Carbon Management Technology Conference

Global CCUS Innovation Nexus

ECO₂NOMICS™ THAT MAKE SENSE

VeloxoTherm™ CO_2 Capture Technology
Rapid Cycle Thermal Swing Adsorption Process

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July 18, 2017 | 1:50 PM

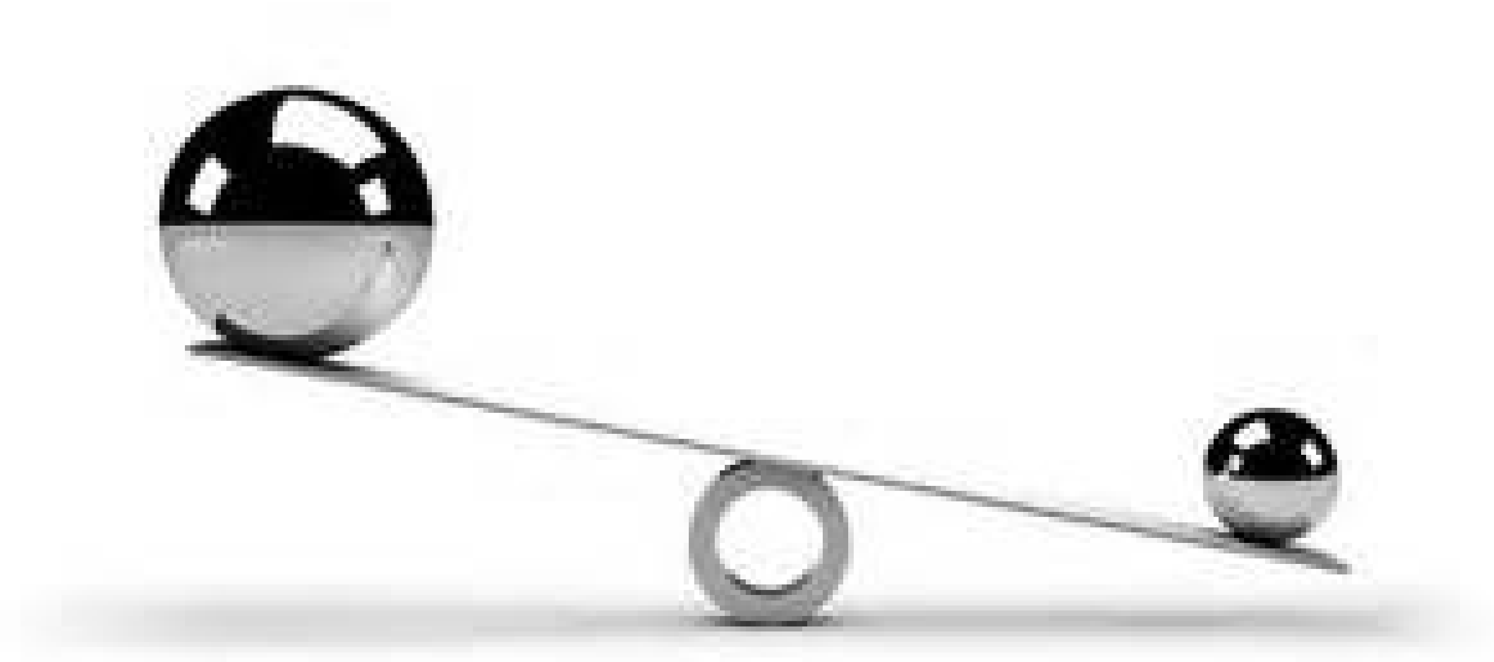
Hilton Americas Houston

"Inventys is developing technical advances that should dramatically reduce the cost of carbon capture so that it can be deployed worldwide.

If successful, our technology could revolutionize carbon capture."

— Inventys Board Member Dr. Steven Chu,
former US Energy Secretary and Nobel Laureate

ECO$_2$nomics That Make Sense



$60-90/tonne

Solvent-Based

Liquid

<$30/tonne

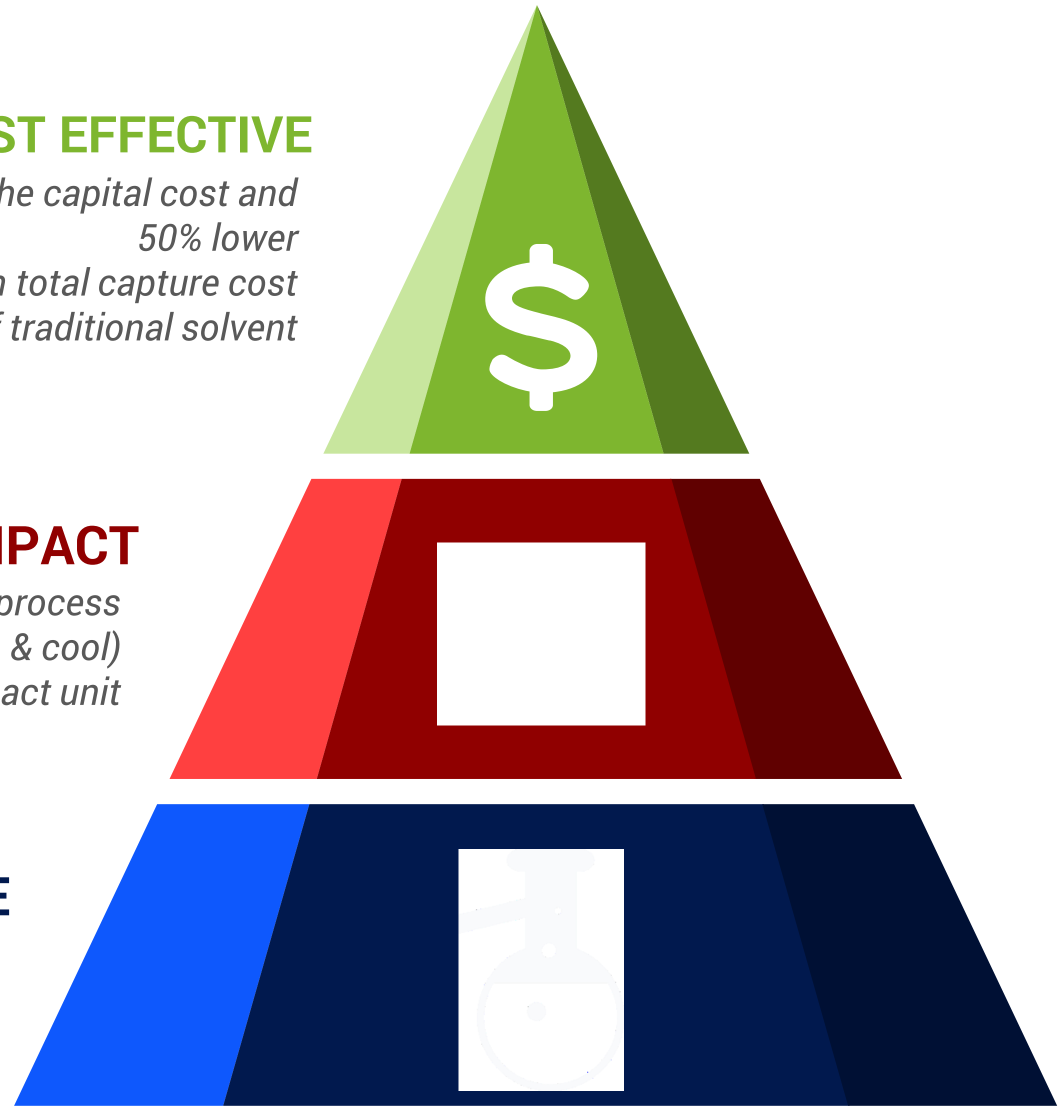
Structured Adsorbent

Solid

Inventys Story

COST EFFECTIVE

*1/3 the capital cost and
50% lower
in total capture cost
of traditional solvent*



COMPACT

*3-steps rapid cycle process
(adsorb, regenerate, & cool)
in one single compact unit*

