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NETL Carbon Management and Oil & Gas Research Project Review Meeting

Point Source Capture and Lab Bench Pilot Projects

ADVANCED STRUCTURED ADSORBENT ARCHITECTURES FOR TRANSFORMATIVE CARBON DIOXIDE CAPTURE PERFORMANCE

DE-FE0031732

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Program Overview

Award Period: May 2019 – July 2021

Project Funding:

Total Funding:	\$3,774,983
Federal Funds:	\$2,999,904
Cost Share:	\$775,079

Overall Project Objectives:

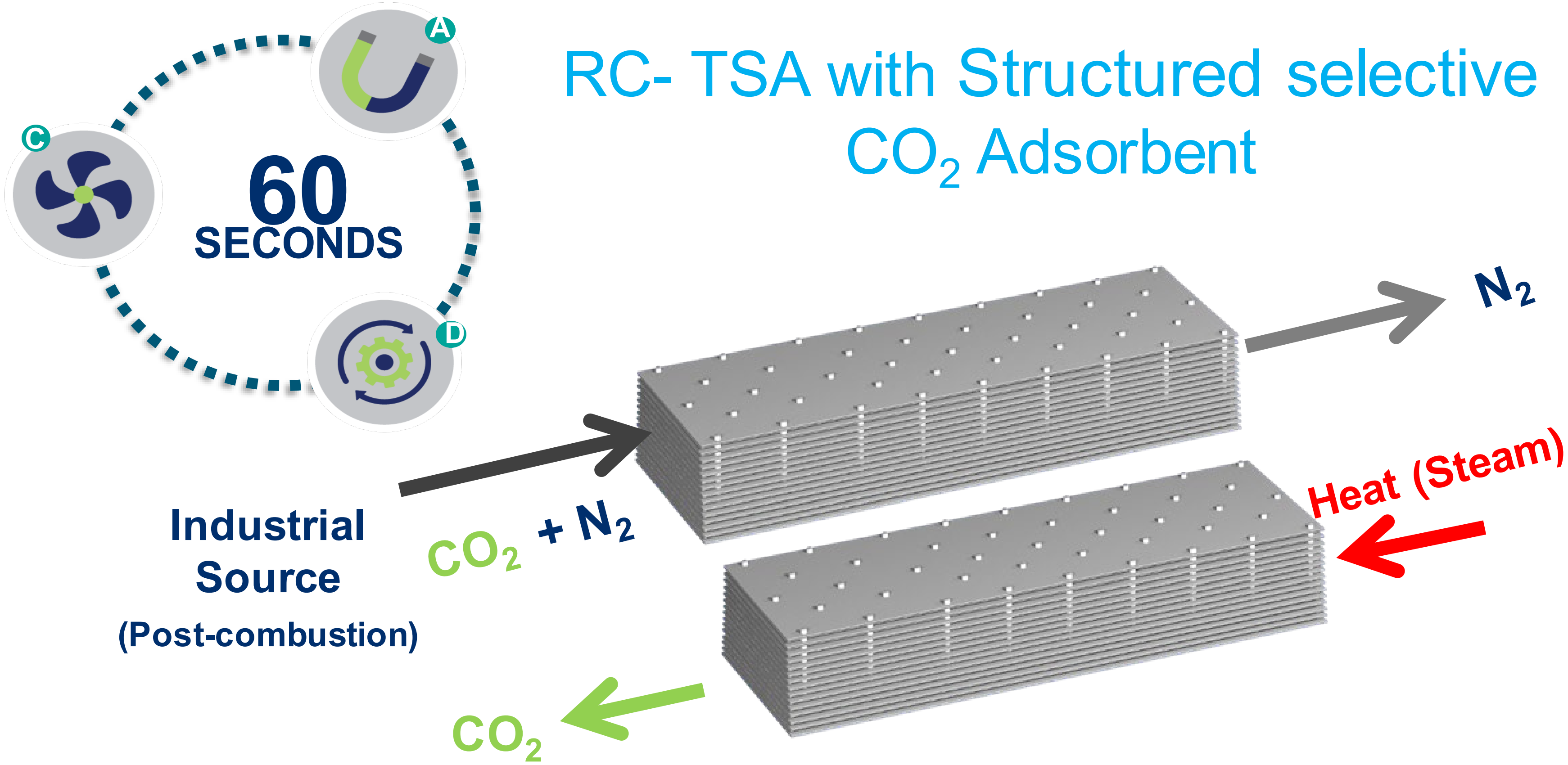
- To evaluate the Svante transformational VeloxoTherm™ Technology using solid sorbents via the development and testing of an advanced structured adsorbent
- To develop and optimize post-combustion CO2 adsorption technology using advanced architectures design, including the Bi-layer and segmented
- Integrated rapid cycle temperature swing adsorption (RC-TSA) cycle, flow path architecture, and adsorbent bed construction and packaging (including gas porting) to progress towards achievement of DOE's Transformational CO2 Capture goals of 95% CO2 purity and a cost of electricity at least 30% lower than a supercritical Pulverized Coal (PC) power plant with CO2 capture, or approximately \$30 per tonne of CO2 captured ready for demonstration by 2030.

Program Overview

Project Participants:

- **Electricore, Inc.** - Prime Contractor and Program Manager
- **Svante, Inc.** - Technical subrecipient, leader in large-scale CO_2 capture responsible for structured sorbent bed development and testing.
- **DNV GL USA Inc.** - Technical subrecipient, responsible for identification, development and updating critical documents including TMP and EH&S. DNV will also perform process modeling and simulations.
- **Susteon, Inc.** - Technical subrecipient, leading the techno-economic analysis (TEA).
- **DOE-NETL:** Project Sponsor **-** Program Manager: Andrew Jones

Technology Background



- High surface area and low thermal mass resulting in a rapid cycle leading to high productivity
- Strong Capex advantage at intermediate capture scale (~500 TPD).
- Highly customized (amines, polymer, MOF), low pressure drop and highly scalable contactor

Technology Background

Fundamental performance enablers:

- Very fast kinetics with contact time, 30-80s total cycle time.
- Highly customable and compatible with large volume manufacturing Contactor
- Low flow resistance of parallel channel structure.
- Low heat capacity relative to adsorption capacity.

