Plastic Additive, Sorbent-Coated, Thermally Integrated Contactor for CO_2 Capture (PLASTIC4CO2)

DEFE0032132

Dr. Albert Stella

Principal Engineer

GE Research

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Management Project Review Meeting
August 15 - 19, 2022

Program Overview

Program Team

GE Research

Additive Contactor Design & Production, Sorbent and Binder Coating Integration, Small & Large Coated Parts Testing & Process & Techno-Economic Modelling

TDA RESEARCH

Metal Organic Framework Sorbent Synthesis, Characterization & Testing, Sorbent Integrated Parts Testing

Berkeley UNIVERSITY OF CALIFORNIA

Covalent Organic Framework Synthesis, Characterization & Testing

USA UNIVERSITY OF SOUTH ALABAMA

Multi-Component Adsorption & Kinetics Characterization

$2.5MM program (40% cost share)

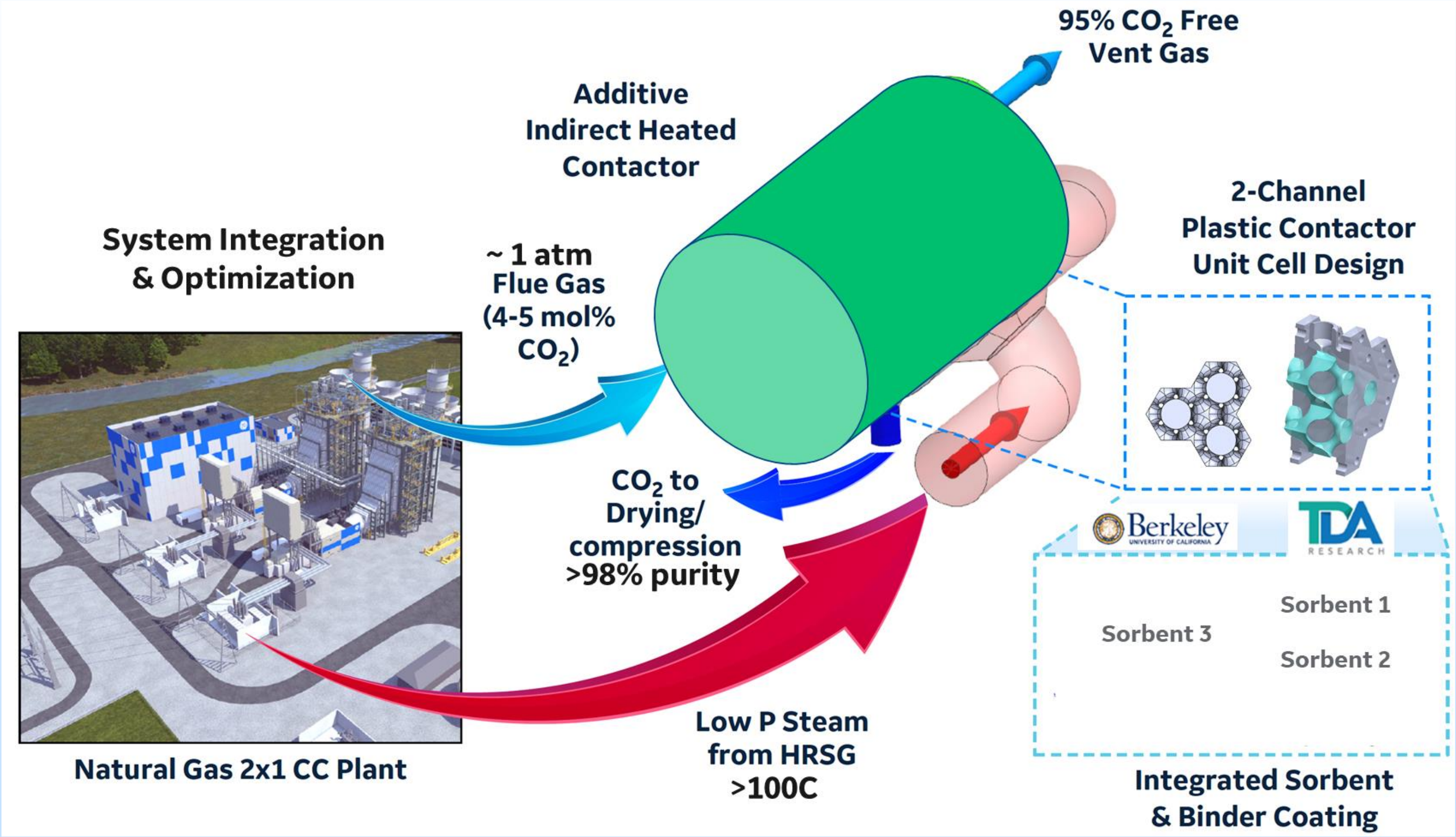
2 Year Program POP 02/25/22 to 12/31/23

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

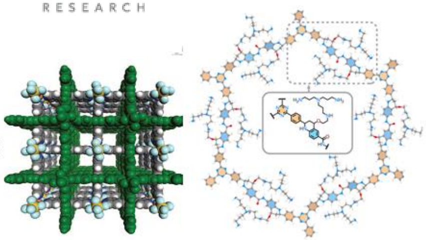


Demonstrate 40% lower CAPEX to get 15% lower LCOE

From Sorbent to Coated Contactor

Chemical Synthesis → Adsorptive Kinetics & Thermodynamics

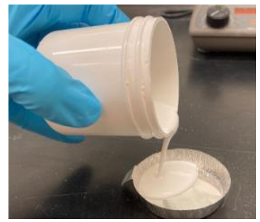
Sorbents



\+ Polymeric Binder

\+ Rheology Modifiers

Solvent →



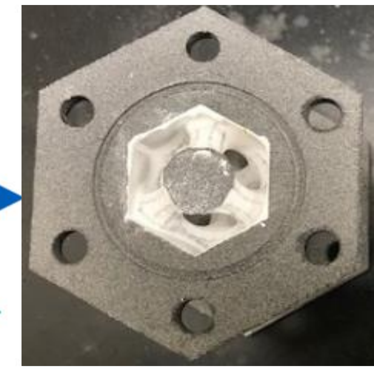
Sorbent-Binder Slurry

Coating Process →

Heat Exchanger Component

Sorbent-Coated Channels

Scalable Form & Function →



	Enabling Chemistries	**Coating Formulation**	**Sorbent-Binder Composite**	**PLASTIC4CO2 Contactor**
Key Parameters:	*CO_2 Sorption Capacity, CO_2 Sorption Kinetics*	*Viscosity, Solids Loading, Slurry Stability, Surface Tension, Drying Behavior*	*Thickness, Adhesion, Porosity, Structural Integrity*	*Pressure Drop, CO_2 Sorption Capacity, CO_2 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

