Kickoff Meeting for:

BENCH-SCALE PROCESS FOR LOW-COST CARBON DIOXIDE (CO_2) CAPTURE USING A PHASE-CHANGING ABSORBENT

DE-FE0013687

GE Global Research

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(Tiffany Westendorf)

November 20, 2013

BENCH-SCALE PROCESS FOR CO_2 CAPTURE USING A PHASE-CHANGING ABSORBENT

Program Team

GE Global Research Niskayuna

- Bench-Scale Design
- Construction/operation of Continuous System
- EH & S Assessment
- Techno-Economic Assessment

coperion
confidence through partnership

- Extruder Design
- Component Integration
- Heat Management

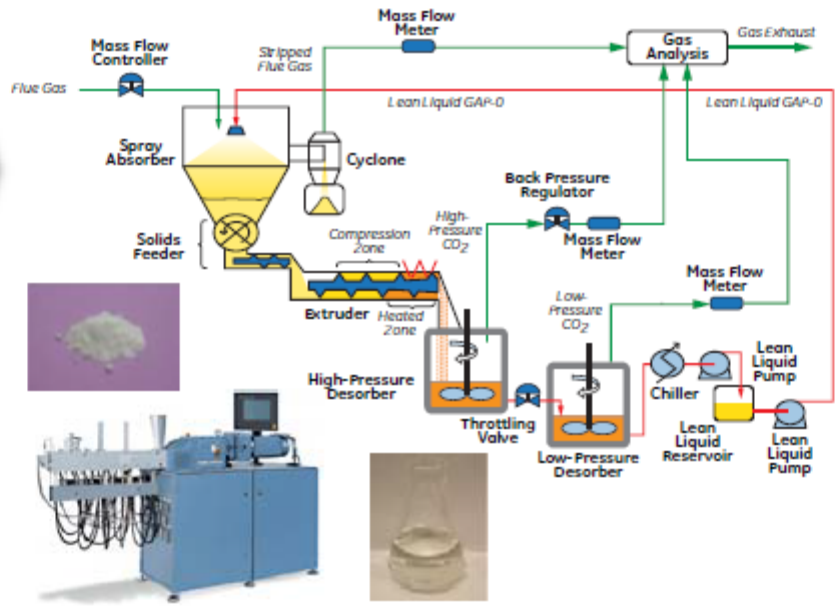
Gelest · SILAR Laboratories · SiVance

Solvent Manufacturers

- Aminosilicone Supply

36 Month, $3.0MM Program to Develop a Phase-Change Process for CO_2 Capture

Program Objective: *Design and optimize a new process for a novel silicone CO_2 capture solvent and establish scalability and potential for commercialization of post-combustion capture of CO_2 from coal-fired power plants. A primary outcome will be a system capable of 90% capture efficiency with less than $40/tonne CO_2 capture cost.*



Technical Approach

- Design and construct bench-scale unit and obtain parametric data to determine key scale-up parameters
- Perform an EH & S and technical and economic assessment to determine feasibility of commercial scale operation
- Develop scale-up strategy

Program Deliverables

- Strategy for future scale-up
- Technical and economic feasibility determined
- Environmental assessment

Anticipated Benefits of the Proposed Technology

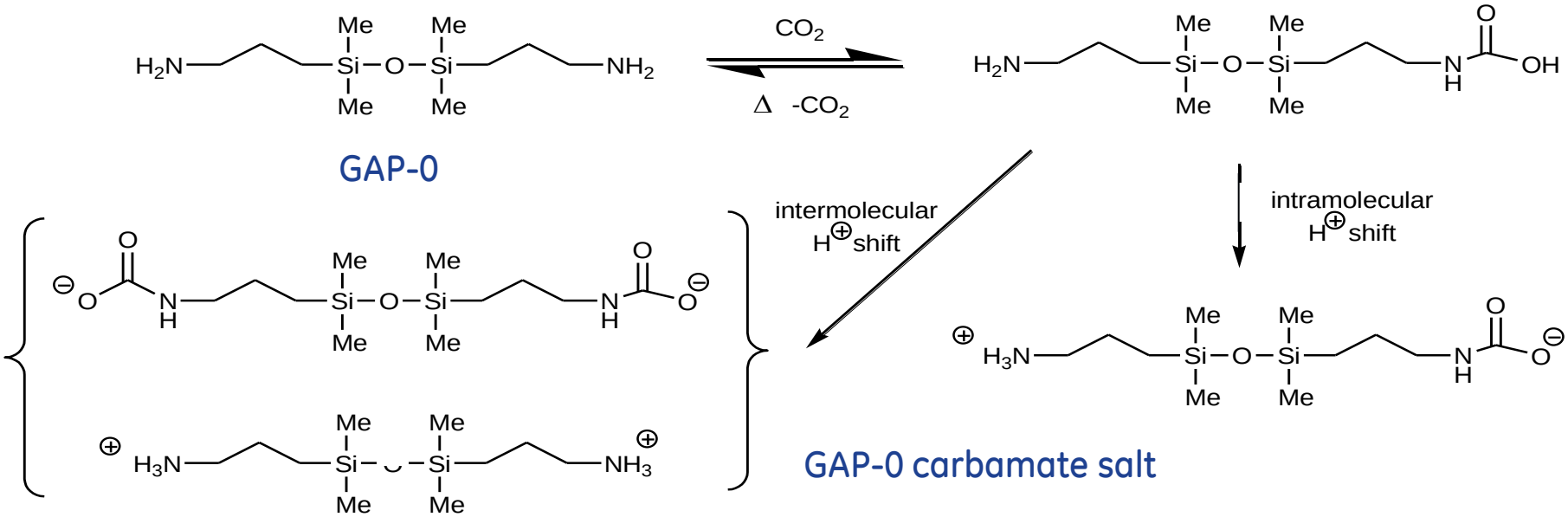
- 90% CO_2 capture
- $40/tonne CO_2 capture cost

Contents

- **Background on the proposed technology and its scientific/technical merit**
- Project objective
- **Technical approach/project scope**
- Project budget
- Project schedule and associated milestones
- Decision points and success criteria
- Project team/project organization
- **Project risks and mitigation strategies**

