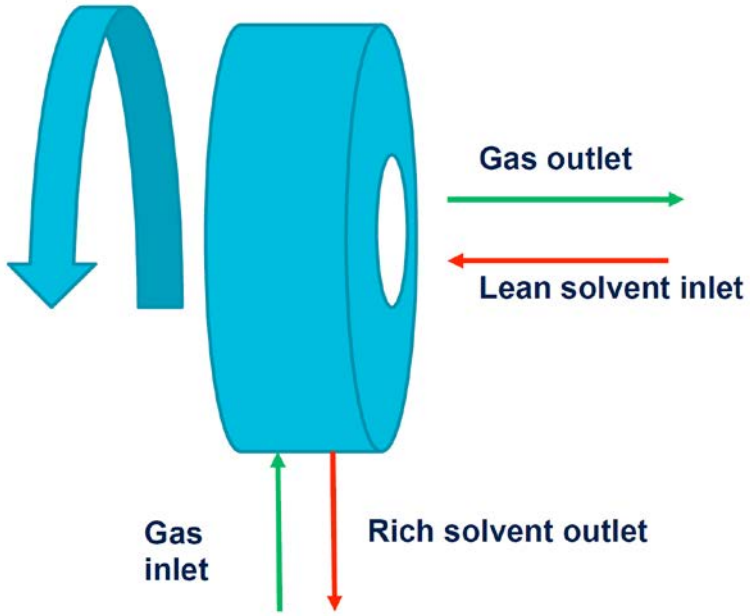
Roles and Responsibilities

Member	Specific Project Roles
gti	• Overall project integration and management • Design and integration of ROTA-CAP, Process Flow Diagrams (PFDs) and Piping and Instrumentation Drawings (P&IDs) • Construct, shakedown and commission bench-scale skid • Perform parametric testing using simulated gas and natural gas burner • Operate the test skid during long-term testing • Analyze experimental data & complete techno-economic analysis
CCS Carbon Clean Solutions	• Develop a preliminary process model for the Rota-Cap system • Preliminary process design and assist GTI on detailed engineering design and integration • Review & identify known scale up issues and comment to the scale-up plan • Analyze experimental data and update process model & complete techno-economic analysis • Provide solvent for testing both at GTI and NCCC
NC NATIONAL CARBON CAPTURE CENTER	• Assist in installation and commissioning of the test skid • Assist in running the test skid

ROTA-CAP Background: Introduction

ROTA-CAP EQUIPMENT

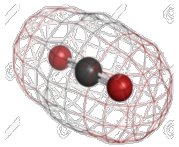
RPB equipment improves mass transfer leading to up to 90% volume reduction from a conventional static column.



INTENSIFIED SOLVENT

Intensified solvent leads to a reduction in energy and equipment size.

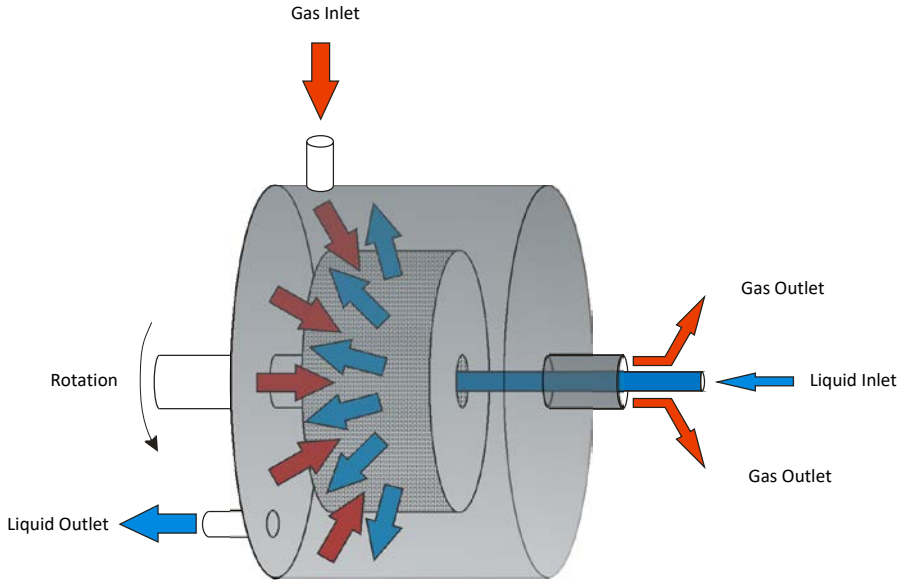
Advanced Solvents (APBS 1)