2022 → Component Understanding & Entitlement

- Sorbent binder coating developed
- Contactor coating process optimized

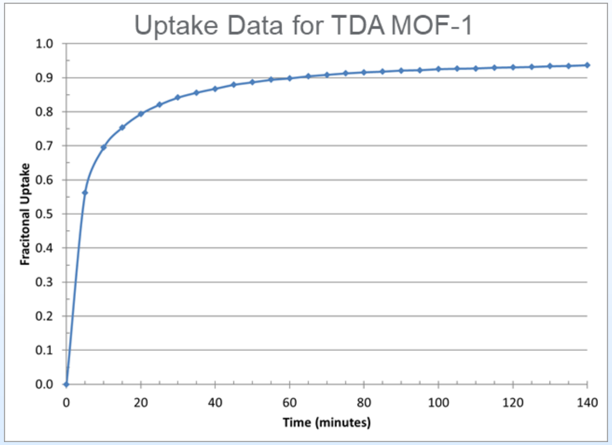
2022 → System Integration

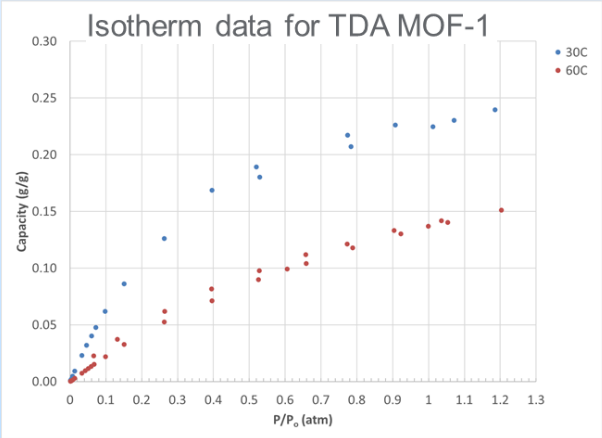
- Additive contactor parts coating & testing
- Integrated system testing completed & meeting requirements
- TEA validated

2023 → System Testing & Analysis

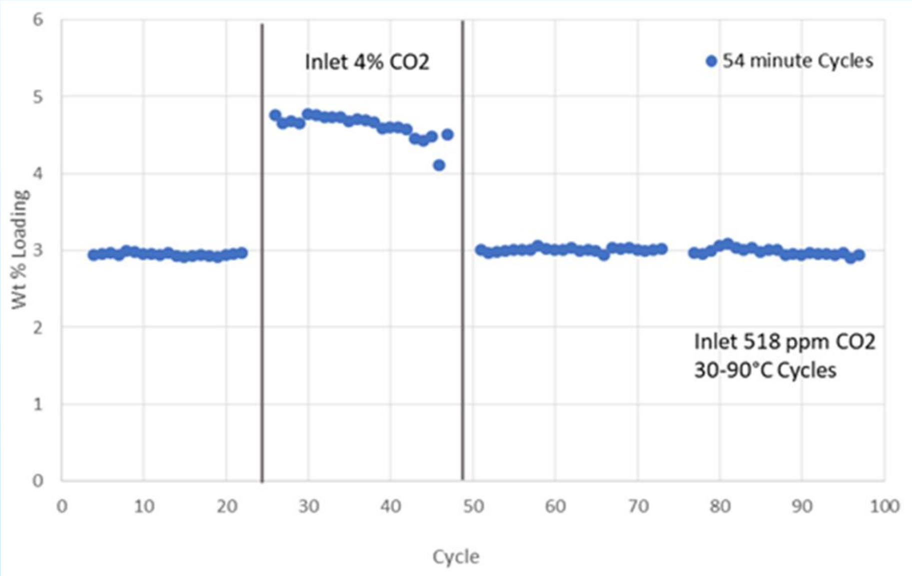
Understand components first then combined system

TDA Sorbents 1 (MOF) & 2 (SSSA)