HIGH PERFORMANCE

*Nanomaterials with
high surface area per unit volume
and no chemical degradation (filling)*

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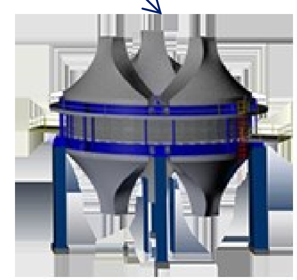
Small Size & Compact Design

~4,800 TPD CO_2 CAPTURE PLANT

orders of magnitude faster & more throughput

Smallest Footprint
Lowest Capital Cost
Low Installation Cost
No liquid amine hazard
Minimum Maintenance Cost

Solvent-based Liquid System



Structured Adsorbent Solid System

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Key Performance Indicators

Performance Objectives	Bench Scale Testing (2016)	Mark I Beds Target (2017)	Mark II Beds Target (2018)
Product CO_2 Purity *(%; dry basis)*	*92*	*85–95*	*90–95*
Recovery *(%; product CO_2/feed CO_2)*	*80*	*75–85*	*85–90*
Productivity *(TPD CO_2/m³ adsorbent)*	✓ **11**	**9–11**	**10–12**
Steam Ratio *(kg/kg; steam/product CO_2)*	*1.5*	*1.3–1.7*	➢ *0.8–1.2*

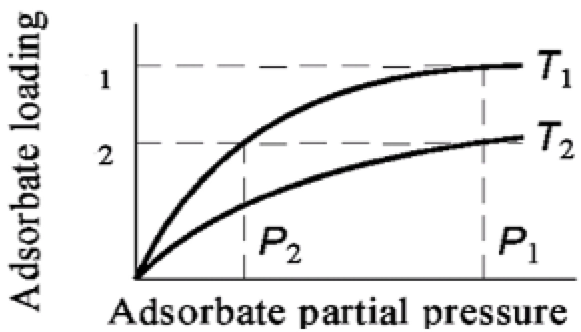
✓ **High Productivity → Compact Solution → Low Capital Cost**

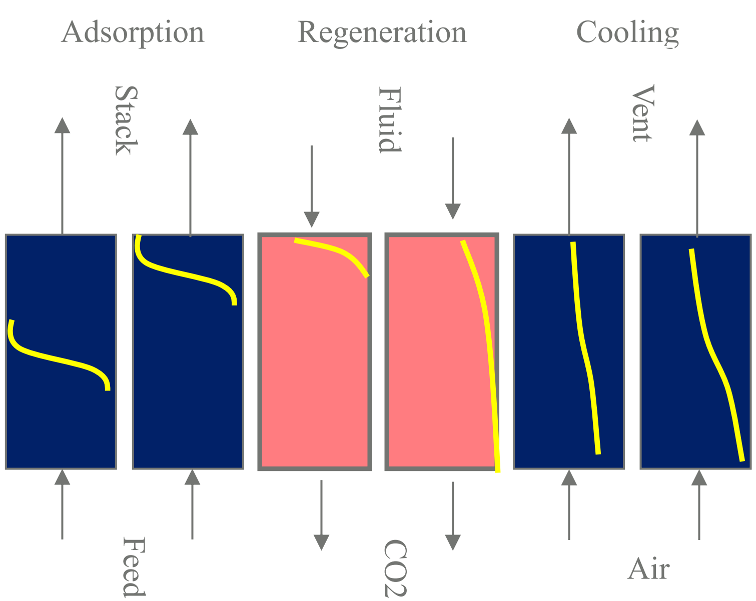
➢ **Low Steam Ratio → Low Regeneration Energy → Low Operating Cost**

Core Competencies

VeloxoTherm™ Process is Fast

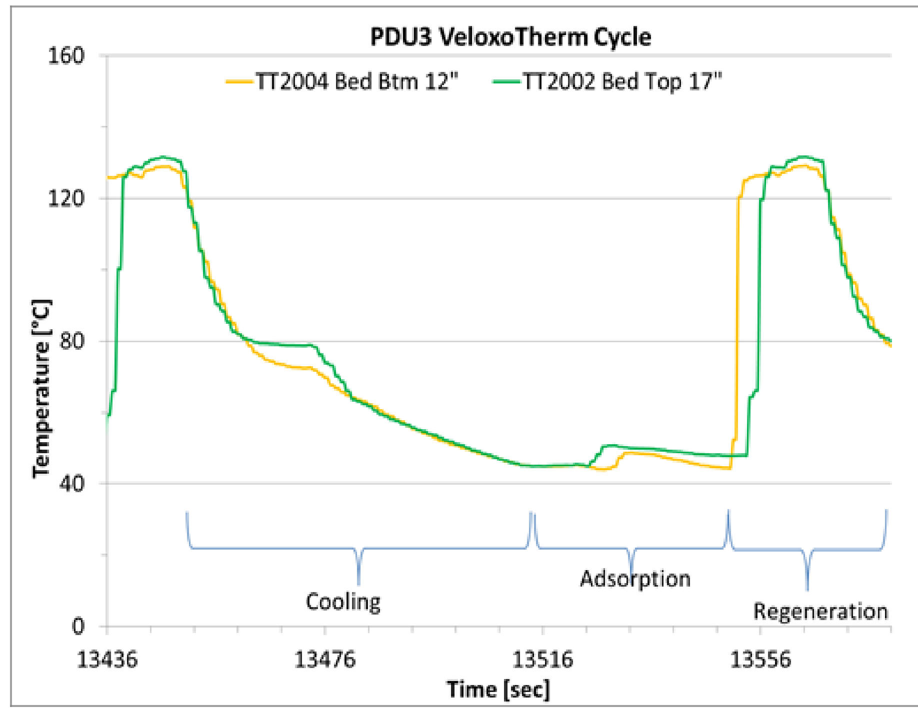
RC-TSA: RAPID CYCLE TEMPERATURE SWING ADSORPTION





» **Utilize cyclic gas concentration profile**

» **Utilize cyclic heat temperature profile**



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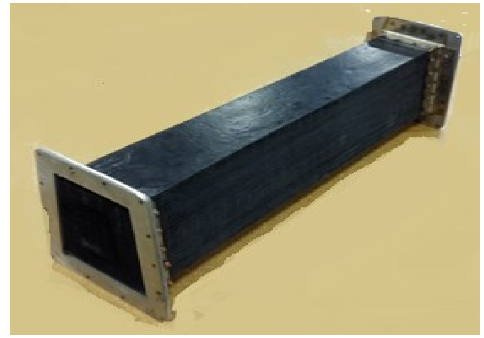
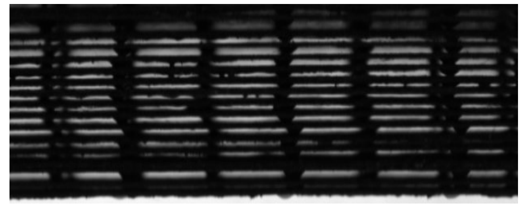
Core Technology