Significant challenges:

- Sorbent lifetime needs to be years (2-5 yrs.)
- Cost of sorbent need to be modest (20-30 $/kg)
- Regeneration energy of process (mainly steam) needs to be minimized

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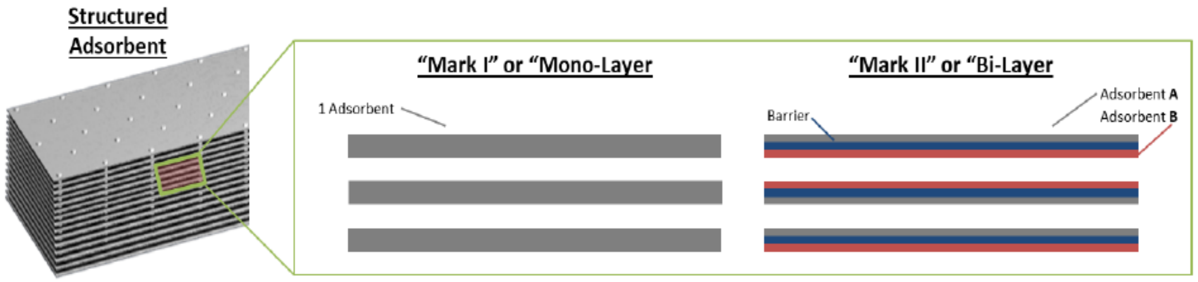
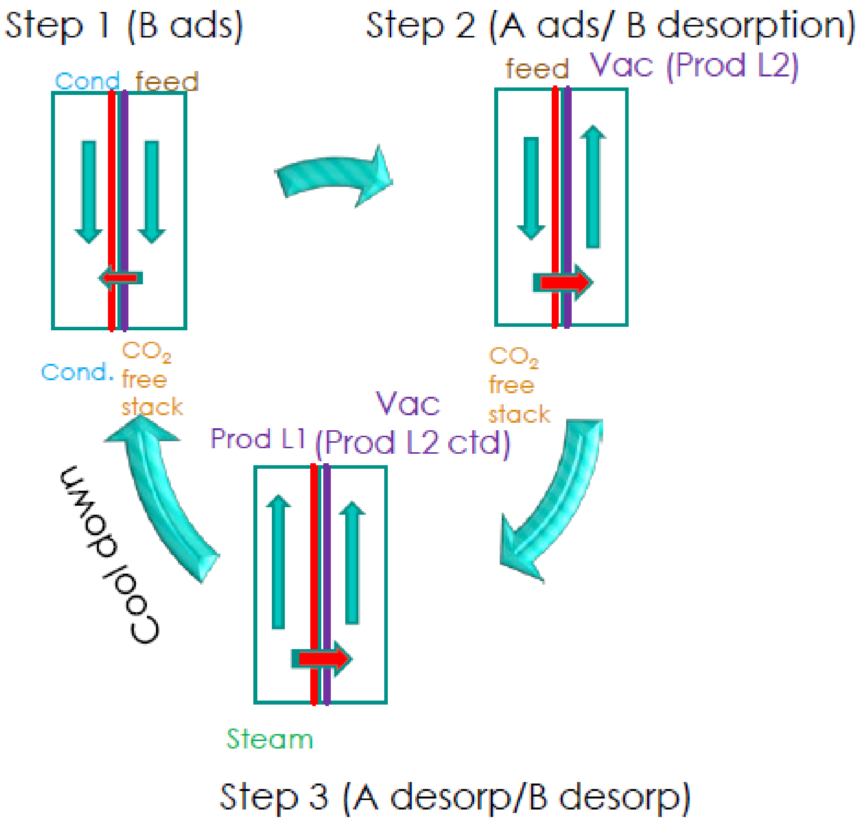
BP1: Structured Bed with Heat Exchange





Layer A:
-Steam compatible
-High heat of adsorption (>70kj/mole)
-Water promotes CO_2 ads
-Fast kinetic

Layer B:
-Low CO_2 heat of desorption (<40kj/mole)
-Air stable up to 120°C
-Stable to feed moisture content
-Fast kinetic

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Technology Background

Prior to program:

- Demonstrated RC-TSA RAM technology with amines doped silica sorbent materials at 30 TPD (Cenovus OTSG Plant in Saskatchewan, Canada)

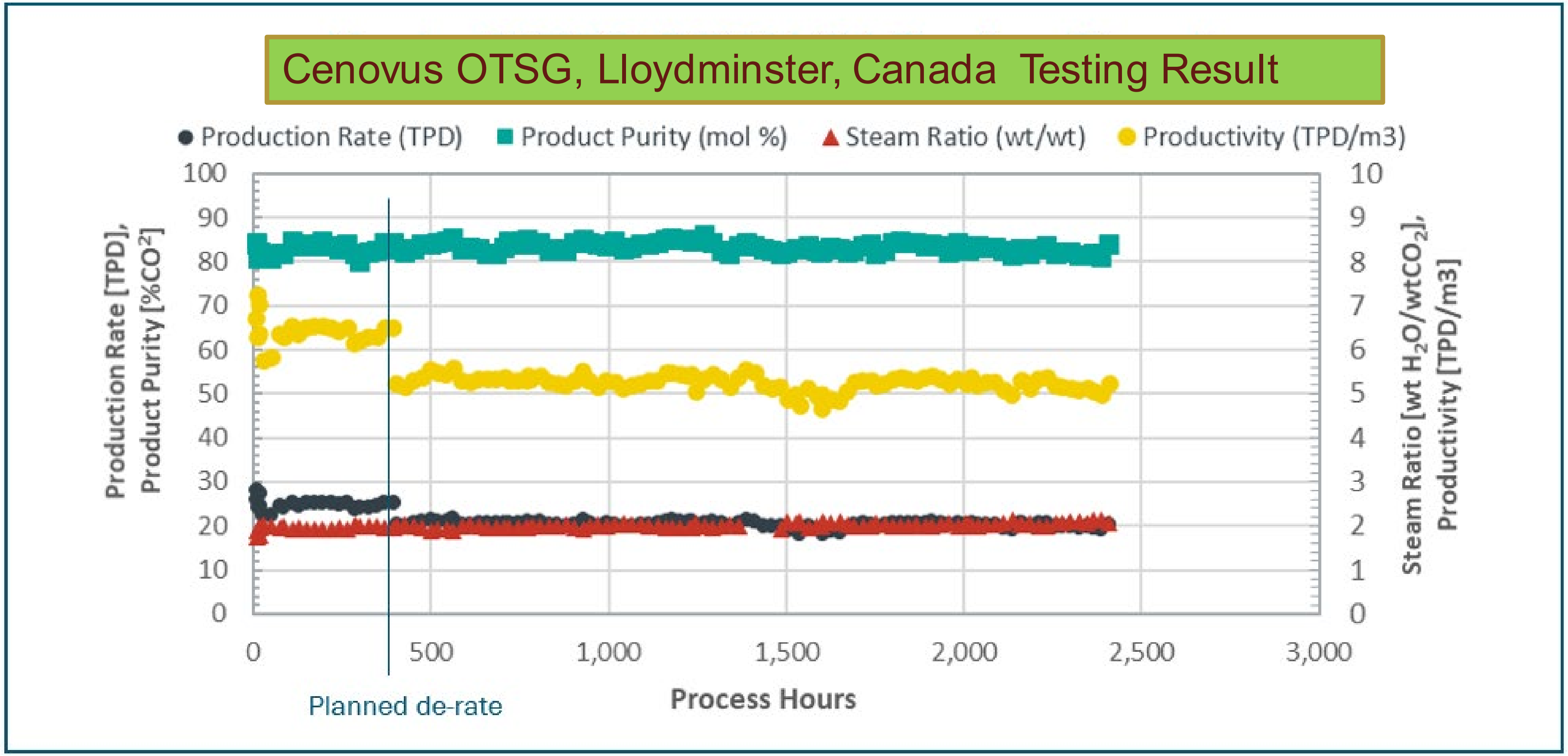
BP1 Achieved Milestone:

- Identified potential MOF for RC-TSA with very good stability to moisture swing.
- Demonstrate a decrease of SR ~30% using the bi-layer concept (MOF/Amine) vs standard single layer bed geometry
- Not able to achieve the desired productivity due to cross-leaking between the two layers during bed assembly

BP2 Objective:

- Confirmed the stability of both amines-based sorbent and MOF sorbent using VeloxothermTM process and steam regeneration
- Proof of Scalability of Svante MOF material (CALF20) at a large scale >200kg
- Evaluate the possibility of using the synergy of two sorbents on a simpler design compatible with actual VeloxoThermTM Rotary Adsorption Machine (RAM)

Confirming Stability of Amine-based Sorbent (Field Testing)



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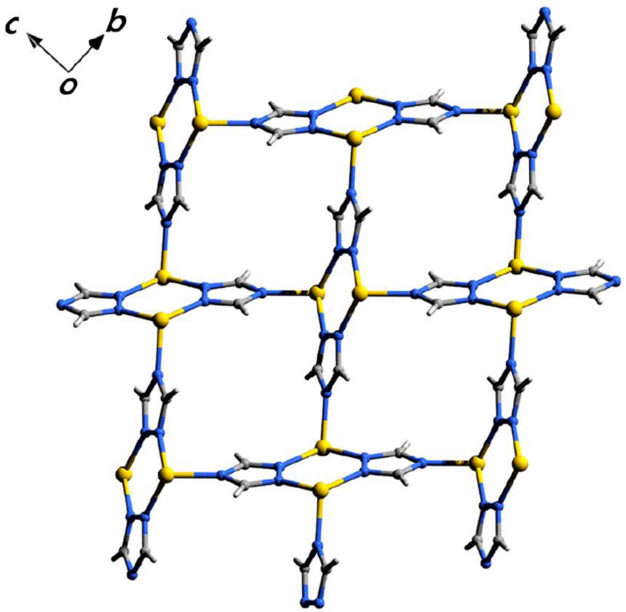
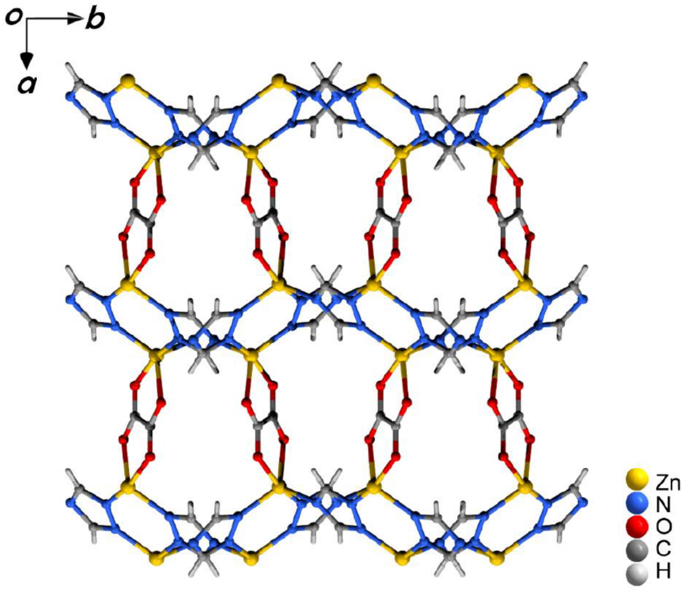
Metal Organic Framework (MOF)

CALF-20 – Zinc 1,2,4-Triazolate Oxalate

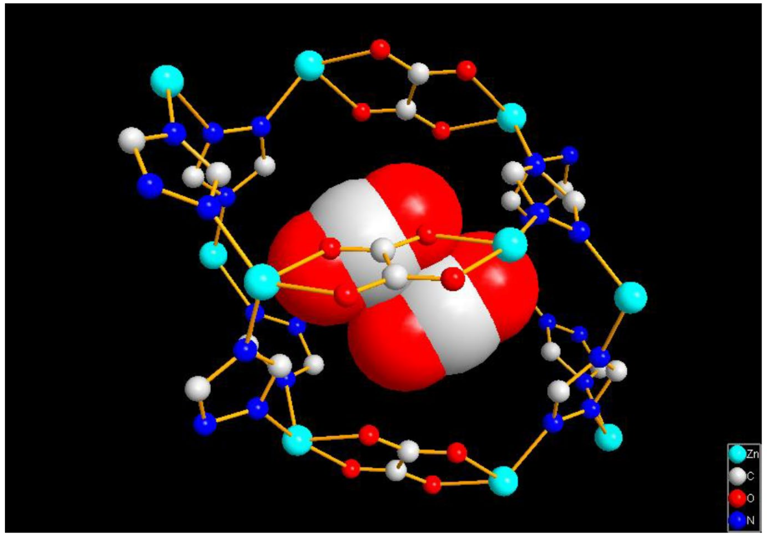




- Structure from Rietveld – crystals have never grown
- 3-D channels comprising 38% of the volume, ~500 m^2/gm surface area.
- pores (vdW radii) of 2.73 × 2.91, 1.94 × 3.11, 2.74 × 3.04 Å ([100], [011], [0-11]

Taylor, Vaidhyanathan, Lin, Mah, Dawson, Iremonger, Deakin, Shimizu
Patent awarded and licensed for post-combustion and air capture.