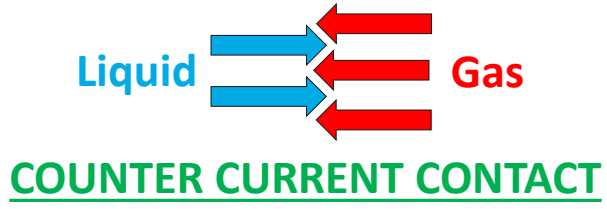


Intensified Solvents (APBS 2)

RPB equipment with intensified solvent will improve typical economics

ROTA-CAP Background: Absorber

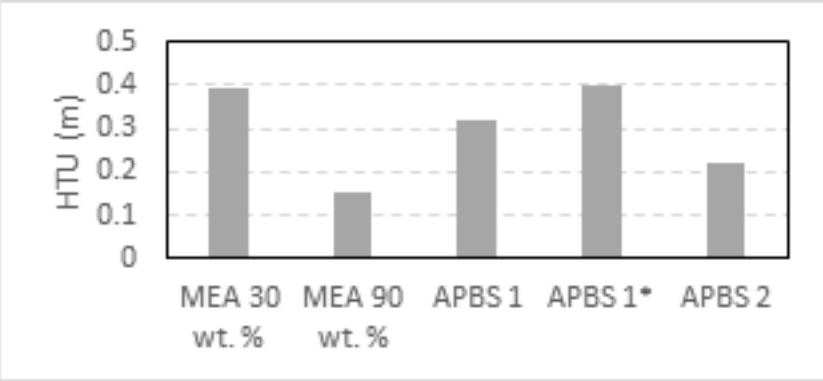




- Initial tests on bench-scale prototype absorber performance measured mass transfer of CO2 (12 vol.%) into 4 solvent systems.
- Counter current contact:
  - Solvent distributed from inner radius to outer radius under centrifugal force generated by rotation of the packed bed.
  - Gas flows from outer radius to inner radius of packed bed.
- Absorber tests measurements:
  - Inlet and outlet gas phase CO2 concentrations
  - Inlet, outlet and sump solvent temperature
  - Gas and liquid flow rates
  - Speed of rotation

Rota-Cap Background: Solvent

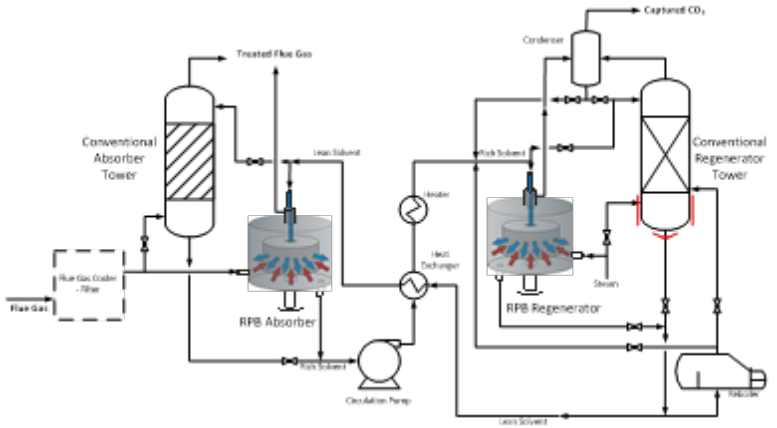
- Intensified solvents have been developed to achieve higher CO_2 loadings than those used in conventional systems – these are more viscous than conventional solvents.
- Intensified solvents (MEA 90 wt.% and APBS 2) exhibited higher mass transfer rates (low HTU) than non-intensified solvents (MEA 30 wt.% and APBS 1).
- Simulation determined a conventional absorption process with 30 wt.% MEA requires packing height of 0.94 m to achieve equivalent mass transfer of CCSL's intensified solvent in RPB with 0.11 packing height – leading to close to 90% size reduction



