Advanced Structured Adsorbent Architectures for Transformative Carbon Dioxide Capture Performance

Project Number: DE-FE0031732

August 30, 2023

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Project Overview

Cooperative Agreement No.: DE-FE0031732

- Award Period: 05/01/2019 through 3/31/2023
- Project Funding
  - Total Funding: $5,121,897.00
  - Federal Funding: $3,890,195.00
  - Cost Share Funding: $1,231,702.00
- Project Participants
  - Prime: Electricore, Inc.
  - Technology, Design and Operation / Cost Share Provider: Svante, Inc.
  - Techno-Economic Analysis (TEA): Susteon
- DOE-NETL Team
  - Project Manager: Carl P. Laird & Andrew Jones
  - Contracting Officer: Jacqulyn M. Wilson

Svante

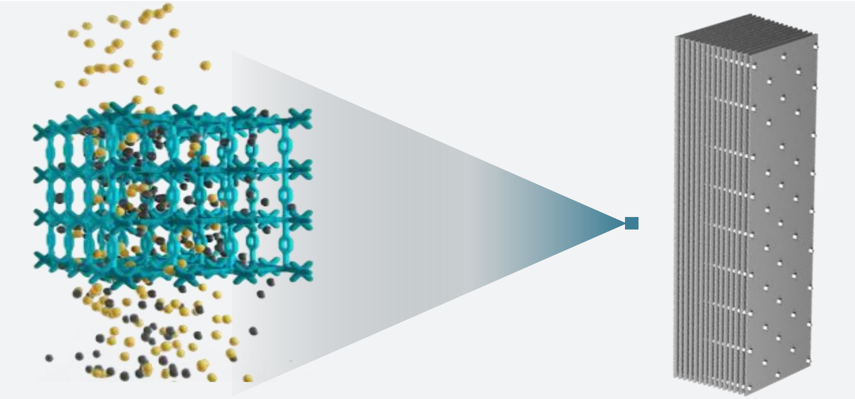
Overall Project Objectives

- Develop an optimized and commercially feasible Mark II VeloxoTherm™ CO_2 capture technology architecture, including:
  - Dual-adsorbent structured adsorbent design
    - Demonstrate the large-scale production of a MOF sorbent
  - Integrated process-intensified temperature swing adsorption (TSA) cycle
- Flow path architecture and bed construction capable of meeting a capture cost of $30/MT of captured CO_2.

Svante's Technology

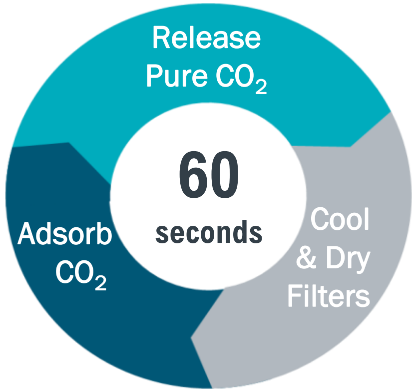
Nanomaterial

- Engineered to have very high capacity for CO_2



Structured Adsorbent

- Formed into thin films and stacked into a solid filter
- Repeatable, modular and scalable
- Platform for multiple sorbents
- Direct heating using low-grade steam

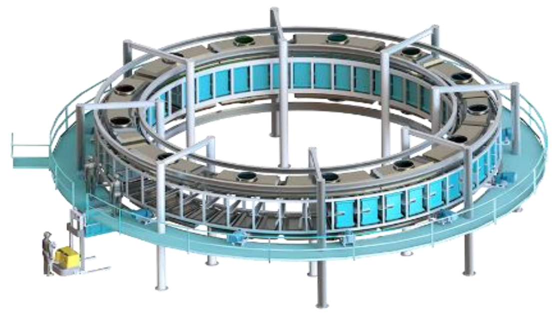


Capture Cycle and Process

- Continuous process – capture CO_2, release it with steam, and prepare filters to capture CO_2 again
- Structured filters with thin-film technology enable rapid cycles of <60 seconds
- No aerosol and nitrosamines releases

Design

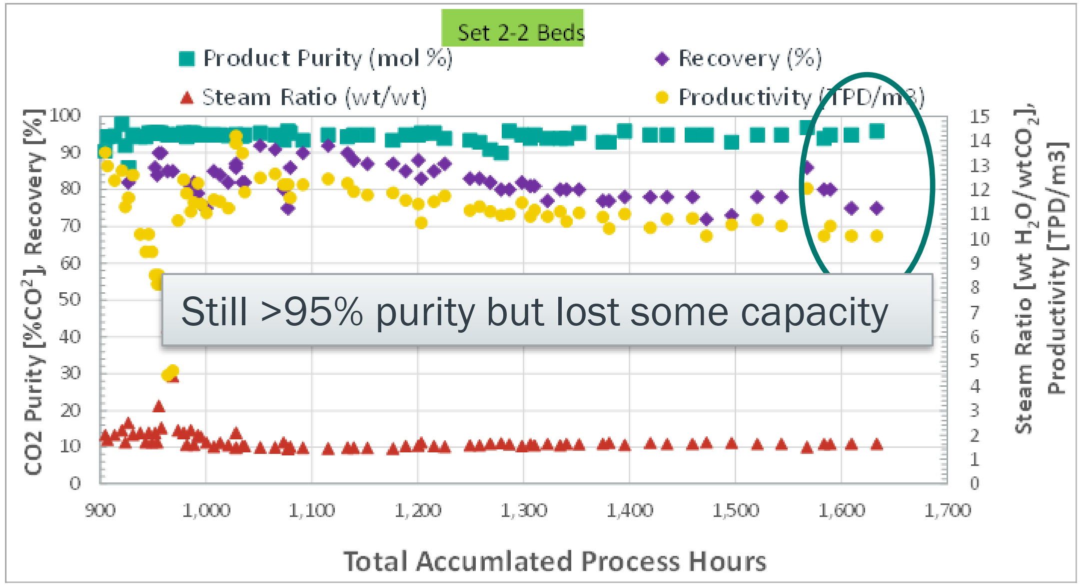
- Enables compact, low-cost contactor equipment
- Modular, repeatable filter design enables mass scalability.

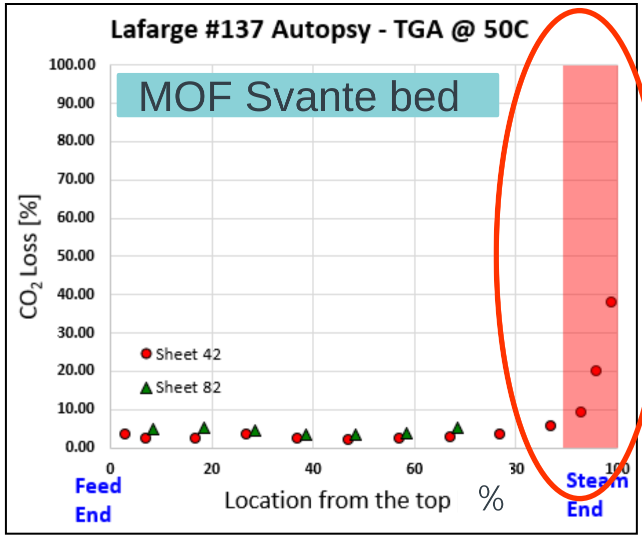


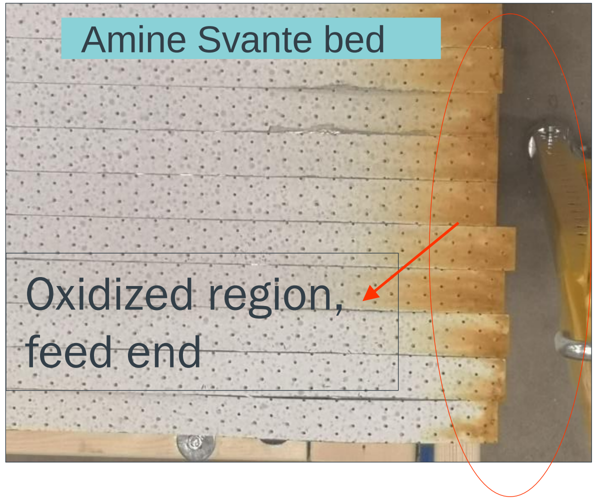
Significant challenges to reach the target capture cost of ~30$/ton:

- Sorbent lifetime needs to be increased (5+ yrs.)
- Cost of sorbent needs to be low
- Regeneration energy of the process (mainly steam) needs to be minimized.

How Svante Structure sorbent can be improved ?