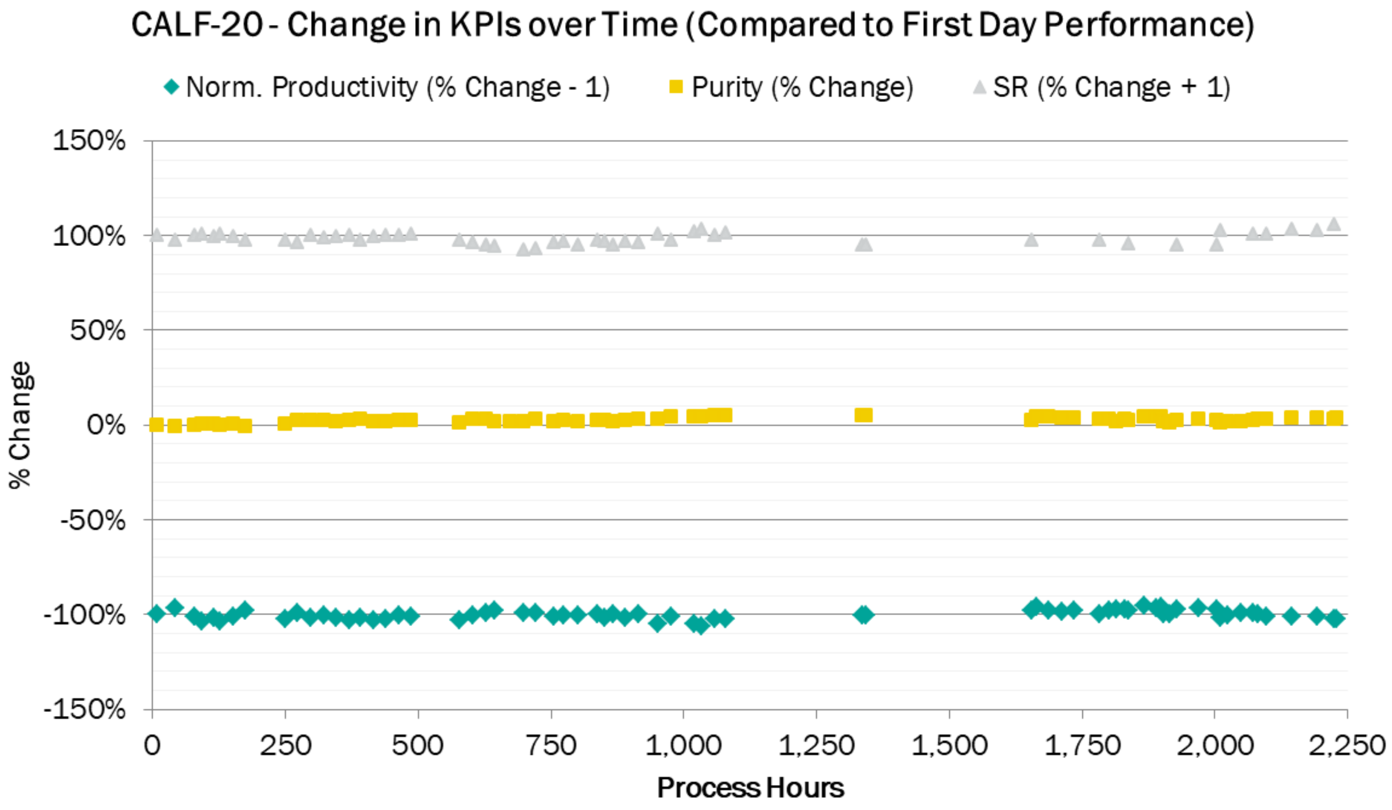
Metal framework (Zn)
Organic Ligand (oxalate)
Not amine based (physisorption)



At 1.00 atm pressure, the main CO_2 binding site is between the oxalate groups.

This MOF has very special properties:
High volumetric and gravimetric CO_2 capacity
Stable to water (liquid, steam)
Stable to O_2 up to 140C
Easily scalable (low cost)
Processable in a laminate
More stable to NOx and SOx

Svante MOF (CALF-20) Long Term Stability-0.1TPD



	KPIs
Flue gas composition	17% CO_2, 10% O_2, 5%H_2O, 12 ppm NO_2, 300ppm NO
Productivity (TPD/m3)	9-11
Recovery (%)	85-95
Purity (%)	90-97
Steam Ratio	1.5-2.0