Uptake loadings for TDA SSSA-1
Surface Stabilized Supported Amine

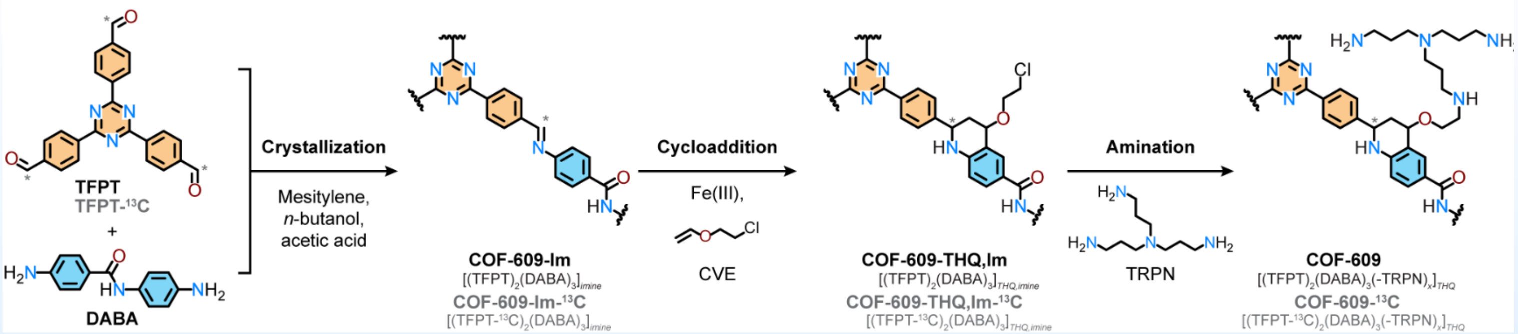


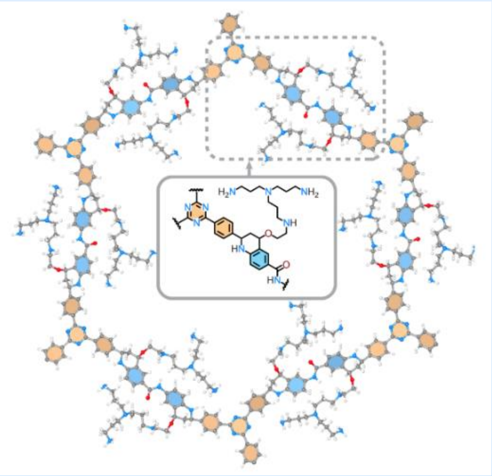
~ 5 wt.% CO_2 uptake and fast kinetics

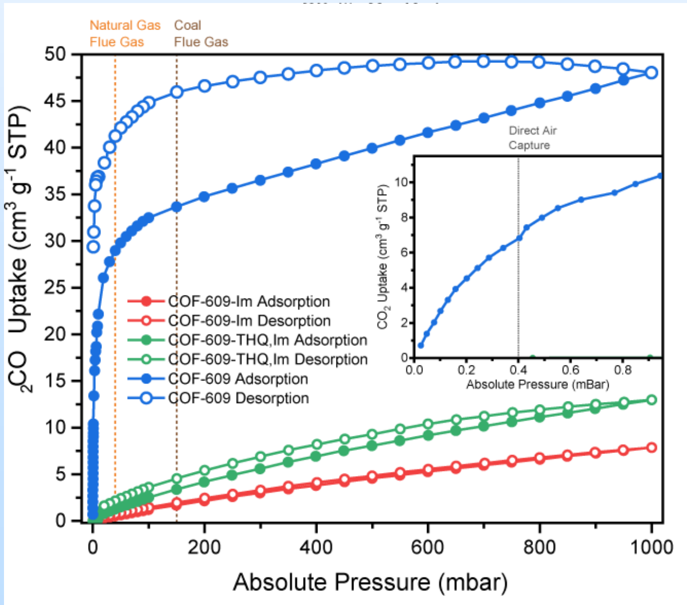
UCB Sorbent 3 (COF-609)

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

CVE=Chloro Vinyl Ether
TRPN = Tris (3-amino propyl) amine







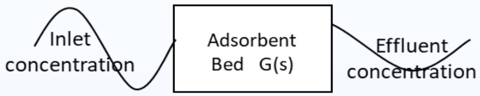
- 4% CO_2 dry flue gas capacity @25°C = 1.29 mol/kg
- Capture Mechanism: carbamate-bicarbonate formation

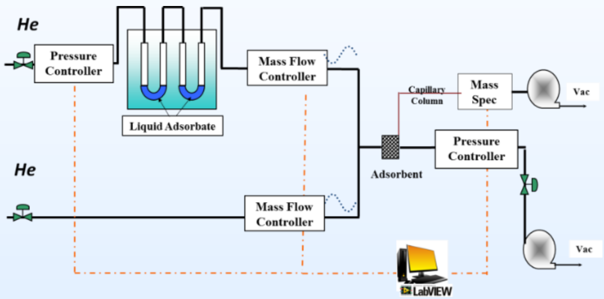
~ 5.7 wt.% CO_2 uptake and kinetics TBD

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

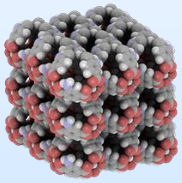


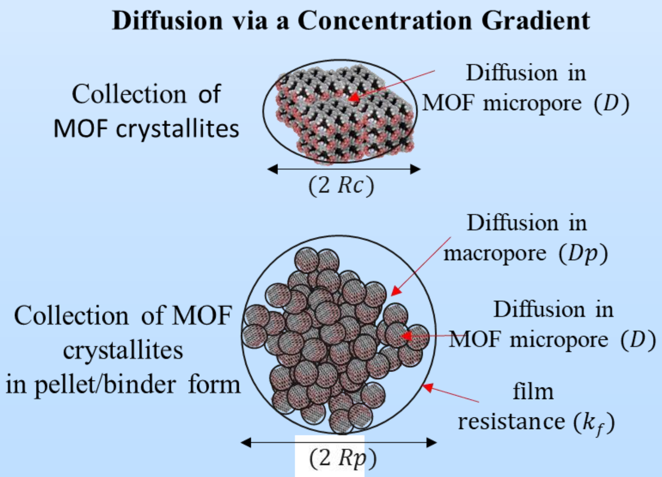


- Frequency response characterizes the sorbent dynamics by measuring the system response to the varying input CO_2 concentration
- The gas concentration sine wave perturbation is known, the effluent is measured, and a transfer function models the behavior