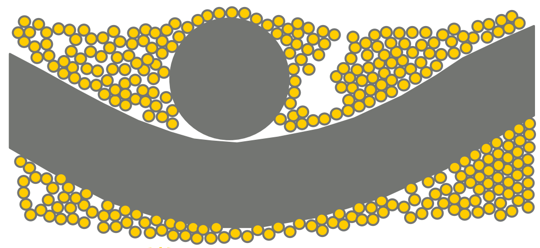
Packaged Structured Solid Adsorbent Bed



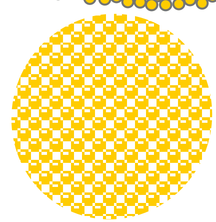
Structured Adsorbent



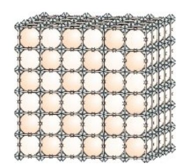
Adsorbent Sheet or Laminate



Solid Adsorbents

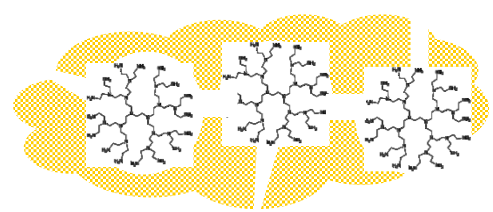


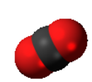
Amorphous

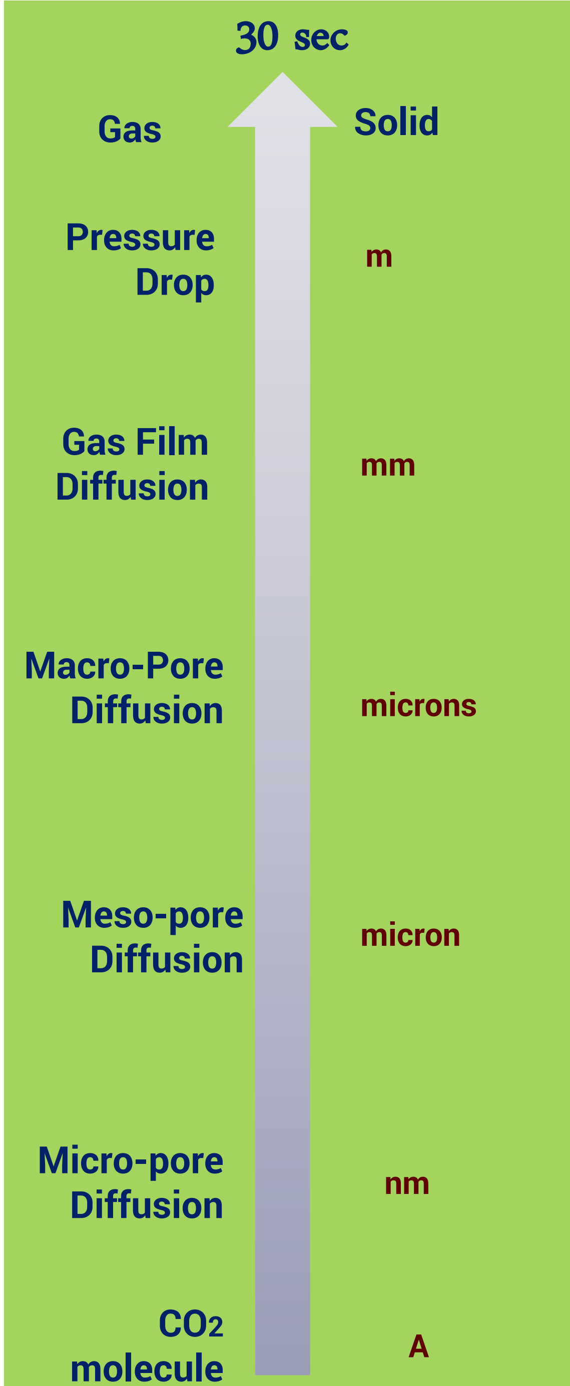


MOF

Porous Nano-Material





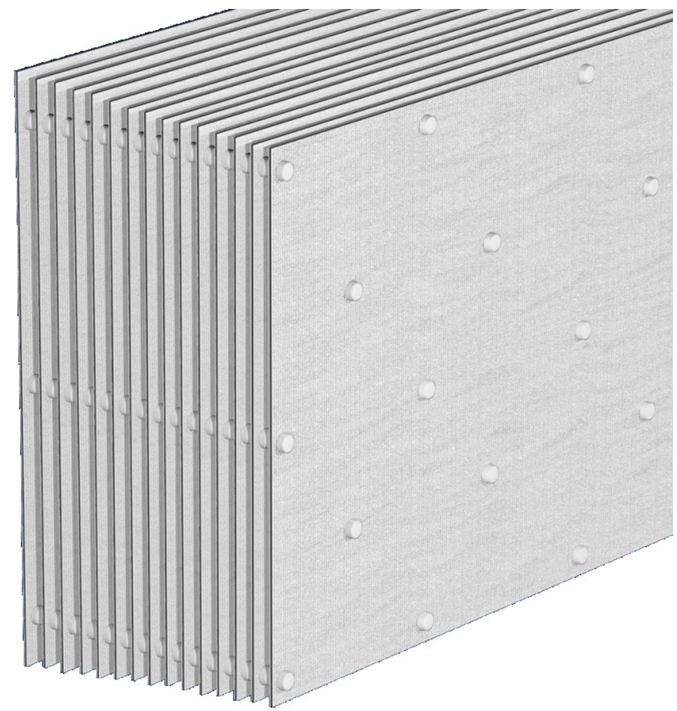


Structured Adsorbents

HOW THEY WORK

» **Inventys' Structured Adsorbents enable critical advantages:**

- **Effective Hydrodynamics** *with very low pressure drop*
- **Fast Transport Phenomena** *with high specific surface area*
- **Higher Durability** *with immobilized adsorbent*
- **Fast Kinetics** *and mass transfer with short diffusion paths*
- **Fast and Controlled Heat Transfer** *with anisotropic properties*
- **No Fluidization** *with immobilized mechanica function*
- **Superior Cyclic Performance** *based on kine separations*
- **High Heat and Mass Transport** *due to short diffusion paths*
- **Independently Engineered Thermal Propert** *of adsorbent*
- **Tailored Kinetic Selectivity** *structures desig*
- **Tailored Void Fraction** *and controlled void ra*
- **Tailored Packing Densities** *in adsorbent she*



Structured Adsorbents

HOW THEY WORK

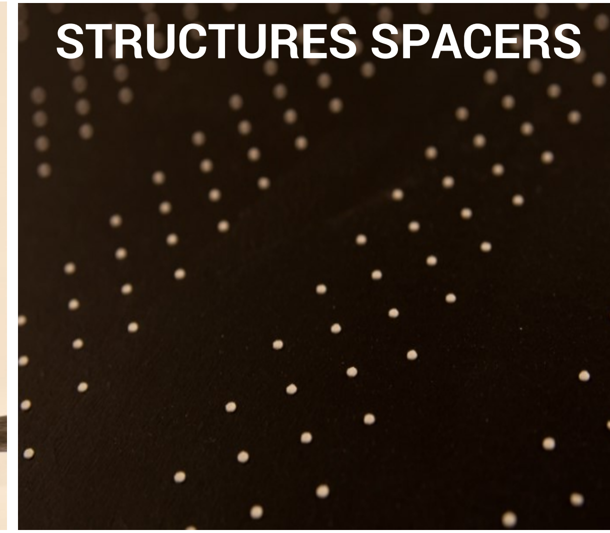
» **Carbon capture requires:**

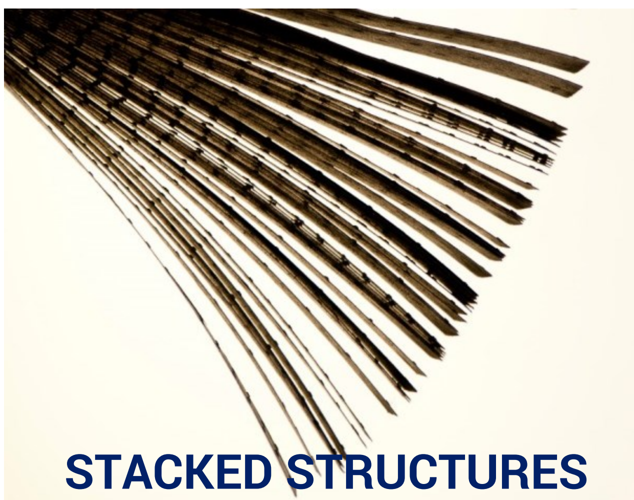
- *Handling large volumes of flue gas at low pressures.*
- *Low pressure drop at high superficial gas velocities required.*
- *High surface area to be able handle the energy in/out with minimum losses.*