Only a small portion of the bed is showing significant degradation

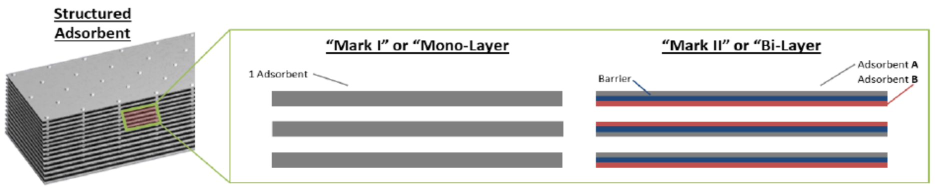
- Can we use a different sorbent or bed structure in those critical region?
- How can we model the flow and capacity at the interface?
- Can the two sorbents/structure be used during the same process?
- What optimization is needed in terms of coating parameters and bed permeability?
- What would be the optimized length for each segment section?
- Can we extend the life of the bed and only removed the more affected area ?

Introductions – Concepts

- Designed a structure beds using multi-sorbents
- Take advantage of the Rapid Cycling VeloxoThermTM Technology with non-equilibrium conditions (RH, temperature, O_2) throughout the bed

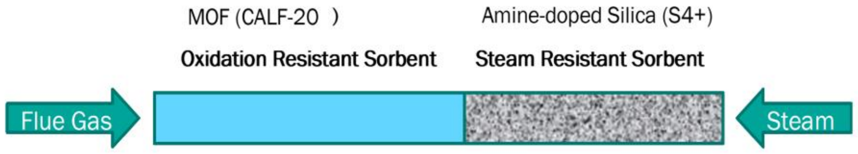
Exploring two configurations of laminates :

Concept 1- Bilayer Structure
05/01/2019 - 07/31/2021



- ❑ Absorbent B can use the heat generated by Absorbent A … Reduce steam
- ❑ <u>Absorbent B doesn't need to be steam resistant</u>… better O_2 resistance.

Concept 2- Segmented Bed Structure
08/01/2021 – 03/30/2023

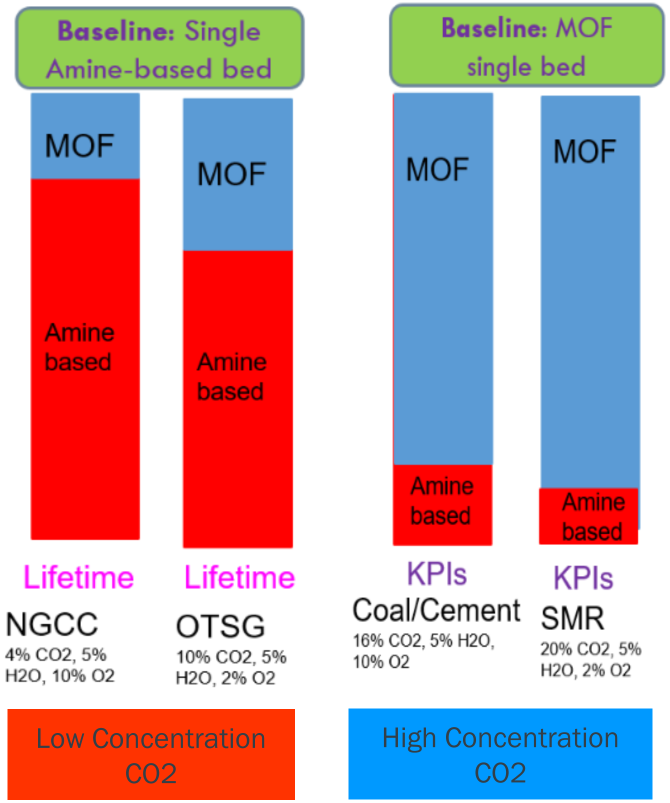


- ❑ Segmented bed concept matches the best sorbent to the position of the bed (based on RH and Temperature profile)

Concept 2 – Segmented bed Structure Adsorbents Budget Period 3

Svante

- Segmented bed concept **matches the best sorbent to the position of the bed** (based on RH, contaminants and Temperature profile)
- **Amine-based sorbents** degrade faster in dry conditions under an oxidative atmosphere.
- Direct integration to the actual Svante RAM and balance of plant technology.



Top of the bed:

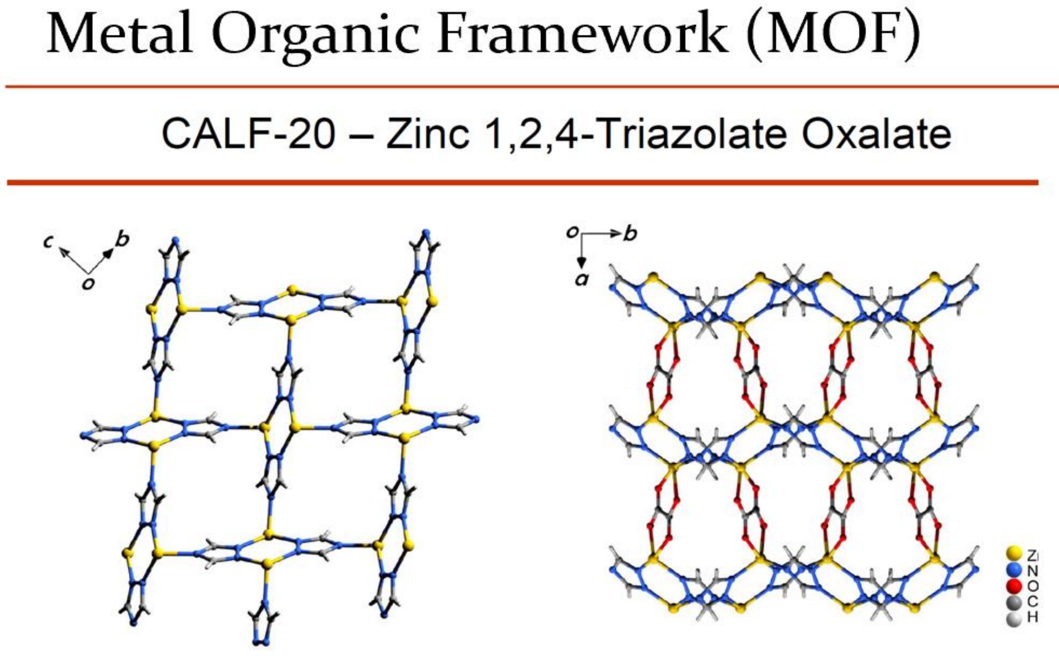
-Low average RH, high oxidation for amines

-The best chemical environment for CALF-20 to be performed (High temp, low RH)

Segmented bed concept gives a chance to optimize CO_2 capacity and lifetime.

Scale-up of CALF-20 MOF
First Large-Scale, "Commercial" MOF for CO2 Capture

- More than 10 tonnes of MOF manufactured so far at BASF.



- Metal framework (Zn)
- Organic ligand (oxalate)

This MOF has very special properties:

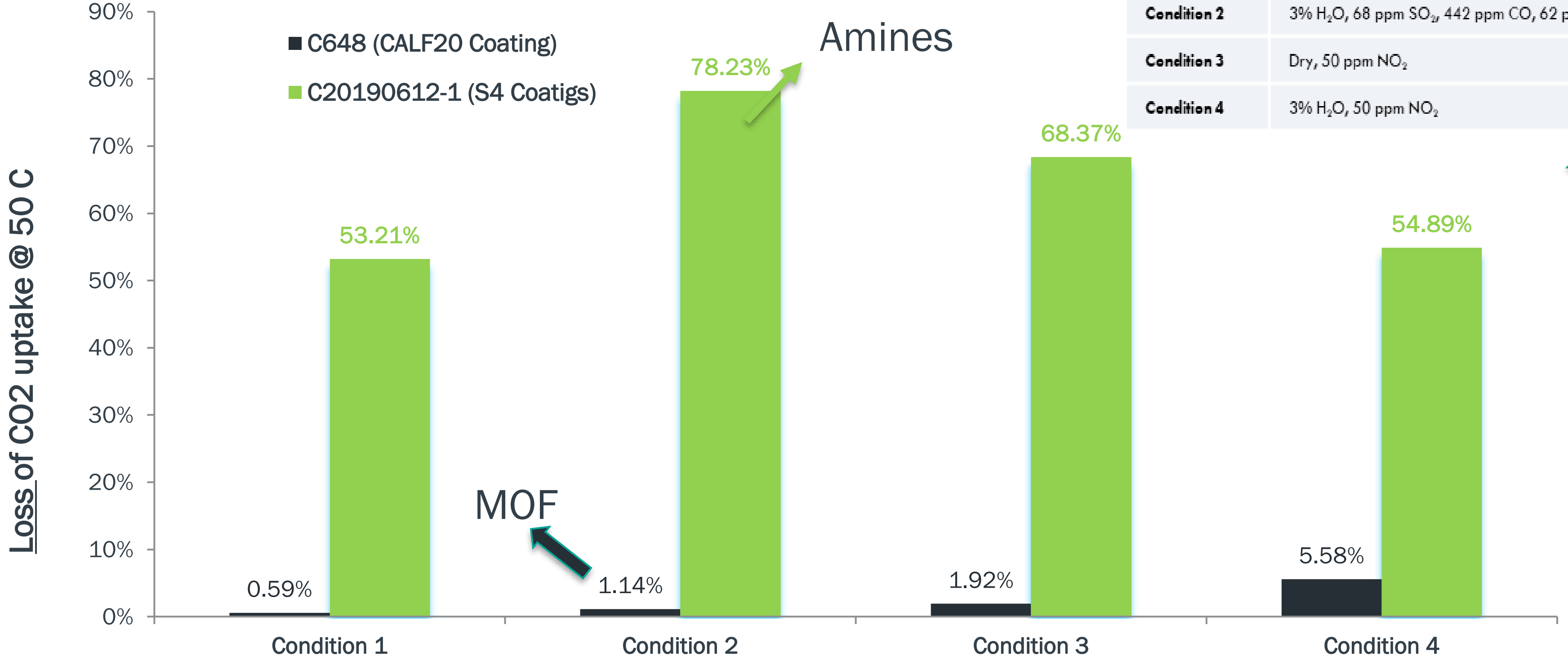
- High volumetric and gravimetric CO_2 capacity
- Stable to water (liquid, steam)
- Stable to O_2 at high temperatures (tested at 150°C, 15d, Air)
- Easily scalable (low cost)
- Processable in a laminate
- More stable to NO_X and SO_X

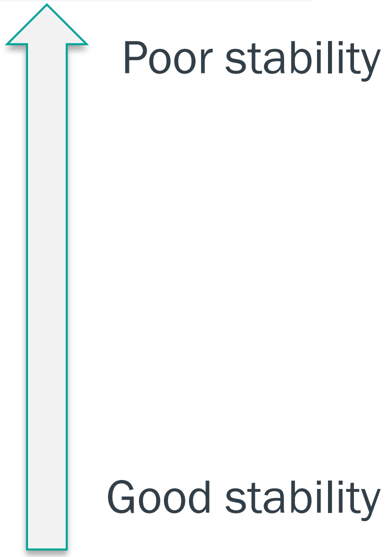
- Paper published in Science (374 (6574), 2021) .

Sorbents Sensitivity to Contaminants

- **Flue gas compatibility study**
  - Accelerated testing with 50ppm NO_2 and 68ppm SO_2 exposure for 24 hours was completed for the Calf20 and S4 *laminates*.
  - Effect of water and other contaminants (typical of flue gas) was tested.

	Gas Composition
Condition 1	Dry, 68 ppm SO_2, 442 ppm CO, 62 ppm CH_4, 18% CO_2
Condition 2	3% H_2O, 68 ppm SO_2, 442 ppm CO, 62 ppm CH_4, 18% CO_2
Condition 3	Dry, 50 ppm NO_2
Condition 4	3% H_2O, 50 ppm NO_2