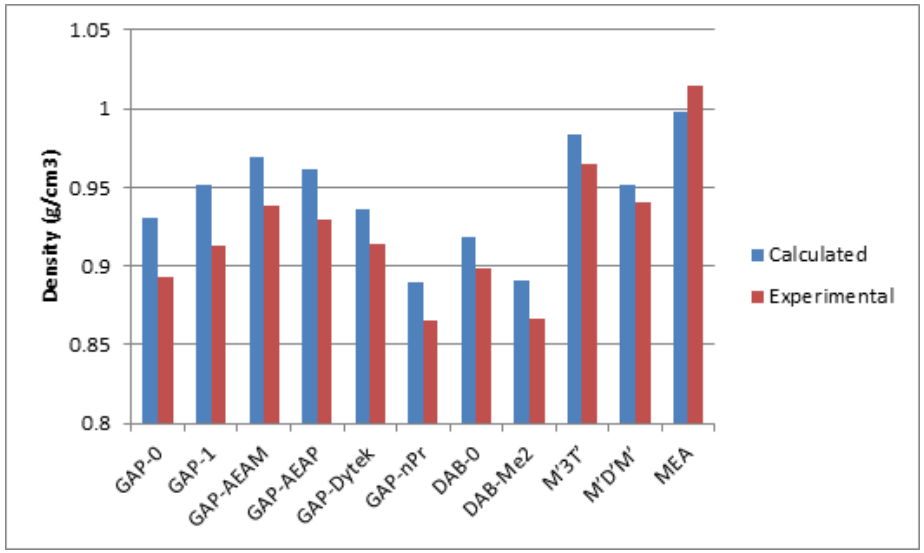
Background

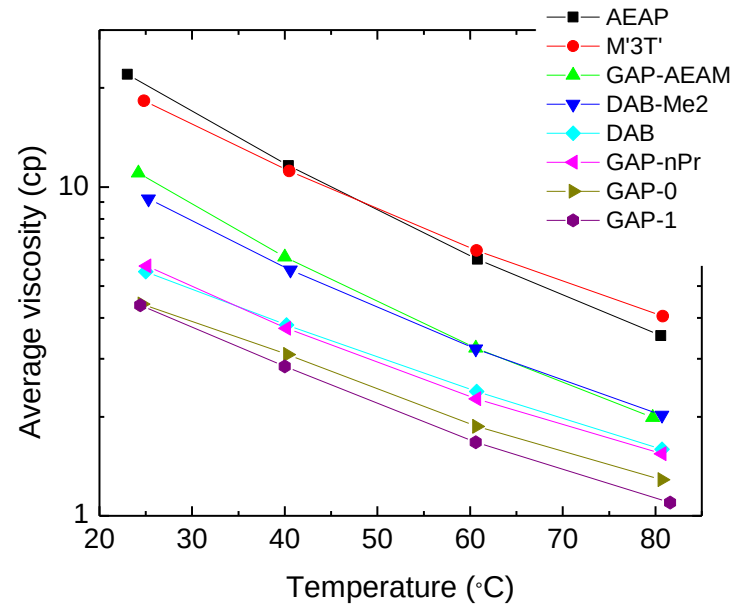
Chemistry of GAP-0 reaction with CO_2

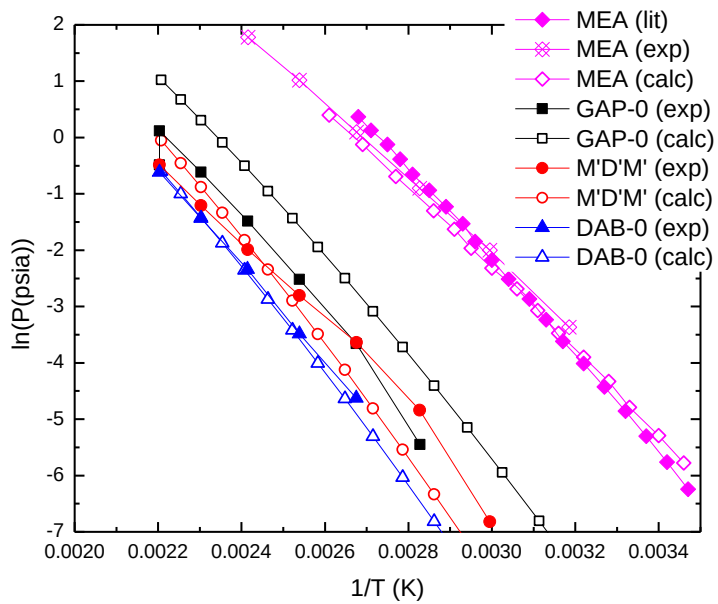


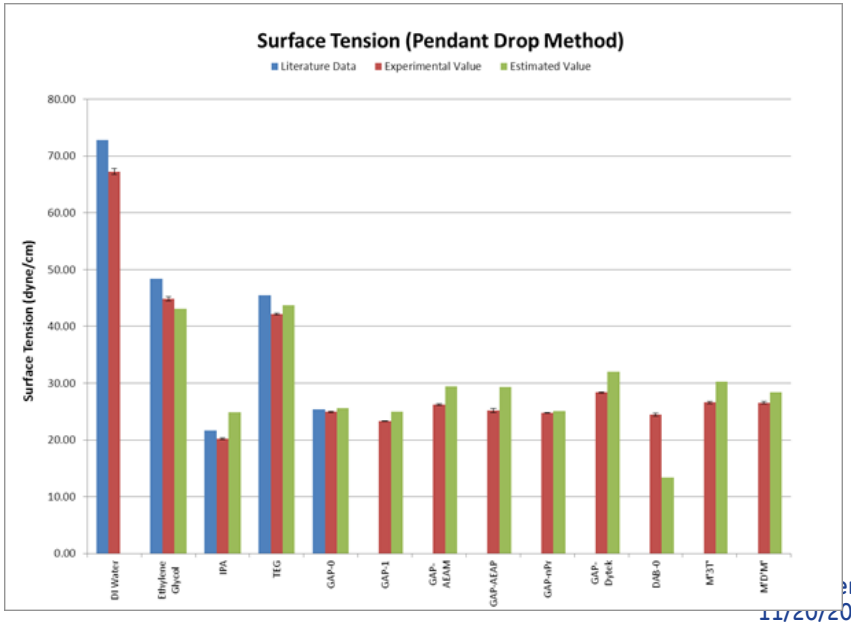
- Extensive screening of multiple solvents
- Absorbs CO_2 very rapidly in the 40-50°C range
- High CO_2 loading (>17% weight gain, >95% of theoretical value)
- Carbamate readily decarboxylates at higher temps
- Carbamate is solid which opened up phase-change option

Physical Properties

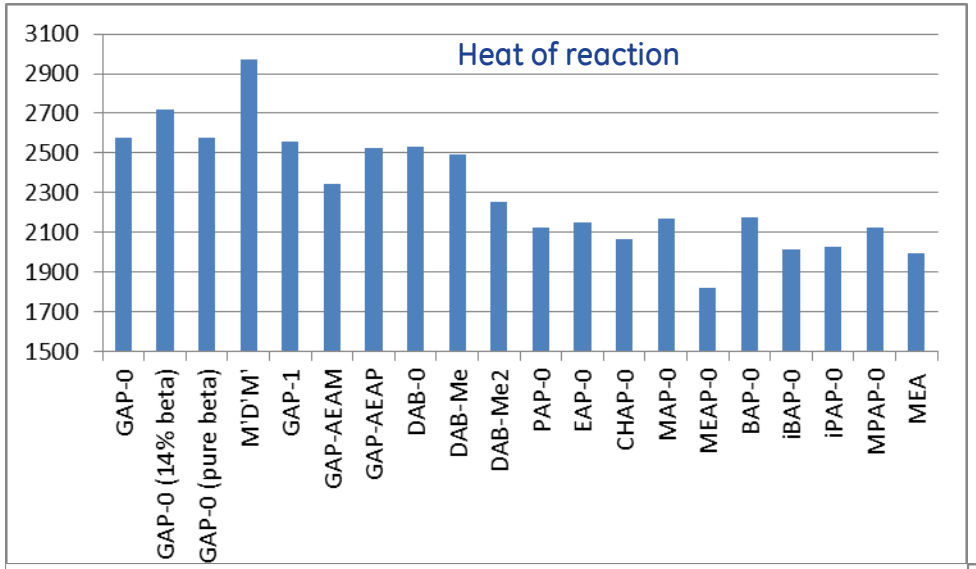




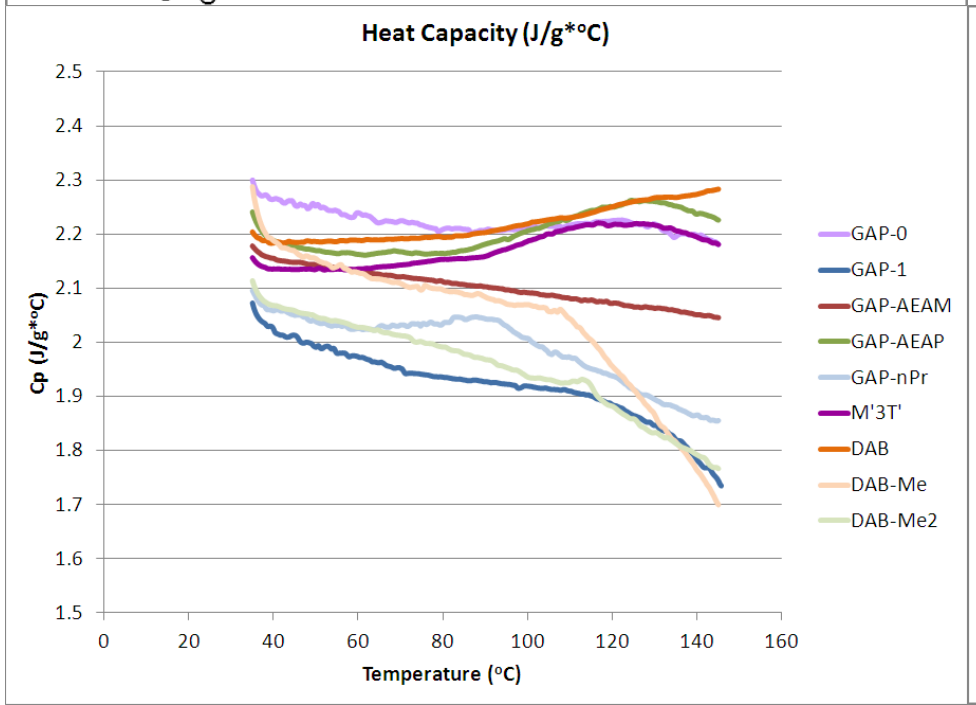


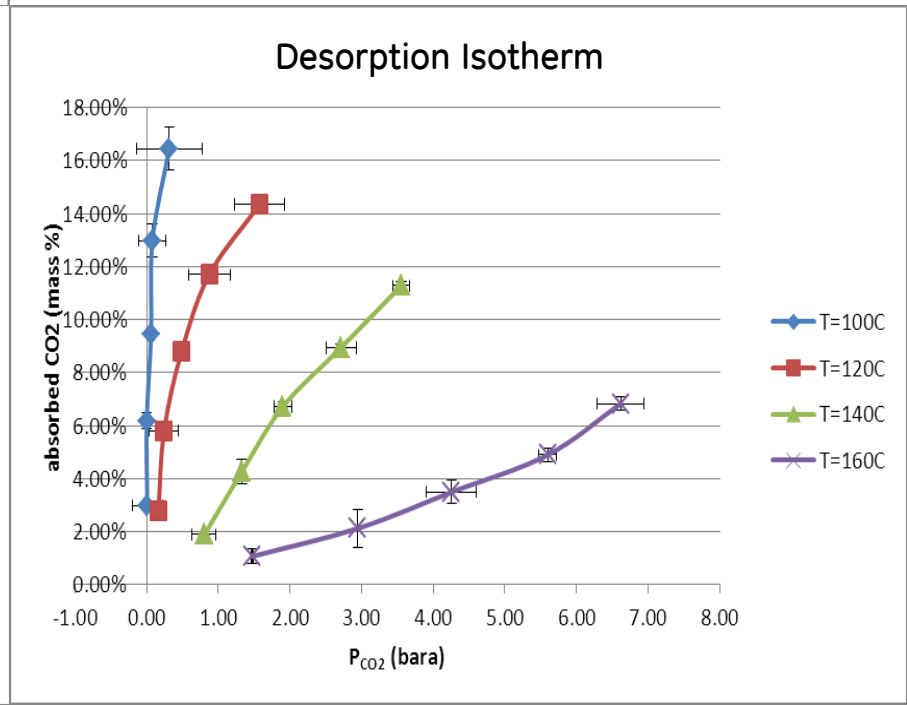


Thermal Properties



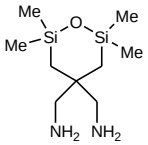
- Wide range of ΔH_{rxn}
- C_p ~½ that of $MEA_{(aq)}$
- >11% Dynamic range @ 6 bara





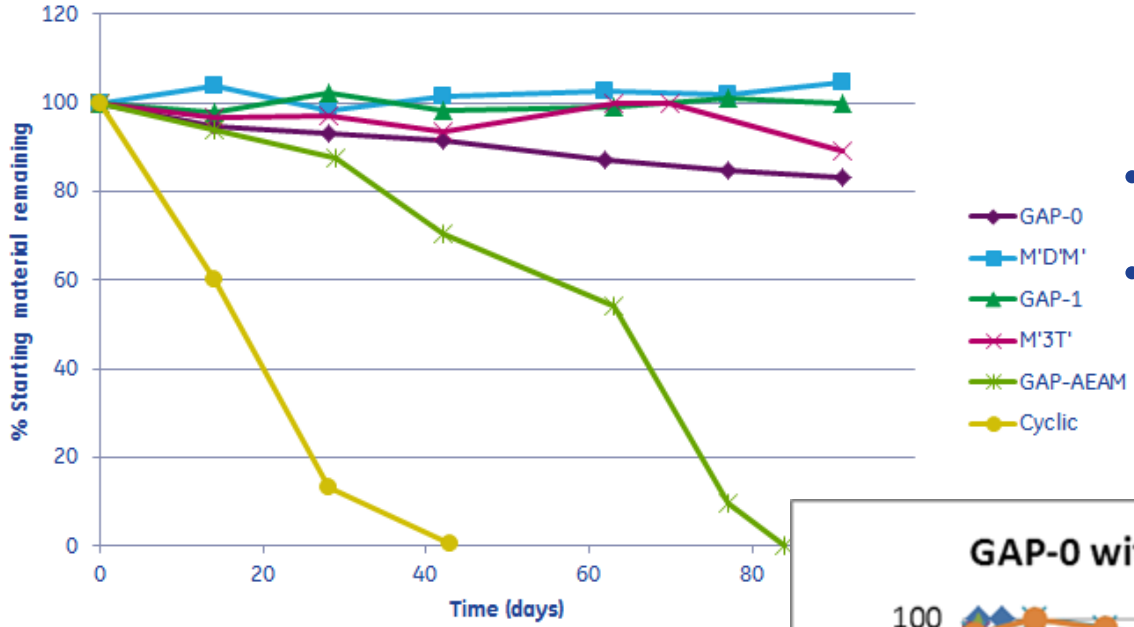
Effect of Water on Carbamate Salt

Impact of dry vs wet CO_2

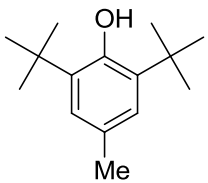
Solvent	Dry % Wt Gain (% of Theoretical)	Dry Salt Form	Wet % Wt Gain (% of Theoretical)	Wet Salt Form
GAP-0	17.3 (98)	Powder	18.4 (104)	Chunky Solid
GAP-1	13.1 (96)	Powder	14.1 (103)	Sticky Wax
M'D'M'	17.8 (99)	Powder	16.6 (92)	Glass
M'_3T'	18.8 (103)	Powder	17.4 (96)	Sticky Gum
	17.3 (92)	Powder	20.7 (109)	Powder