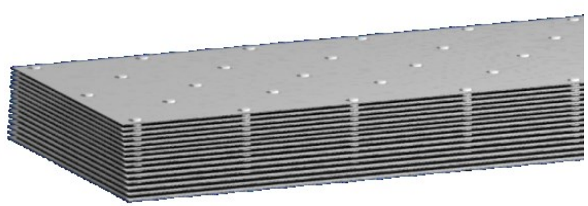
Sorbent Property	Granular	Structures
Sorbent Configuration	*Packed Bed*	*Spaced Sheets*
Characteristic Dimension(s)	*0.7 mm*	*0.1 mm*
Specific Surface Area [m^2/m^3]	*5,400*	*10,000*
Mass Transfer Coefficient [s^{-1}]	*287*	*1629*
Superficial Gas Velocity [cm/s]	*280*	*280*
Pressure Drop (Pa)	*2,000*	*110*

Structured Adsorbents

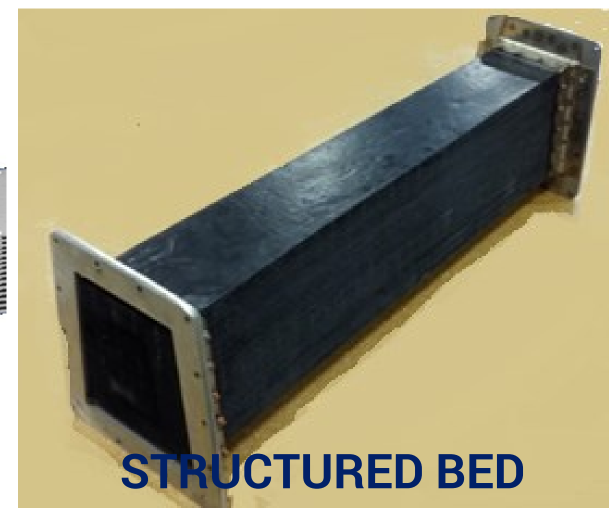
FROM POWDER TO BED







BONDED STRUCTURES



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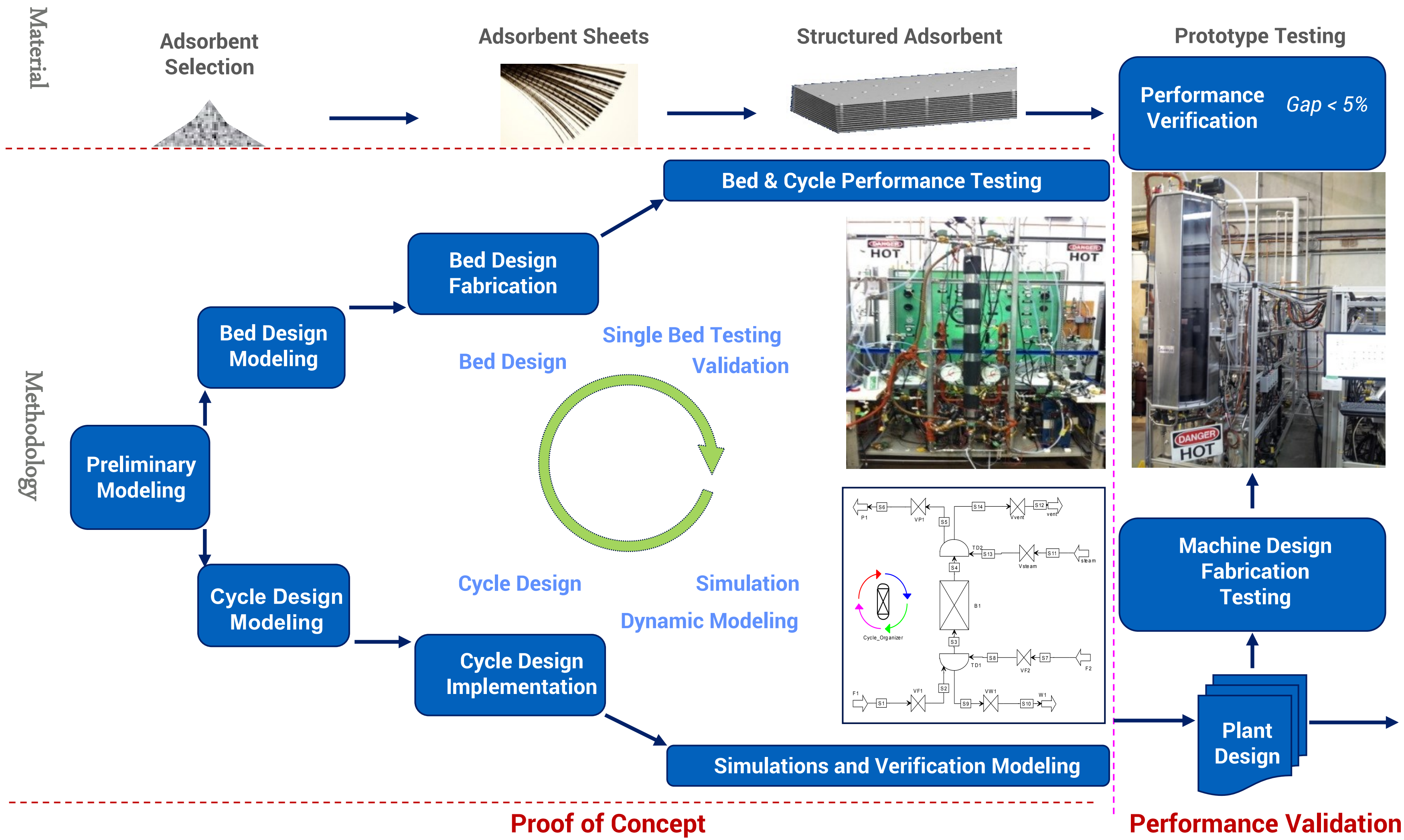
Materials & Cycle Development



Modeling Concept Design → Fabrication → Experimentation → Verification → Detailed Design

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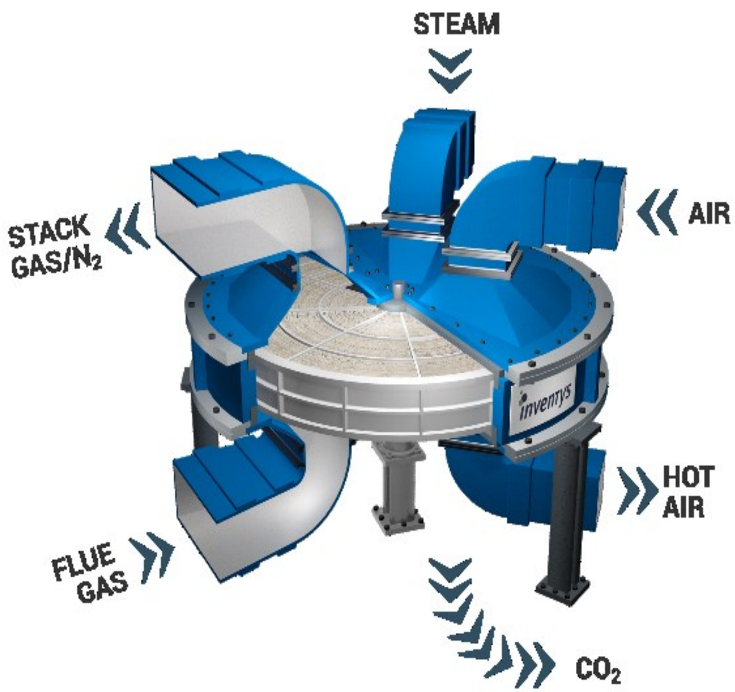
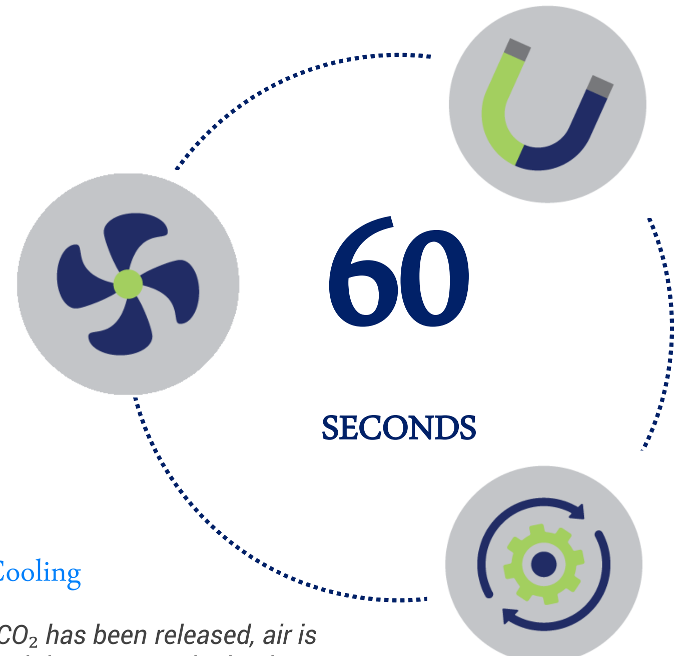
Rapid Cycle Temperature Swing Adsorption