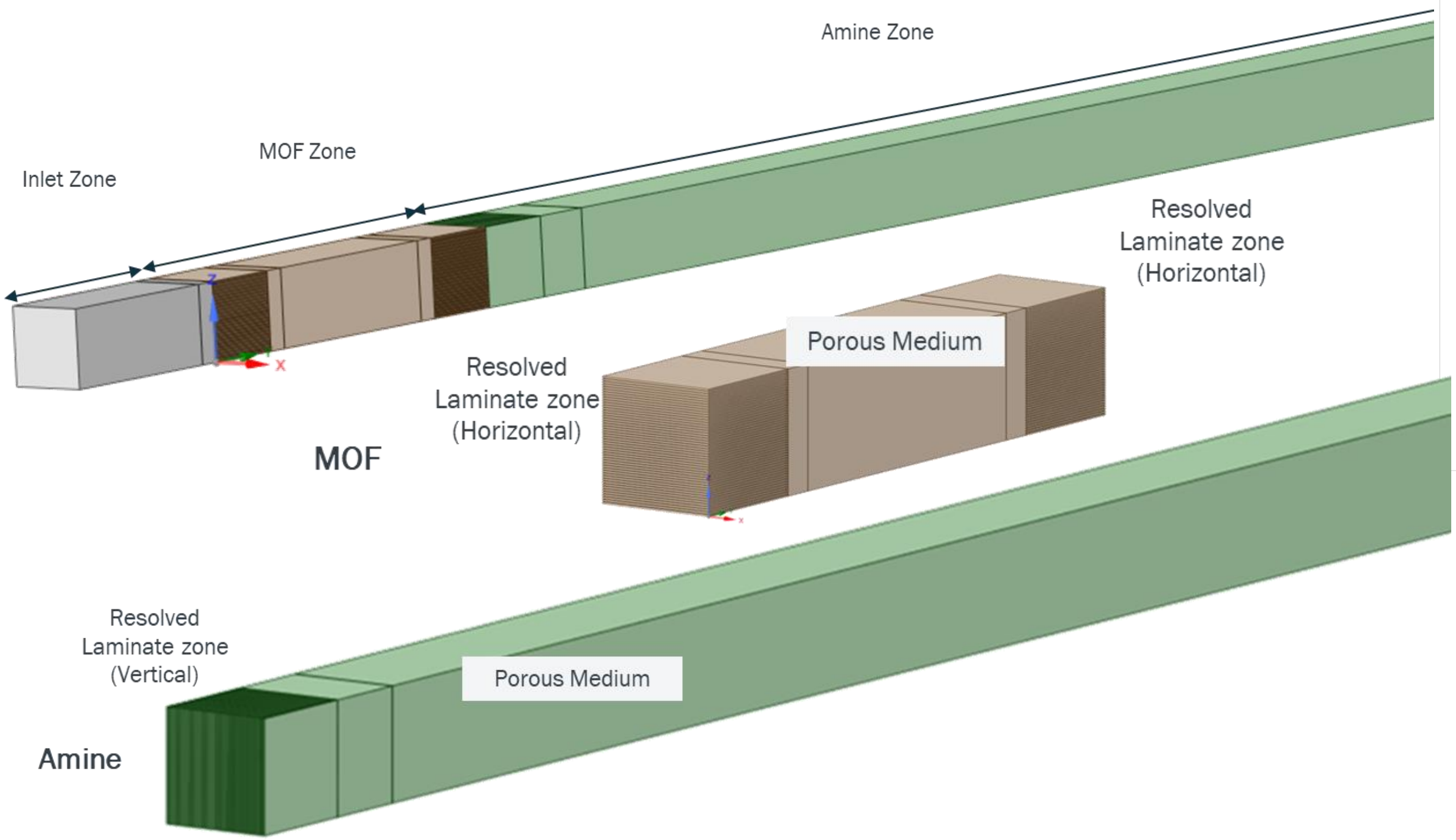


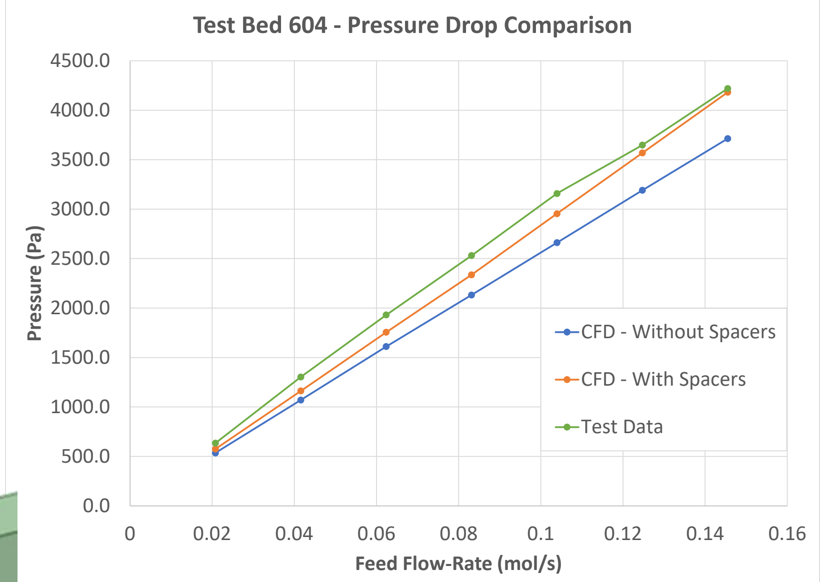


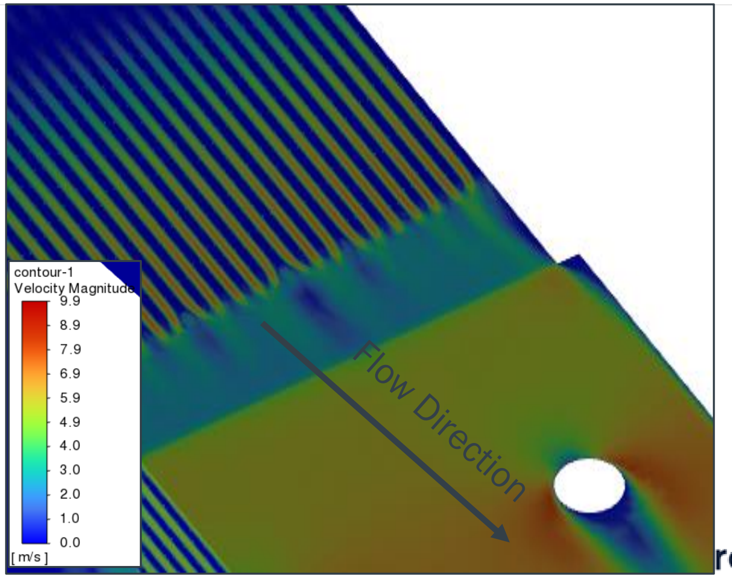
MOF (Calf20) laminate shows excellent tolerance to SOx and Nox, which opens this utilization for harsh flue-gas environments (ex., Cement)

Full Solid CAD Model

We develop a model that will accurately represent the pressure drop and velocity at the interface and throughout the length of the bed.







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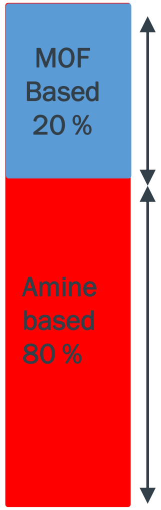
Category 1
Low Concentration CO_2
OTSG Application

Segmented Bed Final VTS Bed-IPACK274 OTSG application & Success Criteria

Final VTS bed with geometry output from Modeling and VTS test was built to verify and finalize PDU bed geometry in Category 1 [Low concentration]

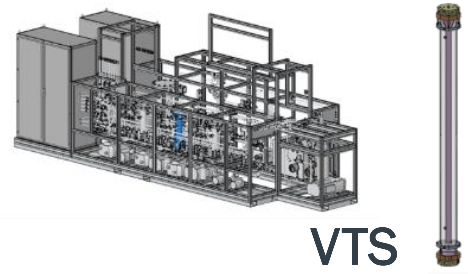
Final VTS bed
Category 1
IPACK 274



VTS KPI- OTSG application(Category-1)

KPI	Amine bed Std. configuration	Final Segmented Bed (20% MOF/80% Amine)	Program Target KPI/ Success Criteria
Productivity [TPD/M^3]	12.2	12.3	>11.0
Recovery [%]	84	>95	>90
Prod. Purity [%]	93.3	95.5	95
Steam Ratio	2.1	2.1 ± 0.2	< 2

Feed: 10% CO2, 4.8-5.0% H20 in feed



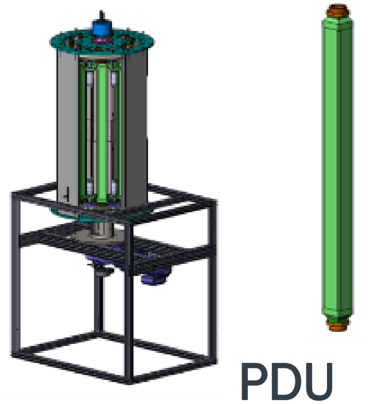
These VTS results allow confirming that the model and test results were aligned. **The PDU bed geometry was finalized at this stage, and the PDU testing is to study the bed lifetime of the Segmented bed on the OTSG application.**

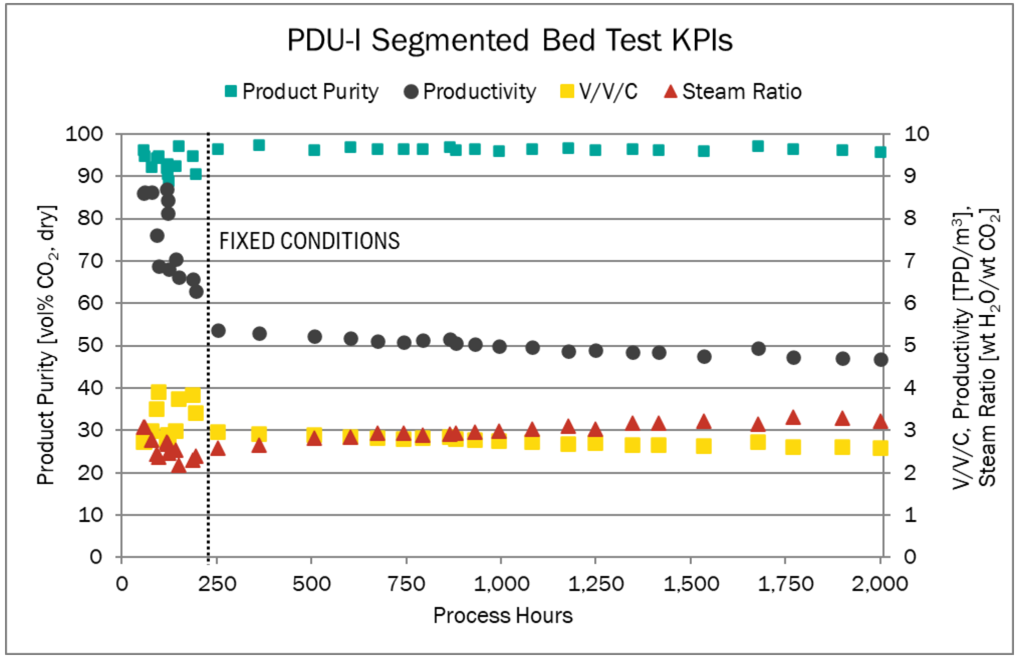
Category1 – Low Concentration CO_2
PDU Segmented Bed Performance & Success Criteria

- Test Hours: 2000 hours reached with >90% uptime

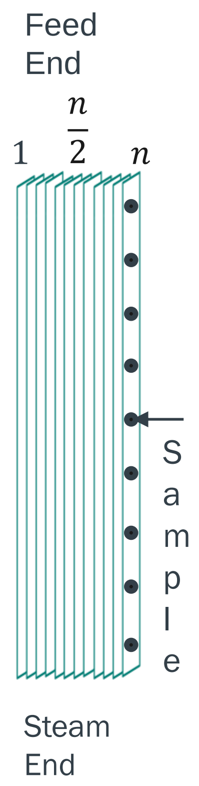
	Project Target &Success Criteria	PDU @ 1.2 CPM (July 12)	PDU @ 0.7 CPM (July 19)	PDU @ 0.7 CPM (Fixed Conditions)
Feed CO_2	8-12%	10.5%	**10.4%**	**8.5%**
Steam Ratio (kg/kg) (+/- 0.2)	≤ 2.0	2.4-2.7	**1.9-2.2**	2.2-2.7
Product Purity (v/v, dry)	≥ 95%	92-94% (98% achieved.)	**92-97%**	**95-97%**
Productivity (TPD/m³) (+/-0.1)	≥ 10	***8.7-10.1***	6.6 - 7.7	5.1-6.1