Solvent	30 wt.% MEA	APBS 2
Absorber Type	Static	RPB
CO_2 in (mol.%)	12.0	12.0
CO_2 out (mol.%)	7.2	7.2
Packing Height (m)	0.94	0.11
Relative Size Reduction	Base	8.5

Advantages Over Traditional Processes

- RPB technology reduces the size and therefore cost of the absorber
- RPB regenerator size reduction is comparable to that of an RPB absorber
- Reduced sizing requirements of heat exchangers, pumps, and coolers by up to 50%
- Lower residence time of the solvent in the absorber
- Reduced oxidative and thermal degradation
- Decreased solvent top-up requirements by approximately 77%
- Reduced waste handling and disposal cost by up to 92%



Simplified ROTA-CAP flow diagram

Potential project benefits and outcomes

- More versatile process compared to other next generation CO_2 capture technologies

  RPB reactors are non-selective to the solvent used

  - Process simulation model for ROTA-CAP

    Used for larger-scale ROTA-CAP technology deployment

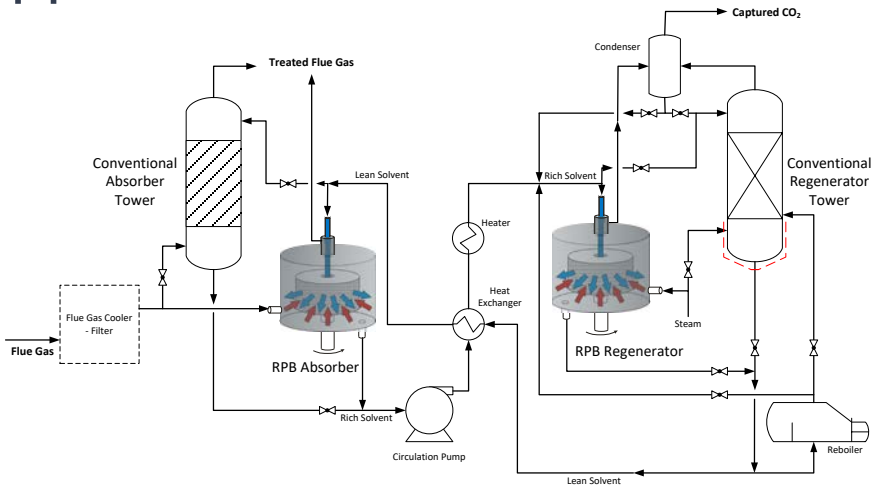
    - High-level techno-economic analysis (TEA)

      Used for proving the value of the ROTA-CAP technology in the carbon capture market

Test Equipment

- 50kWe (1000kg/day CO_2 removal) scale integrated carbon capture skid
- Flue gas cooling and filtration section available to be used when necessary
- Designed to operate with either RPB contactors or conventional columns to allow independent testing of each application

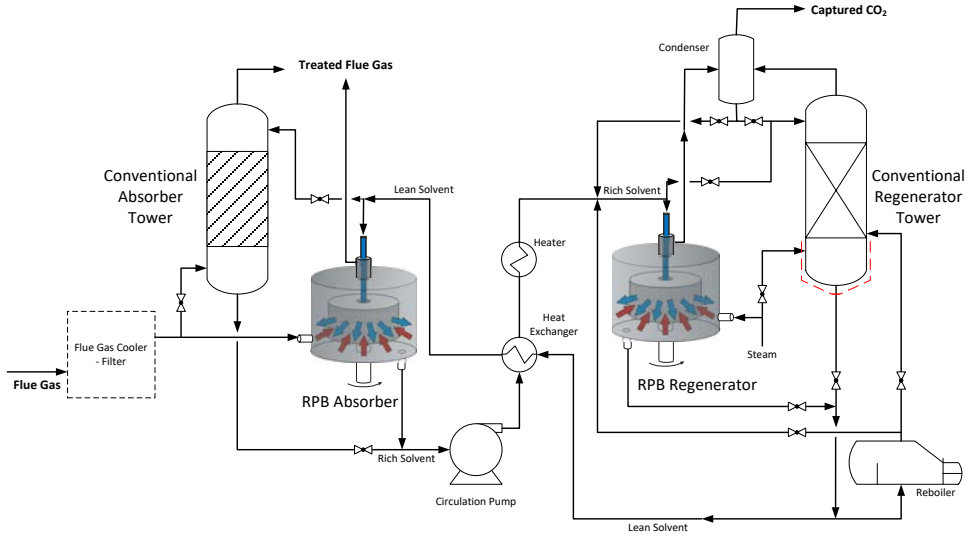
Test Campaign	Duration
Simulated gas testing	3 months
Natural gas burner flue gas	1 month
Simulated or nat. gas burner	1 month
Long-term testing at NCCC	Cumulative 1000 hr



