Plastic Additive, Sorbent-Coated, Thermally Integrated Contactor for CO₂ Capture (PLASTIC4CO₂)

DEFE0032132

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GE Research

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National Energy Technology Laboratory
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Program Overview

$2.5MM program (40% cost share)
2 Year Program POP 02/25/22 to 12/31/23

Program Participants
- GE Research
- TDA Research
- University of California, Berkeley
- University of South Alabama

Demonstrate TRL3 feasibility for a plastic additive contactor design that captures 90-95% of CO$_2$ from a natural gas turbine and demonstrates 15% lower LCOE vs. current liquid amine capture systems
Additive Concept for NGCC Plant

Demonstrate 40% lower CAPEX to get 15% lower LCOE
From Sorbent to Coated Contactor

Chemical Synthesis → Adsorptive Kinetics & Thermodynamics

Sorbents + Polymeric Binder + Rheology Modifiers → Solvent → Sorbent-Binder Slurry → Coating Process → Heat Exchanger Component → Scalable Form & Function → Sorbent-Coated Channels

**Enabling Chemistries**

**Coating Formulation**

**Sorbent-Binder Composite**

**PLASTIC4CO2 Contactor**

**Key Parameters:**
- CO₂ Sorption Capacity, CO₂ Sorption Kinetics
- Viscosity, Solids Loading, Slurry Stability, Surface Tension, Drying Behavior
- Thickness, Adhesion, Porosity, Structural Integrity
- Pressure Drop, CO₂ Sorption Capacity, CO₂ Sorption Kinetics, Sorbent Stability

Molecular structure drives system performance
Technical Approach

3 Program Components for TRL3

Development Program for NGCC Additive System

- Sorbent synthesis and characterization completed
- 2-Channel additive contactor design complete
- Additive printing modalities, materials, testing and down-selection
- Initial TEA completed showing path to lower CAPEX and LCOE
- Sorbent binder coating developed
- Contactor coating process optimized
- Additive contactor parts coating & testing
- Integrated system testing completed & meeting requirements
- TEA validated

Component Understanding & Entitlement

System Integration

System Testing & Analysis

Understand components first then combined system
TDA Sorbents 1 (MOF) & 2 (SSSA)

Uptake loadings for TDA SSSA-1
Surface Stabilized Supported Amine

~ 5 wt.% CO₂ uptake and fast kinetics
UCB Sorbent 3 (COF-609)

TFPT=4,4',4'-(1,3,5-Triazine-2,4,6-Triyl)Tris-Benzaldehyde
DABA=1,2,4-diaminobutyric acid

CPE=Chloro Vinyl Ether
TRPN = Tris (3-aminopropyl) amine

• 4% CO₂ dry flue gas capacity @25°C = 1.29 mol/kg
• Capture Mechanism: carbamate-bicarbonate formation

~5.7 wt.% CO₂ uptake and kinetics TBD
Kinetic Measurements

Frequency response quantifies the rate of CO\(_2\) transport using as little as 5 mg of material.

With the transport rate, and an isotherm, system modeling and technoeconomic evaluations can be completed.

- Frequency response characterizes the sorbent dynamics by measuring the system response to the varying input CO\(_2\) concentration.
- The gas concentration sine wave perturbation is known, the effluent is measured, and a transfer function models the behavior.

**TDA MOF-1 Example Data**

- Measure kinetic parameter \(k\) for powder and film vs. [CO\(_2\)].
- Use values to model bed breakthrough.

**Mass Transfer Resistances**

- Representative generic MOF crystal
- Diffusion via a Concentration Gradient
  - Collection of MOF crystallites
  - Diffusion in MOF micropore \((D)\)
  - Diffusion in macropore \((D_p)\)
- Collection of MOF crystallites in pellet/binder form
  - Diffusion in MOF micropore \((D)\)
  - Film resistance \((k_f)\)
**Measured Sorbent Capacity and Kinetics**

**Sorbent Productivity**
- Productivity is a function of CO$_2$ capacity and uptake rate (CO$_2$/sorbent/time)
- Measured with isotherm and kinetic uptake data
- Main driver for contactor sizing and cost (CAPEX)
- Understand as a function of temperature
- Set minimum based on preliminary TEA for 15% lower LCOE
- Update with future sorbent development (other programs)
Additive Contactor Design

Questions
- Need to determine hydraulic diameter for flow
- What is minimum wall thickness achievable
- Thinner walls desirable for heat transfer and minimizing mass of the contactor
- What is the surface roughness – note desire to coat surface enhanced with some roughness
- Make the parts modular so that the unit can be constructed of pieces.