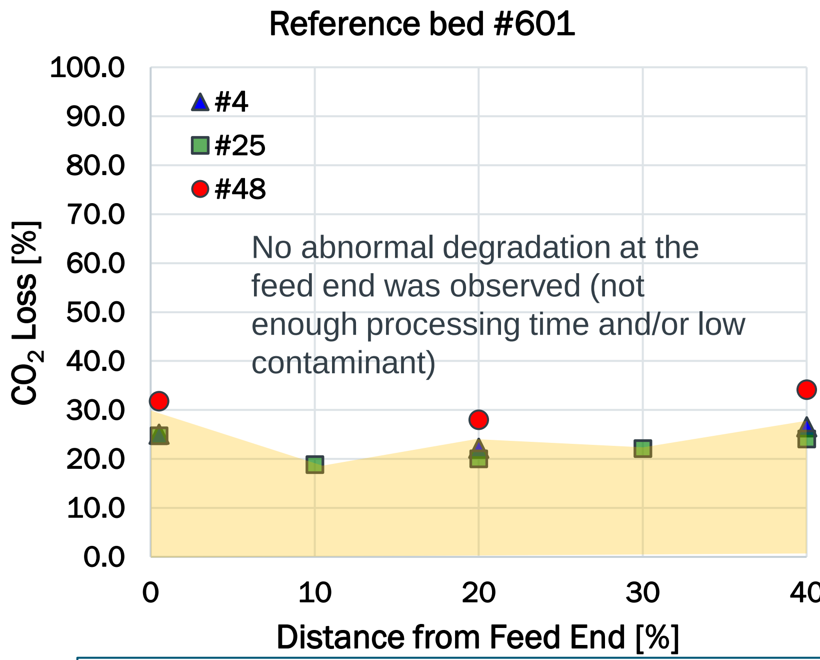
- Testing Condition Fixed at slower cycle speed and lower Feed CO_2 concentration because of balance of plan limitation
- testing units used to assess lifetime measurement (2000 hrs)


PDU



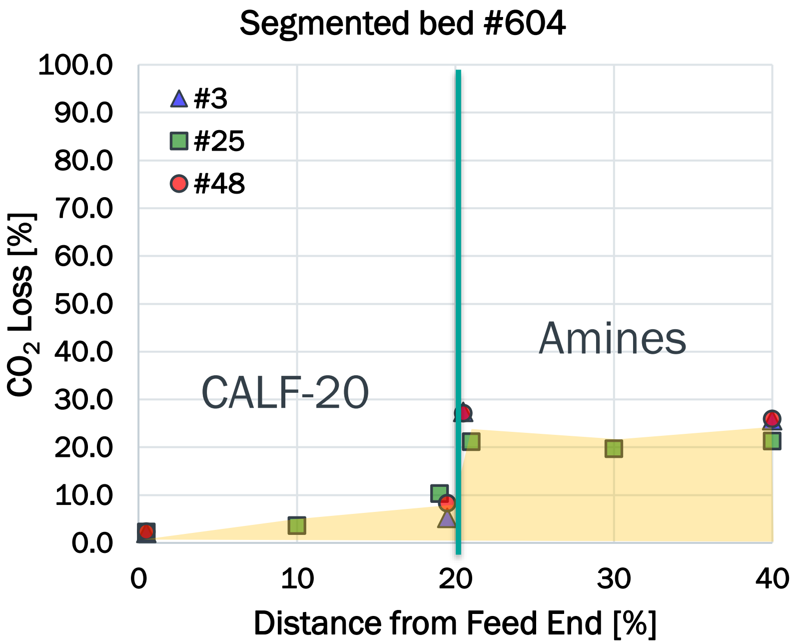
PDU-Post-Mortem Analysis- TGA Results





Bed #601 - Full S4+

- 0-20cm: An average of 25% loss



Bed #604 – 20cm CALF20 : 80cm S4+

- 0-20cm: CALF20 zone, CO2 loss is ~negligible.

-Slow degradation on the feed end (MOF) in segmented design helps reduce the overall performance loss

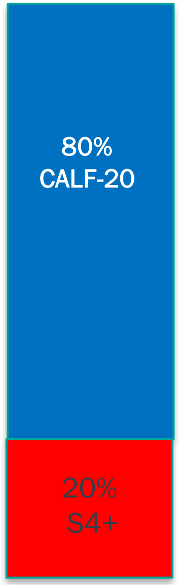
Category 2

High CO_2 concentration

14-20%

Segmented Bed Category 2 (High CO_2 Concentration) Final VTS Bed Results &Success Criteria

Final VTS Bed/ IPACK 295 20% S4+



Final bed, VTS Results

Feed CO_2%	H_2O%	Cycle Time (Sec)	TPD/m^3	Recovery%	Prod. Pur.%	Steam Ratio	Note
16.1	4.8	52	9.4	90	91.2	2.2 ±0.1	Calf20 – Reference bed (IPACK 227)
16.2	5.1	52	9.9	89.3	94.0	1.74±0.1	Baseline cycle (IPack 295)
16.3	4.9	42	11.4	92	95	1.9±0.1	IPack 295 20% less cond
	-	-	*11.0*	*90*	*95.0*	*<1.8*	*Target KPI-Success Criteria*

IPACK 295- segmented bed showing better performance as reference CALF20 with 20% less conditioning (lowering OPEX and CAPEX)

Segmented Bed Field Testing at Lafarge Cement application, 1 TPD

LafargeHolcim CO_2MENT Project, Vancouver, BC, Canada

Demonstrate a first full-cycle solution to capture and utilize CO_2 from a cement plant

LOCATION
Richmond, BC, Canada

CAPACITY
1 tonne/day

PARTNERS

LafargeHolcim · TOTAL · Solidia Technologies · CARBON CURE · Carbon Upcycling

1TPD Beds – Category 2(High Concentration CO2) Base case KPI and durability testing

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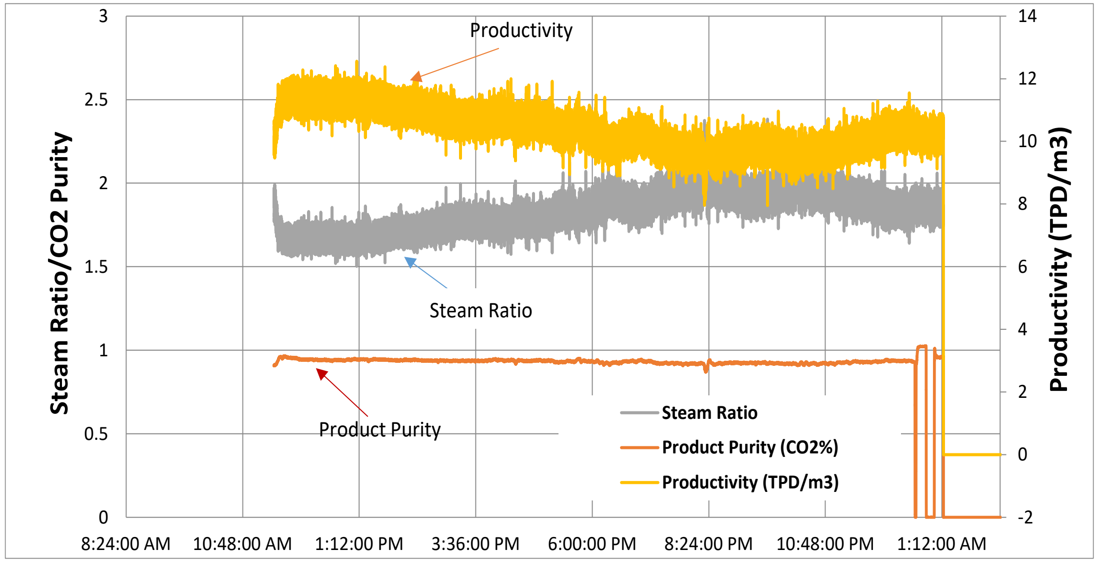
➢ KPI Testing