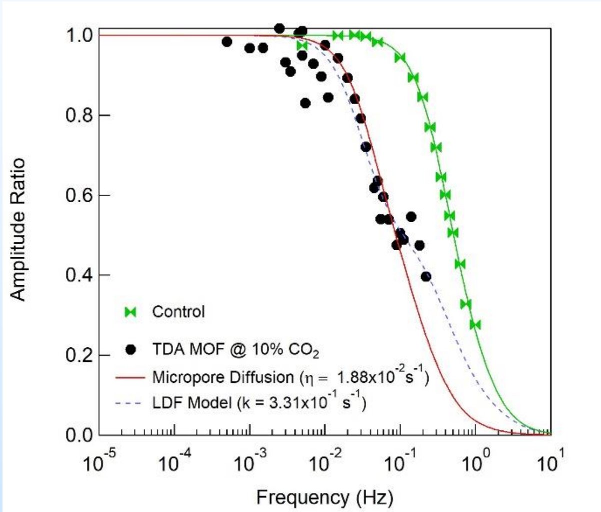
Mass Transfer Resistances

Representative generic MOF crystal





TDA MOF-1 Example Data

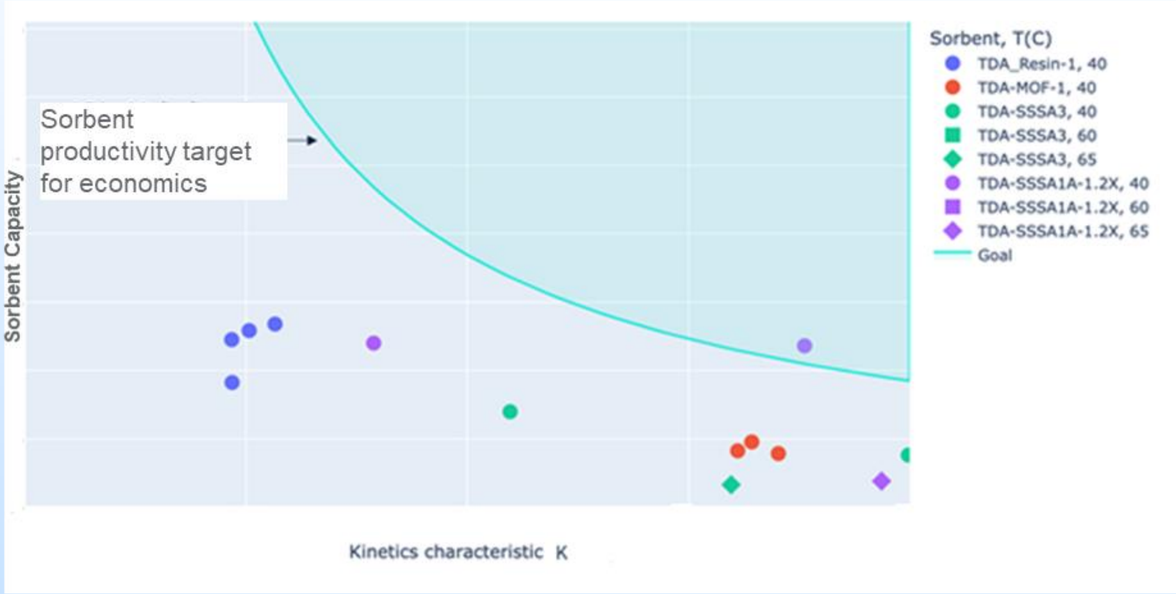


- Measure kinetic parameter k for powder and film vs. $[CO_2]$
- Use values to model bed breakthrough

Measured Sorbent Capacity and Kinetics

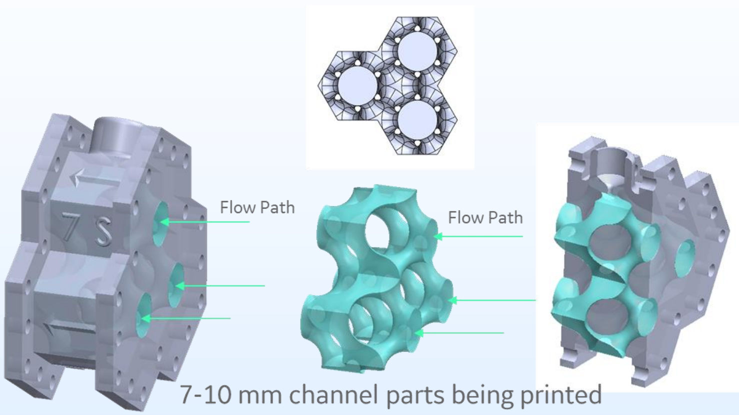
Sorbent Productivity

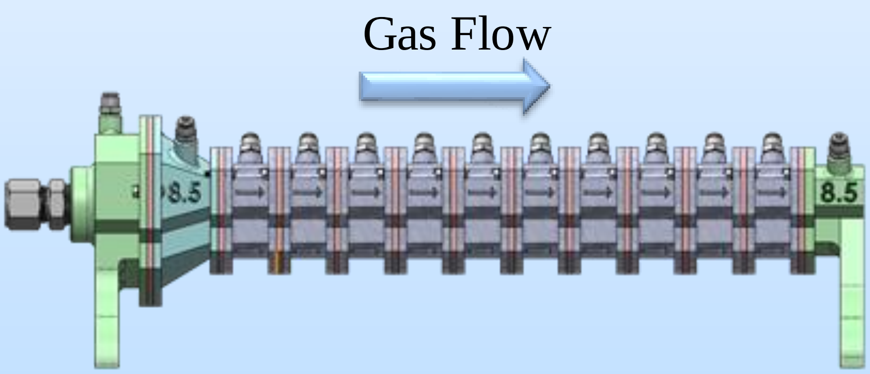
- Productivity is a function of CO_2 capacity and uptake rate (CO_2/sorbent/time)
- Measured with isotherm and kinetic uptake data
- Main driver for contactor sizing and cost (CAPEX)
- Understand as a function of temperature
- Set minimum based on preliminary TEA for 15% lower LCOE
- Update with future sorbent development (other programs)



Determined requirements for sorbent productivity

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.