Simplified ROTA-CAP flow diagram

Key Experimental Parameters

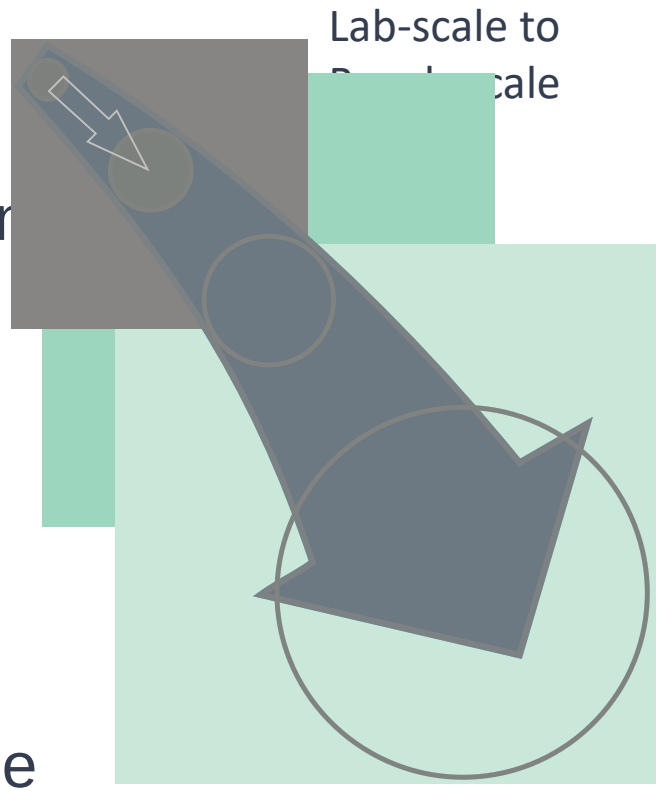
Parameter	Range
Rotational Speed	500–2000 RPM
Absorber Liquid/Gas ratio	0.5–5.0 kg/m3
Solvent Circulation Rate	30–150 kg/h
Solvent Concentration & Viscosity	40–80 wt.% & 5–100 cP
Regenerator Operating Pressure & Temperature	0.0–1.0 bar(g) & 100–130°C
Flue gas composition	Synthetic - Natural gas-fired - Coal-fired