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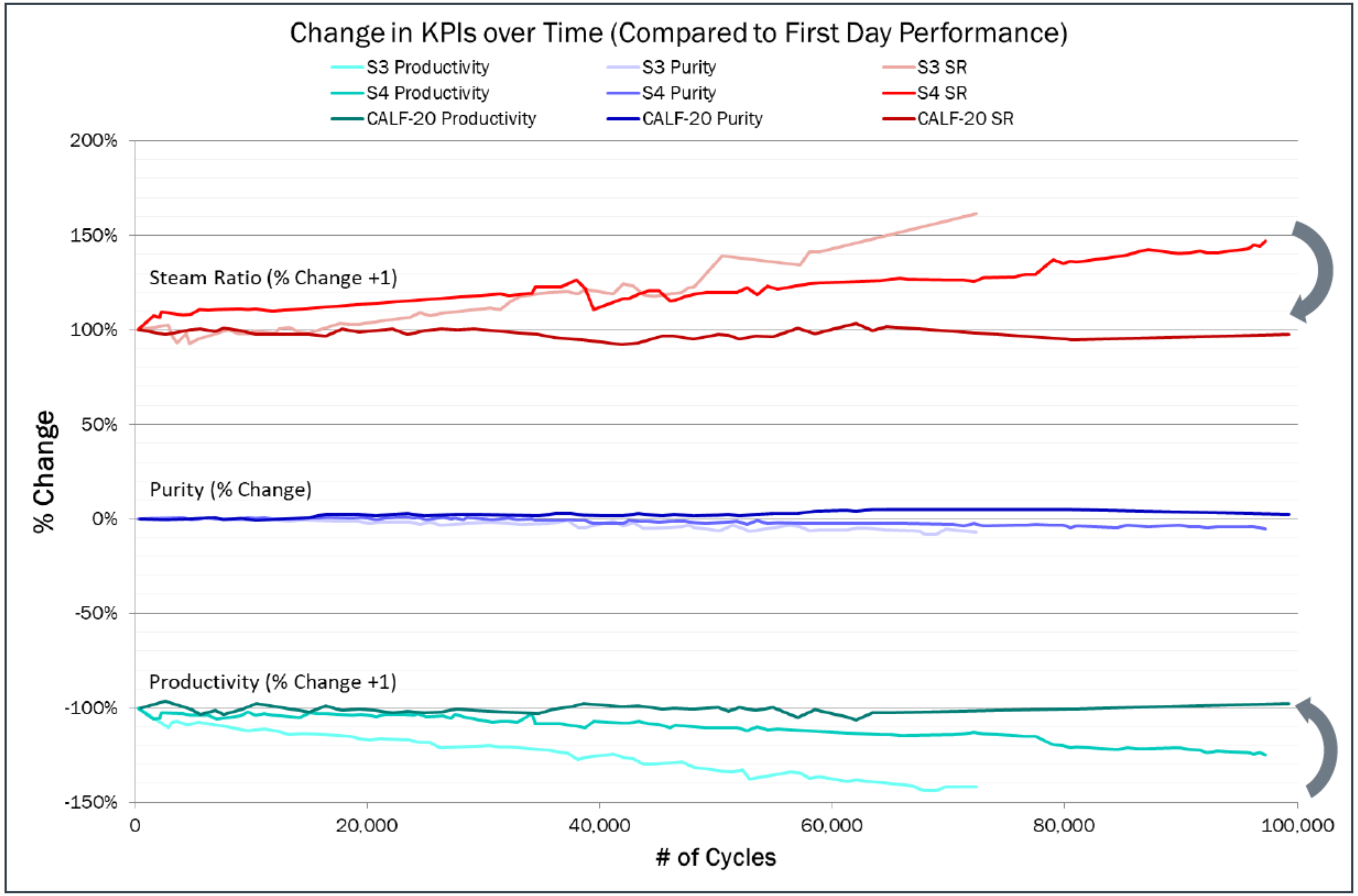
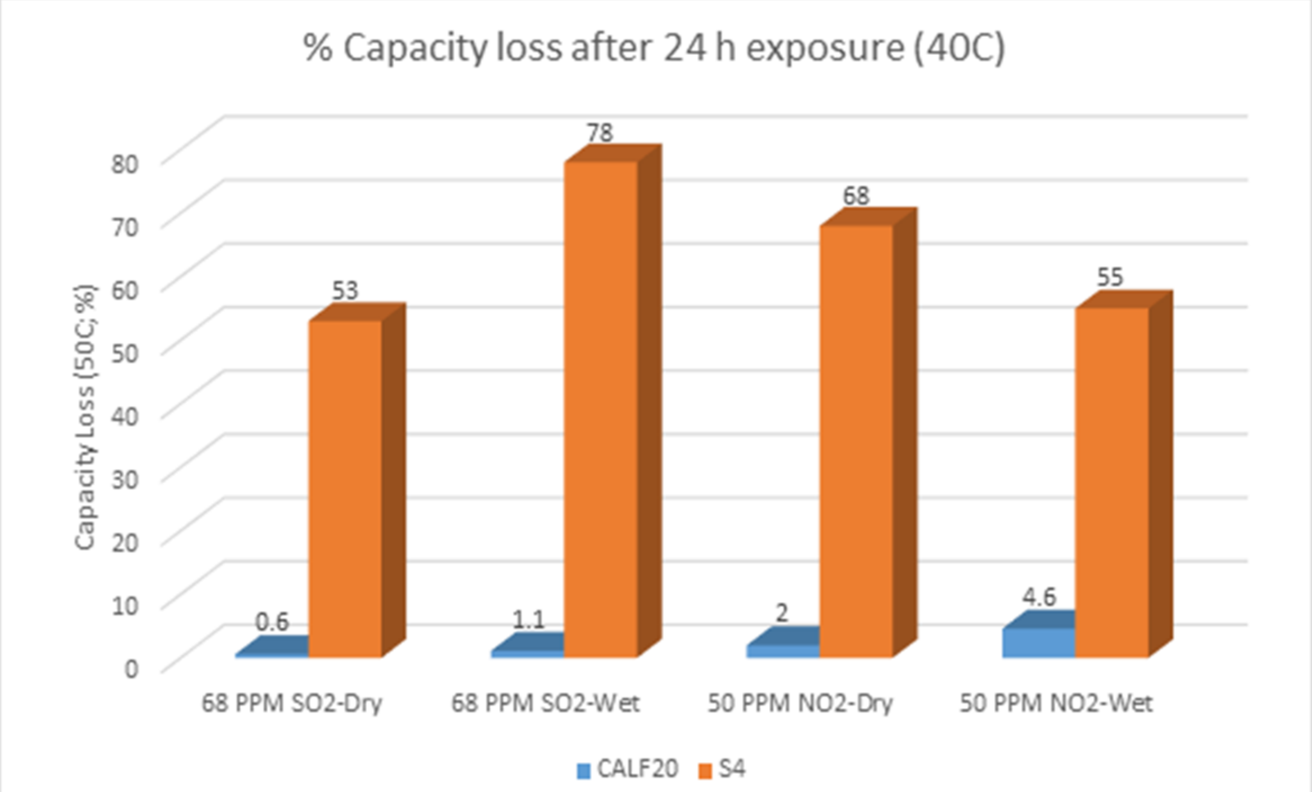
Amines vs MOF Stability



Amines vs MOF Contaminants Stability

Test Conditions:

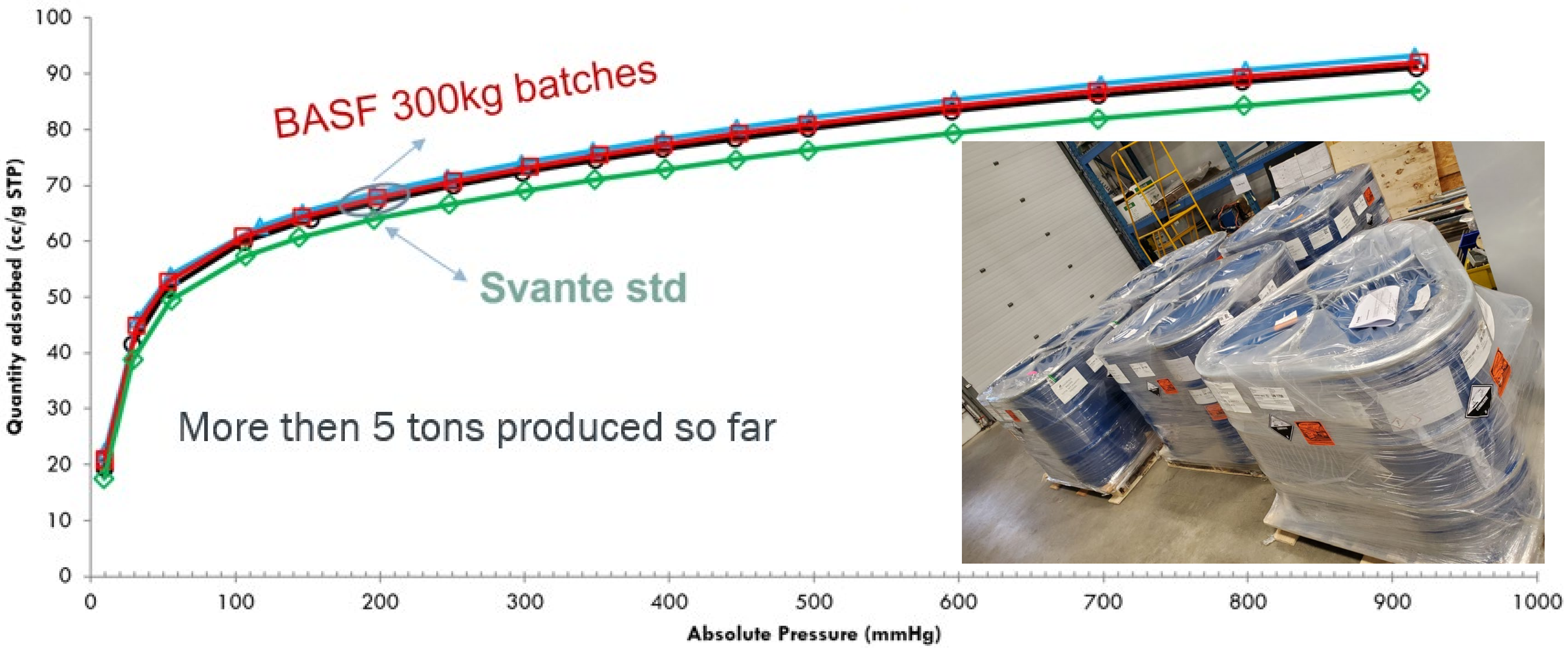
Condition 1	24h	67.8 ppm SO_2, 442.3 ppm CO, 61.7 ppm CH_4, 17.91% CO_2, balance He_ 1 atm, 40 C (dry)
Condition 2	24h	67.8 ppm SO_2, 442.3 ppm CO, 61.7 ppm CH_4, 17.91% CO_2, balance He_ 1 atm, 40 oC, **3.13%** Water (wet)
Condition 3	24h	50 ppm NO_2, 1 atm, balance He_ 40 oC (dry)
Condition 4	24h	50 ppm NO_2, balance He_ 1 atm, 40 oC, **3.13%** Water (wet)



CALF20 is much more resistant to SOx and NOx then amine-based material

CALF20 (MOF) Scale-up

BASF powder characterization – CO_2 isotherm at 25°C



- All of the 300kg batches are showing very uniform CO_2 isotherms with even better capacity than the Std Svante material (4kg batch size)

LafargeHolcim CO2MENT 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

Field Demonstration Unit at a Lafarge Cement Plant in Richmond, BC – 1TPD Phase Based on MOF

Pre-Treatment System & Capture Plant

RAM

What should be the next Generation of Advanced Structure Sorbent?

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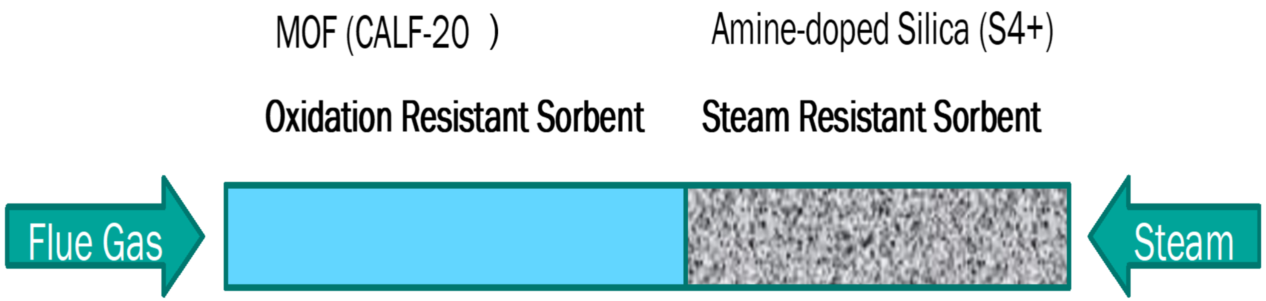
- Bi-layer structure did confirm decreasing the demand on regen energy (steam) of ~30%
  - Some cost penalty with increasing bed assembly and cycle complexity

- Can we have an advanced structure sorbent, using synergy of two sorbents (or more) with lower complexity and fully compatible with actual VeloxoThermTM RAM design ?

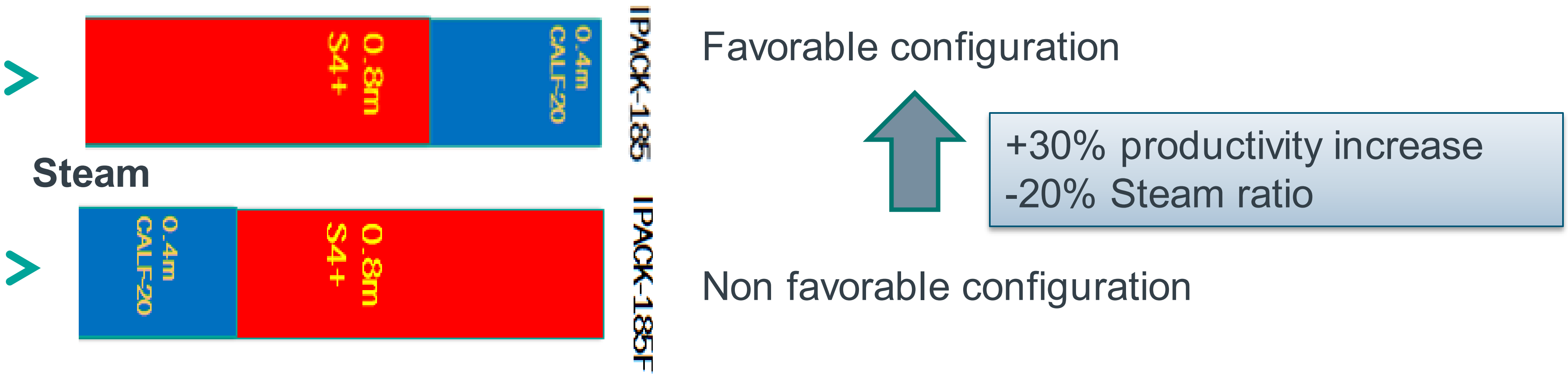
Segmented Bed – Durability Impact

- Segmented bed concept matches the best sorbent to the position of the bed (based on RH and Temperature profile)
- Amine-based sorbents will degrade faster in dry conditions under oxidative atmosphere.
- MOF steam sensitivity may also be improved.
  – Direct integration to the actual Svante RAM and balance of plant technology.