THREE SIMPLE STEPS





Step 1: Adsorption

As flue gas passes through the VeloxoTherm™ Adsorbent Structure, CO_2 clings to the adsorbent while the other gases pass through.

Step 2: Regeneration

After the structured adsorbent becomes saturated with CO_2, it is regenerated. Low pressure steam is used to release the CO_2 from the adsorbent.

tep 3: Cooling

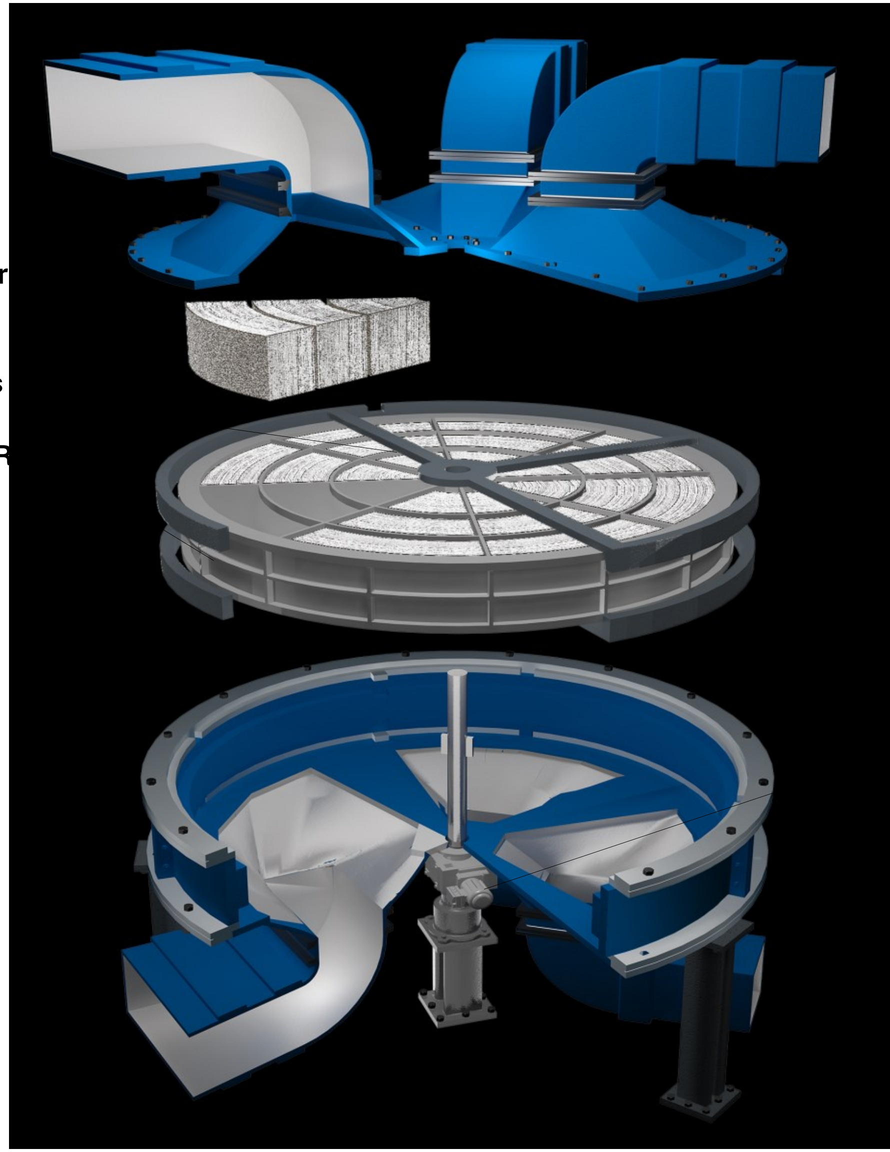
fter the CO_2 has been released, air is used to cool the structured adsorbent, preparing it for the adsorption step and the process is started over again.

Complex Cycle in Simple Hardware

Structured Sor

Gas

R



Motor

Process Cycle Development

Adsorbent Thermodynamic Properties (isotherms, δH)

Structures Transport Properties (δP, D, k, Cp, etc.)

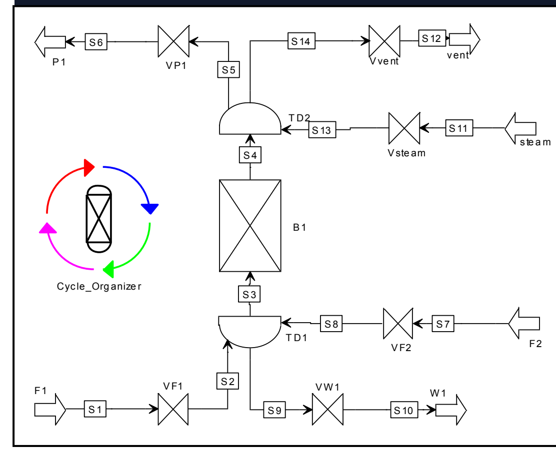
Dynamic Simulation (ADSIM Custom Modeling)

Process Cycle Testing (VeloxoTherm Test Station)

Cycle Design Model Verification (Test = Model)

Dynamic Simulations

» **Proprietary process models; Built on commercial software**
- *TSA Cycle with proprietary custom code*
- *Finite Element Method*
- *Solid & gas phase material energy balance*
- *Momentum mass and heat transfer*
- *Customized for parallel plate geometry*