Critical to Quality (CTQ’s) for Parts
- Non-porous surface between channels
- Good sorbent adhesion
- Pressure capable to 2 bar steam @135°C
- Sealable parts to prevent leakage
- > 1 year lifetime
- Scalable and integration into larger structures
- Cost competitive with traditional contactor designs at scale

TEA to determine cost targets for contactor at scale
# Materials & Matched Modalities

## Thermoplastics (130-190°C HDT)

<table>
<thead>
<tr>
<th>Material Acronym</th>
<th>Material type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyamide 12 glass filled (PA12 GF)</td>
<td>Semicrystalline, ~134°C</td>
</tr>
<tr>
<td>Polyphenylene sulfone (PPSU)</td>
<td>Amorphous, ~189</td>
</tr>
<tr>
<td>Polyetherimide (PEI)</td>
<td>Amorphous, ~153</td>
</tr>
<tr>
<td>Poly(ether ether ketone) (PEEK)</td>
<td>Semicrystalline, ~147</td>
</tr>
</tbody>
</table>

## Thermoset Resins (140-230°C HDT)

<table>
<thead>
<tr>
<th>Material Acronym</th>
<th>Material type</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D 3860</td>
<td>Proprietary Blends of Poly acrylate, methacrylate and acrylic esters</td>
</tr>
<tr>
<td>3D3955</td>
<td></td>
</tr>
<tr>
<td>HT</td>
<td></td>
</tr>
<tr>
<td>HTM140V2</td>
<td></td>
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<tr>
<td>SOMOS Perform</td>
<td></td>
</tr>
</tbody>
</table>

### Printing Modality Options by Material

<table>
<thead>
<tr>
<th>Material</th>
<th>Multi-Jet Fusion (MJJ)</th>
<th>Laser Sintering (SLS)</th>
<th>Fused Filament Modelling (FFM)</th>
<th>Photo-polymerization</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA12</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>PA12 glass fill</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA12 carbon fill</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEEK</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEI</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPSU</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3D 3860</td>
<td>1</td>
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<td></td>
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</tr>
<tr>
<td>IND147 HDT230</td>
<td>1</td>
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</tr>
<tr>
<td>3D3955</td>
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<td>HTM140V2</td>
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<tr>
<td>SOMOS Perform</td>
<td>1</td>
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</tbody>
</table>
Flow Testing Systems

- **Small-scale test Unit**
  - Lab scale up to 2 SLPM
  - Up to 6 combined gas feeds to simulate mixtures and up to 80% RH
  - Desorption using electrical heat
  - Data Acquisition

- **Large-scale test unit**
  - Bench scale flows up to 30 SLPM
  - Up to 6 combined gas feeds to simulate mixtures and up to 80% RH
  - Desorption using electrical or steam media
  - Data Acquisition, automated cycling

Flexible capabilities to test CO$_2$ uptake vs. flow and [CO$_2$]
0D, 1D and 3D Flow Models

Mass Balance Solvers
- 0D – homogeneous sorbent working capacity and kinetics
- 1D model – PDE hydraulic diameter of channel
- 3D model – PDE full dimensions in relevant coordinates

Mass Balance:
\[
\frac{\partial C}{\partial t} - \nabla(uC) + \nabla(K\nabla C) = 0
\]

Linear driving force
\[
K_i \cdot (n_{eq}(C) - n)
\]

Additive design promotes boundary layer mixing

Solve PDE in 1D (fast) and 3D (more accurate) to get contactor sizing
0D Contactor Sizing & Economics

0D Model Inputs
- 7F 2x1 NGCC flows & power
- 90-95% CO₂ removal
- 1 mm sorbent coating
- Sorbent working capacity
- Sorbent utilization
- 30-minute cycle time
- CO₂ and H₂O isosteric heats
- ΔT (adsorb-desorb)
- Sorbent/costing costs
- Contactor costs ($/m²)
- Coating life
- Plant lifetime

0D Model Outputs
- Contactor CAPEX
- BOP CAPEX
- Process OPEX
- Process net power & efficiency
- Updated LCOE vs Case B31B