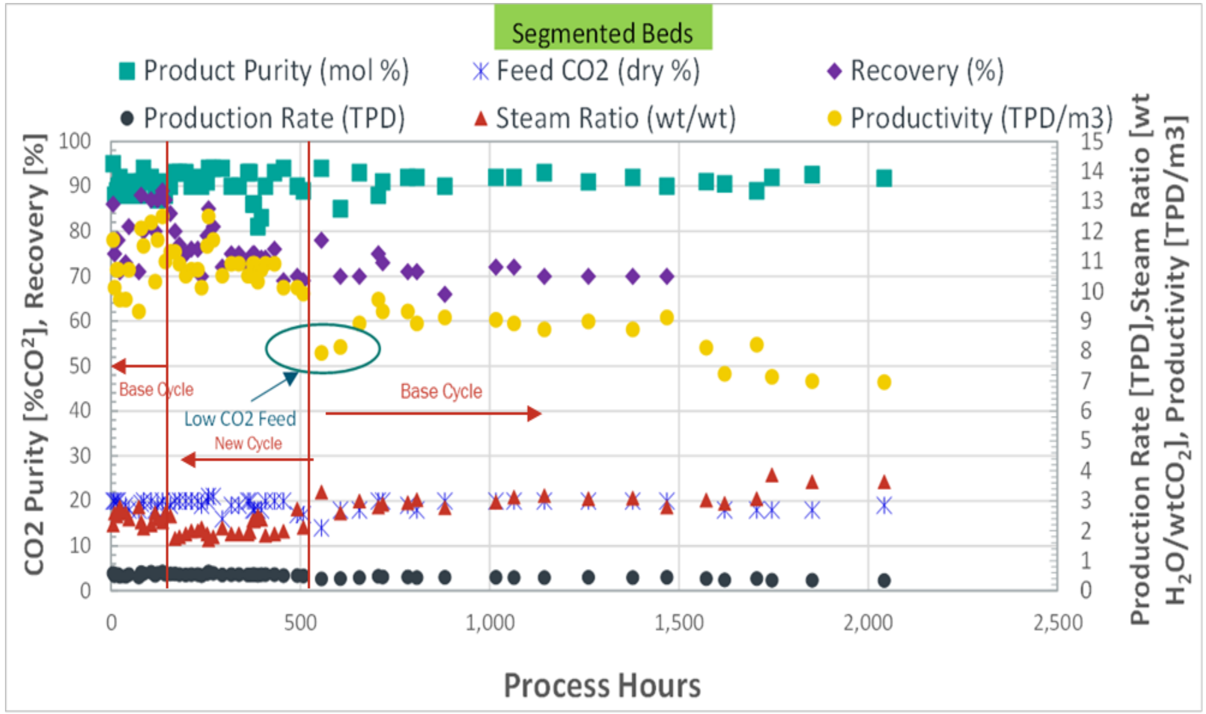
Following KPIs were achieved with 10-15% savings on conditioning flow vs. CALF20 beds at similar operating conditions

Feed CO2 % (19-20%)	Product Purity (CO2%)	Steam Ratio	Productivity (TPD/m^3)	CO2 Recovery
Measured KPIs (1 TPD, Lafarge)	94-95%	1.7-1.9	10-12	85-90%
KPI Targets–Success Criteria	95%	≤ 2	≥ 10	90%



➢ Durability Testing

2000 **hours** of operation accumulated so far on segmented beds



Some drop in capacity was observed because of the effect of contaminants on the amines-based sorbent.

1 TPD/ Post-Mortem Analysis- TGA Results

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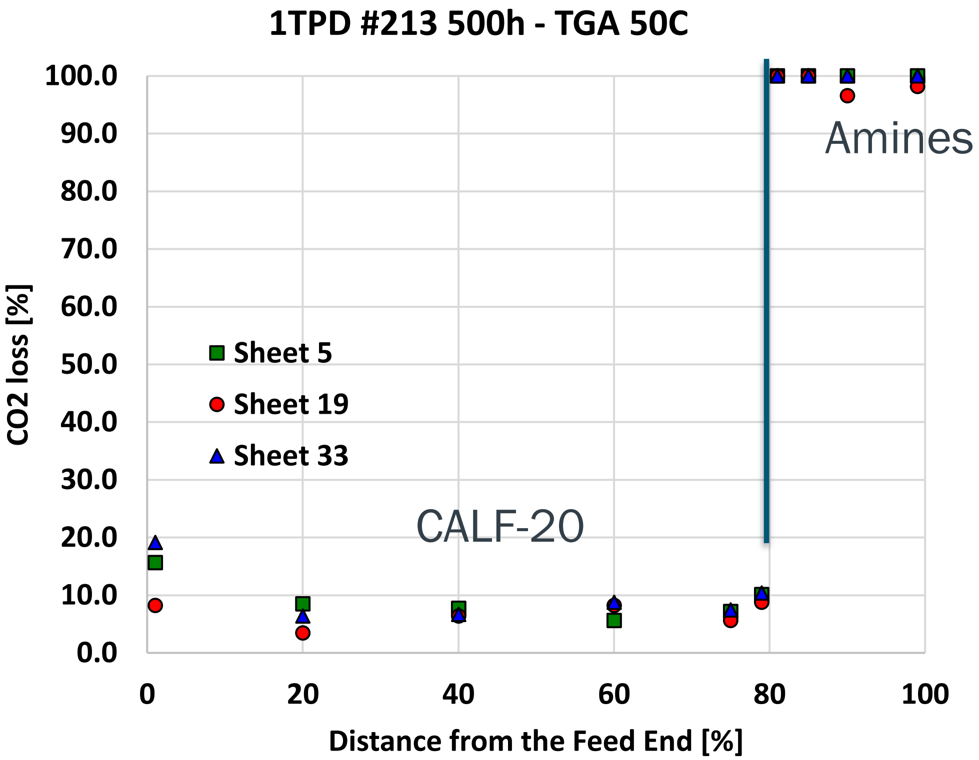
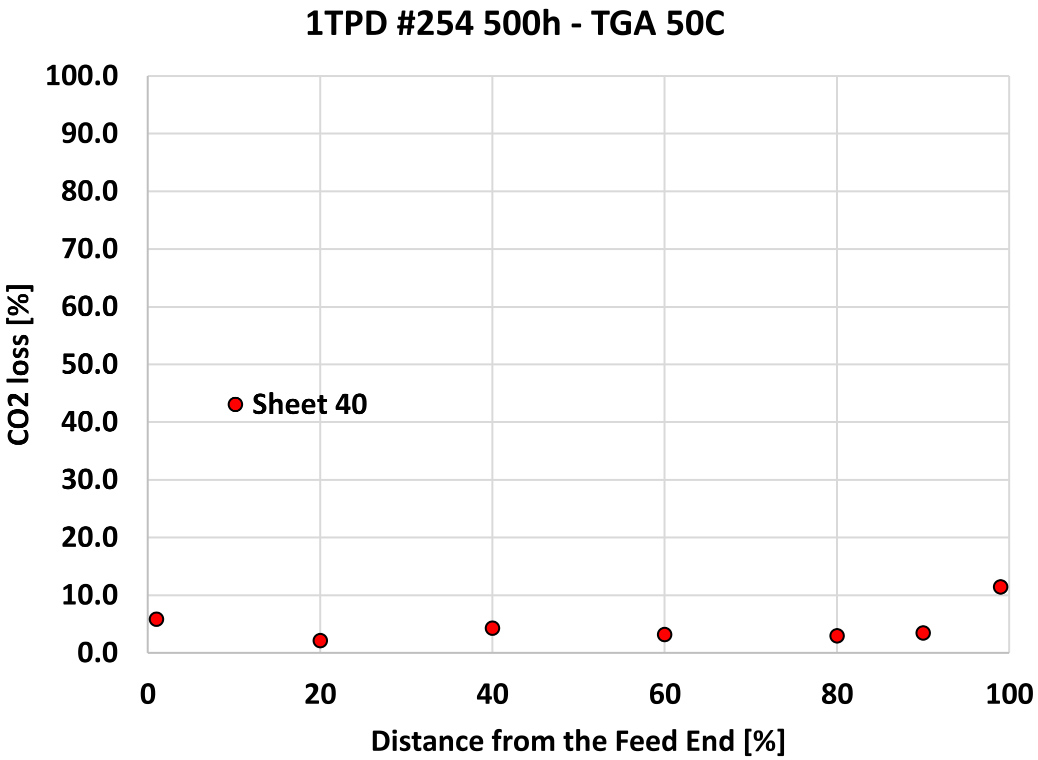