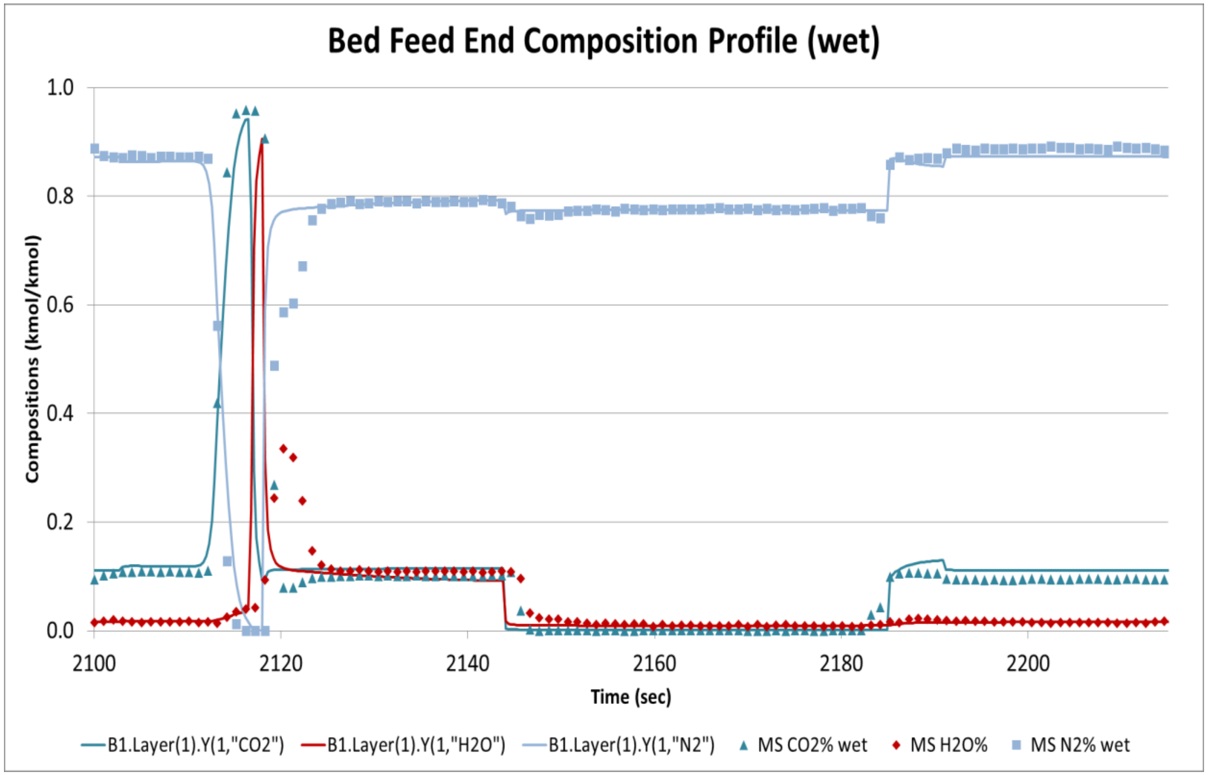
$$-\varepsilon_i E_{zk}\frac{\partial^2 c_k}{\partial z^2}-\varepsilon_i E_{rk}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial c_k}{\partial r}\right)+\frac{\partial(v_g c_g)}{\partial z}+\varepsilon_B\frac{\partial c_k}{\partial t}+J_k=0$$

$$-k_{ga}\varepsilon_i\frac{\partial^2 T_g}{\partial z^2}+C_{vg}v_g\rho_g\frac{\partial T_g}{\partial z}+\varepsilon_B C_{vg}\rho_g\frac{\partial T_g}{\partial t}+P\frac{\partial v_g}{\partial z}+HTCa_p(T_g-T_s)=0$$

$$-k_{sa}\frac{\partial^2 T_s}{\partial z^2}-k_{sr}\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial T_s}{\partial r}\right)+\rho_s C_{ps}\frac{\partial T_s}{\partial t}+\rho_s\sum_{i=1}^{n}(C_{pai}w_i)\frac{\partial T_s}{\partial t}+\rho_s\sum_{i=1}^{n}\left(\Delta H_i\frac{\partial w_i}{\partial t}\right)-HTCa_p(T_g-T_s)=0$$

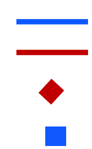
Process Model Verification

Simulated Adsorbent Bed Gas Compositions vs Test



Dynamic Simulation
Finite Element Modeling
INPUTS:

- *Equilibrium Isotherms*
- *Kinetic Diffusion Rates*
- *Mass Transfer Coefficient*
- *Adsorbent Bed Properties*
- *Bed Geometry*
- *Cycle Steps and Durations*



Cost Analysis Methodology

Simulation and Verification Modeling

Identify Key Performance Indicators

Process Flow Diagrams and Major Equipment List

Equipment Cost calculated based on budgetary quotes where possible or APEA

Class IV TEA developed using Factored Estimate (AACE methodology)

Cost Model Definition

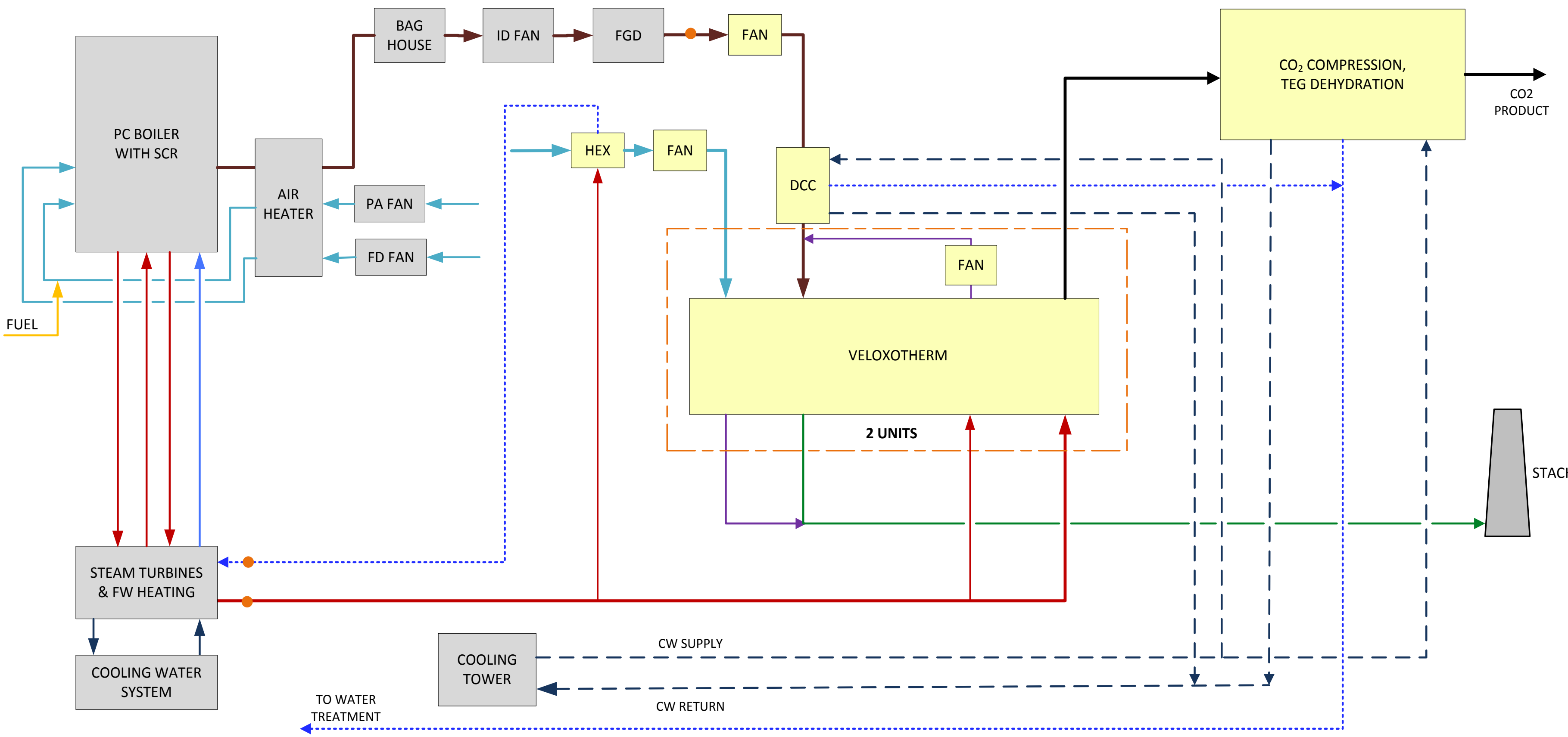
CAPITAL COST ESTIMATION

Using factor methodology - based on AACE International 16R-90 with user variations based on cost factors from recently conducted FEED studies.