- Pure compounds GAP-0 & cyclic diamine looked best
- Oligomer-based salts softened with H_2O & became sticky

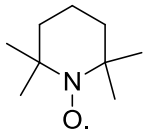
Thermal Stability



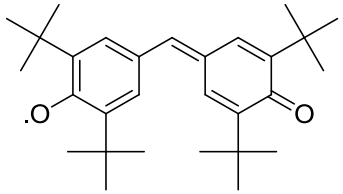
- Good stability of GAP-0
- Improvement w/ stabilizers



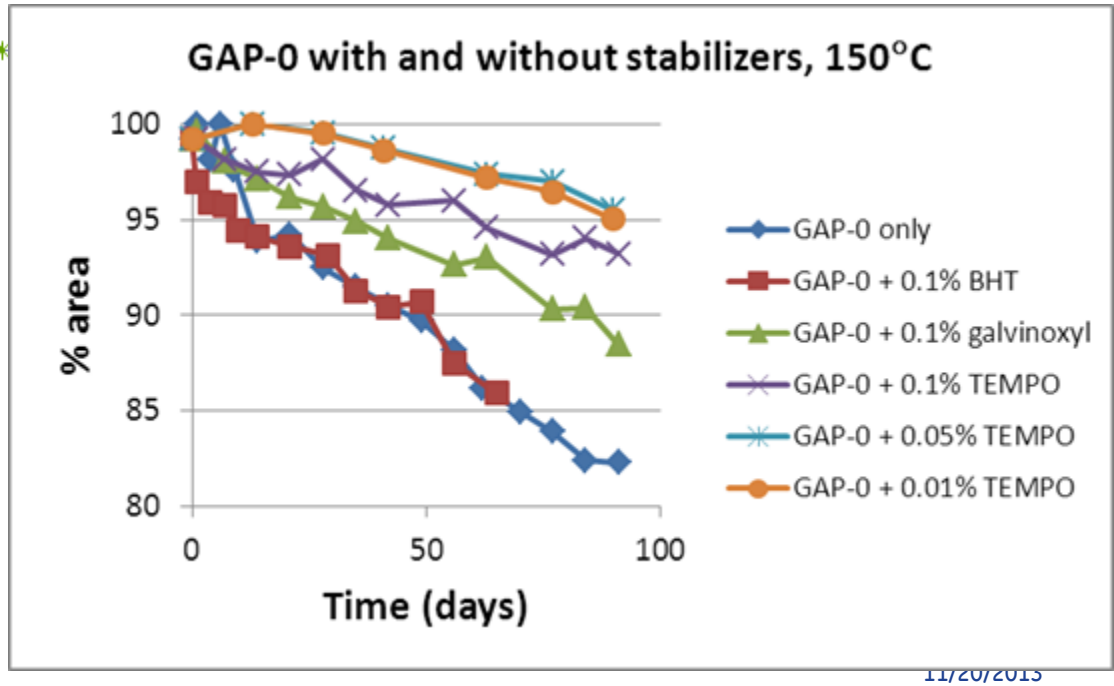
BHT



TEMPO



Galvinoxyl



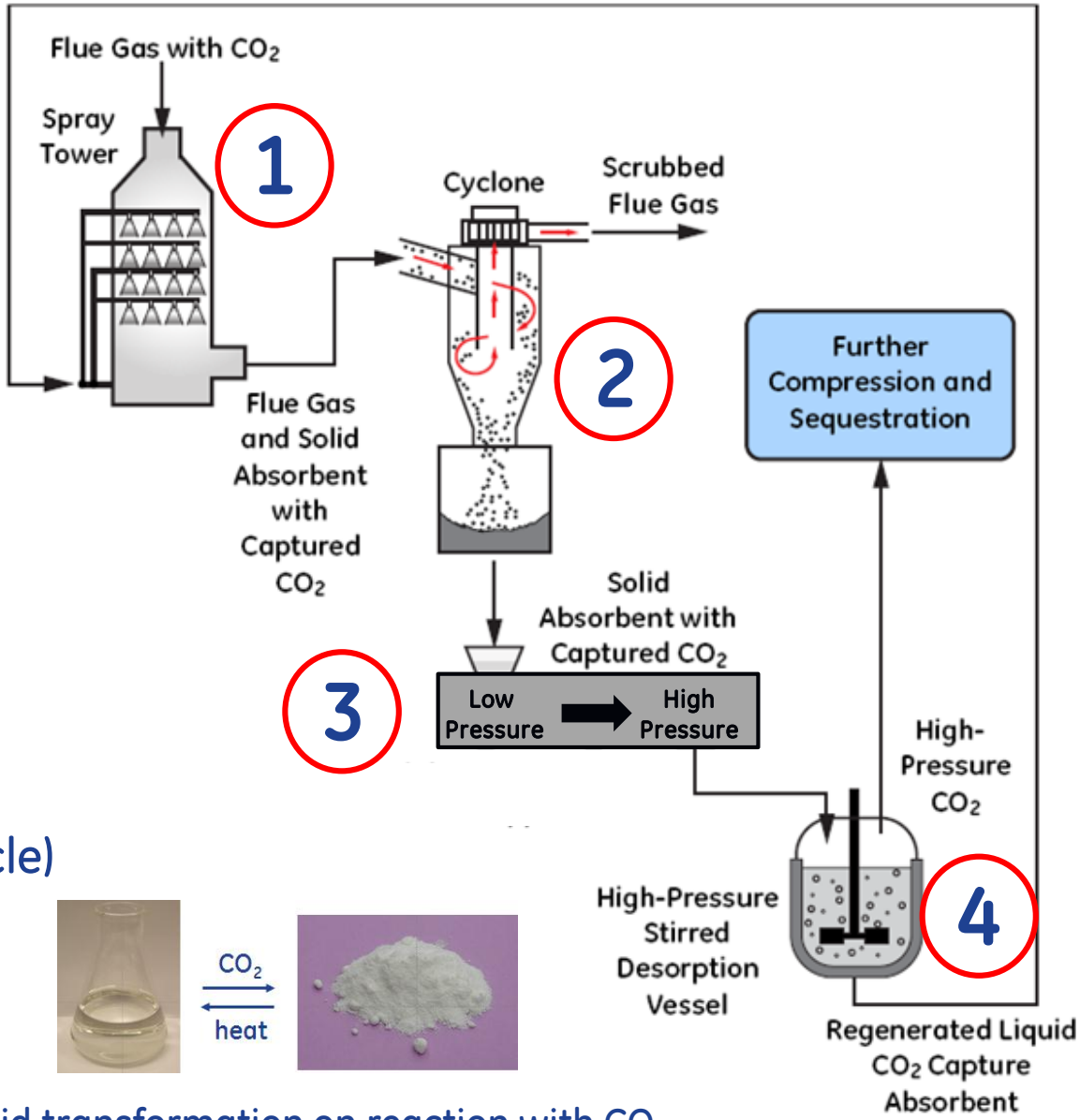
Generic Phase Change Process

1 Make the solid
(Solvent development)

2 Collect the solid
(Solid isolation)

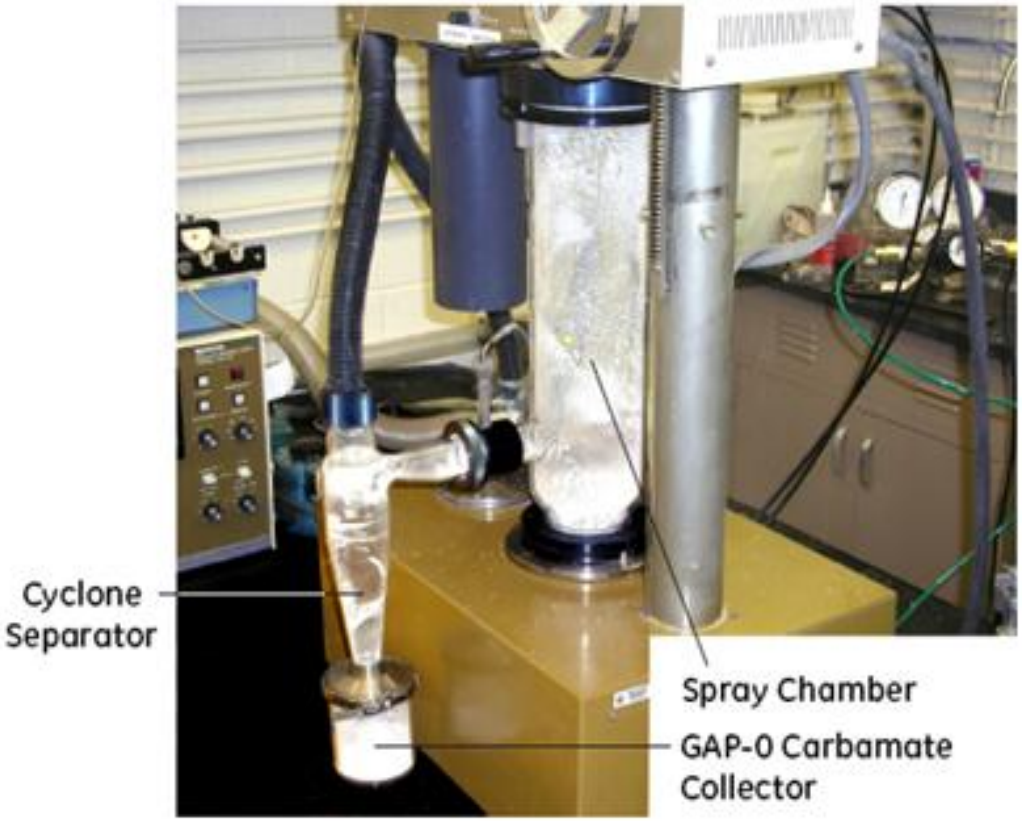
3 Move the solid
(Solids transport)