Initial costing landscape to be then better defined by 1D/3D models
Opportunities for Collaboration

Program is sorbent agnostic and aims to reduce cost of system

- Incorporation of high-productivity sorbents into the contactor design
- Sorbent scale-up and manufacturing
- Sorbent coating processes at scale (dip, spray, …)
- Additive printing processes and scaling
- Polymer materials research in additive systems and lifetime studies
- CO₂ sequestration and utilization applications
- NGCC utility engineering studies
- NGCC CCUS demonstration programs
## Future Scaling of Additive Contactor Systems

<table>
<thead>
<tr>
<th>Scale Size</th>
<th>TRL</th>
<th>Flue Gas Flow (tph)</th>
<th>Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory</td>
<td>3</td>
<td>1.5e-3</td>
<td>FE0032132</td>
</tr>
<tr>
<td>Bench</td>
<td>4</td>
<td>1.9e-2</td>
<td>Future - Demo</td>
</tr>
<tr>
<td>Process Dev 1</td>
<td>5</td>
<td>0.40</td>
<td>Future - Demo</td>
</tr>
<tr>
<td>Process Dev 2</td>
<td>6</td>
<td>19</td>
<td>Future NCCC</td>
</tr>
<tr>
<td>Pilot</td>
<td>7-8</td>
<td>380</td>
<td>Future – Utility site</td>
</tr>
<tr>
<td>First Commercial Plant</td>
<td>9</td>
<td>3,800</td>
<td>Future – Utility site</td>
</tr>
<tr>
<td>Commercial Multi-Plant</td>
<td>9</td>
<td>3,800/plant</td>
<td>Future – Multi-site</td>
</tr>
</tbody>
</table>

### Scaling Progression & Challenges
- Higher productivity sorbents
- Synthesis of sorbents at each scale
- Material & printing costs for additive contactors at each scale
- Additive infrastructure growth
- System Integration
- Contactor and sorbent lifetime
- Maintenance/replacements
PLASTIC4CO2 Summary

Sorbents - 2022
✓ Set targets for sorbent productivity to meet initial TEA
  • Sorbent production at 1 Kg scale
  • Characterization of sorbent performance for capacity and kinetics

Coatings - 2022
• Develop systems for current sorbents on candidate plastic plates
• Test coating adhesion vs. plate morphology

Additive Contactor 2022-2023
✓ Completed design of 2-channel trifurcating architecture
✓ Identified candidate plastics and associated printing modalities
✓ Printed test parts in PA12 GF for both materials and coatings studies
• Print test parts in other candidate materials
• Develop model frameworks for sizing and TEA
❑ Coat and test additive contactor parts for performance at NGCC conditions
❑ Comparison to liquid phase system and conventional contactor system
❑ Determine metrics for additive contactor to compete at scale
Back-Up Information
From Sorbent to Contactor to System

Technology Maturity

**TRL 1-2**
Prior Work

- Sorbent characterization
- Additive design
- Coatings studies
- System models/costs

**TRL 3-4**
FE0032132
PLASTIC4CO2

- Contactor Design
- Candidate plastics
- Printing methods
- Coating development
- Sorbent integration
- Initial techno-economics

**TRL 5-9**
Future Scaling Programs

- Optimize Design
- Scaled process
- Model refinement
- Sorbents at scale
- Coatings at scale
- Printing at scale
- Economic validation

Requirements for 40% lower CAPEX and 15% lower LCOE

How to scale additive processes at lower cost
Risk Mitigation

• Sorbent performance issues
  ✓ Characterize batches before next synthesis
  ✓ Understand materials & process variation
  ✓ Synthesis process control

• Coating adhesion/cracking
  ✓ Coupon testing – understand nature of cracks
  ✓ Surface preparation and roughness modification
  ✓ Adhesion promotors & viscosity modifiers

• Coating performance issues
  ✓ Optimize coating – capacity vs thickness
  ✓ Understand materials & process variation
  ✓ Explore variety of materials options
  ✓ Coupon testing in Test Rig 2 for screening

• Plastic part properties/lifetime
  ✓ Polymer fillers
  ✓ Molecular weight & % crystallinity options
  ✓ End capper options

• Energetics
  ✓ Wall thickness, & hydraulic diameter design
  ✓ Material density and heat capacity options