- **Purchased Equipment Cost (PEC)**
- **Bare Erected Costs (BEC):** *PEC, supporting facilities, materials, bulks/commodities and direct and indirect labor expense*
- **Total Plant Cost (TPC):** *BEC + engineering/construction management/home office and contractor premiums, allowances and freight, process and project contingencies.*
- **Total Overnight Cost (TOC):** *TPC + pre-production costs, inventory capital, financing costs and other owner costs (where applicable).*

Block Flow Diagram

~10,000 TPD CO_2 CAPTURE AND COMPRESSION PLANT



Simple and compact process resulting in low CAPEX

Coal Flue Gas Carbon Capture Cost

» Process design basis and performance targets

Design Basis		
Coal Flue Gas CO_2 Concentration	*%v/v dry*	*15.0*
	%v/v wet	*12.8*
CO_2 Capture Capacity	*TPD*	*9,583*
CO_2 Capture Efficiency/Recovery	*%*	*90*
CO_2 Product Purity	*%v/v (dry)*	*95*
CO_2 Product Pressure	*psia*	*2215*
Plant Capacity Factor	*%*	*85*

Performance Targets		
Steam Ratio	*kg/kg*	*1.5:1*
Max Pressure Drop Per Adsorbent Pass	*kPa*	*10*
Adsorbent Productivity	*TPD CO_2/m^3*	*11*
Auxiliary Flow to Fresh Feed Ratio	*mol/mol (dry)*	*~1.1:1*
O_2 Product Purity	*%v/v*	*Less than 0.1%*

Cost Model Results Summary

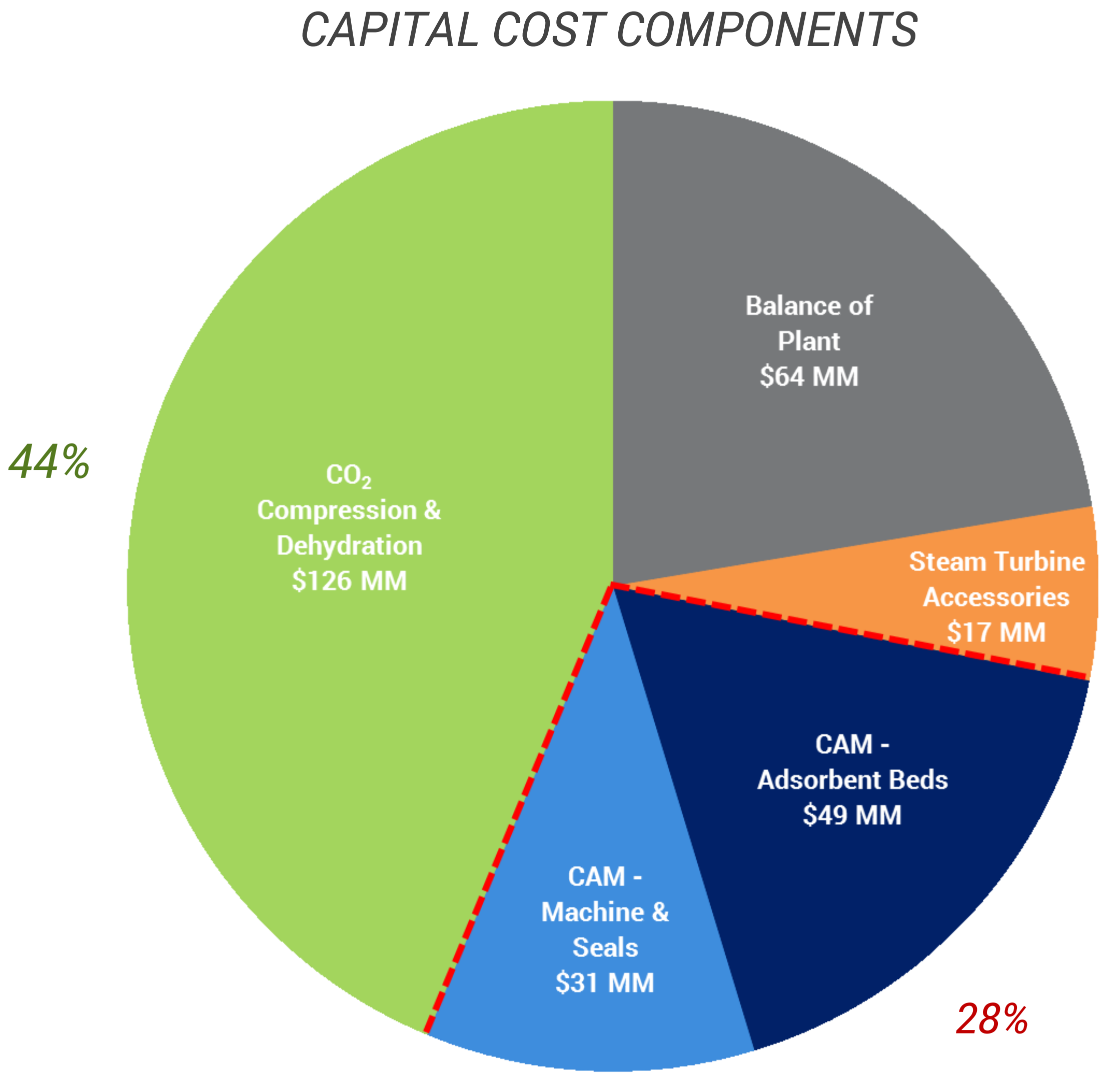
RESULTS ($USD)		
Total Cost of Capture	*$/T CO_2*	*33*
Total Overnight Costs	*$MM*	*288*
*Steam Energy Requirement**	*GJ/T CO_2*	*4.0*
*Auxiliary Heating**	*GJ/T CO_2*	*0.5*
Capture Plant BoP Energy Requirement	*MWe*	*16.3*
Compression Energy Requirement	*MWe*	*47.4*
Steam Ratio	*kg/kg CO_2*	*1.5:1*

*Based on enthalpy of steam at take-off conditions – heat integration and pinch analysis to be conducted

The scope of this analysis, and associated capital and operating cost estimation, considers all unit operations, equipment and utilities implied below:

- *Gross power losses due to steam extraction at LP steam turbines*
- *Net parasitic losses due to increase in auxiliary power demand*
- *Raw make-up water (evaporative and stack losses)*