Simplified ROTA-CAP flow diagram

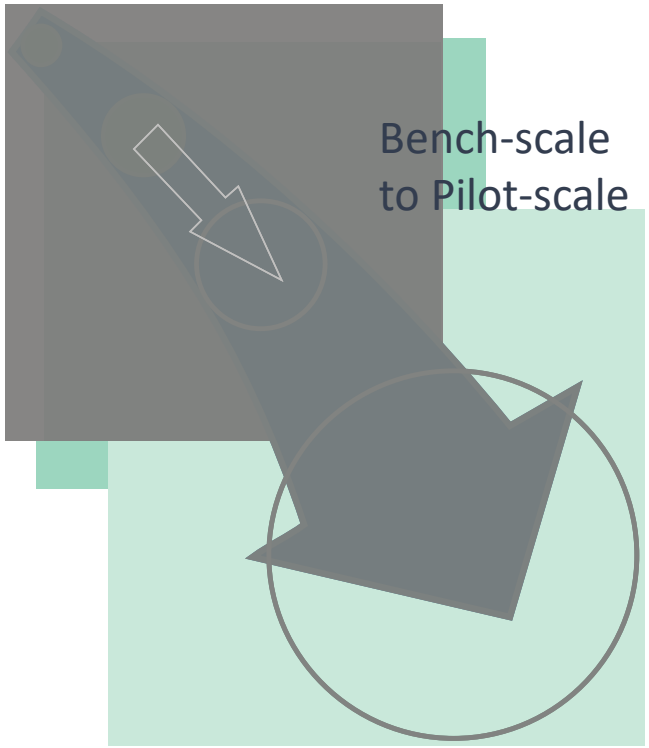
Technical and Economic Challenges

- The integrated use of RPBs as both absorber and regenerator in a single system
- The mechanical design parameters of rotating equipmer
- Solvent stability performance during operation
- Integrating and achieving required solvent regeneration using an RPB regenerator
- During testing we will determine the solvent performance and optimize to meet project objectives



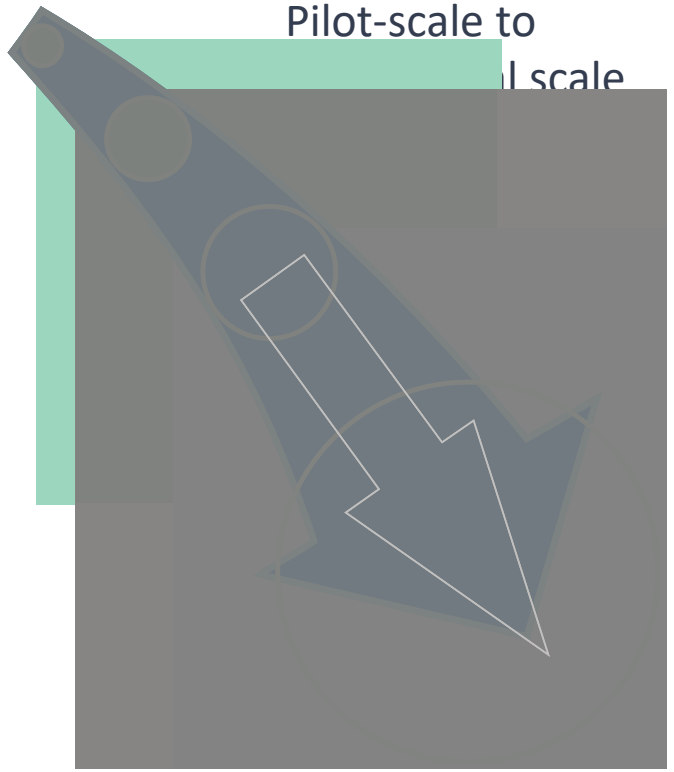
Limitations of Experimental Approach

- Challenges of scale up from bench-scale to commercial scale
- Next expected step up is 10x
- Design of seals, wall effects and area affects are hard to determine for commercial scale