4 Regenerate the solvent
(CO_2 desorption and recycle)

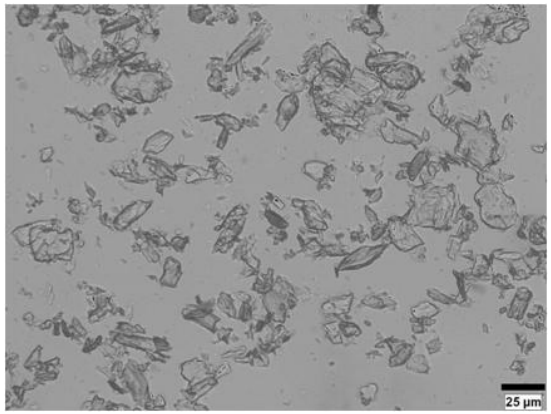


Liquid to solid transformation on reaction with CO_2

Solid Formation and Isolation



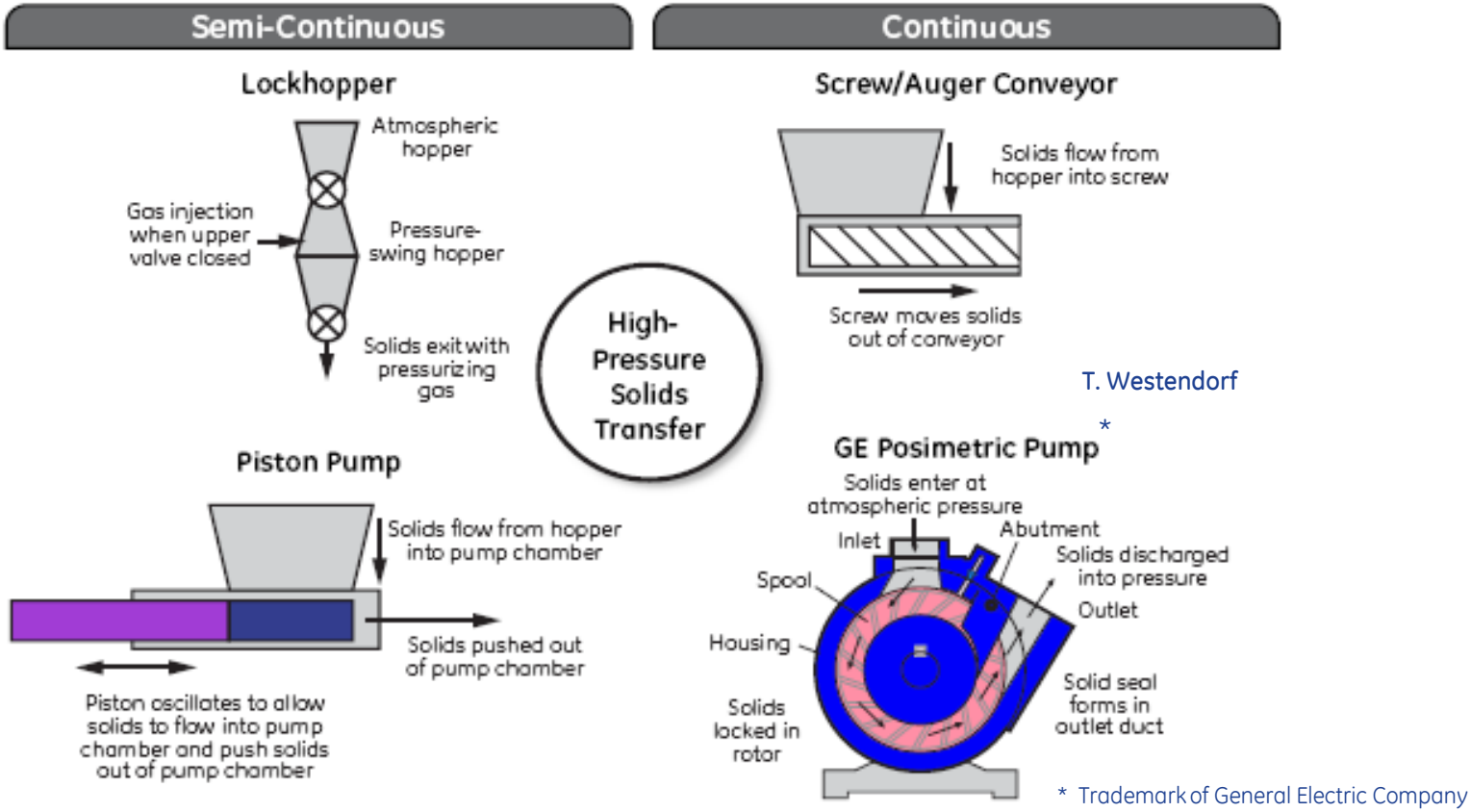
GE GRC Spray Reactor



- Spray reactor with co-current CO_2 flow
- Nearly instantaneous solid formation
- 50-400 g sample size

- Mean particles < 50µm
- Highly crystalline

Options for Solid Transport



- Contingent upon physical characteristics of solid
- Density, shape , cohesiveness, moisture content, thermal stability
- Integration between absorber and desorber
- Low pressure to high pressure
- Slurry transport

Unit Operations

Absorber/spray dryer

- Two spray reactors, 1 w/ MS capability
- Slurry transfer unit with ISCO pumps
- CSTR as high pressure desorption apparatus
- All operations functional
- Next step – integrated system

Slurry Transfer Unit

Desorber Unit

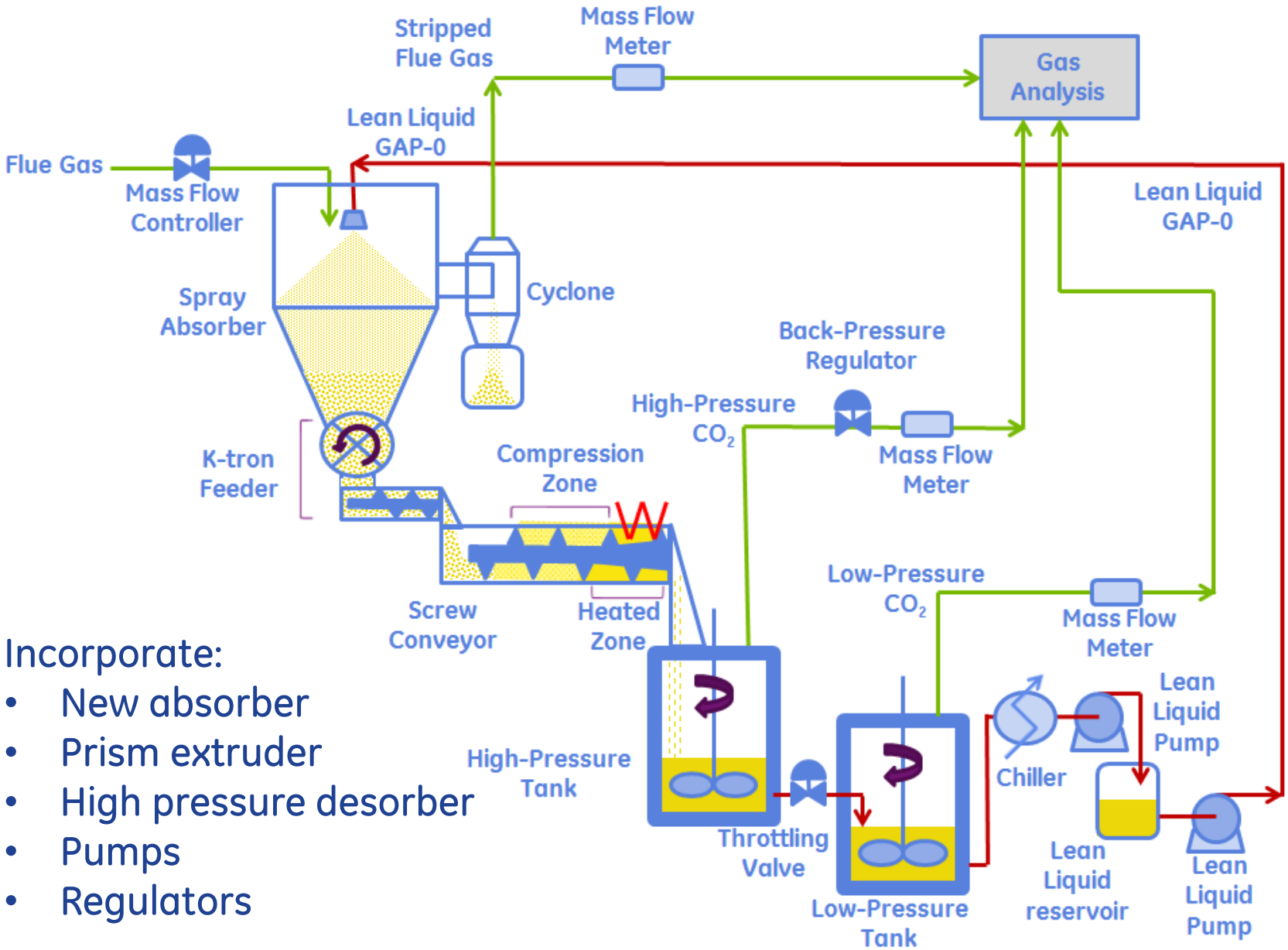
Improvements in Desorption

- Not satisfied with desorption process
- Sacrificing inherent ability of GAP-0
- Revisit solids transport
- Use an extruder as a transport device
- PRISM twin screw extruder

Further Improvements

- Take process one step further
- Use extruder to desorb CO_2 from carbamate
- Combine 2 unit operations
- Save space and money
- Look at effect of rpm and feed rate on performance