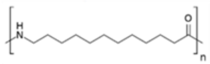
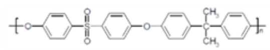
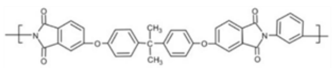
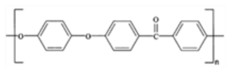
Critical to Quality (CTQ's) for Parts

- Non-porous surface between channels
- Good sorbent adhesion
- Pressure capable to 2 bar steam @135^{o}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^{o}C HDT)

Thermoplastic materials	Chemical structure	Morphology/HDT@264psi	3D print modality
Polyamide 12 glass filled, (PA12 GF)		Semicrystalline, ~134°C	Powder sintering
Polypheneylsulfone (PPSU)		Amorphous, ~ 189	Fused filament
Polyetherimide (PEI)		Amorphous, ~ 153	Fused filament
Poly(ether ether ketone) (PEEK)		Semicrystalline, ~ 147	Fused filament

Thermoset Resins (140-230^{o}C HDT)

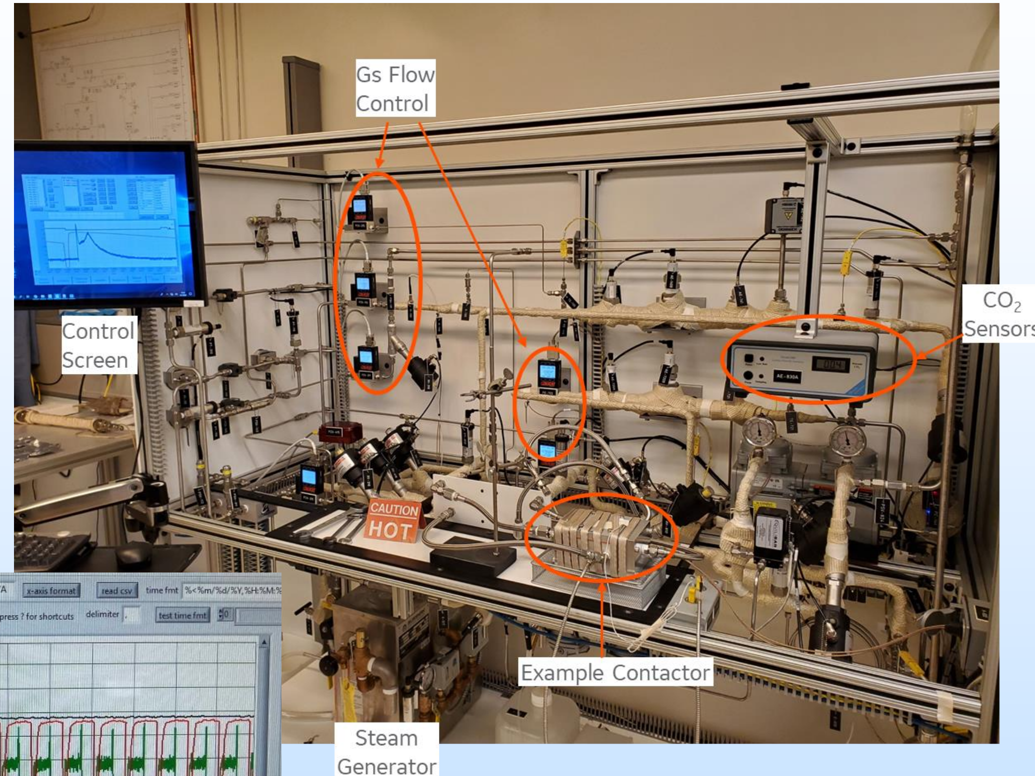
Material Acronym	Material type
3D 3860	Proprietary Blends of Poly acrylate, methacrylate and acrylic esters
IND147 HDT230	
3D3955	
HTM140V2	
HT	
SOMOS Perform	

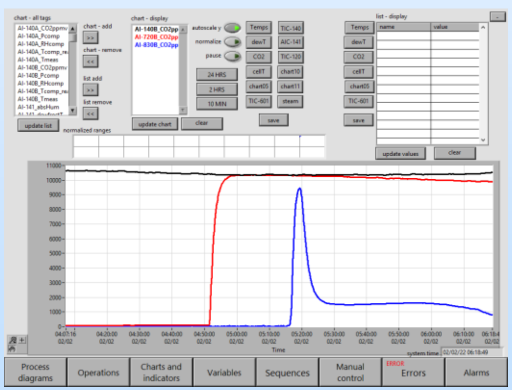
Printing Modality Options by Material

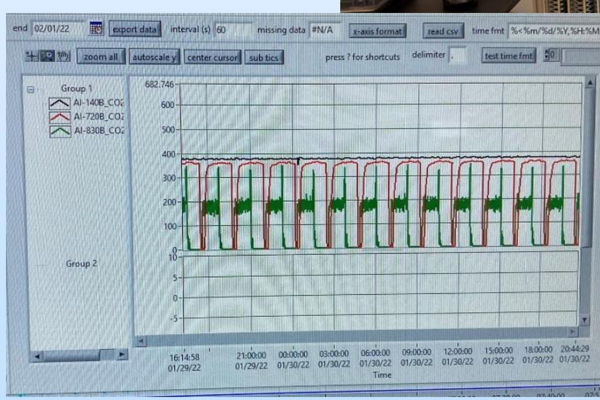
Material	Multi-Jet Fusion (MJF)	Laser Sintering (SLS)	Fused Filament Modelling (FFM)	Photo-polymerization
PA12	2	1	1	
PA12 glass fill	1	1		
PA12 carbon fill		1		
PEEK		1	3	
PEI			2	
PPSU			2	
3D 3860				1
IND147 HDT230				1
3D3955				1
HTM140V2				1
HT				1
SOMOS Perform				1

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

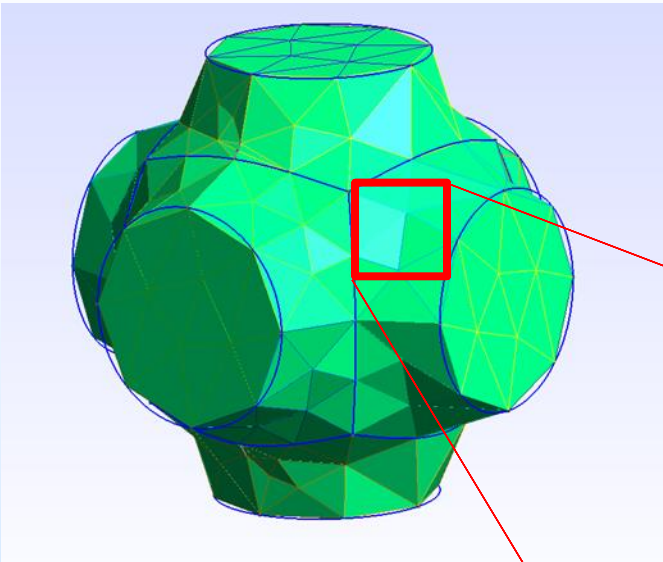
Mass Balance:

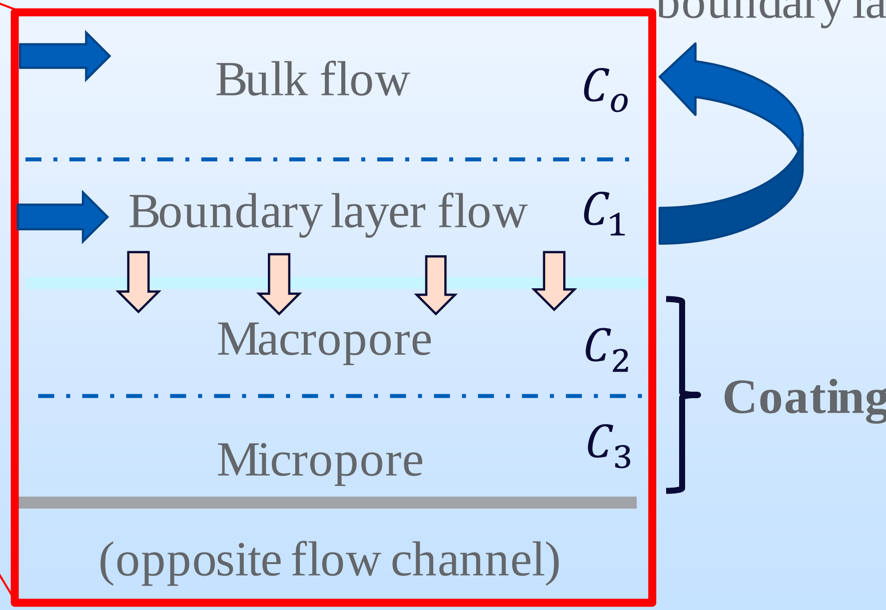
$$\frac{\partial C}{\partial t} - \nabla(\boldsymbol{u}C) + \nabla(\mathrm{K}\nabla C) = 0$$

Linear driving force

$$K_i * (\boldsymbol{n}^{\boldsymbol{eq}}(\boldsymbol{C}) - n)$$

Additive design promotes boundary layer mixing





Mass Balance Solvers

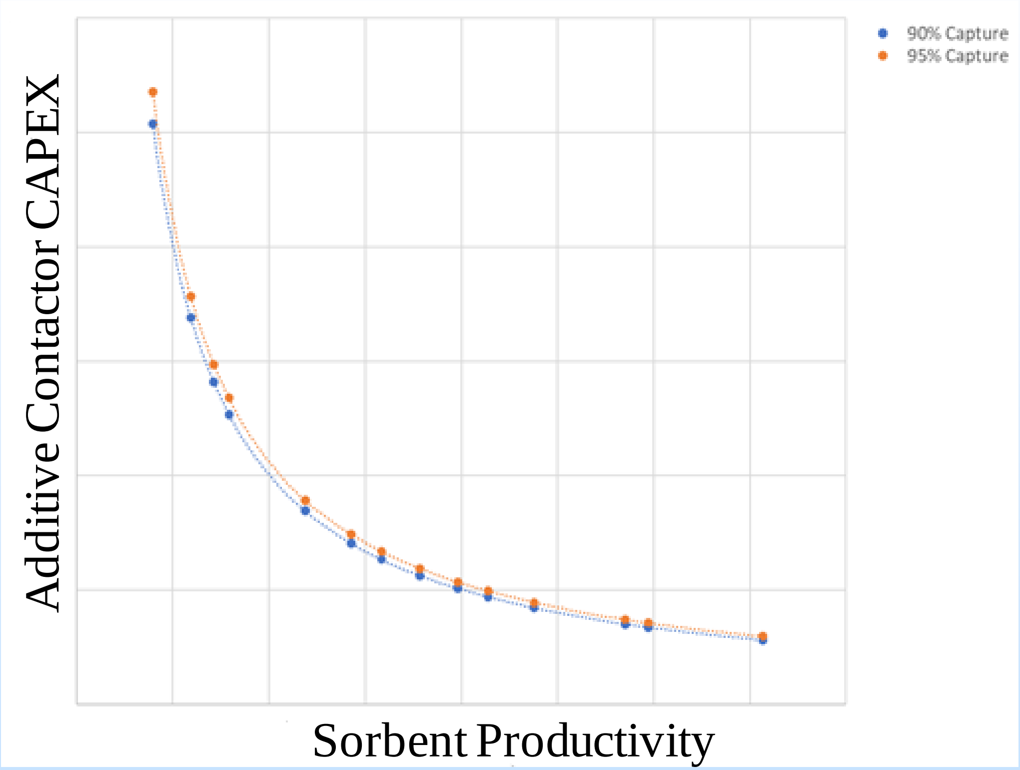
- 0D – homogeneous sorbent working capacity and kinetics
- 1D model – PDE hydraulic diameter of channel
- 3D model – PDE full dimensions in relevant coordinates

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% CO_2 removal
- 1 mm sorbent coating
- Sorbent working capacity
- Sorbent utilization
- 30-minute cycle time
- CO_2 and H_2O isosteric heats
- ΔT (adsorb-desorb)
- Sorbent/costing costs
- Contactor costs ($\$/m^2$)
- 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
- CO_2 sequestration and utilization applications
- NGCC utility engineering studies
- NGCC CCUS demonstration programs

Future Scaling of Additive Contactor Systems

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

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

TDA RESEARCH

- Sorbent development
- Material synthesis
- Sorbent characterization
- System models