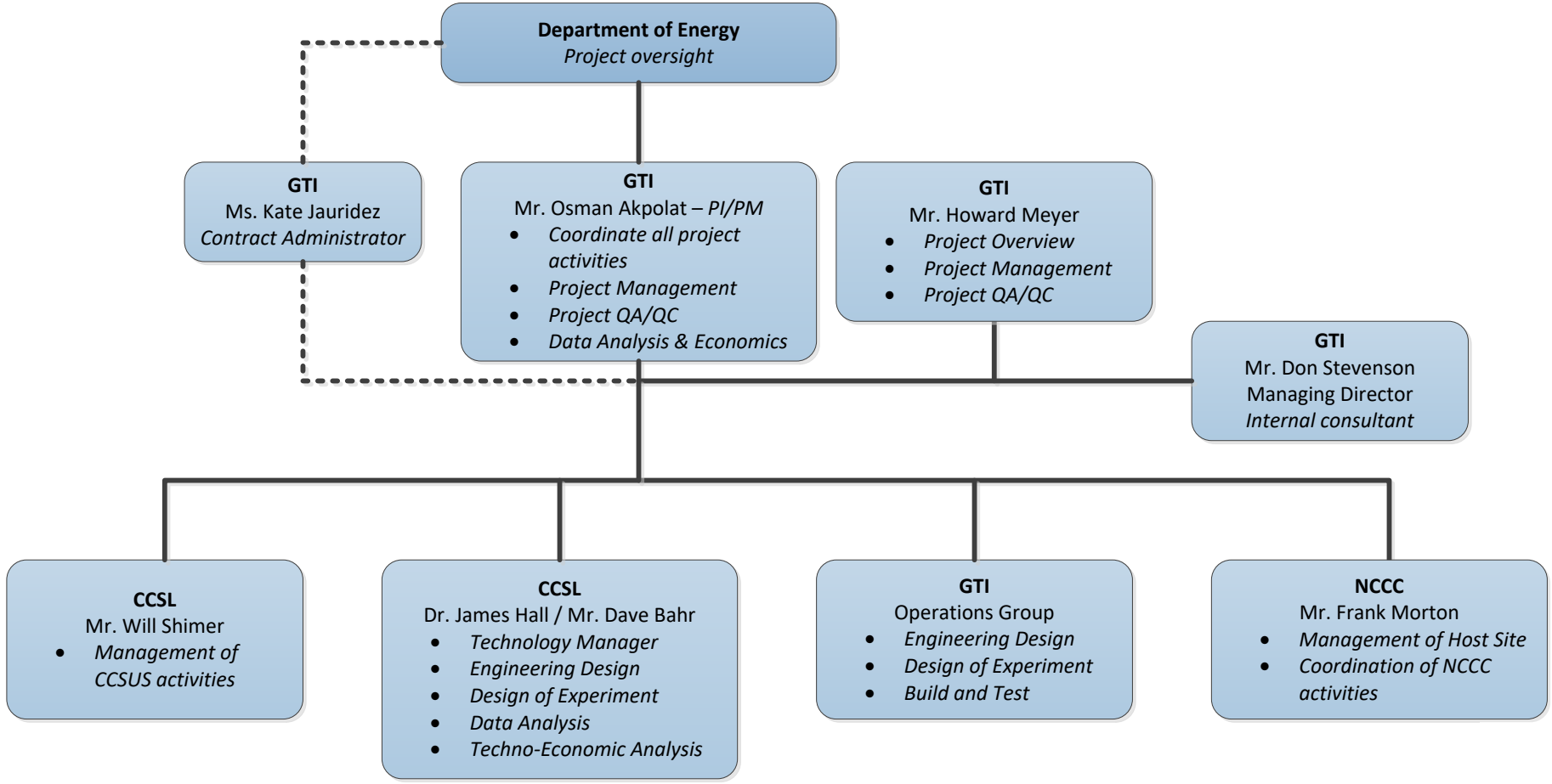
Limitations of Experimental Approach (cont.)

- Scaling up of the RPBs can be challenging
- We will allow for design limitations of rotating equipment and investigate the modular design approach



Administrative Efforts

Planned Project Team



Project Structure – Task Description

Budget Period 1 and 2

Task 1.0 – Project Management and Planning

- GTI will coordinate and plan the project activities with Team Members at CCSUS and NCCC. GTI will report technical progress and financial status to DOE/NETL throughout the duration of the project.
- GTI shall coordinate activities in order to effectively accomplish the work and ensure that project plans, results, and decisions are appropriately documented and project reporting and briefing requirements are satisfied.

Go/No Go Decision Point – Budget Period 2 work under this agreement shall not be authorized without the specific written authorization of the Contracting Officer.

- Successful completion of all work proposed in Budget Period 1;
- Satisfactory achievement of applicable success criteria as identified in the PMP;
- Submission and approval of a Continuation Application in accordance with the terms and conditions of the award.