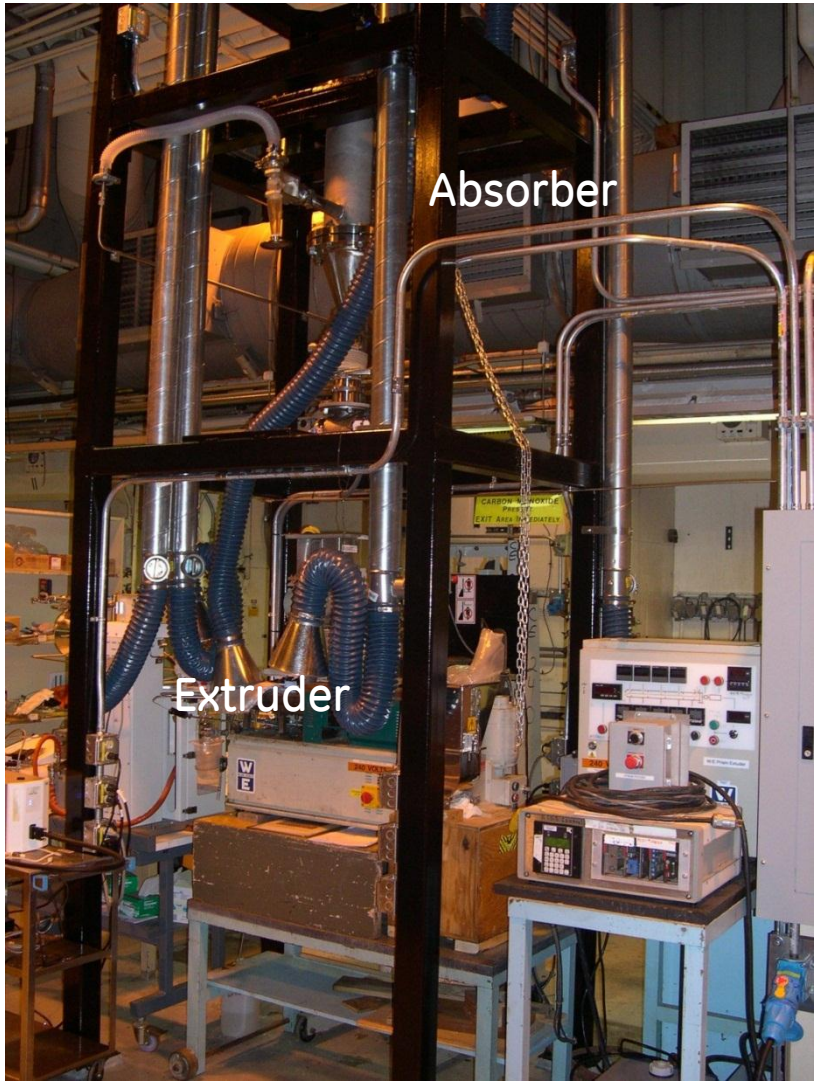
Continuous System



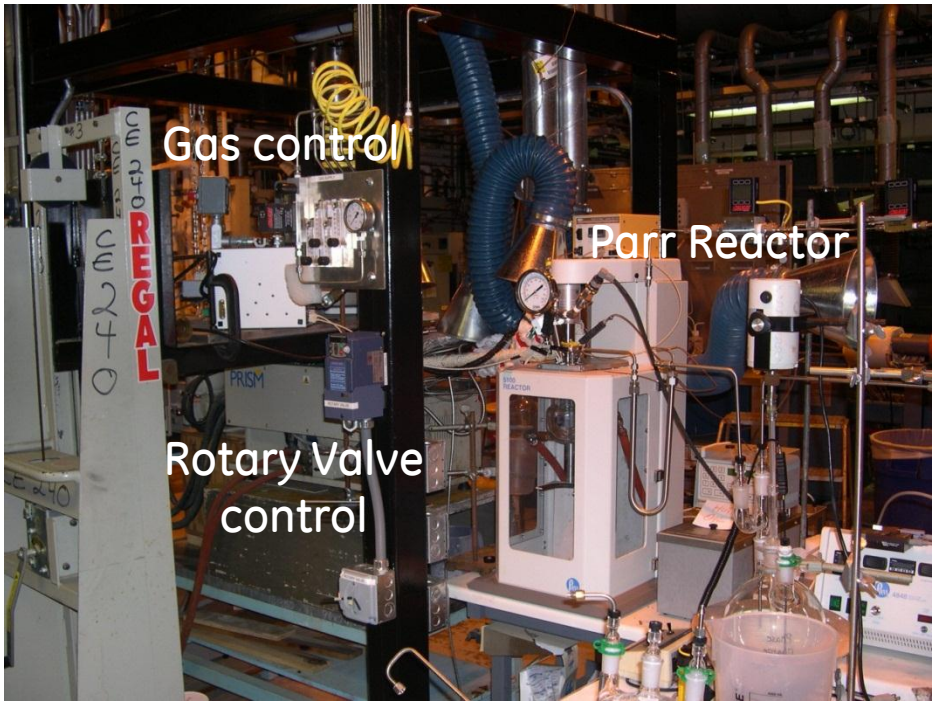
Incorporate:

- New absorber
- Prism extruder
- High pressure desorber
- Pumps
- Regulators

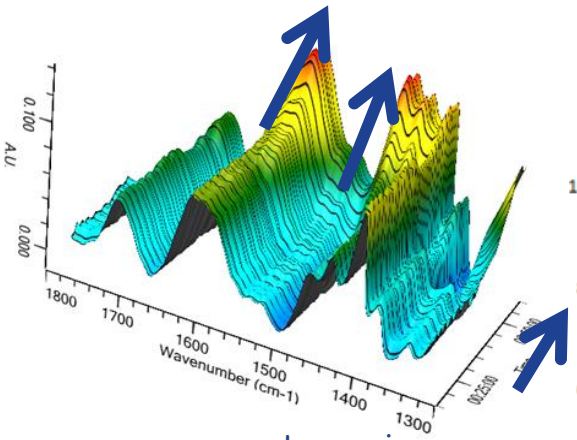
Phase-Change Continuous System



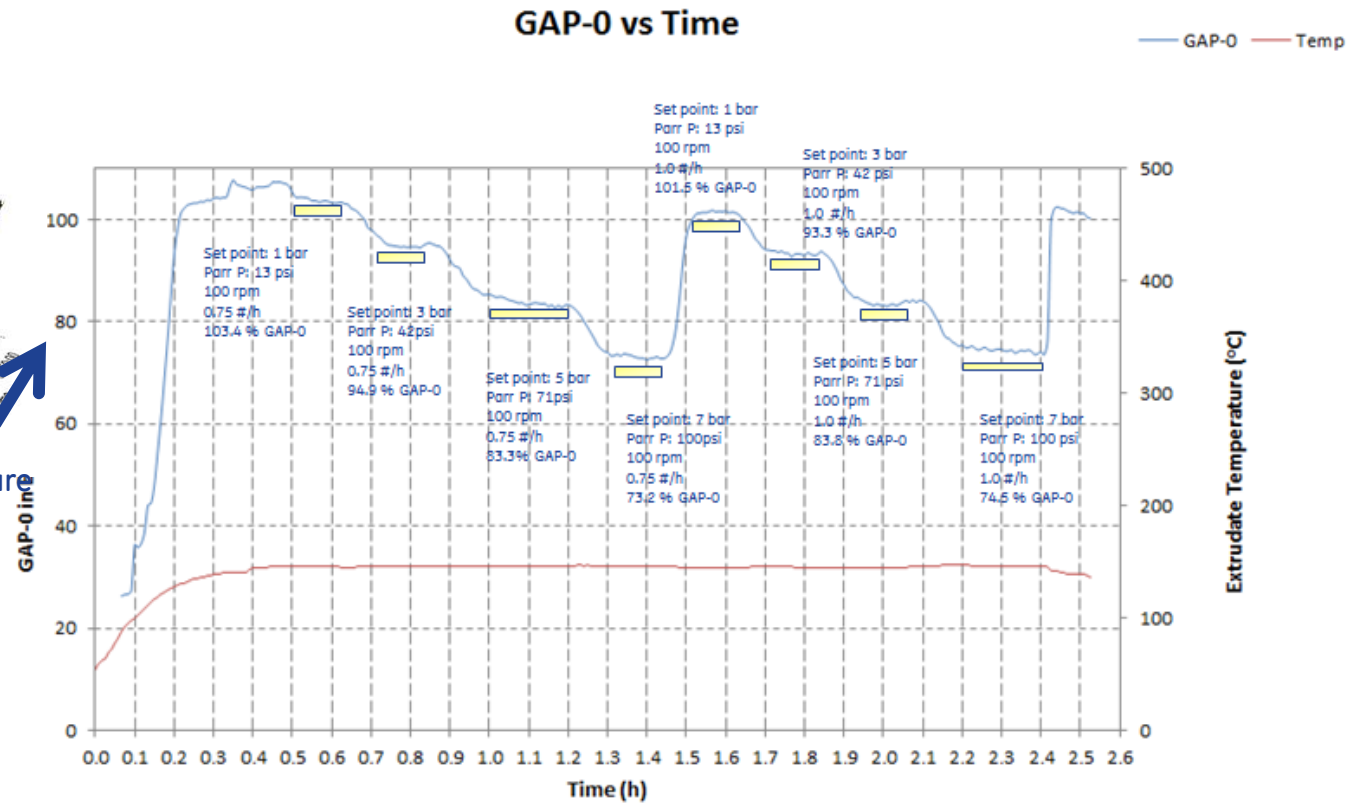
- System operational
- Larger absorption unit
- FT-IR/MS/CO_2 analyzer installed
- 2 months of data gathering