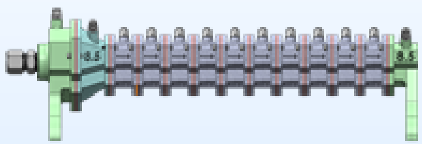
Berkeley UNIVERSITY OF CALIFORNIA

- Sorbent development
- Material synthesis
- Sorbent characterization

UNIVERSITY OF SOUTH ALABAMA

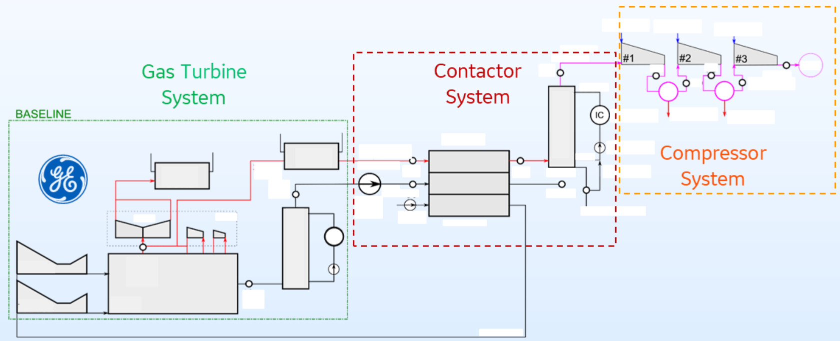
- Frequency response
- Kinetic modelling

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

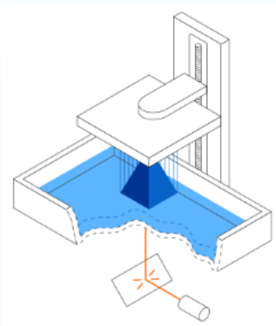
- Sorbent performance issues
  - ✓ Characterize batches before next synthesis
  - ✓ Understand materials & process variation
  - ✓ Synthesis process control
- Coating adhesion/cracking
  - ✓ Coupon testing – understand nature of cracks
  - ✓ Surface preparation and roughness modification
  - ✓ Adhesion 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

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

Additive Printing Modalities

Photopolymerization

SLA, DLP, CLIP



formlabs.com/fdmslasls

Selective curing of layers of photopolymer resin using laser or DLP

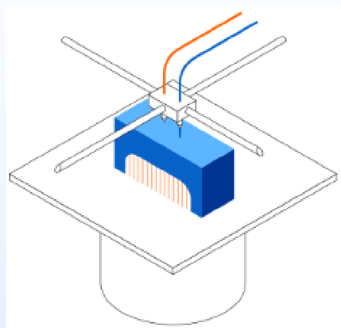
Single material system – support structures same cured polymer as part

Materials: Liquids – acrylates, epoxies

SLA	Stereolithography
DLP	Digital Light Processing
CLIP	Continuous Interface Liquid Production

Extrusion

FDM, FFF



formlabs.com/fdmslasls

Plastic filament from a spool is extruded through moving heated nozzles

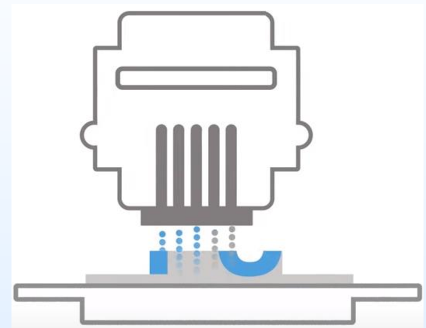
Two material system – support structures are different material from part

Materials: Thermoplastic filament

FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication

Jetting

Polyjet, Multijet



- stratasysdirect.com/technologies/polyjet

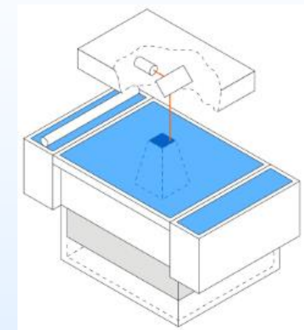
Inkjet printheads drop liquid material where needed. Droplets solidify on contact or are UV cured

Multi-material system – support material is different from one or more build materials

Materials: UV cured liquids, wax

Powder Bed Fusion

SLS, MJF



formlabs.com/fdmslasls

Bed of polymer powder is fused one layer at a time using a laser or other energy source