• Costs and scaling
  ✓ Set cost targets to compete at scale

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<table>
<thead>
<tr>
<th>Perceived Risk</th>
<th>Risk Rating</th>
<th>Mitigation/Response Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budget overrun</td>
<td>L M L</td>
<td>Focus on critical tasks to achieve milestones</td>
</tr>
<tr>
<td>Changes in applied labor rates</td>
<td>L L L</td>
<td>Work with GE finance; update plan accordingly</td>
</tr>
<tr>
<td>Poor cyclability, volumetric productivity, capture efficiency, and adhesion of sorbent-coated plastic contactor</td>
<td>M H H</td>
<td>Improve contactor surface properties, sorbent-binder formulations, coating/curing processes</td>
</tr>
<tr>
<td>Sorbent and contactor scalability; manufacturing, economic and process inefficiencies</td>
<td>M H H</td>
<td>Early and iterative TEA. Leverage GE Additive &amp; Gas Power experience in fluid contactors for mechanical systems</td>
</tr>
<tr>
<td>Suboptimal contactor component form and function results in inefficient heat transfer</td>
<td>M H M</td>
<td>Leverage GE Additive and GE Aviation heat exchanger expertise to balance wall thickness, hydraulic diameter, and alternative materials of construction (fillers)</td>
</tr>
<tr>
<td>Additive printing method does not provide mechanical stability required for trifurcating design</td>
<td>M M M</td>
<td>Evaluate alternative materials of construction including polymers &amp; Al</td>
</tr>
<tr>
<td>Additive printing method does not provide spatial resolution required for trifurcating design</td>
<td>L M L</td>
<td>Evaluate alternative polymers and printing methods</td>
</tr>
<tr>
<td>Availability of key personnel</td>
<td>L M L</td>
<td>Project/resource prioritization with leadership</td>
</tr>
<tr>
<td>Ineffective selection of contactor design, sorbent-binder formulations &amp; coating processes</td>
<td>L M L</td>
<td>Leverage Six Sigma statistical tools and detailed success criteria to down select and advance technologies</td>
</tr>
<tr>
<td>Potential for chemical hygiene, high temperature, or mechanical hazard near misses or incidents</td>
<td>L H L</td>
<td>GE, Berkeley, TDA and USA will employ rigorous institutional standards &amp; processes; leverage EHS personnel to ensure safety and compliance</td>
</tr>
<tr>
<td>COVID-19 pandemic hinders partnering &amp; supply chain</td>
<td>L L L</td>
<td>Leverage virtual communication tools; work with vendors and sourcing to ensure timely delivery</td>
</tr>
</tbody>
</table>
Additive Printing Modalities

**Photopolymerization**
SLA, DLP, CLIP

- Selective curing of layers of photopolymer resin using laser or DLP
  - Single material system – support structures same cured polymer as part
  - Materials: Liquids – acrylates, epoxies

**Extrusion**
FDM, FFF

- Plastic filament from a spool is extruded through moving heated nozzles
  - Two material system – support structures are different material from part
  - Materials: Thermoplastic filament

**Jetting**
Polyjet, Multijet

- Inkjet printheads drop liquid material where needed. Droplets solidify on contact or are UV cured
  - Multi-material system – support material is different from one or more build materials
  - Materials: UV cured liquids, wax

**Powder Bed Fusion**
SLS, MJF

- Bed of polymer powder is fused one layer at a time using a laser or other energy source
  - Single material system – unfused powder acts as support structure
  - Materials: Thermoplastic polymer powder

SLA  Stereolithography  FDM  Fused Deposition Modelling  SLS  Selective Laser Sintering
DLP  Digital Light Processing  FFF  Fused Filament Fabrication  MJF  Multi Jet Fusion
CLIP  Continuous Interface  Liquid Production
Understanding Test Articles

- Printing modalities will give different cross-sectional structures
- Each test configuration will give different stress-strain curve for failure

Test Type 5 articles in each configuration, modality and material to understand stress/strain relationship at desorption $T$
# Program Gantt Chart