Segmented Bed-Proof of Concept

- A prototype segmented bed was fabricated with 0.4m CALF-20 (Top) and 0.8m S4+ (Bottom)
- VTS testing in two orientations and compared to Calf20 1m bed alone [10.6% CO_2 feed condition].
- The KPIs clearly confirmed performance increase when favourable configuration is used (Amines in highest RH region, CALF20 in lower RH region)



Summary

Development and long-term testing of two very interesting CO_2 capture materials that could be important for CO_2 capture for carbon reduction/removal and showing high stability (water and steam) (Direct air capture, coal, cement and SMR).

Scale-up of a steam stable, low cost, MOF material at tons scale using a world expert large chemical company (BASF)

Develop and test the concept of an advanced structured adsorbent architecture (segmented bed) compatible with actual VeloxothermTM Rotary Adsorption Machine (RAM) that could decrease capture cost and increase KPIs (performance and lifetime)

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Project Scope – BP1 Complete

Task/Subtask Number	SOPO Task/ Subtask Title	Completion Date
1.0	Project Management and Planning	04/30/21
2.0	Technology Maturation Plan	04/30/21
3.0	Adsorbent Selection, Characterization and Synthesis (Phase I)	04/30/20
3.1	Finalize candidate adsorbent materials for Bi-Layer program	07/30/19
3.2	Thermodynamic equilibrium measurements of candidate adsorbents	04/30/20
3.3	Dynamic characterization of kinetic behavior of adsorbents	04/30/20
3.4	Flue gas compatibility study – contaminants, composition, and condition	04/30/20
3.5	Adsorbent Down-Selection and Production	04/30/20
4.0	Bi-Layer Laminated Structures Development (Phase I)	04/15/20
4.1	Barrier material selection and optimization	04/15/20
4.2	Bi-Layer coating development	04/15/20
4.3	Bi-Layer spacer and flow-path control printing	04/15/20
4.4	Bi-Layer laminate structure development	04/15/20
5.0	Bi-Layer Structured Adsorbent Bed Development and Design	05/31/20
5.1	Bi-Layer structures packaging development	04/30/20
5.2	Bi-Layer Bed fluid distribution analysis for independent process streams	12/31/19
5.3	Bi-Layer Bed Design	05/31/20
6.0	VTS Modifications for Bi-Layer Bed Testing	05/31/20
7.0	Bi-layer Bed Bench-Scale Testing (Phase I)	07/31/20
8.0	Computational Modeling and Process Simulation (Phase I)	07/31/20

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Project Scope – BP2

MILESTONE LOG			
Budget Period	Task	Milestone Description	Completion Date
1	1	Updated Project Management Plan	7/1/2019
1	1	Kickoff Meeting	8/720/19
1	2	Technology Maturation Plan	9/30/2019
1	3	Initial selection of adsorbent materials for proof of concept (Gen-0) generation of Bi-Layer Architecture	10/30/2019
1	4	Initial stable Bi-layer laminated structure produced for VTS proof of concept bed testing - Gen-0	04/30/2020
1	5	Initial Bi-layer (Gen-0) full-scale structured adsorbent bed produced for VTS testing	05/30/2020
1	7	Gen-0 Bi-layer adsorbent bed demonstrates >30% improvement in steam consumption over Mark I Baseline	07/20/2020
2	9	Final specification of down-selected adsorbents for Gen-1 Mk-II Bi-Layer Architecture	01/31/2021
2	10	Proof of Scalability beyond kg scale of novel adsorbents	12/31/2020
2	11	Final Gen-1 Mk-II Bi-Layer laminate structure production for bench-scale bed testing	12/31/2020
2	12	Final Bi-Layer (Gen-1) full-scale structured adsorbent bed produced for VTS testing	12/31/2020
2	13	Gen-1 (Mk-II) Validated Process Cycle Design and Model for TEA evaluation	
2	14	Submit final Technology Gap Analysis Report	
2	14	Submit Report on final TEA analysis of Gen-1 (Mk-II) Structured Adsorbent CO_2	
2	14	Submit final EH&S Risk Assessment	

Appendix A: Organization Chart

- Electricore will serve as PRIME contractor and Project Director.
- Svante serves as the main technical point of contact for this project and technology provider.
- Susteon is leading the TEA.
- DNV is responsible for identification, development and updating critical documents for natural gas transmission stations and will perform process modeling and simulations.