Bed #213 – 80%cm CALF20 + 20% S4+

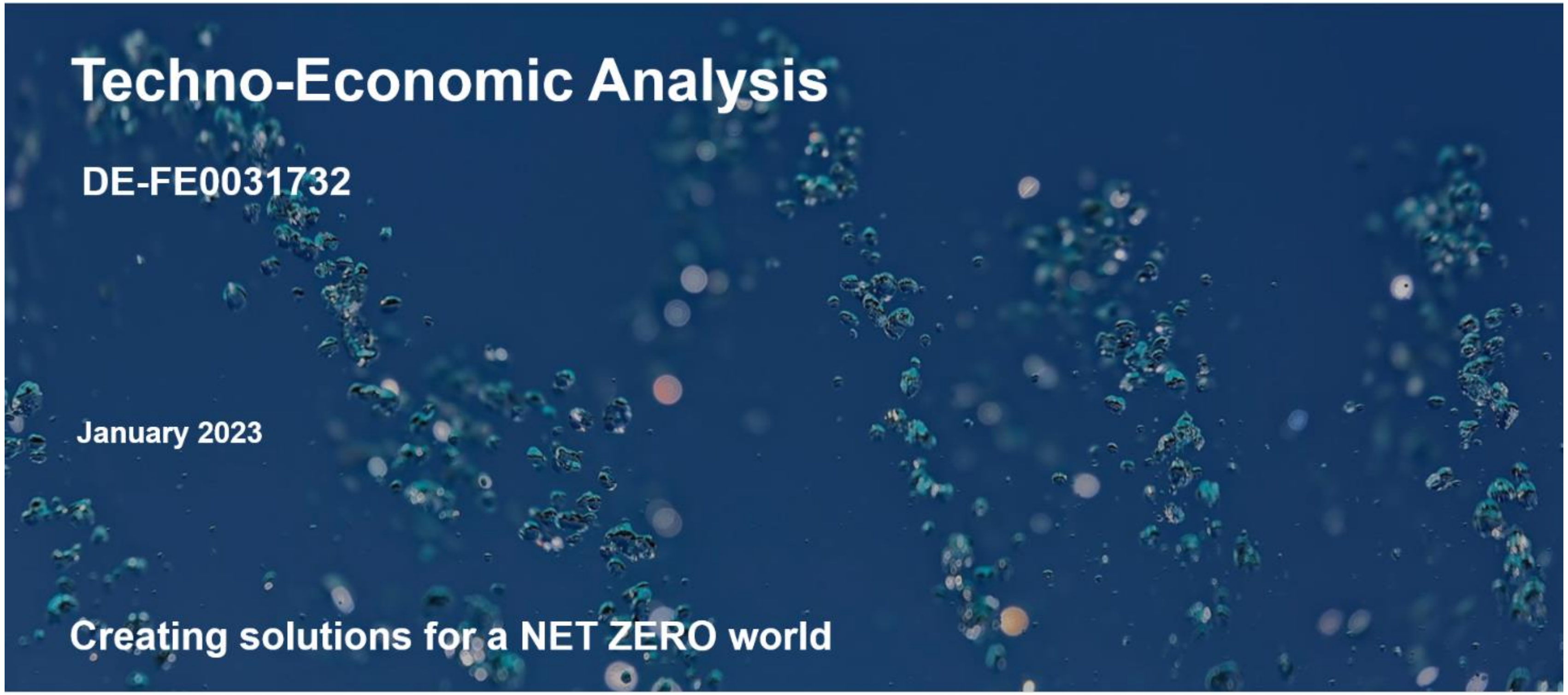
#254 - 100% CALF20



Bed #254 - Full CALF20

This bed is showing high CO2 capacity loss of the amines based section because of the presence of contaminants higher contaminants. MOF material is showing negligible lost after 500 hrs operation.

Techno-Economic Analysis



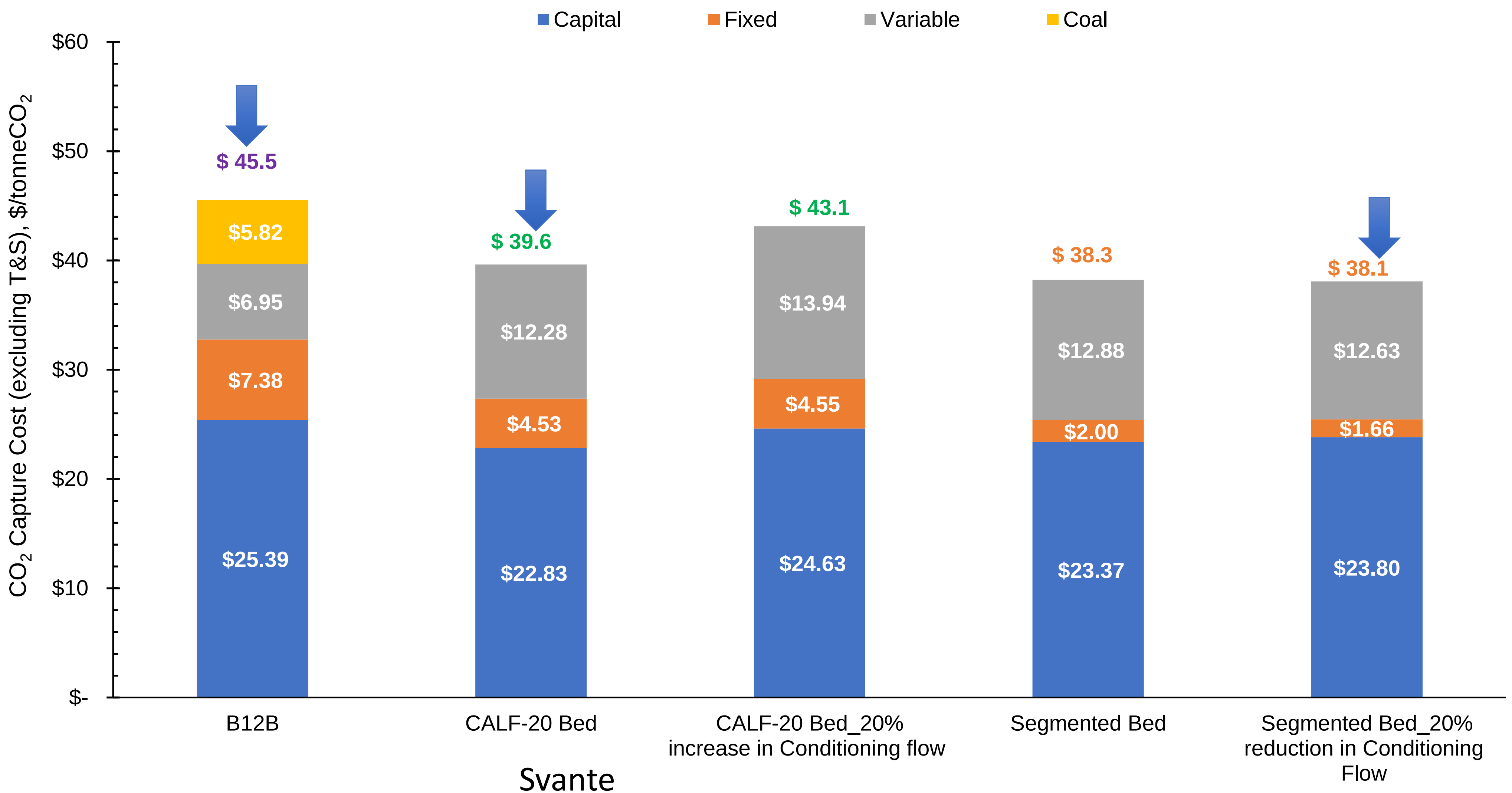
S. James Zhou, Senior Director
Aravind Rabindran, Senior Engineer

TEA Assumptions

TECHNOLOGY MODEL ASSUMPTIONS		
Structure Adsorbent Bed(SAB) Life	years	Refer to TEA-Bed lifetime Sensitivity
Steam Ratio (1)	Kg steam/kg CO_2	1.5 (2)
Productivity (TPD/m^3)	%	12
Pressure drop	-	same

(1)-Steam required for bed regeneration.
(2)-Based on VTS test data and simulation at design basis of higher product vacuum (>20 kPag). The 1TPD pilot plant results were tested at much lower vacuum (< 2 kpag) and achieved a Steam Ratio of 1.7-1.9 on Segmented Bed (shown on Category 2 updated slide).