FT-IR for real time monitoring

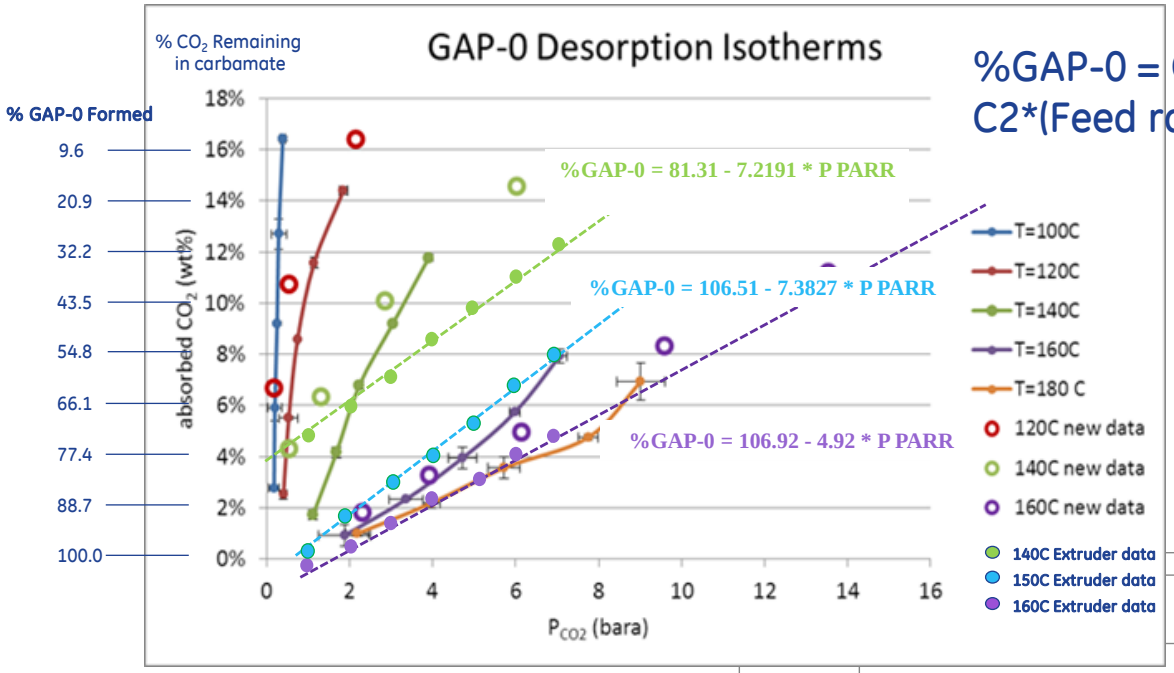


Increasing pressure

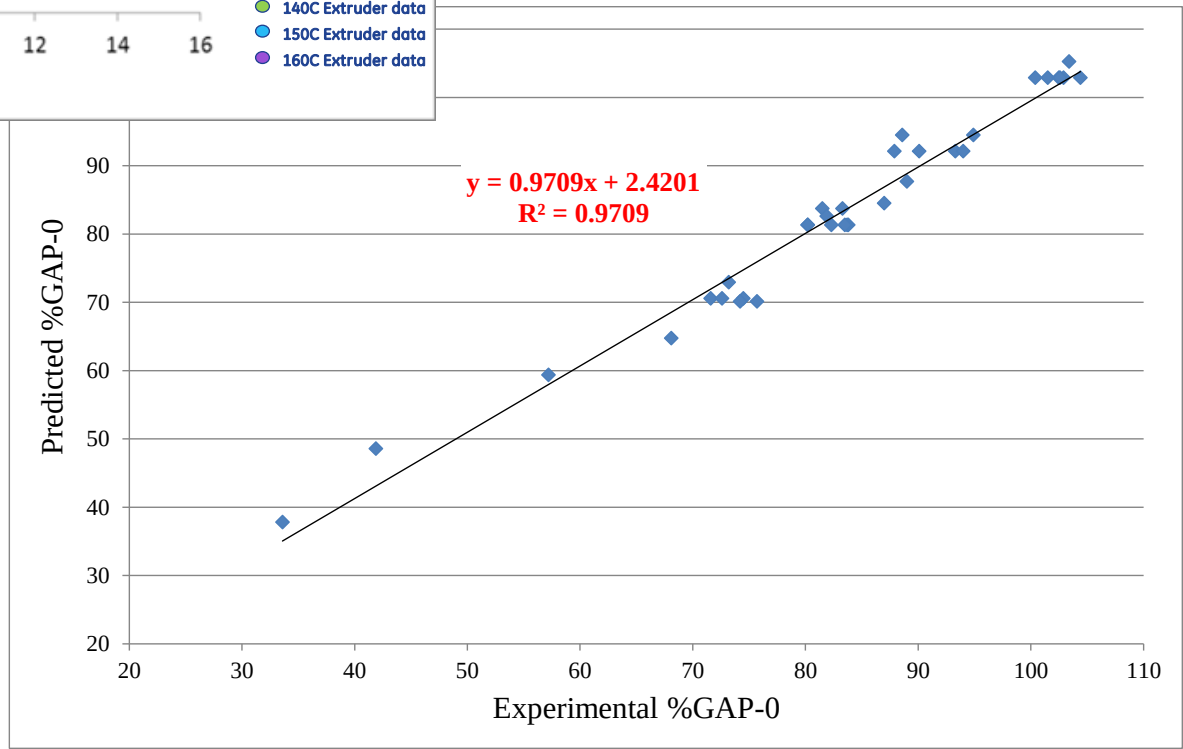


- Effective tool for in-situ monitoring of carbamate formation
- Real time measurement
- Change in intensity of signals related to carbamate concentration
- Develop predictive extruder model

Modeling (Process)



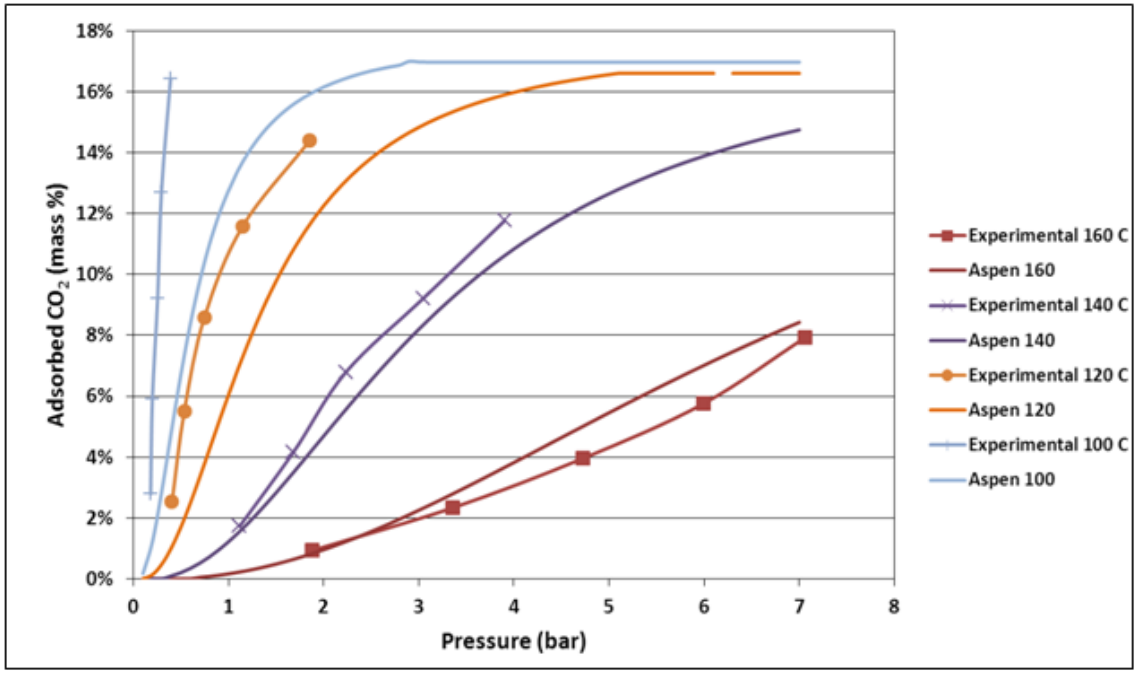
%GAP-0 = C0 + C1*PARR Pressure + C2*(Feed rate / screw speed) + C3*Temperature



- Good agreement
- Good predictability

Modeling (ASPEN)

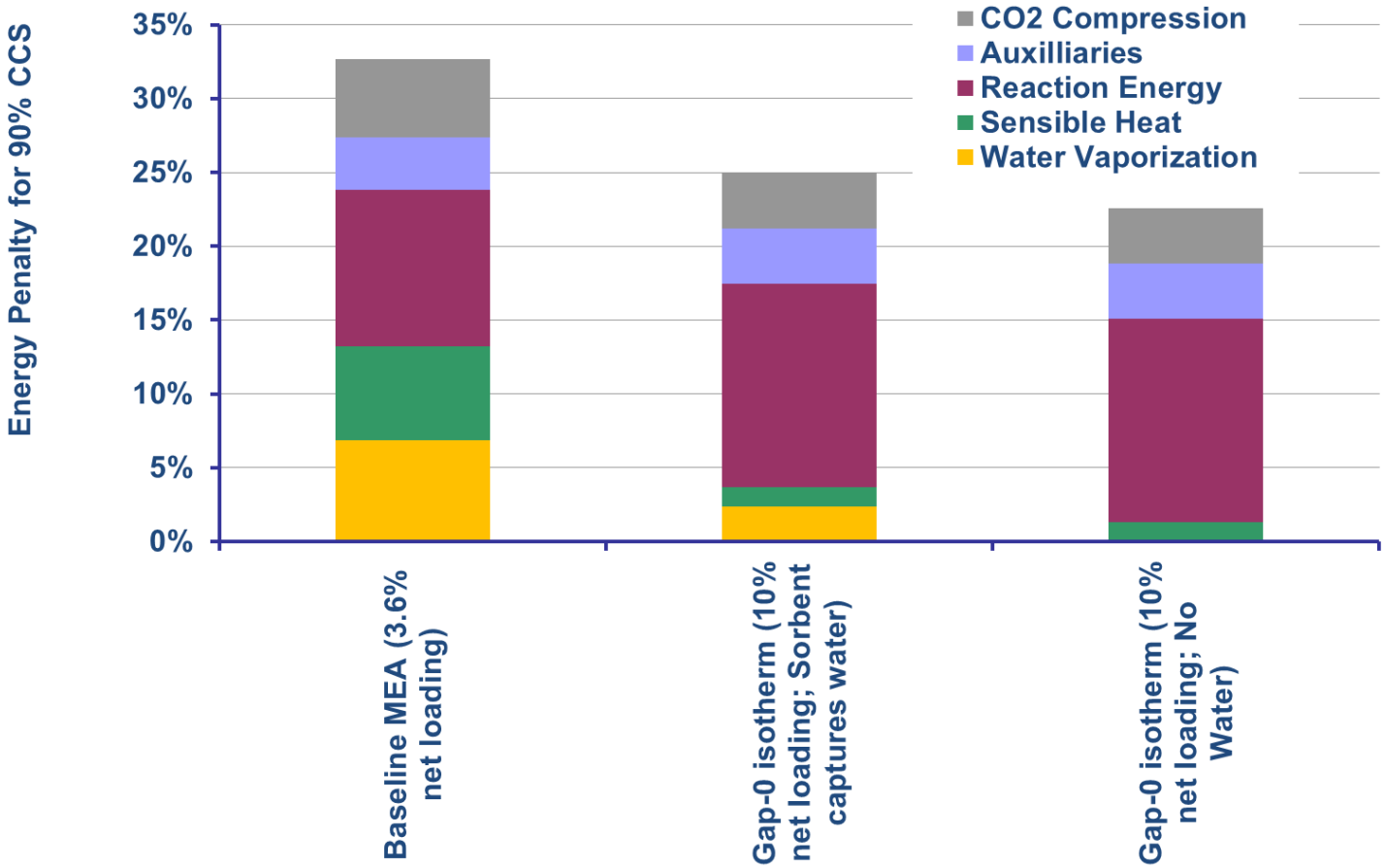
x → Extruder / Desorber → Y = f (x) [Outlet CO_2 loading]



X =

- Residence time of the solvent in the extruder = f (rpm, feed rate, screw geometry)
- Temperature in the extruder = f (heat supplied, viscous generation, HT coefficient)
- Inlet CO_2 loading
- Pressure at outlet
- Reaction Rate

Phase-Change Energy Penalty Waterfall



- Large savings with reduced water
- 24- 32% reduction in energy consumption

End of ARPA-e Program

Project Objective

The objective of this project is the construction and operation of a phase-changing solvent-based, continuous, bench-scale CO_2 capture system.

In the first phase of the project, initial process and cost models will be developed and the individual unit operations will be designed and built.

Project Objective

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In the second phase, testing will be performed on the individual unit operations to evaluate their performance. These data will be used to update the process and cost models. At the end of this phase the integrated system will be assembled.