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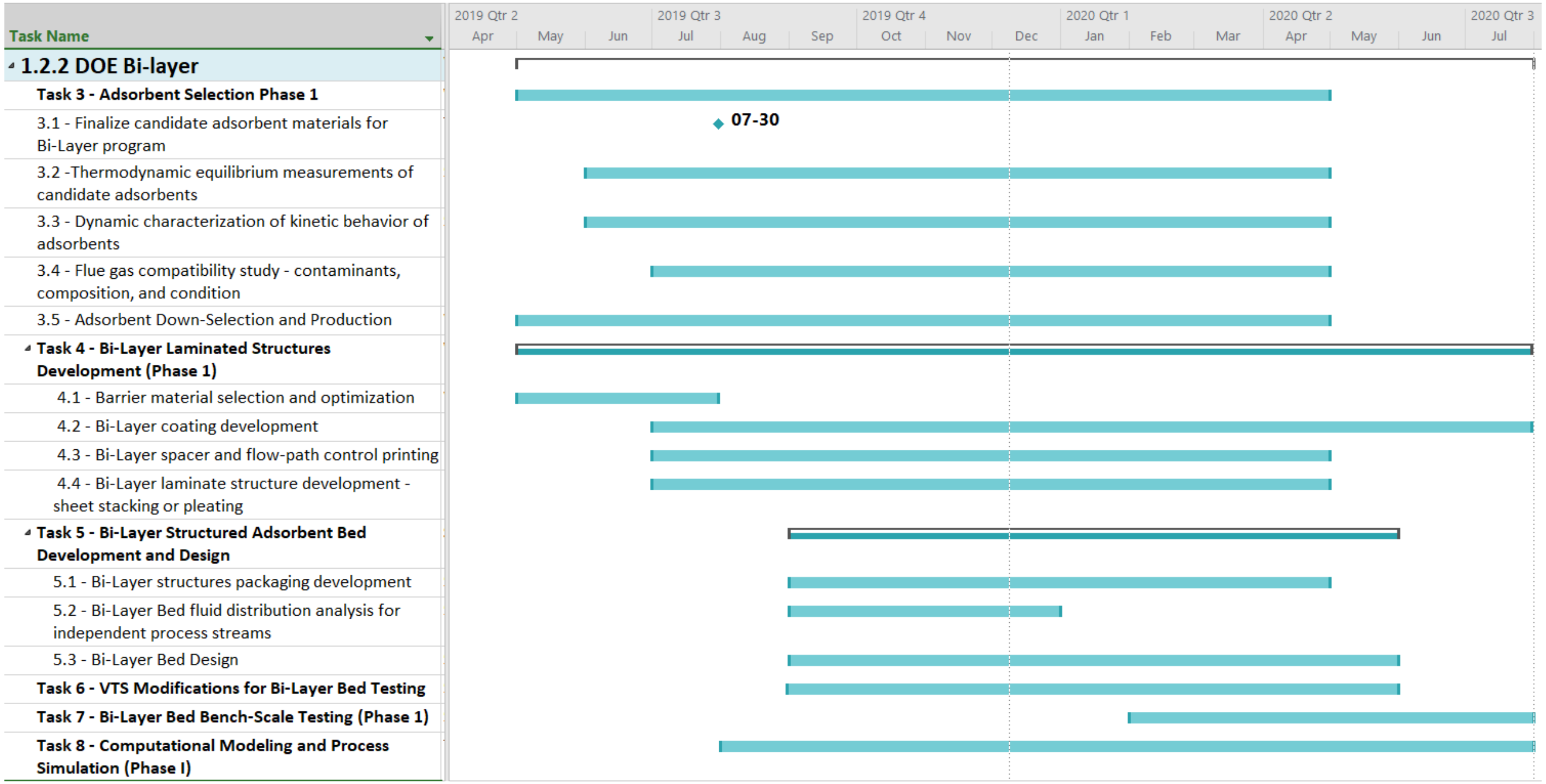
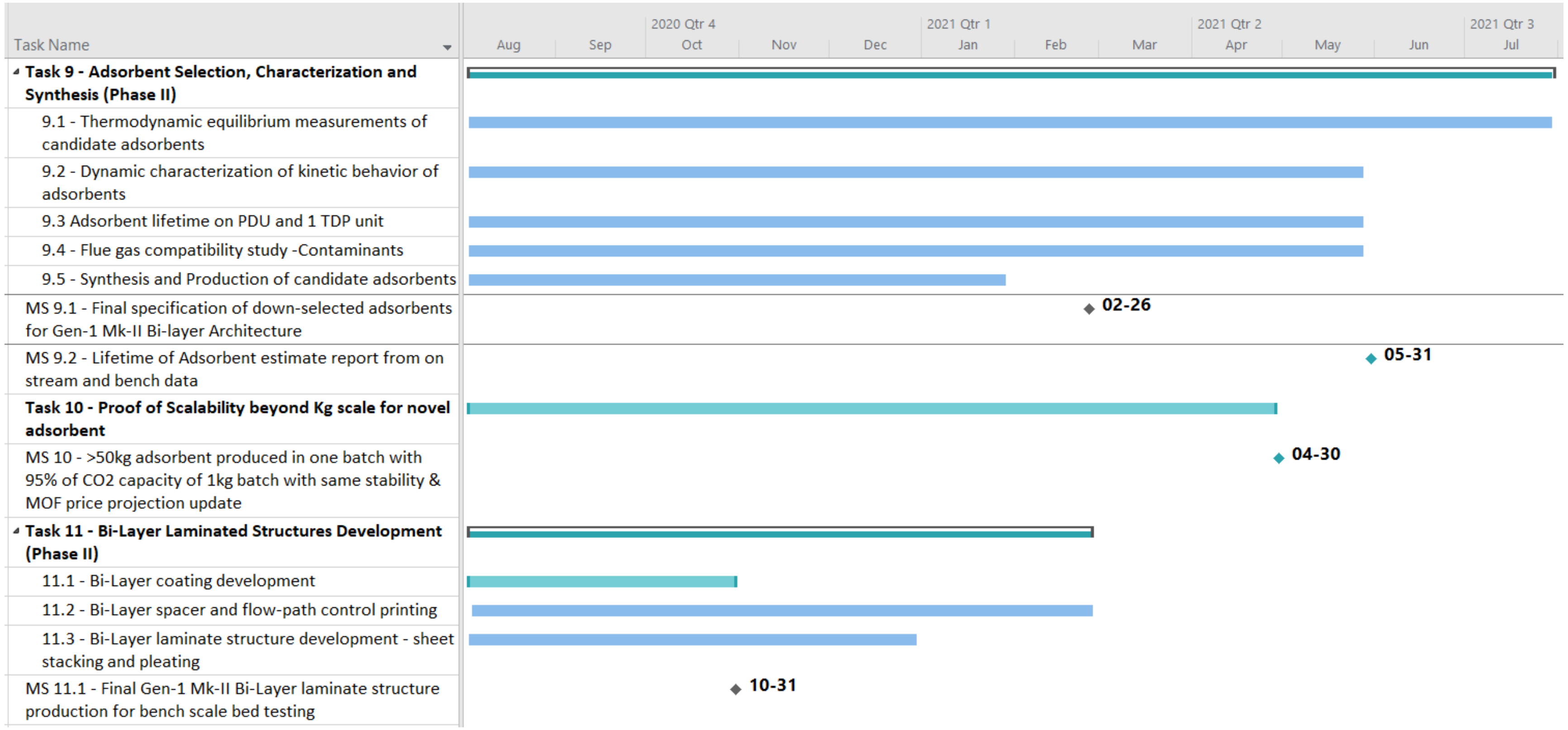
Appendix B: Gantt Chart – BP1



Gantt Chart – BP2



Gantt Chart – BP2 Cont.