Summary for CO_2 Capture Cost ($/tonne$CO_2$)
Breakeven CO_2 sales Price

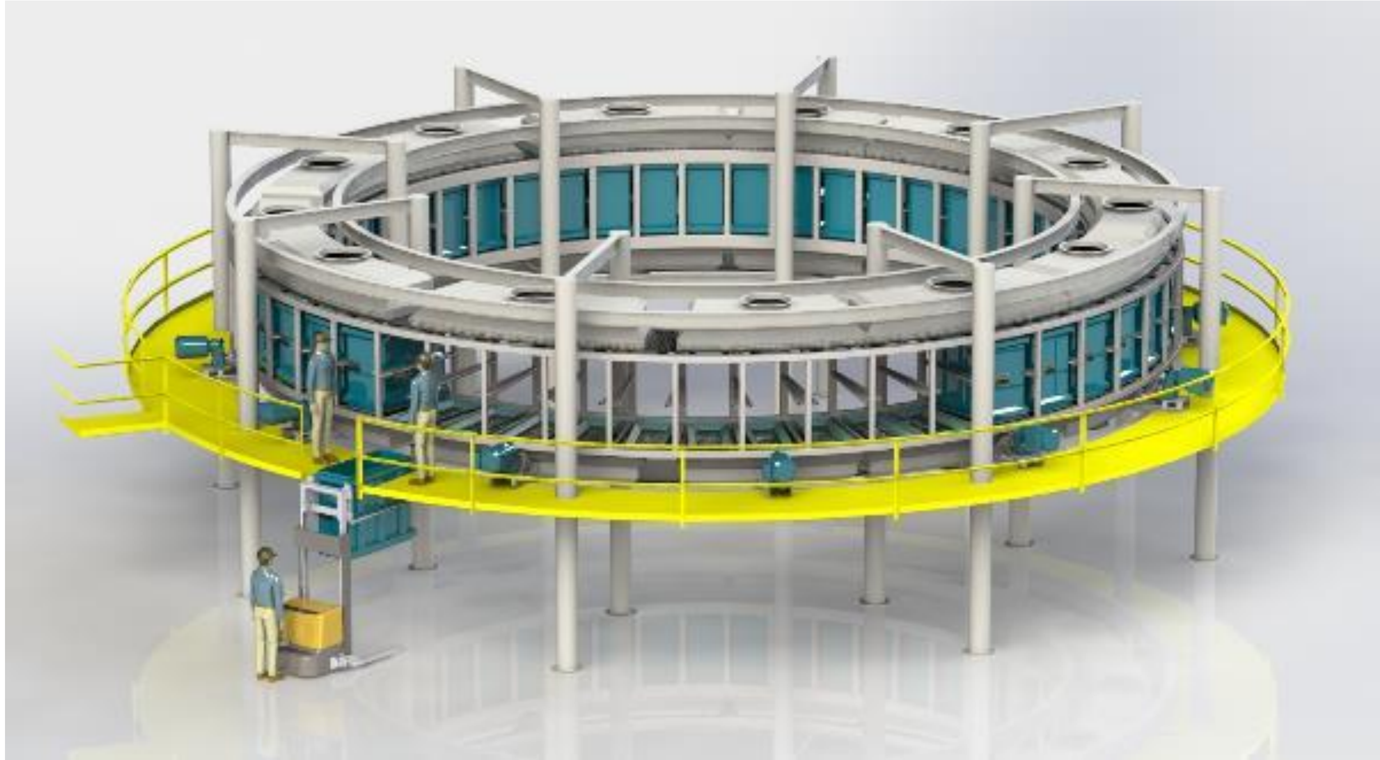


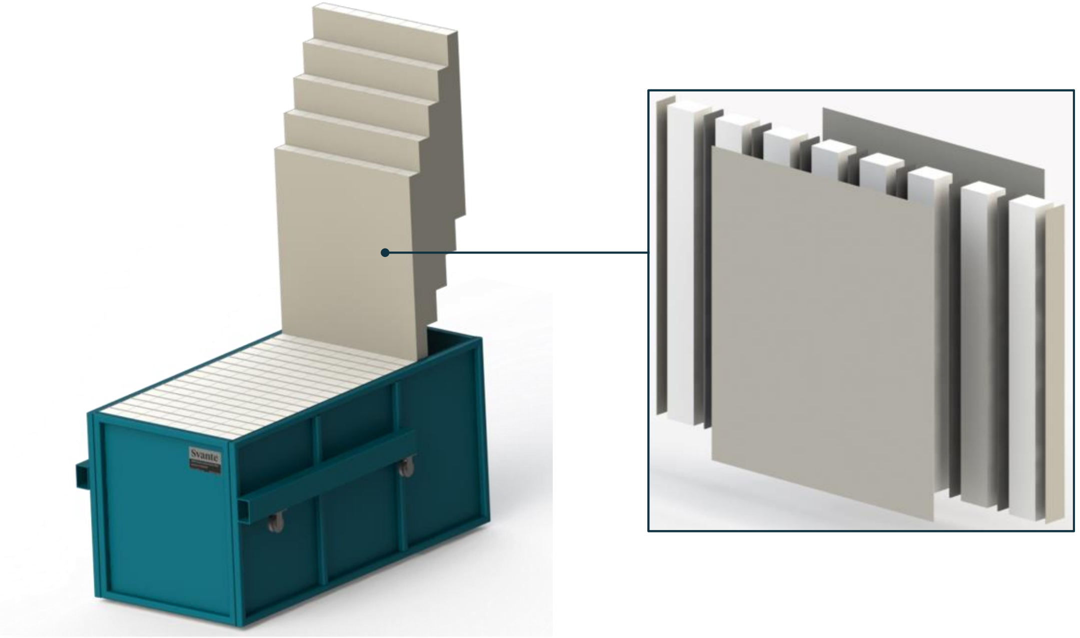
Liquid Amines

Svante
Non segmented beds

Svante
Segmented beds

Commercial Size Rotary Contactor – Series 1000





Segmented bed concept is already included in the design of the next generation RAM (500-1000 TPD)

Conclusions and Lessons learned

- This DOE funded program was key to de-risk and increase the TRL of Svante's carbon capture technology using solid sorbent and direct heat using innovative structure laminates
  - Scale-up, at tone scale, a ground braking sorbent based on metal-organic frameworks (CALF-20) stable in water/steam and contaminants.
  - Works on all aspects of the technology for the implementation of multiple sorbents/section at commercial scale (>500 TPD) (segmented bed concept, BP2 and BP3)
  - Demonstrating using TEA, a cost of CO2 capture of $38.1/tonne, a decrease of 18% vs actual technology (B12B case)
- Lessons Learned
  - Amine-based material is much more sensitive to contaminants then CALF-20 which would require more pretreatment if use in a segmented bed configuration.
  - Representative field-testing is key to assess KPIs AND lifetime (fluctuation in CO2 concentration and contaminant level)
  - Field Testing (customer) can take much more time (emitter maintenance and or day-to-day load variation)

Acknowledgment

This project was made possible by the support and hard work of an amazing team, including:

- DOE/NETL
  - Andrew Jones
  - Carl P. Laid
  - Jacqulyn M. Wilson
- Susteon
  - Ragubir Gupta
  - S. James Zhou
- BASF
  - Stefen Marx
- Electricore
  - Deborah Jelen
  - Sara Odom
  - Kathy Fagundo
- Svante R&D team
  - Zahra K.
  - Andrew L.
  - Omid N.G.

Appendix A: Organization Chart

ELECTRICORE, Inc. – Prime Contractor and Program Manager

Svante Inc. - Technical subrecipient, responsible for Adsorbent & Structured sorbent bed development and testing

R&D (material + process)
+
CFD
+
Manufacturing

Susteon, Inc. – Technical subrecipient, leading the techno-economic analysis (TEA)

DNV GL Technical subrecipient on Phase1 , responsible for process modeling and simulations

Appendix B: Program Schedule

Svante

Task Name

- Task 15.0 – Segmented Bed CALF20/S4+(Gen 1) - Structured Adsorbent Bed Development
  - 15.1 Optimize each Segment coating (density, thickness)
  - 15.2 CALF20 & S4+ Segments length study Optimizing (each Segment length) for each category
  - 15.3 Develop bed packaging for segmented bed concept
- Task 16.0 – Segmented Bed CALF20/S4+(Gen1) - Process cycle Development and optimization for higher KPIs/longer bed lifetim
  - 16.1 Bench-scale VTS testing
  - 16.2 VTS beds data analysis
- Task 17.0 – Segmented Bed CALF20/S4+ - Modeling of segmented bed to guide the bed design/process optimization
  - 17.1: Modeling & simulations of individual segment
  - 17.2: Segmented bed simulation and optimization
  - 17.3: Test data analysis and model verification for final segmented bed optimization
  - 17.4 2D modeling & simulation — CFD: Ongoing
- Task 18.0 – VTS beds Autopsy, characterization in detail and report
- Task 19.0 – High recovery mapping on final segmented beds
  - 19.1 : Category 1/ 10% CO_2 - High recovery mapping
  - 19.2 : Category 2/ 16-17% CO_2 - High recovery mapping
- Task 20.0- Design and fabrication of multiple structured adsorbent beds for multi-bed cyclic steady-state performance assessmen
  - 20.1: Sets of up to 8 or more full-length adsorbent beds will be produced, fabricated, and constructed
  - 20.2: Process cycle design and mechanical implementation
- Task 21.0- In-House PDU testing, data analysis, model verification and report
  - 21.1: Unit commissioning and base case KPI demonstration testing of segmented bed
  - 21.2: Durability test of segmented beds — PDU Test: Ongoing
- Task 22.0- 2 PDU beds Autopsy, characterization in detail and report
- Task 23.0- Design and Fabrication of optimized segmented bed for 1 TPD unit
  - 23.1: Design of 1 TPD segmented bed
  - 23.2: Fabrication of 1 TPD segmented beds/55 beds — 1 TPD Bed Building: Ongoing
- Task 24.0- Process testing the optimized segmented bed unit

All Tasks Completed