Project Structure – Task Description

Budget Period 1

Task 2.0 – Design and Verification of ROTA-CAP System Integrated Bench-Scale Test Skid

Subtask 2.01 – Design and Costing of the Bench-scale ROTA-CAP Test Skid

Subtask 2.02 – Preliminary Commercial Design Check

Task 3.0 –Construction and Testing of Integrated Bench-scale Test Skid

Subtask 3.01 – Construction of Test Skid

Subtask 3.02 – Commissioning of Test Skid

Task 4.0 – Short-term Parametric Testing at GTI

Subtask 4.01 Parametric Testing with Simulated Gas

Subtask 4.02 Parametric Testing with Natural Gas Burner

Subtask 4.03 Data Analysis and Long-term Testing Planning

Go/No Go Decision Point

Project Structure – Task Description

Budget Period 2

Task 5.0 – Long-term Testing with Real Flue Gas

Subtask 5.01 - Transport and Commissioning

Subtask - 5.02 - Reliability and Operability Testing

Subtask - 5.03 – Decommissioning

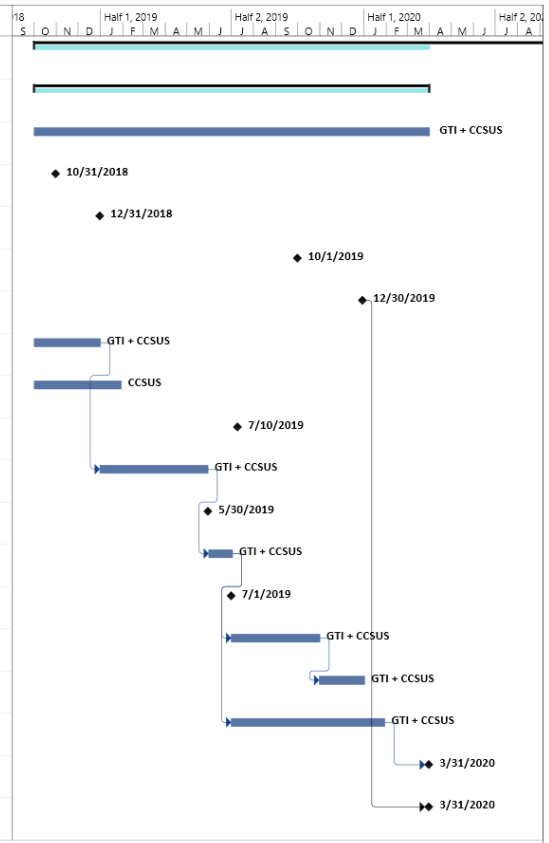
Task 6.0 – Data Analysis, TEA, and Final Report

Success Criteria

Decision Point	Date	Success Criteria
Go / No-Go	3/31/2020	• Complete design for bench scale ROTA-CAP skid utilizing continuous absorption-regeneration operation. • Viable design for a commercial scale unit verified. • Successful testing of the ROTA-CAP bench scale skid with RPB absorber and regenerator using simulated gas and natural gas burner flue gas: 1. 24 hr continuous operation with absorber and regenerator coupled together. 2. Startup and shutdown sequences are 1 hr each.
Completion of the project	3/31/2021	• Successful long duration testing: 1. Cumulative 1000 hr testing with SCPC flue gas. 2. Achieve 90% CO_2 capture under steady state conditions.