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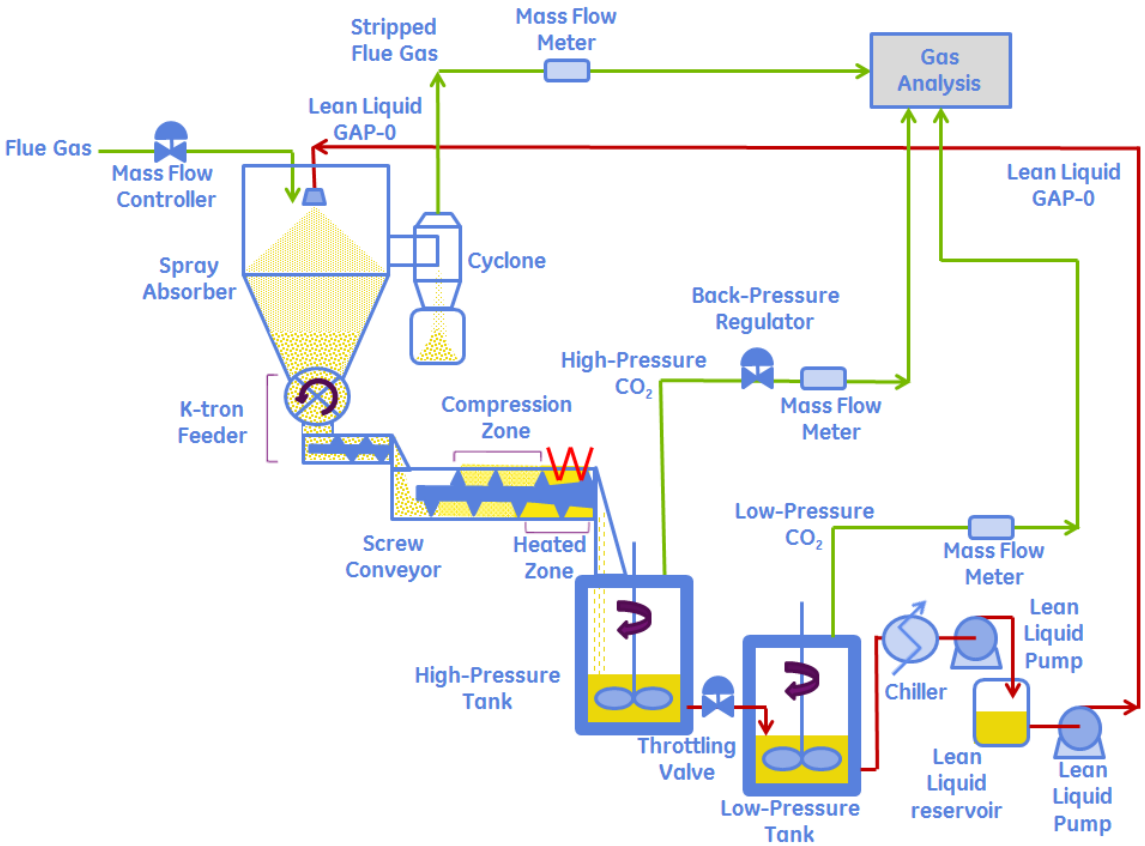
In the second phase, testing will be performed on the individual unit operations to evaluate their performance. These data will be used to update the process and cost models. At the end of this phase the integrated system will be assembled.

In the third phase, the integrated system will be operated under steady-state conditions, and the results will be used to update the models. The ultimate goal of the project is to establish scalability and technical and economic feasibility of using a phase-changing CO_2 capture absorbent for post-combustion capture of CO_2 from coal-fired power plants with 90% capture efficiency and 95% CO_2 purity, at a cost of $40/tonne of CO_2 captured by 2025, and a cost of <$40/tonne of CO_2 captured by 2035.

Technical Approach/ Project Scope

Technical Approach

- Take learnings from ARPA-e program and apply to bench-scale system
- Design, construct and operate continuous system
- Gather economic and technical data for route to commercialization



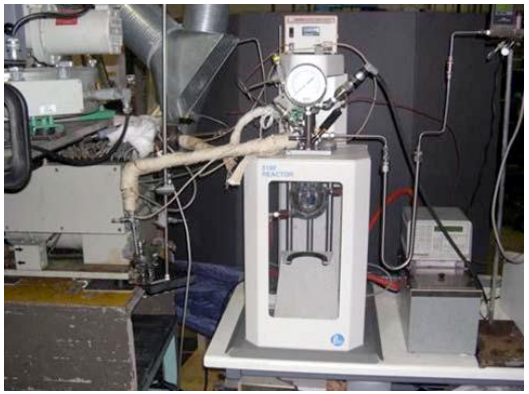
Phase 1

- Design and construction of bench-scale unit
  - Spray reactor
    - efficient aerosol formation and contact with simulated flue gas
    - low fouling nozzle
    - disengagement of particles from gas stream
    - operation at 200 mL/min solvent flow rate
    - 120 slm gas flow rate
    - solids transfer device (rotary valve)
    - work closely with NIRO for design input
  - Extruder
    - system to handle 20-150 lb/hr solid
    - maintain hydrostatic seal
    - design elements to maximize throughput and heat transfer
    - partner with Coperion for extruder strategy

GEA Niro

COPERION

Phase 1

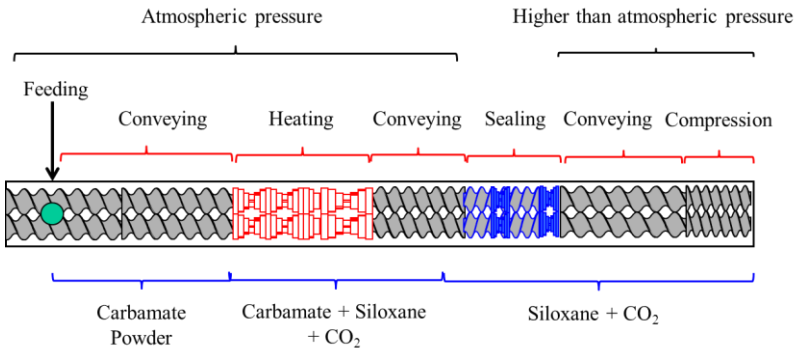


- Design and construction of bench-scale unit
  - Desorber
    - 2 vessels in series
    - elevated pressure to maintain backpressure in extruder
    - atmospheric vessel for polishing
    - deliver sufficient heat to drive complete desorption
  - Integrated system
    - work closely with facilities to install services/utilities
    - process controls/instrumentation specified and installed
    - design for 200 – 1700 mL/min liquid flow rate
    - automated controls where possible
    - data logging capability
- Preliminary Technical & Economic Assessment
  - Leverage model developed in ARPA-e program
  - Generate estimate of cost of CO_2 capture

GO / NO GO decision (90% capture; <$50/tonne)

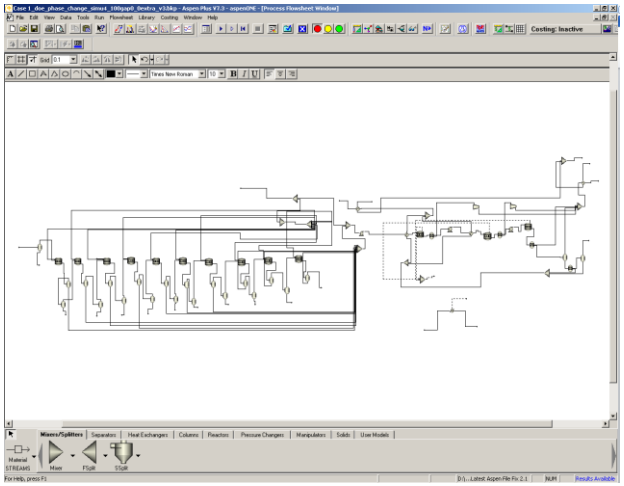
Phase 2

- Testing & Operation of Unit Ops
  - Absorber
    - quality/quantity of solids production
    - nozzle atomization efficiency
    - range of operable liquid and gas flow rates
    - heat management
  - Extruder
    - solids feed rate
    - barrel temperature profile
    - range of operable pressures
    - degree of CO_2 desorption
    - operating parameters



Phase 2

- Testing & Operation of Unit Ops
  - Desorber
    - temperature
    - mixing rate
    - pressure
    - extent of CO_2 desorption
  - Other
    - evaluation of materials of construction
    - manufacturability of aminosilicone solvent
      - cost / quality / availability
    - assemble continuous system
    - technology EH&S risk assessment
    - update process model



GO / NO GO decision (90% capture; <$45/tonne)

Phase 3

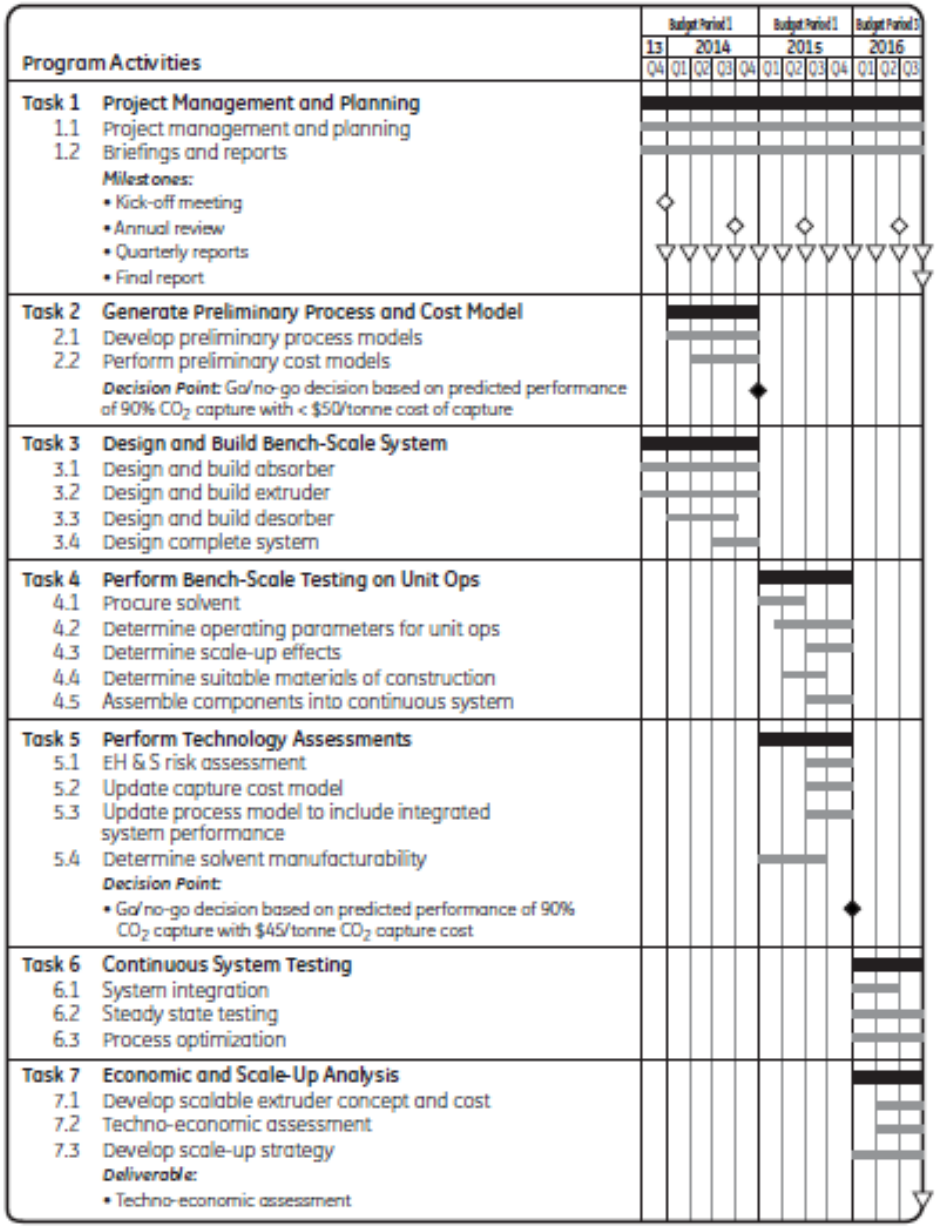
- Operation of Integrated System
  - Generate engineering data needed for final techno-economic assessment
  - Steady-state operation
  - Process optimization
  - Effect of flue gas contaminants
  - Solvent regeneration energy
  - State point data table
- Develop scale-up strategy
  - concept for scalable extruder optimized for process
  - move towards commercialization
- Economic and Scale-up analysis
  - CO_2 separation module
  - Plant model