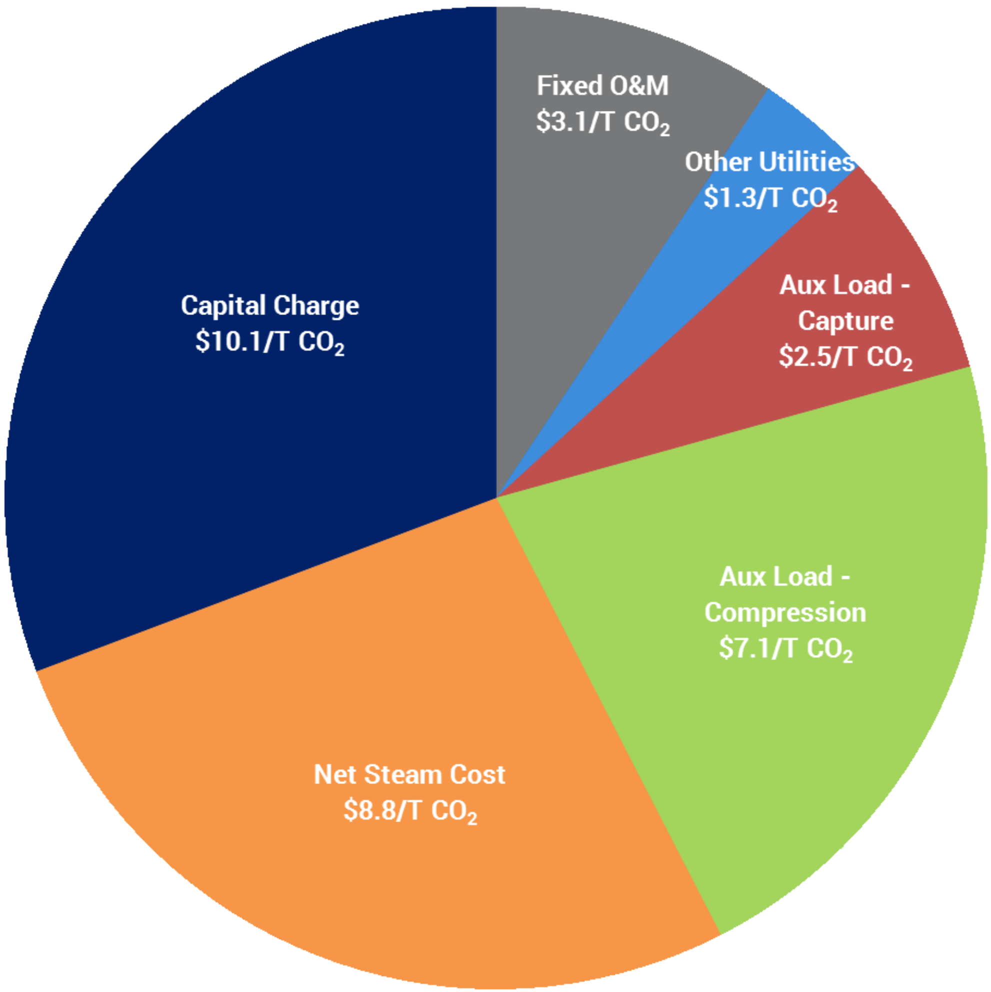
Cost Model Results



Total Capital <$290 MM USD

Cost Model Results

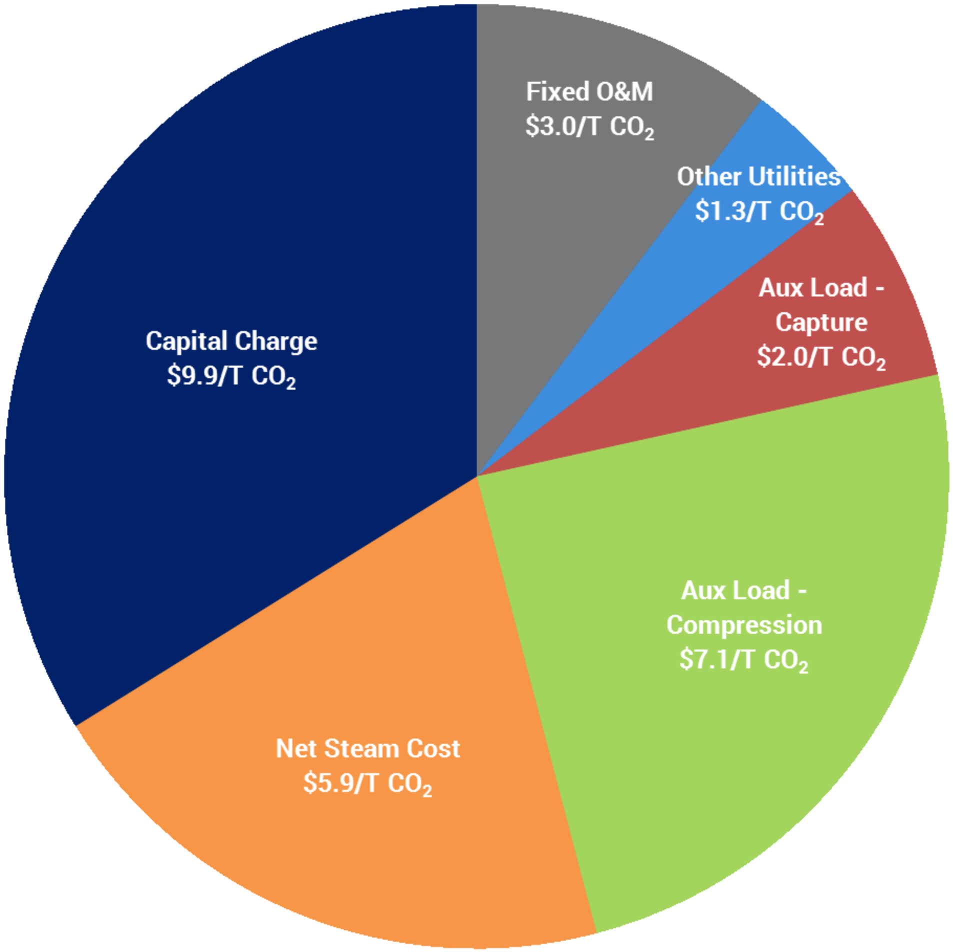
COST OF CO_2 CAPTURE AND COMPRESSION



Total Cost of Capture and Compression <$33USD/MT CO_2

Steam Ratio Sensitivity

COST OF CO_2 CAPTURE AND COMPRESSION
STEAM RATIO 1:1 kg/kg CO_2



Total Cost of Capture and Compression <$30USD/MT CO_2

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Field Demo Plant

LOCATED AT PIKES PEAK SOUTH LLOYD THERMAL PROJECT

Product Development Roadmap

Mark I	*Successfully developed and tested*	*Detailed TEA completed: 3-fold reduction in capital cost*	**$33 USD***
Mark II	*Significant reduction in energy cost, utilizing tailored adsorbent*	*New architecture and adsorbent properties within low-cost embodiment*	**$25 USD***
Mark III	*Adsorbent development program*	*Advances in adsorbent chemistry to utilize waste heat*	**$15 USD***

*Lifecycle cost per tonne of Captured and Compressed CO_2

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Commercialization Path

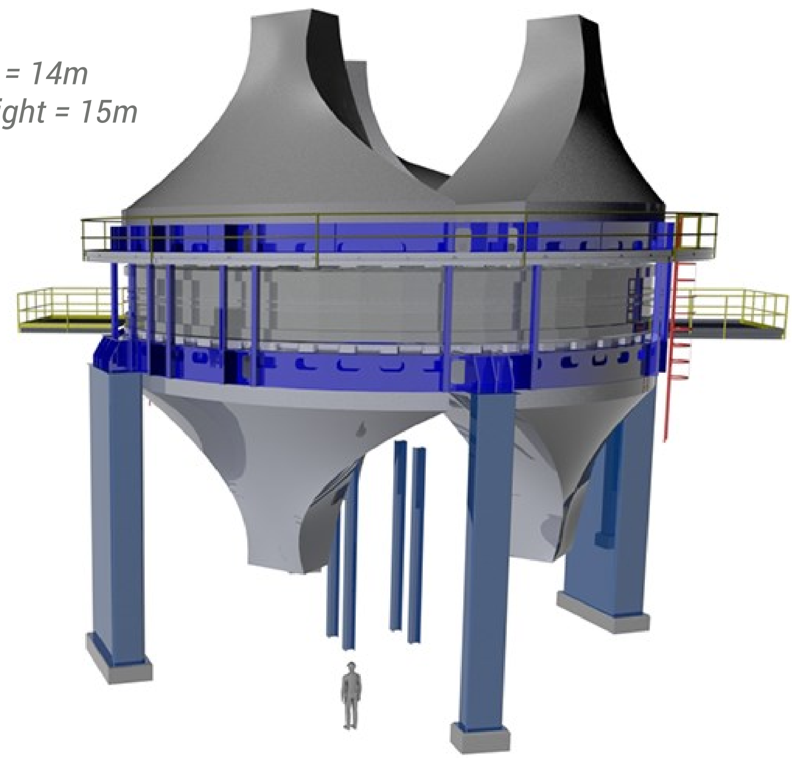
Field Demo Coal Power Plant	Field Demo O&G Heavy EOR	First-of-a-Kind Demo Plant O&G Heavy EOR	First Commercial O&G Heavy EOR
2016	2017	2018	2020

0.5 TPD · **30 TPD** · **600 TPD**

OD = 0.3m
Height = 1.3m

OD = 3.2m
Height = 7m

OD = 14m
Height = 15m



Strong Partners for Execution

INDUSTRIAL, GOVERNMENT, & FINANCIAL PARTNERSHIPS

Customer Relationships

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OXY
Husky Energy
SUNCOR ENERGY

Project Investors

NRC·CNRC
U.S. DEPARTMENT OF ENERGY
energy technologies institute
SUSTAINABLE DEVELOPMENT TECHNOLOGY CANADA™
CCEMC Climate Change & Emissions Management Corporation
Western Economic Diversification Canada

Equity Investors

CHRYSALIX ENERGY VENTURE CAPITAL
Chevron
THE RODA GROUP
MITSUI GLOBAL INVESTMENT

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APPENDIX

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