### Plastic Additive, Sorbent-coated, Thermally-Integrated Contactor For CO₂ Capture (PLASTIC4CO2)

<table>
<thead>
<tr>
<th>Task 1.0. Project Management and Planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. Project Management Plan (PMP)</td>
</tr>
<tr>
<td>Deliverables: updated PMP 30 days after award, Progress, financial &amp; final reports, reviews, presentations.</td>
</tr>
<tr>
<td>1.2. Technology Maturation Plan (TMP)</td>
</tr>
<tr>
<td>Deliverables: updated TMP 90 days after award; final TMP within 90 days of program completion</td>
</tr>
<tr>
<td>Deliverables: Quarterly, financial &amp; final reports, reviews, presentations.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 2.0. Sorbent Synthesis &amp; Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Produce 1 kg of candidate sorbents 1, 2 for initial screening</td>
</tr>
<tr>
<td>2.2 Optimize production process and produce 5 kg of candidate sorbents 1, 2 for testing</td>
</tr>
<tr>
<td>2.3 Produce additional 5 kg of candidate sorbents 1, 2 for larger scale testing</td>
</tr>
<tr>
<td>2.4 Testing of sorbents 1 &amp; 2 for kinetic parameters</td>
</tr>
<tr>
<td>Milestones: 1 kg, 5 kg and a maximum of 4 kg of sorbent candidate 1 &amp; 2 meeting performance criteria</td>
</tr>
<tr>
<td>2.5 Produce 0.5 kg of candidate sorbent 3 and optimize production process</td>
</tr>
<tr>
<td>2.6 Produce 0.5 kg of additional candidate sorbent 3</td>
</tr>
<tr>
<td>2.7 Testing of sorbent 3 for kinetic parameters</td>
</tr>
<tr>
<td>Milestones: 0.5 kg and additional 0.5 kg of sorbent candidate 3 meeting performance criteria</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 3.0 Develop 3-D Printed Plastic Contactor Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Determine contactor physical/chemical properties and design configuration</td>
</tr>
<tr>
<td>Milestone: PLASTIC4CO2 design and component string determined</td>
</tr>
<tr>
<td>3.2 Determine candidate plastics and additive printing modality</td>
</tr>
<tr>
<td>Milestone: Candidate plastics and printing modality selected</td>
</tr>
<tr>
<td>3.3 Produce candidate contactor components</td>
</tr>
<tr>
<td>Milestones: Alpha- and beta-prototype plastic contactor components fabricated</td>
</tr>
<tr>
<td>3.4 Screening testing to determine stability of plastic parts for down-selection</td>
</tr>
<tr>
<td>3.5 Extended testing of down-selected parts for aging/lifetime studies</td>
</tr>
<tr>
<td>Decision Point: Parts down-selected for extended physical and chemical properties testing</td>
</tr>
<tr>
<td>Milestone: Contactor Parts that meet long term physical and chemical properties</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 4.0 Produce Sorbent-Integrated Contactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Develop coating formulations and processes</td>
</tr>
<tr>
<td>Milestone: Sorbent-coating formulation determined for each candidate plastic</td>
</tr>
<tr>
<td>4.2 Create alpha integrated parts for kinetics</td>
</tr>
<tr>
<td>4.3 Testing of alpha integrated sorbent system for kinetics</td>
</tr>
<tr>
<td>4.4 Create beta integrated parts for testing</td>
</tr>
<tr>
<td>4.5 Testing of beta integrated parts for kinetics</td>
</tr>
<tr>
<td>Milestones: Alpha- and beta-prototype coated contactor components fabricated</td>
</tr>
<tr>
<td>Decision Point: Integrated contactor component systems down-selected for beta testing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 5.0. Fabrication and Testing of Sorbent-Integrated Contactor System</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Design and procure upgrades to current testing apparatus</td>
</tr>
<tr>
<td>Milestone: Test apparatuses for contactor component testing constructed</td>
</tr>
<tr>
<td>5.2 Develop testing protocol</td>
</tr>
<tr>
<td>Milestone: Methodology for testing parts finalized</td>
</tr>
<tr>
<td>5.3 Test alpha integrated parts</td>
</tr>
<tr>
<td>5.4 Test beta integrated parts</td>
</tr>
<tr>
<td>Milestone: Bench-scale, sorbent-integrated contactor meets performance metrics</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Task 6.0. Contactor Techno-Economic Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Preliminary system model to determine contactor requirements</td>
</tr>
<tr>
<td>6.2 Refined system model for cost analysis and contactor scaling requirements</td>
</tr>
<tr>
<td>Deliverable: Final State Point Data Table and PLASTIC4CO2 capital and operating cost models</td>
</tr>
</tbody>
</table>