Project Budget

Budget Period	Gov't Share	Cost Share
1/1/14 - 3/31/15	$ 1,021,866	$ 255,467
4/1/15 – 3/31/16	$ 651,639	$ 162,909
4/1/16 – 12/31/16	$ 726,456	$ 181,614
Total	$ 2,399,961	$ 599,990

- $3.00MM program
- Delay start until 1/1/14

Schedule


Program Activities
Budget Period 1
Budget Period 2
Budget Period 3
13
2014
2015
2016
Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3
Task 1 Project Management and Planning
1.1 Project management and planning
1.2 Briefings and reports
Milestones:
• Kick-off meeting
• Annual review
• Quarterly reports
• Final report
Task 2 Generate Preliminary Process and Cost Model
2.1 Develop preliminary process models
2.2 Perform preliminary cost models
Decision Point: Go/no-go decision based on predicted performance of 90% CO_2 capture with < $50/tonne cost of capture
Task 3 Design and Build Bench-Scale System
3.1 Design and build absorber
3.2 Design and build extruder
3.3 Design and build desorber
3.4 Design complete system
Task 4 Perform Bench-Scale Testing on Unit Ops
4.1 Procure solvent
4.2 Determine operating parameters for unit ops
4.3 Determine scale-up effects
4.4 Determine suitable materials of construction
4.5 Assemble components into continuous system
Task 5 Perform Technology Assessments
5.1 EH & S risk assessment
5.2 Update capture cost model
5.3 Update process model to include integrated system performance
5.4 Determine solvent manufacturability
Decision Point:
• Go/no-go decision based on predicted performance of 90% CO_2 capture with $45/tonne CO_2 capture cost
Task 6 Continuous System Testing
6.1 System integration
6.2 Steady state testing
6.3 Process optimization
Task 7 Economic and Scale-Up Analysis
7.1 Develop scalable extruder concept and cost
7.2 Techno-economic assessment
7.3 Develop scale-up strategy
Deliverable:
• Techno-economic assessment
Legend: Milestone Deliverable Decision Point

Project Organization

Program Manager and Principal Investigator
Ms. Tiffany Westendorf
Project Leader
Design Engineer

Technical Management Team
Dr. Teresa Grocela-Rocha
Fuels & Emissions Technology Organization Technology Leader
Dr. Wei Chen
Emissions Systems Engineering Laboratory Manager

Business Management Team
Ms. Johanna Wellington
Sustainable Energy Advanced Technology Leader
Mr. Kelly Fletcher
Business Program Manager

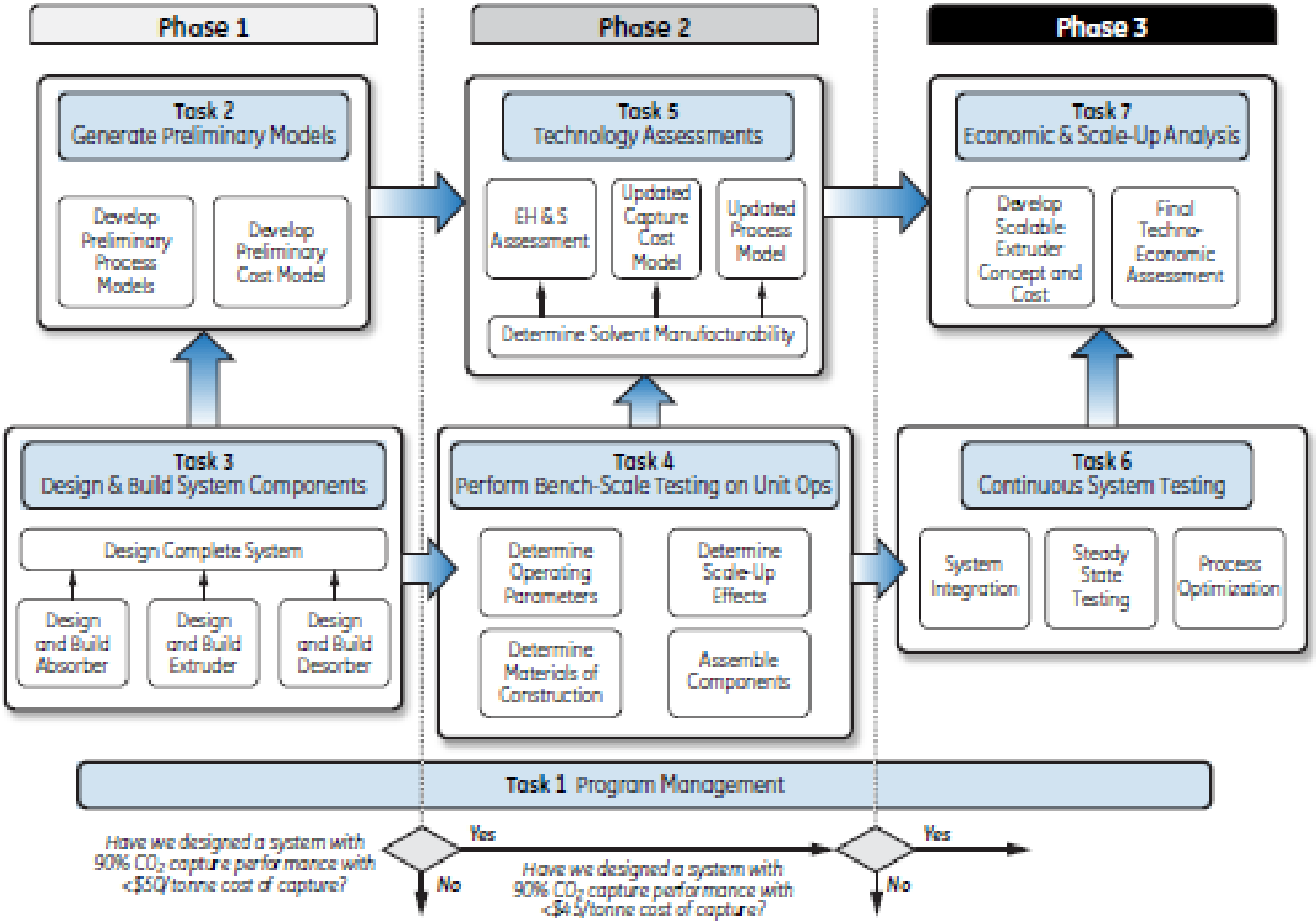
GE Global Research Aerothermal & Mechanical
Mr. Roger Shisler
Process/Cost Modeling

GE Global Research Chemistry & Chemical Engineering
Dr. Robert Perry
Material Analysis
Dr. Benjamin Wood
Systems Design
Dr. Norberto Silvi
Extrusion/Desorption
Dr. Surinder Singh
Systems Modeling

Extruder Consultants
coperion
Dr. Paul Anderson
Extruder Design
Mr. Frank Lechner
Heat Management

Solvent Consultants
Sivance
Gelest
Silar

Program Flow



Budget Period	Task	Milestone	Planned Completion
1	1	Updated PMP	1/31/14
1	1	Kickoff Mtg	12/31/13
1-3	1.2	Annual Reviews	12/31/16
1-3	1.2	Quarterly Reports	12/31/16
3	1.2	Final Report	12/31/16
1	2	Go/No Go Decision	12/31/15
1	3.1	Absorber Built/Operational	12/31/14
1	3.2	Extruder Built/Operational	3/31/15
1	3.3	Desorber Built/Operational	12/31/14
2	4.2	Absorber Parameters Established	3/31/16
2	4.2	Extruder Parameters Established	3/31/16
2	4.2	Desorber Parameters Established	12/31/15
2	4.5	Continuous System Assembled	3/31/16
2	5.1	Technology EH&S risk Assessment	3/31/16
2	5	Go/No Go Decision	3/31/16

Budget Period	Task	Milestone	Planned Completion
3	6	Update State Point data table	12/31/16
3	6	Demonstrate continuous steady state operation	12/31/16
3	6	Material and energy balance for continuous bench-scale system	12/31/16
3	7.1	Scale-up strategy	12/31/16
3	7.2	Techno-economic assessment	12/31/16

Risk Analysis

Technical Risk	Probability	Impact	Mitigation
Unable to heat extruder evenly w/ recovered heat	High	High	Modify screw/barrel heating elements; temp profile
Incomplete decarboxylation in extruder	High	Moderate	Optimize extruder parameters
Bulk density of carbamate is too low	High	Moderate	Compress/compact powder
Unmanageable temp rise in absorber	Moderate	High	Modify absorber design
Extruder throughput is too low	High	Moderate	Larger/multiple extruders
Inadequate supply of Gap-0	Moderate	High	Confirm multiple sources
Beta-isomer causes solids issues	Moderate	High	Define specs for beta content
Fouling of nozzle	High	Moderate	Incorporate mechanism to detect and resolve fouling
Corrosion of process equipment	Moderate	High	Characterize corrosivity of solvent in process equipment; choose appropriate materials of construction

Technical Risk	Probability	Impact	Mitigation
Capacity of absorber does not match desorber capacity	High	Moderate	Modify process to accommodate unmatched feed rates
Not enough residence time in extruder	Moderate	Moderate	Add more barrels; lower feed rate; reduce screw speed
Water presence causes sticky particles	Moderate	Moderate	Decrease water level in exhaust gas; decrease water level in GAP-0; reduce water spray for evaporative cooling
Loss of small particles in absorber unit	Moderate	Moderate	Optimize cyclone or bag filter design
Cost of Solvent is too high	Moderate	Moderate	New manufacture process
Bridging prevents smooth flow of carbamate from absorber and/or into extruder	Moderate	Moderate	Design vibratory hoppers or agitators
Poor solid formation in absorber	Low	High	Determine root cause (droplet size, liquid spray pattern, CO_2:GAP-0 stoichiometry)

Technical Risk	Probability	Impact	Mitigation
Unable to form hydrostatic seal in extruder	Low	High	Redesign extruder screws; optimize extruder parameters (screw speed, solids feed rate, temperature profile)
Solidification of extrudate in lines	Low	High	Heat tracing of lines downstream of extruder
Not able to have real-time measurement	Low	High	Incorporate in-line FT-IR, MS, or CO_2 monitor
SO_2 causes particle change	Low	Moderate	Remove SO_2 prior to contact with GAP-0
Thermal degradation of solvent is excessive	Low	Moderate	Formulate thermal stability additive package

Acknowledgement. The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency – Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000084 and DOE- NETL under Award Number DE-NT0005310.

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