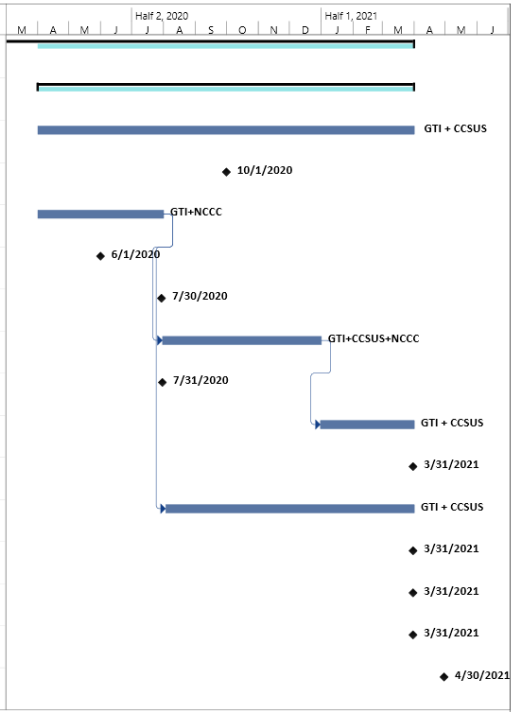
Schedule – BP 1

ID	Task	Milestone Number	Task Name	Start	Finish	Resource Names
1			**Project Total**	**10/1/18**	**3/31/21**	
2			**Budget Period 1**	**10/1/18**	**3/31/20**	
3	1.01		Project Management and Planning (BP1)	10/1/18	3/31/20	GTI + CCSUS
4		1.1	Update Project Management Plan	10/31/18	10/31/18	
5		1.2	Kickoff Meeting	12/31/18	12/31/18	
6		1.3	Submit Annual Report	10/1/19	10/1/19	
7		1.4	Continuation Application	12/30/19	12/30/19	
8	2.01		Design and Costing of the Bench-scale Test Skid	10/1/18	12/31/18	GTI + CCSUS
9	2.02		Preliminary Commercial Design Check	10/1/18	1/29/19	CCSUS
10		2.1	Develop Preliminary Kinetic Model	7/10/19	7/10/19	
11	3.01		Construction of Test Skid	12/31/18	5/29/19	GTI + CCSUS
12		3.1	Finish Construction of Test Skid	5/30/19	5/30/19	
13	3.02		Commissioning of Test Skid	5/31/19	7/2/19	GTI + CCSUS
14		3.2	Start Parametric Testing	7/1/19	7/1/19	
15	4.01		Parametric Testing with Simulated Gas	7/1/19	10/31/19	GTI + CCSUS
16	4.02		Parametric Testing with Natural Gas Burner	10/31/19	1/1/20	GTI + CCSUS
17	4.03		Data Analysis and Long-term Testing Planning	7/1/19	1/29/20	GTI + CCSUS
18		4.1	Update Kinetic Model Based on Experimental Data	3/31/20	3/31/20	
19			**GO / NO-GO Decision Point**	3/31/20	3/31/20	



Schedule – BP 2

ID	Task	Milestone Number	Task Name	Start	Finish	Resource Names
1			**Project Total**	**10/1/18**	**3/31/21**	
2			**Budget Period 2**	**4/1/20**	**3/31/21**	
3	1.02		Project Management and Planning (BP2)	4/1/20	3/31/21	GTI + CCSUS
4		1.5	Submit Annual Report	10/1/20	10/1/20	
5	5.01		Transportation and Commissioning	4/1/20	7/31/20	GTI+NCCC
6		5.1	Transport Skid to Host Site	6/1/20	6/1/20	
7		5.2	Complete Commisioning	7/30/20	7/30/20	
8	5.02		Reliability and Operability Testing	7/31/20	12/31/20	GTI+CCSUS+NCCC
9		5.3	Start Long Term Testing	7/31/20	7/31/20	
10	5.03		Decommissioning	12/31/20	3/31/21	GTI + CCSUS
11		5.4	Removal of Skid and Chemicals from Host Site	3/31/21	3/31/21	
12	6.01		Data Analysis, TEA, and Final Report	8/3/20	3/31/21	GTI + CCSUS
13		6.1	Report Analysis of Experimental Data	3/31/21	3/31/21	
14		6.2	Verify Kinetic Model with Real Flue Gas Data	3/31/21	3/31/21	
15		6.3	Complete Economic Analysis	3/31/21	3/31/21	
16		1.8	Submit Final Technical Report	4/30/21	4/30/21	



Budget – Project Funding Profile

	Budget Period 1		Budget Period 2		Total Project	
	10/01/2018 - 03/31/2020		04/01/2020 - 03/31/2021			
	Government Share	Cost Share	Government Share	Cost Share	Government Share	Cost Share
Gas Technology Institute (Applicant)	$958,623	$0	$925,925	$0	$1,884,548	$0
Carbon Clean Solutions Limited (Subrecipient)	$515,206	$370,000	$384,468	$328,000	$899,674	$698,000
Total	**$1,473,829**	**$370,000**	**$1,310,393**	**$328,000**	**$2,784,222**	**$698,000**
Cost Share	**80%**	**20%**	**80%**	**20%**	**80%**	**20%**

Turning Raw Technology into Practical Solutions

www.gti.energy