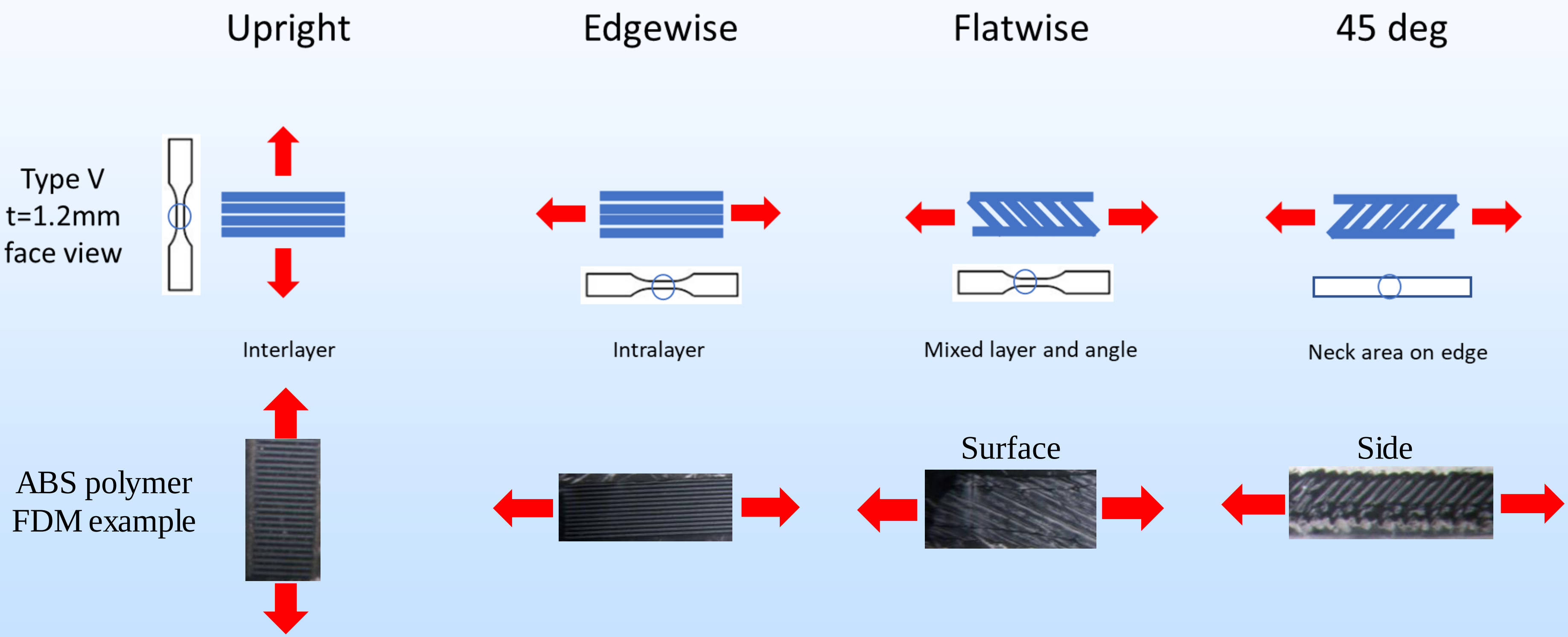
Single material system – unfused powder acts as support structure

Materials: Thermoplastic polymer powder

SLS	Selective Laser Sintering
MJF	Multi Jet Fusion

Understanding Test Articles

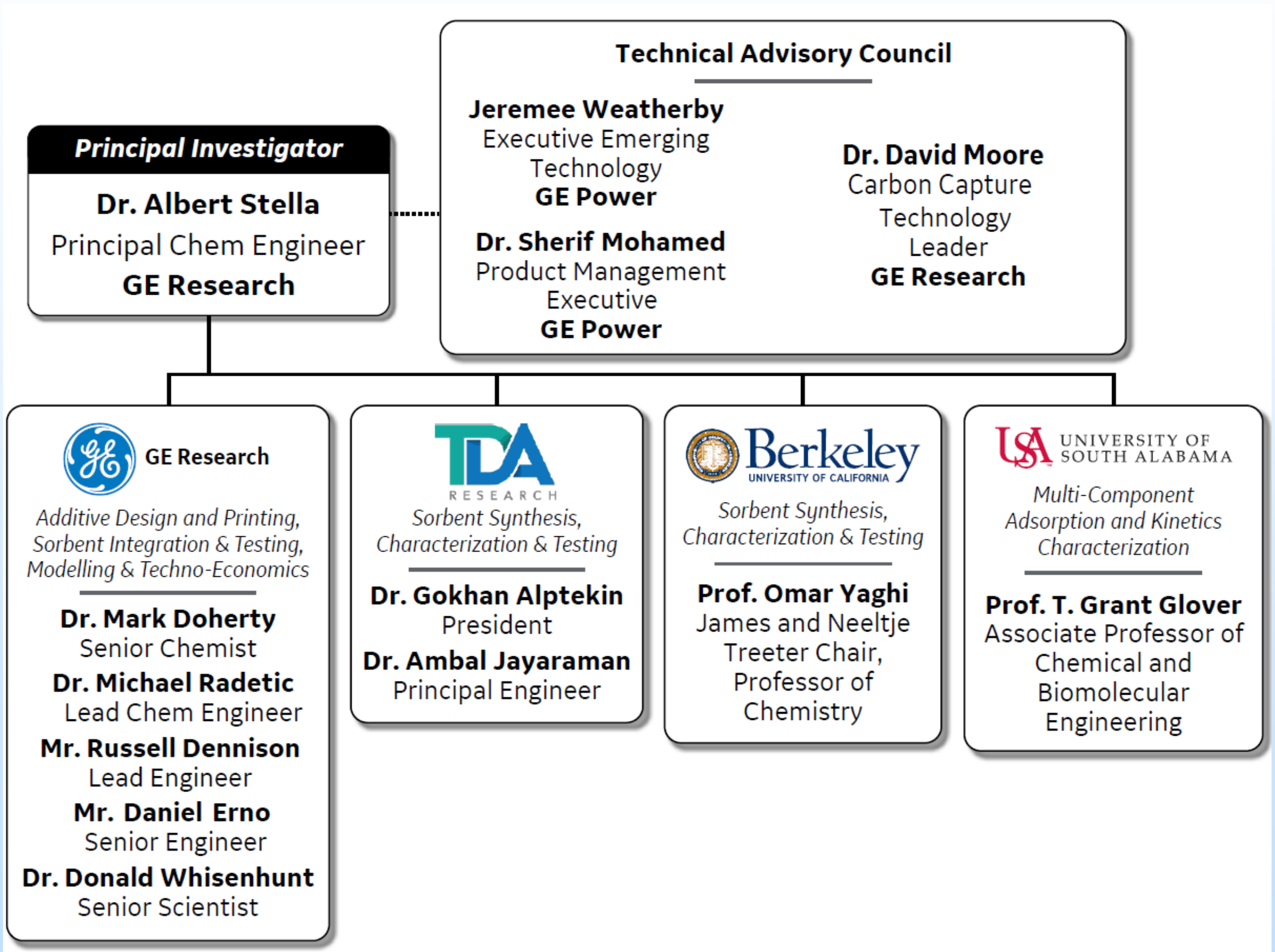
- Printing modalities will give different cross-sectional structures
- Each test configuration will give different stress-strain curve for failure



Test Type 5 articles in each configuration, modality and material to understand strass/strain relationship at desorption T

Appendix

Program Organization Chart



Program Gantt Chart